URANIUM PROJECT DEVELOPMENT – ADOPTING THE RIGHT APPROACH

PRESENTED BY

ALAN TAYLOR

ALTA METALLURGICAL SERVICES

- Uranium exists in a seemingly myriad of minerals (>150 known).
- Further complicated by complicated by different valencies.
- While there may be one or two dominant species, in a deposit, there are often a variety of minor minerals which need to be treated in order to achieve a high recovery.
- On top of this, uranium minerals occur in a wide variety of host rocks.

COMMON URANIUM MINERALS

Type	Name	Composition
Oxides	Uraninite* Pitchblende*	$(U^{+4}_{1-x},U^{+6}_{x})O_{2+x}$ UO_2 to $UO_{2.25}$
Hydrated oxides	Becquerelite Gummite	$7UO_2.11\ H_2O$ Alt. product of uraninite. (May contain silicates, phosphates)
Nb-Ta-Ti Complex oxides	Brannerite* Davidite*	$(U,Ca,Fe,Th,Y)(Ti,Fe)_2O_6$ $(La,Ce,Ca)(Y,U)(Ti,Fe+^3)_{20}O_{38}$
Silicates	Coffinite* Uranophane Uranothorite* Sklodowskite Uraniferous Zircon	$U(SiO_4)_{1-x}(OH)_{4x}$ $Ca(UO_2)_2(Si_2O_7.6H_2O$ $UThSiO_4$ $(H_3O_2)Mg(UO_2)_2(SiO_4)_2.2H_2O$ $ZrSiO_4$

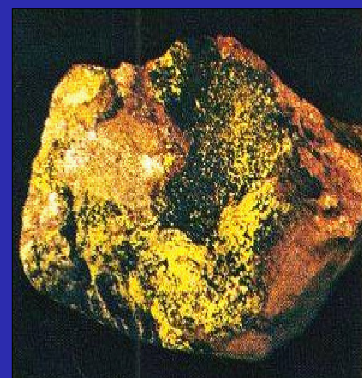
Primary Minerals*

COMMON URANIUM MINERALS (CONT.)

Type	Name	Composition
Phosphates	Autunite Torbernite Saleeite	$Ca(UO_2)_2(PO_4)_2.\ .10\text{-}12H_2O$ $Cu(UO_2)_2(PO_4)_2.\ .10\text{-}12H_2O$ $Mg(UO_2)_2(PO_4)_2.12H_2O$
Vanadates	Carnotite Tyuyamunite	$K_2(UO_2)_2(VO_4)_2.1\text{-}3H_2O$ $Ca(UO_2)_2(VO_4)_2.5\text{-}8H_2O$
Arsenates	Zeunarite	$Cu(UO_2)_2(AsO_4)_2.10\text{-}12H_2O$
Carbonates	Schroeckingerite	$NaCa_3(UO)_2(CO_3)_3(SO_4)F.10H_2O$
Hydro-carbons	Thucholite* Asphaltite	Uraninite complex with hydrocarbons Many varieties containing U-organic complexes

COMMON URANIUM MINERALS

Uraninite



Carnotite

IMPLICATIONS OF MINERAL COMPOSITION

- Dominance of hydrometallurgical processes due to mainly oxidized nature.
- Pre-concentration difficult due to finely generally disseminated mineralogy.
- Minerals can be leached in acid or alkaline (carbonate) solutions.
- Uranium exists mainly in hexavalent (U^{6+}) & tetravalent (U^{4+}) forms.
  - Hexavalent minerals directly leachable.
  - Tetravalent minerals need oxidation to hexavalent.

IMPLICATIONS OF GANGUE MINERALS

- Sulphides: sometimes uranium minerals can be closely associated with sulphides (eg pyrite, base metals):
  - Extraction can be more difficult.
  - May require more aggressive conditions.
  - May cause high level of impurities in leach solution.
  - May increase oxidant consumption.
  - May react with carbonate leach solution.
  - May need to be removed by flotation.
  - May be opportunity for co-product (eg copper at Olympic Dam, South Australia).
  - May be suitable for bioleaching.

IMPLICATIONS OF MINERAL COMPOSITION (CONT.)

- Silicates: cause problems in solid/liquid separation & SX.
- Uranothorite: thorium can be environmental issue.
- Phosphates: adversely effect oxidation role of ferric iron in leach, and can cause re-precipitation of uranium.
- Arsenates: can cause re-precipitation of uranium.
- Vanadates: possible vanadium by-product or troublesome impurity.

