ALUMINA REFINERY DESIGN FOR CLIMATIC EXTREMES

Thomas, D[1,] Pei, B[1]

[1]*WorleyParsons, Brisbane, Australia*

Abstract

For economic and logistic reasons, alumina refineries are often located either close to the upstream bauxite resource or close to the downstream smelter and associated energy supply. The nature of bauxite and energy reserves is such that this often places alumina refineries in less-than-hospitable climates. From the Amazon (Alunorte), to the Saguenay (Vaudreuil), from Siberia (Achinsk) to Nhulunbuy (Gove), the design challenges can be many and varied.

Different climatic conditions pose different design challenges and constraints. There may be impacts on worker comfort and safety, process flowsheet design (including heating and cooling options), materials handling equipment, environmental controls, waste water treatment, residue storage, equipment enclosures, plant civil and steel structural design and product quality controls.

Some new refineries are being built in even more challenging climes. The Middle East is one new frontier for example, with average annual rainfall often below 200mm, temperatures ranging from 0°C to 50+°C, and frequent dust storms.

Contemplating a design for such challenges can lead to a re-think of traditional design paradigms, providing insights that may also be applicable to milder climes

1. Introduction

Location selection for a new alumina refinery is a complex decision, but is generally dominated by five factors:

- Proximity to bauxite.
- Proximity to aluminium smelter.
- Proximity to low cost fuel(s).
- Availability of skilled and low cost labour.
- Availability of other raw materials and water (at least in some places)
- Availability of or cost to build required infrastructures
- Social / environmental / political considerations, including sovereign risk.

These competing forces have led to alumina refinery locations ranging from the equator to 56° North, from the rainforest to the desert, from sea level to 1200 metres above sea level, and from 250 to 2500 mm of rain per year.

This paper discusses some of impacts of climatic extremes on the design (and in particular the process design) of an alumina refinery. The discussion is divided according to the classical Greek elements, Earth, Water, Air and Fire.

Table 1 - Climatic Details for Selected Refineries (source: WorleyParsons internal database, drawn from various published sources

Refinery	Capacity (Mtpa)	Nearest Major Centre	Annual Rainfall (m)	Max Temp* (°C)	Min Temp** (°C)	Elev.
Alunorte	6.3	Belem, Para, Brazil	2.4m	32	22	15m
Pinjarra / Wagerup / Kwinana	4.2 / 2.6 / 2.2	Mandurah, Western Australia	1.2m	30 (43)	56 (-4)	~50m
Queensland Alumina / RTA Yarwun	3.8 / 1.4	Gladstone, Qld, Australia	0.88m	31.2	13.4	20m/ 30m
Worsley	3.6	Collie, Western Australia	0.93m	30.5	4.2	300m
Alumar	3.5	São Luís Maranhão, Brazil	2.4m	31	22	30m
Chiping Xinfa	3.5	Jinan, Shandong, China	0.74m	33	-6	30m
Pingguo (Chalco)	1.8	Nanning, China	1.3m	35	10	~130m
Shanxi (Chalco)	2.2	Hejin & Yuncheng, Chia	0.5m	30	-6	~450m
RTA Gove	2.5	Nhulunbuy, NT, Australa	1.45m	33 (38)	19 (11)	10m
Point Comfort (Alcoa) / Sherwin (Glencore)	2.3 / 1.6	Corpus Christi, Texas	0.82m	34 (43)	8 (-12)	5m
Paranam	2.2	Paramaribo, Suriname	2.22m	33	22	10m
Aughinish	1.9	Limerick, Ireland	0.93m	19 (32)	3 (-11)	20m
Bauxilum	1.7	Puerto Ordaz, Venezuela	0.81m	35 (39)	23 (4)	60m
Damanjodi	1.6	Jeypore, Orissa, India	0.6m	41	9	920m
Clarendon	1.5	May Pen, Jamaica	0.8m	33	22	50m
San Ciprian	1.5	Lugo, Spain	1.1m	24 (40)	1.5 (-13)	20m
Vaudreuil	1.3	Saguenay, Quebec, Canada	0.95m	24 (36)	-22 (-43)	100m
Achinsk	1.1	Achinsk, Russia	0.53m	24	-18	230m
CBA	0.9	Sorocaba, Brazil	1.24m	30 (34)	12 (7)	810m
Poços de Caldas	0.4	Poços de Caldas, Brazil	1.745m	30 (40)	13 (2)	1260m
Jajarm	0.2	Bojnurd, Iran	0.215m	37 (46)	-1 (-16)	950m

* Average daily maximum in hottest month (hottest ever in brackets, if available)
** Average daily minimum in coldest month (coldest ever in brackets, if available)

2. Earth

Refinery site elevation, topography and soil structural properties (including reactivity) can all have impacts on refinery design.

