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ALTA 2011
URANIUM CONFERENCE

PROCESS PLANT DESIGN

DESIGNING URANIUM PLANTS

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ABSTRACT

A great variety of mining and hydrometallurgical process routes are available for the production of uranium concentrate. Designing a process for a particular ore requires a comprehensive comparison of the varying process routes so that the optimal economical and environmental option is selected, these two factors being equally important and critical to the success of uranium projects. To achieve the best process design an understanding of all the options is required.

This paper provides a review of the main milling options, acid and alkali leaching routes, and solution extraction methods currently employed in numerous plants worldwide. Common and novel processing routes are highlighted, and the unit operations and critical design parameters for each step in a typical uranium flow sheet are assessed.

In conclusion, a review of a number of current and prospective Australian uranium mines is presented to illustrate the influence of various ore types and their impact on the processing options selected.

INTRODUCTION

Uranium ore mining and processing presents a number of challenges and options in comparison to the majority of other metals. This is due to the great variety of hydrometallurgical process routes available for the recovery of uranium from uranium ore. Designing a process for a particular ore requires a variety of` process routes to be investigated and compared so that the optimal economical and environmental option is chosen. To achieve the best process design an understanding of all the options is required. This paper provides a review of the main milling options, acid and alkali leaching routes, solution extraction methods, and product precipitation approaches currently employed in numerous plants worldwide. Included is brief review of a number of prospective Australian uranium mines.

PROCESS OVERVIEW

The mining and processing of uranium ore can be broken down into a number of distinctive steps as shown in Figure 1.

<table>
<tr><th colspan="2">Step</th><th colspan="7">Techniques</th></tr>
<tr><td>1</td><td>Mining</td><td colspan="2">Underground</td><td colspan="4">Open Pit</td><td rowspan="3">In-Situ leaching (ISL) or in-Situ recovery (ISR)</td></tr>
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</table>

Figure 1: Steps and techniques involved in uranium mining and processing

The initial step, mining, is not of particular interest in this review. The type of mining (open pit or underground) is easily chosen based on ore grade, quantity and location, and has little-to-no effect on the proceeding process steps.

To achieve the maximum liberation of uranium, mined ore must be reduced in size so as to expose the uranium minerals to the leaching solution and to allow for the ore to be readily slurried when an agitated leach circuit design is employed. Following adequate crushing and grinding the ore particles are prepared for leaching. Conventional leaching techniques used for high grade ore, such as agitated acid or alkaline leaching, require the ore particles to be slurried. Alternatively, techniques such as Heap or Vat leaching require the ore particles to be stacked into large piles or arranged within vessels. In both cases the ore particles may be agglomerated before stacking.

Leaching of the ground ore makes use of either an acidic or alkaline solution to solubilize the uranium minerals, removing them from the solid gangue minerals. A number of leaching systems exist including agitated, pressure, heap or vat leaching. The choice of which leaching technique is employed is based on a number of process variables. Agitated and pressure leaching is typically reserved for high grade ores or low grade refractory ores, while heap and vat leaching is restricted to low grade ores. The choice between acidic or alkaline solution is heavily based on the mineralogy of the ore.

Most systems use an acidic solution, generally sulfuric acid due to its low cost and wide availability. An oxidant is also often required to convert tetravalent uranium to the hexavalent form, as only the latter is readily taken into solution. If the mineralogy of the ore causes high acid consumption an alkaline solution, typically a mixture of sodium carbonate and sodium bicarbonate, is used. The choice of leaching technique is the most crucial decision as it affects both the crushing and solvent extraction circuit designs.

Following leaching most plants employ a solid-liquid separation circuit to remove the leached solids for the uranium-bearing solution. This is often a very important component of uranium processing operations as incomplete washing of solids can result in significant uranium losses. By this point in the process 50 % - 75 % of the extraction costs have been expended and thus any uranium losses will significantly reduce operating profits(2). Most mills typically use either thickening or continuous filtration. A combination of a variety of liquid-solid separation devices may be used, with the best device/s chosen based on process conditions and economics.

The uranium-bearing solution from the solid-liquid separation step often needs to be concentrated and purified before the product precipitation stage. This purification is achieved via ion exchange (IX) and/or solvent extraction (SX). The product uranium solution from this stage, often referred to as the pregnant strip liquor, should have relatively low concentrations of impurities while also having a higher uranium concentration than the feed stream. In rare cases the concentration stage can be avoided if the pregnant leach solution is fairly pure and of high uranium concentration.

The pregnant strip liquor passes to the final precipitation process area. Often the concentrations of certain impurities are still too high to allow for direct uranium product precipitation. Magnesia or lime may be added to the solution so as to form a gypsum cake or iron cake precipitate, thus reducing the concentration of impurities. When appropriate impurities levels are reached, the uranium product is precipitated using a variety of precipitants; often one of magnesia, ammonia, caustic soda, or hydrogen peroxide. Several stages are used to wash trapped soluble impurities from the uranium precipitate using a combination of thickeners, centrifuges, and/or filters. Finally, drying of the product is performed with calciners or other drying equipment, such as oil or steam heated dryers.

ORE PREPARATION

Following removal of uranium ore from the ground, conventional milling requires the ore to be prepared for leaching via a number of processes.

Ore Size Reduction

Crushing and grinding of the uranium ore is necessary to expose the majority of the uranium minerals to the leaching solution. The design of the crushing and grinding circuit and its output specifications is unique for each mill due to site specific variables and varying recovery targets. Historically, conventional crushing and rod mill-ball mill circuits were used. However, adoption of semi-autogenous grinding (SAG) or autogenous grinding (AG) is becoming popular when such techniques are a possible option.

Conventional comminution begins with a primary crusher, typically a jaw type, which aims to reduce ore particles to within a 150mm diameter size(4). Crushing continues with a cone crusher or a similar device which reduces the particles to a diameter of less than 20mm(4). These two primary steps in the crushing and grinding circuit are dry processes, with water used primarily to assist with control dust. To further reduce the size of the ore particles, ball and/or rod mills are used in the grinding stage of the circuit. At this stage water must be added to facilitate the movement of the smaller solids, continue to control dust, and to possibly initiate leaching. Classifiers, thickeners, cyclones and/or screens are used throughout the crushing/grinding circuit to size grinded ore, returning overly coarse materials to varying stages in the circuit.

