**URANIUM- RARE EARTHS KEYNOTE**

# THE WHAT'S AND WHYS OF URANIUM ORE PROCESSING INNOVATIONS PAST, PRESENT AND FUTURE

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## ABSTRACT

The presentation tracks uranium ore processing innovation from the early formative period in the 1950s through to the 2022. It is divided into the following periods:

1950-1970 Early Process Development Period
1970-1980 Innovation To Combat Changing Conditions
1980-2000 Innovation During Prolonged Industry Downturn
2001-2022 Innovation During An Up And Down Period

The major drivers and major process developments in each period are briefly reviewed.

The presentation concludes with the 2023+ Prognosis for Innovation.

*Keywords: Uranium ore processing, innovation, major drivers, future prognosis*

## 1950-1970 EARLY PROCESS DEVELOPMENT PERIOD

Major initial process development period 1950-70 mainly in the USA, Canada, South Africa , Australia, Former Soviet Bloc.

Major drivers included: (Excluding the Soviet Bloc):

- Increasing demand due to growth of nuclear power stations.
- Guaranteed government purchase contracts.
- Small operations suitable for entrepreneurial mining companies.
- Free interchange of process technology and operating experience.
- Technical support from government organizations such as Oak Ridge in the USA, Mines Branch in Canada and National Institute for Metallurgy in South Africa, as well as commercial laboratories.
- Innovations by reagent suppliers and equipment manufacturers.

## 1950-1970 EARLY PROCESS DEVELOPMENT PERIOD

This was a pioneering period in which the basics of uranium ore processing were developed. Major developments included:

- Solid/liquid separation with thickeners and filters.
- The use of chemical flocculants.
- Acid and alkaline leaching.
- Key leaching parameters, PSD, temp., pressure, time, pH, Eh.
- The use of oxidants for tetravalent minerals.
- Separation and purification by IX, SX, as well as precipitation.
- Product recovery by precipitation and roasting/calcining.
- Ore upgrading methods including various combinations of screening, gravity, washing classifiers, cyclones, flotation.

## 1970-1980 INNOVATION TO COMBAT CHANGING CONDITIONS

Major drivers included: (Excluding Former Soviet Bloc):

- Phasing out of government contracts.
- Reduced demand.
- Oversupply.
- Competition from new projects based on large deposits with higher production, lower opex, benefitting from new innovations.

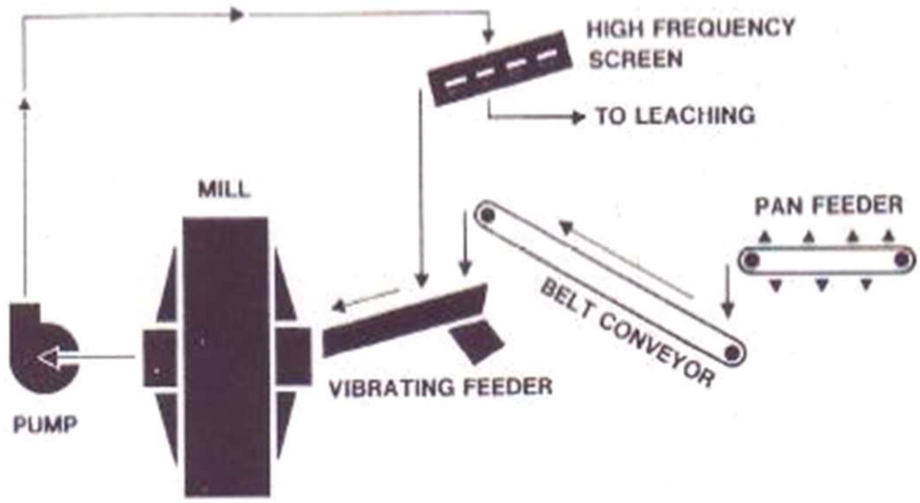
Led to mothballing or closure of many smaller operations.

