Trends, Developments and Opportunities in the Extraction and Recovery of Uranium

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Introduction

Uranium process development work has continued despite the general industry slowdown; drivers include:

- trend towards lower grade and difficult ores
- reliance on saline process water in some locations, such as Australia and Namibia
- capital and operating cost pressures
- tightening environmental regulations.

Paper reviews some recent process developments and highlights opportunities for future innovations.

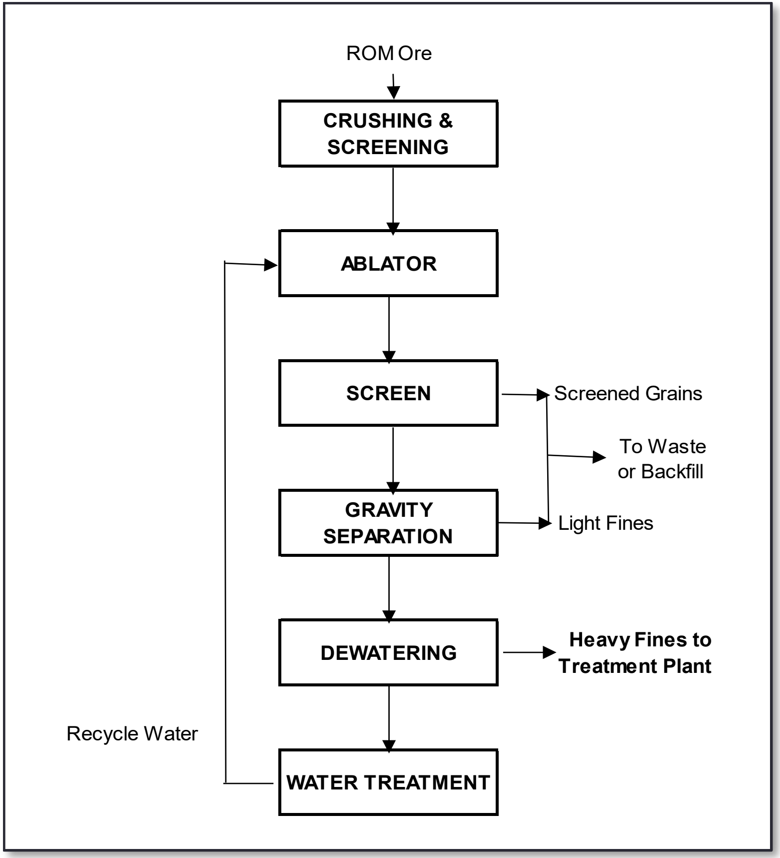
Ore Preconcentration – Ablation Process

- Invented by Ablation Technologies, Casper, Wyoming, USA, initially for gold, then patented for uranium in 2012.
- Mineral Ablation, a joint venture with Black Range Minerals, Australia, was formed in 2012 to market the technology. Black Range was then taken over by Western Uranium, Toronto, Canada, in 2015.
- Western Uranium successfully tested a 5 t/h pilot plant on stockpiled ore at their Sunday Mine Complex in Colorado, and have constructed a 20 t/h facility with a view to moving into commercial operation.

Ablation Process

- Mechanical process using kinetic energy and water to force ore grains against each other through opposing nozzles.
- Removes uranium in coatings and interstitial deposits.
- The fines commonly contain a high percentage of the uranium, and can be separated by screening into a high-grade, low-volume, concentrate.
- Concentrate may be further upgraded by removal of light barren fines by gravity processing.
- Extensive testwork shows typically more than 90% of the uranium can be recovered into about 10% of initial mass.

Ablation Process Flow Diagram



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U-pgradeTM Process

- The process was developed by Marenica Energy, Australia (patent pending), initially for the Marenica Project in Namibia. Has been subsequently tested for a number of other projects.
- It is a physical beneficiation process for upgrading low-grade surficial uranium deposits typically containing carbonates, clay minerals, and often sulphates.
- It involves the sequential removal of gangue minerals by commonly used unit operations to achieve a comparatively high-grade conc. without using chemicals.

