

THE CRITICAL ROLE OF GANGUE ELEMENT CHEMISTRY IN HEAP AND AGITATED TANK LEACHING OF URANIUM ORES

By

Grenvil Dunn and Yong Yong Teo

Orway Mineral Consultants

Presented by

Grenvil Dunn

ABSTRACT

In the uranium leach processes employing sulfuric acid as the lixiviant, only a relatively small quantity of acid is gainfully employed in extracting uranium from the host ore. The remainder of the acid is consumed by the gangue constituent elements. Many new projects that are being considered today have gangue acid consumptions in excess of 95%. Many of the gangue elements that are solubilised by the acid report to the leachate where they build up in concentration in a closed flow sheet. The impact of this may in some case be deleterious to the extraction of uranium, whilst in others there have been some benefits identified when leaching in high solute concentration solutions. The roles played by these elements have been investigated in both heap and tank leach testwork, and are presented in this paper. Discussion of the effect of gangue chemistry focuses on the impact of the gangue elements on the economics of the process and the flowsheet implications.

CONTENTS

ABSTRACT	1
1. INTRODUCTION	2
2. URANIUM DEPOSIT MINERALOGY AND ASSOCIATED CHEMISTRY	2
3. WATER BALANCE EFFECTS ON FLOWSHEET	4
4. LEACH GANGUE ELEMENT BEHAVIOUR.....	5
5. POST LEACH GANGUE ELEMENT BEHAVIOUR.....	16
6. CONCLUSIONS	18
7. REFERENCES	19

1. INTRODUCTION

In uranium leach processes employing sulfuric acid as the lixiviant, only a relatively small quantity of acid is gainfully employed in extracting uranium from the host ore. The remainder of the acid is consumed by the gangue constituent elements. Many new projects that are being considered today have gangue acid consumptions in excess of 95%.

Many of the gangue elements that are solubilised by the acid report to the leachate where they build up in concentration in a closed flow sheet. The impact of this may in some case be deleterious to the extraction of uranium, whilst in others there have been some benefits identified when leaching in high solute concentration solutions.

In contrast, alkaline leach processes do not experience the same high reagent consumption rates as acid processes. The solubility of many of the impurity elements in uranium ores (such as Fe, Mg, and Al) in the alkaline leach is quite low. However, the alkaline operations do encounter some challenges with gangue element solubility.

This paper will examine the role of some of the more common gangue elements in the leaching and processing of uranium ores in heap and tank leach scenarios, using test data to show the effect of gangue chemistry on the process efficiencies and economics.

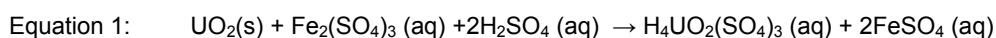
2. URANIUM DEPOSIT MINERALOGY AND ASSOCIATED CHEMISTRY

There are numerous types of uranium minerals in existence, the simplest form being uraninite.



Figure 2.1 Uraninite (UO₂) mineral

The leach chemistry for uraninite is as shown in Equation 1.



Uranium in uraninite is present in tetravalent state and must be oxidised to the hexavalent state for it to be solubilised in an acid solution. Ferric iron is one of several oxidants that is capable of oxidizing the tetravalent uranium (Equation 1).



Figure 2.2 Biotite $\text{KMg}_{1.5}\text{Fe}_{1.5}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$

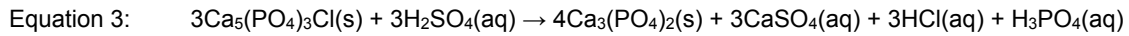
A common gangue mineral found associated with uranium deposits is biotite. Biotite leaching yields elements such as Fe^{2+} , Mg^{2+} , Al^{3+} and Si^{4+} to the leachate in acid processes - refer Equation 2.

Equation 2:

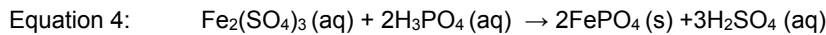


Figure 2.3 Apatite $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$

Another common gangue mineral is apatite. Its reaction with acid is as shown in Equation 3.



Products of the leaching of apatite are Ca^{2+} , PO_4^{3-} and Cl^- . The phosphoric acid formed in this leaching process can further react with ferric in the leach solution, precipitating ferric phosphate (as shown in Equation 4). This precipitation reaction will deprive the leach of valuable ferric oxidant and kinetically impair the uranium extraction process.



Chloride can compete with uranium in the downstream solvent extraction (Equation 5) and ion exchange (Equation 6) recovery processes.

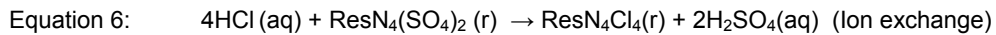
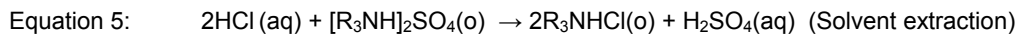


Figure 2.4 Clinocllore ($\text{Mg}_{0.66}\text{Fe}_{0.34}$) $5\text{Al}(\text{Si}_3\text{AlO}_{10})(\text{OH})_8$

Clinocllore, a gangue mineral, can leach in acid according to Equation 7. Again Mg^{2+} , Al^{3+} , Fe^{2+} and Si^{4+} are rendered soluble with silicon precipitating to some extent. Some colloidal silica is also formed. Colloidal silica actively forms crud in solvent extraction processes⁽¹⁾ while silicon compounds in ion exchange coat the resin beads⁽²⁾ used in ion exchange plants, and therein reducing the resin's loading capacity.

Equation 7:

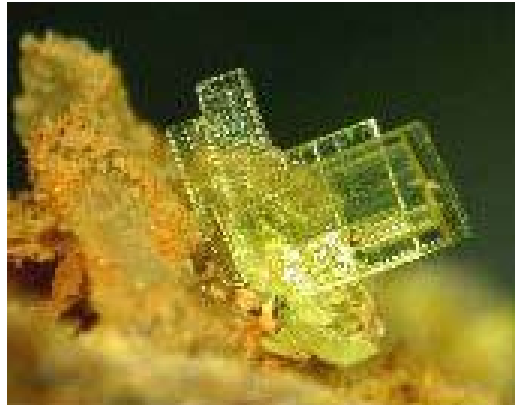
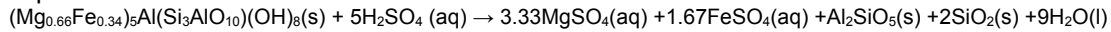
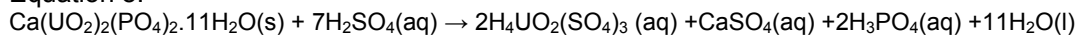


Figure 2.5 Autunite $\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 11\text{H}_2\text{O}$

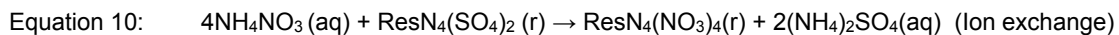
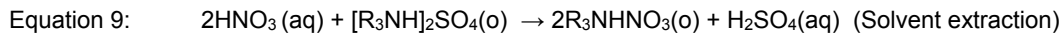
Autunite, a uranium mineral, will leach in acid according to the chemistry shown in Equation 8:

Equation 8:



In the leach, autunite introduces Ca^{2+} and PO_4^{3-} into the solute. The effects of these were discussed earlier.

Aside from those gangue elements that are leached from minerals hosting the uranium, ammonium nitrate residuals from the blasting processes can enter the leach process on the ore. Nitrates can be deleterious in the acid leach circuits where they compete with uranium in ion exchange and solvent extraction processes – refer to Equation 9 and Equation 10.



