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Perth, Australia

24th Annual Conference Proceedings

In Situ Recovery Conference

Including

Enhancing ISR Permeability Forum

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ALTA 2019 IN SITU RECOVERY SESSIONS

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Enhancing ISR Permeability Forum

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Alan Tayor has over 40 years' experience in the metallurgical, mineral and chemical processing industries in Australasia, New Zealand, North and South America, Africa, Asia and Europe. He has worked in metallurgical consulting, project development, engineering/construction, plant operations, plant start-up and technology development. Projects and studies have involved copper, gold/silver, nickel/cobalt, uranium and base metals.

Since 1985, as an independent metallurgical consultant, Alan has as undertaken feasibility studies, project assessment, project development, supervision of testwork, flowsheet development, basic engineering, supervision of detailed engineering, plant commissioning and peer reviews and audits. Clients have included a variety of major and junior mining, exploration and engineering companies throughout Australia and overseas.

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In Situ Recovery Proceedings Contents

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In Situ Recovery Proceedings

Keynote Address

TRENDS IN ISR TECHNOLOGY

By

Dr Horst Märten
Vice President Technology, Heathgate Resources Pty Ltd, Australia
CEO, UIT, Germany

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

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Developments in Uranium ISR

AUTOMATED GROUND WATER MONITORING FOR AN AUSTRALIAN IN-SITU RECOVERY MINING OPERATION

By

[1]Kathie McGregor, [1]Daniella Caruso, [1]Mikko Vepsalainen, [1]Miao Chen, [1]Dylan Marley, [1]David Macedo, [1]Tom Austin, [1]Tony Kilpatrick, [1]Avi Bendavid, [2]Kathryn Levingstone, [2]Andrea Marsland-Smith, [2]Rohan Calley[2] and [2]Gavin Agius

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Presenter and Corresponding author

Kathie McGregor

ABSTRACT

Effective groundwater management is vital for helping in situ recovery (ISR) and other mining sites operate safely, efficiently and meet government regulations. It is also crucial for protecting the environment and local communities. However, the current best-practice method for ISR operations relies upon a manual 'pump and test' method that has significant challenges. These include high installation and labour costs, high maintenance requirements, and lengthy processing times that delay corrective actions. CSIRO has partnered with Heathgate Resources Pty Ltd, Boss Resources and NERA (National Energy Resources Australia) to trial an innovative automated groundwater monitoring and reporting system that will not only save time and money, but also pave the way for a new standard in best-practice for in situ recovery mining.

The CSIRO-developed SENSEI™ system is an end-to-end sensor, hardware and software solution, featuring proprietary, solid-state electrochemical sensors for continuous measurement of multiple chemical properties. It can operate in remote and extreme conditions, including low pH conditions (acid) and ground water pressures of at least 20 bar. CSIRO began a 12-month field trial of SENSEI™ sensor packs at Heathgate's Four Mile West uranium mine in November 2018. The units are being tested side by side with the current low flow groundwater monitoring system, and the effectiveness of the sensors as an alternative to manual sampling and analysis of ground water will be assessed.

Keywords: Sensors, Groundwater monitoring, Real time

2D REACTIVE TRANSPORT SIMULATION OF WELL CLOGGING DURING ACIDIC URANIUM *IN SITU* RECOVERY PROCESS

By

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Presenter and Corresponding Author

Maëlle Vergnaud

ABSTRACT

Katco, a subsidiary of Orano Mining, operates in Kazakhstan to extract uranium with an annual production of about 4000 tons. The mineralization is hosted in a sandy reservoir with interbedded clay layers. These geological conditions allow the extraction of uranium using an acidic *in situ* recovery (ISR) method. The operator of the wellfield has to cope with clogging effects on producer wells, which have a major impact on the mine site productivity. The purpose of this study is to provide the operators with a simulation tool to analyze and predict clogging.

