# Making Hard Rock *In Situ* Recovery a Reality

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## ABSTRACT

Increasing global demand for commodity metals and capital and the greater operating costs of mining and metal production present significant challenges for the metals mining industry. Current conventional technologies may not be feasible for processing deposits of declining grade, challenging mineralogy or those that occur at increasingly greater depths. To overcome these issues, the development of a step-change technology such as *in situ* recovery (ISR), which reduces mining and avoids milling costs, may be vital in ensuring future economic metal production. ISR has been used extensively to treat porous soft rock deposits such as the water-soluble salts, sylvite and halite. Although ISR has typically been used for mining conventionally uneconomic uranium ores, it has also been used less frequently for the treatment of other restricted permeability hard rock deposits, such as those containing copper and gold. The reason for the limited uptake of the technology for hard rock mineralisations is primarily due to low natural rock porosity and permeability and hence poor response to available lixiviant. However, additional challenges include solution containment, management of groundwater and regulatory, ecological and societal requirements and expectations. CSIRO has focused on understanding the challenges of hard rock ISR and identifying global capabilities that can contribute to developing the essential enabling technical areas required to realise ISR. Specific focus areas include geochemistry and advanced resource characterisation; drilling and controlled rock-breaking technologies; solution chemistry and environmentally benign lixiviant systems; lixiviant delivery systems and 'subsurface mixing'; subsurface hydrology and reactive transport mechanisms and models; downstream processing options; legal, social and environmental aspects; and techno-economic modelling. This paper will discuss ISR challenges including industry feedback focused on addressing this issue, gaps preventing ISR from being applied in practice, capabilities to overcome these gaps and the development of a collaborative approach to making hard rock ISR a reality.

## INTRODUCTION

Mining, handling and processing of large volumes of material is often required to recover metals such as copper, nickel, uranium and gold that are present in subpercentage quantities in deposits (unlike bulk commodities such as iron ore and coal). Indeed, a significant proportion of the overall cost of producing these metals can be ascribed to the cost of moving the metal-bearing ore (and other non-value-bearing material) to the surface and reducing the rock to an appropriate size for processing.

Amongst the many general trends in the mining industry, sustained global demand for commodity metals and the increasing costs of metal production present significant challenges for the industry. Current conventional technologies may not be feasible for processing deposits of declining grade, challenging mineralogy or those that occur at increasingly greater depths. To overcome these issues, the development of a step-change technology may be vital in ensuring future economic metal production. *In situ* recovery (ISR) – or the in-place extraction of metals from orebodies by combining controlled rock fracturing, managed lixiviant contact and leaching of specific minerals and subsequent downstream recovery of valuable metals from pregnant leach solutions – may be such a technology as it reduces mining and avoids milling costs.

A preliminary estimate was obtained of the quantification of this opportunity within Australia for four commodities (copper, gold, uranium and nickel) based on the total subeconomic and inferred resources as classified according to the JORC code (we recognise that this approach may be restrictive since some inferred resources may be economic but are not currently classified as such because of limited geological evidence and sampling). Inferred Australian resources as at December 2013 are substantial (see Table 1; Britt *et al*, 2014) and represent a significant opportunity if it is assumed that ISR could be a potential alternative treatment route for even a small portion of these inferred resources.

Not only does ISR have the potential to provide an alternative, more affordable processing technology for lower-

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**TABLE 1**
Australia's demonstrated and inferred copper, gold, nickel and uranium resources as at December 2013 (Britt *et al*, 2014).

| Commodity | Demonstrated resources | | | Inferred resources | Total subeconomic and inferred resources |
|---|---|---|---|---|---|
| | Economic | Subeconomic | | | |
| | | Paramarginal | Submarginal | | |
| Copper (Mt) | 93.1 | 1.4 | 0.4 | 44.1 | 45.9 |
| Gold (t) | 9808 | 317 | 110 | 4520 | 4947 |
| Nickel (Mt) | 19.0 | 4.0 | 0.1 | 19.7 | 23.8 |
| Uranium (kt) | 1167 | 34 | 0 | 592 | 626 |

