Application of United Nations Framework Classification – 2009 (UNFC-2009) for Uranium Resources

Uranium Ore Processing

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Novel technologies developed and implemented by Mintek in South Africa since the 1940’s; during the 1980’s and today applicable to the expected future “new wave” of U production

- Mineralogy and impact on processing options
- Ore preparation and waste rejection
- Leaching
- Extraction
- Product recovery
MAJOR URANIUM MINERALS

- **Uraninite** \((U^{4+}_{1-x}, U^{6+}_x)O_{2+x}\)
- **Coffinite** \(U(SiO_4)_{1-x} (OH)_{4x}\)
- **Brannerite** \(UTi_2O_6\)
- **Davidite** \(U_6Ti_{15}(O,OH)_{36}\)
- **Betafite** \(U_{2-x},Nd_2O_6(O,OH_x)\)
- **Carnotite** \(K_2(UO_2)(VO_4)_{2.3}H_2O\)
Most important factors to consider before choosing a processing route:

- Elemental composition of U-bearing and gangue minerals
- Size of U particles
- U liberation
- U association with gangue minerals
- Nature of the gangue
TYPICAL METALLURGICAL FLOWSHEET

Ore preparation, waste rejection and U upgrading

Leaching

Liquid/Solid Separation

Uranium extraction/upgrading

Product recovery (Precipitation to form yellow cake)
ORE SORTING DEVELOPMENTS

■ Traditionally radiometric sorting
  ▪ Only viable at very coarse particles in mineralogy allows
  ▪ High grade ores
  ▪ Suppliers no longer use these sorters

■ Mintek investigated other sorting technologies
  ▪ Near infrared
  ▪ Optical sorting
  ▪ X-Ray transmission sorting

■ XRF most effective technology
  ▪ Depends on mineralogy of distinct host rock and waste minerals liberated at coarse size
**ORE SORTING**

- **Major Advantages**
  - Dry processing
  - Crushing coarser
  - Lower reagent costs due to upfront waste rejection
  
  - No Water
  - Less Energy
  - Lower OPEX

- **Disadvantages**
  - Only competitive up to 30mm particle size
  - Bottom size determined by throughput economics
  - Not feasible for disseminated ores
FLOTATION DEVELOPMENTS ON HIGH GRADE ORES

- High grade ores such as Springbok flats
- Development phase
- Removing carbonates by selective flotation

Reduce acid consumption in leach
Lower reagent costs
Lower CAPEX
Lower OPEX
Low grade Witwatersrand gold tailings (CIL tailings)

- Uranium, sulphide sulphur, un-leached gold
- Flotation of sulphides followed by oxidation to free Au for leaching - Mintek patent in process

- Increase U grade and recovery
- Reduce cyanide consumption
- Lower reagent costs
- Meets environmental requirements
- Lower CAPEX
- Lower OPEX
LEACHING OF URANIUM ORES

- Atmospheric leaching
- Pressure leaching
- In-situ leaching: suitable for the permeable ore bodies & underlying rocks which provide a barrier to solution
- Heap leaching – acidic, alkaline, bacterial
LEACHING

- **Acid leaching**
  - Alkali-consuming ores (e.g. pyrite)
  - Witwatersrand Ores
  - \( \text{UO}_3 + \text{H}_2\text{SO}_4 \rightarrow [\text{UO}_2(\text{SO}_4)_3]^4- \)
  - Acid consumption depends on gangue minerals not U grade
  - **Typical oxidants:** \( \text{MnO}_2 \), sodium chlorate, ferric, \( \text{H}_2\text{O}_2 \), oxygen, air/\( \text{SO}_2 \)
  - **Main impurities:** Fe, Al, Mg, Ca, V, Mo, Cu, Cl, \( \text{NO}_3^- \), Si
Alkaline leaching

- Acid-consuming ores (e.g. calcite)

\[
\text{UO}_3 + \text{NaCO}_3 \rightarrow \text{[UO}_2(\text{CO}_3)_3]^{4-}
\]

- Sodium or ammonium carbonate – lixiviants

- Less efficient and slow

- Mineralogy can affect efficiency

- Oxidant is required

- Relatively pure PLS

- **Main impurities:** V, Cl\(^{-}\), NO\(^{3-}\) & SO\(^{42-}\)}
Leaching conditions influence design of downstream process

Influencing parameters:
- Type of lixiviant used
- Severity of leach
- Co-extraction of impurities (level & type of impurities)
- PLS grade

Influenced parameters:
- CAPEX, OPEX (reagents, equipment, energy, etc.)
- Plant construction material (i.e. chloride level-stress corrosion)
- Selection and design of downstream process (SX, IX, IX/SX, ppt, etc)
- Environment and safety requirements with associated costs
HEAP LEACH DEVELOPMENTS ON LOW GRADE ORES

- Hydrodynamic performance critical for heap leach to function optimally

- Mintek investigating characterisation of crushed ore for heap leach in 1m column cells
  - Stacking profiles
  - Hydrodynamic properties (pore pressure and conductivity, moisture content)
Refractory minerals deemed difficult to leach (brannerite, Ti-rich coffinite) – Karoo sandstone

Acid consumption high due to presence of carbonates (calcite and dolomite)