2.1 Elevation Impact on Yield

Elevation above sea level is an importand component of climate; Table 1 shows that refineries operate anywhere between sea level and 1260m elevation. One of the main impacts of refinery elevation is its effect on boiling point. For each 100m increase in elevation, the atmospheric pressure drops around 1 kPa and the atmospheric boiling point of Bayer liquor drops about 0.35°C (this is approximately the same as the impact of altitude on the boiling point of water, which falls by about 7°C as altitude is increased from 0 to 2 000m (Kelter et al, 2008, p456 and Smith); while Bayer liquor boils several degrees hotter than water, the boiling point elevation (BPE) is fairly insensitive to altitude).

Since security filtration typically operates at just below atmospheric liquor boiling point, each 100m in elevation decreases security filtration temperature by ~0.35°C. Further, since most refineries have their pregnant liquor A/C ratio limited by gibbsite stability through security filtration, and since each 1° temperature drop reduces gibbsite stability limit by about 0.008 A/C, the impact of elevation on precipitation productivity is around 0.6 g/L yield loss for every 100m elevation. For refineries at around 1 000 m elevation, this represents a very significant loss of around 6 g/L. There may be a slight yield recovery due to lower ambient temperatures (better precipitation cooling) but this is generally small.

This loss of precipitation productivity will impact on capital requirements for refinery areas that are linked to pregnant liquor flow rate (ie Settlers, Security Filtration, Heat Interchange, Precipitation, Classification and Seed Filtration

WorleyParsons estimate of the impact of the increased flow in these areas on capital cost is about $1M capital increase per Mtpa capacity per 100m elevation.

Note that there should be no significant impact on digestion capital costs, nor on operating costs, since digestion vessels are pressurised and their A/C ratio is therefore independent of atmospheric pressure (with the exception of refineries employing atmospheric digestion technology).

Pressure decantation, followed by pressurised security filtration, is an option which should be considered for refineries operating at high elevations. The business case for this combination is considerably stronger the refinery at high elevation than it is for a refinery at sea level.

2.2 Other Elevation Impacts

Similarly, predesilication tanks will generally have to operate 0.35°C lower temperature for every 100m of elevation, which will mean about 1-2% longer residence time requirement.

Vacuum filters rely on atmospheric pressure to push the liquor through the filter cake. Each 100m of elevation will reduce filtration rate by about 0.5%. The business case for pressure filtration instead of vacuum filtration becomes stronger as elevation increases.

Electric motor air cooling is slightly less efficient at higher elevation, so some motors may have to be de-rated slightly to compensate for elevation.

Air compression to a given pressure will require slightly more energy at higher altitude.

On the positive side, cooling towers generally operate slightly more effectively at altitude, with about 0.2-0.5% performance increase for every 100m elevation. Barometric legs on condensers and coolers can be slightly shorter.

2.3 Site Topography

While not strictly a climatic impact, site topography can have an impact on refinery design. From a civil engineering perspective, a gently sloping site is generally preferred. However, from a Process Engineering perspective, there are possibilities to use elevation differences to advantage, to make more use of gravity flows and hence reduce the number of pumping stations. Anecdotal evidence is that civil considerations have historically won out. Refinery sites with fairly steep natural slopes (San Ciprian, Yarwun, Worsley) have tended to choose a flat area or cut a bench into the side of the hill.

"Never measure the height of a mountain until you have reached the top. Then you will see how low it was." - Dag Hammarskjold

3. Water

Water balance is a crucial aspect of refinery design and residue management; climatic conditions (rainfall and evaporation rates) play a significant role in both.

3.1 Bauxite and Rainfall

Climate plays a major role in the formation of bauxites, most of which are formed as weathered products from underlying parent rock (Jarrett 1987, pp 3-10, Smith et al 2009). Lateritic bauxites in particular, are formed in equatorial climates. As a result, much of the world's commercially significant bauxite deposits are located in regions of high annual rainfall, as shown in Figure 1.

