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Considerations and potential economic advantages for the in-situ recovery of gold from deep, hard-rock deposits

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ABSTRACT

The combination of commodity prices and price uncertainty, coupled with ever-increasing capital and operating costs of mining and metal production create significant challenges for the metals mining industry. With current ("conventional") technologies, it may not be feasible to extract and process many known deposits economically. This is because of declining grades, challenging mineralogies and increasingly greater depths, amongst other factors. To overcome these issues, it is appropriate to reconsider the wider application of a step-change technology, such as in-situ recovery (ISR), which reduces or eliminates mining and comminution costs significantly. Although a number of attempts have been made towards gold ISR processing, no commercial applications of this technology exist currently. In this paper, the suitability of various gold-bearing deposit types is discussed with reference to their potential for ISR processing. Solution chemistry-related issues and potential lixiviants for use in ISR are described and the challenges for gold ISR are highlighted. Despite the technical challenges presented, a preliminary techno-economic evaluation indicates the potential profitability of such a process.

1. Introduction

In-situ recovery (ISR) (also referred to as in-situ leaching or solution mining) refers to the recovery of valuable metals from ore deposits by the circulation of a fluid underground and recovery of the valuable metal from the fluid at the surface for further processing. References to ISR date back to 177 BCE, and the Chinese used ISR to recover copper in 907 CE (Morris, 1984). The recovery of soluble salts, such as halite (NaCl), trona ($Na_3(CO_3)(HCO_3)\cdot 2H_2O$), potash (various salts that contain potassium in water-soluble form, such as potassium hydroxide, carbonate, chlorate, chloride, nitrate, sulfate and permanganate), boron and magnesium minerals, has been used extensively (Bartlett, 1998). The first trials of uranium ISR were initiated in the 1960s in USA and Russia and, by 2013, almost half of the world's uranium was being mined from ISR operations, including those in USA, Australia, China, Russia, Kazakhstan and Uzbekistan (World Nuclear Association, 2014). A number of experimental, demonstration and commercial copper ISR operations have been undertaken (Sinclair and Thompson, 2015), with the focus being mostly on oxide material, but no commercial greenfield operations have been established for copper sulfide deposits. A number of gold deposits, particularly paleochannel deposits, have also been considered for ISR, but, to the best of our knowledge, only limited demonstration and no commercial operations have been established. Many ore bodies will remain unsuitable for an ISR approach due to inherent and local factors (such as geology, hydrology, ore and gangue mineralogy, lack of permeability) and there is no universally applicable ISR process even for those deposits with a favourable predisposition. Characteristics of different deposits vary significantly and factors such as the ore mineralogy, valuable metal location/distribution, target mineral liberation and accessibility, depth and deposit temperature, all affect the requirements and selection of the type of ISR process, which can vary from extraction of metal values from broken ore in pits or stopes (often termed in-place leaching) to designated wellfield design with a solution recovery plant (Bartlett, 1998).

2. Recovery of gold by ISR processing

2.1. Historical applications of gold ISR

The first reference to gold ISR was made by the Russians in 1896 (Morris, 1984), but it was not until the 1970s that a three-year pilot plant program was undertaken at the Ajax Mine in the Cripple Creek district, Victor, Colorado, USA (Chamberlain and Pojar, 1984). In this application, chloride- and iodine-containing solutions were investigated for the recovery of gold from telluride minerals. Because of the steeply dipping vein structure in the deposit, it was hoped that lixiviant could

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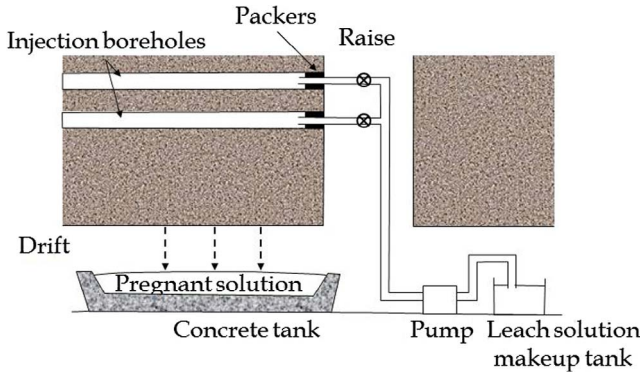

Fig. 1. Pictorial representation of the ISR approach used at the Ajax Mine, Colorado, USA; figure adapted by authors from Chamberlain and Pojar (1984).

be injected through horizontal drill holes for collection in concrete troughs located in a drift (near-horizontal passageway in the mine) at the base of the fractured vein system (Fig. 1). However, problems were experienced in the collection of pregnant leach solutions; the trough and drift were not wide enough to encompass the vein-fractured system and excessive solution losses resulted. Furthermore, problems were experienced in the recovery of gold from tellurides; because metallurgical laboratory leaching tests failed to resolve the leaching chemistry of the ore, no additional test work was conducted to understand the solution flow in detail and test work was ceased.