Definitions (from Britt *et al*, 2014):

Demonstrated resources: sum of 'Measured Mineral Resources', 'Indicated Mineral Resources', 'Proved Ore Reserves' and 'Probable Ore Reserves', which are all defined according to the JORC Code.
Economic: implies that, at the time of determination, profitable extraction or production under defined investment assumptions has been established, analytically demonstrated or assumed with reasonable certainty.
Subeconomic: refers to those resources that do not meet the criteria of economic:
- Paramarginal: that part of subeconomic resources which, at the time of determination, could be produced given postulated limited increases in commodity prices or cost-reducing advances in technology. The main characteristics of this category are economic uncertainty and/or failure (albeit just) to meet the criteria for economic.
- Submarginal: that part of subeconomic resources that would require a substantially higher commodity price or major cost-reducing advance in technology to render them economic.
Inferred resource: that part of a mineral resource for which quantity and grade (or quality) are estimated on the basis of limited geological evidence and sampling.

grade or subeconomic ores, it may lower environmental impacts by reducing water, power and emissions, be more sustainable and therefore be more socially acceptable than many conventional mining practices.

Simplistically, ISR involves dissolving (extracting) a valuable metal from an ore into a lixiviant (a solution that contains other components to assist the desired metal to dissolve) in a manner that allows the orebody to remain in place while the lixiviant is pumped through the ore and back to the surface for further processing. There are numerous technical challenges (some generic and many specific to or dependent on the geological conditions and other local factors) to ensure that the lixiviant reaches the minerals of interest, extracts the target metal(s) and is captured/returned to the surface safely, responsibly and with little to no impact on the local environment.

Using technology developed, for example, by the US Bureau of Mines, ISR (which is sometimes termed solution mining) has been used on conventionally uneconomic uranium deposits and less frequently on gold or copper ores, particularly in the USA and the former Soviet countries (Mudd, 2000). In Australia, some ISR projects have been attempted with varying degrees of success, for example at Beverly, Four Mile, Honeymoon, Manyingee, Gunpowder, Mutooroo and Eastville. Today, ISR is still used extensively for uranium recovery but less frequently for other metals. Globally, the degree of acceptance of ISR as a viable alternative is variable, but it is always sensitive to environmental, flora, fauna and human health risk that could eventuate, particularly from the mobility and loss of control of the fate of lixiviant and pregnant leach solution for deposits associated with groundwater systems.

The use of this approach has generally been limited to orebodies with high natural porosity (and typically associated with a groundwater system), good response to available lixiviants and acceptable geographic locations. This has resulted in limited exploitation of the technology. Challenges to the implementation of ISR include solution containment; management of groundwater; and regulatory, ecological and societal requirements and expectations. Other issues that have limited the uptake of ISR technology include a restricted ability to observe or measure factors influencing ISR performance; the perceived and actual limited ability and availability of ISR tools, and the perceived, real and potential social and environmental risks. ISR has been used less frequently, if ever, for the treatment of restricted permeability hard rock deposits. The limited uptake of the technology for hard rock mineralisations results primarily from the low natural rock porosity and permeability, and hence poor response to available lixiviant.

The limited application of ISR highlights a real or perceived mismatch between existing knowledge, technology and capabilities and those required to achieve hard rock processing by ISR. A scoping study was initiated by CSIRO, with significant contributions from Curtin and Murdoch Universities, to focus efforts on identifying and understanding what the existing knowledge, technologies and capabilities are as related to ISR and what current challenges face the process. The focus of the scoping study was on four commodities (copper, gold, uranium and nickel), with a particular emphasis on hard rock, stranded, deep and otherwise currently uneconomic orebodies. It also placed a natural emphasis on the consideration of Australian research and technology and Australian opportunities. In this paper, we summarise the findings from the scoping study (which drew upon published information and expert knowledge) and provide suggestions for the way forward in developing and executing a technology/capability roadmap and engagement to progress ISR research and development.

