2010 A TECHNICAL EVALUATION OF ELUTION TECHNOLOGIES FOR URANIUM RECOVERY

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1 INTRODUCTION

Ion exchange resins have been widely used for extraction and purification within the uranium industry for many years. Traditionally, batch ion exchange (IX) systems were widely used, however the last 30 years has seen the introduction of continuous countercurrent IX systems into the marketplace. This paper investigated the commercially available elution technologies for sulphuric acid leach environments to determine the ideal elution technology for each different uranium elution flow sheet. The study focused on 4 different commercially available elution technologies, namely:

Clean-iX® Continuous Straight Column Elution: Clean TeQ's continuous moving packed bed elution systems, where solutions are contacted with resin in a continuous counter-current mode.

Clean-iX® Concentration Desorption U-column Elution: Clean TeQ's U-column utilises a concentration desorption process to maximize product concentrations and minimize impurities.

Carousel/Batch Elution: The carousel elution system consists of 3 columns in series with two columns in operation and one column loading/unloading resin.

NIMCIX® Elution: Originally developed by the National Institute for Metallurgy (NIM), the NIMCIX elution occurs in a series of fluidised stages inside a column.

For each elution technology, a process flow diagram and mass balance was developed based on a typical uranium acid leach design criteria. From the mass balance a high level mechanical design was completed to allow comparison of the following parameters:

- OPEX/CAPEX
- Performance (uranium recovery and iron scrubbing)
- Operability (maintenance requirements, availability, etc)

A separate study was undertaken to determine the optimum combination of elution technology to a commercially available product recovery route for yellow cake production. The main unit processes considered in this analysis were:

- Elution (U-column and Straight/Carousel)
- Neutralisation (lime, magnesia and sodium hydroxide)
- Precipitation (peroxide and ammonia)
- Eluex (ion exchange/solvent extraction [AMEX])

A mass balance was constructed to estimate the reagent consumption for each unit process to allow a comparison to be completed. This paper summarises the available alternatives for each unit process to determine the potential optimum flow sheet.

2 ACID ELUTION SYSTEM COMPARISON

2.1 ELUTION PROCESS DESCRIPTION

For each system it was assumed uranium in the form of uranyl sulphate complex is stripped from an SBA (Type II) resin in the elution circuit and the eluted resin in the sulphate form is returned to adsorption. The adsorption system was assumed to be a carousel resin-in-pulp (RIP) plant, and therefore, suitable buffering capacity is required upstream and downstream of the elution system to allow for sufficient resin to be received and sent to RIP. While an RIP adsorption circuit was assumed, it should be noted that each elution technology can also be used in Heap Leach or ISL applications.

The uranium recovery for each elution was assumed to be the same for all technologies, at 98%. Each technology was designed to achieve this result. In the case of the U-column, there is a small amount of uranium that slips with the waste solution (0.5-1%) but the size of the elution plant has been increased to account for this. Other size adjustments were made based on the availability of the Elution column in "operation" mode due to its operating philosophy.

2.1.1 Clean-iX® Continuous Straight Column Elution

Clean TeQ's Continuous Straight Column Elution system utilizes continuous movement of the resin counter-currently to the flow of solution to ensure the driving force of reaction is maximised and reduces the resin inventory required in the system. The resin is intermittently transferred in and out of the column in small batches via an airlift. In each column, resin enters the top and is transferred from the bottom. Solution is pumped into the bottom of the column and overflows into a launder or through a screen. The following is a basic schematic demonstrating the flow of resin through the elution system:

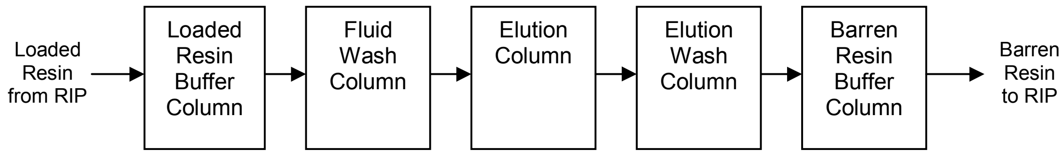

Figure 1: Block flow diagram of continuous straight elution

A brief description of the elution process is as follows:

1. Resin enters the Loaded Resin Buffer Column via a loaded resin screen, where it is separated from slurry and washed to remove any solids entrained with the resin. The column is sized to hold one batch of resin contained in an RIP tank.
2. Every 30-60 minutes a small batch of resin is transferred via an airlift from the bottom of each column into the top of the next column. The resin transfer sequentially starts from the end of the elution system (Elution Wash Column) and progresses back through the elution system one column at a time. During this transfer no solution is being pumped into the column. Once the transfer from that column is complete, the column returns to a run mode and solution resumes pumping. Therefore the "offline" time of each column is only 1-2 minutes.
3. The Fluidised Wash Column elutriates any fine solid particulates remaining on the loaded resin after screening by passing water up the column to momentarily fluidise the resin bed.
4. The Elution Column contacts clean loaded resin counter currently with fresh eluent to remove uranium and remaining impurities from the resin and return the resin to its sulphate form according to the equation:

$$R_4[UO_2(SO_4)_3] + 2SO_4^{2-} \rightarrow 2R_2SO_4 + [UO_2(SO_4)_3]^{4-}$$

   Loaded resin enters the top of the column, where the solution with the highest concentration of uranyl sulphate complex is discharged. Fresh eluent solution (H_2SO_4) enters the bottom of the Elution Column counter currently to the flow of the loaded. As the eluent solution flows up the column, uranium as uranyl sulphate complex ion is stripped off the resin. Concentrated eluate solution (uranyl sulphate complex) overflows from the top of the column.

5. The Elution Wash Column uses raw water to wash excess eluent (sulphuric acid) from the resin. The overflow from this column is sent to an eluent make up tank. This ensures any entrained acid on the resin is recovered to eluent make up to minimise reagent consumption.
6. The Barren Resin Buffer Column holds one batch of barren resin for transport back into the adsorption circuit. After an RIP tank has been emptied and cleaned, the column is pressurised using air to push the resin from the bottom of the column into a resin distribution manifold, allowing resin to enter any one of the RIP tanks.