CRA Ltd applied for permission to use an ISR process to recover gold at Eastville (a buried alluvial gold-bearing Victorian Deep Leads deposit) in central Victoria, Australia, in the early 1980s by using cyanide as a lixiviant (Bell, 1984; Heath et al., 2008). The principle for prevention of contamination of the aquifer was based on extraction pumping exceeding injection volumes. However, this deposit was located in a rural farming area and, after initial pump and dye tracer tests, regulatory approvals were denied (O'Gorman et al., 2004). Additional technical reasons, such as the availability of oxidant have been cited as leading to the project being unsuccessful (Heath et al., 2008). CRA later abandoned the project. Also in the 1980s, in-situ leaching of underground stoping areas was tested using thiourea solution in a Witwatersrand mine in South Africa, but the technology was not commercialized successfully (O'Gorman et al., 2004; van Staden and Laxen, 1989). In the late 1980s, low levels of gold were found in water pumped from underground workings at a gold mine in the Northwest territories, Canada. Weak cyanide solution from overlying tailings impoundment had entered the mine workings and leached some of the gold. This water was pumped from underground as process water, was used in the mill and resulted in an incremental increase in gold recovery.

2.2. Challenges to gold ISR

Despite the feasibility of gold ISR as evidenced by the unintended leaching of gold in the Canadian Northwest territories, the limited number of attempts that have been made at gold recovery by ISR and the fact that no commercial operations have been established for gold mining using cyanide or other lixiviant(s) hint at the various challenges and hindrances to this process. A variety of technical challenges that limit the application of ISR to various deposits still need to be overcome as described in Kuhar et al. (2015). In this paper, two areas are focused on, namely, mineralogy/geology and leach chemistry.

These challenges may be related to *mineralogy/geology* and deposit characteristics (such as gold location in veins or disseminated material, variability in mineralogy and liberation) and are especially apparent in the application of ISR to hard-rock mineralizations where the low natural rock permeability may have to be enhanced. A number of advances have been made in technologies such as hydraulic fracturing and directional drilling (DET CRC, 2014), and alternative methods to enhance solution access to the deposit, including chemically induced dissolution of gangue minerals to ensure efficient contact of solution with gold values; low-intensity blasting; cryogenic fracturing (Cha et al., 2014; Liu et al., 2014); infrared, microwave and high-voltage pulse technologies (Zuo et al., 2015) and hydrothermal spallation using supercritical water (O'Dowd, 2015; Potter and Tester, 1998) are being researched and developed.

An understanding of *leach chemistry* (leachability, lixiviant and oxidant behaviour, stability, operating window and performance in the leaching of valuable and gangue minerals) at high temperature and pressure also needs to be developed. Also related to the lixiviant is solution recovery, containment, reagent costs and environmental concerns and regulations, which may restrict its use (Chamberlain and Pojar, 1984; Marsden and House, 2006). An environmentally benign lixiviant–oxidant solution for gold beneficiation would be essential for an ISR application.

Aspects related to these two challenging areas (mineralogy/geology and leach chemistry) are discussed below.

2.3. Gold mineralogy and deposit suitability for ISR

Gold most commonly occurs as the native metal, as electrum (alloyed with some silver at 25–55% silver content), as a telluride or as ultrafine solid–solution inclusions within a sulfide mineral structure (such as arsenopyrite, pyrite, tetrahedrite and chalcopyrite) (Marsden and House, 2006). Marsden and House (2006) discuss the requirements for understanding gold ore mineralogy to select the optimum gold extraction process. They classify gold-bearing materials into 15 mineral processing-based categories: (i) placers, (ii) free-milling ores, (iii) oxidised ores, (iv) silver-rich ores, (v) iron sulfides, (vi) arsenic sulfides, (vii) copper sulfides, (viii) antimony sulfides, (ix) tellurides, (x) carbonaceous ores, (xi) gravity concentrates, (xii) flotation concentrates, (xiii) tailings, (xiv) refinery materials and (xv) recycled gold. Some ores are classified by more than one category. The ore is also classified as refractory where the gold is not able to be recovered by conventional carbon-in-leach (e.g., gold is not easily liberated or contains gold cyanide preg-robbing carbonaceous material). The potential suitability of nine of these deposit types as classified by Marsden and House (2006) will be discussed for ISR processing, considering factors such as depth and accessibility, but without extensive reference to lixiviants and the leachability of gold and gangue mineralogy.

Placers (Fig. 2) are formed after gold particle liberation by weathering and their transport away from a primary gold deposit (Marsden and House, 2006). Gold contents in placer deposits are often of a lower concentration than that of the associated primary hard rock deposit, which may make them amenable to ISR processing, however, they are also often commercially significant for conventional processing. A potential advantage for ISR processing includes the fact that the gold in placers exists in centimetre- to micron-size particulates or in a loosely consolidated form and natural processes have led to the gold being mostly liberated. Because of the typically higher liberation, the gold-grain access may not be as significant a hurdle for ISR as in deposits in which access to the gold grains needs to be created and in which finer, disseminated grains would be less favourable for ISR.

Marsden and House's (2006) *free-milling-ores* classification includes two main classes, namely, paleoplacers and quartz-vein gold ores that contain gold mineralization in a hard-rock matrix. These ore types are consolidated and largely unliberated. Based on the fact that conventional processing requires gold liberation by crushing and grinding, challenges in ISR processing would include creating access to the gold, unless the gold were located in isolated zones such as veins. Because these ore types are typically hard, it is likely that additional energy would be required to create access to the mineralization. The typical deposit depth lends itself to ISR processing with paleoplacer gold deposits having been mined at depths of up to 3 km. For conventional operations, ore deposits at this depth may require relatively high gold

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