## EXISTING CAPABILITIES AND CHALLENGES IN EACH FOCUS AREA

To enable its assessment, ISR was initially classified into nine focus areas for investigation:

1. social and environmental
2. economics
3. resource characterisation
4. ore porosity and permeability
5. drilling, blasting and rock fracturing
6. lixiviant system selection
7. lixiviant management and reactive transport modelling
8. groundwater management and hydrogeology
9. monitoring and forecasting.

The focus areas were selected based on a sequential approach that could be adopted in ISR project development (as illustrated in Figure 1), and were not weighted equally in terms of importance or breadth of focus. For example, the social and environmental focus area, besides being relevant

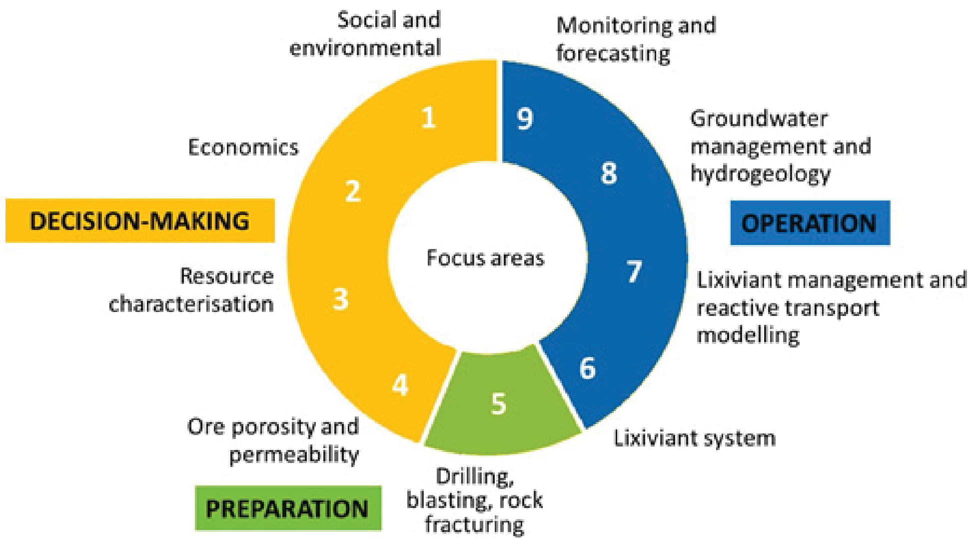


**FIG 1** – *In situ* recovery (ISR) study focus areas following a sequential approach that could be adopted in ISR project development.

and interlinked with many of the other focus areas, is critical for the progression of ISR and may therefore be considered to be more important than some of the other areas.

The information collated from the scoping study is presented here as classified originally. It is recognised that successful ISR of hard rock opportunities will require combining the technologies and interdisciplinary thinking of these multiple complex areas, and that combining these may prove challenging. Much discussion is currently underway on the optimal and logical combination of these focus areas for future work and optimisation of synergies between areas.

A short description of what each area encompasses, the current capabilities and various challenges are summarised in the following sections.

## Social and environmental

*Aspects related to understanding the social/local community influences, environmental assessment and monitoring, licence to operate and public perceptions.*

Research underpinning the acceptability of ISR has tended to focus on the environmental aspects of the technology and its application. Limited social research on the acceptability of ISR has been undertaken. One international study (Millenacker, 1994) identified that public information was equal in importance to the technical planning and engineering aspects of ISR mine development, and, in many cases, was linked to successful permitting and social acceptance of ISR operations. A recent study conducted by CSIRO identified that in Australia, public knowledge and awareness of ISR is low but there does not currently appear to be any entrenched social opposition to the technology (Moffat, Zhang and Boughen, 2014). Overall, it is evident that the integration of expertise in environmental risk assessment and social research to better identify the concerns and limitations to ISR acceptability is paramount to the successful development of the process as a transformational technology.

