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Including

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In Situ Recovery (ISR) Keynote

TRENDS IN ISR TECHNOLOGY

By

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ABSTRACT

After a 60-years history, the development of ISR technology enters into its fourth stage: ISR 4.0. The challenges and possibilities of applying ISR to produce metals in general – and technology metals in particular – are outlined by (i) systematizing the feasibility criteria (ore morphology/grade distribution, hydrogeology, mineralogy, groundwater chemistry, microbiology), (ii) characterizing the combination of ISR wellfield hydrology and leaching chemistry (including thermodynamics and kinetics) both determining achievable production rates, and (iii) generically describing the dependence of ISR projects economics on key variables (including deposit criteria and design parameters).

By referring mainly to recent advancements in the ISR of uranium, the overview on the following key areas of ISR project development and application includes:

(i)   ISR-specific exploration/delineation methodology and 3D deposit modelling
(ii) State-of-the-art and innovative test procedures, ISR-specific requirements and model-based up-scaling to field conditions
(iii) ISR wellfield design, optimization and control, in particular, emphasizing:
   a.   model-based software tools (overview)
   b.   potential of permeability enhancement (e.g. by fracturing)
   c.   chemical pre-conditioning options
(iv) Metal processing in ISR operations (also reviewing model-based software tools for control and optimization)
(v)   Post-mining measures and ISR aquifer restoration

In the case of reduced minerals (e.g. tetravalent U minerals and metal sulfides), leaching involves redox processes to oxidize the metal-bearing minerals and to dissolve the metals of interest. The underlying thermodynamic conditions and specific kinetics of these redox reactions (including competing processes) are characterized and discussed with reference to practical applications (feasibility at industrial scale).

Recent core assays and tests demonstrate the role of mineral texture and relevant reactive surfaces for leaching kinetics, whereas the degree of hydrological heterogeneities at various scales (studied by tomographic methods) determines the achievable effective contact of leachant and mineral. The ISR productivity in general and the time dependence of metal leaching from wellfields in particular depend on this interplay between pore-volume exchange rate and leaching kinetics. The potential of (model-based) ISR wellfield design and performance and constraints of ISR productivity are systematically demonstrated.

The role of microorganisms in the in-situ recovery of technology metals, in particular by acid leaching from reduced ores, attracts increasing interest. Based on electron-balance criteria and practical application conditions the potential of bioleaching in ISR applications is characterized. Finally, the review provides a summary of key factors to implement ISR 4.0.

Keywords: in-situ recovery (ISR), mining (ISR) 4.0, geophysical survey, borehole logging, 3D deposit modelling, sedimentary deposits, redox reactions, leaching kinetics, reactive transport, bioleaching, ISR wellfield design, ISR operation, ISR economics

INTRODUCTION 1: IN-SITU RECOVERY

In-situ recovery (ISR), also referred to as in-situ leaching (ISL), is based on the (mostly selective) leaching of metals by applying a hydraulic regime (mostly a cycle) of a chemically conditioned leaching solution (lixiviant) through (mostly confined) underground orebodies.[2][19] Whereas the general term 'in-situ leaching' does actually characterize a natural process in geological systems, 'in-situ recovery' stands for a mining method. A first reference to in-situ recovery can be found in Agricola's 'De Re Metallica'[1] (metal-bearing mine effluent concentrated by evaporation). The 'standard ISR' is understood to be the operation of wellfields consisting of injectors and extractors (production wells) according to an appropriate wellfield geometry (regarding spacing and pattern) with wells of both categories screened in the zone of interest under saturated conditions. The metal(s) are usually recovered from the pregnant leach solution (PLS) by ion exchange (IX) or solvent extraction (SX) followed by the refortification (chemical re-conditioning) of the barren solution and recycling to the injectors. Wellfields are developed in a consecutive manner to sustain the production of the life of mine (Figure 1).
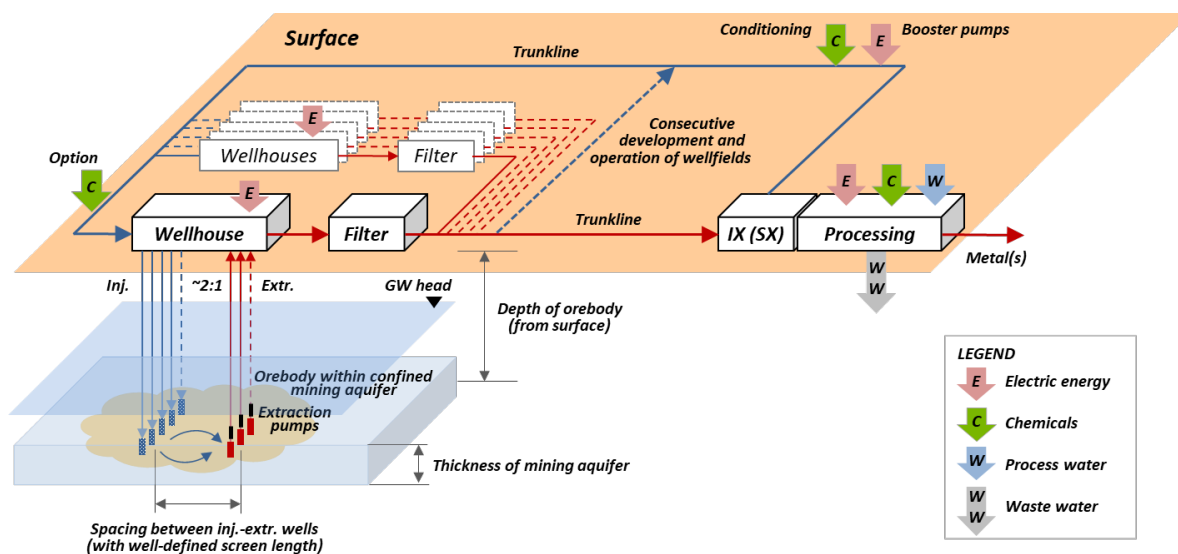

Figure 1: Scheme of 'standard' ISR by operating wellfields under saturated conditions

ISR operated in saturated and mostly confined orebodies is mainly applied for uranium production (>50 % of current world production). ISR of non-uranium metals has been reviewed by Seredkin et al.[14][15], distinguishing between industrial-scale (Zn/Cu/Au-Ag/Li) and pilot scale (Ni-Co/Re/V/Se/Sc/REE/Mn/W/PGM/Pb) applications.

Alternative ISR technologies, mostly operated under unsaturated conditions (percolate lixiviant flow), include:

(i)   Underground ISR zones in unsaturated orebodies operated by the use of injection systems/wells and suitable drainage systems/wells for PLS recovery

(ii) ISR applied to hillside orebodies (either natural or open pit access)

(iii) Block (stope) leach systems developed in underground mines

Whereas options (i) and (ii) are more conceptual (not yet applied for quantitative industrial scale recovery), option (iii) has been developed and used in several countries (F, USA, RU, GDR) in the 70's and 80's with the Koenigstein uranium mine in East Germany (GDR) being the largest known operation (about 17 million lbs U_3O_8 produced by ISR) by applying several technologies including drilling and blasting for permeability stimulation).[6]

INTRODUCTION 2: HISTORY AND FUTURE OF IN-SITU MINING

The history of ISR mining can be categorized in phases as illustrated in Figure 2. After the early development in the USA and the former Soviet Union around 1960 and the first industrial applications (ISR 1.0), large-scale ISR had been applied in several countries in the 1970's and 1980's (ISR 2.0), however, not yet meeting environmental compliance. The stagnation phase around 1990 and closure of many ISR mines revealed significant environmental legacies. Modern ISR technology has been developed since about 2000 (ISR 3.0). It is characterized by the

implementation of more efficient and environmentally compliant technological approaches in accordance to more stringent regulatory standards. The next-generation ISR technology is expected to follow general Industry 4.0 trends.[6][14]
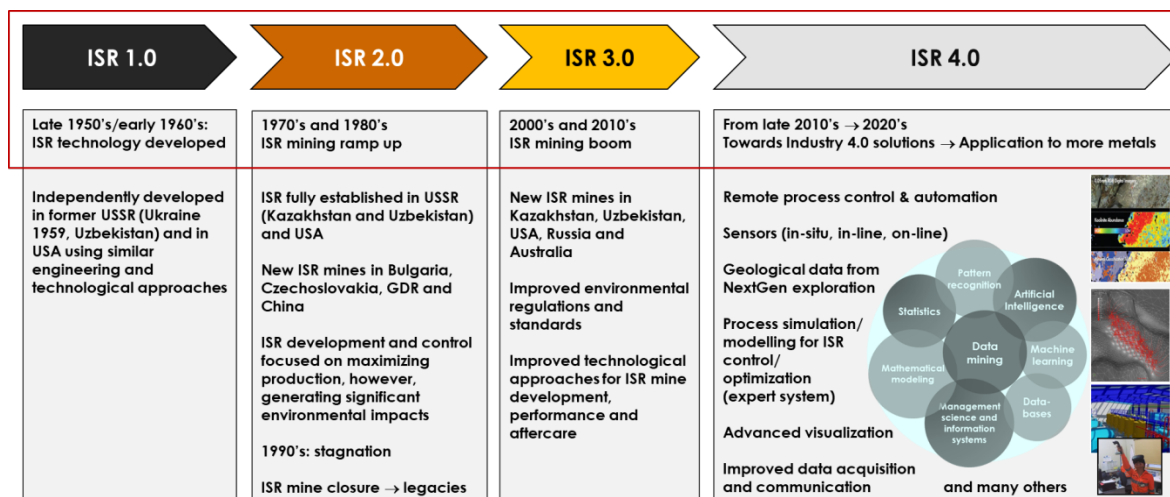

Figure 2: Development phases of ISR technology

In addition to the increasing application of Industry 4.0 standards in large-scale conventional mining (underground and open-pit) projects, future mining operations will face new, more challenging conditions. Current trend analyses reflect several key factors of future mining including:

(i) **Extreme mining:** In view of world-wide resource depletion, mining will be developed at new frontiers (i.e. at larger depths/less ore grade, in new areas like sea-floors, etc.).