IMPLICATIONS OF GANGUE MINERALS (CONT.)

- Quartz: major component of many deposits; non-reactive in leaching.
- Carbonates: consume acid and may make acid leaching uneconomic.
- Silicates: secondary silicates biotite, chlorite, sericite and various clays occur in many deposits.
  - Consume acid - increases with lower pH & higher temp.
  - Sub-micron silica slimes adversely affect solid/liquid separation, solution clarification and phase disengagement in SX, and form crud in SX.
  - Can cause percolation problems in heap leaching.
- Gypsum: reacts with carbonate leach solution, leading to higher opex.

IMPLICATIONS OF GANGUE MINERALS (CONT.)

- Iron Oxides: hydrous oxides-hydroxides such as goethite attacked by acid:
  - Contribute ferric ions to leach solution, which are vital for oxidizing tetravalent uranium minerals.
  - Consume acid.
- Hematite and magnetite: only attacked by acid in very aggressive conditions below pH 1.0.
- Fluorite: attacked by acid:
  - Can enhance leaching of uranium minerals.
  - Consumes acid - increases with lower pH & higher temp.
  - Can cause colloidal silica formation.
  - Increases corrosion.

IMPLICATIONS OF GANGUE MINERALS (CONT.)

- Carbonaceous Material: generally unreactive, but can still cause problems:
  - Can lock away uranium mineral.
  - Tends to float during leach so that contained uranium may not be properly exposed to conditions.
  - Can cause foaming in leaching.
  - Can adversely affect solid/liquid separation.
  - Can adversely effect phase disengagement and form crud in SX.
- Rare Earth Minerals:
  - Included in some uranium minerals (eg coffinite, uraninite & brannerite).
  - Variable solubility in acid leach. Possible by-product.

Carry out initial thorough and systematic geological and mineralogical studies, and detailed chemical analyses of drill samples to:

- Classify the ore deposit versus other known types of deposits.

- Identify ore types within the deposit with potentially different metallurgical properties based on chemical and physical properties of gangue and uranium minerals.

Benchmark the deposit against other past and present commercial operations and/or projects attaining feasibility study level for similar deposits to:

- Gain information on successful and unsuccessful geological interpretation resource assessment, mining and treatment methods, metallurgical testwork and scale-up strategies, climatic effects, logistical, political and social issues, and performance data.
- Activities can include site visits, searching for available reports and published papers, and talking to personnel and consultants involved.

Undertake a THOROUGH Scoping Study covering ALL aspects of the project including:

- Initial resource tonnage and grade estimates at various cut-offs.
- Identification of potential ore types.
- Development of conceptual mining strategy and costs.
- Identification of most likely treatment methods.
- Identification of potential impurity problems and/or by-product opportunities.
- Assessment of ore upgrading potential.
- Development of conceptual flowsheets.
- Development of preliminary strategies for disposal of waste, residue, tailings or solution bleed streams.

- Identification and preliminary assessment of potential water sources.
- Preliminary testwork for most likely processes based on mineralogy, grade and benchmarking.
- Conceptual flowsheet, key equipment sizing, conceptual layout.
- Preliminary assessment of logistics and infrastructure.
- Preparation of order-of-magnitude capex and opex.
- Identification of possible climatic, environmental, social and political issues.
- Preliminary market study
- Preliminary economic and risk analysis covering all aspects of the project.
- Selection of preferred process or short listed mining methods and treatment processes.

Make a decision whether to:

- Move on to a Prefeasibility Study (PFS).
- Undertake further scoping level work.
- Bring in a partner.
- Sell the project.
- Walk away.

Factors influencing decision include:

- Marginal economics due to refractory ore, low grade or insufficient ore reserves.
- Lack of funding.
- Lack of reliable water supply
- Major environmental issues.
- Remote location and/or difficult logistics.
- High risk social and/or political issues.

If proceeding with a PFS:

- Specify preferred or short listed mining methods and treatment processes for the PFS.
- Incorporate metallurgical and mineralogical input to procedures for drilling program and geological model.
- Prepare project development plan, schedule and cost.

Factors to consider when selecting possible treatment routes include:

- Basic processes are unchanged from the previous uranium boom in 50s – 80s.
- Various process steps and equipment were "borrowed" from the initial uranium flowsheets and further developed in the treatment of copper, gold and nickel-sulphide ores. These developments can now be transferred back into the new wave of uranium operations.
- There are also some new innovations which can be considered.