A full and rigorous identification of the range of impacts of ISR (generic and context-specific impacts, surface and *in situ* impacts and impacts related to mining and post-closure phases) and how they would be mapped to different ISR operations and their regulation is required. This would also provide a way of mapping key social and environmental impacts and how these identified issues need to be managed and communicated at various stages in the life cycle of ISR operations.

Four key areas of environmental research are required to support improved environmental monitoring and assessment of ISR:

1. identifying and understanding the environmental impacts of various ISR applications and new technology developments
2. improved methods of waste recovery/disposal, with a particular focus on processes that are required during various phases of mining activity
3. increased accuracy and reliability in the prediction of long-term groundwater and surface water impacts
4. the development of innovative options for the restoration of groundwater and surface water quality and post-closure land use.

These four key areas may use the same or similar models as those identified for lixiviant and groundwater management.

Improved understanding of environmental monitoring and assessment of ISR also informs the development of a comprehensive and structured approach to understanding the range of associated social dimensions of the technology. Key activities for integrating environmental and social aspects of ISR include:

- building understanding and knowledge of public (and other stakeholder) perceptions of ISR
- designing a strategic program of engagement for diverse stakeholders
- developing a comprehensive approach to assessing risk and value for diverse stakeholders.

It is important to note that the treatment of social and environmental aspects in an ISR project would require very different approaches. The former is based on process, dialogue and an appreciation of competing societal values, while the latter is based on data, modelling and risk assessment.

## Economics

*Methodologies for evaluating and ranking opportunities, risk analysis and benchmarking, including logistics, infrastructure, mine design, mineral economics, mine cost estimation, downstream processing, process design, techno-economic ranking, costing comparison (benchmarking ISR versus ISR and/or against conventional processes), energy integration and the use of renewables.*

With respect to techno-economic models for opportunity prioritisation and ranking of ISR and conventional deposits, only conceptual-level models and flow sheets exist for uranium and copper ISR processes. No publically available models exist for gold, although CSIRO has developed a preliminary conceptual gold model. In addition, no framework, model or ranking criteria exist to evaluate opportunities by metals, deposits, energy savings, cost savings, water use or waste generation, while some typical conventional flow sheets do exist, in many cases flow sheets of conventional routes cannot be compared directly with ISR mining methods.

Conceptual, preliminary techno-economic evaluation tools and models are required to identify potential key sensitivities to variables of an ISR project (eg borehole arrangement and associated drilling costs, pumping costs, recovery rates etc), and research efforts must be focused on optimising and minimising the key sensitivities to reduce the economic risks. Customised flow sheets and detailed techno-economic models for conventional (most likely open cut and heap leach) and ISR process routes for gold, copper, uranium and possibly nickel laterites must therefore be developed. A number of key variables could affect capital and operating cost footprints and other financial indicators (eg ore grade; permeability; porosity; sweeping efficiency; breakthrough time; recovery and yield; chemical flow rates; hydraulic conductivity; specific reagent consumption; well-field pattern; energy consumption for pumps; drilling costs; conditioning costs; solid and liquid waste disposal issues; on-site chemical risk management; on-site and off-site risk radiation management; air emission management; availability of power, energy and water sources; nearest access road distance and delivery point for product transport; mine closure variables; and post-decommissioning measures). The initial focus in this area may be on naturally porous and permeable deposits to draw upon the available models and information, and this focus can then shift towards non-porous hard rock deposits.

## Resource characterisation

*Defining, determining and understanding the important properties of an orebody and its surroundings, including geological characterisation, geochemistry, geophysics, mineralogy, mineral grain size, gangue etc.*

Advanced resource characterisation is a multiscale process and requires integration of data sets collected at (kilo)metre to micron scales. Existing capabilities in advanced resource characterisation include geophysical resource and *in situ* downhole characterisation technologies. The collection and integration of data sets using these and other technologies can be applied to generate a three-dimensional mine/ deposit model. Additional properties that are specific to ISR processing, such as texture, hardness and mineralisation, will be critical in informing decision-making for ISR processing and would also act as a 'baseline' during ongoing monitoring of ISR.