3. WATER BALANCE EFFECTS ON FLOWSHEET

3.1. ENVIRONMENTAL CONSIDERATIONS IN FLOWSHEET DEVELOPMENT

The release of treated process water to the environment both in liquid and vapour form is receiving increasing attention in all hydrometallurgical processes, including uranium processing.

In the past, some established processes have been permitted to release liquid effluent streams from the plant after treatment. Others have released untreated process liquids to inadequately lined tailings facilities where there has been considerable uncertainty surrounding the magnitude of seepage. Such practices are on the decline. In the uranium industry, it is unlikely that positive or potentially positive water balance circuits will be permitted in the future.

Most operators are now considering tailings ponds with impermeable liners employing the best available technology and negative water balance concepts with limited commitment to the ongoing construction of evaporation ponds.

“Dry tailings” processes have been considered in the uranium process field and require the following:

- The final discharge slurry being dewatered to provide solid material that will be conveyed to the tailings facility rather than pumped with centrifugal pumps.
- Tailings that are generally free of seepage fluids.
- Gangue acid derived solute to be contained as the interstitial fluid in the tailings.
- Tailings be capped progressively after fill to mitigate solute migration from rain water ingress.

- Equipment that is currently being employed to produce “dry or highly dewatered tailings” e.g. vacuum belt filters, belt pressure filter presses and in some cases paste thickeners.

3.2. ECONOMIC BENEFITS OF A NEGATIVE WATER BALANCE

Aside from the environmental constraints, uranium projects also have to be economically feasible. One of the major operating costs for uranium processing is the reagent cost. In the case of tank leaching, raffinate or barren solution can be recycled as wash liquor to the leach discharge counter current decantation thickeners (CCD) or filter circuit. A slip stream of the raffinate solution can be recycled to the comminution process (“milling in acid”) to reduce reagent consumption and maintain a negative water balance (Figure 3.1). Similar practices have been adopted in several operating plants such as Sepon Copper Plant in Laos⁽³⁾.

An example of a Dry Tailings/Negative Water Balance process is given in **Figure 3.1**. All gangue elements dissolved in the leach leave the process in the interstitial fluid within the residue. Of note is that there are no neutralisation steps for excess fluid in the overall flowsheet, a feature of most previous process flowsheets.

The residue will have to be stored in a well constructed, lined pond - this feature of the flowsheet would undoubtedly have been required even if effluent neutralization had been adopted. Taking into account both capital and operating cost considerations, this is a potentially lower cost option compared to a process with a “positive” water balance that would require additional effluent storage capacity.

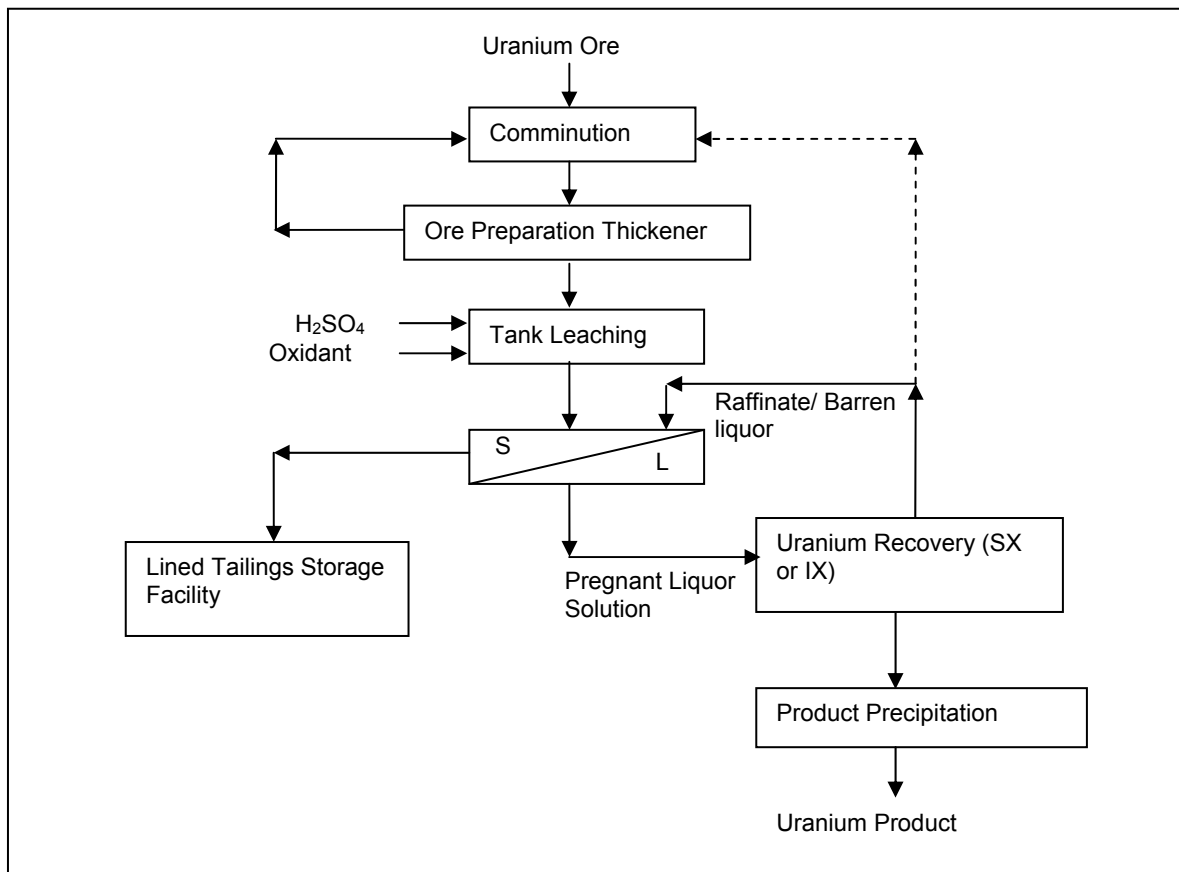


Figure 3.1 Uranium Tank Leaching Block Flow Diagram

4. LEACH GANGUE ELEMENT BEHAVIOUR

A “dry tailings” disposal concept referred to in Section 3 is considered as the flowsheet adopted for further discussion of the impact of gangue element chemistry on acid uranium leach processes.

Most of the attention will be devoted to the leach circuit; however, the downstream effect of gangue acid derived solutes cannot be ignored and will be briefly addressed.

4.1. COMMINATION, ORE PREPARATION

No discussion on the subject of gangue element chemistry in uranium processing would be complete without a reference to the radionuclides and specifically radon.

Radon is a gas with a half life of 3.8 days. It is derived from radium which is a decay product from Uranium²³⁴ and Thorium²³⁰ respectively. Radon gas, while short lived, can decay in the lungs to form dangerous daughter products as shown in **Figure 4.1**.