Also,

- Current deposits are typically lower grade and/or more mineralogically complex. (except of course the very high grade Canadian deposits).
- Environmental and decommissioning regulations are generally more stringent.
- On the positive side – **Uranium price is higher.**

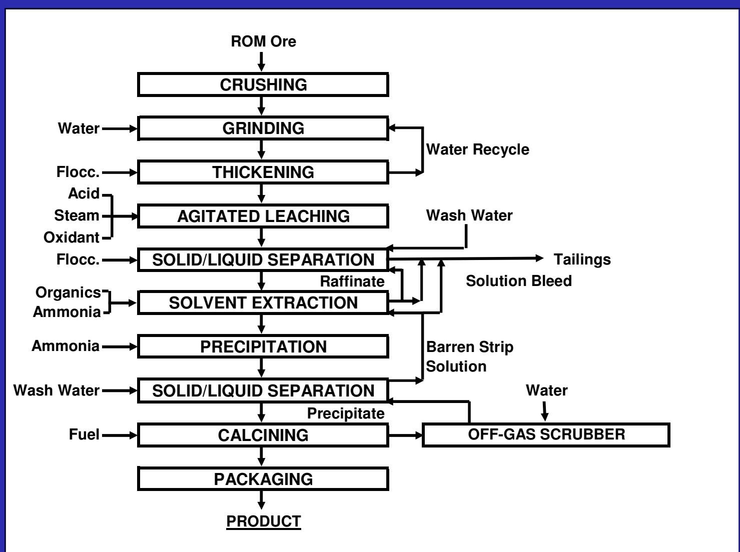
BASIC PROCESSES ARE

- Agitated leaching with sulphuric acid solution at atmospheric pressure and low to medium temperature.
- Agitated leaching with sodium carbonate-bicarbonate solution at atmospheric pressure and medium tot high temperature.
- In-situ leaching with sulphuric acid or bicarbonate solution.

And,

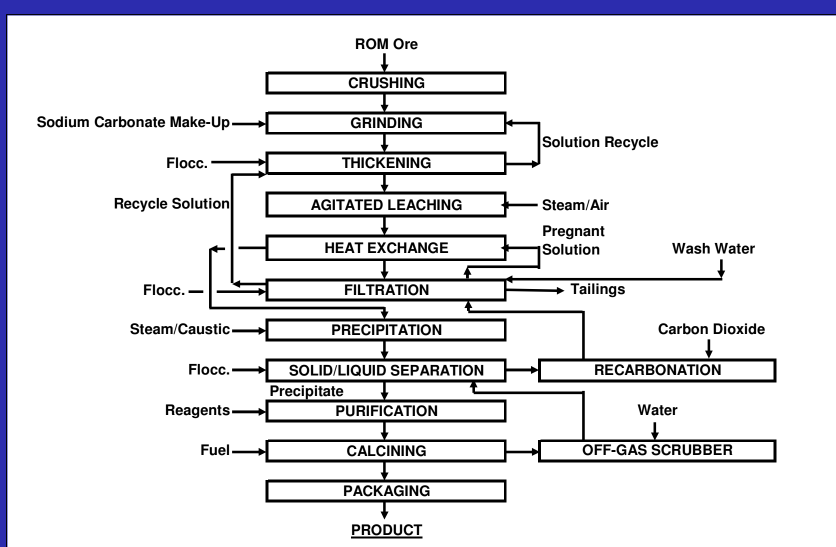
- Strong acid pugging and curing.
- Pressure leaching with sulphuric acid or bicarbonate solution.
- Heap leaching with sulphuric acid or bicarbonate solution.
- Vat leaching with sulphuric acid solution.

