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In situ recovery of uranium — the microbial influence

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ABSTRACT

In situ recovery (ISR) has become an increasingly utilized technology worldwide for the economical extraction of uranium (U). Microorganisms play a significant role in U mobilization/immobilization and have therefore been used for the bioremediation of U contaminated sites. In natural environments a wide range of microorganisms has the ability to oxidize or reduce U compounds as part of their metabolism. Hence, microbiota is very likely to play an important role at all stages of U ISR; however the effect of resident microbial communities subject to ISR has not been investigated. Therefore, this review focuses on the interactions between microorganisms and U and the possible effects this could have on ISR operations. Microorganisms may affect ISR in either a positive or negative way, e.g. assisting in U mobilization via the oxidation of U or immobilizing U by reducing it into an insoluble form. The use of native microbial communities to influence the mobilization/immobilization of U during ISR could help to increase U recovery rates or speed-up post-mining remediation.

1. Introduction

With the effects of global warming being felt world-wide, there has never been a stronger, more vocal push to protect the stable, yet fragile environment which Earth's creatures inhabit. Governments are being called upon to make urgent, yet dramatic changes to implement legislation, which may help to mitigate global warming. In addition to the environmental impacts of climate change, Stern (2008) estimates that global warming could decrease global gross domestic product (GDP) by as much as 25% by 2090, while reducing our Greenhouse Gas (GHG) emissions to offset global warming would only cost about 1% of the current global GDP. We therefore must make changes to the amount of GHG being emitted into the Earth's atmosphere and those changes must be made expeditiously. The major source of GHG emissions is the use of fossil fuels to produce energy (UNFCCC, 2008). To cut down GHG emissions it is imperative that we find energy producing solutions that do not require the use of fossil fuels (which, in itself is a limited, increasingly scarce resource). Such technologies exist and include “renewable” energies, such as wind, solar and geothermal energy, as well as nuclear. Of these solutions nuclear energy is seen as an attractive alternative to fossil fuels in many countries, with 430 nuclear power stations currently in operation and 70 under construction across 31 countries worldwide. Proponents of nuclear technologies argue that it produces more power, with often lower costs than “renewable” energy sources (Adamantiades and Kessides, 2009; Karakosta et al., 2013). In 2009, Adamantiades and Kessides (2009) stated that nuclear power had contributed to a 10% reduction in CO_2 emissions from energy production. The 4th generation nuclear reactor designs being developed by a US-led association of 13 countries may help to address some of the concerns that traditionally come with the use of nuclear technologies, further promoting the use of nuclear power (Adamantiades and Kessides, 2009). Hence, it appears that nuclear energy is here to stay and future energy needs will be increasingly met through nuclear energy in some countries.

Driven by the world's ever-increasing need for nuclear power, uranium (U) consumption has been rapidly increasing (Fig. 1). Conservative estimates speculate that the annual demand for U in 2030 will reach between 80,000 t and 148,500 t (Outlook for the Uranium Industry, 2030), increasing by 50 to 179% from the 58,000 t having been being produced in 2012 (Fig. 2). Kazakhstan (36.5 %), Canada (15 %) and Australia (12 %) currently account for approximately 63.5 % of the world's U production (Fig. 2). Uranium has been mined using underground mining, open pit mining or *in situ* recovery (ISR) methods from a great diversity of deposits (Cuney, 2009). Over the past two decades, the use of ISR has been progressively increasing and now accounts for 45 % of the worlds U production (World Uranium Mining Production: World Nuclear Association, 2012). The Chinese appear to have been the first to use ISR for the extraction of copper in 907 A.D., with references of solution mining dating back to 177 B.C. (J. ML, 1984; Mudd, 2001a). This was proceeded with the ISR of elemental sulfur by the French and gold by

Abbreviations: GHG, Greenhouse gas; ISR, *in situ* recovery; XFM, X-ray fluorescence mapping.

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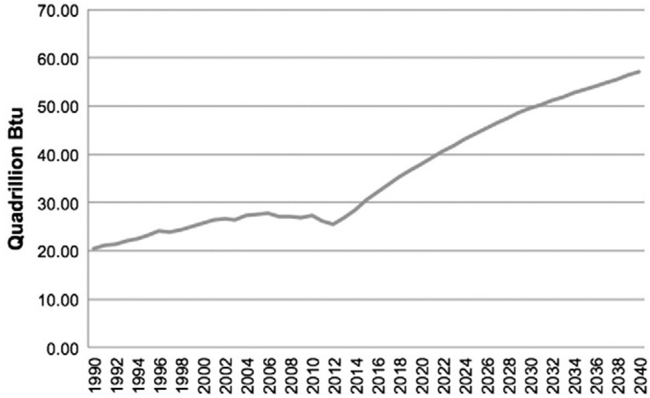

Fig. 1. World nuclear energy consumption. Data extrapolated from U.S. Energy Information Administration (Energy Outlook, 2013).

the Russians (J. ML, 1984; Mudd, 2001a). During the 1960s the ISR of U was developed by the USA and the Soviet Union (Taylor et al., 2004). By the 1990s ISR accounted for 95% of U mined in the USA, and the technology is being increasingly globally applied (DoE, 1999; World Uranium Mining Production: World Nuclear Association, 2012).

