ECONOMIC AND TECHNICAL CHALLENGES OF NON-CHINESE CLAY HOSTED RARE EARTH DEPOSITS

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Mineralogy - IADs

- Ionic Adsorption Deposits (IAD) operating in China, Myanmar and Vietnam are characterised by clay minerals (kaolinite and halloysite)
- Rare earths (REs) are weakly adsorbed onto the surface structures, contained in hydration layers or substituted with exchangeable cations
- REs can be released (via desorption) into solution via cationic exchange – typically using ammonium sulphate solution
- Desorption efficiency and kinetics can be enhanced in slightly acidic conditions – typically ~ pH 2 to 4
- Typical RE content is 500 to 2000 ppm TREO with a higher distribution of the HREs (Sm to Lu + Y) than the hard rock and mineral sands deposits
- Currently accounts for ~70 to 80% of the world's HRE production

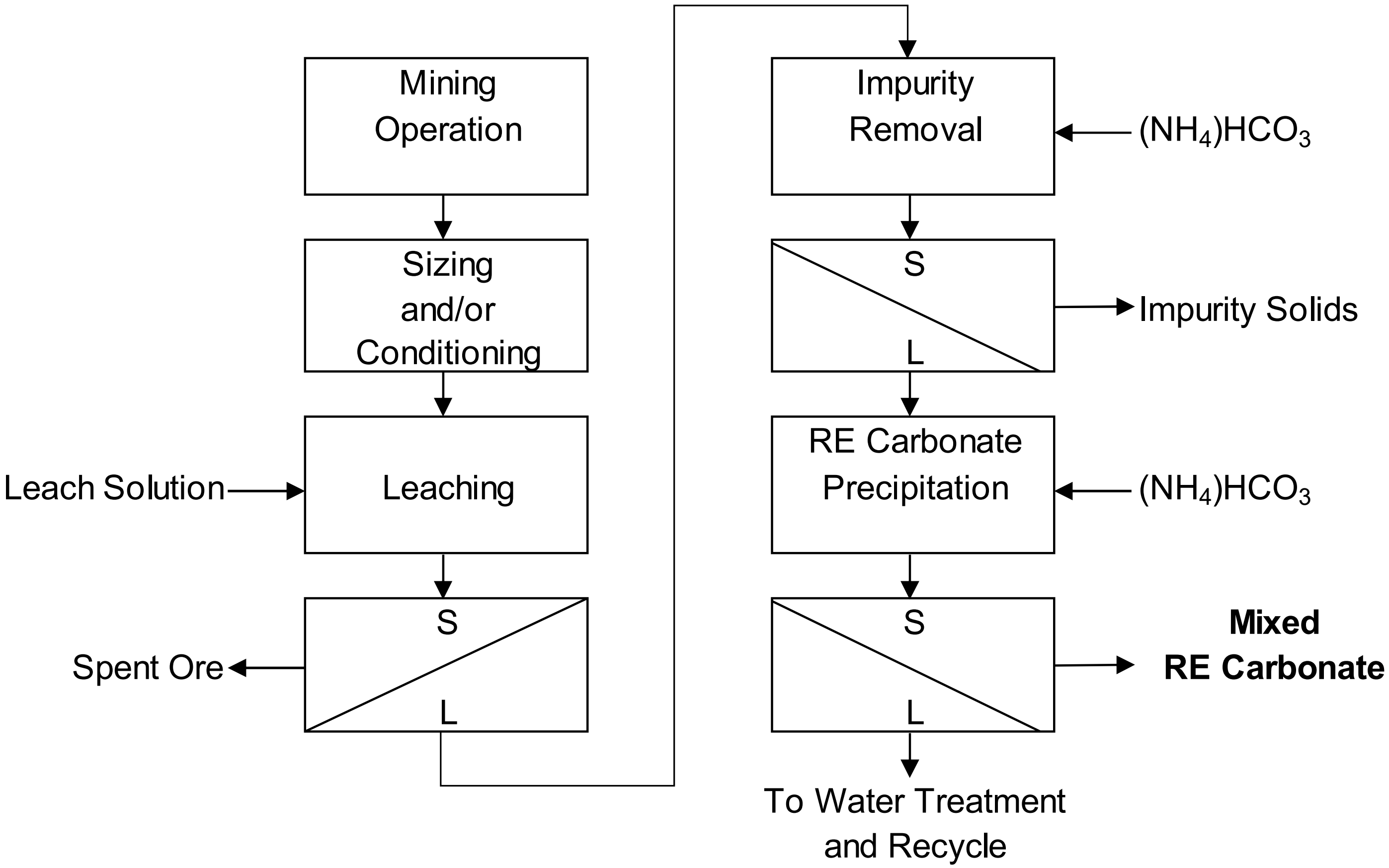
Mineralogy - WAE

- Weak Acid Extractable (WAE) clays are characterised by minimal RE extraction with straight cation exchange
- Require acidic solution to release the REs
- Typically some RE extraction are seen at moderate pH values (pH 4), however low pH values down to pH 1 are generally required
- Most likely a combination of strongly bound ionic adsorption clays and of acid soluble minerals (bastnaesite, apatite etc) present
- Some historical evidence of this processing in China, but now uncommon due mainly to environmental constraints
- Significant impurities (Fe, Al, Si etc) will also be solubilised

