THE ALUMINA REFINERY OF THE FUTURE

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ABSTRACT

Technology improvement over recent decades has drastically reshaped many aspects of our lives. Computing and telecommunications advancements for example have made social interactions virtually unrecognisable. Emergent technologies such as self-driving vehicles look likely to reshape the world further.

The Bayer Process for alumina production, relative to forty years ago, remains somewhat disappointingly recognisable.

In forty years' time what could a modern alumina refinery look like? What are the research and development initiatives needed to support significant change, and is there sufficient business case to fund this R&D? Are we destined to remain disappointed with the rate of technological improvement?

This paper reviews the major innovations delivered over the last forty years and contemplates future directions for step changes in capital cost, operating cost and EHS performance.

1. INTRODUCTION

In 1978, global alumina production was 30 million tonnes; alumina price was around US$164/t (~$645/t in today's dollars) and there was significant interest in technological developments to produce alumina from clay using hydrochloric acid (Baumgardner & Hough, 1978).

Forty years later, global production has quadrupled, long term alumina price has halved in real terms, and the Bayer process remains the dominant route to alumina.

This paper contemplates what a modern alumina refinery might look like in 2058.

2. CHANGES IN THE LAST 40 YEARS

2.1 The Technology of 1978

In 1978, the world's largest refineries (QAL and Pinjarra) were producing around 2.5 million tonnes each (Stephen, 1988). Within the next few years, construction was to start on 8 new refineries (San Ciprian, Puerto Ordaz, Aughinish, Wagerup, Worsley, Alumar, Damanjodi and Alunorte). The installed equipment and flowsheets of these refineries provide a snapshot of the "state of the art" at the time. Additional perspective is given by Hudson (Hudson, 1988).

2.2 Unit Capacity

In 1978, the largest Bayer units produced around 0.8 million tonnes per line per year. Today that has increased to around 2.0 million tonnes, although the majority of operating plants are still below 1 million tonnes per line.

2.3 Digestion Technology

In 1978, refineries using split-stream digestion heating technology outnumbered single-stream by about four to one (Advisian database estimates). For units built in the last 10 years, this ratio has reversed. The incentive is improved energy efficiency and reduced cleaning frequencies.

Average energy consumption per tonne production for new refineries is now about 30% lower than in 1978 (Advisian database estimate).

Digestion variations of Sweetening and Double Digestion have found opportunistic applications dependent on bauxite grades.

Digestion vessels have tended to move away from mechanical agitation in order to improve reliability and facilitate robotic cleaning. Flash tank design has shifted from top-entry to bottom-entry.

2.4 Mud Separation, Washing & Disposal

This is the area of the Bayer process that has probably seen the most significant technological developments.

The polishing filtration unit operation has been revolutionised by equipment developments. Where previously there were dozens of horizontal leaf filters requiring manual hose-out in an unpleasant operating environment,

we now see a handful of large (~600m^2) automated vertical leaf filters.

The development of synthetic flocculants to replace starch led to an order of magnitude increase in settler capacity. Washer feedwell and rake technology subsequently evolved to take advantage of the high densities achievable with these flocculants.

Mud disposal evolved from subaqueous disposal to sloped paste deposition, and is now generally moving to dry cake deposition.

While residue beneficial re-use has increased, it still only represents around 1.3% of total residue production (world-aluminium.org, accessed April 2018).

2.5 Precipitation

Precipitation yield (production rate per unit volume of liquor) for sandy alumina production has increased from 40-50 g/L (Kirke, 1982) to 65-100 g/L. The main drivers have been:

a) Improved process control on the red side, which enables higher average alumina supersaturation delivered to the white side.

b) Development of cost-effective seed filtration equipment, which reduces spent liquor recycle and thereby increases both precipitation rate and holding time.

c) Improved cooling equipment to support additional stages of cooling without additional evaporation.

d) Operation at higher caustic concentrations and solids concentration. There were several enablers behind this, including seed filtration, improved particle size measurement equipment, improved agitation technologies and improved understanding of precipitation fundamentals.

2.6 Calcination

Prior to 1978, the majority of operating alumina calciners were rotary kilns, but improved technologies had already been developed in the 1960's and 70's (Williams & Schmidt, 2012). Virtually all capacity installed since 1978 has used stationary calciners.