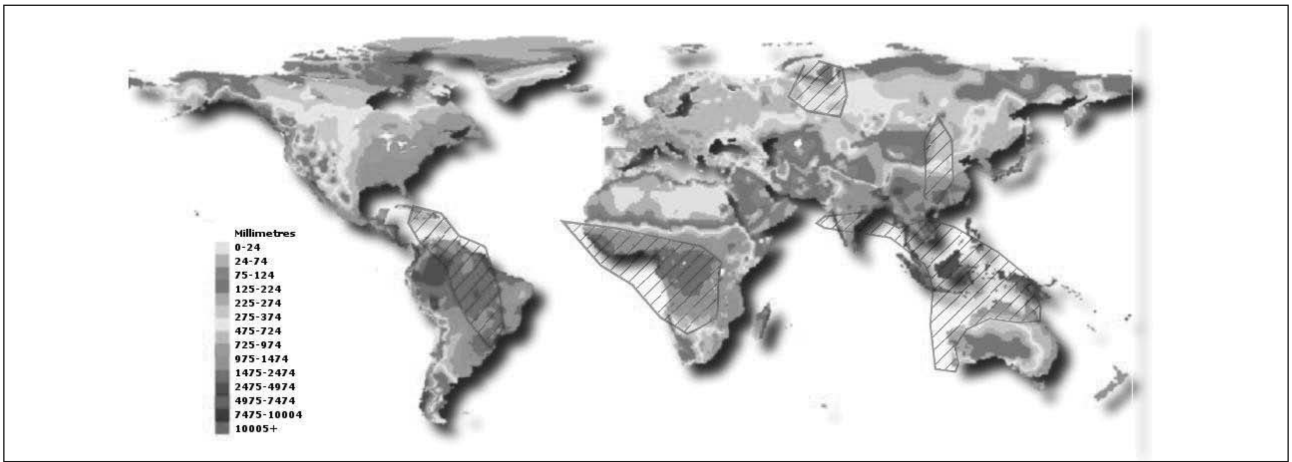

Figure 1 - Annual Rainfall and Major Bauxite Deposit Regions

Bauxite transportation costs create a commercial driver to locate refineries close to the bauxite deposit, and consequently many of the world's alumina refineries are located in high rainfall areas.

3.2 Rainfall Impact on Refinery Process

Water entering the Bayer liquor circuit is rarely welcome, whether it be from hosing, instrument purge, pump glands or rainfall. As a rule of thumb, a tonne of water costs 0.1 tonne of production and also has an impact on caustic soda and energy consumption.

The projected area of tank tops is typically around 6 000-20 000 m^2 per Mtpa production capacity, so the potential cost of 1 metre of rain per year falling into open-top tanks will typically cost between 600 and 2 000 tonnes of lost production per year for a 1 Mtpa refinery. There may also be an even more significant impact on water balance. Tank roofs have been used in many refineries to prevent either rain or snow entering into the tank.

As well as the tanks themselves, rain falling on the bunded process areas around the tanks also needs to be managed. These bunded areas typically occupy 100 000-200 000 m^2 per Mtpa production capacity, ie about 10 times the tank area. Rain falling on this area may have a significant impact on water balance and potentially on cost if it can not all be diverted to the process water circuit.

In low-to-moderate rainfall areas, it is not uncommon to find that process bunded areas are treated like just another "tank", used to collect tank overflows, process line drain-downs and so on. Quite apart from the question of whether this is acceptable from a containment / risk management point of view, there is a fundamental inefficiency associated with mixing process spills with rainwater.

In high rainfall areas, it becomes impossible to ignore the issues associated with rainfall onto bunded areas, and it is necessary to address the issue by either:

- Preventing rainfall from reaching the slab; any process materials collected by the slab are routed back to the process
- Preventing process liquors and slurries from reaching the slab; any rainfall landing on the slab may be safely (after suitable check points) discharged to the environment

The former may be achieved by adding roofs over process areas. This may be expensive, but is relatively straightforward. Of course if the rain tends to be wind-blown "horizontal rain" then the effectiveness may be limited and side walls may also be required.

The second alternative (prevent process liquors from reaching the slab) may be achieved by a re-think of "traditional" sources of slab contamination (tank overflows, sample points, drain valves and blow-down lines). For example tank emergency overflows might be re-routed to bypass the slab - Figure 2 below shows one way (although by no means the best way) of achieving this. The diverted emergency overflow is contained and can be pumped back to the appropriate process tank.