(ii) **Adaptive mining:** The operational efficiency in conventional mining can be secured by new forms of selective (precision) mining to reduce any forms of residues by implementing a higher degree of automation and using versatile, modular equipment.

(iii) **Digital mine:** Current trends have already demonstrated that a higher productivity in mining operations can be achieved by secured, data-driven operations.

(iv) **Value mining networks:** Economic experts predict a higher level of integration of suppliers and subsequent partners along the value chain for improved operational excellence.

In the context of the above general trends, the so-called 'in-place mining'[2][13], also referred to as 'invisible' mining, is considered to be the key to achieve minimized surface footprint, minimized or vanishing waste heaps/tailings, reduced surface infrastructure, reduced consumption of energy and chemicals, improved environmental compliance, minimized costs, and increased social acceptance. In-place mining could be differentiated into three main categories:

In-line recovery:
Selective (precision) mining and underground physical beneficiation

In-mine recovery:
Selective (precision) mining in combination with mechanical beneficiation and chemical digestion in the underground

In-situ recovery:
Selective leaching of metal(s) by operating hydraulic systems (e.g. wellfields) with dedicated lixiviants

Note that some references consider the term 'in-mine recovery' as integrating the above first two options (in-line and in-mine recovery), i.e. referring to any method to produce a concentrate in the underground mine and leaving a significant amount of residues underground.

ISR FEASIBILITY CRITERIA

Figure 3 summarizes the five main categories of ISR feasibility criteria for a given deposit.[11] The ore grade distribution in 3D and the hydrological characteristics of both the orebody and the surrounding geological formations define the setup of the hydrological ISR regime (wellfield design). The confinement criterion is critical with regard to environmental compliance. Tectonic faults or other hydraulic connectivities could render ISR impossible. Porosity and permeability (both interrelated) define the available reaction space and lixiviant flow rate that are critical to get reactants in and the leached metal out. Permeability stimulation, e.g. by fracturing, is an option to improve the applicability of ISR. The mineralogy of the ore body (including interfering components) along with some influence of both the groundwater (GW) chemistry and microbiological conditions in the mining zone needs to be understood in detail to set up an appropriate leaching chemistry in order to realize a leaching rate for quantitative production.
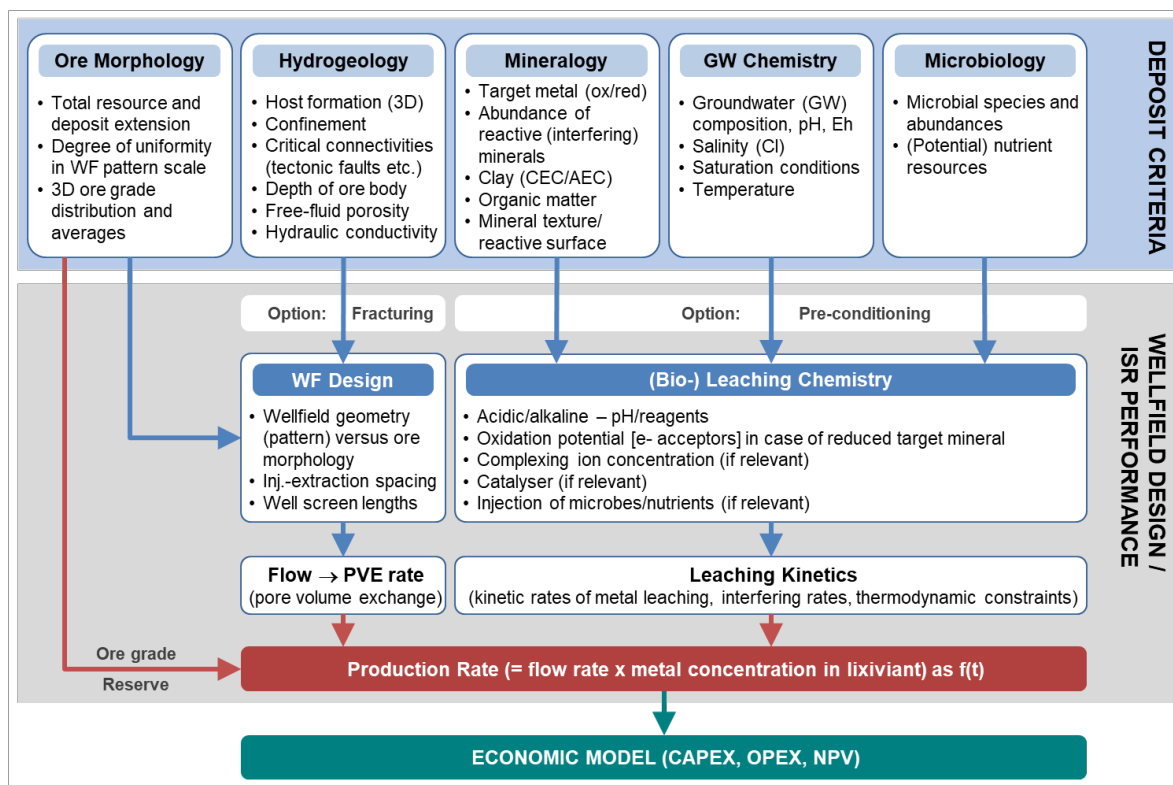

Figure 3: ISR feasibility criteria and effect on wellfield hydrology, leaching chemistry, production rate and ISR economics

Figure 3 points out the two main sides of ISR: ISR hydrology (typically given in terms of pore volume exchange rate and characterizing the conditions of lixiviant-ore contact) on the one side and ISR chemistry (integrating both thermodynamics and kinetics, in particular, for redox leaching conditions) on the other side. Reactive-transport modelling tools are a combination of both and are used for the environmentally compliant optimization of the wellfield design (including performance) as well as for the prediction of production rates (flow rate times metal concentration) over the lifetime of the wellfield. Finally, the practicability of an ISR project depends on the economics.

KEY AREAS OF ISR PROJECT DEVELOPMENT AND APPLICATION

This section summarizes recent advancements in ISR technology by Heathgate/UIT with regard to key areas of ISR project development and ISR performance (including aftercare).

ISR-Specific Exploration/Delineation Methodology and 3D Deposit Modelling

Figure 4 summarizes the state-of-the-art methodology of exploration/delineation methods applied to comprehensively characterize sedimentary U deposits. 3D software packages are used to represent the hydrogeological framework and structural model (stratigraphy and irregularities), to develop a regional 3D hydrological model to be adjusted against numerous monitoring data and tests, and to digitize the 3D deposit model including U grade distribution, petrophysical, geochemical, and mineralogical data. Heathgate/UIT's main advancements include:

- Application of recent innovative, high-resolution 2D-3D seismic/acoustic methods (both hybrid seismic and Acoustic Zoom® are currently tested)

- Borehole logging of porosity distributions by nuclear magnetic resonance (NMR) tools, also used to estimate permeability

- Full implementation of APFN+ borehole logging tools based on pulsed neutron generator technique in combination with time-resolving neutron counting and time-resolving high-performance γ-spectroscopy to measure pU_3O_8 and eU_3O_8 accurately (and the disequilibrium between both), to determine several geophysical parameters, and to log elemental/mineral abundances – all by one tool.[12]
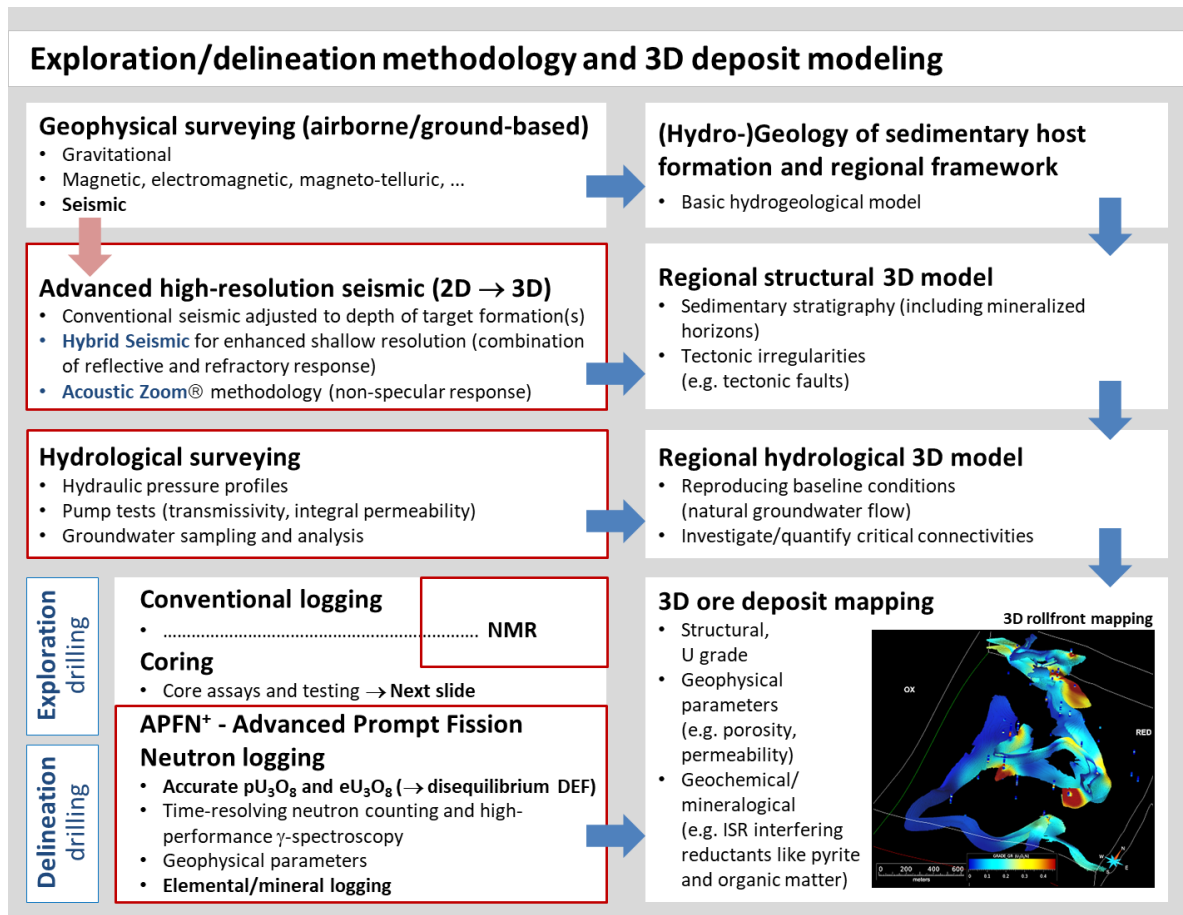