Incremental improvements in efficiency have reduced energy consumption to below 2.8 GJ/t, compared to rotary kiln consumption of around 4.5 GJ/t.

2.7 Impurities Removal

The need for improved impurities removal processes has been driven on the input-side by increases in bauxite impurity levels and on the output-side by improved washing of mud.

A full discussion is beyond the scope of this paper and a simple list of significant innovations which have been applied on an industrial scale in the last forty years follows:

- Organics removal technologies (liquor burning and wet oxidation).
- Improved causticisation technologies.
- Improved evaporation equipment to support salting-out processes.

2.8 Product Quality

Forty years ago, the industry shift from floury to sandy alumina production was in full swing. That conversion is now essentially complete. Product quality requirements, and typical refinery performance, have remained relatively constant over the last forty years.

2.9 Process Control

In 1978, process control was largely PLC-based. The shift to DCS-based control has enabled better supervisory control which enables a few extra percent of performance to be squeezed from the same equipment.

Instruments for online analysis (for example, liquor composition, mud settler interface), combined with better laboratory apparatus and methods, allow the refinery to be operated closer to theoretical limits.

The data collection, storage and analysis capabilities of today were unheard of forty years ago and enable better troubleshooting.

2.10 Cleaning & Maintenance

In 1978, process cleaning and maintenance activities were mainly manual, apart from caustic cleaning and acid cleaning.

Today, robotic descaling equipment in conjunction with high pressure water-cleaning technologies have reduced the manual component of cleaning and maintenance activities.

While the use of automated valves has increased, we estimate that less than 5% of cleaning and maintenance isolations are automated.

Variable speed drives have largely eliminated the need for control valves in slurry pumping services, which has reduced the frequency of pump and valve overhauls.

2.11 Capital Costs

Greenfield refineries built in the early 1980's had an average capital cost of around $800 per annual tonne (Kettle, 2005). Applying the ENR Construction Cost Index, the equivalent cost today would be around $2150 per annual tonne.

While costs vary depending on location and infrastructure requirements, today's costs are significantly lower. This can be largely attributed to the technical developments listed above, particularly:

- Increased process productivity (production per unit flow) mean less equipment in general.
- Improved technologies in specific area, for example, synthetic flocculants reducing required washer size, further reducing the equipment list.
- Economy of scale, both in terms of equipment size and overall refinery capacity.

2.11 Operating Costs

The main variable costs in alumina production are bauxite, caustic soda and fuel. Have there been significant shifts in this cost matrix to drive technological change?

In 1978, a barrel of oil cost $14; after inflation this is equivalent to $55 per barrel which is coincidentally the same as the 2017 average price (source: www.statistica.com).

Bituminous coal price was ~$25/t in 1978 (U.S. Energy Information Administration 2012), equivalent to $98/t in 2018, which is around double today's coal prices in real terms.

Caustic soda price index increased from 100 in 1980 to 436 in March 2018 (U.S. Department of Labor 2018). This represents an inflation-adjusted increase of 44%. Insofar as caustic production is subsidised by chlorine sales, it is worth noting that global PVC production has undergone a four- to five-fold increase in the same time, comparable to the increase in alumina production.

Bauxite was around $30/t CIF in 1978 (Baumgardner & Hough 1979) which would be around $118/t today; USGS quotes an average 2017 price of $30/t for US imports but we estimate global average shipped bauxite prices to be closer to $50/t.

Shipping costs decreased by around 9% in real terms between 1978 and 2015 (Olan 2017).

2.12 Non-Bayer Routes to Alumina

Global bauxite reserves are plentiful, and the Bayer processes consumes around one third the energy of non-Bayer processes (Senyuta et al 2013), so there needs to be significant strategic and/or or logistical incentive for Sinter-type processes to be favoured over Bayer. The end of the Cold War and the successful development of bauxite exports from Guinea and Brazil have reduced incentive for non-Bayer production.

To some extent, the existence of alternative technologies (sinter and/or acid processes for alumina production, Solvay process for caustic production) provides a ceiling for commodity prices.

In 1978, around 6% of world production was from non-Bayer processes. Today that figure is around 2%.

3. A POSSIBLE REFINERY OF 2058

The discussion above shows gradual improvements over forty years via a series of evolutionary, rather than revolutionary, improvements in equipment and technology. The lack of revolutionary changes can in part be attributed to a relatively stable cost framework (section 2.11 above).