Deposit texture is an important characteristic that would allow for the domaining of a deposit (based on permeability, hardness, alteration etc). However, no current data acquisition methods allow for the direct observation of texture underground. Since scale, style and degree of heterogeneity in mineralisation, along with relevant aspects of gangue and porosity features, will very likely influence the viability of a deposit for ISR, methods that target prospective and non-prospective textures are required. A further significant impediment to managing the analysis of the volumes of sample material required for developing models of a resource for ISR is understanding what parameters are key to modelling a system at the appropriate scale to allow for sensible domaining of a deposit (what scale of heterogeneity can be modelled effectively to inform decision-making). This understanding requires a multilayer and iterative approach to data analytics. Significant effort is required in the data analytics area to achieve representative sampling approaches and multiscale data integration. This includes developments required for qualitative to quantitative data conversion, linking multiscale data sets for interrogation/modelling, iterative resource modelling and model reduction approaches for understanding system properties at appropriate scales.

In terms of geophysical methods, knowledge of mineralisation styles being investigated or sought and the selection of an appropriate strategy to employ geophysics may be required. A database of physical, petrophysical and electrical properties for lithologies within prospective zones would be useful, as would knowledge of relationships between petrophysical, physical and electrical properties and mineralising styles in prospective areas.

## Ore porosity and permeability

*Porosity and permeability of the natural resource and surrounding rock, after fracturing and during and after leaching; understanding the effect of fines mobilisation on porosity and permeability.*

Ore porosity, permeability and access of lixiviant to the target mineral is required for recovery of the valuable metal. Knowledge of the rock's baseline permeability will assist in defining requirements for fracturing or other means of creating access to the minerals. Furthermore, an understanding of changes in accessibly during processing (from mineral dissolution, swelling, precipitation etc) is vital to maintain recoveries.

Ore porosity and permeability are closely linked and are influenced by a number of the focus areas, and an ability to characterise and measure these properties in a deposit is vital. Although considered in many other sectors, permeability and porosity measurements are seldom considered in metalliferous mining and are only given cursory attention in percolation leaching operations. Rock porosity can be measured in a number of ways on small-scale samples (< 25 mm). On a larger scale (1–10 m), porosity is not measured easily (directly) and would likely require investigation into whether existing measures can provide an indirect/proxy estimate. Permeability can be measured in rocks using gaseous or liquid fluids, while classified images and tomography can provide subjective estimates. Hydraulic conductivity can be inferred from pumping tests and used to give a proxy for permeability, especially where supported by gas permeametry.

Challenges exist in characterising the 'accessibility' of ore minerals in coarse rock samples. A possible option for estimating ore mineral accessibility involves analytical imaging methods. Extrapolation of laboratory-scale measurements to orebody scale would require identification of rock mass and ore mineral textures. This may be possible using drill core but would be more challenging from drilling if fragmented or powdered samples were recovered (no retention of original texture). A means to calibrate textural information from core with proxies obtained from other drilling methods would be required.

Large-scale permeability of the rock mass, measurement of *in situ* rock stress and its orientation with the mineralisation may require optimisation via modelling if absolute *in situ* measurements of these properties are not possible. The calculation of initial conditions may be similar to the existing and emerging capability used for oil/gas reservoirs. However, dynamic modification of permeability in a leaching context will require innovative approaches. An understanding is required of the changes in rock stability, the mechanical properties of the stressed rock mass and nano-micro porosity during leaching.