Figure 4: Synopsis of exploration/delineation methodology and 3D modelling

State-of-the-art and Innovative Test Procedures, ISR-Specific Requirements and Model-Based Up-scaling to Field Conditions

In addition to the advanced mineralogical core assays like the combination of scanned electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (QEMSCAN or MLA) to characterize the mineral composition and texture (including mineral-specific grain size distribution), Heathgate/UIT have been investigating new core test techniques such as (Figure 5)

- 3D X-ray computer tomography µCT (to characterize pore distributions and simulate permeability and fluid flow dynamics in 4D) in cooperation with LIAG Hanover, resulting in insights on porosity and fluid flow heterogeneity on a µm to mm scale (Figure 6)

- GeoPET, 4D positron emission tomography to imagine fluid flow through core samples in space and time (in cooperation with HZDR Dresden-Rossendorf/Leipzig), resulting in insight on fluid flow heterogeneity on a cm to dm scale (Figure 7)

- Specialized (p,T)-controlled, automated column test facilities for crushed ore samples as well as original (undisturbed) drill cores (triaxial cell design), and others

These test techniques provide the basis for lab-scale reactive-transport simulations (vs test data) and upscaling to 3D reactive-transport conditions in real wellfields.
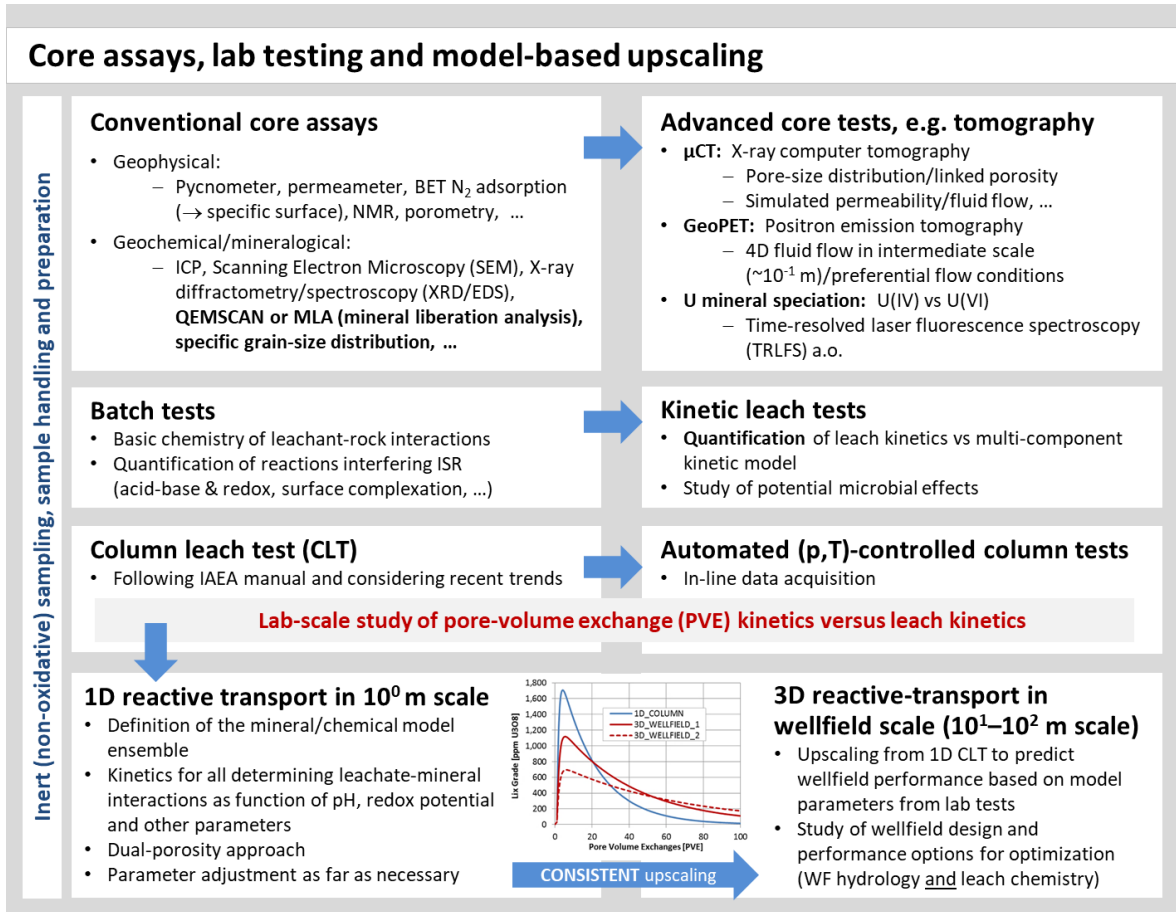
Core assays, lab testing and model-based upscaling

Inert (non-oxidative) sampling, sample handling and preparation

Conventional core assays
- Geophysical:
  - Pycnometer, permeameter, BET N_2 adsorption ($\rightarrow$ specific surface), NMR, porometry, ...
- Geochemical/mineralogical:
  - ICP, Scanning Electron Microscopy (SEM), X-ray diffractometry/spectroscopy (XRD/EDS), **QEMSCAN or MLA (mineral liberation analysis), specific grain-size distribution, ...**

Advanced core tests, e.g. tomography
- **μCT:** X-ray computer tomography
  - Pore-size distribution/linked porosity
  - Simulated permeability/fluid flow, ...
- **GeoPET:** Positron emission tomography
  - 4D fluid flow in intermediate scale ($\sim 10^{-1}$ m)/preferential flow conditions
- **U mineral speciation:** U(IV) vs U(VI)
  - Time-resolved laser fluorescence spectroscopy (TRLFS) a.o.

Batch tests
- Basic chemistry of leachant-rock interactions
- Quantification of reactions interfering ISR (acid-base & redox, surface complexation, ...)

Kinetic leach tests
- **Quantification** of leach kinetics vs multi-component kinetic model
- Study of potential microbial effects

Column leach test (CLT)
- Following IAEA manual and considering recent trends

Automated (p,T)-controlled column tests
- In-line data acquisition

Lab-scale study of pore-volume exchange (PVE) kinetics versus leach kinetics

1D reactive transport in 10^0 m scale
- Definition of the mineral/chemical model ensemble
- Kinetics for all determining leachate-mineral interactions as function of pH, redox potential and other parameters
- Dual-porosity approach
- Parameter adjustment as far as necessary

3D reactive-transport in wellfield scale (10^1–10^2 m scale)
- Upscaling from 1D CLT to predict wellfield performance based on model parameters from lab tests
- Study of wellfield design and performance options for optimization (WF hydrology and leach chemistry)

CONSISTENT upscaling

Figure 5: Synopsis of core assays and test methodology

Cretaceous silty sandstone: Quite homogeneous

Cretaceous diamictite: Quite heterogeneous

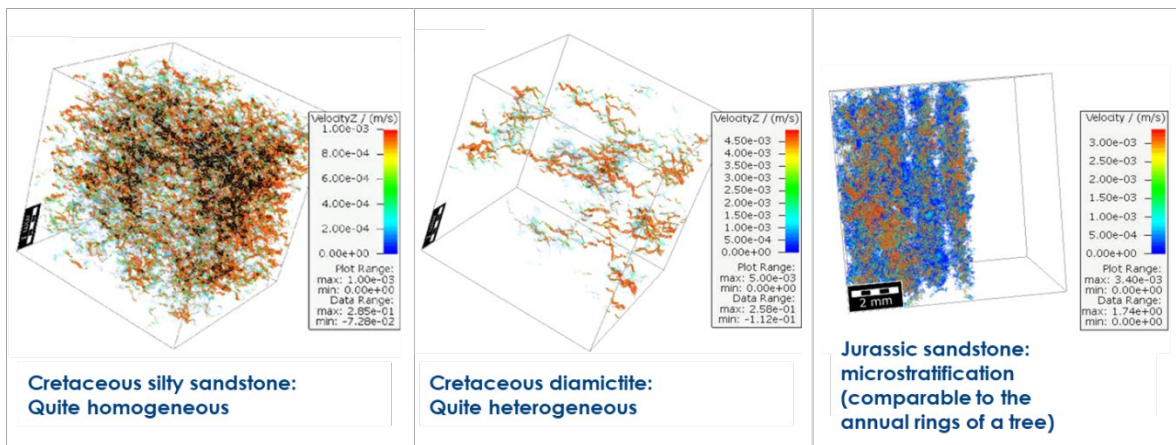Jurassic sandstone: microstratification (comparable to the annual rings of a tree)