2.1.2 Clean-iX® Concentration Desorption U-Column Elution

The concentration-desorption process is different from a conventional Carousel or Straight column elution as it uses the selectivity of the resin for uranium and continuous nature of the process to produce a high tenor, high purity, concentrated eluate solution. In all other elution systems, there is a dilution effect on the product eluate from elution. Typically the concentration of uranium is reduced by a factor of 2-5 times in the product eluate when compared to the loaded resin capacity (a dilution "factor" of 2-5). The concentration-desorption process occurring in the U-column typically has a dilution factor of 0.5-1.0. The benefit of this is all downstream unit process size and reagent costs can be reduced.

Figure 2 shows a basic schematic demonstrating the flow of resin through the elution system:

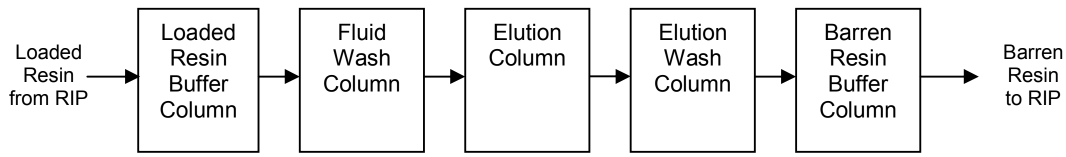

Figure 2: Block flow diagram of continuous U-column elution

A diagram of the U-column is provided in ***Figure 3***. Loaded resin enters the top of the left hand side (LHS) of the U-column as a moving packed bed and is transferred periodically out of the right hand side (RHS) by pressurising the LHS with plant air. Eluent in the form of sulphuric acid is pumped into the RHS of the U-column counter-current to the resin flow.

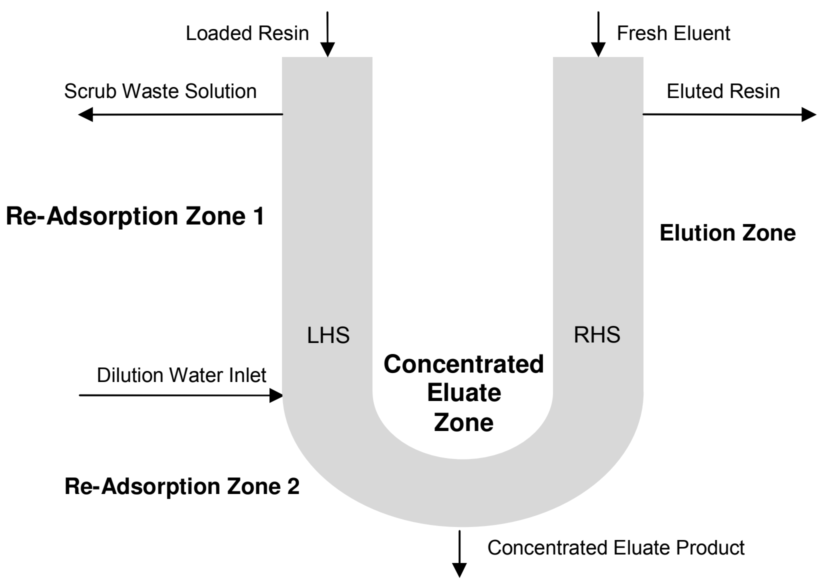

Figure 3: Stream nomenclature for the U-column

The following is a description of each of the areas of the U-column:

Re-Adsorption Zone 1 Resin in this area will be subjected to favourable adsorption conditions through the addition of dilution water. To ensure adsorption conditions are maintained in this section of the column, the sulphate concentration must be less than 50g/L. Under these conditions, the resin will selectively adsorb uranium in preference to the more poorly selected species, which have loaded under more favourable conditions in adsorption, i.e. such as Fe(III). As uranium replaces these ions they are displaced into the scrub waste solution.

The use of water injection into the column is optional and is only required when high eluent concentrations are used to ensure adsorption conditions are achieved.

Re-Adsorption Zone 2 Resin in this area will be exposed to a high uranium concentration in solution created by the concentration effect at the bottom of the column.

	As the resin is exposed to a higher uranium concentration in solution than compared to adsorption, the resin will load to a higher capacity as predicted on the adsorption isotherm. The majority of impurities are chromatographically pushed off in favour of the uranyl sulphate complex.
Concentrated Eluate Zone	Resin is partially desorbed and is bathed in a highly concentrated eluate/eluent solution. This is the point of highest concentration of uranium in solution and is the point for product extraction.
Elution Zone	Resin in this area has exchanged all the adsorbed metals for sulphate functional groups and the resin is restored. The restored resin is now fully eluted and in the sulphate form.

2.1.3 Carousel Elution

While the stages of elution remain the same for both Carousel and Continuous elution modes, the main difference is a batch of resin is transferred from RIP and enters a column, where it remains for the entire duration of the elution cycle.

Each Elution Column holds 1 RIP tank volume (12-24 hours) of resin. Each column is a closed system where liquid travels in an *upflow* direction and exits via a "candle stick" drain to a valve manifold. From the drain manifold the solution is discharge to a corresponding inventory tank depending on the sequence in the elution cycle. All three columns are identical in design.

Once the resin has been loaded in the RIP circuit it is screened and washed to remove all the entrained slurry from the RIP circuit. Clean resin falls by gravity or transferred via a water eductor into one of three Elution columns. Once the column is full with loaded resin the elution sequence commences as outlined below.