Preliminary observations show that the intensity and frequency of clogging are related to the depth and location of the mineralized reservoir. Pregnant solutions, extracted from the wellfield, contain high concentrations of aluminum and sulfate, which imply high saturation index for alumino-sulfate species and potentially lead to precipitation in the reservoir. Precipitates were observed on the well screens using a downhole video camera. Moreover, a hydrodynamic study showed that the pressure losses are mainly located in the close vicinity of the screen. This information is consistent with estimation of volumes of secondary minerals performed by a combination of mass balance and reactive transport simulation.

It is assumed that acidic solution leaching of the reservoir dissolves elements which are able to re-precipitate as secondary minerals and that the head losses in the vicinity of producer wells are a consequence of these secondary minerals precipitation.

This study presents 2D reactive transport simulations conducted with the HYTEC software, developed by MINES ParisTech in a collaboration with Orano Mining. Based on a description of the reservoir properties, leaching solutions, and regional aquifer water, the simulation represents the evolution of the fluid composition through the reservoir to the producer well. The simulations are performed in 2D horizontally, with a refined mesh around the wells. The evolution of the fluid, and saturation index, can be followed under different configurations: different reservoir settings, various operational parameters.

The results of the simulation allow to assess clogging mechanisms and their location in the reservoir and to prepare recommendations on operational lever to avoid or mitigate clogging.

Keywords: Uranium Recovery, Acid Leach, Well Clogging, Reactive Transport Simulation, Hytec

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Use of Bacteria

MICROBIALLY-ASSISTED IN SITU METAL RECOVERY – WHERE DOES IT MAKE SENSE?

By

Frank Roberto

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Presenter and Corresponding Author

Frank Roberto

ABSTRACT

In situ recovery of copper and uranium have so far utilized primarily carbonate or sulfuric acid. Water-soluble salts such as potash, sodium chloride, and sodium sulfate can be leached by water alone.

Microbiological leaching (bioleaching) of copper from sulfide minerals such as chalcocite, covellite, enargite, and chalcopyrite in heaps or dumps is accomplished by chemolithotrophic, acidophilic bacteria and archaea. This process involves oxidation of sulfides producing sulfuric acid and ferric iron (in the case of pyritic minerals). Other bacteria and fungi are known to produce organic acids that can solubilize phosphate under circumneutral conditions. This latter process has not been reduced to practice to date. There is also potential to recover rare earth elements with microbially-produced organic acids.

Acidophilic microorganisms employed in bioleaching of metals from sulfides are obligate acidophiles, requiring conditions below pH 3.5. Sources of energy for growth include reduced iron and sulfur compounds, oxygen, and carbon dioxide. Some mixotrophic, acidophilic microbes are known to oxidize sulfides when complex sources of carbon (such as lipids, carbohydrates, or amino acids are available to promote growth.

Neutrophilic bacteria and fungi require complex carbon sources for growth and production of organic acids that may complex phosphate or other metallic anions.

This presentation describes some of the key environmental parameters controlling microbial activity that could promote (or inhibit) the in situ generation of biolixiviants for metal recovery.

Keywords: Copper, sulfide minerals, acidophilic, mixotrophic, chemolithotrophic, bacteria, archaea, fungi

THE USE OF BUGS FOR IN SITU RECOVERY OFFERS A NEW FRONTIER FOR MONETISING STRANDED ASSETS

By

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Presenter

James K Dirstein
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Ian MacCulloch

ABSTRACT

Mining via in situ recovery (ISR) methods is a familiar concept for uranium recovery but has been less successfully implemented in gold recovery. Known ore resources that cannot be conventionally developed due to grade, deposit reserves, waste rock/ore stripping ratio, and refractory gold/mineral association all may contribute to a decision to not mine a mineral resource.

Today, advanced technologies are available for ore discovery, characterization and production with in situ natural and augmented biological processes or non-toxic chemical leaching. The new technical discoveries mitigate or eliminate many of the above disadvantages to in situ leach recovery processes.