Figure 6: μCT results for various sedimentary core samples, all software-transformed to flow velocity distributions in 3D to visualize flow heterogeneities on a μm to mm scale – cooperation with LIAG Hanover
(different flow velocity thresholds set for better imaging)

The recent field leach trial (FLT) in a high-grade, quite clayey Cretaceous ore formation has been combined with 4D electro-resistivity tomography to image the leachant (lixiviant) distribution in one wellfield test pattern (i.e. to visualize fluid flow heterogeneity at 10^1 m scale), thus, providing an excellent reference for validating/adjusting the 3D reactive-transport model (Figures 8 and 9).
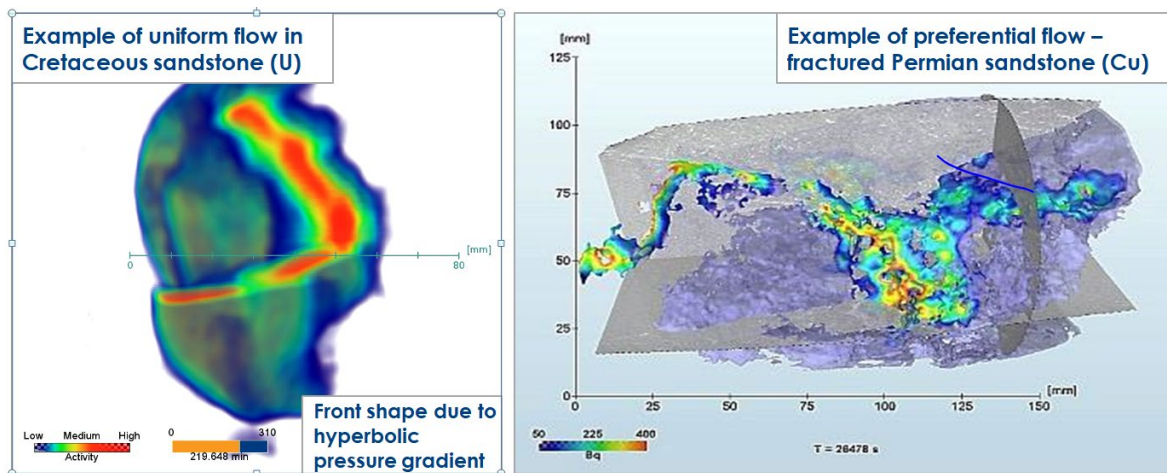
Figure 7: GeoPET images (snapshots) for homogeneous sandstone (left) and fractured rock (right) [4] to visualize the flow heterogeneity on a cm to dm scale – cooperation with HZDR
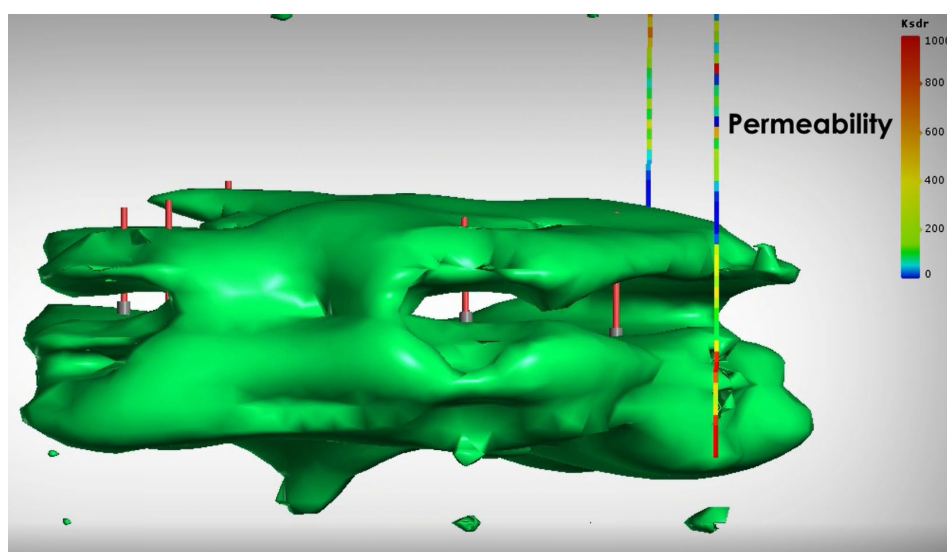

Figure 8: 4D ERT image (snapshot) showing the extension (shell) of the lixiviant flow in a 7-spot wellfield pattern in an advanced stage of wellfield performance (heterogeneity in 10^1 m scale explained by vertical variability of permeability from borehole logging)

ISR Wellfield Design, Optimization and Control

As schematically illustrated in Figure 6, ISR wellfield design and performance planning comprises both (i) the hydrologically optimized setup of injection/extraction well patterns to realize the best dynamic contact of leachant to U-mineralization and (ii) the definition of leachant chemistry (optionally in phases) to maximize selective U leaching (leach efficiency and economics) as well as to minimize interfering reactions and environmental impacts. In particular, Heathgate/UIT's software tools are suitable to solve the redox puzzle by adjusting the oxidant concentration and other chemical parameters like pH to clearly favor the leach of U^{4+} minerals against the interfering dissolution of sulfidic minerals like pyrite (FeS_2) or organic matter (xCH_2O). Wellfield monitoring and control provides data to optionally adjust wellfield performance if required and to prove environmental compliance of the operation (Figure 6). The loop *wellfield design → wellfield performance → wellfield monitoring → wellfield adjustment* for optimization (hydrology/chemistry) is efficiently supported by modelling tools. Finally, a monitoring well ring around the ISR area is used to measure hydrological and chemical parameters in the mining aquifer as well as in adjacent formations vs excursion control limits (ECL) defined within the regulatory approval. As illustrated in Figure 3, the ISR wellfield design and preparatory measures include permeability stimulation (see relevant section below) and chemical pre-conditioning (in particular, the acidification of the mining zone before starting the oxidative leaching of uranium) followed by adjusting the oxidation potential of injected lixiviants depending on wellfield depletion.
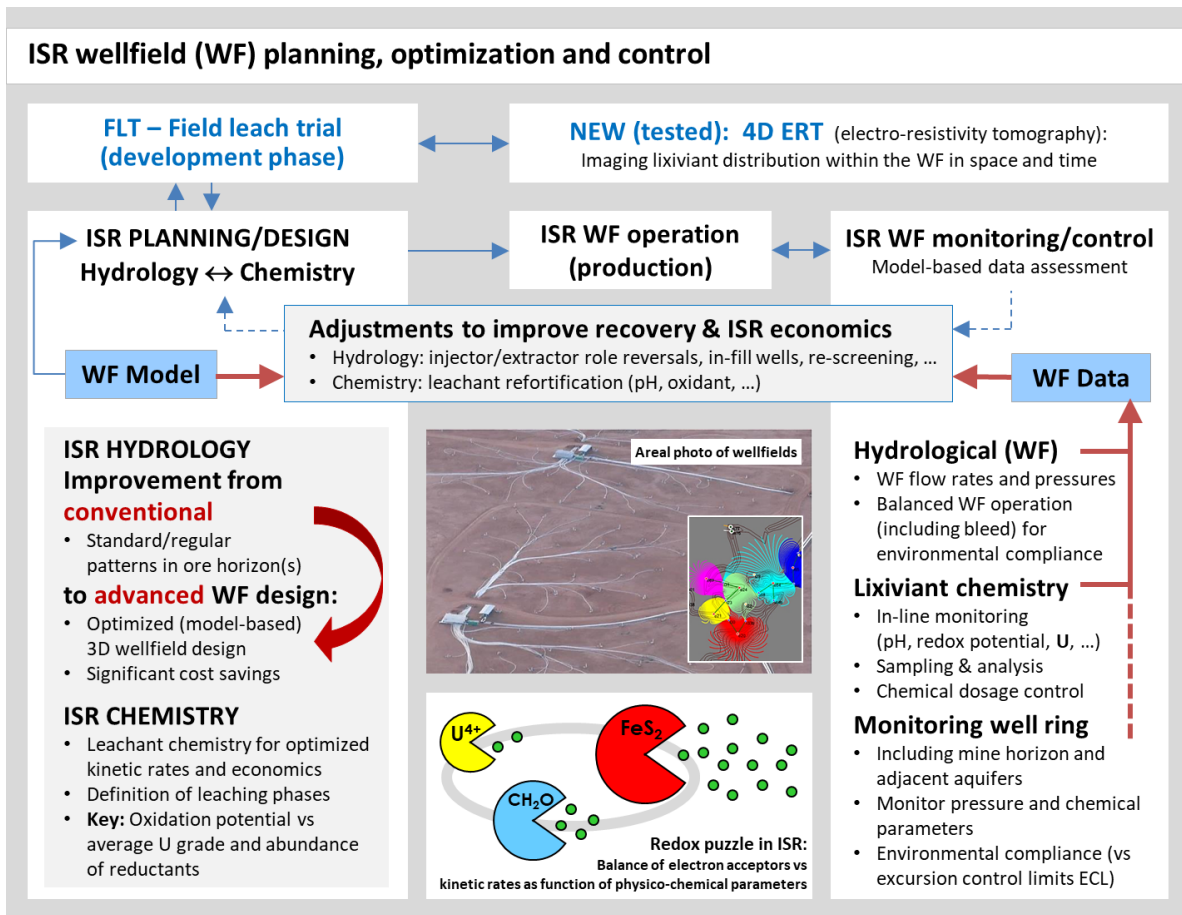
ISR wellfield (WF) planning, optimization and control