Figure 4 is a basic schematic demonstrating the flow of resin through the elution system:

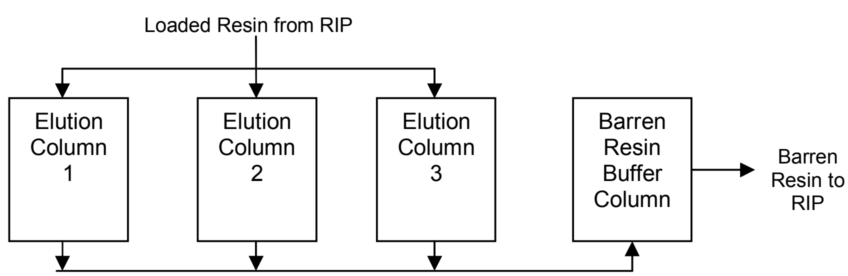

Figure 4: Block flow diagram of Carousel elution

Two columns are operating in series through steps 2 to 4 while one column is unloading and reloading resin. The elution sequence is described by the following steps:

1.	Resin Filling	Resin is pumped from the RIP tank via the loaded resin screen.
2.	Displacement	Eluent is passed up the column remove the water from the resin bed, limiting the dilution of the product eluate stream.
3.	Elution	The Elution process step contacts loaded resin with eluent to remove uranium and remaining impurities from the resin and return the resin to the sulphate form. The elution sequence is divided into three stages where fresh eluent is repeatedly passed through the column to build the uranium concentration in solution.
3a.	Product Elution	Eluent, which has already been passed up through the preceding column (steps 3b and 3c) is passed up the column to partially strip the resin and to build the concentration of uranium in the solution stream to its maximum. The solution exiting the column during this step is product eluate.
3b.	Recycle Elution	Eluent previously passed up the column (step 3c) is recycled through the column to further strip the resin and build the concentration in the solution stream. This solution is used for product elution.

3c. Final Elution — Fresh eluent (H_2SO_4) is passed up the column to fully strip the already partially eluted resin. Solution exiting the column in this step is used for recycle elution. The resin after this step is now fully eluted.

4. Elution Wash — Raw water is passed up the column to remove any entrained eluent in the resin bed. Solution exiting the column is sent to the eluent make-up tank.

5. Resin Unloading — After washing, the resin is transferred to the Barren Resin Buffer Column for transportation into the RIP circuit.

2.1.4 NIMCIX Elution

The operation of a NIMCIX column is similar to that of a straight moving packed bed column with the key difference being the use of a series of fluidised stages, created by perforated trays in the column, forming discrete resin stages for ion exchange.

Due to the design parameters of a NIMCIX column design, it was found that operating two NIMCIX columns in series reduces the volumetric flow of the eluent (H_2SO_4) and product eluate considerably (see Section 2.2.2). Both single and two-stage NIMCIX elution options have been considered in this paper. The operation of both NIMCIX columns in the two-stage scenario are similar, therefore only the single stage NIMCIX process description is discussed below.

Figure 5 is a basic schematic demonstrating the flow of resin through the elution system:

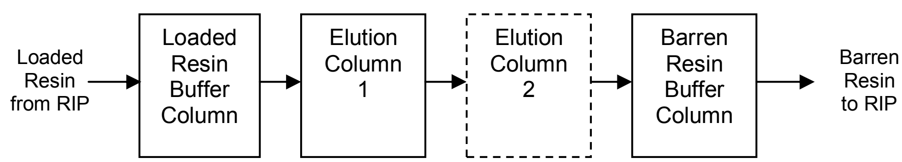

Figure 5: Block flow diagram of NIMCIX elution

Clean loaded resin enters the Loaded Resin Buffer Column and is transported at regular intervals into the Elution Column via airlift. The Elution cycle is comprised of 5 steps:

1. Forward Flow — Eluent solution flows up through the column, counter-currently to the flow of resin. The flow of solution fluidises the beds of resin contained in each stage of the column, ensuring effective mixing of resin and solution. Once the solution has passed through all stages it overflows in to a launder where it flows by gravity to a tank.

2. Settling — The solution flow is turned off allowing resin to fall through the perforations in each tray to the stage below. Depending on the settling characteristics of the resin in the solution, this only takes a short amount of time.

3. Reverse Flow — A fixed volume of solution and resin is removed from the bottom conical section of the column into a resin transfer vessel using a pump. During this time, resin continues to settle from one stage to the stage below through the perforated trays.

4. Delay and Flush — Solution is circulated through the conical section at the bottom of the NIMCIX column and the Resin Transfer Vessel, flushing any resin that may be contained in these sections into the resin transfer vessel.

5. Resin Transfer — The Resin Transfer Vessel is isolated from the NIMCIX column. Hydraulic pressure in the Resin Transfer Vessel, created by the resin transfer pump, is used to transfer the resin into the top of the succeeding column. Typically this resin/solution stream passes over a dewatering screen. The dewatered resin enters the top of the next column and the underflow returns to the solution tank.

As dewatering screens are used after the NIMCIX columns, there is no elution wash step. As the NIMCIX column can tolerate higher solids in solution, a fluidized wash step is also not required.

2.1.5 Regeneration

Regeneration is required if there is a significant build up of impurities (e.g. silica) reducing the performance of the resin. Typically a dilute sodium hydroxide solution is used to reduce the silica content of the resin to acceptable levels. For the purposes of this paper, regeneration was not included in any of the technology designs.

2.2 RESULTS AND DISCUSSION

The following section discusses the relative advantages and disadvantages of each elution technology, focusing on hydrometallurgical performance, design, capital cost, operating cost and operability.

2.2.1 Performance

Loaded Resin Washing and Particulate Removal

Packed resin beds act as highly efficient particulate filters, capturing fine particles in the solution stream as it comes in contact with the bed. Batch/Carousel systems are particularly vulnerable to particulates, as the resin bed is moved very infrequently as it is exposed to a much higher volumetric flow rate of solution before it is transferred. Typically a TSS of <5ppm is acceptable in solutions entering into Carousel systems ensuring the pressure increase across the resin bed is minimised. In the case of the Carousel system in this study the resin is removed every 72 hours Therefore it is likely that higher TSS can be tolerated in solutions (~10ppm).

The Clean-iX® Straight and U-column elution technologies intermittently move the resin (30-120 mins). Therefore any solids built up in the resin bed are removed into a fluidised wash column for particulate removal. Typically, these technologies can tolerate up to 100ppm TSS in solutions before performance and operation of the column is affected.