U-pgradeTM Process

- The rejection of carbonate minerals produces a leach feed suitable for acid leaching, and generally simpler and cheaper than alkali leaching.
- The reduction in mass typically lowers opex by 50-70% and capex by 30-50% compared with conventional processing of deposits of this type.
- The low mass also provides the flexibility to process the concentrate on site or transport to a third-party operation, which reduces project development costs and the size of deposits that are financially viable.

U-pgradeTM Process

- The initial step typically comprises wet scrubbing and screening to separate into fine and coarse fractions.
- The undersize fraction contains most of the uranium as an intermediate concentrate that may be further processed in a secondary beneficiation stage to produce a high-grade uranium concentrate.
- Possible methods for secondary beneficiation include desliming, gravity separation, flotation, reflux classification and magnetic separation.
- Testwork indicates concentration to less than 3% of the mass and upgrading by more than 30 times without the use of leaching chemicals, producing an inert waste.

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Up-Current Classification

- Vimy Resources Limited are developing the Mulga Rock Project in Western Australia to treat ore with the uranium mainly as uraninite associated with uranium-bearing lignite, lignitic clay/shales and carbonaceous shales. Up to 65% of the ore is coarse silica-rich sand.
- In the proposed flowsheet, the beneficiation section consists of a mineral sizer and log washer for ore slurrying and attritioning, then slimes removal using hydrocyclones.
- This is followed by upgrading of the resulting middlings fraction by rejection of about 50-60% of the mass, consisting of barren quartz sands.

Up-Current Classification

- Upgrading uses two stages of upward current classification (UCC) to produce an upgraded concentrate and a low-grade reject, typically containing 60 ppm U_3O_8.
- The overall ore upgrading ratio for the combined slimes and concentrate is reported to be 2 to 2.5, with about 4% loss of uranium to the final tails.
- A successful pilot scale test programme was carried out in 2016 as part of a definitive feasibility study targeted at a commercial production of 1350 tpa.