Figure 9: Synopsis of wellfield design, performance and monitoring

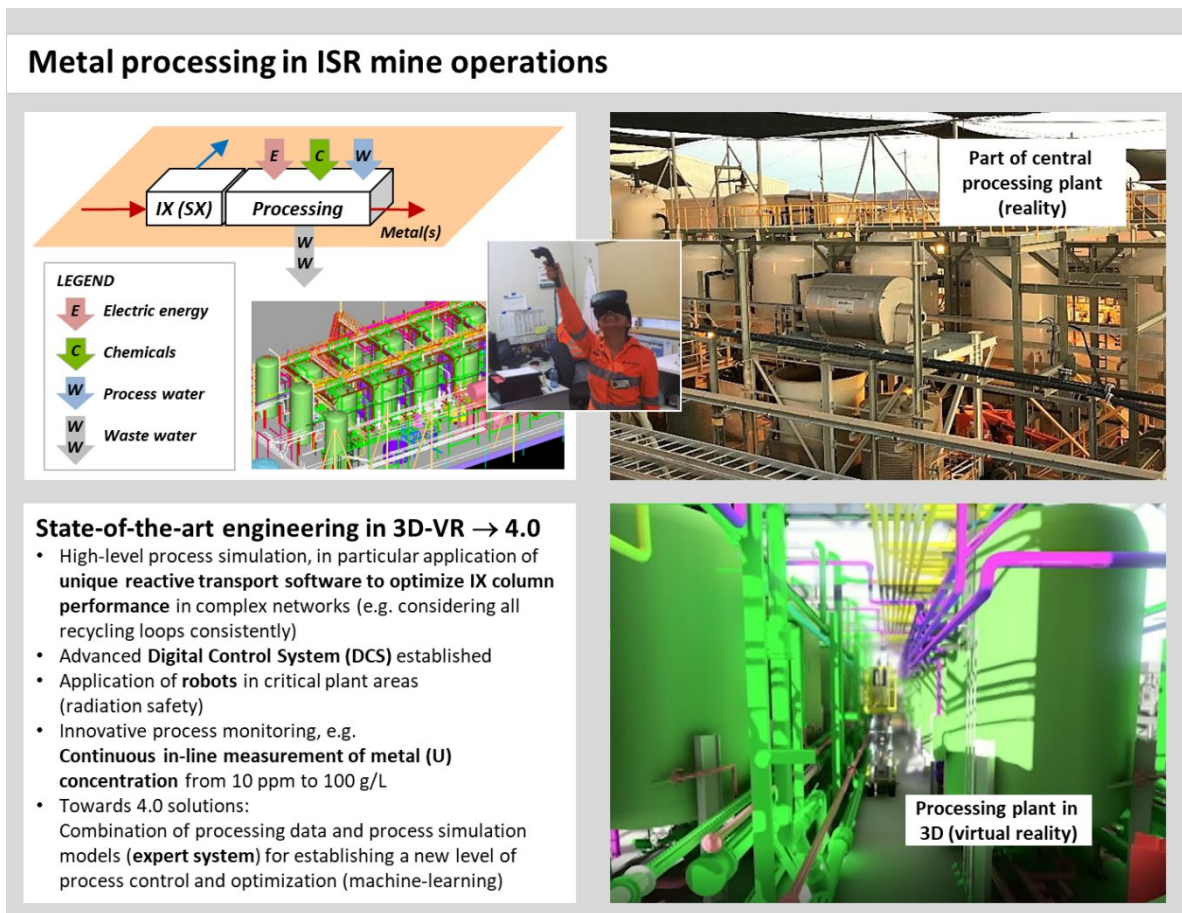## Metal processing in ISR mine operations

Figure 10: Synopsis of processing plant operation and steps towards ISR 4.0

Metal Processing in ISR Operations (Also Reviewing Model-Based Software Tools For Control and Optimization)

Figure 10 demonstrates the engineering and technological framework developed by Heathgate/UIT to optimize metal processing and to improve the performance by implementing Industry 4.0 principles, in particular, by combining real-time on-line/in-line measurements of chemical parameters including metal concentrations with process modelling software – facing new challenges and opportunities.

Post-Mining Measures and ISR Aquifer Restoration

The chemical attenuation of the leachant during its passage through the ore body (verified and quantified every day by controlling the leachant refortification) continues after wellfield shutdown long term and leads to its neutralization and chemical reduction (thus, immobilizing U) in a time frame that is tolerable in view of Heathgate's ISR application in aquifers of no-use-category (Figure 11). This effect called natural attenuation (NA) could be enhanced, if required based on long-term monitoring, and by remediation measures Heathgate is prepared for ('enhanced NA' - ENA). As part of the regulatory procedure, Heathgate/UIT have demonstrated on the basis of both dedicated lab/field testing and reactive transport modelling that NA leads to the restoration of the mining aquifer in a timely and acceptable manner.[9]
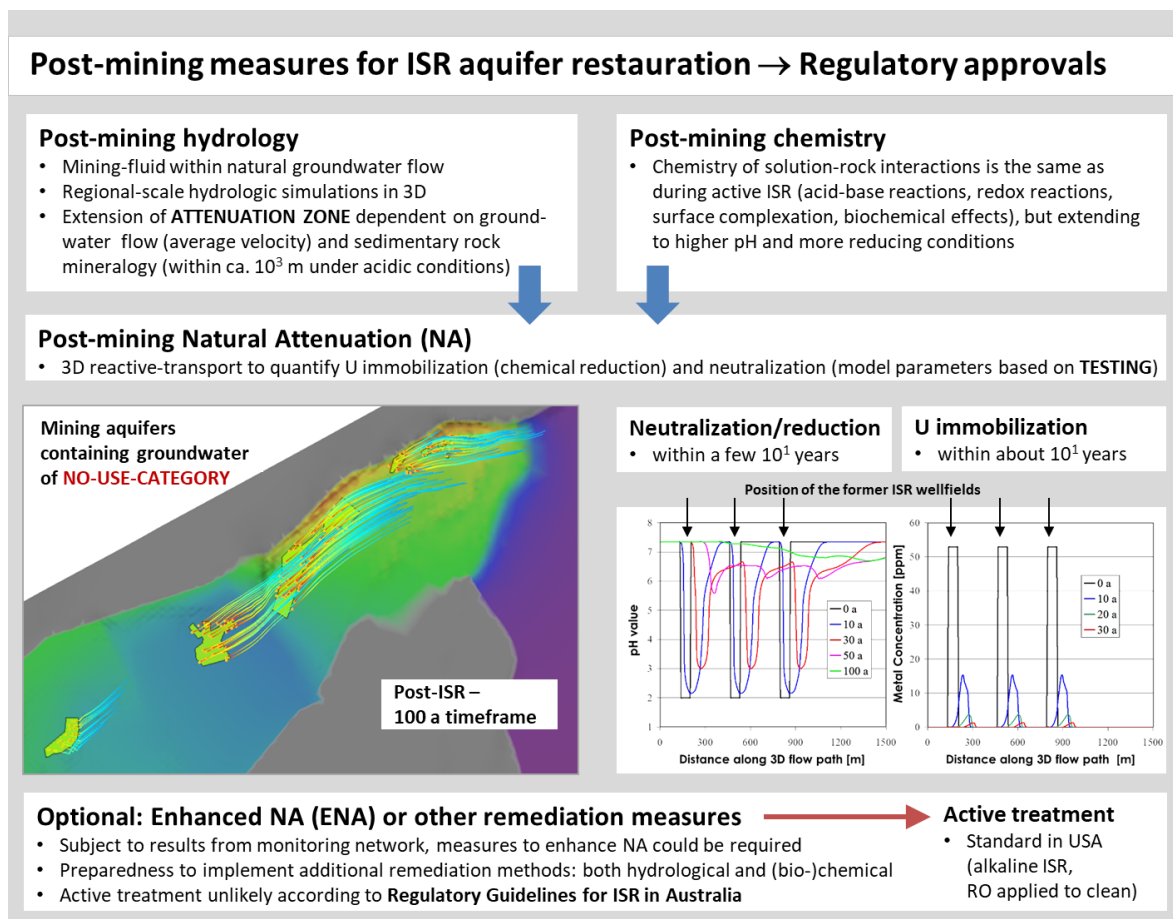

Figure 11: Synopsis of aftercare/aquifer restoration

INTERPLAY OF ISR HYDROLOGY AND ISR (GEO-)CHEMISTRY

ISR wellfield **hydrology** is mainly characterized by the realized flowrate Q and the effective pore volume V_P in the leaching zone (model space), both resulting in the pore volume exchange (PVE) rate $q = Q/V_P$ (the inverse of the average hydraulic retention time HRT). In real systems, heterogeneities of both porosity and permeability could impact the contact between the lixiviant and ore, thus, reducing the overall recovery.

The leaching chemistry is characterized by: (1) the thermodynamics of all species, phases and exchange sites involved (i.e. acid-base reactions, redox processes, surface effects like cation

exchange capacity and surface complexation on clays), altogether defining leach conditions and sometimes constraints (e.g. due to the availability of oxidation potential in redox leaching), and (2) the kinetics, usually expressed in terms of leached moles per reaction surface per time unit, $\tilde{r}_0[mol/(m^2 \cdot s)]$, that can be reduced for specific wellfield conditions to an relative integral rate quantifying the percentage of remaining reserve leached per time unit r[d^{-1}]. The rates q and r define the leaching performance with regard to the magnitude of the production rate and shape of the time dependence (see below).