AGITATED ATMOSPHERIC ACID LEACH FLOWSHEET



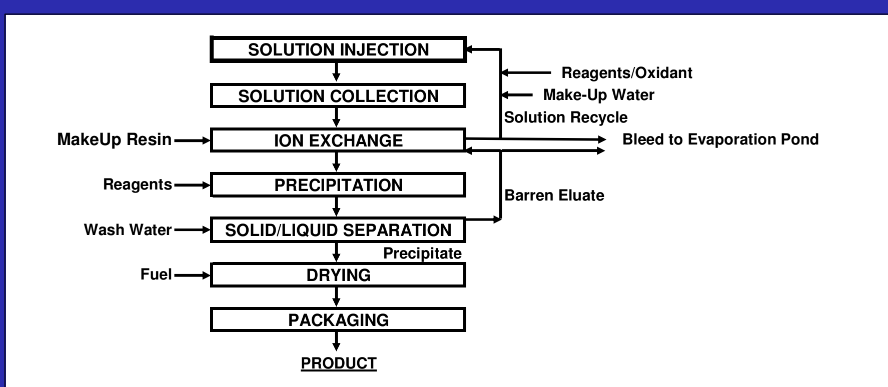
ATMOSPHERIC AGITATED ACID LEACH CIRCUIT, USA

AGITATED ATMOSPHERIC CARBONATE LEACH FLOWSHEET



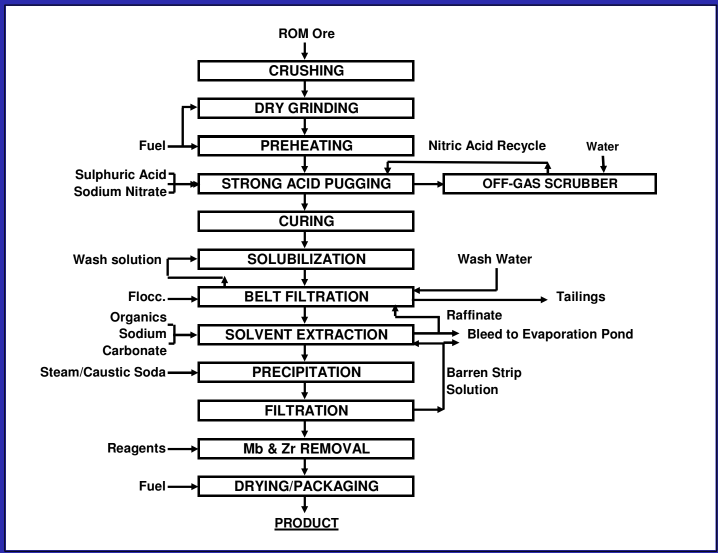
LANGER HEINRICH OPERATION, NAMIBIA

IN-SITU LEACHING FLOWSHEET



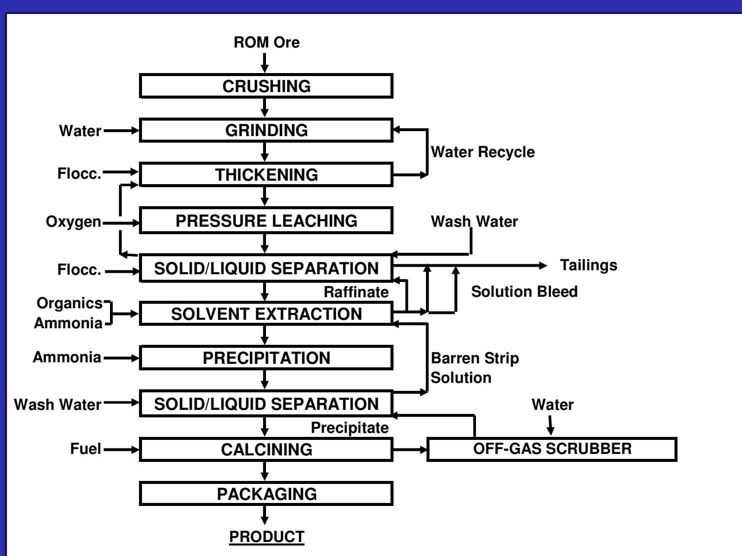
BEVERLEY ISL OPERATION SA

STRONG ACID PUGGING FLOWSHEET (SOMAIR, NIGER)



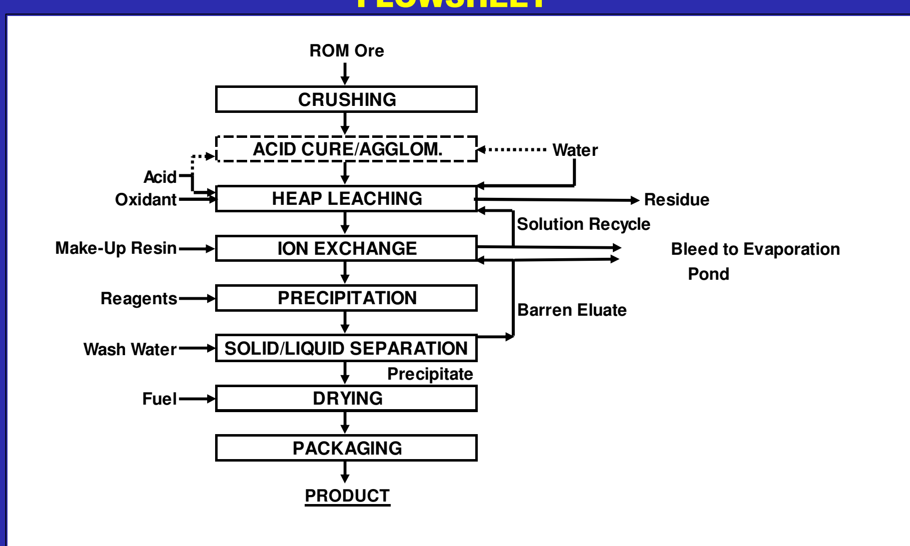
SOMAIR OPERATION, NIGER
(Ref: Areva Presentation at ALTA 2009)