Recently, semi-autogenous (SAG) or autogenous grinding (AG) has been favoured as a replacement for the conventional crushing/grinding circuit. These new techniques combine part or all of the crushing and grinding operations into one unit. Advantages of SAG and AG include energy and cost savings, along with an improved working environment due to the reduction in dust generation and radon release. Sticky, clay-like ores which tend to plug a crushing plant are also handled better by SAG/AG mills(2). The main issue with selecting a single stage circuit is the difficulties and risk associated with the process design of the unit. These difficulties are mostly associated with the determination of the inter-relationship between abrasion and impact breakage for the particular ore being milled(8). Single stage circuits are only an option when the Bond Index of the ore is not overly high. If a relatively fine grind is required, as is the case for alkali leaching, ball or pebble mills will be required following the SAG or AG unit. SAG combined with ball milling has been used by Queensland Mines Limited at Nabarlek, Australia. The same design has been incorporated at the Denison Mines Ltd. mill and the Rio Algom Stanleigh mill, both located in Elliot Lake, Canada.

Pre-Leach Beneficiation

In recent decades pre-leach beneficiation, the pre-concentration of uranium minerals by physically separating them from the gangue minerals following crushing, has been investigated but has not been readily included in milling processes. Pre-leach beneficiation has been proven to have economic potential when treating low grade ores. Pre-leach pre-concentration techniques employ differences in properties such as radioactivity, size, shape, density and surface characteristics to separate the desired mineral. A number of techniques have been considered, including radiometric sorting or the scrubbing and washing of the ore particles.

Energy Resources Australia (ERA), in 2008, commissioned a radiometric ore sorting plant at its Ranger mine in the North Territory, Australia. The sorting plant was anticipated to be able to upgrade 350,000 tones of low grade ore per year(3). Likewise, treatment of the El-Missikat mineralized granite in Egypt using gravitative and magnetic separation techniques has resulted in an increase of U concentration from 0.1950% to 1.0264%(9). This was possible due to the uniquely high radioactive fluorite-rich granite. Alternatively, the treatment of the Mutanga mineralisation in Zambia uses mainly scrubbing and washing techniques, resulting in a noticeably higher quality feed for proceeding process steps(7). In this case, the ore could be beneficiated due to uranium mineralisation occurring on the surface of sand particles.

Radiometric sorting is usually employed between crushing and milling as too small a particle size doesn’t work favourably in radiometric sorting.

Pre-leach beneficiation can only be useful for unique situations and thus its inclusion in uranium ore milling has been limited. Generally, low cost routes such as heap and in-situ leaching methods have been favoured over pre-leach beneficiation/pre-concentration due to their higher recovery to cost ratios(13). The use of pre-leach beneficiation is useful on low grade refractory ores when heap leaching can not be used such is the case with ARMZ’s Elkon uranium mine(18) where radiometric sorting is being considered.

Roasting

The third ore preparation step which was commonly used in the past is the roasting of ground ore, which can make the processing of the ore easier by altering its chemical composition. In cases where large amounts of organic carbon are present in the ore, roasting helps to remove the organic carbon which would otherwise cause problems in the purification processes. Roasting can also be used for the treatment of carnotite ores containing high vanadium concentrations. Other uses of roasting aim to eliminate sulfides oxidize uranium and dehydrate clays. Roasting is now rarely used as it has lost its economic advantages to the improvements that have been made to hydrometallurgical processing technologies. The environmental challenges with roasting negate its use in modern day uranium processing facilities.

LEACHING

The design of the leaching circuit for a uranium mill requires a good number of decisions to be made and is most crucial in bringing about the desired product specifications. The leaching method employed affects:

- The proportion of uranium solubilised from the ore;
- The quantities of reagents required;
- The concentration of solids and impurities in the leached solution (this will consequently affect the solid-liquid separation, solution extraction, and precipitation processes);
- The output specifications for the crushing and grinding circuit.

The uranium ore may be leached using either an acidic or alkaline solution. The different leaching systems, and the type of solution typically used with each, are:

- Agitation leaching at atmospheric pressure (acid or alkaline);
- Pressure leaching (acid or alkaline);
- Strong acid pugging and curing (acid);
- Heap leaching (acid and recently alkaline);
- In-situ leaching or in-situ recovery (mainly acid).

Oxidants

Whether acidic or alkaline leaching is employed the uranium must be in the hexavalent form, U6+, for it to be readily taken into solution. Most readily available uranium minerals, such as uraninate, contain uranium in the tetravalent form, U4+, and thus an oxidant must be present to convert the tetravalent uranium to its hexavalent form. In acidic lixiviants ferric ions are most commonly used to achieve this oxidation via the following process:

$$UO_2 + 2Fe^{3+} \rightarrow UO_2^{2+} + 2Fe^{2+}$$

The use of ferric ions to oxidize tetravalent uranium results in ferrous ions which must be oxidized to maintain the required ferric ion concentration. Typically a concentration of 1 to 2g/L is sufficient for the oxidation of uraninate(4). To maintain this ferric ion concentration an oxidant is required. Conventionally manganese dioxide (the mineral pyrolusite) is used:

$$2Fe^{2+} + MnO_2 + 4H^+ \rightarrow 2Fe^{3+} + Mn^{2+} + 2H_2O$$

During the oxidation of ferrous iron using pyrolusite high amounts of acid are consumed. The possibility exists to reduce this consumption by approximately 50% by using either chlorate or Caro's acid instead of manganese dioxide as the source oxidant(4):

$$2Fe^{2+} + \tfrac{1}{3}ClO^{3-} + 2H^+ \rightarrow 2Fe^{3+} + \tfrac{1}{3}C1^- + H_2O$$

$$2Fe^{2+} + H_2SO_5 + 2H^+ \rightarrow 2Fe^{3+} + H_2SO_4 + H_2O$$

Originally in Australian uranium plants pyrolusite was used almost exclusively. The mineral has become less popular due to its low oxidizing capacity per tonne, thus making it only viable when shipping distance between the source and mill is short.

An alternative to using the more conventional source oxidants (eg. manganese oxide) during acid leaching is to use bacteria, such as Thiobacillus ferrooxidans, to convert Fe^{2+} to Fe^{3+}. This option is usually only applicable for heap leaching.

In alkaline-carbonate mediums ferric ions cannot be maintained and therefore quite different operating conditions are required for alkaline leaching to be successful. Alkaline-carbonate leaching generally requires higher temperatures and pressure, longer leaching times and a finer ground ore.

These extreme conditions are required to drive the oxidation of tetravalent uranium using oxygen as the oxidant:

$$UO_2 + \frac{1}{2}O_2 \rightarrow UO_3$$

Acidic versus Alkaline Leaching

During the leaching stage of uranium ore milling, most designs make use of an acidic solution due to the wide availability and low cost of sulfuric acid (refer to Figure **2**). However, in situations where a high carbonate ore would consume excessive amounts of acid, an alkaline solution is favoured (refer to Figure 3).