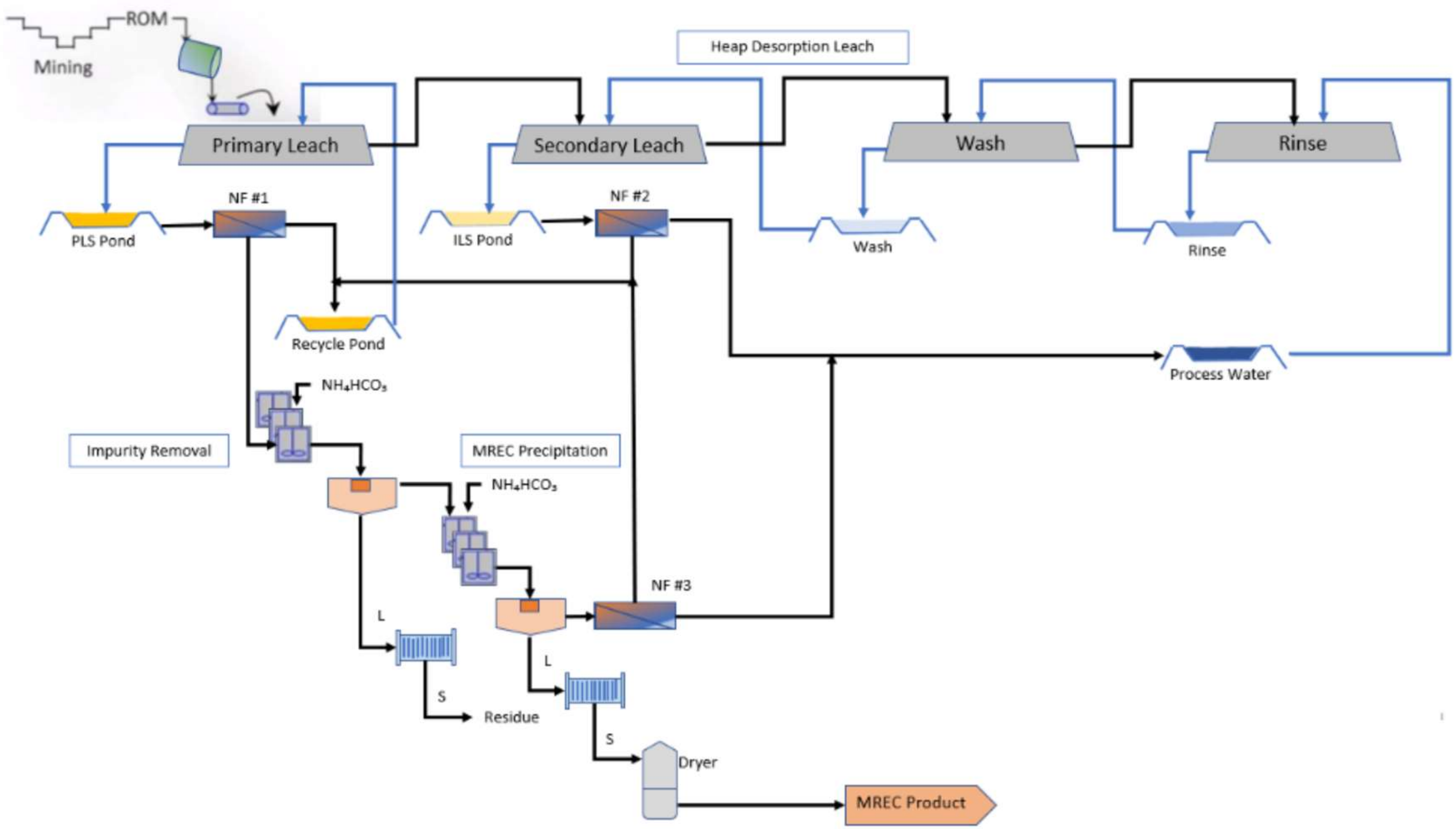
Mineralogy - Other

- Low concentration of RE host minerals such as:
  - Refractory phosphates (monazite/xenotime)
  - Refractory silicates (allanite/euxenite)
  - Acid soluble phosphates (apatite)
  - Acid soluble fluorcarbonates (bastnasite/synchesite)
- Ionic desorption via ammonium sulphate is not effective
- High acid consumptions expected for acid soluble minerals with gangue minerals being the major consumer
- Refractory RE minerals only minimally solubilised ever at strong acid strengths

General Flowsheet



Heap Leach Flowsheet



Makuutu Rare Earths Project Stage 1 DFS Process Flowsheet

Ionic Rare Earths ASX Release 20 March 2023

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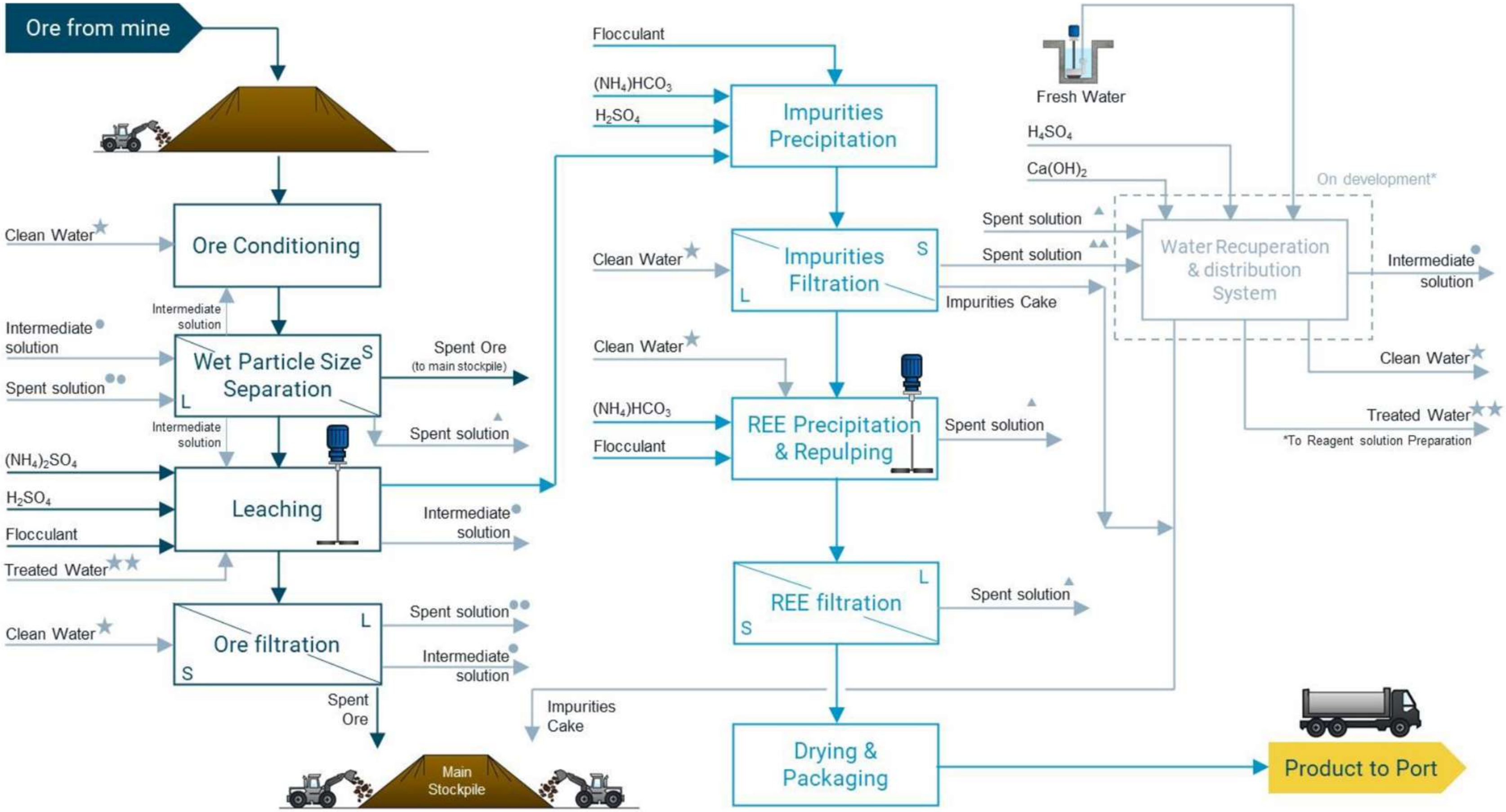
Stirred Leach Tank Flowsheet