## Drilling, blasting and rock fracturing

*Rock drilling, blasting and fracturing technologies/techniques (eg continuous, directional and branching drilling; explosive and hydraulic fracturing; proppants and scale-up; geomechanics, structural geology and understanding the relationship between mineralogy and fracture patterns).*

Drilling is applied to gain access to the ore, whereas hydraulic fracturing and/or blasting is used to create additional surface area and permeability in the rock mass or between the injection and production boreholes. The technology and models around drilling, blasting and rock fracturing exist or are under development. For example, theoretical and experimental approaches are being used to improve drilling mechanics, and performance and research is being conducted into drilling efficiency to reduce drilling costs significantly. Hydraulic fracturing can be used to generate fractures that extend to 50 m radius or larger from the borehole, and blasting is used to fragment rock, produce large surface area and enhance permeability, either or both of which could be applied to in-place ISR.

The approach and type of drilling, blasting and fracturing technology to apply at a site will depend, to some degree, on the site details and will ultimately require full-size field trials. Characterisation of the natural fracture systems, their permeability and their relationship to mineralisation will be important. Tools need to be developed to quantify the fracture system (and creation of surface area and permeability) once the techniques of drilling, blasting and rock fracturing have been applied.

Options for accurate, lower-cost directional drilling (as applied in petroleum-based directional drilling) along thin mineralised planes may also need to be established, and an assessment of the effect of blasting on boreholes or wells needs to be determined to quantify their potential damage from blasting.

Research to quantify the effect of hydraulic fracturing in a massive orebody is also required. Drilling costs can be reduced by spacing boreholes further apart, which is an approach that requires effective extended fracturing of the ore between the boreholes. Hydraulic fracture growth is affected by interactions with natural fractures and shear zones and with other recently placed hydraulic fractures. The process of hydraulic fracture growth in naturally fractured rock requires additional research. The degree of self-propping (maintained increase in permeability) that occurs must also be determined to assess whether artificial proppants are required or if self-propping is sufficient. An assessment of changes in conductivity (permeability × fracture aperture) during hydraulic fracturing and leaching would need to be studied to quantify this effect. The asymmetric fracture growth with respect to the injection borehole needs to be better understood so it can be allowed for in the well-field design.

It was noted that the geothermal industry has investigated heat recovery from deep crystalline rock formations. Despite limited success due to the approach taken and tests being pressure-limited, drilling to and fracturing at the proposed depths is possible.

## Lixiviant system selection

*Relevant commodity-based extractive metallurgy, lixiviant systems/development, solution chemistry, thermodynamic modelling, effect/reactivity of gangue, precipitation, downstream processing, lixiviant recycle and waste treatment.*

Lixiviant systems are relatively well established for conventional leaching processes. However, although ISR has been conducted globally, the behaviour and impact of lixiviants on various chemical and physical deposit properties is unknown in many cases. Challenges are also associated with establishing a laboratory methodology and tools, including thermodynamic and kinetic modelling, to evaluate lixiviant systems for ISR applications (elevated pressure and temperature and anaerobic conditions) and determine leaching performance that simulates ISR conditions.

There may be a requirement for the development of new, environmentally friendly (or at least benign), cost-effective, rapid leaching selective lixiviants. Similarly, oxidant efficiency, solubility, delivery and reactivity are areas that require research. Gangue and value mineral chemistry effects such as reactivity, decrepitation, precipitation, adsorption and the effect on permeability/porosity and ground instabilities may need to be considered. However, because the scale-up effects using suitable equipment and methodologies from laboratory to ISR are not understood, it may not be possible to conduct laboratory-scale tests to fully quantify many of these effects.

Therefore, laboratory lixiviant evaluations most likely need to be complemented at a field trial scale with potential refinements and correlations with laboratory methodology based on field data. Furthermore, the research focus is commodity-dependent, meaning that the establishment of a suitable field test site early in the research program is vital.