## 1970-1980 INNOVATION TO COMBAT CHANGING CONDITIONS

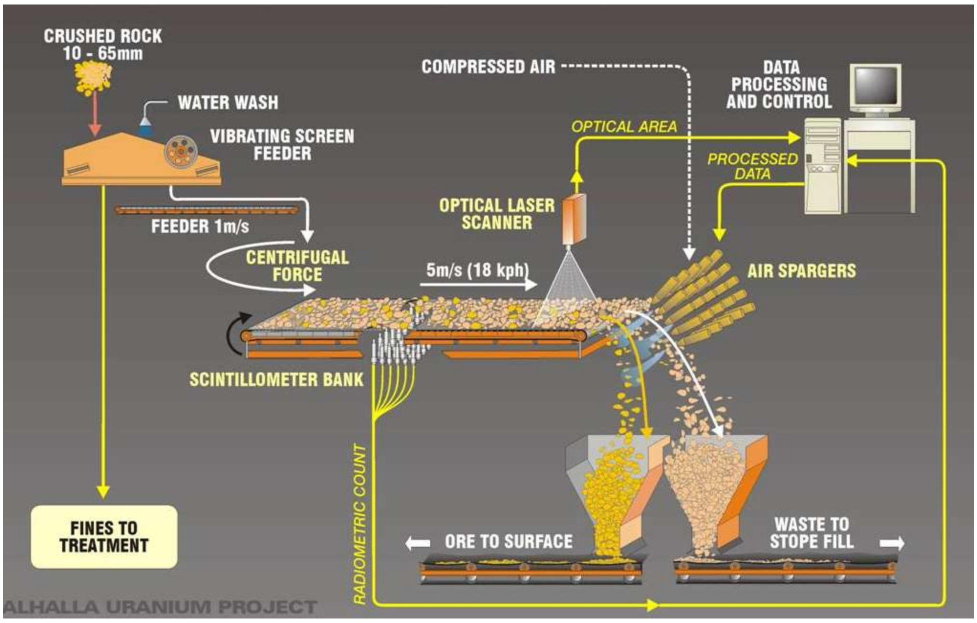
Some significant new innovations introduced in this period included:

- Semi-Autogenous grinding (SAG) - lower capex, inside the building for cold climate operations.
- Radiometric ore sorting.
- High-capacity thickeners - lower capex, low footprint, inside building for cold climates.
- Belt filters – lower footprint and cost than CCD, avoids tailings dam.
- New CIX systems for unclarified solutions – eliminates clarification.
- Krebs SX mixer-settlers – lower capex and reagent inventory, low footprint, located inside building for cold climates.
- Uranium by-product from phosphoric acid and copper leaching- low cost, no mining.

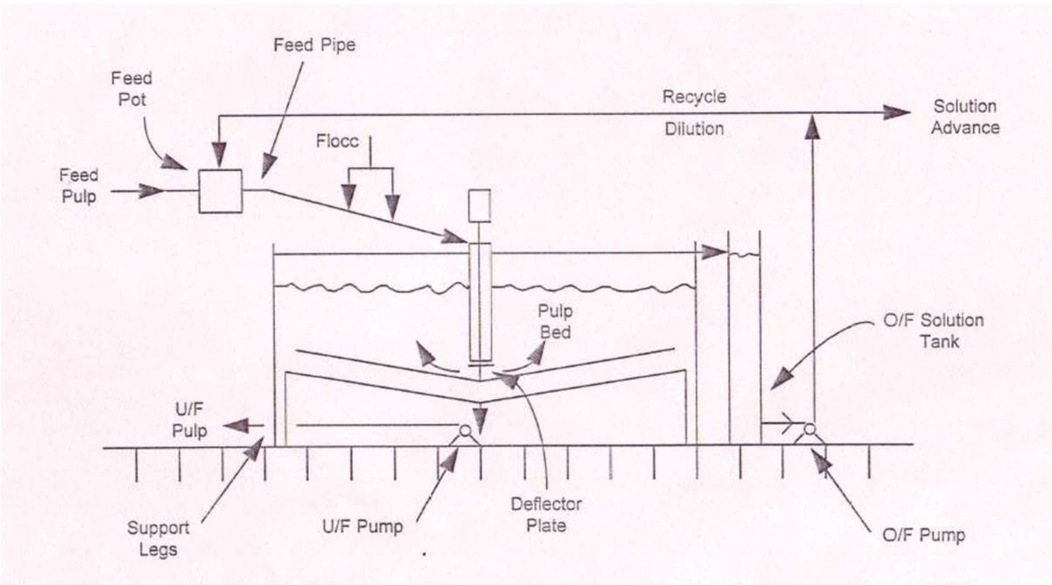
## TYPICAL SAG MILL CIRCUIT - SANDSTONE ORE