It is possible that the next forty years also sees a relatively stable cost framework; the likely refinery changes in this scenario are discussed in 3.1 below.

It is also possible that alumina refining sees disruptive changes in cost framework, particularly around energy, transportation and caustic soda prices. Two possible scenarios are presented in 3.2 ("Energy Centre Scenario") and 3.3 ("Renewable Energy Scenario").

A significant shift to non-Bayer production over the next forty years seems unlikely; it requires a combination of low energy prices and high bauxite costs. Since the delivered cost of bauxite is highly indexed to fuel price, this is an unlikely combination.

If alumina production continues to double every 20 years then around 27 billion tonnes of bauxite will be consumed between now and 2058. This compares with estimated global reserves of 30 billion tonnes and resources of 55-75 billion tonnes (U.S. Geological Survey 2018).

A final possibility is that alumina demand dissipates over the next forty years and that there is no "alumina refinery of the future".

3.1 Business as Usual Scenario

With relatively stable underlying economic fundamentals, the refinery of 2058 is likely to be the culminations of multiple small improvements upon the design of today. Refinery productivity and efficiencies will continue to increase as improved technologies are adopted.

One might expect to see:

- Autonomous cleaning and maintenance 'droids and drones;
- Smarter instrumentation, perhaps self-cleaning and self-calibrating;
- More sophisticated AI-based assimilation of available data to support better decision-making;
- Several process and equipment innovations that were not in use in 2018.
- Steadily increasing quantities of residue re-use instead of storage.

3.2 Energy Centre Scenario

If the price gap between transportable energy (coal, fuel oil, LNG) and stationary energy (such as hydroelectric) becomes large enough, there is a business driver to bring the refinery to the energy source rather than the other way around. In this scenario, new alumina refineries would be expected to spring up around the major energy production centres.

Freight costs for transporting large quantities of bauxite will in part be offset by proximity to the aluminium smelters, which would cluster around the same energy centres.

The economics of residue disposal would be highly unfavourable due to the concentration of industry around the energy centres. At the same time, opportunities for re-use of residue as feedstock for neighbouring industries would increase. A zero-waste refinery becomes a practical option.

Figure 1 shows the possible refinery flowsheet for this scenario. The by-products in this case are zeolite and iron ore. The zeolite production route is a variation of that proposed by Siklósi et al (2002).

Other changes that might be seen with this scenario include:

- Electrical heating and/or Mechanical Vapour Recompression replacing conventional steam heating.
- Integration of utilities (steam, water, air) with neighbouring facilities including aluminium smelters.
- Waste and by-product integration with neighbouring facilities.