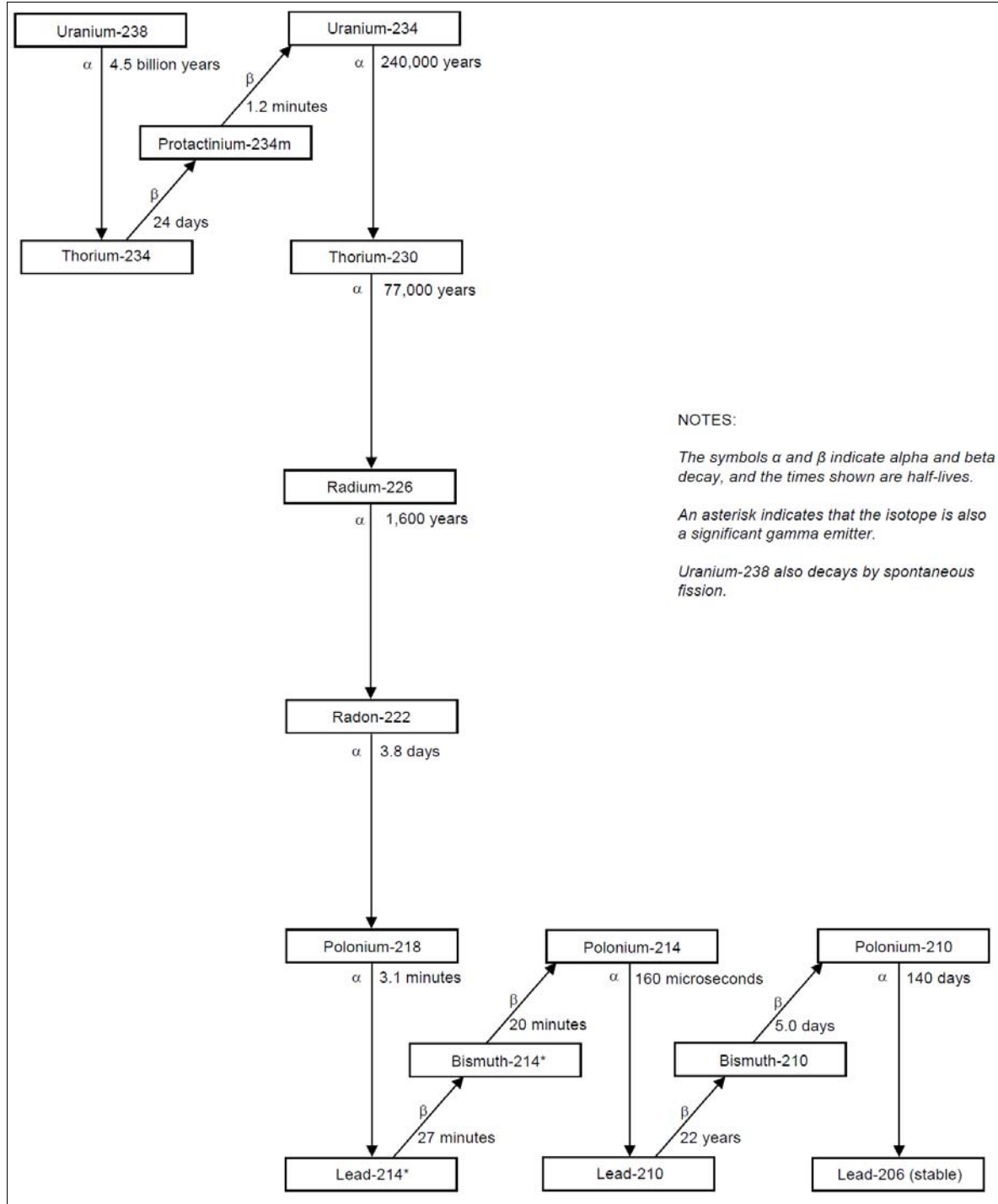


Figure 4.1 Natural Decay Series for Uranium 238⁽⁴⁾

Consequently, in the ore preparation circuits of the tank leach process where radon is released, the sealing and safe ventilation of process equipment must be considered (**Figure 4.2**).



Figure 4.2 Closed Ventilation System for Mill Discharge Trunnion in Uranium Operation⁽⁵⁾

4.2. COLUMN LEACH TESTWORK

A feature of conducting testwork for hydrometallurgical process is that open circuit tests employing water can lead to unoptimised outcomes compared to those derived from a closed circuit test, where a mature solution composition is employed.

This is illustrated by means of testwork data obtained from a Southern African project, which features primary ore and has the uranium mineralization as uraninite and coffinite with some orthobrannerite present.

During the testwork the ore was crushed to a P100 of 8 mm and subjected to column leaches using open and closed solution circuits. While the uranium extractions were similar (**Figure 4.3**) in both the open and closed circuit, the acid consumption was significantly lower when the leach was conducted in a mature solution in closed circuit (**Figure 4.4**).

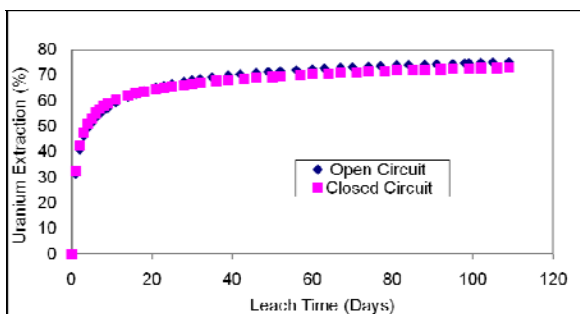


Figure 4.3 Column leach uranium extraction comparisons between open and closed circuit

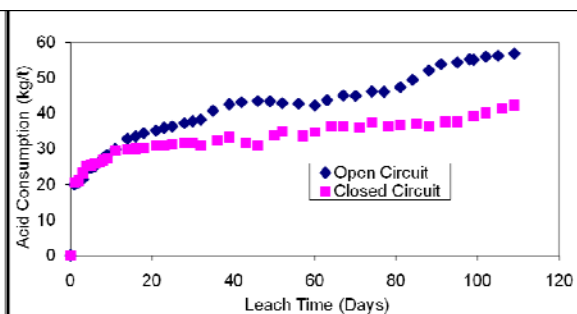


Figure 4.4 Column leach acid consumption comparisons between open and closed circuit

An identical outcome was achieved for the same ore with a 19 mm crush size. **Figure 4.5** confirms a similar uranium extraction for both the leach begun in water and operated in closed circuit with a solvent extraction (SX) process and that began and ended in a mature solution containing 250 g/L sulfate also employing SX circuit.

In the case of the test commenced in water, the acid consumption was again approximately 10 kg/t higher than that commenced in mature solution – refer **Figure 4.6**.

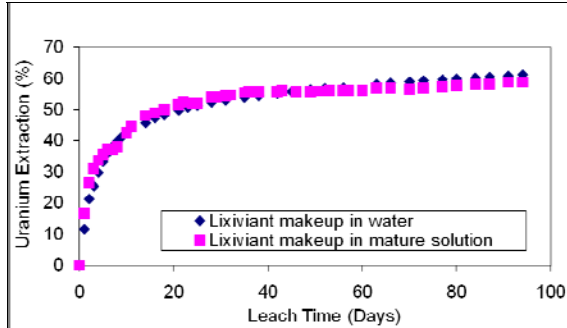


Figure 4.5 Column leach uranium extraction comparisons between lixiviant makeup in water and mature solution

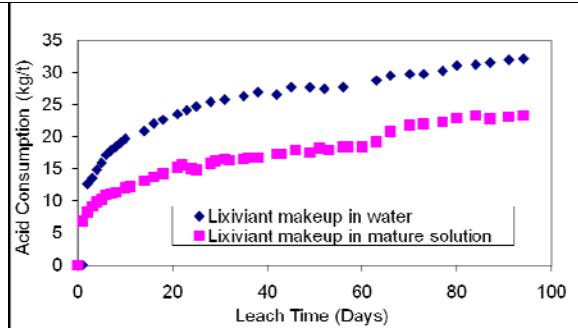


Figure 4.6 Column leach acid consumption comparisons between lixiviant makeup in water and mature solution

The major gangue elements concentration in the PLS for the column leach that began in water are shown in **Figure 4.7**, and can be compared to those obtained for the test that began in mature solution, shown in **Figure 4.8**.

Figure 4.7 shows an increase in soluble gangue elements in the PLS compared to the initial concentrations in the lixiviant, with the concentration of aluminium in particular increasing with leach time.