Wellfield Hydrology Based on Porosity-Permeability Conditions

Correlation of Porosity and Permeability and Consequences for PVE Rate

(Free-fluid) porosity ϕ and permeability K of sedimentary rock (standard ore category for ISR) are well interrelated as shown in Figure 12. The Kozeny-Carman equation for average conditions has been included as guideline. It can be scaled according to the sediment rock type. Most of the industrial-scale ISR operations fit into the feasibility window $\phi > 12\%$ and K>0.1 m/d.
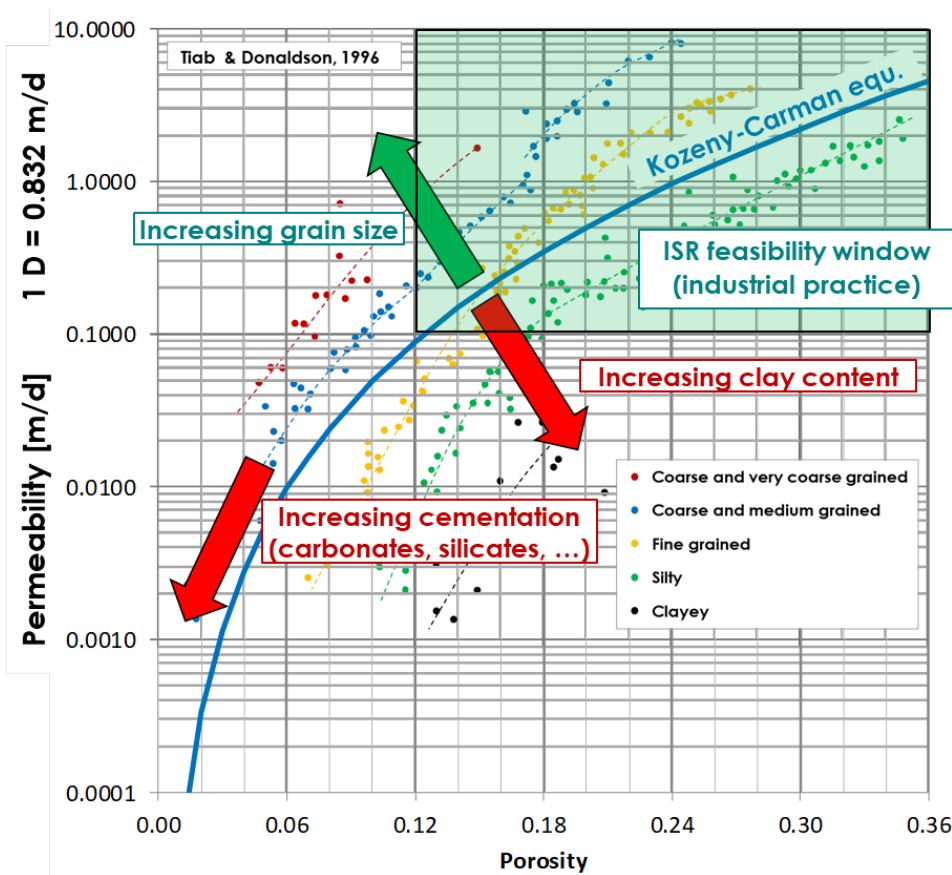

Figure 12: Correlation of (free-fluid) porosity and permeability for sediment rock from reference[19] (redrawn) highlighting overall trends and the common ISR feasibility window

The permeability K determines the achievable flow rate for an ISR pattern in a given aquifer (at thickness T and water head H above extractor) and well design (well spacing R and extractor screen radius r_S). For a 7-spot wellfield pattern the Thiem equation for flow rate Q reads:

$$Q = \frac{2\pi \cdot K \cdot T \cdot H}{ln\left[\frac{0.8 \cdot R}{r_S}\right]}$$

The PVE rate q = Q/V$_P$ is an important parameter quantifying both the mass (and leaching effect) of chemicals injected into the reaction space V$_P$ and the mass of metal extracted (dependent on lixiviant grade c). For industrial applications, q is found in the range of 0.05 to 0.2 d^{-1} corresponding to an HRT between 20 and 5 days. Heathgate runs ISR wellfields at q = 0.15 – 0.3 d^{-1}.

Permeability Stimulation (Fracturing)

In order to increase both ϕ and K of cemented sediments or even hard rock ores for ISR applications, various methods of permeability stimulation have been considered in studies. The technical options include:

- Hydraulic fracturing (pressure up to 100 MPa to crack rock)
  - Water fracturing (optionally by using friction-reducing chemicals)
  - Hydraulic proppant fracturing (viscous gels, proppants)
  - Hybrid fracturing (combination of both)
- Acidizing
  - Applicable mainly to calcareous formations
  - Various concepts dependent on injection pressure versus formation fracture pressure
- Thermal fracturing
  - Contraction effect due to cold-water injection in high-temperature formations
- Specific techniques including
  - Explosive stimulation (e.g. high-energy gas fracturing by deflagration of injected liquid explosives
  - Acoustic stimulation (ultrasonic waves)
  - Electric stimulation (electro-thermal or electrodynamic)
- Drilling and blasting
  - Historically applied in-situ block leach applications by Wismut[7]
  - New concepts under development[8]

Note that fracturing is constrained by the incompressibility of the rock. Known drilling and blasting applications and concepts consider compensation volumes[7][8] to efficiently rubbelize the formation.

Leaching Chemistry

Leaching kinetics in real ISR applications is quite complex. Typically, the leach rate in terms of moles per unit time is expressed by the equation

$$\tilde{r}\left[\frac{mol}{d}\right] = \widetilde{r_0}\left[\frac{mol}{d \cdot m^2}\right] \cdot S \cdot \prod_j F_j$$

with S being the effective reaction surface (correlated to porosity) and F_j being various kinetic terms describing the dependence of kinetic rate on physico-chemical parameters.

A typical and most general parameterization reads

$$\tilde{r} = \widetilde{r_0} \cdot S \cdot [H^+]^a \cdot [A^{e-}]^b \cdot [C]^c \cdot e^{\frac{E_a}{R \cdot T}} \cdot F_D \cdot F_{bio}$$

a, b, and c are mineral-specific parameters (quantified for several minerals containing U, Cu, Zn, Fe and organic matter degradation).

$[H^+]$ – H^+ concentration
$[A^{e-}]$ – concentration of electron acceptors (oxidation potential)
$[C]$ – concentration of complexing ion (carbonate in alkaline leaching)
E_a – activation energy in the Arrhenius term as function of temperature (R – gas constant)
F_F – flow dependence term (Damkoehler)
F_{bio} – microbial term (enzyme kinetics, e.g. Michaelis-Menten kinetics)

For generic estimates of overall wellfield performance (not to be mismatched with the 3D reactive-transport simulations for planning and optimization purposes) we express the rate r in relative terms, i.e. with reference to the available mineral reserve M(t) at time t, i.e. $r = \frac{\tilde{r}\left[\frac{mol}{d}\right]}{M[mol]}$. The depletion of reserve follows the simple differential equation dM/dt = -r·M(t) resulting in the depletion M(t) = M_0·exp(-r·t) that starts after pre-conditioning (acidification and transition to oxidative leaching). Industrial-scale leaching rates for ISR applications range from ca. 0.01 d^{-1} to 0.001 d^{-1} corresponding to depletion half-lives of 2.2 and 23 months, respectively. Heathgate operates ISR wellfields at r between 0.01 and 0.005 d^{-1}, i.e. at minimized ISR wellfield lifetimes for better economics.

For illustrative purposes only, we reduce the general advection-dispersion-reaction/source (ADR) equation (set of partial differential equations for species i as a basis for reactive-transport

simulations in 1D to 3D)

$$\frac{\partial c_i}{\partial t} = -v \cdot \frac{\partial c_i}{\partial x} + D_L \cdot \frac{\partial^2 c_i}{\partial x^2} + \Phi(c_i, c_j)$$

(v – pore velocity, D_L – dispersion coefficient, Φ - source term) to a simplified differential equation (dispersion term ignored)[10]:

$$\frac{dc}{dt} = -q \cdot c + r \cdot \frac{M(t)}{V_P}$$

Together with the above depletion kinetics this results in the analytical solution (under the condition $q \neq r$)

$$c(t) = c_0 \cdot \frac{r}{q-r} \cdot \{e^{-r \cdot t} - e^{-q \cdot t}\}$$

with $c_0 = M_0/V_P$ (M_0 – original reserve figure). Finally, we get the production rate $P(t) = c(t) \cdot Q$:

$$P(t) = M_0 \cdot q \cdot \frac{r}{q-r} \cdot \{e^{-r \cdot t} - e^{-q \cdot t}\}$$

This equation can only be used if no thermodynamic constraints apply (for instance, reduction of the kinetic rate due to missing oxidation potential)! It demonstrates the essential roles of the reserve, q and r in determining the magnitude of production, whereas the right-hand term within brackets represents a shape function (time dependence).
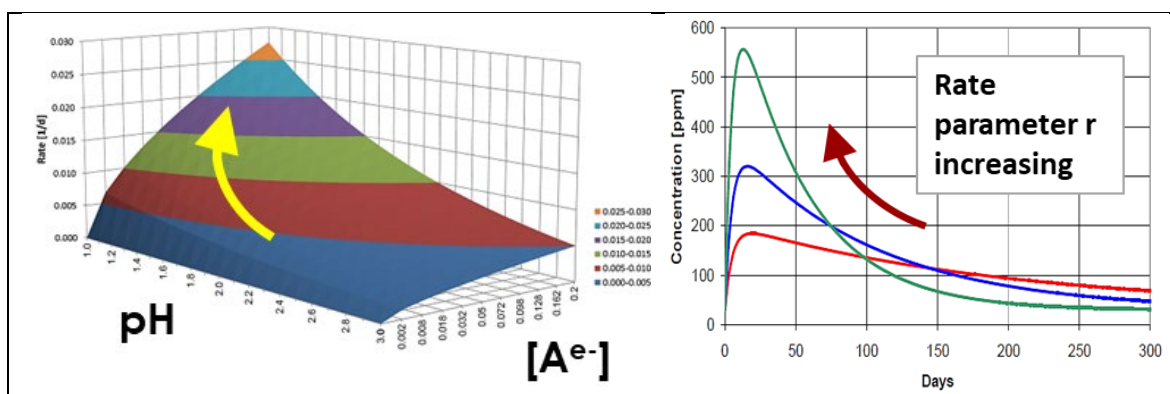