PRESSURE ACID LEACH FLOWSHEET



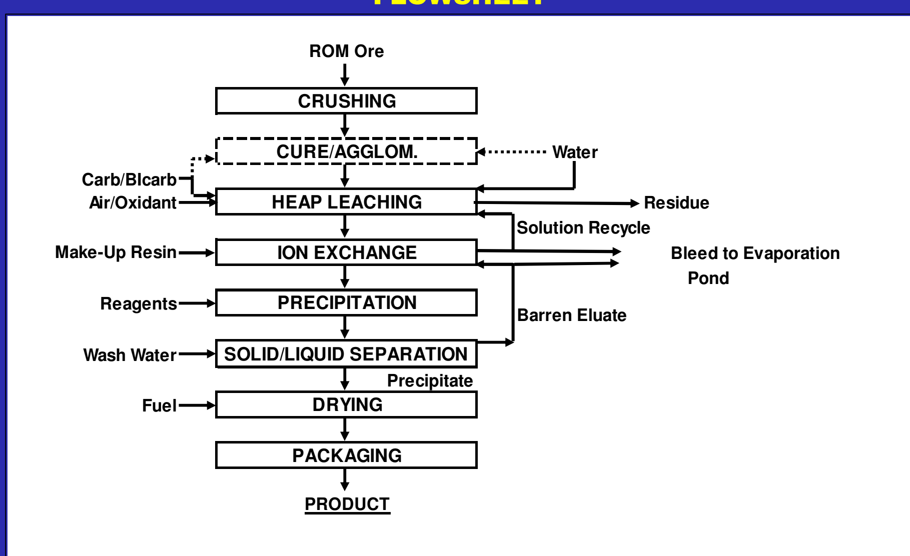
DOMINION REEFS OPERATION, SOUTH AFRICA

TYPICAL URANIUM ACID HEAP LEACHING FLOWSHEET



CAETITE HEAP LEACH OPERATION, BRAZIL
Ref: Gomiero Presentation at IAEA Meeting, Nov. 2009

TYPICAL URANIUM CARBONATE HEAP LEACHING FLOWSHEET



TREKKOPJE HEAP LEACH, Ref: African Mining, June 2010

PRECONCENTRATION OR PRETREATMENT CAN SOMETIMES BE USED, INCLUDING:

Radiometric Ore Sorting to:

- Increase grade and possibly reduce acid consumers.

Flotation to:

- Produce sulphide concentrate for leaching.
- Reject sulphides prior to carbonate leach to avoid high carbonate consumption.
- Produce sulphide to reject acid consuming carbonate gangue minerals.
- Reject consumers in a flotation concentrate.

Sizing for:

- Sand/slime separation with rejection or separate leaching of sands.
- Attrition grinding followed by classification, with screens or cyclones
- Dry grinding and air classification.

Magnetic Separation for:

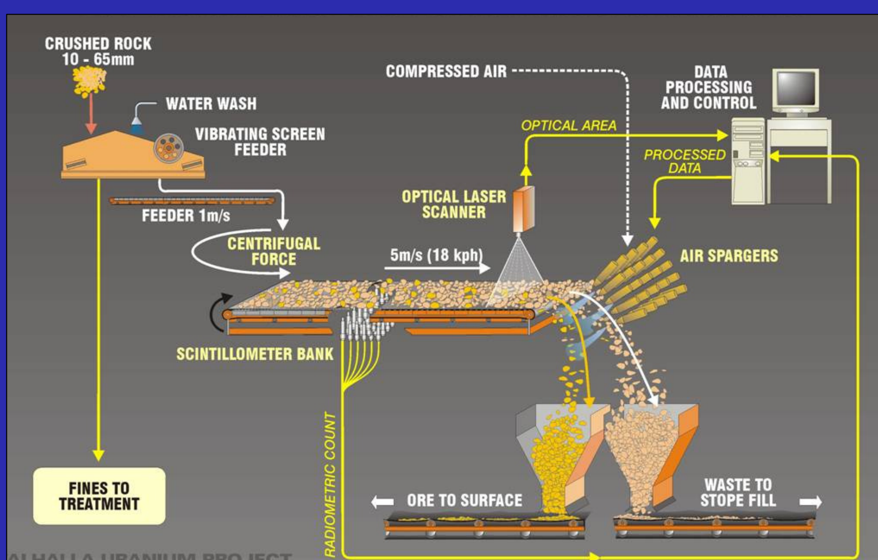
- Dry beneficiation for arid regions.