Figure 4.8 shows that, in the column leach that began in mature solution, the concentration of the major gangue elements at the end of the column leach test is either the same or less than that in the initial lixiviant. This suggests there may be reduced dissolution of gangue elements in the mature solution column leach, which explains the lower acid consumption. It is also possible that the gangue elements may have been reprecipitated in the mature solution.

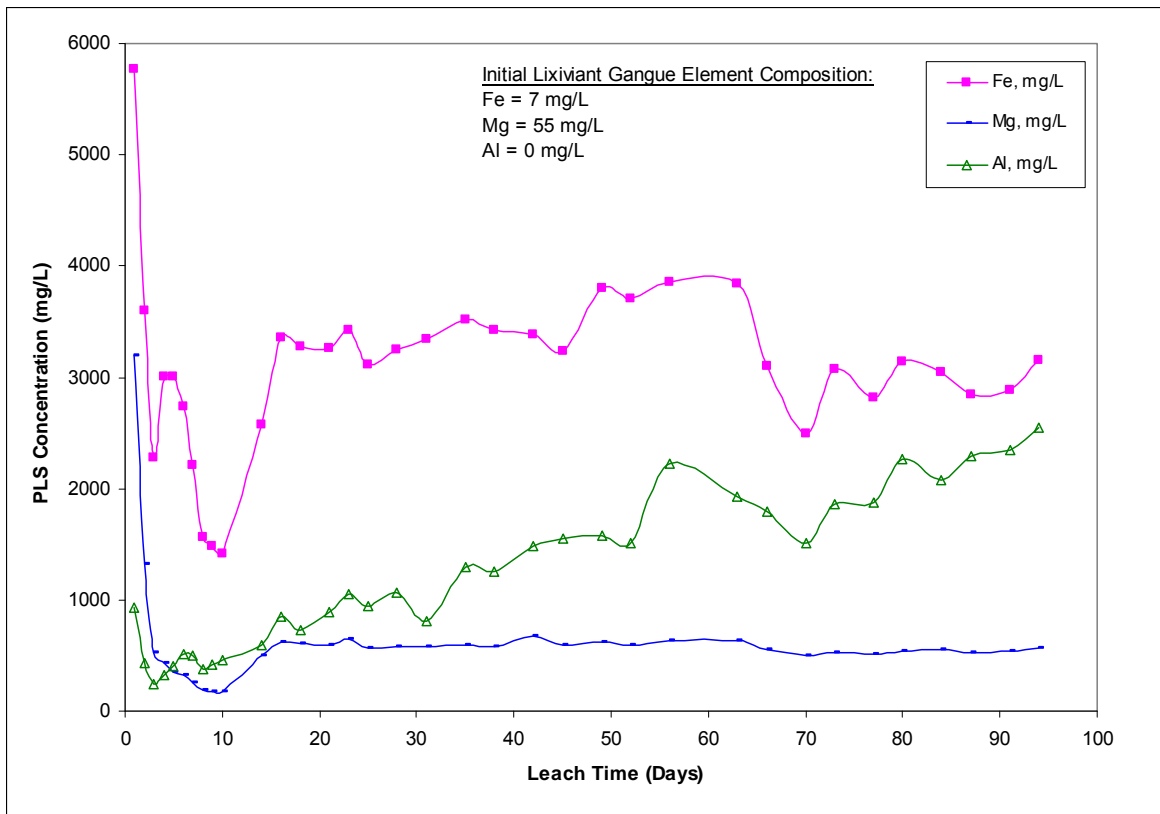


Figure 4.7 Major Gangue Elements Concentration in the PLS of Column Leach Began in Water

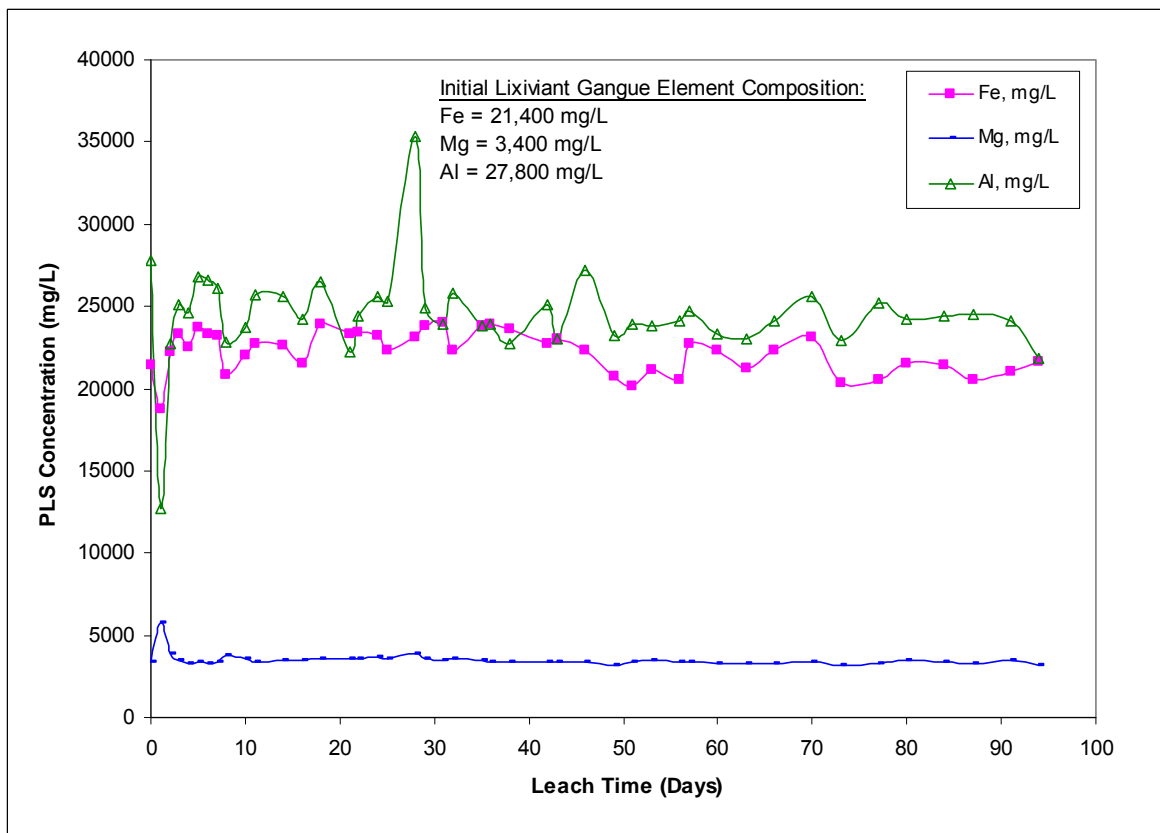


Figure 4.8 Major Gangue Elements Concentration in the PLS of Column Leach that Began in Mature Synthetic PLS

The extent of reprecipitation was investigated by carrying out a Scanning Electron Microscopy (SEM) analysis on the solid residue from the column leach testwork that began in mature synthetic PLS. A gypsum precipitate was found in the residue, in this instance it does not have uranium associated in either solid solution or as a surficial precipitate. – refer **Figure 4.9**.