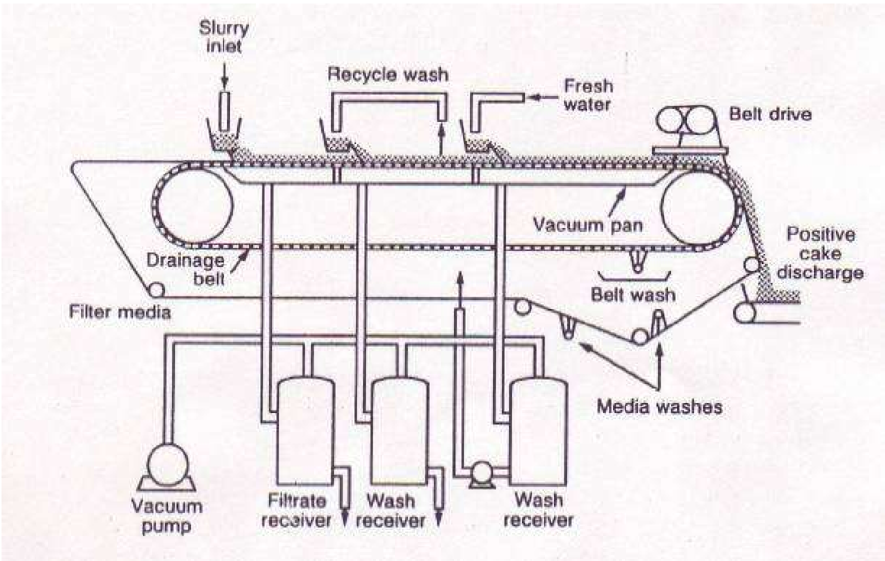

## TYPICAL RADIOMETRIC ORE SORTING SYSTEM



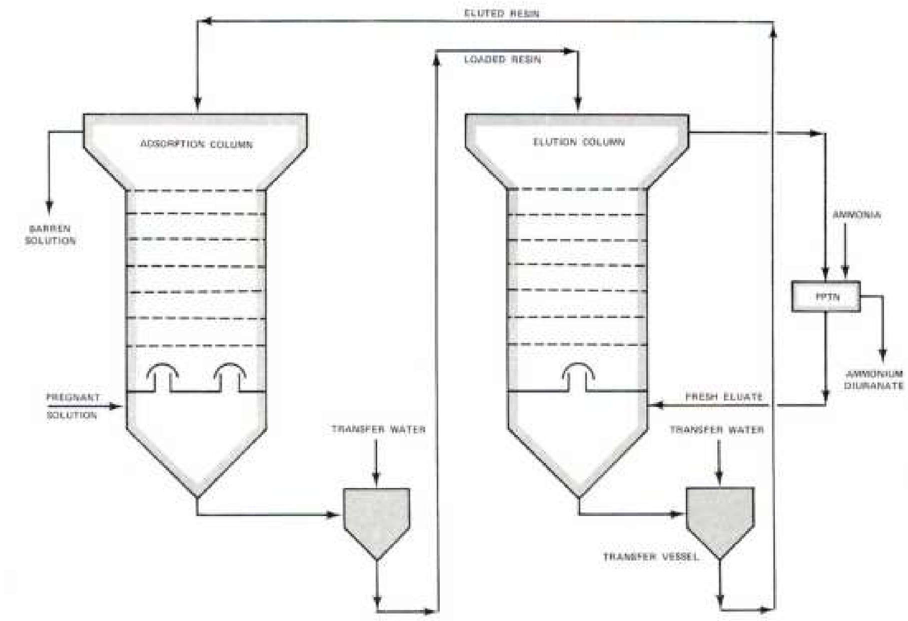
# HIGH CAPACITY THICKENER ARRANGEMENT (ENVIRO-CLEAR)