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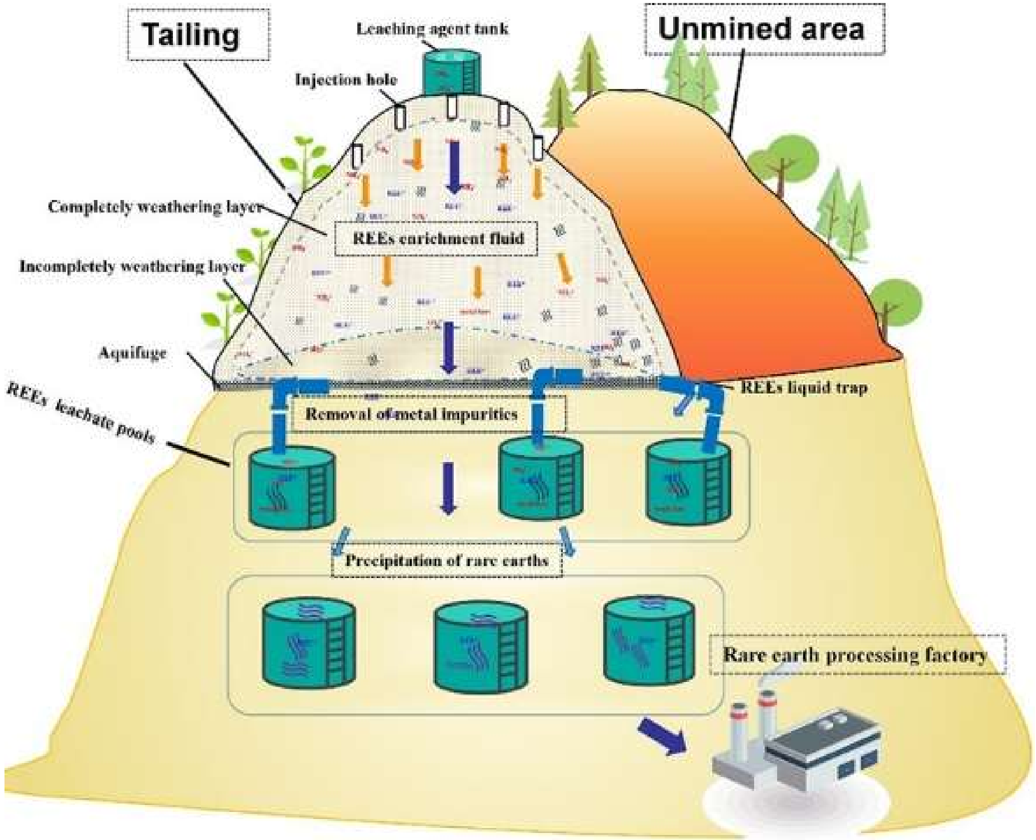
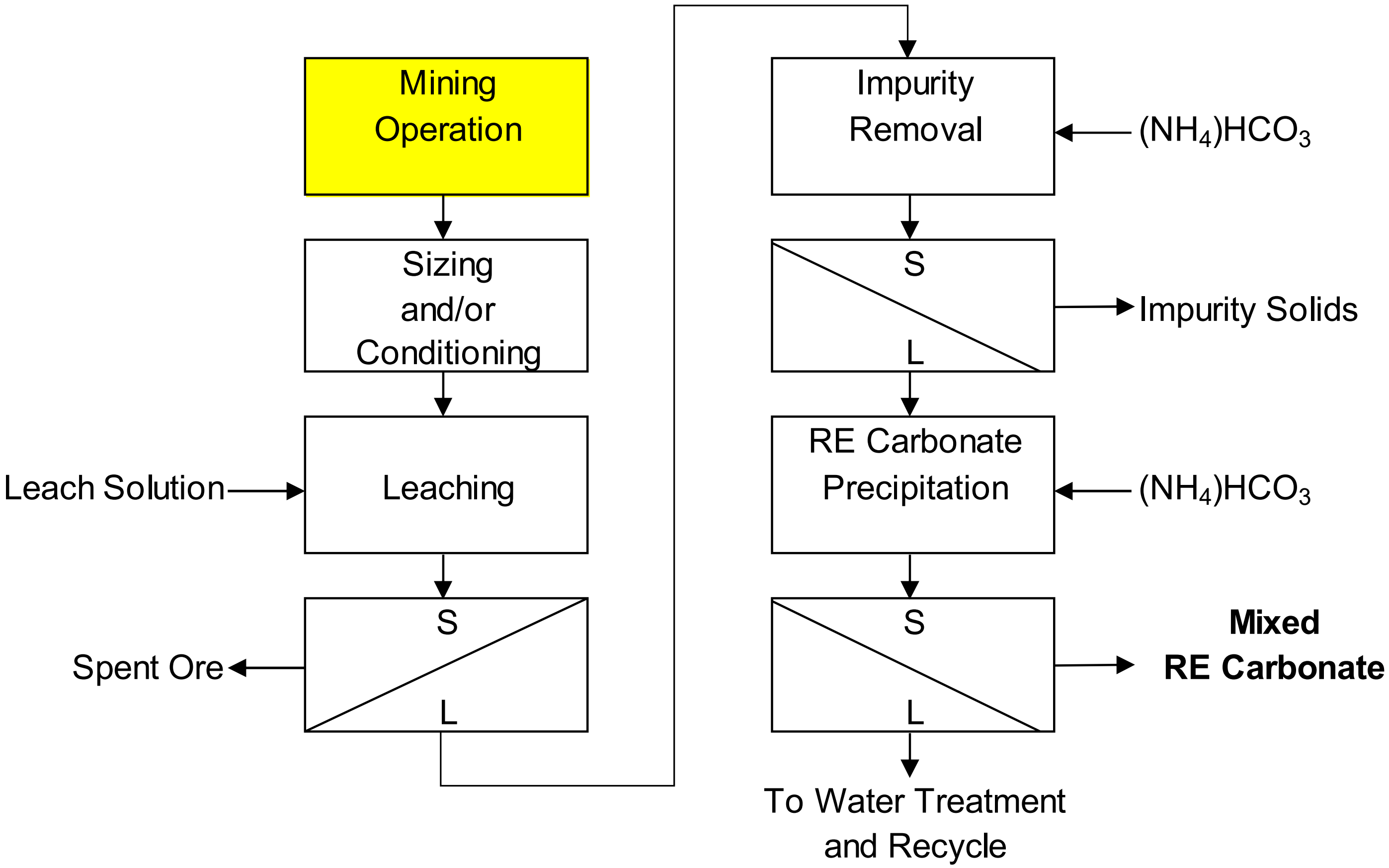
In-situ Leach Example