Leaching with bacteria opens up a tool box of methods to suite a particular environment. This tool box allows for the manipulation of both the ore and gangue minerals. The bacteria can be bioaugmented by adding performance enhancing bacteria to fulfil a variety of extra tasks such as the mobilisation of gold, the removal of silica encapsulation, the dissolution of sulphides to release both precious metals such as gold and silver along with the PGE group and base metals such as copper, zinc etc. All processes are undertaken at a neutral pH. This results in a bacteria grouping being tailor made for the ore type specifics rather than adapting the ore type to suite the particular features of the 'universal' bacteria species.

The presentation will give a brief rundown on the tool box itself. Possible targets include gold in cemented tertiary gravels, stranded resources in the form of a drilled-out gold project in the Front Range, Rocky Mountains, Colorado and the creation of coal seam gas from black shales and coals along with possible metal mobilisation, the new frontier for exploration.

Keywords: In situ recovery, refractory, gold, bioaugmentation, stranded resources, tailor made, tool box, silica encapsulation, ISR, bacteria, in situ leach

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ISR for Non-Uranium Metals

IN-SITU RECOVERY FOR NON-URANIUM METALS

By

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Presenter and Corresponding Author

Maxim Seredkin

ABSTRACT

In-situ recovery (ISR) transfers hydrometallurgical processing of mineralised bodies to the subsurface to directly obtain solutions of commodities. As a result, there is little surface disturbance. For ISR to be successful, however, deposits need to be permeable. Furthermore, commodities need to be readily amenable to dissolution by leaching solutions over a reasonable period, with an acceptable consumption of leaching reagents.

ISR accounts for more than 50% of world uranium production. Other than uranium, the most common commodity extracted by ISR methods is copper. Copper is extracted by sulfuric acid. Several copper deposits were previously subject to ISR in Arizona. The Gumesevskoye deposit in the Urals, the Morani deposit in Zambia and the Florence deposit in Arizona are currently in operation by ISR, while the Gunnison ISR mine in Arizona is nearing production. Some deposits in South Australia (Moonta, Kapunda) are also considered to have the potential for ISR.

After copper, the next most popular commodities for ISR are gold and its by-product silver. These commodities are extracted by chlorine or sodium hypochlorite. The Gagarskoe and Dolgy Mys deposits in the Urals are currently in operation. Several projects in Russia are nearing production, and some projects in Australia and the USA are presently being assessed for ISR potential.

ISR is also likely to be used for extraction of nickel and cobalt in the near future. Several field cluster tests have been completed on four nickel-cobalt deposits in the Urals and Eastern Kazakhstan. Sulfurous anhydrite and sulfuric acid were used as alternate reagents for leaching with pure metals produced. Kazakhstan will potentially be the first country to start a nickel and cobalt ISR mine. Manganese is also a commodity which can be extracted by a similar lixiviant. Pregnant solutions with this metal were also obtained in field tests.

A successful push-pull test for tungsten using a complex lixiviant with hydrochloric and ethanedioic acids was also recently completed in Kazakhstan.

Potential methods for ISR of other base metals and PGE have also been recently developed. Zinc can be leached by a lixiviant with sulfuric acid and chloride of sodium, while lead can be leached by methanesulfonic acid. PGE can be leached by a complex lixiviant with ammonium thiocyanate and ferric chloride. Successful tests have also been completed for boric acid and lithium.

Scandium is extracted as a by-product from pregnant uranium solutions at Dalur in Russia. Successful tests have also been completed which show potential for extraction of rhenium, molybdenum, selenium, vanadium, rare earth, yttrium as by-products of pregnant uranium solutions.

ISR could be both an interesting and plausible alternative mining method for many commodities. However, deposits require specific characteristics and conditions for its successful application. Hydrogeological and hydrometallurgical test work should be completed very early during project evaluation to assess the potential to use ISR methods.