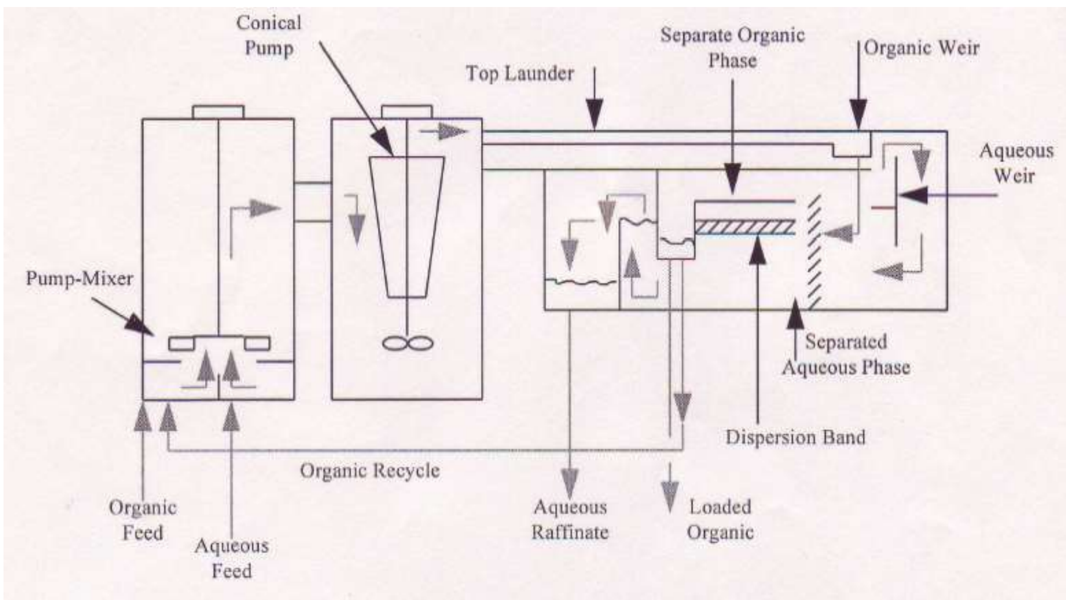

# BELT FILTER ARRANGEMENT



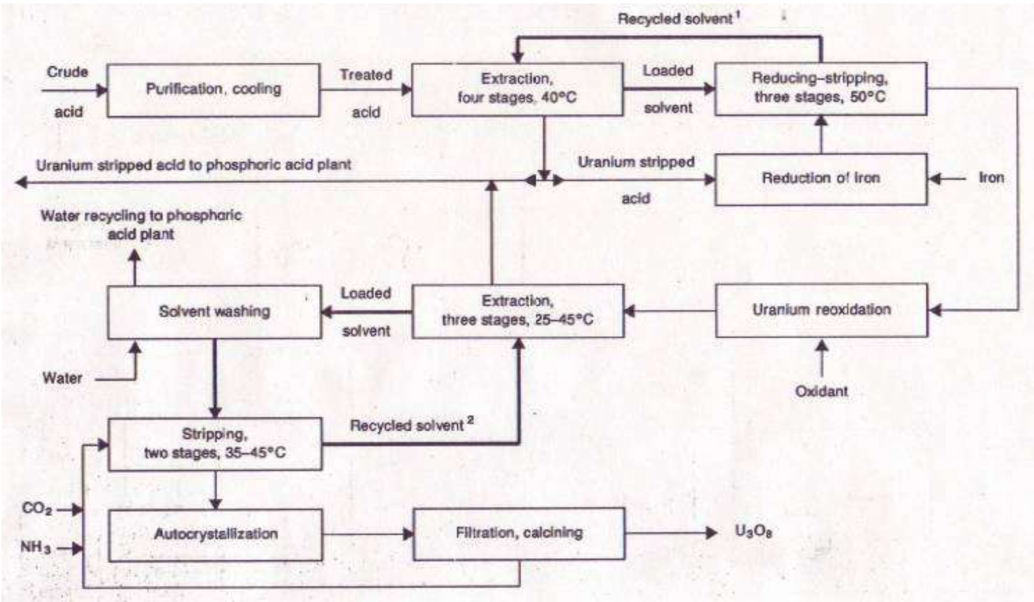
# TYPICAL NIMCIX SYSTEM




# KREBS MIXER-SETTLER WITH TWO MIX BOXES AND ORGANIC RECYCLE



## D2EHPA-TOPO PROCESS FOR RECOVERY OF URANIUM FROM PHOSPHORIC ACID




## 1980-2000 INNOVATION DURING PROLONGED INDUSTRY DOWNTURN

Drivers included:

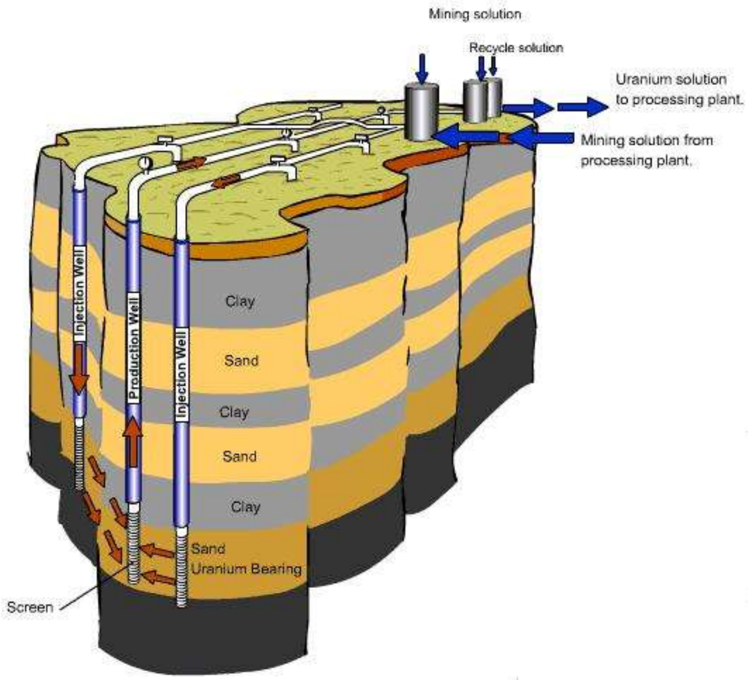
- New operations limited to ISR and very high-grade Canadian ores
- Limited new nuclear power stations.
- Uranium oversupply.
- Low price.
- Chernobyl accident in 1986.
- New operations mainly limited to ISR and very high-grade ore treatment in Canada.