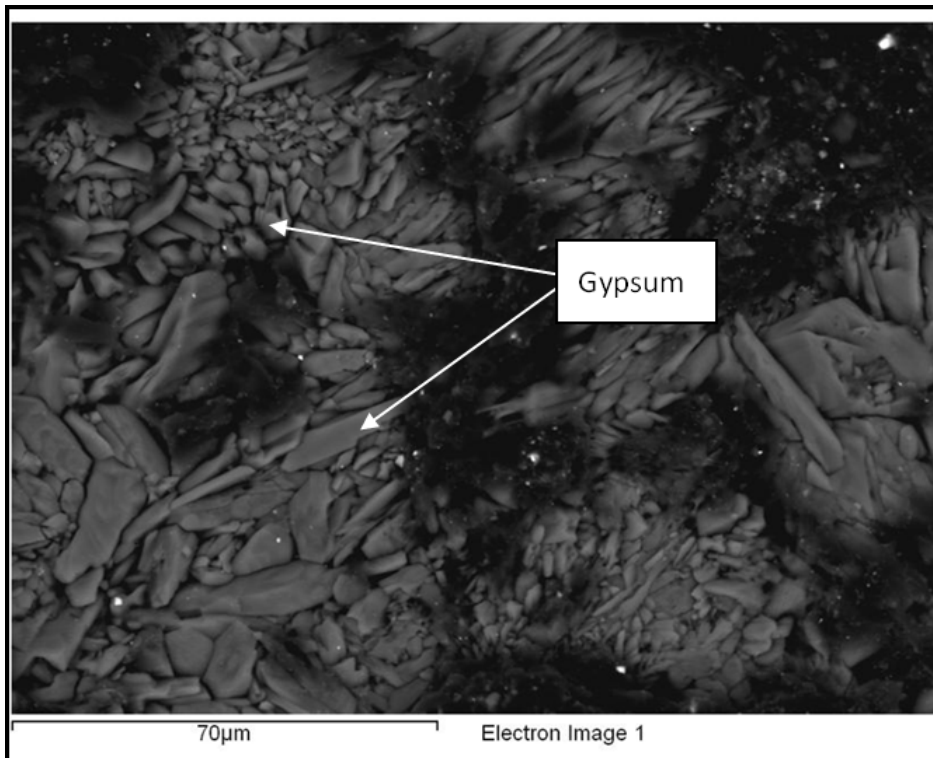


Figure 4.9 Gypsum precipitate in a Column Leach

In addition to gypsum precipitate, the high solute leach also resulted in poorly crystalline precipitates with the composition of a Ca-Fe-Al-Si-OH phase (of the amphibole type) with trace amounts of uranium found associated with this precipitate (**Figure 4.10**).

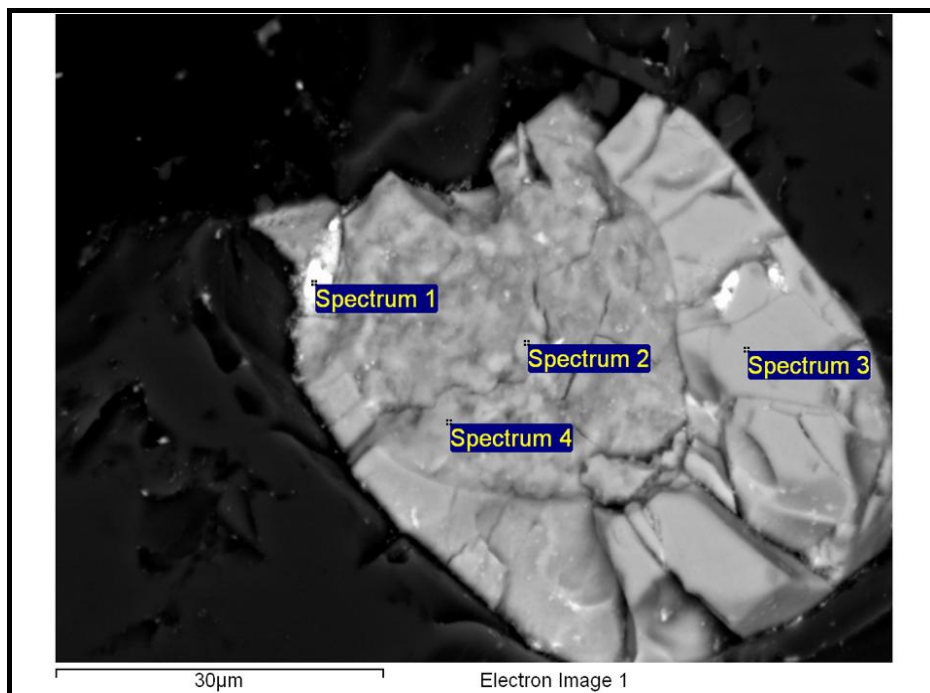


Figure 4.10 Amphibole type precipitate from High Solute Liquors

Calcium and silica precipitates are often prolific at the toes of heap leach pads (**Figure 4.11**) and can include elevated levels of uranium.



Figure 4.11 Precipitates at the Toe of a Heap Leach Pad

The high solute concentration in closed circuits may not impact the extent of leaching of uranium, but it appears that it could have an impact on the leach kinetics.

Coffinite and uraninite in the micro cracks of particles such as that shown in **Figure 4.12** may be isolated from the normal diffusion paths of lixiviant in and out by the precipitation of gangue elements from the solute. The leach may be concluded before these minerals have been completely attacked by the lixiviant.

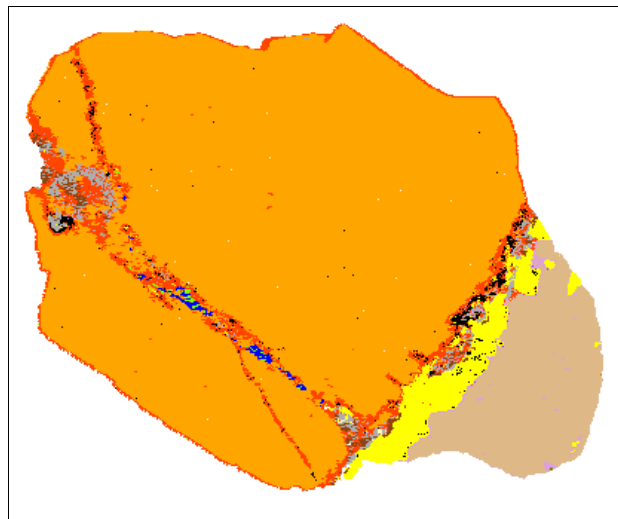


Figure 4.12 Uranium within Fractures

This hypothesis was tested by conducting sequential five day bottle roll tests on 4 distinct ore lithologies. Fresh ore was used at the commencement of each test, but mature solution was generated by using the leachate from the previous test as the lixiviant in the next test.

Sulfuric acid levels were restored in the lixiviant by the addition of concentrated sulfuric acid to achieve the 100 g/L target. In this fashion, the solute levels were increased in the leachates during these sequential bottle rolls.

Each ore type gave higher uranium retentate values as the sequential bottle roll tests proceeded – see **Figure 4.13**.

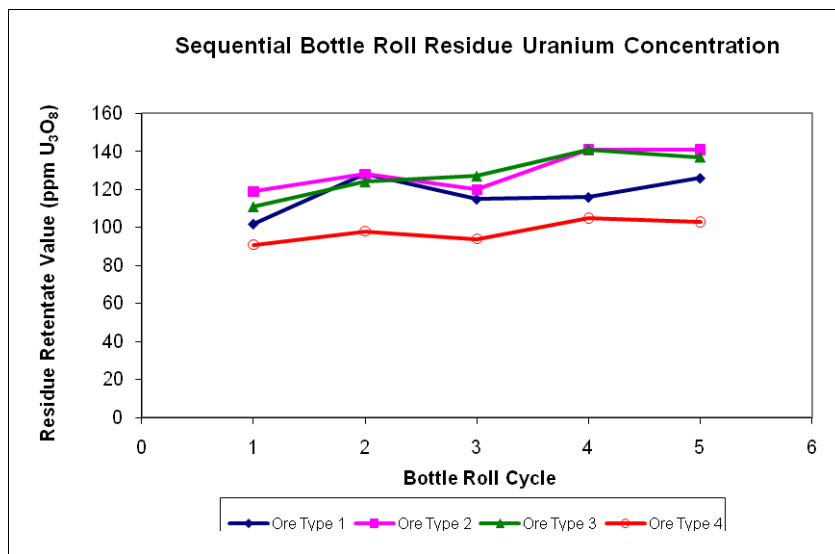


Figure 4.13 Impact of Solution Concentration on Leach Extent at 5 days

This work suggests that the leach kinetics for uranium may be impaired in these bottle roll tests as solute and uranium concentration in the PLS liquor grow; however, no inference can be made on the impact of solute concentration on the final uranium recovery. The result of **Figure 4.5** suggest there maybe no impact of high solute levels on the final leach uranium extraction for the tests conducted at both high and low solute concentrations.