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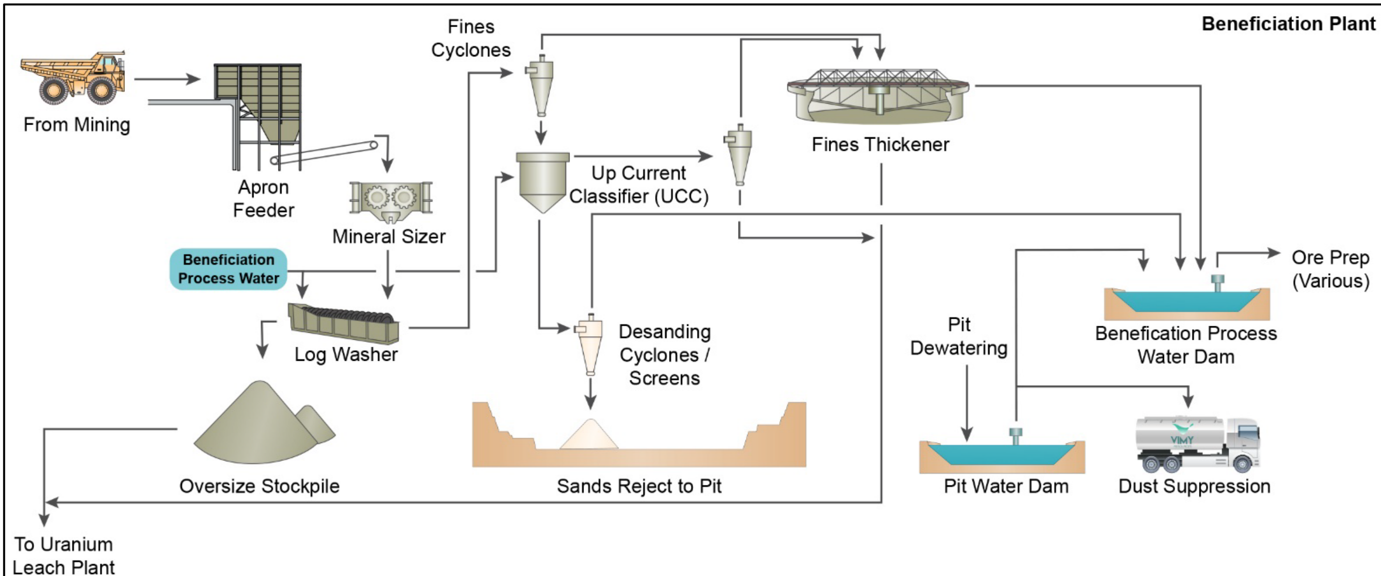
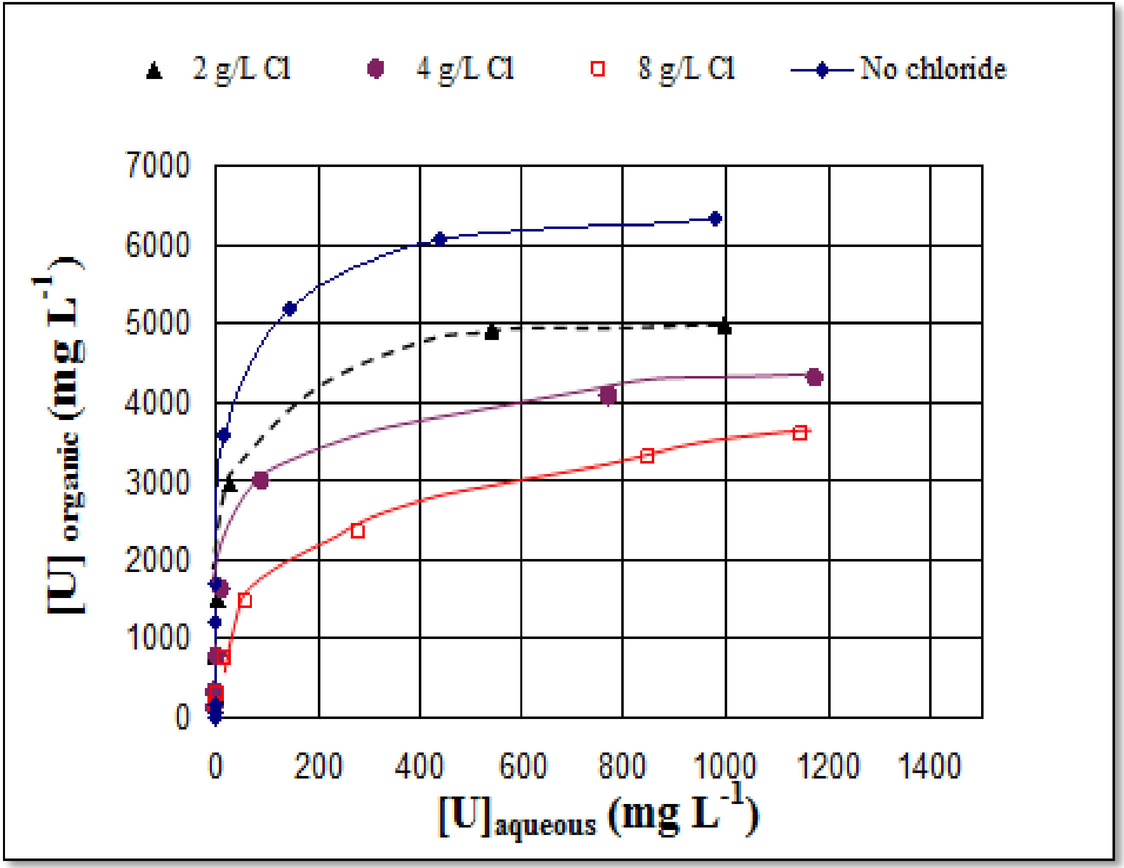
Mulga Rock Beneficiation Flowsheet



SX and IX for High Chloride – Honeymoon ISL

- Commissioned in South Australia in 2011 with 8–9 g/L chloride in PLS due to ground water, and operated by Uranium One till suspended 2014.
- A novel D2EHPA/tertiary amine synergistic SX was adopted as the standard tertiary amine system was unsuitable due to preferential loading of chloride.
- A drawback of the novel system is loading of ferric iron, which needs acid scrubbing, and then sodium carbonate strip, due to the D2EHP (however Honeymoon leach solution has relatively low iron level of 0.5 g/L).
- New SX systems have been proposed and tested by a number of organizations, including CSIRO, ANSTO and BHPB Olympic Dam.