## 1980-2000 INNOVATION DURING PROLONGED INDUSTRY DOWNTURN

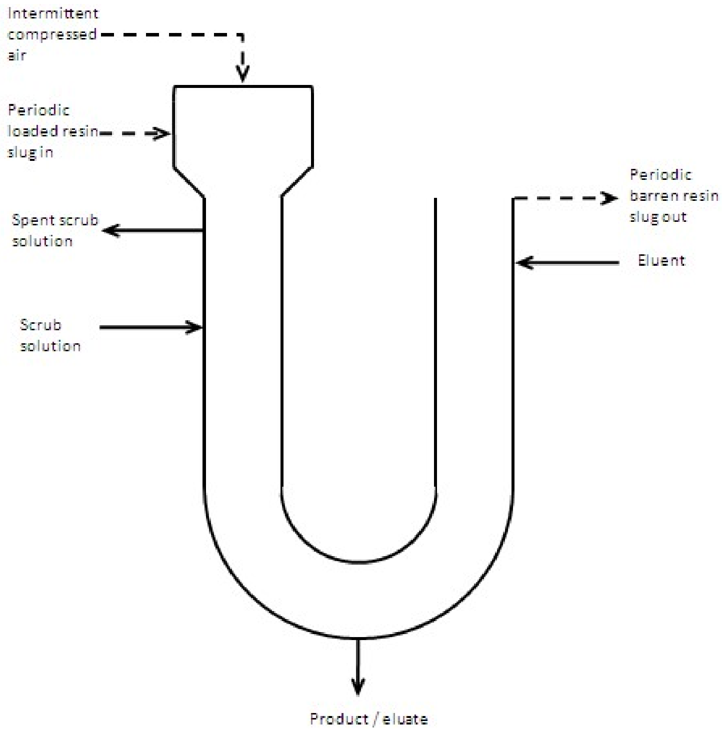
Significant innovations included:

- Development of acidic and alkaline ISR technology – low cost, no conventional mine, minimal surface impact.
- U-Tube IX elution system, especially for ISR operations in Kazakhstan - optimized resin inventory, high concentration eluate and purity product solutions.
- Pulsed Columns for SX – low footprint, lower organic evaporation and fire risk.
- Strong acid SX strip – avoids need for ammonia bleed.
- Peroxide precipitation - more selective than ammonia or magnesia, avoids product calcination and off-gas scrubbing.

## TYPICAL ISR SYSTEM

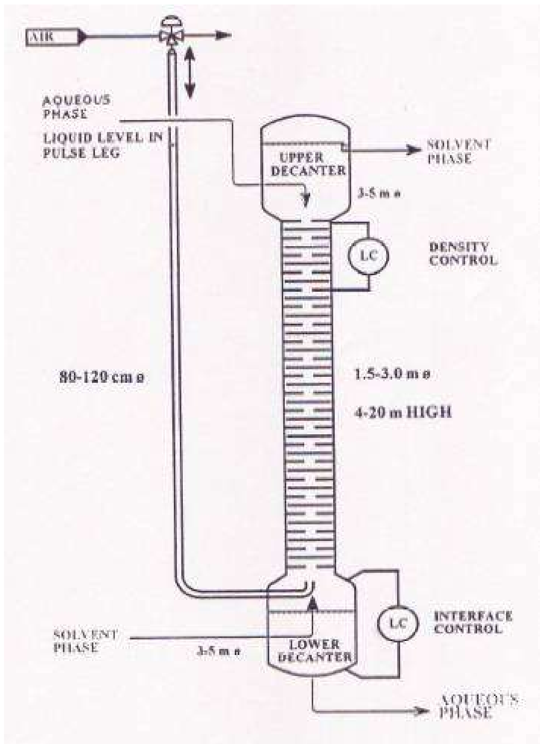


# U-TUBE ELUTION CONCEPT




# PULSED COLUMN

# SCHEMATIC OF TENOVA DESIGN



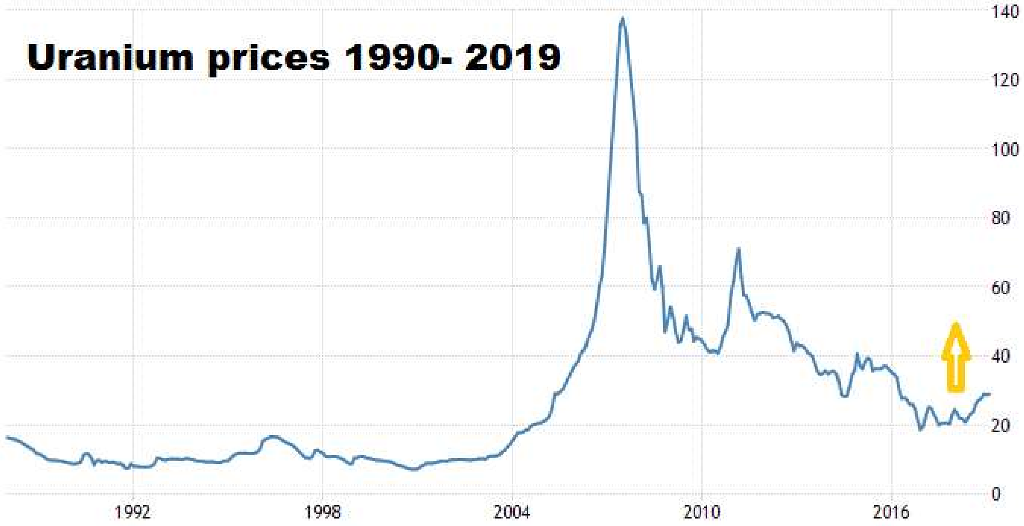
## 2001-2021 INNOVATION DURING AN UP AND DOWN PERIOD

Major driver:

- A steep price rise from 2004 peaking in 2007 and followed by a steep fall.
- Increased interest in nuclear power generation as a base load power alternative to fossil fuels.
- Concern over depletion of uranium stockpile.