4.3. BATCH TANK LEACH TESTWORK

Effect of Mature Lixiviant in Tank Leaching

An Australian sandstone hosted uranium deposit (in which the uranium mineralization was primarily coffinite) was subjected to a series of stirred tank leach tests, using water in one case and synthetic process liquor in the other. All the conditions of grind size, temperature, solids density, Eh and residual free acid were identical in these two tests.

The resistate uranium values in the leach residue were higher for the test conducted in water compared with the same conditions repeated in synthetic process liquor. The synthetic process liquor contained approximately 40 g/L of sulfate prior to the leach – refer **Figure 4.14**.

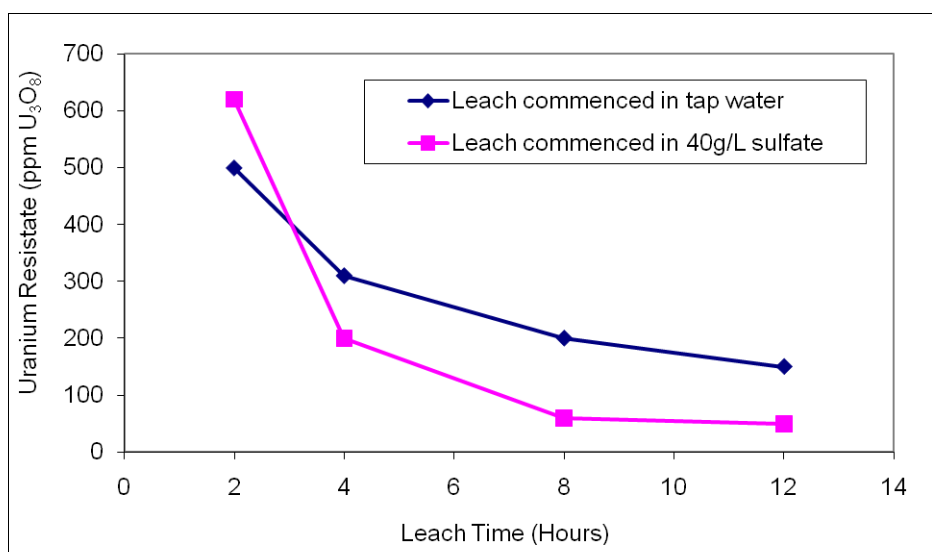


Figure 4.14 Agitated Uranium Tank Leach Resistate

In this case, and contrary to the sequential bottle roll testwork discussed in Section 4.2, the impact of higher solute levels did not materially influence the leach kinetics (**Figure 4.14**) and the leach essentially was complete in just over 8 hours – a very similar outcome to the test conducted in tap water. This result is possibly explained by the attrition of precipitate through inter-particle collision.

Effect of Phosphate and Solute Concentration in Tank Leaching

Ore from a North African uranium deposit hosted in hydrothermally altered cataclasite containing significant quantity of apatite was subjected to agitated tank leach test at varying solute and phosphate concentrations.

The phosphorus extractions were essentially complete in a dilute water leach (0.5g/L phosphate), but at high solute levels (approximately 25 g/L S or 110 g/L total solute and 15g/L phosphate) the phosphorus extraction was lower at approximately 50%. Uranium extraction also follows a similar trend – refer **Figure 4.15**.

It is speculated that during the high solute leach, phosphorus in the apatite had leached (Equation 3) and reprecipitated to a compound containing iron (e.g. iron phosphate - Equation 4). The precipitated iron phosphate may potentially include uranium. The lower uranium recoveries achieved at the high solute concentrations could also be attributed to the precipitation of uranyl phosphate in the leachate.

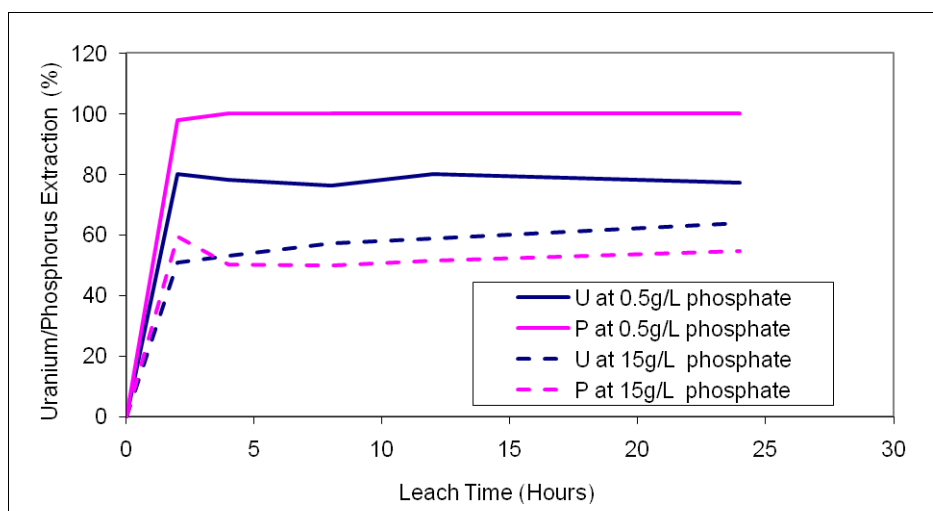


Figure 4.15 Effect of Aqueous Phosphate Concentration on the Extraction of Uranium

4.4. CONTINUOUS TANK LEACH TESTWORK

An integrated continuous tank acid leach process, treating high silicate ore and operating at 65 to 70% solids in 6 equal sized tanks is shown in **Figure 4.16**. The relevant leach feed and discharge stream assays for this pilot campaign are given in **Figure 4.17**.



Figure 4.16 Pilot Plant Leach Tank

	Feed Ore (%)	Repulp Liquor (mg/L)	Leach Discharge Residue (%)	Leach Discharge Liquor (mg/L)
Mn	0.01	5789	0.04	7131
Fe	2.83	2874	2.81	7533
K	4.03	1132	4.09	1486
Na	1.47	4342	1.52	4876
Ca	0.97	569	0.97	521
Mg	1.08	4229	1.29	4642
Al	6.25	845	6.15	5322
P	0.03	0	0.03	2210
S	0.46	15828	0.48	29580

Figure 4.17 Leach Feed and Discharge Composition

The residual free acid was between 2 and 4 g/L across the acid leach tanks, the leach temperature was approximately 30°C and repeated at 60°C, the total iron concentration was 8 g/L. The oxidant was pyrolusite which was added to the first and third tanks.

Some evaporation occurred during the leach.

The profile for this leach is given in **Figure 4.18** and the ferric to ferrous ratio across the leach is given in **Figure 4.19**.