Keywords: in-situ recovery, copper, gold, silver, nickel, cobalt, manganese, base metals, zinc, lead, tungsten, PGE, scandium, rhenium, molybdenum, selenium, vanadium, rare earth, yttrium, boric acid, lithium

THE POTENTIAL OF INSITU RECOVERY FOR COPPER, GOLD AND OTHER METALS, THE KAPUNDA PROJECT AS A POSSIBLE EXAMPLE

By

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Presenter and Corresponding Author

Leon Faulkner

ABSTRACT

Environmental Copper Recovery Pty Ltd (ECR) started investigating the potential for Copper ISR on the historic Kapunda copper mine north of Adelaide in 2016 under a Term Sheet with tenement holder Terramin Pty Ltd (ASX: TZN). ECR secured investor funding for the project in August 2017 for $1.8m over 3 years from Thor Mining PLC (AIM, ASX: THR).

In July 2018 ECR then secured a CRC-P (Cooperative Research Centre Projects) Grant for $2.85m with collaboration partners University of Adelaide, CSIRO, Mining 3, Thor and Terramin.

Research into insitu recovery has progressed significantly in the last 3-5 years in a number of areas including: lixiviant technology, mapping fluid distribution, fluid barrier technologies and social license. These advances mean that ISR as a technique can now be applied to a far wider range of deposits than previously thought, opening up a potentially significant number of previously stranded assets to profitable, low impact recovery. A selection of these advances are being applied at the Kapunda project to see if the remaining copper deposit could be profitably recovered with a low impact form of mining

Keywords: Insitu Recovery, Copper, environmentally benign lixiviants, Pilot Plant, CRC-P Grant, low footprint, social license to operate

STAGED LEACHING OF BORNITE WITH ACIDIC SOLUTIONS AT MODERATE TEMPERATURE IN AN IN-SITU RECOVERY ENVIRONMENT

By

[1,2]Tania Hidalgo, [2]Robbie McDonald, [2]Laura Kuhar, [1]Andreas Beinlich and [1]Andrew Putnis

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Tania Hidalgo

ABSTRACT

Sequential-staged leaching with different lixiviant and oxidant systems may be viable in an in-situ recovery (ISR) environment and may provide an opportunity for the leaching of refractory minerals if these can be converted into more readily leachable secondary products. An understanding of the leaching behaviour of secondary products when in contact with a different lixiviant system from that used in the first leaching stage may provide valuable information for ISR operations. Bornite (Cu_5FeS_4) has been found to be replaced by secondary sulfides, such as covellite and chalcocite, when leached with acidic solutions with restricted oxidant. The secondary sulfide phases may be easier to oxidize or passivate the surface and reduce the reaction rate. The leaching of resulting products of chalcopyrite, such as the dissolution of bornite that formed from the sulfurization of a chalcopyrite concentrate in the presence of gaseous sulfur has been addressed previously, but to the authors knowledge a sequential analysis of refractory, coarse copper sulfide samples, such as bornite, which have been leached previously in acid solutions with a second-stage dissolution in oxidant/lixiviant solutions has not been undertaken. In ISR, mineral contact with acid may result in viable oxidant solutions for copper sulfide leaching; for example, after acid dissolution, iron oxides and hydroxides may provide a source of iron (III) oxidant.

A synthetic goethite sample was dissolved in methanesulfonic acid to obtain a ferric methanesulfonate lixiviant for bornite leaching. A natural sample of bornite with quartz was cut into coarse pieces and leached sequentially with two different solutions (hydrochloric acid followed by ferric methanesulfonate solution). The first stage was performed in a closed incubator for a maximum of 20 days and the second stage was conducted over two days in a Parr reactor at 110°C. Leaches were conducted with a minimum oxygen present to simulate an ISR environment.

This paper presents results on the chemical composition of the solutions after each stage, and a cross-sectional analysis of the samples post-leaching, as determined by X-ray diffraction, scanning electron microscopy and quantitative evaluation of materials by scanning electron microscopy (QEMSCAN). Information is provided on the dissolution efficiency, product identification and an analysis of final textures. This study provides guidance on the potential for application of sequential-staged leaching to ISR and for the treatment of refractory copper sulfides in an ISR environment.