## URANIUM PRICE CHART

(Seeking Alpha Website seeking alpha.com)



## 2001-2021 INNOVATION DURING AN UP AND DOWN PERIOD

Drivers for process development work despite the long turndown included:

- 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.

## 2001-2022 INNOVATION DURING AN UP AND DOWN PERIOD

Innovations during the downturn include:

- Ablation and U-pgrade™ ore preconcentration processes.
- Nanofiltration Membranes for upgrading IX eluate and SX strip liquors, and recovering and recycling reagents.
- A potential major breakthrough for alkaline SX.
- IX for high chloride acid leach solutions.
- Application of IX to strong acid strip solution.
- Fluidized bed product precipitation system.
- Permeability enhancement for hard Rock ISR.

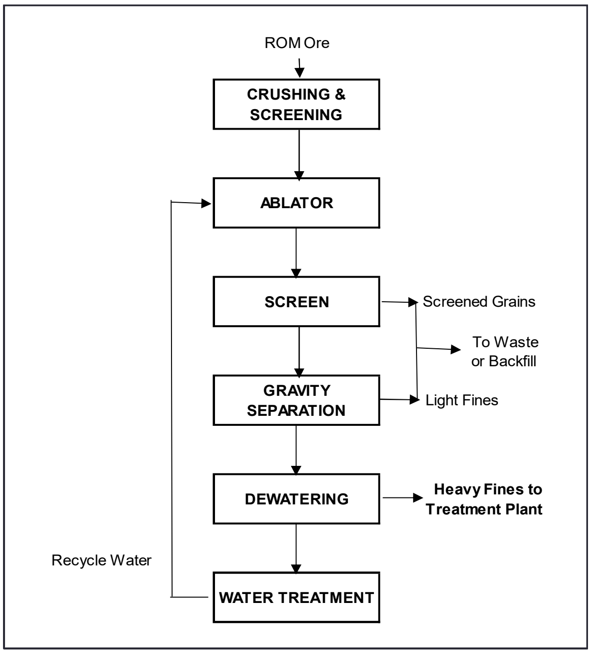
## ORE PRECONCENTRATION – ABLATION PROCESS

- 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 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




# U-PGRADE$^{TM}$ 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 concentrate without using chemicals.

## U-PGRADE™ PROCESS

- The rejection of carbonate minerals produces a leach feed suitable for acid leaching, and generally simpler and cheaper than alkali leaching normally used for carbonate ores.
- 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 to transport it to a third-party operation which reduces project development costs and can render a small deposit financially viable.

## U-PGRADE™ 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.

## NANOFILTRATION

- A commercial nanofiltration system designed by BMS Engineers, Perth, Western Australia was installed at the Kayelekera uranium operation in Malawi in 2013 for recovering and recycling acid from IX eluate prior to precipitation.
- A second commercial plant was installed at Langer Heinrich, Namibia, in 2015 to recover sodium bicarbonate from the IX eluate.
- Nanofiltration has been proposed and/or tested for a number of developing projects including Mulga Rock and Honeymoon in Australia, Letlhakane in Botswana, Ivana in Argentina, Michelin in Canada, and Mkuju River in Tanzania.

## KAYELEKERA NANOFILTATION SYSTEM

## NANOFILTRATION POTENTIAL

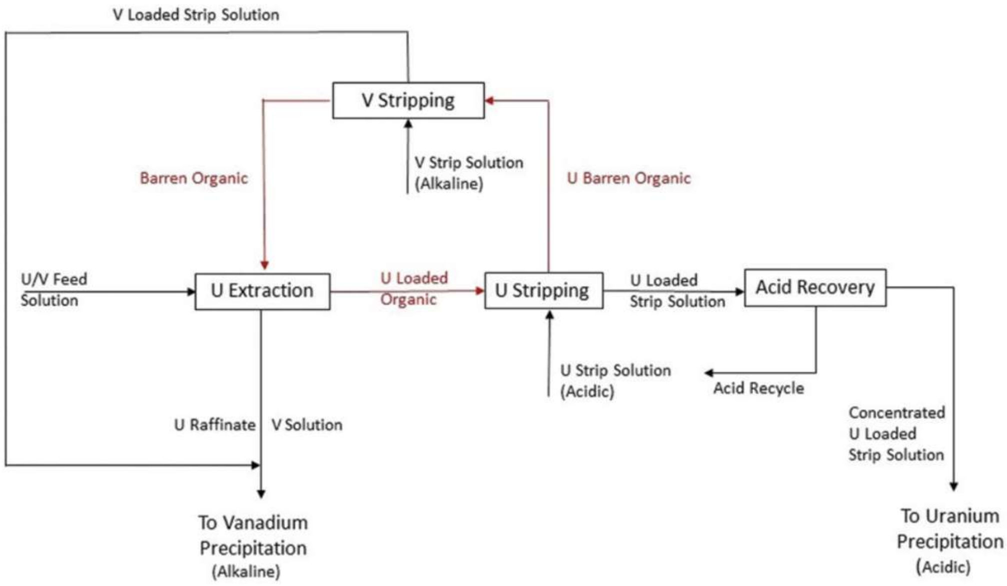
Potential applications in uranium operations include:

- Concentration of SX or IX feed solution to reduce the capex of the leaching facility and recover and recycle acid or carbonate reagents.
- Treatment of waste or bleed streams.
- Treatment of acid rock and mine drainage.