Example of In-situ Leaching

Mining

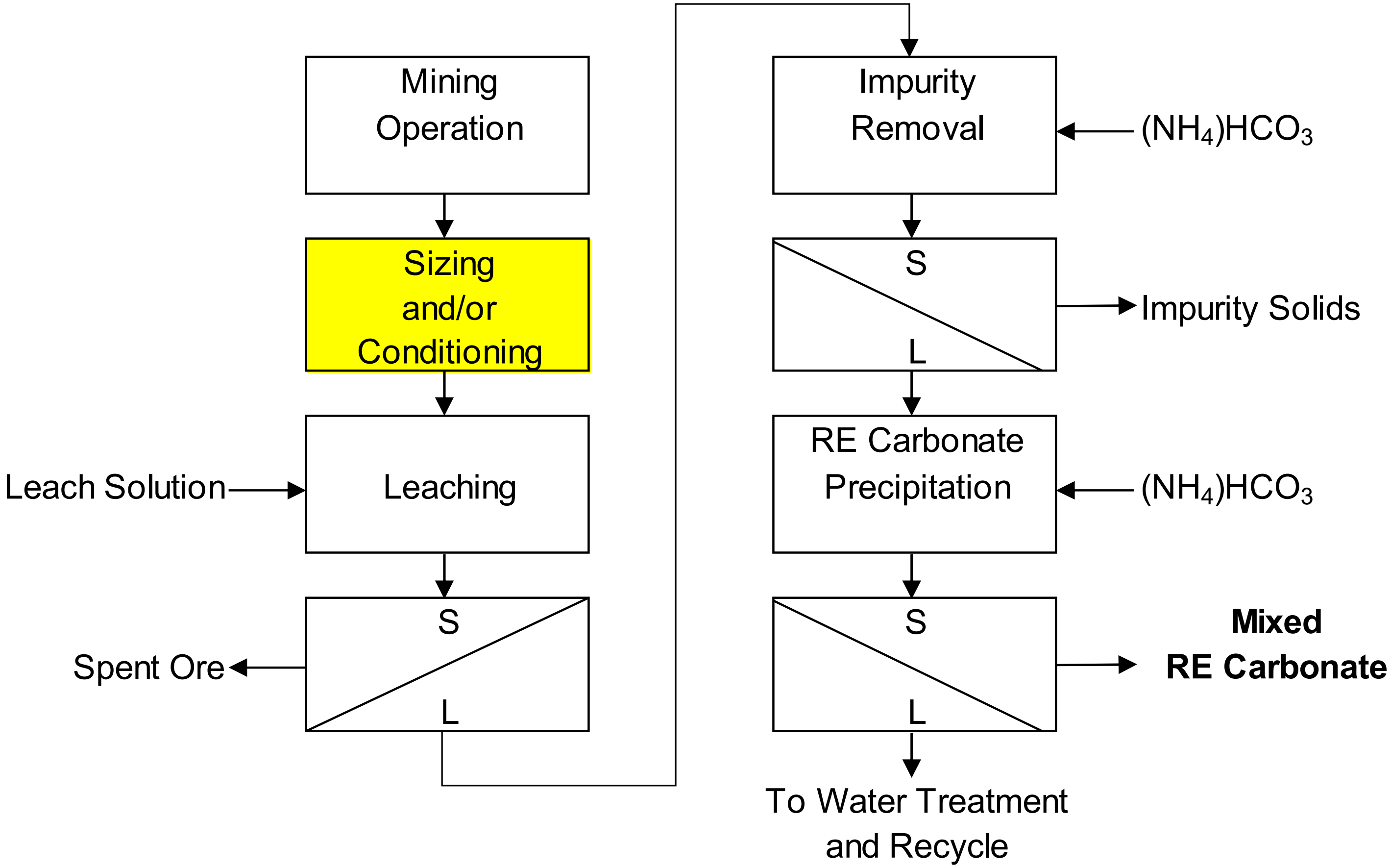


Mining Operation
Sizing and/or Conditioning
Leach Solution
Leaching
S
L
Spent Ore
Impurity Removal
(NH4)HCO3
S
L
Impurity Solids
RE Carbonate Precipitation
(NH4)HCO3
S
L
Mixed RE Carbonate
To Water Treatment and Recycle

Hydraulic Mining Example

Former rare earth mining site in Jiangxi province, China
Photo: Michael Standaert – Yale 360