Investigating acid ferric leaching

Improve rate and extent of uranium dissolution
  - Increased acid dosages during agglomeration
  - Curing duration
**IN-SITU BIOLEACHING DEVELOPMENTS ON LOW GRADE ORES**

- **Witwatersrand CIL Tailings**
- Tailings dumps compacted, water and air permeabilities are low

**Suitable for in-situ bioleaching**
- Irrigation with dilute acid solution to reduce pH
- Suitable for bacterial oxidation instead of MnO$_2$
- Tailings washed after time to recover uranium
Advantages of BioLeaching over acid-ferric leaching of uranium

- Lower acid consumption
- Reduced heating requirements
- Lower environmental impact due to bacteria performing as oxidant
- Lower OPEX
BIOLEACHING DEVELOPMENTS ON LOW GRADE ORES

- Novel flowsheets for incorporating bioleaching into uraninite extraction from pyritic flotation concentrates – Witwatersrand ores

- Biological and chemical leaching together
  - Bio-oxidation of pyrite for the production of ferric
  - Sulphuric acid generated in process

- Split feed system bioleaching system
  - Pyrite leached in autoclave and uranium subjected to bacterial leach
Limitations

- Perform better at smaller particle sizes
- Perform better at lower sulphide concentrations
- Slower leaching kinetics
- Limited by feed solids concentration that could be tolerated by micro-organisms
- Narrow critical temperature range required for biological environment
- Not currently economically viable since U tenor (leach liquor composition) in solution below the 100mg/L required
URANIUM IN SOLUTION => “YELLOW CAKE”

Uranium ore leaching

Pregnant leach liquor

Depending on $U_3O_8$ grade, impurities levels, physical characteristics of liquor, complexity of S/L separations, etc.

Ion exchange → Solvent extraction → Precipitation

“yellow cake”
IX and SX – used to upgrade uranium prior to yellow cake precipitation

SX for high grade streams (>800mg/L)

IX for low grade streams
Extraction Developments Over the Years

- Fixed bed IX with precipitation of ammonium diurate (ADU)
- Bufflex process – IX and SX on eluate from IX
  - Much higher grade of ADU
- Purlex process – SX only
- NIMCIX™ – Continuous fluidised bed ion exchange
  - Major advantage: Can handle 200-300g/L suspended solids in feed
- Resin-in-Pulp (RIP)
Major Advantages

- Minimal or no upstream Solid/Liquid separation required
- Can handle up to 60% solids
- Lower wash water requirements
- Improvement of overall metal recoveries
- Lower discharge metal concentrations => decrease of problems associated with wastes disposal - Environmentally acceptable
- Economically viable
- Can be retrofit to existing U plants
- Feasible for U < 800 mg/L

Main Disadvantage

- Resin loss and durability
  - Mintek can assist with resin selection
  - Process optimisation prior to RIP can handle impurities
- Silica fouling and impact on OPEX
  - Design to limit uranium losses
MINTEK DEVELOPMENTS IN RIP TECHNOLOGY

- Metal Recovery through Ion Exchange (*MetRIX™*) technology
- Developed by Mintek and TENOVA in 1980’s for base metals
- *MetRIX™* technology revived for uranium recovery from low-grade sources in 2007
  - Truly continuous system
  - Independent resin and pulp flows – optimal metallurgical performance
  - Shorter resin residence time - limits resin fouling
  - Lower CAPEX (Resin inventory 30-40% of carousel system)
  - Easy integration to existing plants
METRIX™ RIP SECTION OF THE PLANT
METRIX™ DEMONSTRATION PLANT

RIP

Leach Tanks

Neutralisation Tank

Elution Circuit
MINTEK DEVELOPMENTS IN RIP TECHNOLOGY

- Major resin developments:
  - Larger, more durable resin produced
  - Mintek resin durability evaluation techniques:
    - Pilot plant and laboratory scale tests

- Resin replacement from MetRIX™ plant operated at Harmony:
  - Resin replacement cost attributed <1% to plant OPEX
SOLVENT EXTRACTION

Mixer-settler contactors

Bateman Pulse Column
SOLVENT EXTRACTION DEVELOPMENTS

- Karoo sandstone deposits with coffinite, uraninite and pitchblende
  - Mo concentrations in feed high - Selective extraction
  - Presence of calcite and sulphide minerals – Acid and base consuming

- Direct precipitation (after leaching)
- Precipitation from eluate (after SX, IX)

Improved U dissolution
Reduced acid consumption in leach
Lower reagent costs
Lower OPEX
FLOWSHEET EXAMPLES

- Uranium One, Klerksdorp: CCD ➔ BPC SX ➔ ADU
- Ezilweni: CCD ➔ NIMCIX ➔ SX ➔ ADU ppt
- Langer Heinrich: CCD ➔ Clarification ➔ FBIX ➔ Ppt
- Vaal River South: CCD ➔ NIMCIX ➔ MS SX ➔ ADU
- Trekkopje: Heap leach ➔ NIMCIX ➔ SDU
- Kayelekera: RIP ➔ direct ppt
- AngloGold Ashanti: South Uranium upgrade, Kopanang extension: NIMCIX / RIP
SUMMARY

- No fixed flowsheet choice

Key drivers:
- Mineralogy
- Reagent consumption
- Uranium grade & impurities level
- Ability to upgrade
- CAPEX & OPEX

Process selection criteria:
- Throughput
- Selectivity
- Costs