## A MAJOR BREAKTHROUGH FOR ALKALINE SX?

- Cyphos 101, a tri-hexyl(tetradecyl)phosphonium salt and Aliquat 336, a quaternary amine, were both tested by CSIRO and the Parker Centre, Perth, Australia, for the recovery and separation of uranium and vanadium from alkaline leach solutions with promising results. (Ref: CSIRO paper, ALTA 2013).
- The CSIRO SX concept is included in the proposed flowsheet being tested for Blue Sky Uranium Corporation's Ivana Uranium-Vanadium Project in Argentina. (Ref: Process design for the Ivana Uranium-Vanadium mill, Chuck Edwards, CIM Journal, 11:4, 231-237, 2020)
- SX from alkaline leach solutions is a key missing link in uranium ore treatment and, if successful, the application at Ivana will be a major industry breakthrough.

## PROPOSED IVANA ALKALINE SX FLOWSHEET



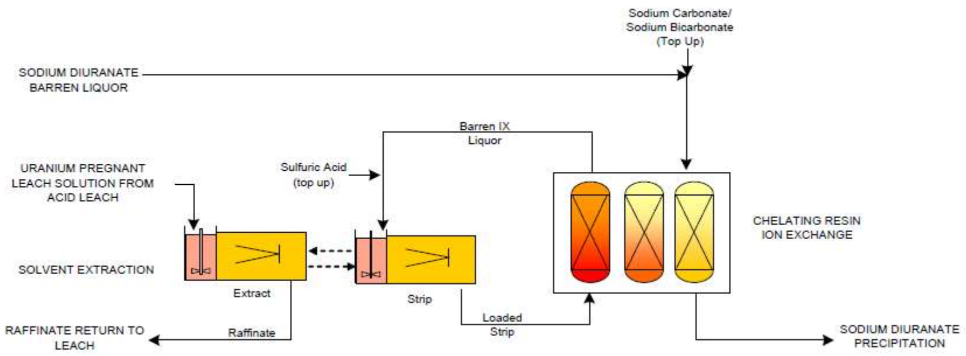

## IX FOR HIGH CHLORIDE SOLUTIONS

- Chloride has a negative impact on the recovery of uranium from sulfuric acid leach liquors using ion exchange.
- ANSTO Minerals investigations indicated that WBA resins are more effective than SBA up to 12 g/L Cl and can be eluted in a conventional manner using 1 M NaCl. (Coupled with nanofiltration for eluate reagent recycle, this process can be quite attractive.)
- However, in an extensive testing program for the Boss Resources Honeymoon ISR project, South Australia, a newly released high capacity SBA resin outperformed a WBA resin, which in turn has been shown to outperform conventional SBA resins.
- The laboratory findings have been validated by a continuous pilot plant trial. Future work will focus on optimising the elution process, which is based on the use of NaCl.

# APPLICATION OF IX TO STRONG ACID SX STRIP SOLUTION

- Novel application of IX (chelating type) to recover uranium from strong acid SX strip solution to recycle acid to SX strip and reduce acid and lime consumptions in product recovery circuit.
- Sodium diuranate is precipitated from eluate then redissolved in sulphuric acid, and $UO_4$ product is precipitated with peroxide.
- Developed, tested and patented for the Letlhakane heap leaching project in Botswana, where a strong acid leach is required.
- Could render strong acid leaching of refractory ores feasible. and economic.
- Nanofiltration was considered as an option for Letlhakane but there was concern over the stability of the membrane in the 4 M acid conditions, and the perceived effect on the water balance (the commercial NF facility at Kayelekera operates on IX eluate at about 1 M acid strength).

# IX PROCESS FOR STRONG ACID SX STRIP SOLUTION



## ORANO FLUID BED PRECIPITATION PROCESS

(Ref: Adelaide Control Engineering presentation, ALTA 2013)

- Patented process developed and commercialized by Areva (now Orano)
- Available from Adelaide Control Engineering (ACE), South Australia
- Claimed advantages (by ACE):