The NIMCIX column operates as a fluidised column, and therefore the effect of particulates is greatly reduced. Typically NIMCIX columns can operate with up to 3% solids before operation and performance is affected. While this is an advantage for its use as an adsorption column, there can be no solids entering the downstream SX and uranium precipitation circuits. Therefore it is likely that the use of the NIMCIX column as an elution column will require some form of filtration to ensure any solids carried on the resin do not enter into downstream product recovery. It should also be noted that impurity metals present in solids can continue to leach out into the solution phase in IX feed and through the column. Therefore there is a risk that the impurity levels can continue to rise if solids are not completely removed from the loaded resin. The potential effect of this can be established during lab scale testwork.

Eluted Resin Washing

The methods for washing the eluted resin differ for each technology. Both the Straight and U-column elution technologies use continuous counter-current washing of the resin in a moving packed bed column to wash the resin. The Carousel column washes the resin bed volume after elution using *upflow* washing. The NIMCIX column utilises a static screen to wash the interstitial solution from the resin.

Incomplete washing of the resin can affect its performance in adsorption and therefore should be considered during detailed design. Washing with sprays or on screens (as in NIMCIX elution) will only remove the eluent that is carried with the resin. During the elution process, eluent is diffused throughout the entire resin bead, and therefore, time is required to allow for the majority of this to diffuse out.

Effect on Downstream Unit Processes

There are several different product recovery alternatives that can be considered for a uranium acid system. The two main process routes are direct precipitation (peroxide/ammonia) or SX followed by precipitation.

The suitability for direct precipitation over SX/precipitation is determined by the volumetric flow and uranium tenor of the product eluate stream from Elution. If the uranium tenor is sufficiently high enough, the reagent consumption in neutralisation prior to uranium precipitation is minimised and the direct precipitation option becomes the most economic alternative. Because of the concentration effect occurring in U-column elution, the product eluate volumetric flow is much smaller than the other elution technologies. Typically U-column product eluate flow rates are one third that of Straight, NIMCIX or Carousel elution technologies.

The suitability of direct precipitation over SX is also dependent on the impurity levels in the product eluate stream. In particular for an acid system, iron is of specific concern. Typical Yellow Cake product specifications suggest a composition of 75% uranium and 0.15% iron. Based on these values the uranium concentration must be 500 times higher (a U/Fe impurity ratio of 500:1) than iron to meet this specification.

If the iron concentration is less than 500mg/L in the product eluate and the U/Fe ratio in solution is ideally above 500:1, then the use of SX is not required, as the concentration multiplier is acceptable for final product specification. Compared to the typical performance of elution technologies, U/Fe ratios with U-column elution tend to be 1.5-2 times higher than other elution technologies. This is because U-column elution utilises re-adsorption, where additional scrubbing occurs as the re-adsorption conditions displaces iron for uranium on the resin. Therefore this higher level of scrubbing in the U-column gives a much higher purity product. The concentration effect occurring in the U-column elution also increases the uranium concentration relative to iron, further increasing this ratio.

If the purity of the product eluate from U-column elution is not sufficiently high, SX will be required before precipitation to ensure product quality. If this is required, the Straight Column elution option would be the preferred option in an Eluex arrangement. High uranium concentrations in the product eluate have the potential to cause high viscosity in the organic phase in SX loading. This causes a third phase to form, which is removed with the raffinate. Therefore the product eluate from U-column elution would have to be diluted, negating its benefits.

2.2.2 Design Considerations

Continuous vs. Carousel

In continuous moving packed bed elution systems, the resin is intermittently moved down the column. Every transfer, a volume of resin is removed from the bottom of the column and a fresh amount enters the top of the column. Assuming the column has a residence time of 12 hours, there would be 12 discrete bed volumes of resin in the column. The solution entering the bottom of the column contacts the bottom bed volume first, with this liquid continuing to contact the 2nd bed volume, 3rd, and so on. Therefore in this column there are 12 bed volumes (BVs).

In Carousel operation, the resin is not moved until the cycle is complete. Therefore there is 1 bed volume in a Carousel column.

In both cases, the same amount of solution will be used. If 3BV/hr is required to elute the resin for 12 hours, continuous operation will use a total of 36BVs. Similarly the Carousel column will use 36BVs to elute the loaded resin.

The difference lies in the solution management for both systems. Because a bed volume resin for a Carousel system is so much larger than in Continuous column (12 times in this example) the eluent, product eluate and wash water tanks have to be significantly larger to have this solution available.

One way to reduce this effect is to increase the number of elution columns in a Carousel system to reduce the size of the bed volume in each, and therefore, the flow rate required. Either the solution can be pumped through succeeding columns (i.e. the overflow from column 1 enters the bottom of column 2) or intermediate tanks and pumps can be used. The benefit of using intermediate tanks is that the pressure required to pump the solution through the columns is reduced as the pump has to pump through one column rather than multiple columns. The other benefit is that if these tanks are made to be larger than just a surge tank, if there are any fluctuations in resin loading, the variations of uranium concentration can be normalised.

One other notable point is that the more stages that are available, the higher the efficiency of mass transfer. Therefore continuous systems will always be more efficient than Carousel systems, unless the number of bed volumes in a continuous column is matched by the number of Carousel columns in series.

To equal the efficiency of a Continuous system, 12 columns would be needed in series. While there would be a reduction in the flow rate requirements through the system, the capital and operating requirements would likely to be much higher than a single continuous counter current column.

NIMCIX Column Mechanical Design Considerations

The primary drivers of elution design are governed by the strength of eluent, the flow rate of eluent and the residence time of the resin required. All three of these variables are interconnected and can be determined during feasibility lab-scale testing. No matter which elution technology is used, these three process parameters are required to be met.

The mechanical design parameters that become secondary are:

- The aspect ratios of the column ensuring adequate theoretical transfer steps are created.
- The superficial velocity of the solution through the resin bed to ensure plug flow and enough turbulence to reduce the size of the film layer (not too slow) and to ensure the resin bed does not expand (not too fast).
- The height of the column to ensure pressure on resin is not too high.