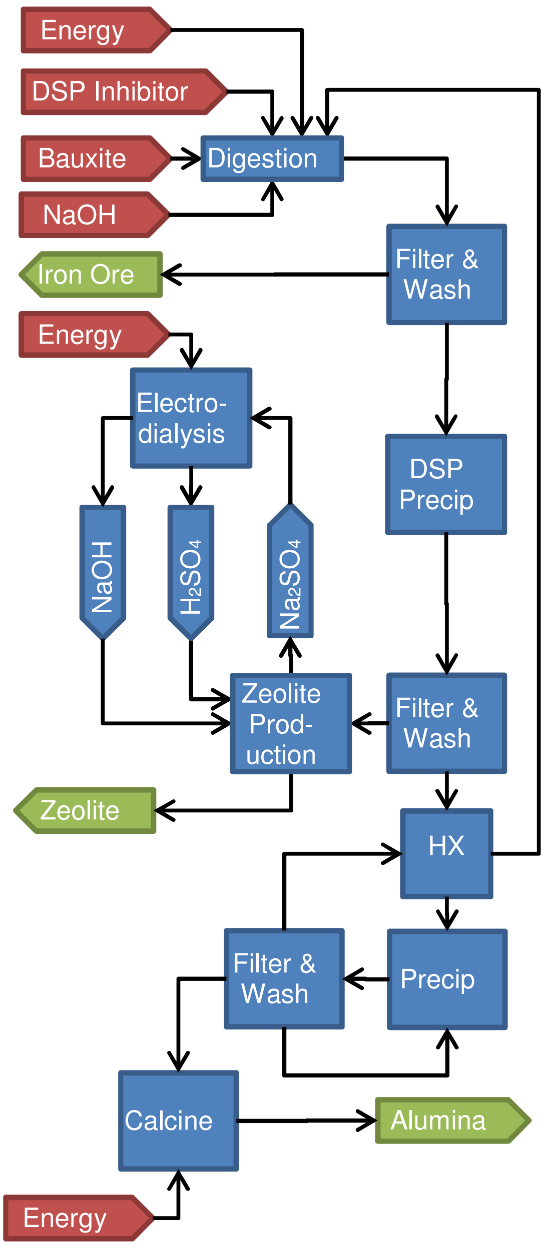

Figure 1. Block Flow for Energy Centre Scenario

3.3 Renewable Energy Scenario

If transportation costs become prohibitively high, we may see a trend towards refineries located close to the mine, using whatever renewable fuel sources are available at the mine location.

In this scenario, the availability of energy is assumed to vary from day-to-day and season-to-season. The refinery design must support rapid startup and shutdown, and must be able to maintain product quality through such stop-start operation. Process control must be able to respond to large changes in liquor composition because the spent liquor A/C ratio will be much lower at the start of each digestion campaign than it will be at steady-state.

Where solar energy is abundant, the refinery may feature:

- Solar-thermal energy supply to digestion.
- Solar calcination of alumina.
- Solar pre-treatment of bauxite (drying, organic carbon removal, boehmite activation).
- Solar-driven impurities removal processes.

If delivered caustic soda price is high enough, some alternative technologies may become attractive:

- Solar causticisation of soda ash ores (trona).
- Solar bauxite-lime-soda sinter process.
- Recover of caustic soda from DSP.

Storage facilities (tanks, stockpiles, sheds and silos) are likely to dominate the refinery landscape, providing surge capacity for short-term imbalances between digestion, mud processing, precipitation and calcination throughputs.

Capital cost economics will probably drive shorter precipitation holding times (when operating) and so precipitation yields may, counter-intuitively, be lower than today's.

There is less techno-economic incentive for residue re-use in this scenario compared to the other scenarios considered above. The remoteness of the mine site adds a freight burden to the re-use opportunity, and the mined-out areas may offer an option for residue storage.

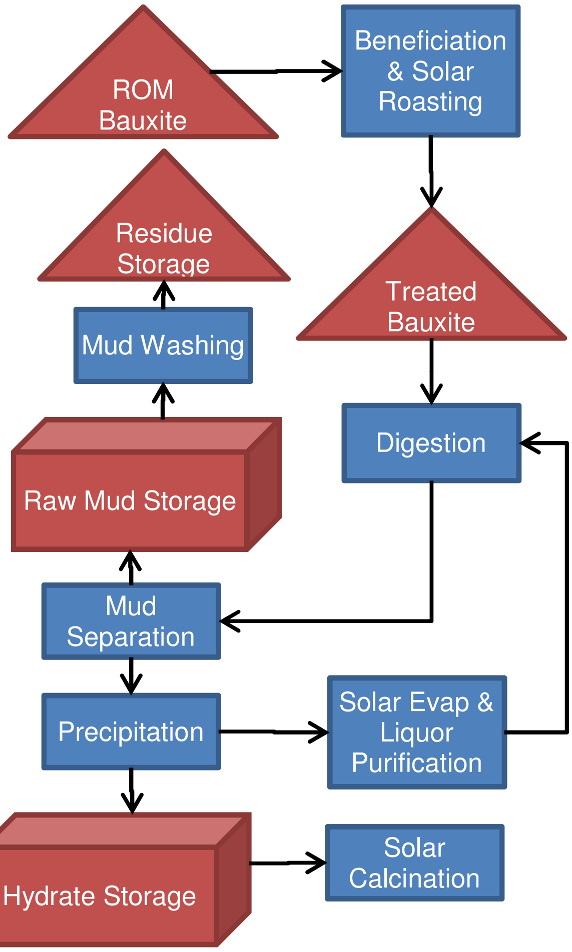

Figure 2. Possible Block Flow for Renewable Energy Scenario

4. CONCLUSION

The refinery of today remains similar in many ways to the refinery of forty years ago, due largely to the underlying economics being also very similar. Nevertheless, significant improvements in productivity and efficiency have been achieved.

The refinery of the future may evolve in one of several directions, depending largely on energy market developments over the next forty years.

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