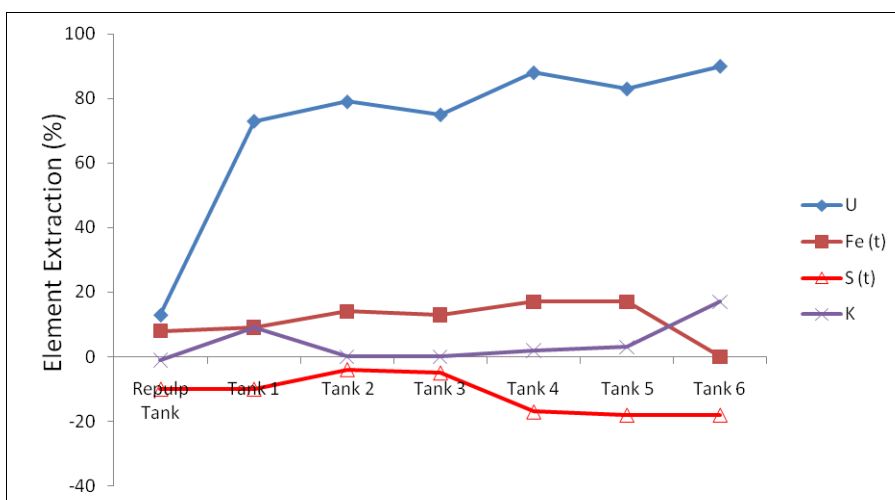


Figure 4.18 Leach Profile at 30°C (Leach Pilot)

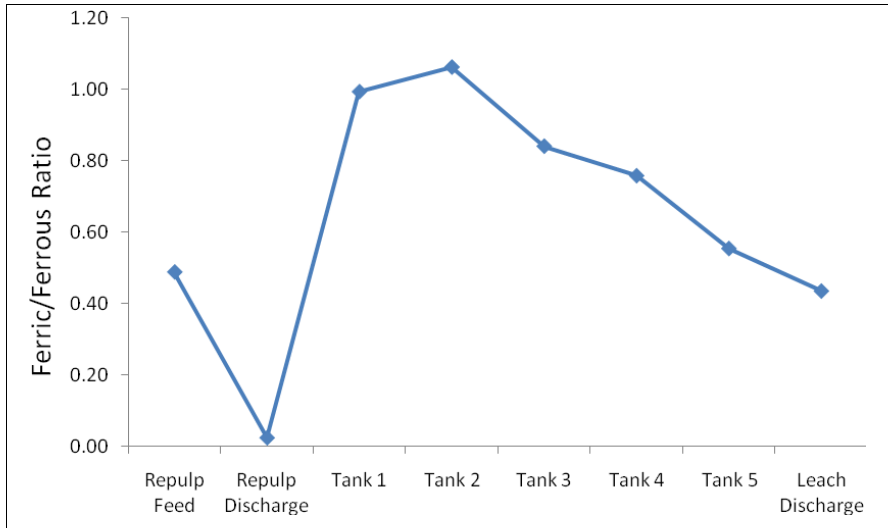


Figure 4.19 Ferric:Ferrous Ratio (Leach Profile)

The uranium extraction was rapid and almost complete by the third tank. Iron and sulfur appear to demonstrate a net positive leach extraction in the first three tanks of the cascade (**Figure 4.18**).

A similar trend for the department of iron and sulfur was noted for the leach conducted at 60°C (**Figure 4.20**). However, the hydrolysis of iron was far more pronounced at this elevated temperature.

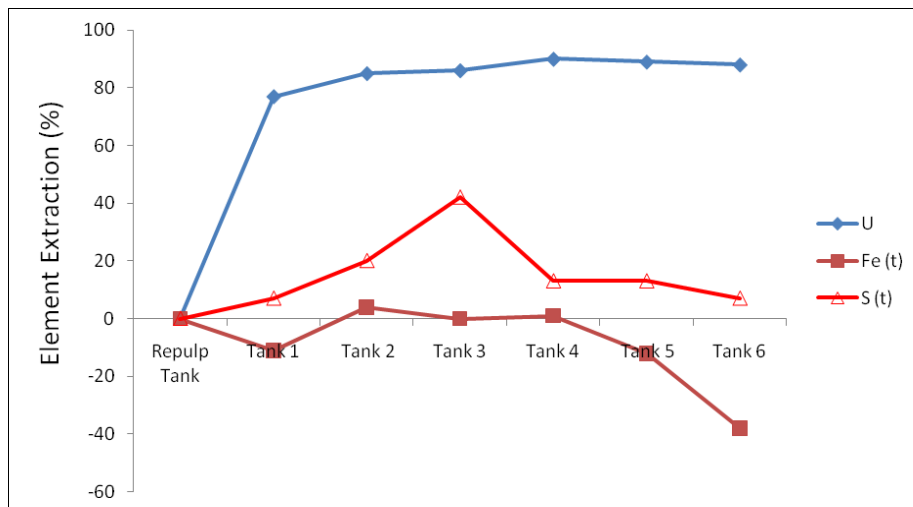


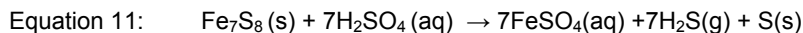
Figure 4.20 Leach Profile at 60°C

The results in **Figure 4.20** are as expected given that the kinetics for jarosite formation (Equation 12) are more favourable at elevated temperatures.

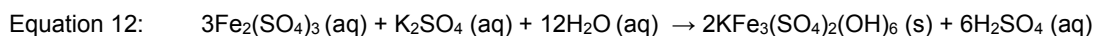
It is likely that a dynamic transformation process is occurring within the leach and not simply one of leaching followed by precipitation.

An examination of the semi-quantitative mineralogy (not provided here) shows that:

- iron (ferrous) and potassium (and other gangue elements) are leached from the biotite (Equation 2) and clinocllore minerals (Equation 7) in the early stages of the leach and the reaction extent tapers towards the middle of the leach. Iron is oxidised by the pyrolusite to a target Eh range, and
- sulfur is removed very significantly from the solution in the first tank where the acid is added. This is possibly explained by the decomposition of the pyrrhotite and again this reaction slows as the exposed mineral surfaces are corroded.



The chemistry of jarosite precipitation (Equation 12) appeared to be occurring over the entire leach period and possibly was dependent on the iron, sulfur and potassium concentrations in the leachate. As the fast dissolution of gangue in the early leach tanks declines towards the end of the leach, the immobilisation of the iron and sulfur assumes a more dominant role as shown in **Figure 4.20**.



It is uncertain whether this precipitation process negatively impacted the extraction of uranium.

4.5. ALKALI CIRCUITS

In alkali leach circuits, gangue elements do not leach to the same extent as they do in their acid leach counterparts.

Sulfate

With the Namibian alkali leach circuits the presence of soluble sulfate (predominantly gypsum and to a lesser extent celestite (strontium sulfate)) can result in high reagent consumptions.



Calcium carbonate is only sparingly soluble and its precipitation removes the carbonate lixiviant from the leach liquors. Any sulfides present in the ore can be oxidised at the elevated leach temperature and also consume sodium carbonate reagent.

Most of the sulfates are surficial and consequently the efficiency of the strip activity can be critical to the process economics of these Namibian alkali leach circuits.

One of the operations washes the ore on the leach pad prior to commencing irrigation with a sodium carbonate/bicarbonate lixiviant. This is done to reduce the levels of sulfate being introduced to the leach.

Carbonates

The carbonates of magnesium and calcium have low solubility in the leach once they are formed and are known to scale and precipitate. The indirect heating of aqueous streams from a leach have been known to deposit hard scale on the heat transfer surfaces.

5. POST LEACH GANGUE ELEMENT BEHAVIOUR

The high solute levels in the leachate can impact the performance and the mechanical availability of the uranium recovery steps after the leach. Considerable care has to be taken in the selection and design of equipment downstream of the leach in situations where the solute is supersaturated at the prevailing conditions. Pilot plant campaigns over several weeks may not reveal all the design issues concerning the deportment of the gangue elements.