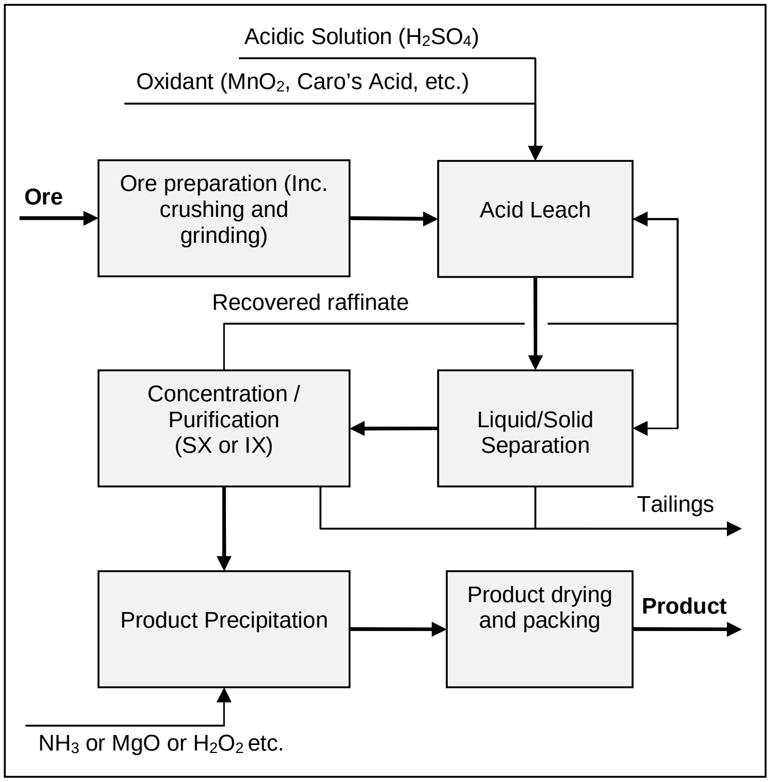


Figure 2: General acid-leach process

Alkaline leaching also has the advantage of being milder and more selective, thus reducing the dissolution of gangue minerals, lowering the impurities concentration in the pregnant leach solution. This, in turn, allows for the uranium product to be directly precipitated from the pregnant leach solution in some cases.

The disadvantage is that the ore must be ground very fine to expose all of the uranium minerals to the lixiviant since the gangue minerals are not readily broken apart. Alkaline leaching is also disadvantaged by the extreme requirements needed to bring about oxidation of tetravalent uranium to its hexavalent form.

While both acid and alkali leaching methods each have a number of advantages and disadvantages, the choice between the two is mainly based on the mineralogy of the uranium ore being milled. The behaviour of uranium ores during processing are generally described under two classifications:

Group 1: Uranium mineral taken into solution with sufficient ease, however treatment details still determined by both uranium and gangue minerals.

> Group 1.a Minerals with uranium in tetravalent state and hence requiring oxidant. These materials are readily dissolved in sulfuric acid at pH of 1.8 - 2.0, 40°C, for 12 hours4.

Group 1.b Minerals with uranium in the hexavalent state and thus not requiring an oxidant (Very uncommon).

Group 2: Uranium mineral requires severe conditions for dissolution so that mineralogy/chemistry of gangue usually determines if ore can be processed at all. The mineral cannot be dissolved using alkaline conditions.

For ores that fall into the latter classification, acid leaching is the only applicable option. This is because even when extremely fine ground ore is available, the uranium minerals cannot separate from the gangue minerals without the latter being also attacked and taken into solution. Those ores which fall into the first group can be treated by either acidic or alkaline solutions. Acid leaching is generally favoured because of the milder operating conditions, even though gangue minerals will be dissolved into the pregnant leach solution and will thus require removal at a later stage. Alkaline leaching is thus only reserved for group 1 type ores with very high carbonate levels, generally above 7-9%(2.

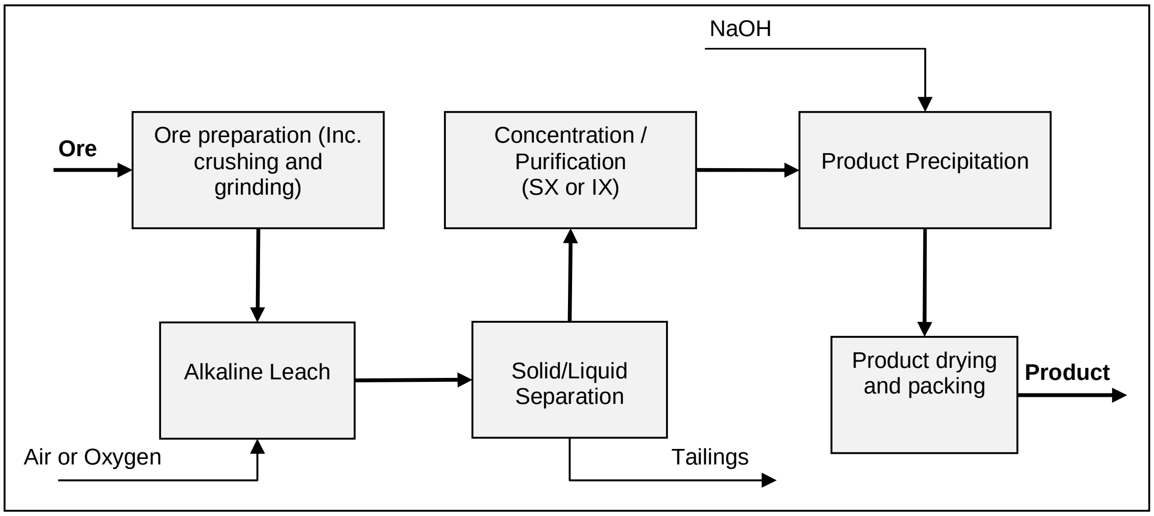


Figure 3: General alkaline-leach process

Chemistry of Acid and Alkaline Leaching

Nearly all acid leaching plants make use of sulfuric acid due to its low cost and high availability. Other applicable acids, such as hydrochloric and nitric, are more costly and are of greater risk to the environment(2) Leaching using sulfuric acid results in the dissolution of hexavalent uranium via the following steps(4).

$$UO_2^{2+} + SO_4^{2-} \rightarrow UO_2SO_4$$

$$UO_2SO_4 + SO_4^{2-} \rightarrow [UO_2(SO_4)_2]^{2-}$$

$$[UO_2(SO_4)_2]^{2-} + SO_4^{2-} \rightarrow [UO_2(SO_4)_3]^{4-}$$

It is important to ensure there is enough free acid concentration to attack uranium minerals without dissolving a large quantity of the gangue. Furthermore, at the completion of leaching, sufficient free acid is required to stop precipitation of uranium from the pregnant leach solution in the washing circuit.