## Lixiviant management and reactive transport modelling

*Knowledge and technology relevant to the understanding and optimisation of fluid flow within the ore and the creation of ISR models. This includes models that exist to integrate chemical reactions with fluid transport, lixiviant and rock face contact, pumping, subsurface stirring technology, electrokinetic enhancement of ion transport, packers and lixiviant delivery.*

Numerical models of coupled fluid flow, solute transport and chemical reactions exist and could likely be applied to 'simpler' ISR problems (porous media and evenly distributed fractures). The application of the simulation of physical transport in media with dominating discrete fractures (applications have generally been limited to single fractures) and reactive processes involving more complex lixiviant systems (beyond simple acid leaching) has been limited, and only fairly simplistic scenarios have been treated. Some thermodynamic databases exist and although rate laws exist in literature, they have had limited application and have often not been compared with measured data. Reactive transport modelling of more complex ISR systems/technologies would therefore require the development of suitable modelling approaches and tools. Models (either highly resolved or reduced-complexity models) need to be established for hydro-fractured media. The effects of pressure, temperature, geomechanical properties and changes in rock transmissivities would need to be included in these models. Technologies such as electrokinetics, if considered for the enhancement of lixiviant transport, need to be incorporated into the models, and the computational efficiency of the limited number of existing simulation codes to model such processes would need to be improved, tailored and tested for ISR applications.

Along with the challenge of the numerical treatment of the simulation problems, there will be a significant need for testing and improving numerical models for data sets obtained under controlled experimental conditions. Reactive transport modelling tools could accompany and be used to interpret experiments that may range from the pore-scale to ISR field trials, starting from simple setups, followed by successively complex experiments with respect to flow/transport and geochemical complexities. The effect of mechanical heterogeneities (eg permeability and local alterations) on the centimetre to metre scale needs to be determined, and reactive transport simulation expertise in fractured media must be established.

## Groundwater management, hydrogeology

*Characterisation, assessment, monitoring and management of natural groundwater distribution and movement, including environmental considerations where impacted/related to ISR.*

An understanding and ability to manage the deposit groundwater and hydrogeology is dependent on two main elements that would contribute critically to the determination of ISR feasibility:

1. an assessment of the potential and properties of the ore-bearing and surrounding rock for fluid flow and recirculation (hydrogeological investigations and groundwater flow and solute transport)
2. the identification of possible contamination hazards to the land surface and associated or nearby groundwater, and optimal design of a groundwater monitoring network.

A three-dimensional model is required of the physical (hydraulic conductivity distribution) and chemical (physico-chemical properties of ore rock and surrounding rock, and their spatial distribution) heterogeneity for ISR applications. The hydraulic conductivity distribution within ore-bearing and surrounding rocks needs to be better characterised to minimise environmental impact (and assess the extent to which the fraction and location of low-permeable rock formation is estimated correctly to enable lixiviant access).

Hydrogeological characterisation of the subsurface is expensive. Therefore, there is a need to develop a framework for optimisation of the site characterisation using spatial statistics, Monte Carlo simulation and global optimisation techniques.

The monitoring network needs to be optimised to account for physical and chemical heterogeneity, flow path heterogeneity and plume dimension and progression. Natural attenuation is an important mechanism to mitigate impacts from contaminant plumes, but there is large uncertainty about the predicted concentration evolution in space and time. Such uncertainty must be quantified and factors that contribute most to the uncertainty must be identified.

## Monitoring and forecasting

*Monitoring and understanding real-time leach performance, groundwater monitoring and its environmental relevance, improving performance and optimisation in ISR (eg downhole and underground monitoring).*

A variety of tools exist for deposit mapping (eg grade, mineralogy, elemental concentrations, and physical parameters such as pressure, temperature, density and fluid flow) using conventional, above-ground analysis of sampled materials (drill cores or chips) and downhole tools; *in situ* monitoring of fracturing (eg radiotracers, microseismics, tiltmeters, acoustic measurements and resistivity imaging) and surface monitoring (eg fracturing by sensors on pumps and leaching by pressure, temperature, solution potential, pH and solution assay measurements on the outputs of offset holes). Limited techniques exist for *in situ* monitoring of leaching, with physical measurements including tracer injection or temperature and pressure logging of injected fluids and corresponding measurements in offset holes to determine fracture location and flow rates.