Ore Preparation



Ore Preparation

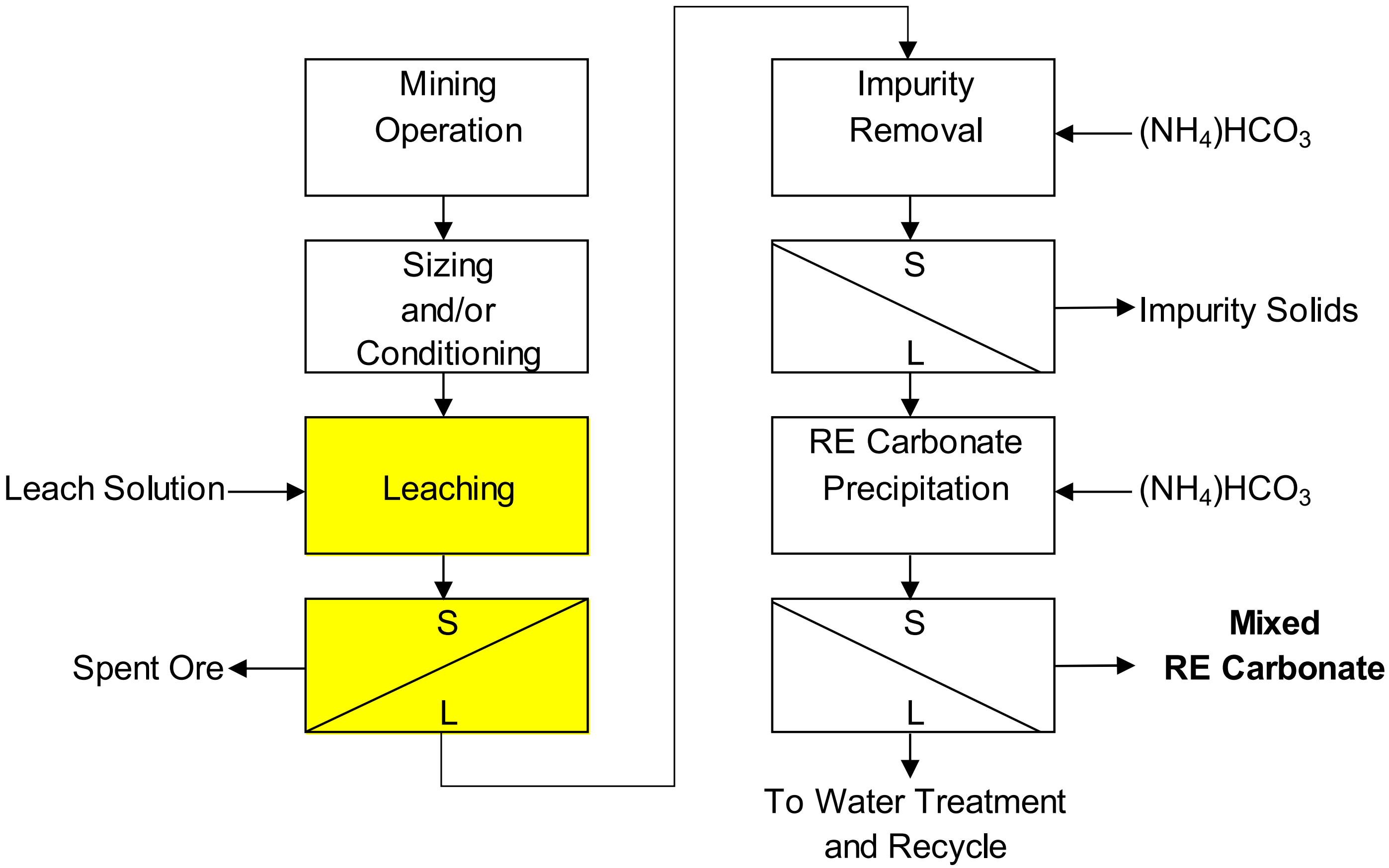
- In-situ leaching
  - Requires appropriate aquifer and solution monitoring preparatory work along with injection and recovery holes
  - Questions of soluble sulphate and ammonia remaining in-situ?

- Heap leach
  - Screening, agglomeration, and careful stacking
  - Clays are prone to swelling and structural challenges in heaps
  - Percolation and channelling considerations

- Stirred leach tanks
  - Scrubbing and desliming – can use leach or spent solution

- Significantly more costly than Chinese practices!

Leaching



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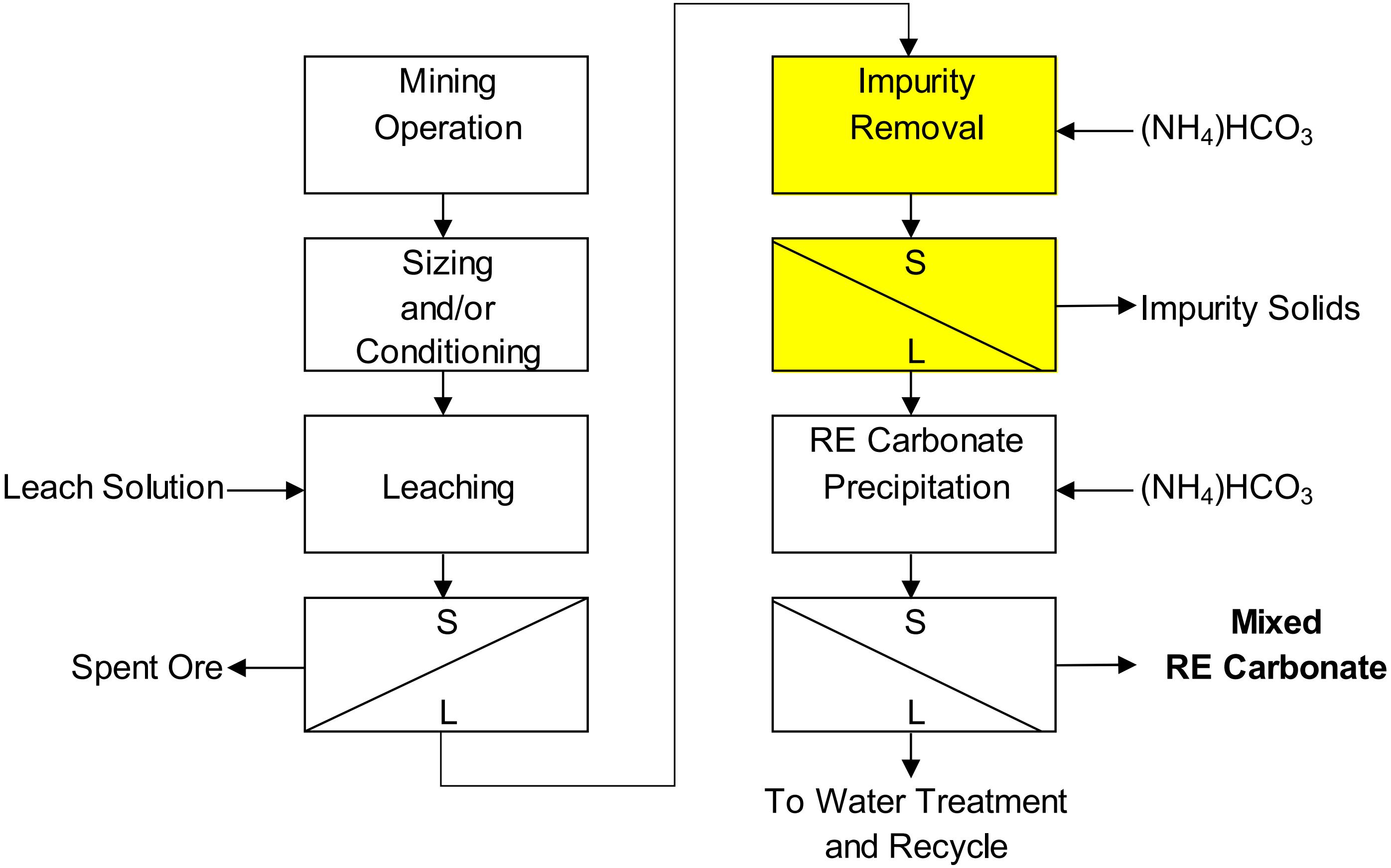
Leaching