Alkaline leaching typically makes use of a carbonate-sodium bicarbonate solution. The first step in the process following oxidation is given by(2).

$$UO_3 + 3Na_2CO_3 + H_2O \rightarrow Na_4UO_2(CO_3)_3 + 2NaOH$$

Bicarbonate is required to neutralize the resulting hydroxyl ions as a large rise in pH would precipitate leached uranium as sodium diuranate. Thus the final equation for alkaline systems is(4):

$$UO_2 + \tfrac{1}{2}O_2 + Na_2CO_3 + 2\,NaHCO_3 \rightarrow Na_4UO_2(CO_3)_3 + H_2O$$

Leaching Systems

A number of leaching systems are available for uranium ore milling. Most systems can make use of either acidic or alkaline solutions; however, some systems are typically only ever viable in conjunction with one solution type. The choice of which system to implement is based on a number of variables including ore grade, mineralogy of the ore, throughput, and the uranium recovery target.

Agitated Atmospheric Leaching

Agitated atmospheric and pressure leaching, along with strong acid pugging, are the best methods for high grade ores. The choice between the three is heavily based on the mineralogy of the uranium, with agitated atmospheric leaching most popular. Agitated leaching at atmospheric pressure is employed for ores that fall into the first classification (described in the section Acidic vs Alkaline Leaching), whereby an acidic solution is used to dissolve uranium minerals into solution.

Typically a number of tanks in series are utilized and agitation may be provided mechanically or via air-injection in Pachuca tanks. The choice of agitation depends largely on ore density, particle size, size distribution and particle abrasiveness. Pachuca's are typically favoured for fine or abrasive slurries which would otherwise damage the components of a mechanical agitator.

The vast majority of uranium mines worldwide make use of agitated atmospheric leaching. Two of Australia's three uranium mines, and all mines in the Saskatchewan Lakes area of Canada, employ agitated atmospheric, acid leaching. Together these two countries accounted for 41% of worldwide production in 2009(12). Air-agitated Pachuca's were utilized in South Africa and the USA from the 1950's until the late 1970's, and is presently still used in the Ukraine and Czech Republic(5).

Pressure Leaching

Agitated pressure leaching is applied to high carbonate ores requiring alkaline leaching, complex refractory ores, or ores which are high in sulfides. Alkaline leaching is conducted in agitated pressure leaching systems as high pressures are necessary to bring about the oxidation of tetravalent uranium using oxygen. Ores high in sulfides also benefit from this system, as the sulfides can be converted to sulfuric acid and ferrous sulfate at elevated temperature and pressure(4).

The ferrous sulfate can then be oxidized to ferric sulfate, thus providing the ideal oxidant for tetravalent uranium, while the sulfuric acid can act as the leaching solution. The higher capital cost required for pressure leaching is offset to some degree by the lower operating costs, which are reduced as no addition of reagents is required.

On at least one project(18), which requires the application of pressure leaching due to refractory Brannerites, Pachuca's are being considered at elevated pressures and temperatures. Limiting the diameter to ensure adequate mixing is an important consideration. Oxygen utilisation is expected to be lower in Pachuca's than in mechanically agitated autoclaves, which ultimately impacts on the operating costs due to higher compressor power consumption and higher vent gas handling rates. With mechanical agitation, one can consider enriched air, or oxygen which may speed up kinetics as oxygen mass transfer is normally the rate limiting step and therefore reduces leach circuit volume requirements. As a consequence a large number of Pachuca's would be required to achieve the same recovery when compared to horizontal autoclaves.

Pressure alkaline leaching is no longer a popular method. The Feldioara uranium mine located in Brasov, Romania operated by the Romanian National Company is to the authors' knowledge the only remaining mine to utilize pressure alkaline leaching.

Strong Acid Pugging

Strong acid pugging and curing entails impregnating coarsely ground dry ores with small volumes of concentrated sulfuric acid and curing at 65°C to 100°C for 12 to 24 hours(4). Following this period, the solubilised uranium is washed from the ore. While conditions are more severe than dilute acid leaching, advantages of strong acid pugging are that no fine grinding is required thus simplifying liquid-solid separation and that the hot concentrated acid can be a sufficient oxidizing reagent.

Heap Leaching

Low grade ores are typically treated via heap, vat, or in-situ leaching. The choice between the three methods depends on the amount and location of the low grade ore. For these methods to be effective the ores must have mineralogical characteristics and textual features that permit the access of reagents to the uranium mineral over a sufficiently long period of time. Heap leaching is an especially attractive option for low grade ores due to the modest capital and operating costs in comparison to conventional leaching routes. The method involves the arrangement of the ground ore in large piles above a collection system. Leach solution is distributed over the upper surface and passes downwards through the pile. The complete leaching of a pile typically takes several weeks.

Heap leaching is disadvantaged by poor recovery and relatively small cost savings compared to in-situ leaching. Water balance issues in both dry and wet conditions are also critical to the operation, where large quantities of water must be either imported or treated and disposed of respectively. It therefore occurs that heap leaching is most ideal for low grade ore which has been stockpiled during normal mining operation of higher grade ore.

Presently, ERA is concluding a feasibility study into the possibility of expanding its operation at the Ranger mine in the Northern Territory by employing a heap leach facility to treat low grade ore which has been stockpiled over the life of the existing operations3.

Heap leaching is widely used in China, where five of the eight main production facilities currently in operation (the Lantian, Chongyi, Qinglong, Shaoguan and Benxi centres) all employ heap leaching to treat mined ore(12).

In-Situ Leaching

In recent years in-situ leaching has been reclassified as a mining, rather than leaching, technique, and is often now referred to as in-situ recovery (ISR). ISR differs greatly from all other mining techniques and corresponding processing steps as the leaching solution is pumped directly into the ground. The solution extracts the uranium minerals from the surrounding gangue minerals before being pumped to the surface for processing. ISR is limited to confined sandstone formations (high permeability) containing small deposits which are of low grade and are located at shallow depths. Since ISR does not require expensive crushing and leaching circuit equipment, it can be of economical advantage in certain situations. The main disadvantages include low recovery and environmental concerns regarding the contamination of ground waters.