In a moving packed bed column design (such as Straight Column and U-column Elution), there is a trade-off between the aspect ratio used and the superficial velocity. Typically if the superficial velocity of the column is between 1-20m/hr there will be minimal bed expansion due to the height of the resin bed and the use of pressurised columns.

In NIMCIX systems, the superficial velocity becomes much more important. In each stage in a NIMCIX column, there is a resin bed with a height of 0.5-1m. Solution travelling up the column causes the resin bed to expand in each stage. An increase in superficial velocity can fully fluidise the resin bed, causing resin to travel up through the perforated plates in each stage, “mixing” the discrete resin beds. This mixing of the resin beds will reduce the overall performance of the column due to short circuiting.

A further complication is caused by the density difference of loaded versus eluted resin. When the loaded resin enters the top of the column, it is denser than the eluted resin at the bottom. Therefore at a fixed superficial velocity the bed at the bottom of the column will expand more than the bed at the top. For SBA resins which require higher concentrations of sulphuric acid (150-200g/L) to completely elute the resin, the density differential between the resin and the acid becomes small, reducing the superficial velocity required to fluidise the bed. The consequence of this is the elution column must be very wide to ensure the superficial velocity is kept low for fine bead resins and that the bed height is lower than typically designed. The opposite is also true, whereby larger bead resins require a much higher superficial velocity to expand the bed. These considerations are required to be addressed in the design stage to ensure no operational issues. Also because of this the turndown of the NIMCIX column is very small, as it effects the physical movement of the resin in the column.

By designing two NIMCIX columns in series the column diameter can be reduced and allows the required superficial velocity to be reduced in order to expand the bed. While this has made the NIMCIX column more competitive from a performance point of view, the capital and operating costs are higher than that of Straight and U-column technologies.

Availability

Within each of the elution system control philosophies there are process downtimes as resin is transferred in the Continuous technologies, or there is change of step in the Carousel elution.

In both Straight and U-column elution, there is typically a 2 minute transfer period where the resin is airlifted out of the column over a 60 minute period. Therefore the maximum availability of the elution systems is 96.7%.

In Carousel elution system, one column remains offline for loading and unloading of resin. There is also a 30 second delay between each sequence step. Therefore the availability of a single column is 46%, while the overall system has a plant availability of 99.1%

For the NIMCIX system, the column typically takes 10-12 minutes to transfer eluted resin with a total elution cycle time of around 170 minutes. Therefore the availability of the NIMCIX column for elution is 92.9%.

Therefore in terms of plant availability, the Carousel elution system has the largest period of downtime, which must be accounted for in process design.

Operability and Maintenance

The following is a summary of the maintenance issues unique to each elution technology:

- NIMCIX: The main maintenance issue in a NIMCIX column is the fouling on the interstage perforated plates. Typical NIMCIX mechanical design allows for a man-hole at each stage level to allow for access to the perforated plates during downtime. The column must be emptied to a point below the perforated plate in order to service it and due to nature of the column; it is typically classified as a confined space. Access also can be an issue with either permanent scaffolding or stairs required to get access to all levels.
- Carousel: Due to the nature of design, there is a large amount of automated valves required at the top and bottom of each column to allow automation of the circuit. Typically there are 8-10 automated valves per column. Normally the Carousel column is operated at pressure to hydraulically transport resin after a complete cycle. Due to the pressure required to transport the resin the columns may be deemed as a pressure vessel and therefore will be subject to AS1210/ASME8 pressure vessel code.
- U-column: The concentrated eluate is extracted from the bottom of the column from a mesh screen. Typically if there are solids with the resin, they will settle in the bottom section. Typical design is to have the take-off point on the side of column (on the U) with provision for a second take-off next to it, in case there are any blockages.

  Due to the pressure required to transport the resin the U-column it may be deemed as a pressure vessel and therefore will be subject to AS1210/ASME8 pressure vessel code.
- Straight: Similar to the U-column, the moving packed beds utilise candle stick screens as the drain points at the tops of the columns. There is potential for these screens to block, but each screen is removable and readily accessible from the top of the column and would require a minimal maintenance window to change out or clean.

2.2.3 Operating Cost

The following table is a summary of the relative operating costs for each of the technologies.

Table 1: Relative operating cost comparison (200g/L H_2SO_4)

Item	U-column	Straight Column	Carousel Column	NIMCIX 1 Column	NIMCIX 2 Column
Consumable (Variable) Costs	0.85	0.85	0.88	1.81	0.94
Fixed Costs	0.15	0.16	0.17	0.17	0.17
Total OPEX	**1.00**	**1.01**	**1.05**	**1.97**	**1.11**

It can be seen from ***Table 1*** both Straight and U-column elution give the lowest operating cost with the NIMCIX 1 Column system giving the highest.

Sulphuric acid was by far the largest single contributor to operating cost with the overall operating cost sensitive to the sulphuric acid consumption rate. The cost can be directly related to the amount of eluent used in each technology, with both NIMCIX columns coming out the highest due to the higher eluent flow rates required.

The eluent strength considered was 200g/L, which is high when compared to other IX circuits operating on uranium elution around the world as it was assumed that a particularly strong base resin was used. Alternative resins may be eluted with 120-150g/L acid, significantly reducing this portion of the operating cost. Table 2 shows the new reagent costs using an eluent concentration of 150g/L. While overall the operating costs for all plants would be reduced, there is only a marginal change in the relative operating costs between systems.

