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## Assessment of amenability of sandstone-hosted uranium deposit for in-situ recovery



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## ABSTRACT

Laboratory studies to characterise mineralogy and hydrometallurgical behaviour can be used as an essential and critical sub-component of field leach trials to reduce the risk associated with the implementation of an in-situ recovery process. Sample characterisation, bottle-roll leach tests, column leach tests and ion-exchange studies were conducted on samples from the sandstone-hosted Bennet Well deposit (Yanrey Station) in Western Australia, to obtain an understanding of the ore properties, leach behaviour and lixiviant/oxidant options, uranium recoveries and impurity treatment with a view to determining the suitability of this deposit for in-situ recovery processing. Drill core samples from the deposit contained coffinite, were suspected to contain autunite, and contained uranium associated with coal particles and titanium oxides. The main gangue mineral was quartz, and moderate quantities of K-feldspar, kaolinite and muscovite were present. Bottle-roll and column leach tests indicated that sulfuric acid or a carbonate/bicarbonate lixiviant would be suitable for leaching, with the former yielding a higher maximum uranium extraction. Acid column tests on five drill core samples from different deposit locations yielded between 57% and 84% uranium extraction, and 32% to 69% uranium extraction was achieved for the carbonate column leach tests, without oxidant addition. Oxidant addition increased the uranium extraction to 93%–98% for the acid column leach tests and 38%–70% for the carbonate column leach tests, however, oxidant addition complicates downstream processing. Column leach tests yielded lower recoveries compared with the bottle-roll leach tests and recoveries are expected to be lower for a field-scale implementation. A number of ion-exchange resins were found to be suitable for uranium recovery, with up to 100% loading and elution achieved in the acid and carbonate systems. This approach provides an experimental guideline for similar application to deposits that may be amenable to ISR processing.

### 1. Introduction

In-situ recovery (ISR) (also referred to as in-situ leaching or solution mining) refers to the recovery of valuable metals from underground deposits by the circulation of a fluid through the in-situ ore and the recovery of the valuable metal from the fluid at the surface for further processing (Bartlett, 1998). ISR is proposed to provide reduced environmental impacts and to lower costs because of its reduced mining and eliminated comminution requirements (Seredkin et al., 2016). The lower uranium commodity price has made the exploitation of many uranium deposits by other means uneconomic, whereas ISR of uranium remains a relatively attractive option (Seredkin et al., 2016). Despite ISR being used to extract almost 50% of the global uranium supply

(World Nuclear Association, 2014), its uptake in many countries (for uranium or other metals) has been limited. This results, in part, from the uncertainties associated with running ISR operations. In most cases, only limited deposit characterisation may be undertaken because of cost constraints, and significant uncertainties often remain with respect to deposit mineralogy, permeability and safe containment. The de-risking and successful application of ISR relies on having an appropriate knowledge of the properties and setting of the target mineral system, an understanding of the access to and the interaction of the mineral system with a selected lixiviant system and an efficient downstream process for value recovery and lixiviant recovery, recycle or other handling (Kuhar et al., 2015; Seredkin et al., 2016; Sinclair and Thompson, 2015).

To reduce the risk associated with the implementation of an ISR

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process, and as an essential and critical sub-component of field leach trials, complementary laboratory studies, material and process characterisation can help to better understand the hydrometallurgical behaviour of potential ISR deposits. In this study, samples from the Cauldron Energy Bennet Well deposit on the Yanrey Station (approximately 85 km to the south of Onslow and 230 km southeast of Exmouth in northern Western Australia) were studied to provide an indication of the amenability of this deposit to ISR processing. The Bennet Well deposit is considered an attractive option for ISR processing because of its aerially extensive geometry with sub-horizontal accumulations of uranium. The host sequence is shallow unconsolidated sands with the mineralisation separated into four sub-horizontal lenses. The permeability of the mineralised zones exceeds 1000 mDa, which are confined by an almost impermeable aquiclude and basement. The deposit is saturated and all mineralisation exists beneath the top of the water table. Bottle-roll and column leach tests were undertaken using an acid and a carbonate lixiviant/oxidant system on milled and coarse material to elucidate the leach and solution chemistry, complemented by various mineralogical characterisation techniques. The development of a comprehensive feasibility testing approach will be useful for the evaluation of the amenability of many similar uranium deposits to ISR processing.

## 2. Materials and methods

### 2.1. Characterisation

Scanning electron microscopy (SEM) was conducted to determine the sample elemental composition and to provide information on the morphology and location of the uranium minerals. A JEOL 7001F instrument fitted with Bruker QUANTAX EDS and QUANTAX EBSD attachments (both using ESPRIT software) was used. Backscattered electron images were collected for grain and polished sample mounts typically using electron-beam conditions that correspond to a 20 kV accelerating voltage and a 1 nA probe current at a working distance of 10 mm.

Milled half-core from six drill holes (labelled A to F) was available in ~10-cm intervals. These interval samples were split using a riffle splitter, and blended to produce a composite material. A sample from each of the six mineralised-zone drill-hole composites; selected samples from the aquiclude and basement; selected samples from permeable, non-uranium-containing sections of the deposit and some samples that contained low silicon and that were located close to the mineralised zones were analysed by X-ray diffractometry (XRD). Samples were back-pressed into 32-mm XRD sample holders. XRD measurements were carried out using a PANalytical high-resolution multi-purpose powder diffractometer (Empyrean) using Co-K $\alpha$  radiation and operating at 40 kV and 40 mA. A Bragg–Brentano high-definition incident monochromator and PIXcel3D photon counting X-ray detector were used to collect the data over an angular range of 3–90° 2 $\theta$  with a continuous scan mode for 1 h. Semi-quantitative XRD data were interpreted with HighScore Plus (3.04) software using the ICDD database (2011). Micro-XRD analysis was obtained using the same XRD instrument, where the sample was placed in the middle of the stage with its flat upper face parallel to the top of the XYZ sample stage.