In recent decades ISR has become increasingly popular, with ISR production exceeding that of open-pit mines in 2006 and is expected to be the future dominant uranium production method(12). Australia's most recently commissioned uranium mine, Beverly in South Australia, employs acid in-situ leaching. Future projects currently in the design or construction phase, including Honeymoon and Four Mile both in South Australia, will also make use of ISR. ISR is also extremely popular in Kazakhstan where 15 of the 16 existing operations employ the method(12). This method is popular in the region due to the widespread sandstone type deposits and has resulted in Kazakhstan becoming the world's number one producer of uranium oxide due to quick employment of ISR plants. ISR is also cost competitive due to the elimination of the need to mine provided the geology of the deposit is suitable to ISR technology.

SOLID-LIQUID SEPERATION

The solid-liquid separation component of a uranium ore milling plant is extremely crucial as incomplete washing of solids resulting in loss of solubilised uranium can dramatically reduce operating profits. In addition to these soluble losses, process water circuits and tailings storage facilities require careful management since they contain appreciable levels of uranium which pose an environmental risk. Factors that affect the design of the solid-liquid separation circuit include;

- Ore characteristics
    - Impurities in the ore impact on the solution chemistry and may result in precipitation or formation of complex ions
- Particle size distribution:
    - Finer particles result in slow settling and filtration rates.

- Solid concentration:
  - Equipment size and cost decreases with increasing feed slurry concentration.
- Particle shape and surface characteristics:
  - Optimal particle is spherical with zero porosity. Operational costs increase as particles characteristics move away from these optimal conditions.
  - Surface chemistry will influence flocculant type and dosage.
- Liquid viscosity:
  - An increase in viscosity will cause a decrease in settling and filtration rates.
  - In severe climates, maintenance of a steady temperature is necessary to maintain relatively constant viscosity values.

Both conventional and high rate thickening are widely used in the industry. A major advantage of high rate thickeners is that their unit area can be as little as 10-25% the size of that required by conventional thickeners(2).

Filtration is particularly preferred for higher grade ores where the mass ratio of leach residue solids to recovered uranium is lower(2). The benefits of filters over thickeners include that they take up less space, have lower soluble losses, have better wash efficiencies, and they result in higher water recovery; however, generally filters have higher capital and operating costs.

Solid-liquid separation is utilized in multiple parts of a uranium processing plant. Thickening or filtration is often employed before acidic leaching, where maintaining acidity is important. By maintaining high slurry densities, a lower acid consumption can be achieved and smaller leaching equipment can be used. Separation is also used following leaching for two primary reasons. The first is to allow for reagent conservation and to help improve recoveries. The second and most important reason is to remove barren solids from the pregnant leach solution in preparation for solution purification and product precipitation. It is highly important that all soluble uranium is washed from the removed solids before they are disposed of. In conventional ion exchange (IX) systems, clear solution is required for smooth and efficient operation since excessive particulate matter can cause column plugging.

Solvent extraction (SX) also requires a clear solution so as to prevent high losses of the organic phase since organic materials will absorb onto particulate matter, forming a crud. To meet the requirements of these technologies, a polishing and clarification step is typically installed before SX/IX with the objective of reducing the total suspended solids (TSS) concentrations of the solution leaving the clarification circuit down to a typical target TSS of 10ppm(4), however operating TSS concentrations of greater than 50ppm is typical.

Resin-in-pulp (RIP) technology allows the uranium to be extracted directly from the pulp. The pulp, depleted of uranium is dewatered prior to depositing the uranium free residue to the tailings dam.

SOLUTION CONCENTRATION AND PURIFICATION

SX and IX are the two most widely used methods to concentrate and purify the uranium leach solution. Selection from these methods is determined by the:

- Concentration of uranium in the PLS.
- Amount and concentration of impurities.
- Desired final purity of the uranium product.

For conventional acid leaching, solvent extraction or ion exchange, or a combination of the two, can be considered. In comparison, alkaline leach solutions are typically treated via ion exchange. In some rare cases, alkaline leach solutions may be treated by direct precipitation due to the selective nature of the leach solution which results in very little solubilisation of the gangue minerals.

The design of the concentration-purification process is unique for each uranium processing plant due to varying PLS compositions. For example, low grade, complex ores which introduce impurities such as nickel, cobalt and arsenic to the pregnant leach solution, are typically treated solely by solvent extraction. Solvent extraction and ion exchange are similar in nature. Both consist of two main stages as shown in Figure 4.

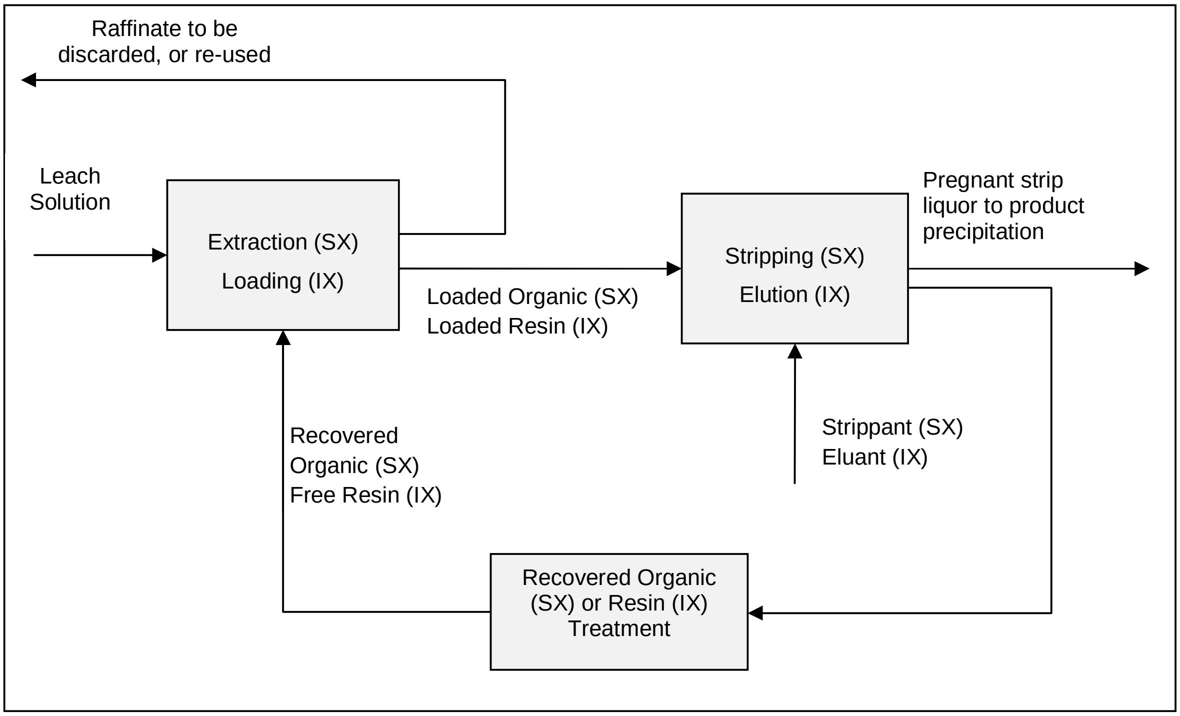


Figure 4: Simplified diagram showing stages of SX and IX systems.