- Leach conditions typically:
  - ~20 g/L ammonium sulphate
  - pH 2 to 4 adjusted with sulphuric acid for IAD mineralogy
  - pH 1 or lower for WAE with acid consumptions 50 to 100 kg/t
  - Fast desorption or REs – typically <15 minutes
- RE extraction is usually "modest" at between 30 to 50%
- Heap leach requires agglomeration for stability and percolation
- Tank leaching will require:
  - Classification (screening and/or cycloning)
  - Filtration is challenging in these clays
  - Spent ore must be <u>well</u> washed of sulphates and ammonia for pit/unlined disposal

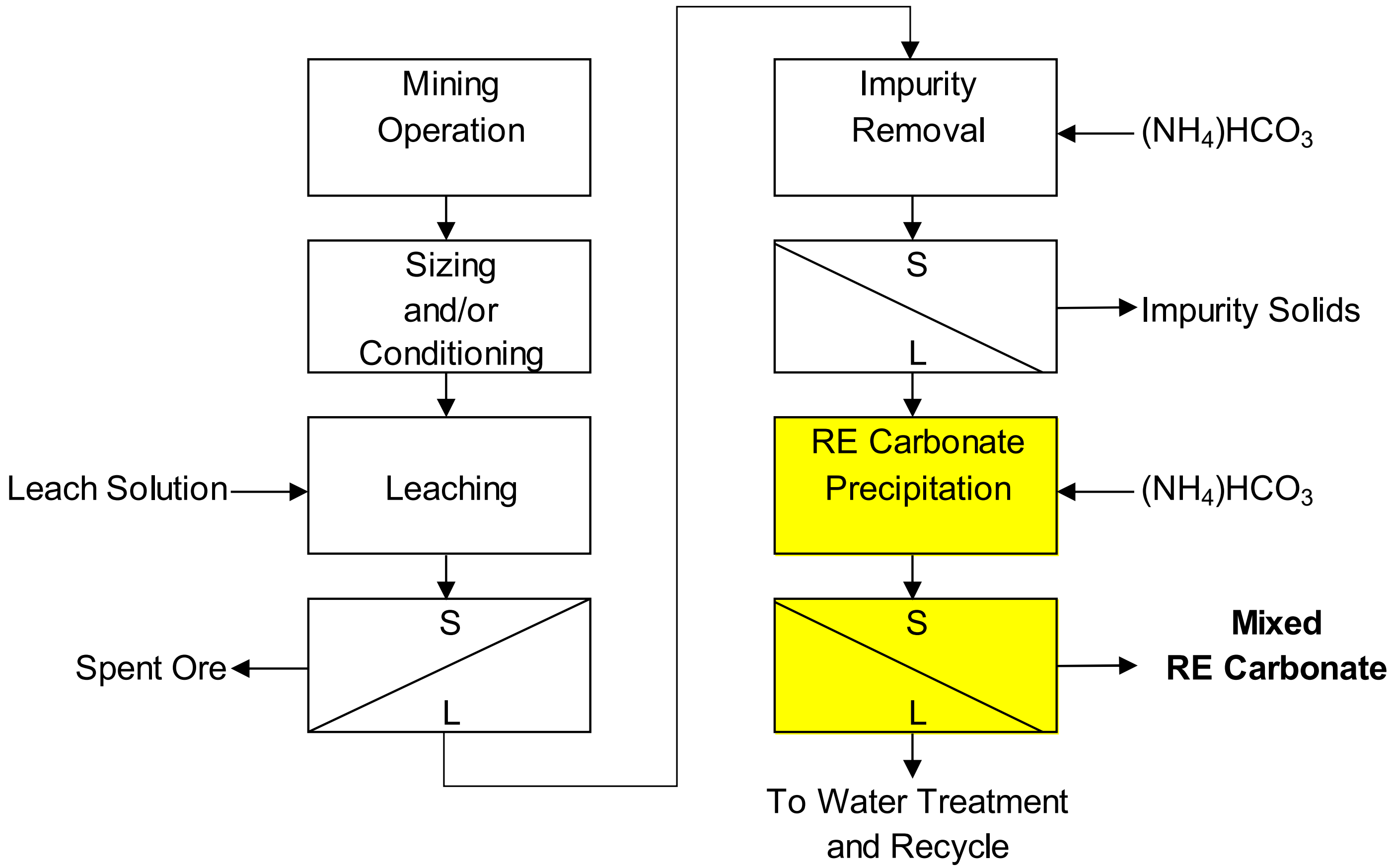
Impurity Removal



Impurity Removal

- Raw leach solution has a very high impurity:RE ratio compared to RE mineral concentrate refineries - **an order of magnitude higher**
- RE losses invariably are high during solution purification
- Ammonium bicarbonate commonly used – expensive
  - Caustic soda and lime can't be used due to co-precipitation of REs
- Removes Fe, Al, Si and Th as hydroxides
- Aluminium and silicon can often make gels which can "rob" dissolved REs
- High addition rates of flocculent required