Effect of Chloride on Amine Loading



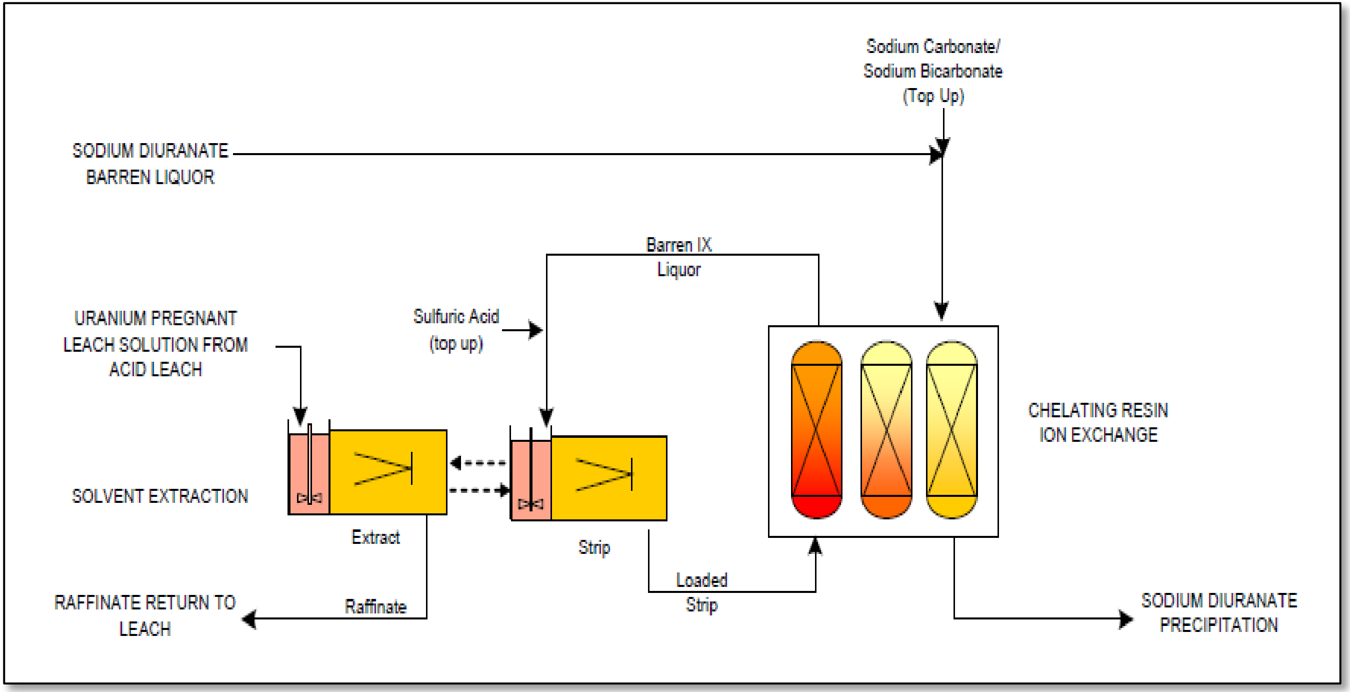
Honeymoon ISL

- New Owners, Boss Resources initiated testwork at ANSTO on various IX mediums including weak-base anionic, strong-base anionic, and chelating-type resins.
- The resulting preferred resin (unidentified) has a higher loading capacity than the others.
- The high selectivity for uranium over iron and other base metals allows direct precipitation from eluate without further impurity removal stages.
- The prefeasibility strategy is to restart the existing SX system, then expand capacity using IX in parallel. The IX system will process the majority of the leach solution and produce a high-tenor eluate.

IX for Strong Acid Strip and Eluate Solutions

- A-CAP Resources, Australia, have developed a novel IX process using a chelating IX resin to extract uranium from strong (4M) acid SX strip solution for the Letlhakane Heap Leaching Project in Botswana.
- The loaded chelating resin is stripped with sodium carbonate/bicarbonate solution. Sodium hydroxide is added to precipitate sodium diuranate, which is separated and redissolved in sulphuric acid. Uranium oxide is then precipitated and dried.
- The process was successfully tested on a semi-continuous mini-plant scale.