Inter-stages for both IX and SX are required for either scrubbing impurities or regeneration of the reagent, depending on specific impurities and the reagent used.

Solvent Extraction

While extensive research has been done to improve both SX and IX systems, SX remains the most popular option. This is because SX remains the most economical choice for the treatment of moderate to high uranium concentration solutions. Ion exchange is only suited to relatively low concentration solutions, typically of less than 1g/L, such as the leach solutions obtained from in-situ recovery.

The extractant used in solvent extraction is typically long chain aliphatic primary, secondary or tertiary amines (R3N – where R represents an aliphatic organic radical). The tertiary amines have the added advantage of being selective for uranium in the presence of impurities such as iron, thorium, phosphate and rare earth metals(6). For the extraction of uranium, the amine must be converted to an appropriate salt. This is typically achieved using sulfuric acid(2):

$$2R_3N + H_2SO_4 \rightarrow 2(R_3NH)_2SO_2$$

The converted aliphatic amine is carried as a solution within an organic phase, known as the diluent, which is immiscible with both the aqueous leach solution and the strippant. The usual diluent in uranium SX is kerosene high in aliphatics, low in aromatics. To increase the solubility of the amine in the kerosene, an organic material called a modifier is often added. The general modifier used is a long-chain aliphatic alcohol.

In acid leach solutions the uranyl ions form stable complexes (uncharged or anions) with the sulfate ion, most commonly $[UO_2(SO_4)_3]^{4-}$. The extraction of the uranium from acid leach solutions using a tertiary amine is represented by the following process equation(2):

$$2(R_3NH)_2SO_2 + [UO_2(SO_4)_3]^{4-} \rightarrow (R_3NH)_4UO_2(SO_4)_3 + 2SO_4^{2-}$$

Following extraction, conventional stripping is achieved with ammonium sulfate as illustrated in the following equation(2):

$$(R_3NH)_4UO_2(SO_4)_3 + 2(NH_4)_2SO_4 \rightarrow (NH_4)_4UO_2(SO_4)_3 + 4R_3N + (NH_4)_4UO_2(SO_4)_3 + 2H_2SO_4$$

Equipment selection for solvent extraction is generally limited to multistage mixer-setters with counter-current aqueous and organic flows. Pulsed columns have been in use at Olympic Dam in Australia for a number of years while both Dominion and Honeymoon mines will operate pulsed columns when in operation.

SX is employed at two of the three operational Australian uranium mines, and is incorporated into all processing facilities in the Saskatchewan Lakes area of Canada. In particular, the Key Lake and McClean Lake mills use ammonium sulfate SX stripping (followed by ammonia precipitation), while the Rabbit Lake mill employs strong sulfuric acid stripping (followed by hydrogen-peroxide precipitation).

Ion Exchange

Ion exchange systems are only economical in situations where the leach solution is low in uranium concentration and thus more extreme measures are required to strip the uranium from the solution. The ion exchanger used in IX is typically beads of organic resins which are chemically treated to provide active IX sites. The resins are designed to ideally absorb the uranium complexes selectively from the leach solution containing many other anionic complexes. They must be able to do this rapidly and also reversibly so that the uranium can be recovered by elution. Loading capacities and kinetics of the resin are important as these variables determine the volume of resin necessary to give a certain amount of product. Typically, strong base anion exchange resins such as Amberjet 4400 are used. Following loading of the resins, rapid elution is achieved via the use of acidified solutions (i.e., nitric or sulfuric acid). First generation ion exchange systems operated as fixed bed systems, while more recent developments has seen the adoption of continuous ion exchange (CIX) systems utilizing fluidized beds.

During the 1970's, the National Institute for Metallurgy (NIM) developed the NIMCIX technology which enabled the recovery of uranium from unclarified solutions. The Vaal Rover South plant commissioned in 1978 is still in operation. Two new plants, Ezulweni and Trekkopje have been recently commissioned (or in the process of being commissioned). A number of proposed uranium projects in Africa are considering NIMCIX technology for the recovery of uranium from low grade ores(17).

IX is typically always used in conjugation with ISR. Four Mile in South Australia, which plans to make use of ISR will employ IX to extract uranium from the extracted solutions. Furthermore, all existing ISR operations in Kazakhstan employ IX. With the popularity of ISR increasing, it is likely that a similar trend will be seen in the use of IX for the extraction of uranium from solution.

PRODUCT PRECIPITATION AND DRYING

The final stage in most uranium mining and processing facilities is that of product precipitation and drying. This stage often causes the most issues, as precise conditions for precipitation are highly site specific and have to be optimized experimentally in each case. In some cases, direct precipitation from the leach solution can be considered, doing away with the use of either solvent extraction or ion exchange. However, most often SX or IX is required to purify and concentrate the metal bearing solution before precipitation.

Following concentration and purification, considerable impurity levels may still need to be addressed. Additives such as lime or magnesia are used to form a gypsum cake or iron cake precipitate. At the Ltee Cluff Lake Phase I mill, impurities such as aluminium, iron, molybdenum and vanadium are controlled via iron-cake precipitation(2). Likewise, iron-cake precipitation using lime and ammonia reduce impurities at both the Denison Mined Ltd. mill and the Rio Algom Quirke mill, both at Elliot Lake(2).

The uranium, yellowcake product can be precipitated using a large number of precipitates. The type of reagent chosen is influenced by factors such as:

- The purity of the feed solution to the precipitation;
- The preceding process chemistry;
- The product specifications demanded (quality, etc);

- The relative reagent and associated capital/operating costs;
- The possible environmental impact of the reagent.

Hydrogen peroxide, caustic soda, magnesia, ammonia and ammonium hydroxide are commonly used to precipitate uranium from acidic stripping solutions. The use of the non-hydroxide products results in a diuranate precipitate. Hydroxide reagents are especially useful in situations where other metals may undesirably co-precipitate. The use of hydroxide reagents results in uranium peroxide products. The use of gaseous ammonia, or ammonium hydroxide, has been most common. The reaction of this precipitation is(4):

$$2UO_2(SO_4)_3 + 6NH_4OH \rightarrow (NH_4)_2U_2O_7 + 2(NH_4)_2SO_4 + 3H_2O$$

Alternatively, sodium hydroxide is the most commonly utilized reagent for the precipitation of uranium from alkaline solutions:

$$2Na_4UO_2(CO_3)_3 + 6NaOH \rightarrow Na_2U_2O_7 + 6Na_2CO_3 + 3H_2O$$

Hydrogen peroxide is commonly used to produce an oxide product when low levels of iron are present:

$$UO_2(SO_4)+H_2O_2+2H_2O \rightarrow UO_4.2H_2O+H_2SO_4$$

Following precipitation, several stages are used to wash trapped soluble impurities from the uranium precipitate using a combination of thickeners, centrifuges, and/or filters. Drying of the product is performed with calciners or other drying equipment, resulting in a grey, U_3O_8 product. While calciners have been popular in the past, their high fuel costs have driven a shift towards alternative drying approaches. For instance, where possible, a more attractive method is to use indirectly-heated equipment such as steam or oil-heated dryers and/or rollers.