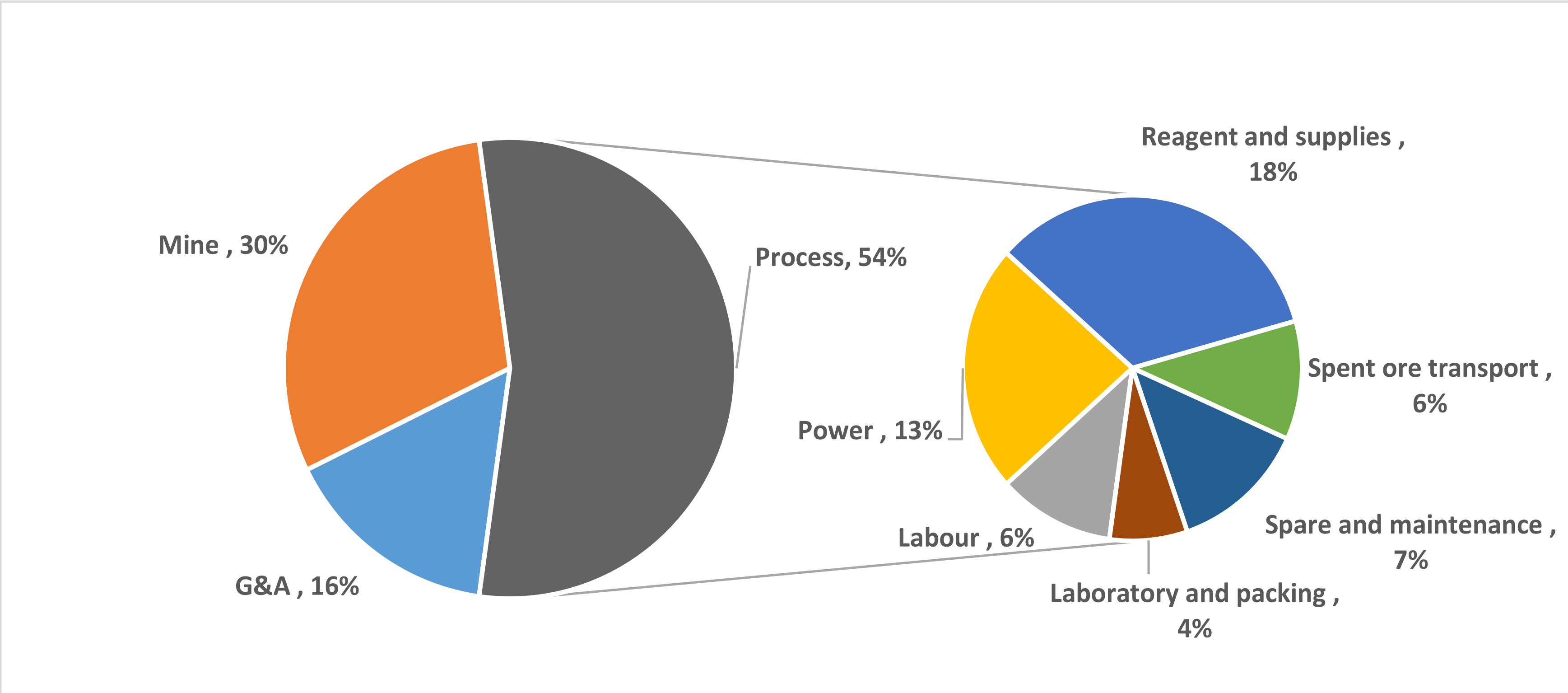
Mixed RE Carbonate Product



Mixed RE Carbonate Product

- MREC is generally precipitated using ammonium bicarbonate
- Low Al_2O_3 (0.1%) is required for Chinese spec MREC. Even lower for Europe.
- Purity often difficult to meet unless RE recovery compromised or MREC refined
- Usually radionuclides (Th and U) within spec, but watch the decay daughters
- Final product is dried and bagged for export

Example of OPEX Cost Breakdown



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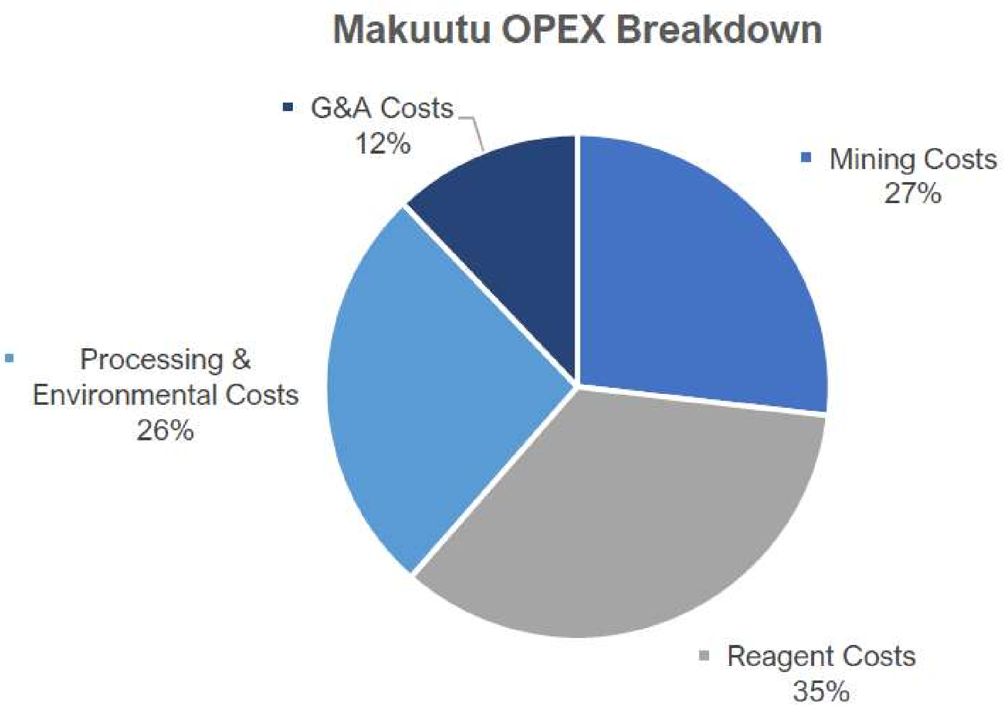