Figure 13: Kinetic rate of uraninite leaching as function of pH and oxidation potential given in mol/L [Ae-] of electron acceptors (left). The arrow indicates the optimization pathway. Right: generic effect of changing kinetic rate on PLS grade as function of time

Reactive-Transport Models to Simulate Wellfield Performance

Full-scale reactive-transport simulations are performed for wellfield design and optimization by using 3D software tools and implementing the complex hydrological and chemical input summarized above. Figure 14 demonstrates two essential outcomes of the simulation:

- The wellfield hydrology is embedded in the regional hydrological groundwater model. In this way it is possible to study lixiviant flowlines out of the wellfield into the environment. This tool is used to adjust the performance for environmental compliance (Figure 14, left).
- Reactive-transport models are used to follow up the ongoing wellfield performance. By using plant data (e.g. flow rates, injected lixiviant composition) as direct input the model is compared to plant data in a retrospective manner, followed by the forecast under varying performance parameters for optimization (Figure 14, right).
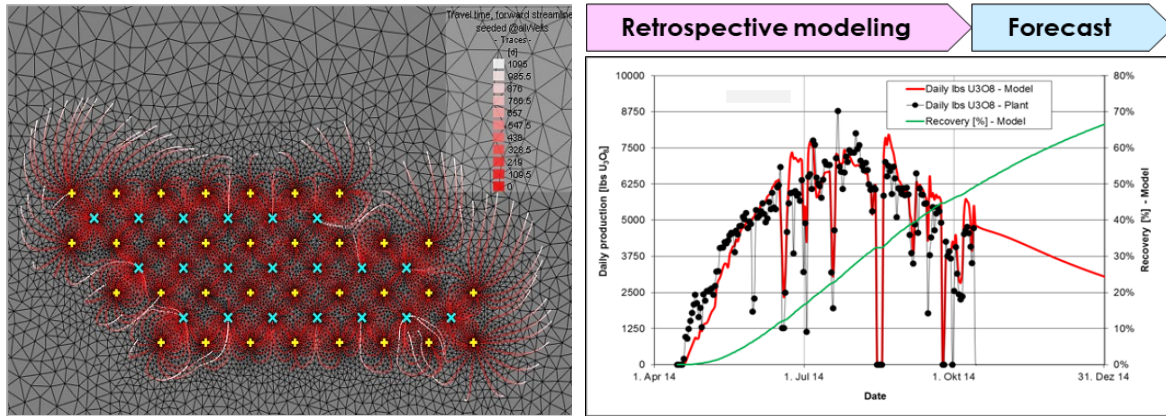
Figure 14: Lixiviant flow lines from a 5-spot wellfield model embedded in the regional groundwater model (left). Right: Example of reactive-transport simulation of an individual wellfield (model input from real wellfield operation in the retrospective phase: plant data of daily production versus model results)

The definition of the wellfield performance parameters with regard to injection pH and oxidation potential is a particular task that has been solved by the use of the reactive-transport model. The leaching rate for the metal of interest (e.g. U as shown in Figure 13, left) needs to be balanced against the impact of interfering minerals including competitive redox reactions (e.g. pyrite dissolution, organics' degradation) and dissolution of gangue minerals (rate increasing by lowering pH). By solving this redox puzzle and relating the simulated production rates to the economic model the chemical leaching conditions (injection lixiviant composition) are setup in an optimum manner.[12]

REDOX LEACHING AND POTENTIAL ROLE OF BIOLEACHING IN ISR

Specific Consumption of Oxidation Potential

In order to realize a redox leaching reaction, the equivalent mole number of electron acceptors <u>must</u> be provided (charge conservation law). For instance, to leach 1 mole uraninite UO_2, 2 moles of electron acceptors must be available to oxidize the tetravalent U in uraninite to the hexavalent U in the uranyl ion UO_2^{2+}.
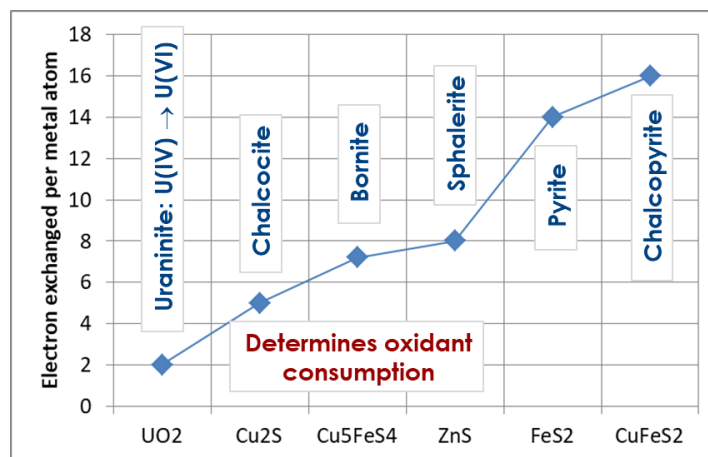

Figure 15: Number of electrons to be exchanged for the complete oxidation of one molecule of the minerals considered (moles of e- acceptors per mole of mineral)

In order to illustrate this more quantitatively in terms of ISR, let's consider the pressure injection of a lixiviant at 200 kPa and 25 °C corresponding to a maximum concentration of dissolved pure O_2 (to be added) of about 80 ppm or $[A^{e-}] = 10$ mmol/L. From this oxidation potential, we can estimate the maximum metal concentration in the lixiviant (actually, the leach kinetics discussed in the previous section applies):

        Uraninite (UO_2):   max. 1,190 ppm U
        Chalcocite Cu_2S: max. 128 ppm Cu

Bornite Cu₅FeS₄: max. 89 ppm Cu
Sphalerite ZnS: max. 81 ppm Zn
Pyrite FeS₂: max. 40 ppm Fe
Chalcopyrite CuFeS₂: max. 40 ppm Cu

This demonstrates why the ISR of uranium works very efficiently, whereas the in-situ leaching of sulphides is constrained by the available oxidation potential (solubility of O_2 as function of p and T). In order to overcome the physically limited solubility of O_2, ferric iron could be used as an oxidant, i.e. $[Fe^{3+}] = [A^{e-}]$, but in this case the consumed ferric resulting in ferrous iron has to be re-oxidized before injection, i.e. contributing to the chemicals' costs (i.e. by H_2O_2) considerably. Biooxidation in reactors on the surface has been considered conceptually[4], but the overall CAPEX and OPEX figures make this alternative uneconomic in most applications.

Bioleaching in ISR

Microorganisms, in particular iron and sulphur oxidizers, can contribute to the leaching in an <u>indirect</u> way by in-situ re-oxidizing of iron to ferric. The primary leaching is catalysed by ferric iron, as demonstrated in the following example of chalcopyrite leaching:

Net reaction	$CuFeS_2 + 4O_2 \rightarrow Cu^{2+} + Fe^{2+} + 2SO_4^{2+}$	
(1)	$CuFeS_2 + 4Fe^{3+} \rightarrow Cu^{2+} + 5Fe^{2+} + 2S^0$	spontaneous (chemical)
(2)	$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$	by iron oxidizers
(3)	$2S^0 + 3O_2 + 2H_2O \rightarrow 2SO_4^{2+} + 4H^+$	by sulphur oxidizers

Bioleaching works well and is applied economically in tank and heap leaching applications where the oxygen can be provided (aerated) in a cost-effective manner. In the case of ISR, the O_2 solubility constraint applies[15].

ISR ECONOMICS

ISR cost models can be developed on the basis of production rate forecasts and by integrating the CAPEX and OPEX figures. Note that wellfield construction costs depreciate over the lifetime of the wellfield (one of the economic advantages of ISR). Figure 16 shows the economic model scheme linked to the ISR feasibility criteria and production rate forecast in Figure 3. Note that every ISR project is specific (regarding deposit criteria and country-specific conditions).
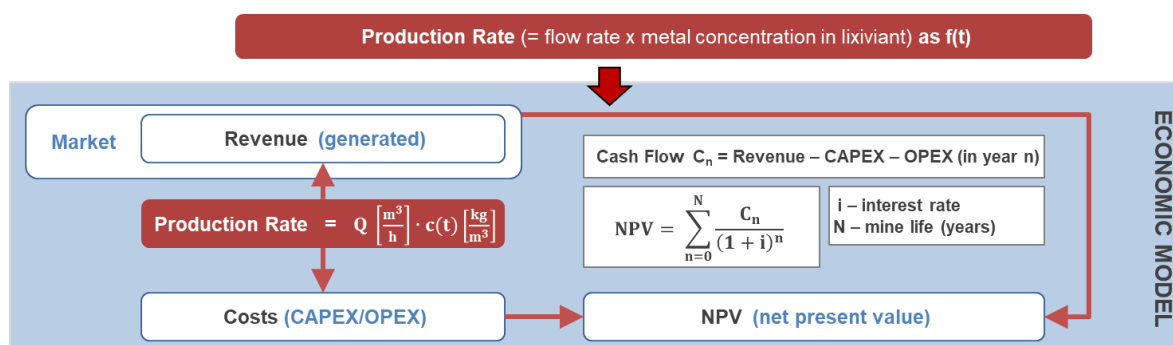