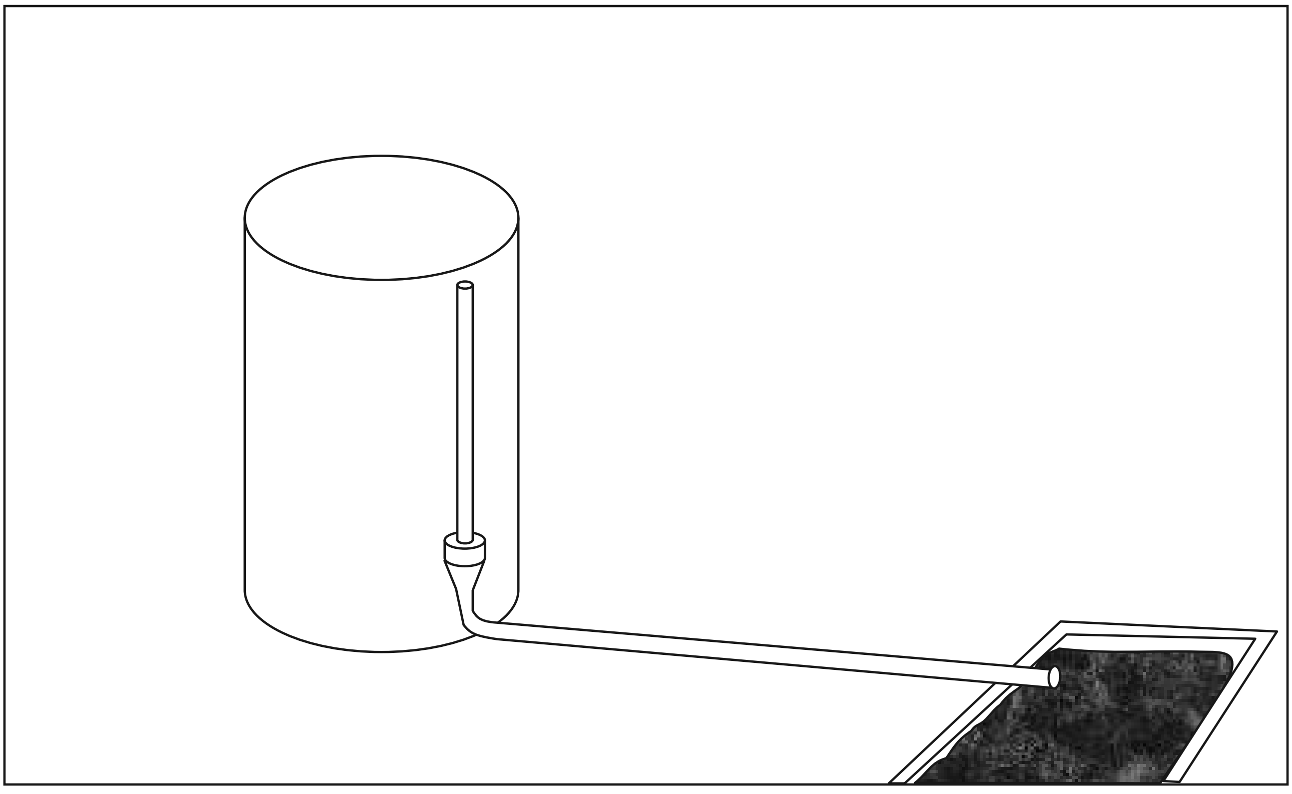

Figure 2 - Example of Emergency Overflow Diversion

In addition to rainfall on the refinery, the water balance must also consider rain falling on the bauxite residue area. Current refineries all have residue areas of between about 0.5 and 2 square km per Mtpa of residue production. In high rainfall areas this generates potentially contaminated water in quantities well in excess of refinery water demand, and so there is an incentive to find new ways of minimising the residue footprint.

3.3 Low-Rainfall Design

At the other extreme, refineries in low-rainfall climates often have difficulties sourcing sufficient fresh water to meet refinery water demands. In this case, the refinery flowsheet should be designed to conserve water where possible.

Since the two biggest water sinks in a typical refinery are evaporative cooling and bauxite residue moisture, the process design in low-rainfall areas is likely to include:

- Alternative cooling utilities (air-cooled or seawater-cooled)
- Bauxite residue filtration

With these technologies employed, water usage can be reduced from typical levels of ~2.5 t/t to well below 1 t/t water/Al_2O_3. Even further reductions may be possible by employing stack condensors on the Calciners and in theory the refinery can become a net producer of water (by "harvesting" the crystal water from the gibbsite: $2\ Al(OH)_3$ à $Al_2O_3 + 3\ H_2O$).