Tools are required to improve deposit mapping, including the measurement of grade and rock properties down drill holes and measurement while drilling. There appears to be a limited requirement for new tools for *in situ* monitoring of fracturing since a variety of these exist already. However, new tools are required for *in situ* monitoring of leaching. These may include injectable sensors that could be recovered and interrogated and geotomographical sensors based on the use of seismic, acoustic or electromagnetic energy waves and deployed in downhole or between-hole configuration to characterise pore structure (and fluid flow) or rock fracturing. Improved online sensors may be required for surface-based monitoring.

It is proposed that the deployment of sensor technologies from other fields be investigated and literature of current state-of-the-art smart dust sensors be reviewed. High-resolution microseismic equipment may need to be designed and built, the capacity to handle large volumes of data in real time may need to be developed and other essential new sensors may be identified from experimental test work.

# THE WAY FORWARD

To further develop ISR as an alternative technology to conventional mining, the perceived and real impacts and risks must be addressed and reduced, tools must be developed, an underlying understanding of all areas of the process must be obtained and ISR technologies must be demonstrated.

This could be achieved by collaboration with research and industry partners with a focus on topic-specific research programs. Test work will need to be conducted at small/laboratory scales to develop non-existent or undeveloped capabilities, techniques, technologies, models and tools in various areas. Where technologies are relatively mature (and may not have been used specifically in ISR applications) or where experimental conditions that would occur in an ISR environment cannot be simulated in the laboratory, testing of current (and future) techniques, technologies, models and tools will need to be conducted at large/field trial scales. Iterative work will focus on establishing required databases, developing models and predictions and conducting physical test work to evaluate predictions and update models.

A unique collaboration will be required between researchers, technology suppliers and mining companies to integrate capabilities, with industry engagement being especially necessary for site testing.

Potential considerations for test site selection include physical properties (eg texture, mineralisation, deposit type, depth, geometry, seismic activity or instability and hydrological amenability), economic assessment, practical considerations (eg a brownfield site may be most suitable for test work because of existing infrastructure, permitting/licencing, facilities and expertise) and specific characteristic details.

The important consideration of the social and environmental aspects and the development of techno-economic modelling and understanding have been identified as priorities. These, along with the progression of certain other technical areas and the identification of a potential test site, will be the immediate focus. In parallel, an engagement plan will be developed for industry, technology providers and external research entities.

# CONCLUSIONS

ISR has the potential to provide an alternative, more affordable processing technology for lower-grade or subeconomic hard rock deposits with a lower environmental impact. However, a number of challenges have been identified that have limited its uptake. To progress ISR implementation, certain social and environmental aspects must be addressed, and techno-economic evaluations must be conducted as a priority to evaluate and direct further work. A number of technical areas require development, and a unique collaboration and engagement between researchers, technology suppliers and mining companies is needed. Also of importance is the establishment of a suitable site for testing relatively mature commodity-based (and thus site-based) technologies, assessing additional developmental requirements and integrating different areas.

The scoping study that was conducted does not intend to provide a comprehensive analysis and interpretation of information provided by contributors in the nine focus areas. Rather, it has allowed us to identify challenges and areas of required development for progressing ISR. More importantly, it has allowed us to assess how we should proceed with an ISR research and development project. A definition of the optimum progression route remains a work in progress; however, it is proposed that the information in this document be used in consultation with research and technology providers, industry and government to develop:

- a technology demonstration roadmap
- a research/technology development plan
- an industry/government engagement plan.

As ISR is a complex and interdisciplinary field of research, no single group may be able to tackle the issues related to the technology completely independently. Collaboration across groups with expertise in various areas relevant to ISR may add the most value. CSIRO will be exploring options to progress these areas in collaboration with research groups, industry, government and technology providers.

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