Keywords: Copper Recovery, Bornite Leaching, Hydrometallurgy, Staged Leaching, Surface Passivation, Mineral Replacement, Surface Product

LIXIVIANT SCREENING FOR APPLICATION TO COPPER- AND GOLD-CONTAINING ORES IN IN-SITU RECOVERY APPLICATIONS

By

Laura Kuhar, Amy Evans, Rebecca Meakin, Gay Walton, Robbie McDonald and Jian Li

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Presenter and Corresponding Author

Laura Kuhar

ABSTRACT

In-situ recovery (ISR) has been applied in the uranium industry for more than 50 years. Increased 1) technical progress, 2) technological innovations and 3) research directed towards establishing ISR as a viable alternative to conventional technologies has provided a positive outlook for the potential application of ISR to other metal deposits such as copper- and/or gold-containing ores. However, limited experimental test programmes exist with a focus on assessing the amenability of such ores to metal recovery via an ISR process. Furthermore, although some traditional measures of leaching success, such as reagent consumption, are relevant to an ISR application, the assessment of other factors, such as the 1) system stability (which is necessary because solutions may have to travel tens of metres without the ability to control their properties) and the lixiviant interaction with coarser material, 2) the surrounding groundwater conditions and 3) variable environmental conditions (such as variable temperature and pressure) become critical.

In this study, two case studies are considered, one with a focus on samples from an oxidised copper deposit (that also contains gold), and the second on samples from a variety of gold- and/or copper-containing deposit types. Approaches and possible experimental methodologies that are designed to screen lixiviant systems (for their application in the ISR processing of such ores) are discussed. An assessment of the lixiviant suitability based 1) on the pH of a saline solution in contact with the ore, and 2) stabilities of parameters such as pH and Eh under fixed leaching conditions is proposed.

Keywords: In-situ recovery, Lixiviant screening, Ore amenability, Copper ore, Gold ore, System stability

THE LEACHING OF GOLD BY ALKALINE GLYCINE IN MICROCHANNELS

By

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Presenter and Corresponding Author

Mohammad Reza Azadi

ABSTRACT

Recently, an aqueous glycine solution has been proposed as a non-toxic environmentally friendly lixiviant to leach precious metals such as gold. To investigate the in-situ leaching of gold using alkaline glycine, we employed a microchannel system with controlled flow, temperature and pH. Microfluidic systems allow manipulating a small amount of fluids into micro-scale channels; the concept is used in this paper in order to leach a nano-scale gold layer. The thickness of gold is monitored in real-time using a microscopic camera. In this paper, we explain the microchannel fabrication process and the experimental set up. We show the results of gold recovery in different conditions of pH and temperature. In addition, we discuss the advantage and the limitation of microchannel systems in studying of leaching process. Our results show that this technique has the ability to provide fast outcomes with low chemical consumption.

Keywords: Leaching, alkaline glycine, microchannels

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In Situ Recovery Proceedings

Enhancing ISR Permeability Forum

INNOVATIONS IN ROCK FRAGMENTATION AND FRACTURING - CREATING ACCESS FOR LEACHING

By

Ewan Sellers, S Dehkhoda, Ebrahim Fathi Salmi and R Puscasu

Mining3, Australia

Presenter and Corresponding Author

Ewan Sellers

ABSTRACT

The application of in situ leach technologies to metal recovery requires new access creation methods due to the low permeability and different geology of the target formations. New technologies for rock fracturing and fragmentation have been developed recently with increasing requirements to extract ore from underground in novel ways. The target of the new technologies is to improve productivity, protect the environment, health and safety as reduce the usage of energy and water. Many of these of these technologies could be applied in hard rock recovery processes.

In hard rock, fracturing is necessary for the lixiviants to contact enough ore to create larger recoveries. The mechanisms of fracturing have been known since the stone age and include direct pressure, indirect pressure, splitting, heating and cooling, often applied in combinations. The potential to apply these mechanisms for creating flow paths in the rock mass are considered. Opportunities for applying these mechanisms using new technologies are provided by advances in materials and knowledge. New methods for fracture development include cryogenic fracturing, microwaves and pulsed detonations. Additional challenges in application of these techniques for in situ recovery include the geological setting of the ore the in- situ stress and the extent of initial fracturing.