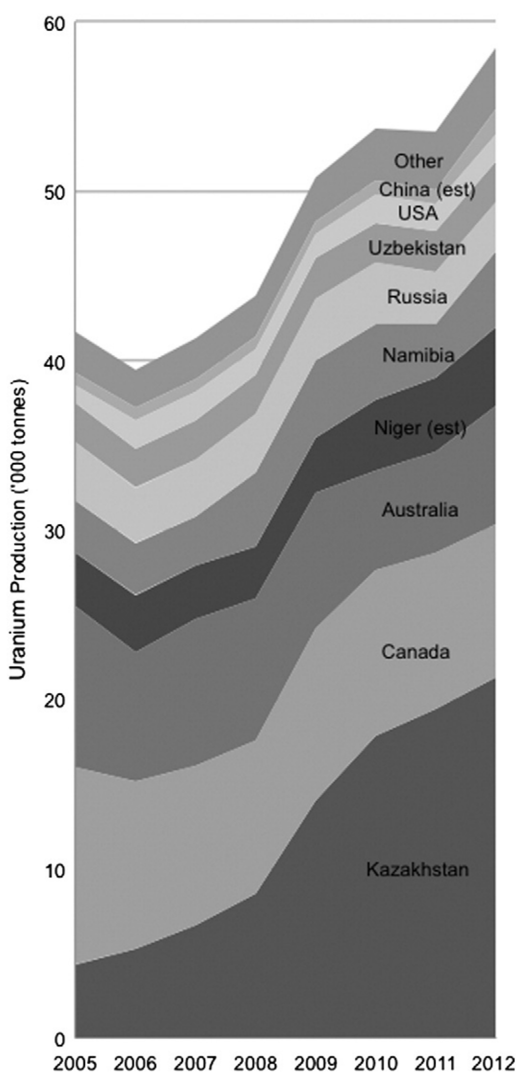

Fig. 2. World uranium production. Data extrapolated from World Uranium Mining Production: World Nuclear Association, 2012.

In situ recovery of U involves drilling boreholes into the ore deposit (Habib, 1981), pumping a leaching solution down injection boreholes, flowing the solution through the mineralized horizon so it can dissolve the ore, retrieving the solution from production boreholes, and extracting U from the solution in a plant at the surface (Fig. 3). The solution may travel through the ore via natural rock porosity, or via porosity generated by mineral dissolution (acid leach) or artificial fragmentation (hydraulics or explosives). The leaching solution can be alkaline or acidic depending on the mineralogical and geochemical properties of the deposit. In the USA U recovery by ISR uses mainly alkaline chemistry, while in Russia, Kazakhstan, Australia and Asia acid is generally used (Mudd, 2001b; Taylor et al., 2004). Acid is used when carbonate content is less than 1.5–2% and is the preferred technique as recovery rates are typically higher than when using alkaline leaching methods (Taylor et al., 2004). However, a good understating of hydrogeology and extensive monitoring are required as the use of acid can lead to heavy metals and radionuclides being mobilized and leached into the environment, contaminating ground water supplies.

Despite these issues, ISR allows for the recovery of U without the need for removing the ore body from the ground (Fig. 3). Hence, ISR of U holds many advantages over traditional open pit or underground mining methods, including:

- Reduced environmental impact
  The surface environmental footprint of ISR is substantially smaller compared to other mining methods. Brierley (2010) states that as the world's populations become more urbanized, people will live closer to mining operations and ISR is a technology which markedly reduces the surface impacts of mining. Low grade U deposits, which are produced using open pit or underground mining methods, result in large tailings dams contaminated in U and radionuclides; such tailings are not generated by ISR (Fyodorov, 2002).
- Reduced safety hazards
  The use of ISR has been reported to substantially reduce the radiation dosages experienced by mine-site employees and reduce hazards associated with the movement of large quantities of ore and waste rock (Grutsynov, 2000).
- Reduced production costs
  Increasing environmental restrictions on U mining coupled with the prevalence of low-grade ore deposits and increasing energy costs has meant that ISR has become an attractive, economically viable extraction method for many U deposits.

In view of the push to apply ISR technology to a wider range of deposits of ever decreasing grades and with increasingly stringent environmental and safety requirements, there are still a number of issues that need to be addressed in order to realize the full potential of U ISR:

- Uranium dissolution as a result of ISR is not well understood
  Heterogeneous hydrogeological, mineralogical, geochemical and geobiological conditions mean that the recovery rates from ISR vary greatly, and are often lower than using conventional methods (typically 70–90% recovery using acid leaching, and 60–70% recovery from alkaline leaching: Taylor et al., 2004).
- The consumption of the leaching solution by "parasite" reactions and reduced porosity of materials must be addressed
  Acid leaching (mainly sulfuric acid) is the predominate form of U ISR, because of its low cost, availability, and relatively high recovery rates (Edwards and Oliver, 2000). For acidic ISR the ore zone should contain less than 2% calcium carbonate; at higher concentrations alkaline leaching is required, which is often less effective than acid leaching (Taylor et al., 2004). Reduced porosity, which can be caused by the growth of biofilms or the formation of gypsum can greatly decrease the effectivity of leaching and is another major problem for acid ISR operations (Mudd, 2001b).
- The activity of leaching solutions must be closely monitored
  Thorough monitoring and control of leach solutions must be