CURRENT AND PROSPECTIVE AUSTRALIAN URANIUM MINES

Currently there are three fully operational uranium mines in Australia; Olympic Dam in South Australia, Ranger in the Northern Territory and Beverley in South Australia.

Olympic Dam in South Australia is the largest known uranium ore body in the world with copper, gold and silver also extracted from the large underground mine. In recent years annual production capacity for uranium oxide at the site has been expanded from 1800 to 4600 tonnes(15). Plans are underway to increase production at the site by developing an open pit mine. A total uranium output of 16,100 t/y is predicted(15). Processing facilities at Olympic Dam make use of acid leaching and solvent extraction to extract the uranium from the copper concentrator tails. Uranium SX follows copper SX where kerosene with an amine as the solvent is used in the first stage of SX. The solvent is stripped using an ammonium sulfate solution and injected ammonia gas. Yellow ammonium diuranate is precipitated from the loaded strip solution by raising the pH.

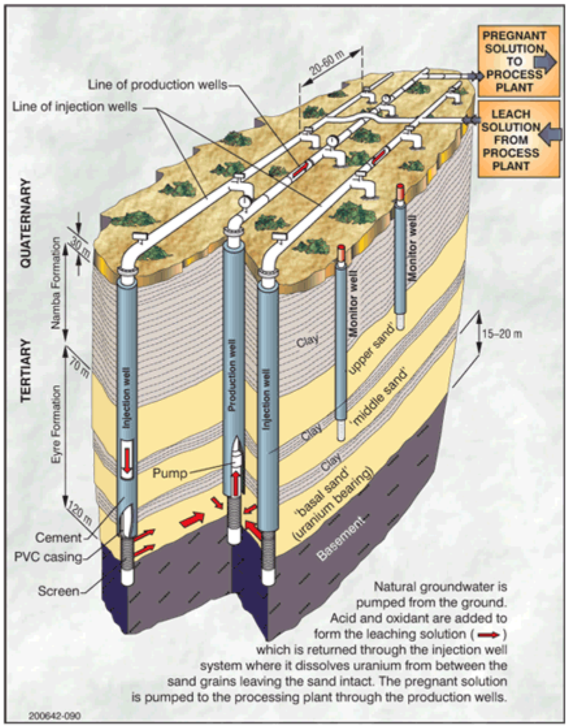
ERA Ranger in the Northern Territory is Australia's second largest uranium mine with an average output of above 4000t/y U_3O_8 for the past decade(15). Leaching and solvent extraction methods are similar in nature to those employed at the Olympic Dam mine. With ore grade dropping, feasibility studies are underway to investigate the expansion of the processing facilities to treat low grade ore which has been stockpiled during normal mining operations via a heap leach process. The heap leach facility is expected to treat 10 million tonnes of low grade mineralised material per year, contained in stockpiles and the operating Ranger pit, to produce a total of between 15 to 20,000 tonnes of uranium oxide(16).

Beverley in South Australia is the nation's first in-situ leaching facility. Operations began in 2000 with at an output of ~550t/y of U_3O_8, half the value the site is licensed to produce(15). Beverley is also the first mill in Australia to make use of a resin ion exchange system to extract uranium from the leach solution.

While only three mines are currently operating in Australia, a number of future mines are planned or are already in the construction phase.

Honeymoon, SA

Honeymoon in South Australia, a joint venture between Canada's Uranium One (51%) and Japan's Mitsui (49%), will be Australia's fourth uranium mine and the second to make use of in-situ leaching. The orebody has an indicated resource base of 6.5 million pounds of U_3O_8 with an average grade of 0.24%14). In 2011 the mine aims to produce 400,000 pounds (~180t) of uranium oxide equivalent, eventually ramping up to 880,000 pounds (~400t) per year(15). Since the deposit is generally of the "sediment hosted" or "sandstone uranium" type, in-situ leaching is considered the most suitable mining technique. The mine will make use of a "7-spot" pattern technique whereby six injection wells are arranged to form a 20-60m hexagon, with a centrally located production well(10). To achieve the specified output, 30 production wells need to be in operation at any one time. A solvent extraction circuit will be used to recover uranium from the leach solution as indicated in Figure 5 and Figure 6. Commissioning activities commenced during Q2 2010, and production during commissioning is expected to commence in 2011(14).



Natural groundwater is pumped from the ground. Acid and oxidant are added to form the leaching solution (→) which is returned through the injection well system where it dissolves uranium from between the sand grains leaving the sand intact. The pregnant solution is pumped to the processing plant through the production wells.

Schematic ISL wellfield, Honeymoon deposit.
(courtesy Southern Cross Resources)

Figure 5: Simplified diagram of prospective operations at Honeymoon, SA.