4. Air

"You pray for rain, you gotta deal with the mud too. That's a part of it" - Denzel Washington

4.1 Wind-Borne Dust

Dry, windy areas may be prone to intermittent dust storms, which have potential to contaminate process slurries, leading to contamination of alumina product. Dust can also cause direct contamination during calcination and subsequent alumina handling.

The Jajarm refinery in Iran is in a dust-storm prone location. As can be seen in Figure 3, all process vessels (setters, precipitators, etc) are covered at Jajarm. This will help minimise direct contamination of process slurries.

Dust contamination of bunded areas also needs to be considered, and the corresponding sumps may need to be redirected appropriately.

All rotating equipment (pumps, motors, etc) will need to be suitably selected and designed to tolerate dust loads. Air intakes (boilers, calciners, etc) may require filtration.

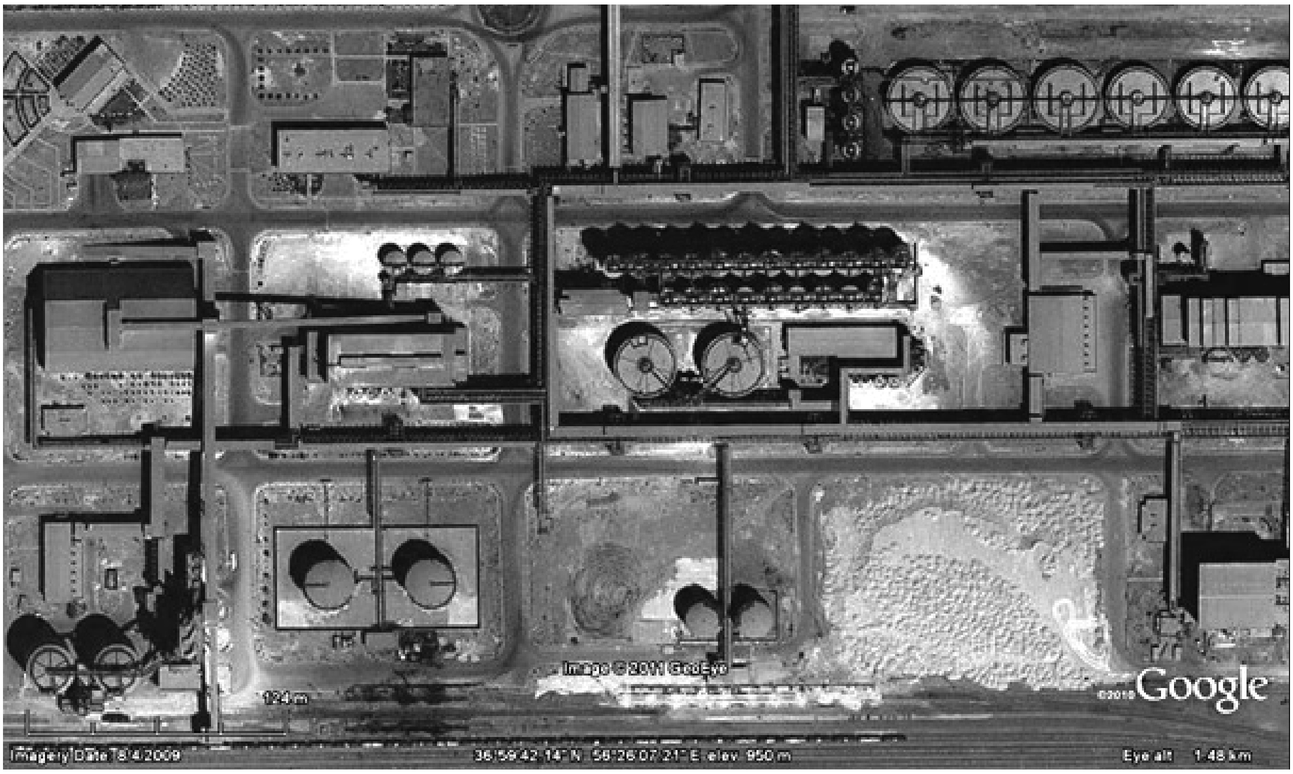

Figure 3 - Jarjarm Refinery, Iran (Image © Google 2010, © GeoEye 2011)

4.2 Hurricanes / Cyclones / Storms

Tropical areas associated with bauxite deposits and/or alumina refineries are often prone to tropical storms. These are infrequent enough that there is generally little or no impact on process design, other than perhaps a slight Operating Factor allowance. Civil/structural design must however contemplate the appropriate wind loadings and flash flooding factors.