Strong Acid SX Strip Solution/IX Arrangement



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IX for Strong Acid Strip and Eluate Solutions

- The IX step allows the acid in the strip solution to be recycled and re-used, and eliminates the need for partial neutralization with lime.
- Testwork indicates approx. 60% reduction in opex of SX through to product recovery, and an increase in uranium recovery due to eliminating the uranium loss associated with partial precipitation.
- A-CAP are planning a pilot scale testwork campaign as part of a definitive feasibility study. They hold a patent for the process, which can also be applied to strong acid eluate solutions.

Nanofiltration - BMS Eng./Paladin Energy

- Paladin Energy commissioned a patented nanofiltration system in 2013 at Kayelekera, Malawi, to recover and recycle acid from 1M IX eluate.
- The facility was designed by BMS Engineers, Australia, and is believed to be the first commercial operation of its type.
- In addition to saving 40 t/day acid, it reduces the chemical requirements of downstream neutralizing.
- A second facility was commissioned at Langer Heinrich, Namibia, 2015, to recover sodium bicarbonate from IX eluate.
- BMS have exclusive rights for the technology in the uranium industry.

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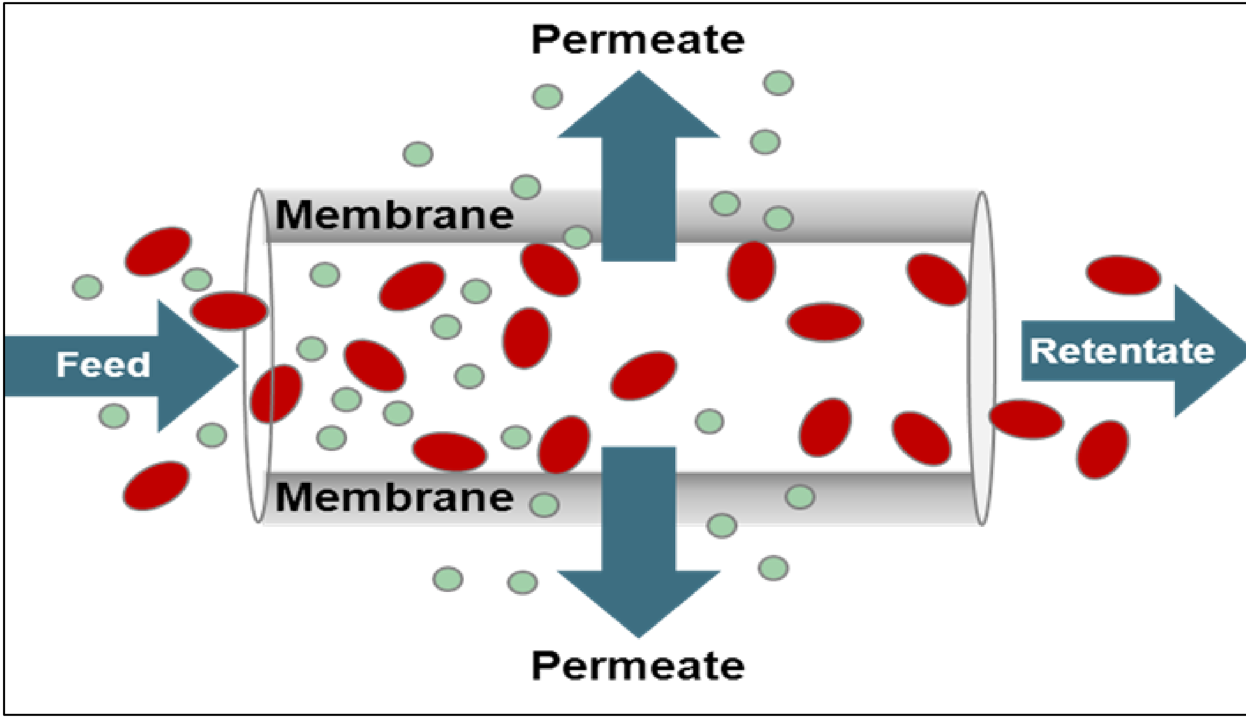
Other Potential Uranium NF Applications

- Nanofitration is proposed for the Mulga Rock and Honeymoon Projects in Australia.
- It has also been tested for a number of other uranium projects, including Letlhakane in Botswana for A-CAP Resources, Michelin in Canada for Aurora Energy, and Mkuju River in Tanzania for Uranium One.