### 2.2. Leaching tests

Preliminary acid and carbonate leach tests in a factorial design experiment were conducted to determine the feasible operating window for leaching. Fifty-four acid and thirty-six carbonate bottle-roll leach tests were conducted on milled material. Acid concentrations were varied at 0.1, 1 and 10 g L<sup>-1</sup> H<sub>2</sub>SO<sub>4</sub>, each with no oxidant, a moderate oxidant concentration of 0.01 M Fe(III) (the stoichiometric requirement to oxidise all of the uranium in the richest sample if it existed as U(IV), added as ferric sulfate) and an extreme oxidant concentration of 0.6 M Fe(III) (the stoichiometric requirement to oxidise all of the uranium if it

existed as U(IV) as well as all of the iron and sulfur if it existed as pyrite, added as percarbonate). In the carbonate leach tests, the total carbonate concentration was 0.25 M, the pH was set at 8.5 or 10 by altering the carbonate/bicarbonate ratio, and either no oxidant, a moderate oxidant concentration of 0.005 M H<sub>2</sub>O<sub>2</sub> or an extreme oxidant concentration of 0.3 M, supplied as percarbonate, was added. These oxidant additions were calculated based on the same parameters as for the acid system. Leach solutions were prepared using Bennet Well site water (~1.8 g L<sup>-1</sup> Cl, < 0.02 mg L<sup>-1</sup> Fe, 140 mg L<sup>-1</sup> Mg, 210 mg L<sup>-1</sup> S, 20 mg L<sup>-1</sup> Si, 130 mg L<sup>-1</sup> Ca, 50 mg L<sup>-1</sup> K, 1.2 g L<sup>-1</sup> Na, < 0.2 mg L<sup>-1</sup> P, < 0.02 mg L<sup>-1</sup> Al). The solution pH and Eh were not controlled during the tests to better replicate what may occur in a natural in-situ environment. Milled half-core from the six drill holes was split using a riffle splitter, and blended to produce a composite material. Sample (20 g) and solution (200 mL) were added to a 250-mL Nalgene bottle and the solutions were agitated in a bottle tumbler at 30 °C for 24 h for the acid leach tests and at 30 °C for 7 days for the carbonate leaches. Samples were filtered and the solutions were analysed by inductively coupled plasma optical emission spectroscopy (ICP-OES) for Fe and S and ICP-mass spectroscopy (MS) for Ba and U. Solid head samples were analysed by ICP-OES for Ba, Ca, Fe, K, Mg, Na, P, S and U. Extractions were determined based on the solution analyses and the elemental head compositions.

Column leaching tests were run on five of the six available drill hole samples. The drill hole sample depths varied from 12 to 31 m. To obtain an estimate of the leach kinetics, two 1-m-high, 2.3-cm-inner-diameter, plastic columns were packed with ~1.5 cm sections of uncrushed ore obtained from every 10 cm along the length of drill hole B. After site water flushing of the column in upward flow (100 mL/24 h) using a ceramic piston pump, and prior to acid or carbonate solution injection, a bromide tracer test was run where the column was spiked for 2 h with a 770 mg L<sup>-1</sup> bromide solution (prepared from potassium bromide). Tracer tests were conducted to test for preferential flow. Effluent samples from the columns were collected every 2 h using a fraction collector. Bromide concentrations were analysed by ion-chromatography. Continuous fresh acid (10 g L<sup>-1</sup> H<sub>2</sub>SO<sub>4</sub>, pH 1, no oxidant) or carbonate (0.25 M carbonate + bicarbonate, pH 10, no oxidant) leach solution was injected into the columns for 12–16 days with four-hourly sampling. Oxidising lixiviant (the leach solution plus 0.6 M ferric sulfate for the acid system and 0.3 M percarbonate for the carbonate system, added as percarbonate) was injected into the columns and the columns were run for an additional 4 days. The columns were flushed with site water. Solution concentrations of U, Ca, Fe and S were analysed by ICP-OES. The columns were emptied and the solids were dried in an oven at 50 °C for a week before being ring-milled and sub-sampled for solids analysis by lithium borate fusion, digestion, and ICP-OES and XRD.

Subsequent column tests were run in 1-m-high, 5.4-cm-inner-diameter, plastic columns. The columns were similarly packed with ~1.5 cm sections of material obtained from every 10 cm along the length of drill holes A, D, E and F (drill core C was not leached in the column tests). After the bromide tracer tests, acid and carbonate leaches without oxidant (and with the same conditions as were used for drill hole B) were conducted for 8 days. Oxidising lixiviant was injected into the columns for 5 days (with the same conditions as were used for drill hole B). Thereafter, columns were processed as described above.

To study features that had been observed in the SEM microscopy, particles from a – 250/+ 125  $\mu$ m fraction from drill hole B were glued to glass slides. Fiducial marks were recorded to establish a coordinate system for pre- and post-SEM imaging of particle surfaces that has been leached in 10 g L<sup>-1</sup> sulfuric acid solution or 0.25 M carbonate + bicarbonate solution for 3 days and then washed gently with a stream of deionised water.

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