  - Lower cost of production and maintenance

  - Increased recovery of uranium

  - Increased uranium content of calcined product

  - Larger particle size

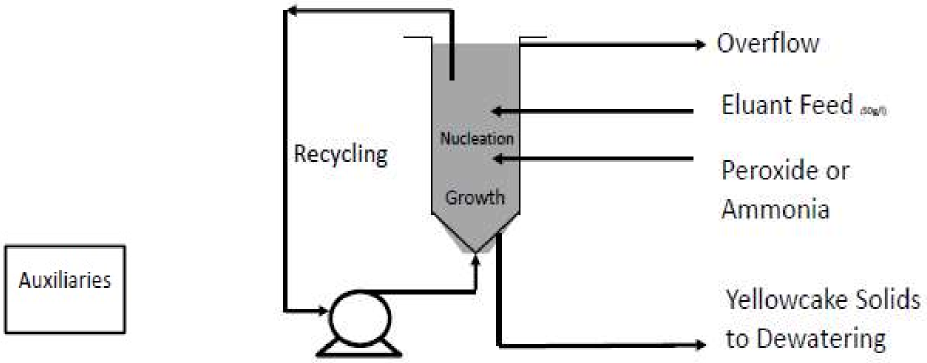
  - Reduced fines, less dust and lower risks to operators

## ORANO FLUID BED PRECIPITATION PROCESS (CONT.)

- Improved dewatering reduces calcining costs or allows increased throughput
  - Increasing calcined product bulk density - lower transport cost.
  - Facilitating drying or calcining with horizontal kiln – previously, too much product was lost in off gas and stuck inside tube.
  - Flexibility for peroxide or ammonia precipitation.
  - Modular construction, smaller site footprint.
- Retrofitting a Fluid Bed Crystalliser can significantly debottleneck systems by:
  - Increasing filtering and dewatering equipment capacity.
  - Increasing drying and calcining equipment capacity.
  - Reducing product waste and recycle.
  - Improving utilization.

## ORANA FLUID BED PRECIPITATION PRINCIPLE

(Ref: ACE presentation, ALTA 2013)




(AREVA Patent)

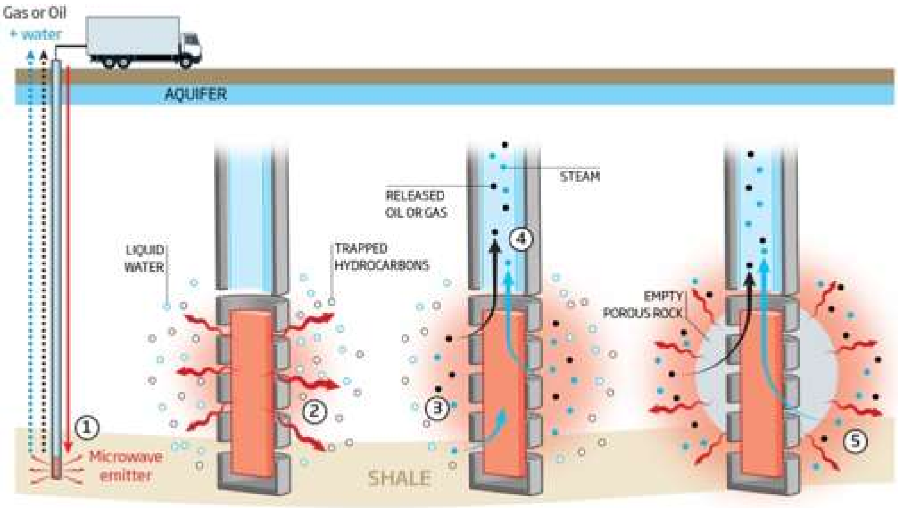
## ISR PERMEABILITY ENHANCEMENT

- Uranium ISR is currently limited to permeable ores, typically sandstones
- However, there are extensive R&D programs to enhance the permeability of hard rock ores for recovery of gold, copper, and nickel as well as uranium.
- Enhancement methods being investigates include:
  - Further development of previously used methods including underground basting, drilling and blasting, hydraulic fracturing, and directional hydraulic fracturing.
  - Newer techniques including microwave fracturing, thermal fracturing, acoustic or electrical stimulation, laser fracturing, biomineral alteration, liquid nitrogen fracturing, non-explosive demolition agents, non-explosive demolition agents.

*Permeability enhancement is one of the key focuses of the annual ALTA ISR Conference held in partnership with CSIRO who had the vision for an annual event.*

# MICROWAVE FRACTURING CONCEPT

(Mining3 Presentation ALTA 2019)




# 2023+ PROGNOSIS FOR INNOVATION

- Uranium market prospects are improving due:
  - to falling inventory
  - increasing interest in nuclear as a clean energy for base load power
  - potential of **small modular reactors** (SMRs).
- According to the IAEA, Small Modular Reactors:
  - offer better upfront capital cost affordability
  - are suitable for cogeneration and non-electric applications
  - offer options for remote regions with less developed infrastructures
  - possibility for synergetic hybrid energy systems that combine nuclear and alternate energy sources, including renewables.

## A RISING MARKET SHOULD ENCOURAGE INNOVATION

A rising market should lead to funding becoming available for new innovations.  Candidates could include:

- Use of NF membranes for leach solution upgrading.
- Commercialization of SX for alkaline leach solutions.
- Application of IX for strong acid SX strip solutions for processing of refractory ores.
- ISR for hard rock ores after permeability enhancement.

**Acknowledgement**

First Presented at IAEA “Technical Meeting to Collect and Document Innovations in the Uranium Production Cycle”
Virtual Event 6-10 June 2022