Nanofiltration Concept



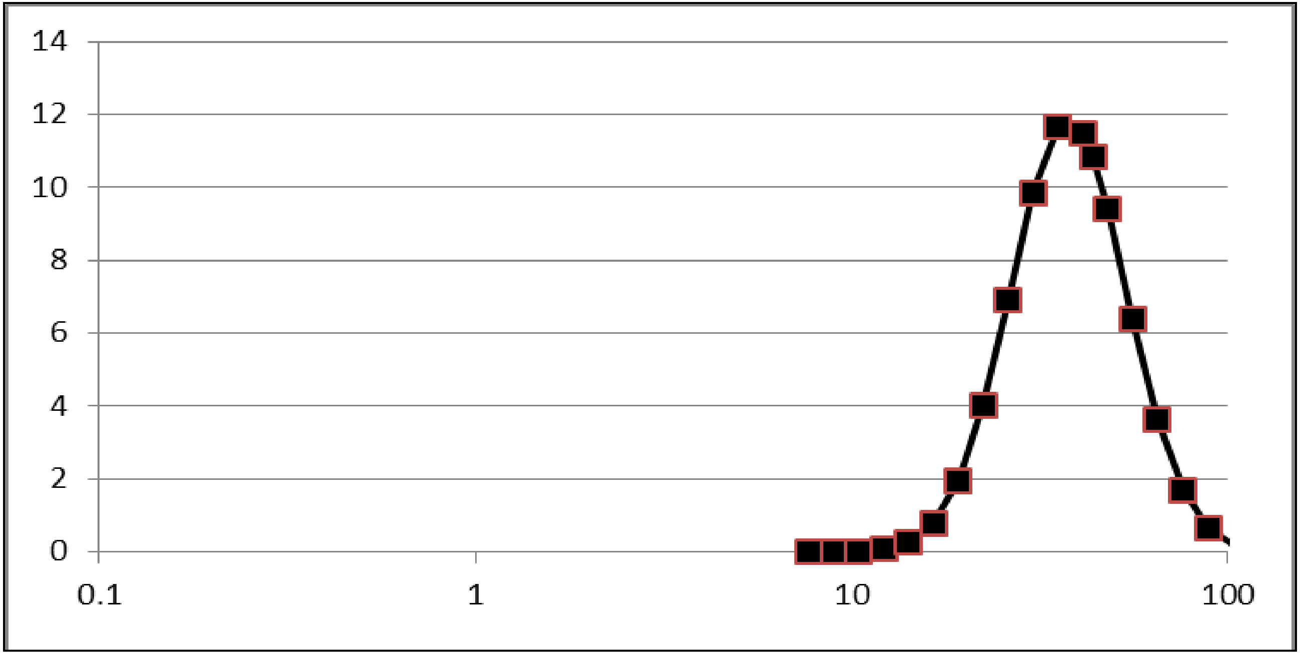
Areva Fluidized Bed Precipitation System

- Areva has developed and commercialized a patented continuous fluidized-bed precipitation system to produce a more spherical, larger particle size with reduced fines.
- Results in improved flowability, enhanced dewatering, and reduced dust emission in subsequent drying or calcining.
- Because of the reduced dusting, a horizonal kiln can be used, with more flexibility in operating temperature in acting as either a dryer or calciner, depending on the selection of the precipitation reagent.

Areva Fluidized Bed Precipitation System

- Testwork indicates that density and uranium content of the product can be increased by up to 40% and 10%, respectively, by optimizing the calciner operating temperature, which reduces transport costs.
- The products also have a very low level of impurities, considered to be due to their physical characteristics, leading to better washing and reduced ingress of solutions into the particle structure.
- Boss Resources propose using a fluidized-bed system to produce coarser $UO_4 \cdot 2H_2O$ product to increase the existing filtration and drying capacity for their Honeymoon Project.