Table 2: Relative operating cost comparison (150g/L H_2SO_4)

Item	U-column	Straight Column	Carousel Column	NIMCIX 1 Column	NIMCIX 2 Column
Total OPEX	1.00	1.01	1.06	1.92	1.11

2.2.4 Capital Cost

The following is a summary of the capital cost for each technology:

Table 3: Relative capital cost comparison for elution plant

Technology	U-column	Straight Column	Carousel Column	NIMCIX 1 Column	NIMCIX 2 Column
Total Equipment Cost	0.34	0.30	0.50	0.32	0.36
Total Discipline Installation Costs	0.66	0.47	0.82	0.62	0.71
Total Direct Cost	**1.00**	**0.77**	**1.32**	**0.94**	**1.07**

Table 3 shows that the Straight Column system is the cheapest, with the NIMCIX 1 elution the second most. This is due to:

- The straight elution column is a smaller column all other columns.
- Due to the resin expansion requirements and the number of man-holes to service the interstage plates, the NIMCIX columns are more expensive than other columns. But because there are fewer columns in the system when compared to U-column or Straight Column, the NIMCIX system is cheaper.
- While the process tanks for all continuous options are similar, due to the larger inventory of solution required for the Carousel Column operation, the tank cost is significantly higher.

Overall the Carousel system is the most expensive due to the high tank costs. The least expensive is the U-column with the Straight Column and NIMCIX single column options display similar prices.

3 URANIUM PRODUCT RECOVERY COMPARISON

3.1 PROCESS DESCRIPTIONS

3.1.1 Direct Precipitation

Depending on the elution technology if the concentration is sufficiently high enough then direct precipitation becomes a viable recovery process. In the case of the U-column, direct precipitation is feasible via neutralisation with lime, caustic or magnesia followed by precipitation.

Figure 6 shows the block flow sheet used in all precipitation unit processes:

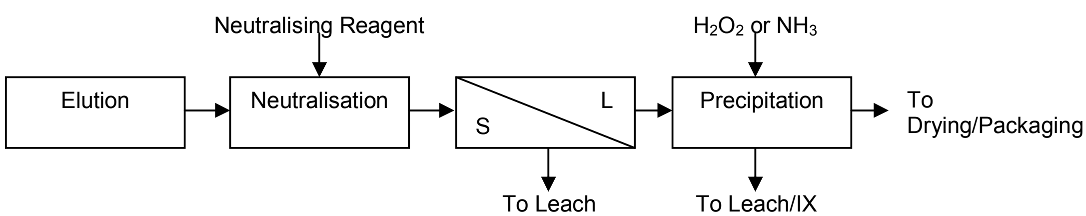

Figure 6: Typical precipitation flow sheet

3.1.2 Ion Exchange-Solvent Extraction (Eluex)

In some instances where the uranium tenor from elution is not sufficiently high enough for direct precipitation or there are deleterious elements still present then solvent extraction (SX) is required. The process where IX is combined with solvent extraction (SX) is known as Eluex. Traditional batch ion exchange systems require high eluent volumes to fully elute the resin and typical strong base resins are not selective towards uranium over other metals.

The Eluex process uses the relative strengths of each unit process and combines them to produce a high purity product. While there are several options available for stripping of the organic solution, the most popular is the use of ammonia/ammonium sulphate because when it is paired with ADU precipitation, several of the streams can be recycled through the process to minimise reagent costs. The Eluex flow sheet integrates the elution and solvent extraction unit processes. A typical flow sheet is shown below:

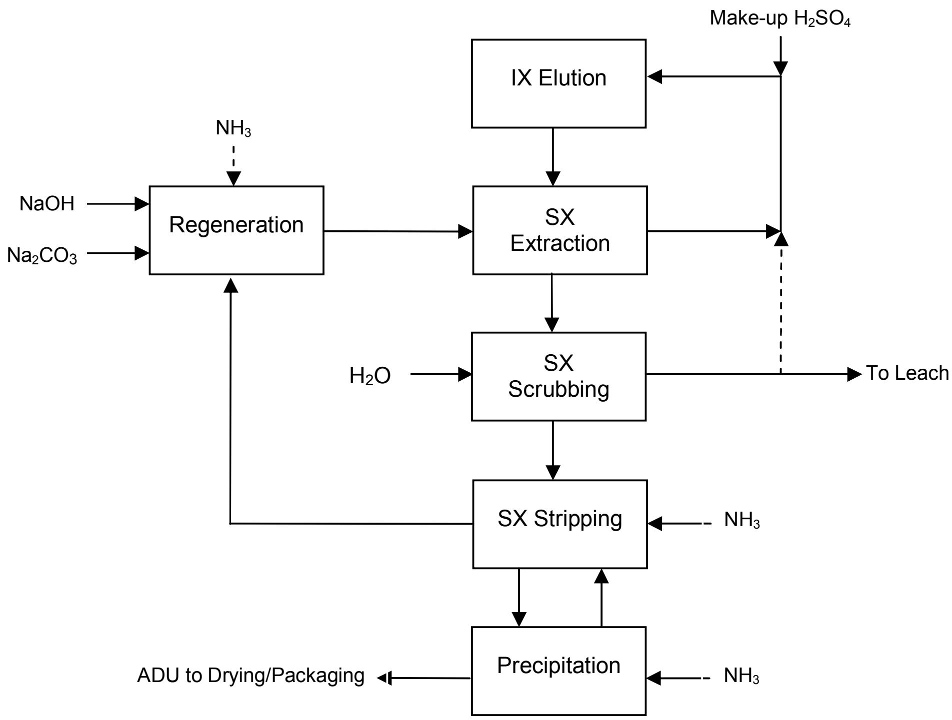

Figure 7: Typical Eluex flow sheet

The product eluate from elution enters into the SX extraction stage, where the amine extracts the uranyl sulphate complexes. The raffinate returns to eluent feed, with make-up sulphuric acid to replace acid consumed in elution and SX extraction.

While the recycling of acid reduces the overall acid consumption of the plant, the free acid in the IX product eluate can affect the performance of SX. Higher acid concentrations increase the level of bisulphate ions in solution, which directly compete with uranyl sulphate complexes on amine extractants. Therefore it is preferred to reduce the acid concentration in the product eluate to give a better performance in SX. This can be done by resin selection and elution optimisation.

Overall the net benefit of the Eluex process is the large recycle streams of both acid and ammonia to reduce total acid and ammonia consumption, giving a net result better than IX or SX alone.

3.2 RESULTS AND DISCUSSION

3.2.1 Comparison Direct Precipitation and Eluex

A high level model was developed to analyse the operating costs for each system. It was assumed that the uranium production through each system was the same.