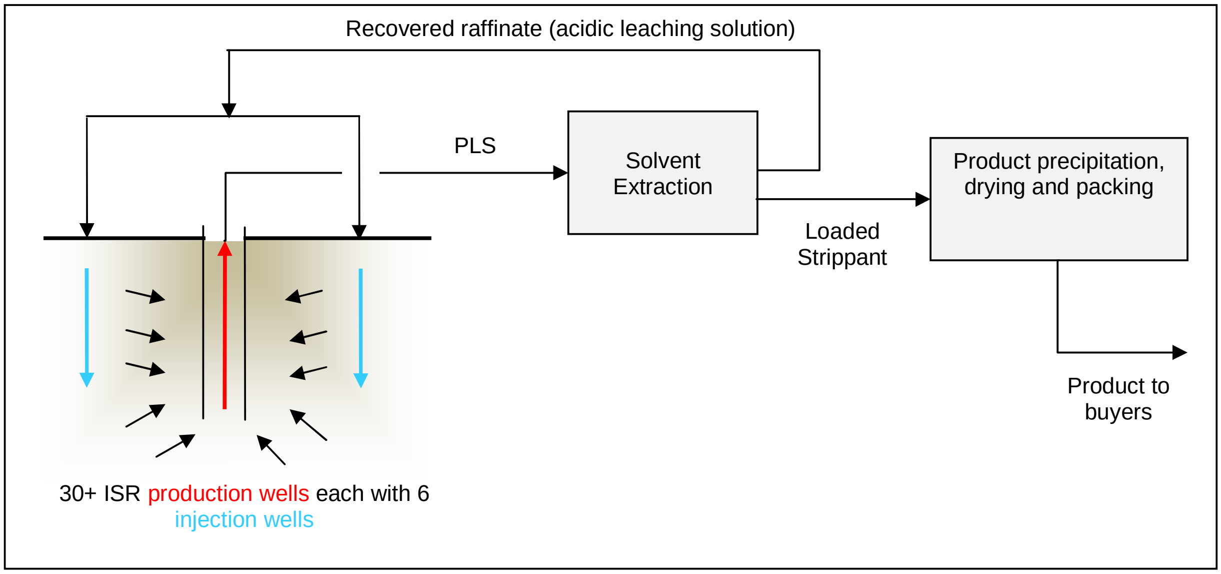


Figure 6: Simplified diagram of prospective operations at Honeymoon, SA.

Four Mile, SA

Four Mile in South Australia, a joint venture between Quasar Resource and Alliance Resource Ltd, was to commence first stage in-situ leaching in 2010 with an initial output of 680t/y of U_3O_8(15). A final production rate of 2000 t/y by the end of stage 3 of construction is planned. Latest mineral resource estimates suggest a total indicated and inferred resource base of 9.8 million tonnes at 0.33% uranium oxide(16). The mine is designed to utilize ion exchange to extract uranium from the PLS. Loaded resin will be transported to the existing Beverly plant for stripping shown in figure 7. The commencement of the mine has been delayed by the Native Title Mining agreement and due to a legal feud between the partners. As of September 2010, a mining lease was yet to be issued and work on the project continued on a scaled down basis only(1).

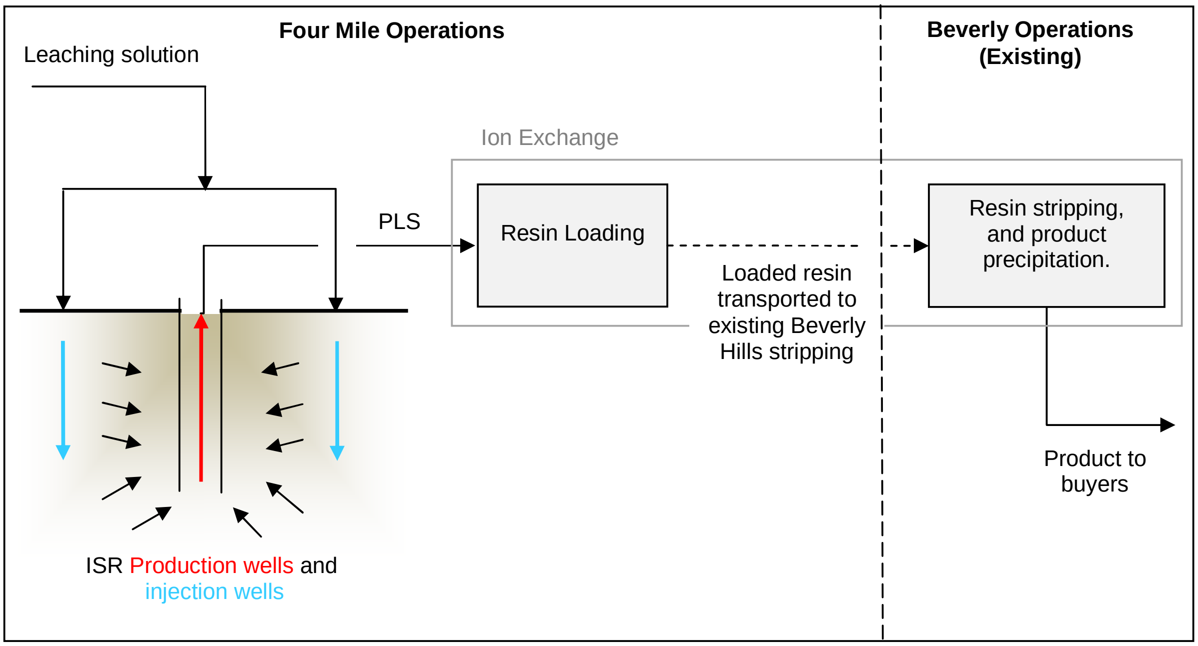


Figure 7: Simplified diagram of prospective operations at Four Mile, SA.

Kintyre, WA

Kintyre in West Australia is presently continuing its drilling program to confirm previous resource estimates of 80 million pounds (~36 000 tons) of uranium oxide. The lease owners, Cameco (70%) and Mitsubishi (30%), envisage starting mine construction in 2013 and operating in 2015, with an output of 2700 to 3600 t U_3O_8 per year for 15 years(15). The vein-type nature of the orebody will make it possible to use radiometric ore sorting so that the mill feed is effectively very high grade. In 2011, Cameco expects to reduce evaluation activities as they near the completion of the pre-feasibility stage.

Jabiluka, NT

Jabiluka in the Northern Territory, located 20km north of the existing Ranger uranium mine, is one of the world's largest high-grade deposits. Energy Resources Australia estimates the resource to contain 11.8 million tones of ore at a grade of 0.50%, containing reserves of 73,940 tonnes of U_3O_8(15). Development of the underground mine did commence, however mining is yet to proceed. The project is on hold while agreements with the local Mirrar Aboriginal people are discussed. The planned use of the existing Ranger processing facilities means mining at Jabiluka cannot continue until production at Ranger mine decreases.

In December 2010, Heathgate Resources received government approval to mine the Beverley North deposits, which will maintain production through the Beverly Plant in South Australia.

CONCLUSION

While the general process design of conventional uranium milling has remained unchanged in recent decades, changes to equipment design, reagent use and most significantly, our understanding of the process chemistry, has led to overall improvements in product throughput and quality.

Given the large variety of hydrometallurgical process routes available for the recovery of uranium, an increased understanding of the process chemistry has paved the way for more efficient and effective decision making during process design. In recent years, improvements to the less conventional methods such as heap and in-situ leaching have led to a quick rise in their use.

In-situ leaching or recovery (ISR) has become extremely popular due to the reduced capital and operating costs associated with the method. Implementation of ISR technology is rapid and site remediation efforts are low once the resource is exhausted. New technologies such as NIMCIX are being "re-discovered" as the market demand for uranium increases creating opportunities for owners of smaller uranium resources to enter the market.

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