Example Particle Size Distribution



(D_{50}~ 44 μ, D_{10} ~ 17 μ)

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Unconventional U Sources – PhosEnergy Process

- Phosphoric acid typically contains 150-175 ppm U_3O_8. Commercial recovery plants were built in the USA and other countries in the 1970s.
- While all used various SX processes, IX was tested by a number of organizations to reduce cost, avoid the phase disengagement problems in SX, avoid post-treatment of the acid, and improve environmental impact and safety.
- Resins tested included chelating types and resin impregnated with D2EHPA–TOPO (tri-*n*-octylphospine oxide). No commercial plants eventuated.
- More recent IX testwork has been carried out by organizations including ANSTO, Dow and Lanxess.

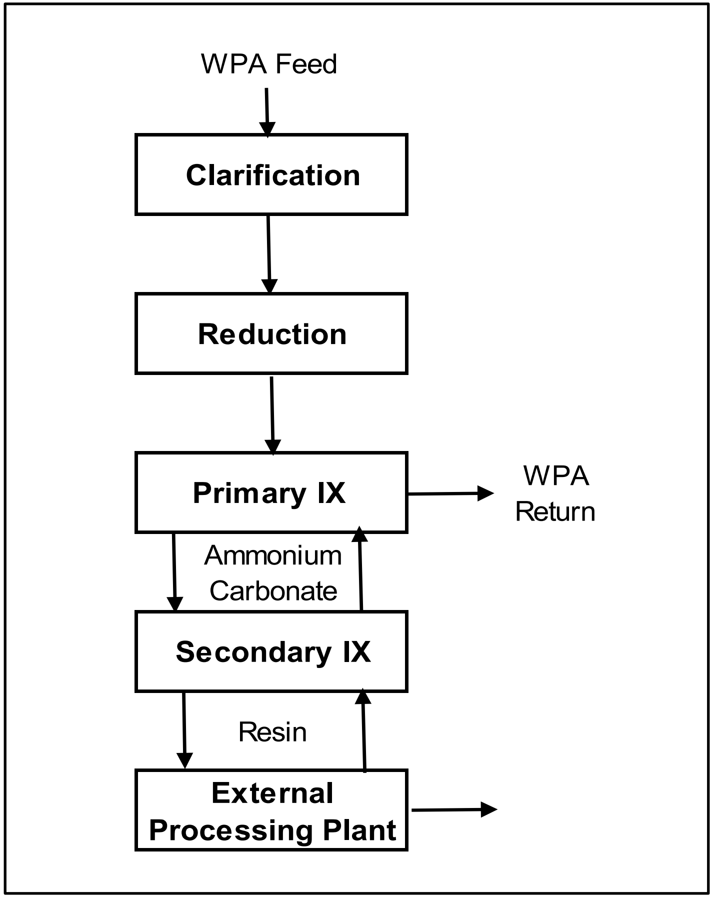
PhosEnergy Process

- New IX-based process was developed by Urtek LLC, USA, (jointly owned by PhosEnergy Limited, Aus., and Cameco Corporation, Canada) in conjunction with ANSTO, Aus.
- Extensive bench and pilot scale testwork at ANSTO in 2008 culminated in a modular demo plant at a US fertilizer producer in 2015, connected directly to their plant.
- It achieved > 92% U recovery with no deleterious build-up of impurities in extraction media. Chemical and reagent consumptions were within expected range, and the feed stream was unaffected except for the removal of U and V.
- Testing of the product at an external uranium processing facility showed that a saleable final product was achievable.
- A PFS indicated opex was very attractive, but capex too high for current market, and work was initiated to cut costs.

PhosEnergy Process

- An electro-reduction process was developed to reduce ferric iron to ferrous to avoid iron loading on the resin without chemical addition.
- A two-stage IX system is included. Aminophosphonic resin is used for primary IX with ammonium carbonate elution, while a conventional strong-base resin is used in secondary IX.
- The loaded secondary resin is sent to an external processing plant for elution and product recovery.

PhosEnergy Process Flow Diagram



OPPORTUNITIES FOR FURTHER PROCESS IMPROVEMENTS AND DEVELOPMENTS

- Further development of IX and SX systems for high chloride solutions.
- Application of nanofitration to leach solutions for increasing uranium content and reducing flow rate, especially for low concentration HL solutions.
- Recovery of uranium from base metal leach solutions.
- Application of SX to alkaline leach solutions.
- Application of vat leaching with covered vats or in a building as an alternative to heap leaching in areas subject to cyclones or heavy rain storms to avoid environmental risks.