Direct Reagent Costs

The main reagents consumed in direct precipitation are:

1. H_2SO_4 for elution
2. $Ca(OH)_2$ for neutralisation

3. NH_3 for precipitation
4. Resin replacement

The main reagents consumed in the Eluex process are:

1. H_2SO_4 for elution and extraction
2. NH_3 for stripping
3. Solvent replacement
4. NH_3 for precipitation
5. Resin replacement

As the uranium throughput was the same for both systems, it can be assumed that the ammonia consumption in ADU for is the same. Therefore the main process variables to be investigated were:

- Acid strength in elution
- Uranium loading capacity
- The dilution factor in elution. For all elution systems (with the exception of the U-column) the concentration of uranium is lower in the product eluate than on the loaded resin (i.e. a dilution factor >1). In U-column elution, the concentration of uranium in the product eluate is often equal to or greater than the loading on the resin (i.e. a dilution factor of <1) due to the concentration effect. The lower the dilution factor, the less product eluate is being sent downstream and therefore the smaller the downstream processes and the lower the amount of acid required to be neutralised.

A high level mass balance was completed for both direct precipitation and Eluex to determine the estimated reagent costs for different variable set points. Direct precipitation consisted of elution, neutralisation with lime and precipitation with ammonia. Eluex consisted of elution, solvent extraction and precipitation with ammonia. Each of the three variables listed above were analysed to determine their relative effect on the reagent cost. For each variable, the dilution factor was used as the main variable for comparison, with the effect of the other variables relative to this analysed. The mass balance was designed to assume a fixed uranium throughput.

Figure 8 gives the total relative reagent costs for both direct precipitation and Eluex with changing acid concentration in the eluent. The reagent cost for solvent extraction is only marginally affected by the eluent acid strength and the dilution factor. As the majority of the acid in the product eluate is recycled back to eluent after solvent extraction, the only acid consumed is for uranium extraction (solvent protonation) and therefore remains relatively stable.

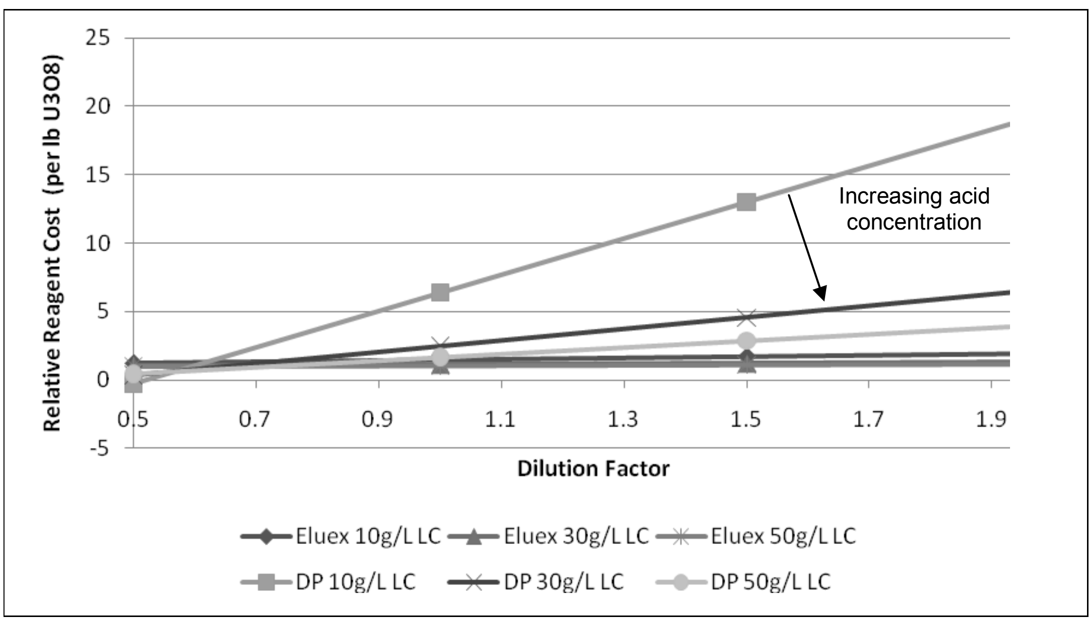

Figure 8: Relative reagent costs with changing acid concentration (50g/L U_3O_8 resin loading)

Conversely direct precipitation is sensitive to both variables. Decreasing the dilution factor causes more of the eluent solution (still containing high amounts of acid) to travel up the left hand side of the U-column and discharge at scrub waste. As this solution is sent back to leach, this acid offsets the acid required for leaching. Therefore this acid can be counted as a credit in the whole flow sheet, reducing the relative cost. A higher dilution factor means that more acid is being sent to neutralisation, increasing lime consumption and increasing the amount of acid required to be replenished.

Also a higher acid concentration in the fresh eluent increases the acid concentration in the product eluate, requiring more acid to be neutralised (increased lime cost). Therefore the overall reagent cost increases.

The other variable investigated was uranium loading capacity. Uranium loading changes the amount of eluent used in elution and the amount of acid required for solvent extraction. It can be seen from ***Figure 9*** that the reagent cost for direct precipitation is relatively sensitive to the uranium loading, as the main reagent cost is in neutralising the acid. Decreasing the uranium loading increases resin flow rate required to maintain the uranium throughput, which increases the size of the eluent flows required.