Makuutu Rare Earths Project Stage 1 DFS Process Flowsheet

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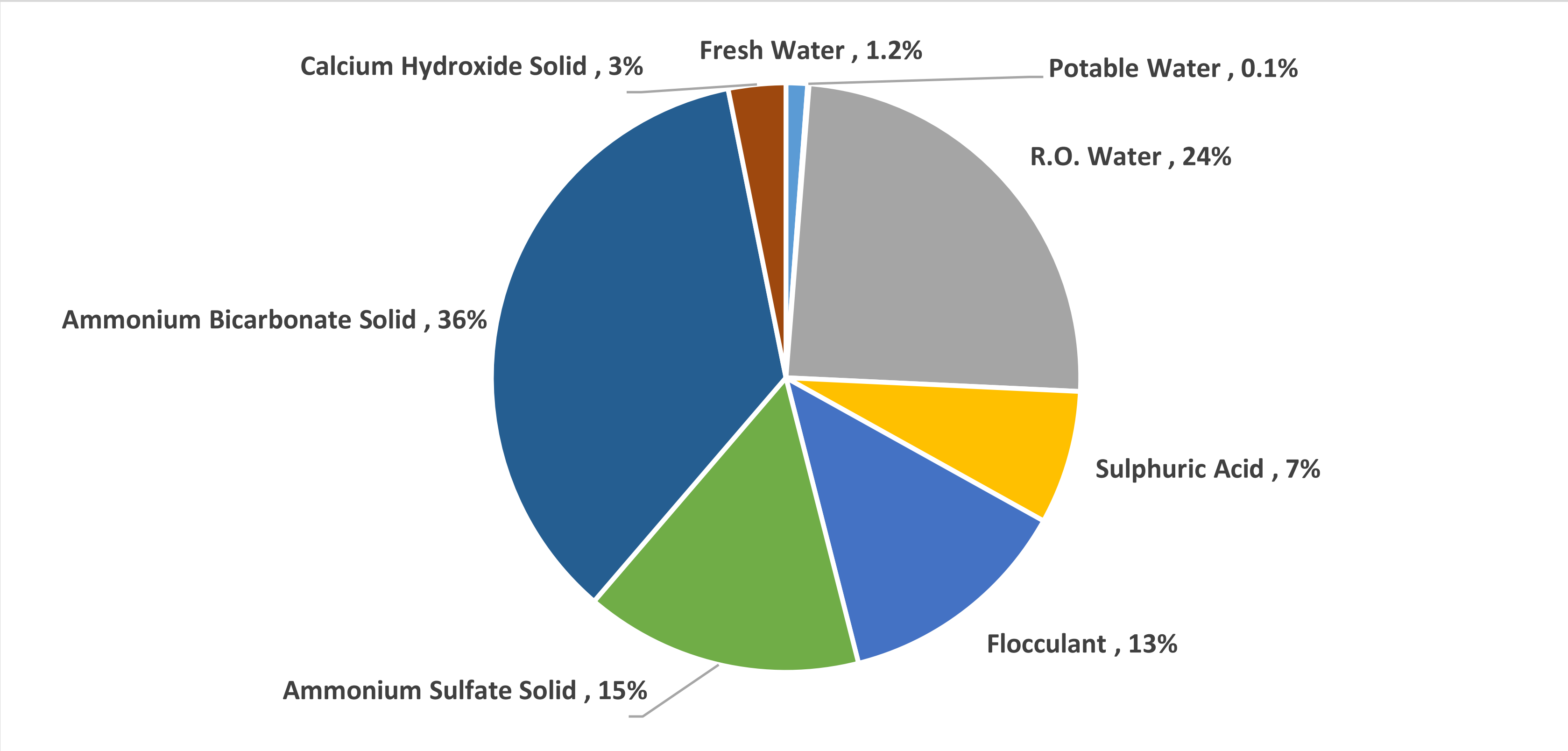
Example of Reagent Cost Breakdown
% of Total Reagent Only



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OPEX Commentary

- Reagent costs represent between 10 to 35% of total OPEX
- Ammonium carbonate reagent is the largest reagent expense – especially if leach liquor contains excess free acid
- Due to the high volumes of clays, flocculent costs are significant.
- The process requires a LOT of water to both extract REs and to remove soluble sulphates and ammonia from spent ore prior to rehabilitation
- Water treatment costs for recycle (nanofiltration) and/or discharge should not be underestimated

CAPEX Commentary

- Stirred tank reactor design:
  - Large tanks required, but offset by very fast desorption kinetics
  - Very large plate and frame filters
- Heap leach:
  - Potential for significantly reduced plant costs
  - But – increased risk of poor percolation
  - Agglomerator and stackers required

Assumed Revenue from RE Carbonate

- Off-take contract terms are now becoming more widely known
- Typically only 6 REs are paid for:
  - La, Ce, Pr, Nd, Tb and Dy
- Terms may be “simple”, eg
  - Very small % of La/Ce and high % of Pr, Nd, Tb and Dy of separated oxide pricing paid outright
- Or “complex”, eg
  - Above 6 RE separated oxide pricing less: refining charges, losses, admin charges
- Assigning a blanket discount value to fully separated basket pricing as oxide equivalents will overstate likely true sales revenues!

Take Home Thoughts

- Simple laboratory desorption tests provide a “go-no-go” assessment as to RE desorption mechanisms at play
- How much reagent are you using? If the combined cost of the H_2SO_4 and $(NH_4)_2SO4$ if more than >10% of the “basket price” of Nd, Pr, Tb + Dy then you will be up for a challenge
- Don’t forget radionuclides – these may be low in the ore but will concentrate with the REs into the RE carbonate (hint – Ac^{227})
- Last thought – are the Chinese/Myanmar operations actually “profitable” in a Western business model?

Thank you
&
Questions?