The paper discusses two options for providing access to leach recovery. The first involving in situ operations with drill holes from surface. The second method being In Mine Recovery for marginal ores in existing mines by creating leach silos. A review of potential fracture methods for each, including the recent literature and patents is presented to provide an overview of current technologies for rock breaking. Practical applications from other mining operations such as cave mine preconditioning are considered as options.

Keywords: Insitu Recovery, Rock Breaking, fracturing, stress, Pressure, Heat, Cooling

POTENTIAL USE OF BLASTING TO ENHANCE PERMEABILITY

By

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ABSTRACT

Chemical energy in the form of commercial explosives is the most efficient and lowest cost energy source used to fragment and fracture rock. When compared to mechanical energy used in comminution, it has been calculated to be approximately 50 times more efficient.

Modern explosives and detonating systems, along with a better understanding of detonics, including fundamental computer modelling, are providing new insights into how the application of explosives can be used in an ISR mining system.

Unlike hydrofracturing, blasting is a dynamic process with the reaction occurring in microseconds. The rate of this reaction has its benefits and its disadvantages. If the explosive-induced stress waves can reflect from free surfaces, they can cause significant damage, resulting in fractures and fragments over a large area. If constrained within a solid rock mass the damage envelope will be restricted to the area immediately around the blasthole. The local in situ stress field also has a significant impact on the accumulation of blast-induced fracturing in the rock mass.

This paper attempts to explain the benefits and limitations of explosives to precondition the rock mass to increase permeability. Explosives may be used alone or can form part of a hybrid mining system combining hydrofracturing and conventional mining techniques.

Keywords: detonics; computer modelling; fractures and fragments; insitu stress; preconditioning; permeability; hybrid mining techniques;

AN ARTIFICIAL FRACTURE STIMULATION TECHNIQUE FOR ENHANCED IN SITU RECOVERY USING NON-EXPLOSIVE DEMOLITION AGENTS

By

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ABSTRACT

Conventional mining methods (open-pit and underground) are becoming increasingly uneconomical with declining ore grades. In-situ recovery (ISR) is becoming an alternative technology which could potentially replace conventional mining operations provided that the existing limitations of ISR can be addressed. Industrywide application of one limiting factor of ISR is the poor recovery rates due to the low permeability of the host rock formations.

In this study, we developed a patent-pending non-explosive rock fracturing compound called 3G-DTM, which can be used for artificial fracture stimulation in sensitive environments (such as marine environments and aquifers) where conventional methods of fracturing such as explosive blasting and hydraulic fracturing cannot be used. The fracturing compound 3G-DTM was successfully tested in the laboratory to fracture low permeability sandstone specimens under confining stresses up to 20 MPa. Due to the fracturing nature of 3G-DTM, the fracture density can be significantly improved (by 116%) with an increase in the confining pressure (from 70 kPa to 20 MPa). Furthermore, the rock is subjected to a gradual fracturing process in 3G-DTM fracturing (10–15 h in the laboratory experiments) allowing for a safer, more controlled fracture propagation, making 3G-DTM a substitute for conventional rock fragmentation in sensitive environments.

Following the fracturing tests, the fracture permeability of the specimen was calculated. Compared to the miniscule intact rock permeability of 7.6 x 10^{-20} m^2 of the sandstone specimen an improved permeability of 1.48 x 10^{-13} m^2 at a confining pressure of 30 MPa was observed after fracturing the specimen using 3G-DTM, which makes 3G-DTM charging a potential method for permeability enhancement in ISR applications.

Keywords: Artificial fracture stimulation, enhanced in- situ recovery, non-explosive demolition agents, fracture permeability

IN-SITU RECOVERY ENHANCEMENT IN HARD MASSIVE ROCKS BY HYDRAULIC FRACTURING

By

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ABSTRACT

Ore deposits are expected to be permeable (e.g. porous media) to grant the success of In-situ recovery (*ISR*). However, the *ISR* from hard deposits which lack of porous media is still challenging, due to poor understanding of the fracability i.e. connectivity between pre-existing and artificial fractures.