The following are circuits that will be affected:

Thickeners – frequently scale at the water line in acid leach circuits. This scale often contains Ca-Fe-Al-Si-S-OH. Removal of this scale in a uranium process is not a trivial matter as it often contains elevated levels of radiation as well as uranium.

Belt Filters – scale has been known to develop in the filter fabrics and within the vacuum box, largely as a consequence of the temperature drop in this section of the equipment. Consequently washing programmes should be considered in the filter operating cycle.

Surge Ponds – are often installed to improve the plant availability. Supersaturated liquors from the leach circuit have been known to approach equilibrium in the surge ponds with the concomittant formation of precipitates. Partitions within the ponds can facilitate cleaning operations that are

required periodically. Again these precipitates, like those in the thickeners, contain elevated levels of radionuclides and appropriate care is necessary in cleaning the ponds.

The presence of ultraviolet light can facilitate the conversion of ferrous to ferric in those ponds that are exposed to light. Some of the ferric thus formed, can be lost from the circuit in the form of precipitates – thus removing a valuable oxidant from the system.

In alkali leach circuits algal blooms have been known to form – possibly from the presence of nitrates, phosphates and potassium that have leached from the ores.

Ion Exchange – In acid and alkali circuits the quaternary ammonium resins load not only uranium, but also some of the gangue components including:

- chlorides
- iron sulfate complexes
- nitrates, and
- silicates.

Silica requires a different elution process to that employed for the other loaded species.

Solvent Extraction – the behavior of gangue elements in the solvent extraction circuit is not too dissimilar to resin systems. Of note are the following:

- colloidal silica resulting from the decomposition of gangue minerals can form cruds in the extract circuit unless treated with an appropriate coagulant;
- nitrates (from blasting explosives) together with ferric iron and chlorides have been known to impact the life of the organic extractant in those solvent extraction circuits that are fed with an eluate from an upstream ion exchange circuit⁽⁶⁾. Nitrosamines and secondary amines were reported to have been formed requiring a total change out of the extractant.

Reagent Loss in Ripios – can represent a significant operating cost in heap leach operations. In processes where the acid level in the lixiviant is several percent, the loss of this acid could be 5 to 10 kg/tonne of ore. Water washing of the ripios is not a practical solution to recover the interstitial acid hold up as it also returns the unwanted gangue solute with the acid.

The flowsheet in **Figure 5.1** could be considered for using the acid component in the drag out within the ripios. If high acid consuming and uranium containing surficial ores are available, then the ripios could be washed to displace the acid containing solute. The washate arising from this can be irrigated on the high acid consuming ore to recover uranium and “kill” the acid. The uranium in the leachate from the alkaline ore can be recovered (by IX or SX) before the barren liquor is returned to the wash cycle.

In this manner the acid in the ripios is gainfully employed while the high solute levels are retained within the ripios of both heaps.

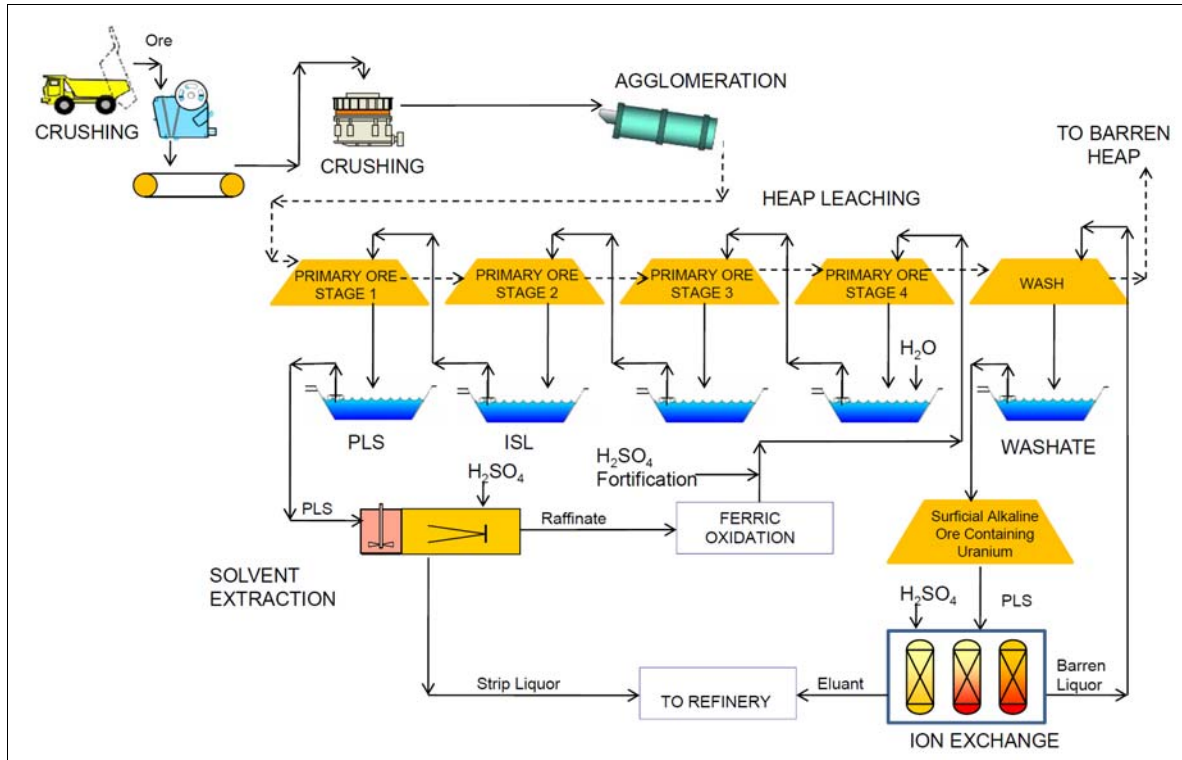


Figure 5.1 Use of Acid Drag out in Ripios

6. CONCLUSIONS

In heap leaching, highly concentrated solutes may be responsible for the reduced uranium extraction kinetics and this may be a result from precipitates in the micro cracks and pores reducing the diffusivity of the lixivants in the case of heap leach scenarios. However, the work referred to in this paper suggests that the overall uranium reaction extent does not always appear to be impaired by high solute concentrations in the lixiviant.

In tank leaching the inter-particle collisions possibly reduce the magnitude of precipitation within particle pores to a greater extent than in heap leaching. Higher leach extents have been observed in high solute containing liquors compared with water.

High solute levels have reduced the acid consumption in both tank and column leach tests.

Phosphate precipitation from liquors containing soluble phosphoric acid appears to suppress the extraction of uranium. The mechanism could be one in which iron phosphate is precipitating and occluding uranium. The lower uranium recoveries achieved at the high solute concentrations could also be attributed to the precipitation of uranyl phosphate in the leachate.

7. REFERENCES

1. Crane P et. al., "Analysis and Troubleshooting in Uranium Solvent Extraction Circuits", ALTA 2010 Uranium Conference.
2. Rezkallah A. and Cable P., "Towards a Functional Polymer for Mining", ALTA 2010 Uranium Conference.
3. Baxter, K. et al., "The Sepon Copper Project: Development of a Flowsheet", Hydrometallurgy 2003-Fifth International Conference in Honor of Professor Ian Ritchie- Volume 2: Electrometallurgy and Environmental Metallurgy, 2003, 1487-1502.
4. Natural Decay Series: Uranium, Radium, and Thorium, Argonne National Laboratory, EVS, Human Health Fact Sheet, 2005.
5. Image from Sharon Paulka.
6. Munyungano, B.M., "Solvent degradation – Rossing Uranium Mine", The Journal of The Southern African Institute of Mining and Metallurgy, 2007, 415-417.