Figure 16: Economic model scheme linked to Figure 3 (ISR overview)

Figure 17 represents the CAPEX and OPEX cost figures for assumed ISR scenarios of acidic leaching of chalcocite (sulfidic copper) ore at 3wt% ore grade, 25% porosity, and 250 m depth (without metal processing costs), right-hand diagrams, and then changing to oxidized ore (upper right) and to lower depth (lower right). This example explains why shallow ISR of oxidized copper ore might work, whereas deep and/or sulfidic Cu ISR would be uneconomic under current market conditions.
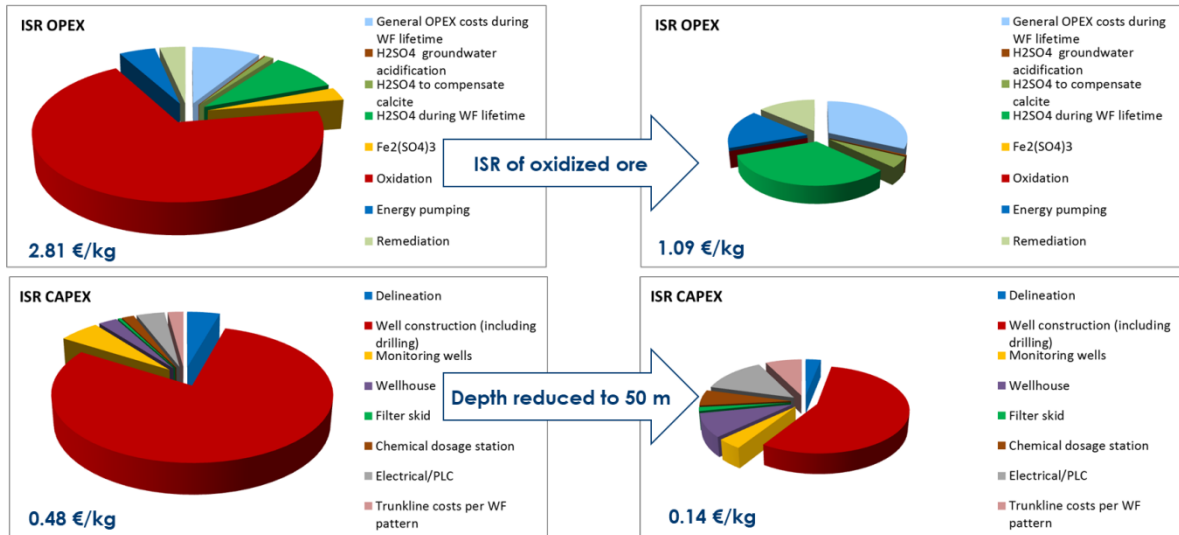
Figure 17: Examples of CAPEX/OPEX cost figures for varying conditions[4]

In view of the complexity of ISR with regard to many influencing factors the economic assessment of a new ISR mining project may be very challenging. Only a comprehensive feasibility study following the scheme outlined in Figure 3 and validated by multi-fold testing, ultimately by a field leach trial, will result in reliable economic figures.
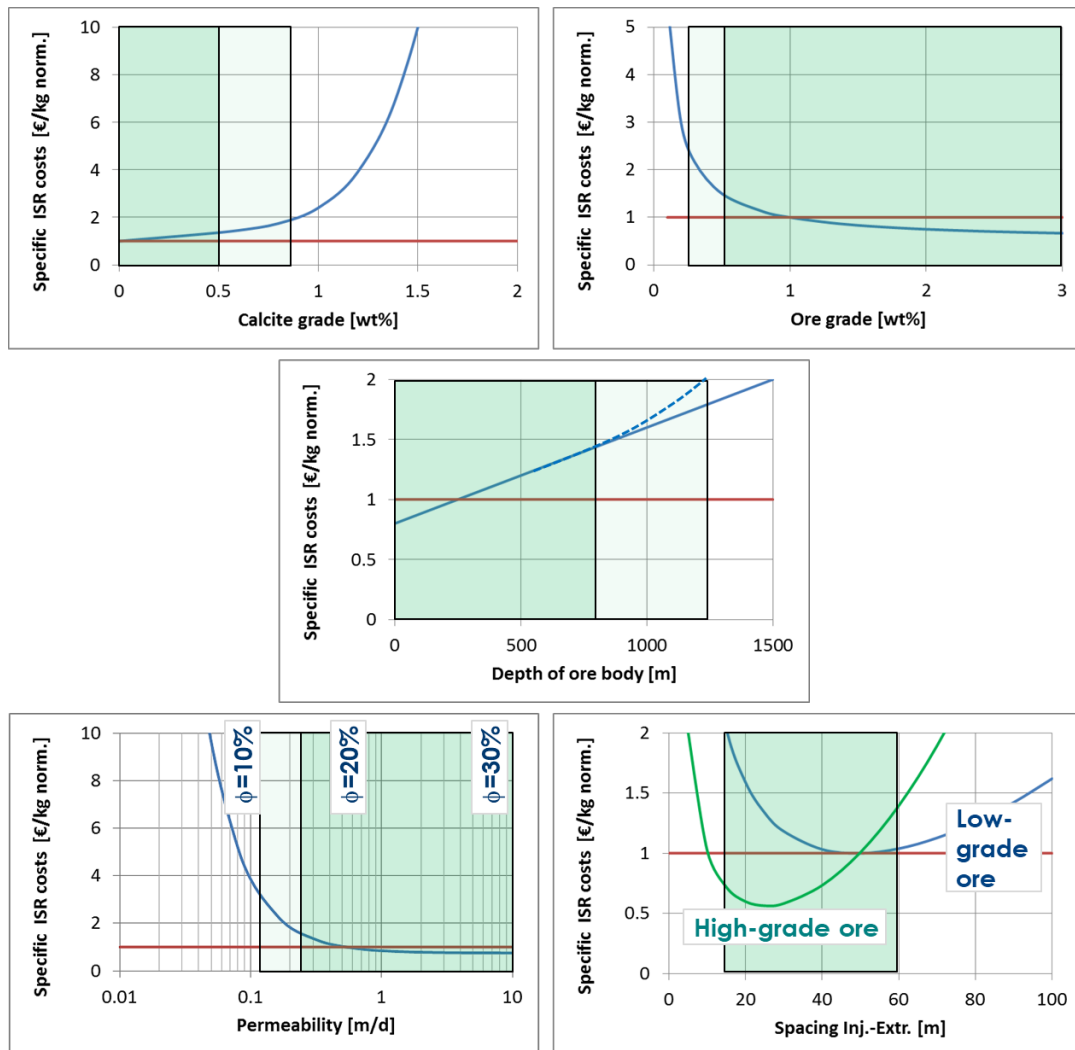

Figure 18: Dependence of specific ISR costs (in relative units) on key parameters[4]. The green-shaded areas are considered to reflect the feasibility of industrial applications.

Figure 18 represents the dependence of ISR costs (acid leach) on key parameters based on a generic simulation for ISR model cases and normalized to 1 for viable performance scenarios[4]. The costs do not include metal processing expenditures.

The following cost trends are emphasized:

- Dependence on calcite grade:
  The higher the grade of calcareous minerals, the higher the acid consumption to pre-condition the wellfields. In addition, there is the risk of pore clogging by gypsum precipitation at too high of a calcite concentration, thus, making sulfuric acid ISR infeasible.

- Dependence on ore grade:
  Provided that the appropriate leach chemistry is applied, the ore grade directly scales the magnitude of the production rate as demonstrated above. There is an economic limit on the applicability of ISR at low ore grades.

- Dependence on the depth of the ore body:
  The higher the depth, the higher both the well construction costs and the pumping costs. There is an economically determined limit of applicability depending on the value of the metal.

- Dependence on permeability (interrelated to porosity):
  Nowadays, industrial ISR is used for sedimentary ore deposits at a typical permeability in the order of 1 to 10 m/d. Lower permeabilities down to 0.1 m/d could work, if other parameters are favorable.

- Spacing between injection and extraction wells:
  The optimum spacing is dependent on several deposit parameters including the ore-grade (balance of the value of recovered metal versus costs in view of the effect of lower recovery at high spacing due to less efficient lixiviant-ore contact as simulated by 3D reactive-transport models).

SUMMARY AND CONCLUSIONS

ISR technology is highly complex and requires the application of a versatile, comprehensive methodological basis to optimize recovery economics under the primary condition of environmental compliance. Heathgate/UIT have developed advanced means and tools to face this challenge under varying deposit conditions, i.e. to gather all required data before, during, and after ISR operation ('data mining'), to use this comprehensive database for *model-based* ISR planning, performance, and after-care ('move theory to practice'), in particular, for (remote) process control and automation, – towards a next-generation ISR technology. Heathgate operates the Beverley mine, located in the Frome Basin close to the Northern Flinders Ranges, South Australia, about 550 km north of Adelaide. After exploiting the original Beverley deposit within the Miocene Namba Formation[5], Heathgate explored and developed further sedimentary U deposits amenable to in-situ recovery (ISR) located in the Eocene Eyre and in Cretaceous diamictite host formations under quite different petrophysical, geochemical and mineralogical conditions, thus, requiring the adjustment of ISR technology for optimized performance[11]. Based on the implementation of advanced ISR methodologies summarized in this paper Heathgate realized a significant and sustainable increase of production ($\geq$4 Mlbs U_3O_8 p.a.) by operating a processing plant with an original nameplate capacity of 3 Mlbs p.a. in an environmentally responsible manner.

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