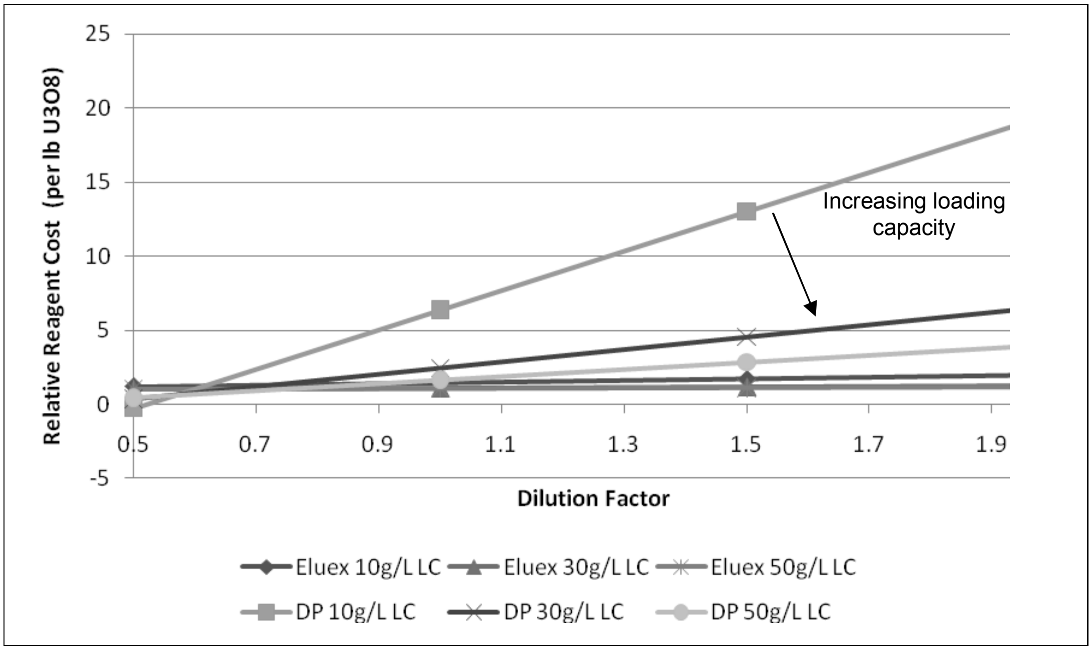

Figure 9: Relative reagent cost with changing uranium loading (150g/L H_2SO_4 in eluent)

There are other effects on solvent extraction that have not been quantified but should be noted.

While the amine groups are relatively insensitive to the acid concentration compared to SBA resins, there is an effect on performance as the acid concentration increases. Previous work (Mackenzie, 1997) has shown that as the acid concentration increases, the performance of the extractant decreases. Therefore a larger system with more extractant or a system with more stages is required to ensure the overall performance of SX is not affected. For example, increasing the acid concentration from 100g/L to 140g/L in the eluate can decrease the solvent loading by up to 15%.

Conversely the reagent cost for SX is not greatly influenced by the uranium loading, as the main consumption of acid in SX is through uranium extraction, which has been assumed to be fixed. Acid consumption for scrubbing decreases with increasing loading capacity as the increasing loading capacity reduces the flow of resin and consequently the product eluate flow to SX. Acid is used to adjust pH of the scrub solution to pH 1. Reducing the overall size of the SX plant reduces the scrub flow rate required and hence reduces the acid required.

It can be determined that direct precipitation becomes more cost competitive at higher uranium resin loadings, as the resin flow rate is reduced through the system, reducing the eluate flow rate and the acid flow to neutralisation.

Taking into consideration these additional operating costs, it is likely that the cross over point between SX and direct precipitation is a dilution factor of 1-1.5. Less than 1-1.5, direct precipitation with U-column elution is likely to be the lower cost option. Above this range, Straight column and

Carousel systems are better suited to Eluex, as the concentration effect of the U-column holds no performance advantage with SX.

The model only quantified the reagent costs associated with each of the unit processes. It did not take into consideration the additional capital and indirect operating costs associated with SX. It is likely that when all of these items are factored in, the relative operating cost differential between Eluex and direct precipitation would be reduced, such that the cross over point from SX to direct precipitation would be in the range of 2-3.

Based on reagent costs, if U-column elution operates at a dilution factor of 1 or less, it will be the most economic option. At dilution factors greater than 1, Eluex tends to be the most economical process route for this study. Therefore straight column or Carousel column elution technologies can be utilised here.

4 CONCLUSIONS

4.1 URANIUM ELUTION TECHNOLOGY

Based on the design criteria used as the basis for design in this report, the following conclusions can be determined:

For the use of direct precipitation for uranium product recovery, the U-column is the most cost effective elution technology due to reduced sulphuric acid neutralisation costs.

For the use of SX downstream of elution, the Straight Column is the most cost effective elution technology as a high uranium concentration product eluate is not desirable in SX and Straight Column elution is the cheapest elution alternative.

The Carousel elution is the least efficient form of elution. Carousel systems are more suited for ground water remediation, where the movement of resin is extremely low.

While the NIMCIX Column is as efficient as the Straight Column for uranium extraction, due to mechanical design constraints, the NIMCIX system is larger and more expensive in both capital and operating costs. For unclarified solutions of 2-3% solids, it is likely that the NIMCIX Column will be the optimum process. The NIMCIX system also has minimum plant turndown capacity and must operate near the designed eluent flow rate.

4.2 URANIUM ELUATE NEUTRALISATION

The three reagents investigated were lime, magnesia and sodium hydroxide, all of which have been used in uranium mines historically. Reagent cost analysis showed that lime precipitation was by far the cheapest option for neutralisation of acid. The relative costs of neutralisation with changing product eluate flow, eluent acid concentration and uranium flow rate remained insensitive, suggesting that at all process conditions for elution, lime neutralisation would be the most cost effective.

4.3 DIRECT PRECIPITATION AND ELUEX

Based on the reagent costs, Eluex would be the most cost competitive option. A dilution factor of 1--1.5 or less is required for direct precipitation to be the cheapest option. In acid elution, this is only possible with a U-column. Based on operating plants, a dilution factor of 1.0 is typical of sulphuric acid plants, with nitrate elution having a lower ratio. To eliminate SX from the flow sheet, U-column elution is required (It is assumed that impurity levels in the product eluate from U-column elution are sufficiently low for direct precipitation). If Eluex is used, it is recommended a Straight column system is utilised, as the operation of these units is simpler compared to a U-column.

When the cost of capital is taken into consideration, it is likely that the cross-over point for SX/direct precipitation is 2-3, due to the larger capital cost of the SX plant.

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