Gravity Separation to:

- Make sand/slime split to produce a sand reject.
- To produce HG uranium conc. With separate treatment of tails.
- To scavenge base metal float tails.

Methods used include jigs, spirals, Reichert **cone**, tables, and heavy media,

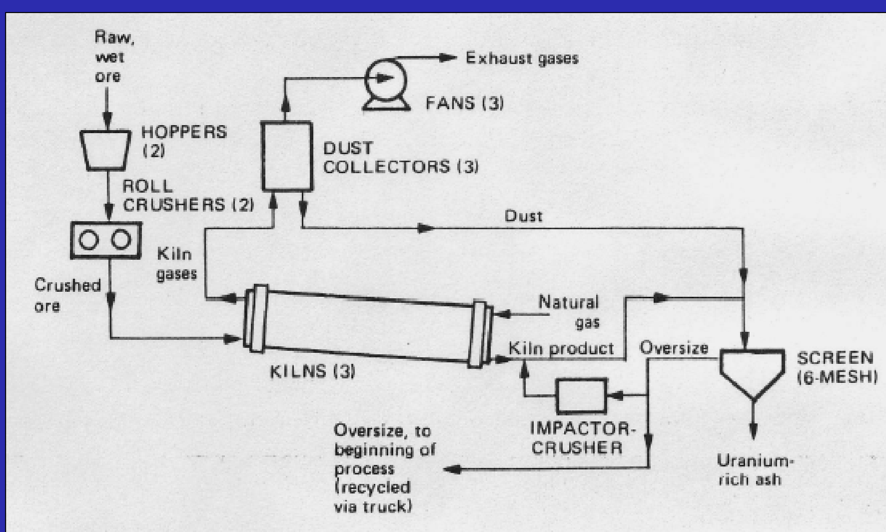
RADIOMETRIC ORE SORTING SYTSEM



Pre-roasting sometimes used:

- Salt roasting with sodium chloride to improve recovery of vanadium from carnotite ores.
- Oxidizing roast to improve uranium recovery from tetravalent minerals.
- For clayey ore to improve solid-liquid separation characteristics after leaching (utilized before availability of effective flocculants).
- To remove troublesome carbonaceous materials.
- To pre-treat uraniferous lignites to produce U rich ash for further treatment.

LIGNITE CALCINATION FLOWSHEET



- **Leaching testwork must be carried out with upgraded or pre-treated ore**
- This can significantly increase sample requirements, costs and testwork program duration.
- It can also be difficult to replicate the commercial scale preconcentration of pre-treatment step on a laboratory. A large pilot plant semi-industrial scale facility may be needed to reduce risk.
- Such a program is much easier for a brown field project with operating facilities on site. These challenges are particularly acute for a green field project
- Example: radiometric ore sorting has generally been adopted for existing operations.

Technology and equipment transfers/further developments include:

- Resin-in Pulp (RIP): >uranium>gold>uranium
- Solvent Extraction (SX): >uranium>copper/cobalt nickel>uranium
- Heap leaching: copper>uranium>gold>copper>uranium
- Vat leaching: copper>uranium
- Pressure leaching: nickel/cobalt>uranium>gold>nickel/cobalt>copper>uranium
- High Capacity Thickeners> copper/cobalt nickel>uranium.
- Belt Filters: uranium>copper>uranium.

New innovations for consideration include:

- Pulsed column (Bateman) for SX.
- HPGR (high pressure grinding rolls) for fine crushing ahead of heap leaching.

There may be opportunities for by-products such as:

- Vanadium
- Molybdenum
- Base metals
- REEs

Possible methods for recovery can be gained from benchmarking against previous operations.

A thorough, systematic initial project phase covering all the basis lays a sound foundation and is a sound investment.

THE TEMPTATION TO TAKE SHORT CUTS

SHOULD BE AVOIDED AT ALL COSTS!