Therefore, in this study, extremely hard Foliated Silicified rock (Uniaxial compressive strength (*UCS*)=55kpsi, Density=2.8gr/cc, Young's Modulus (*E*) =15.7 million psi) was acquired from subsurface of 3900ft, meta-sedimentary deposit, Western Australia. The irregular sample was moulded into a 15cm cubic polyester resin which can fit our in-house built 1600KN *TTSC* (True Triaxial Stress Cell). To investigate the potential of stimulated orebody volume, we conducted three hydraulic fracturing experiments (i.e. initial fracturing and two additional refracturing) associated with reopening tests in the *TTSC*. The magnitude of field stress state was initially simulated as σ_1=5100psi, σ_2=3700psi, and σ_3=2500psi but the direction was changed during refracturing tests. Meanwhile, wellbore pressure and microseismicity were simultaneously monitored and recorded. High energy CT scanning (Medical CT, 140KV, 1000MA) was conducted on the pre and tested sample. CT image was then processed to demonstrate the characterization of pre-existing cracks and induced fractures.

Base on CT images (pre-tests), one pre-existing longitudinal crack nearly cross the entire rock. The breakdown pressure of 5800psi, 5600psi, and 5950psi were recorded respectively during initial fracturing and two subsequently refracturing tests. Based on the hypocenter localization of microseismic events and CT images (after tests), both longitudinal (double wings) and transverse fractures (double wings) were generated and extended to the boundary of rock sample. The induced hydraulic fractures propagated as approximately two dimensional geometry governed by minimum principle stress**.** Furthermore, no secondary branch of fracture was observed from microseismicity and CT images, which indicated that the complexity of fracture network is low. Therefore, we elucidate that the stimulated volume of Foliated Silicified rock is limited and hydraulic conductivity can only be partly improved by the main fractures.The good correlation between hypocentre localization of microseismic events and CT images of induced fractures illuminate that the field engineers can infer the geometry of induced fractures based on microseismicity, which is essential for recovery well placement and up-scaled modelling in such type of ore reservoir.

Keywords: hydraulic fracturing, microseismicity, morphology, hydraulic fracture, hydraulic conductivity

HYDRAULIC FRACTURING IN IN SITU RECOVERY – METHODS AND EQUIPMENT FOR FIELD TRIALS

By

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ABSTRACT

Hydraulic fracturing is used widely in the petroleum industry to increase the permeability of reservoirs via stimulation of oil and gas wells and is increasingly being adopted in the minerals industry to precondition ore bodies for block cave and sublevel cave mining and for preconditioning roof rock for coal mining.

For application of hydraulic fracturing in a mining environment specialized equipment and methods are required to meet the operational requirements and objectives of the program. Hydraulic fracturing equipment used for mining operations is typically purpose built to meet the considerations for surface and underground use, considering regulatory and operator requirements. Specialist methods have been developed to characterise the rock mass so hydraulic fracturing programs can be designed and optimized.

To establish the feasibility of hydraulic fracturing as a means of increasing rock mass permeability for in situ recovery, the predicted fracture orientation must be determined by measuring in situ stress conditions. Other parameters that need to be measured include rock permeability, pore pressure, tensile and compressive rock strength, and rock fracture toughness.

Hydraulic fracture orientation, growth rate, efficiency and asymmetry can be measured using offset borehole monitoring, tiltmeter monitoring, video and acoustic borehole scans and micro seismic monitoring.

These parameters are site specific and typically a hydraulic fracturing trial is carried out at the intended site to collect these data. Based on the data collected a suitable hydraulic fracturing system can be specified, down-hole fracturing tools selected and a fracturing program designed.

This paper describes the type of equipment required for the application of hydraulic fracturing for in situ recovery and the methods used to characterise and monitor hydraulic fracture growth.

Keywords: Hydraulic Fracturing, Tiltmeter monitoring, Rock Mass Characterisation, In Situ Stress Measurement, Hydraulic fracture growth,