"I can't change the direction of the wind, but I can adjust my sails to always reach my destination." – Jimmy Dean

5. Fire

5.1 Operator Comfort and Safety

It can be seen in Table 1 that many refineries experience temperatures above 40°C. This, combined with proximity to hot process equipment, and the humid environment above process vessels, can result in very inhospitable conditions for refinery operators. From a process design perspective, this favours:

- a high degree of process automation
- easily swappable process modules, which may then be taken back to an air-conditioned facility for cleaning and maintenance

Non-process factors to incorporate into the design include sun shades, adequate ventilation, cooled potable water and air-conditioned operator shelters.

For cold climes, one has to consider the impact of sub-zero temperature on pumping, for example, of process water, raw caustic etc. Means have to be provided for breaking frozen bauxite. Workers need warm protective clothes, warm safety showers etc.

5.2 Cooling Utilities

In hot climates, cooling tower water temperatures may approach 40°C, necessitating higher recirculating flow rates and larger heat exchangers for the same process duty. It may be more cost-effective to sacrifice some precipitation yield and some evaporation economy by raising cold-end target temperatures.

5.3 Solar Energy

Concentrated Solar Power (CSP) technology uses mirrors or lenses to concentrate sunlight into a small area, thereby generating high temperature. This is a growing technology, with CSP power generation currently around 1 GW world-wide.

The efficiency of CSP is limited by the conflicting efficiencies of solar energy collection (most efficient at low collector temperature) and the Carnot power-generation cycle (most efficient at high collector temperature). To achieve reasonable Carnot efficiencies, high collector temperature is required, preferably above about 350°C. This requires the use of collector technologies with a high solar concentrating factor (see Figure 4), which adds to capital cost.

A low-temperature alumina refinery on the other hand only requires a heat source at around 200°C (or potentially as low as 130° for atmospheric digestion). This means the solar collectors only need a concentration factor of around 10, which means lower cost collector technologies may be employed, such as Compact Linear Fresnel reflectors (CLFR). The lower temperature also opens up a range of possibilities for energy storage, to allow stored solar energy to be used at night.

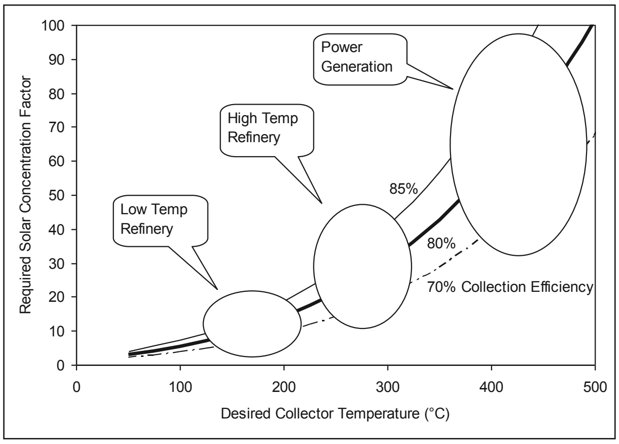

Figure 4 - Solar Concentration Factor Requirement vs Collector Temperature

Around 0.25 km^2 of solar reflectors, at 80% collection thermal efficiency, could provide sufficient energy (when the sun is shining) to meet the thermal requirements of a 1 Mtpa refinery. A 1 km^2 collector array combined with heat storage may be able to provide most of the energy requirements for a suitably located 1Mtpa refinery. Note that required land area is up to 10 times the collector area.

O! for a muse of fire, that would ascend the brightest heaven of invention" - William Shakespeare

6. Thought Experiments

"Extremis angulis illu inventum"

6.1 A Refinery on Mount Wai'ale'ale

Clearly nobody is suggesting that Mount Wai'ale'ale in Hawaii would be a good place to build a refinery. For one thing, it is home to the Alaka'i Wilderness Preserve, a large boggy area that is home to many rare plants. Also there is the minor detail of the lack of bauxite in the area…

However, since this is one of the wettest places on earth (annual rainfall 9.5 metres) and situated at 1569m above sea level, it makes for an interesting "thought experiment" to contemplate what such a refinery might look like.

Figure 6 - Lake Wai'ale'ale, on Mount Wai'ale'ale

The first and most obvious issue is that of water balance. Many refineries have the luxury of running at a net water deficit – so any rainfall landing on the refinery site can generally be collected and absorbed into the process, typically via the mud washing system. Would this be possible on Mount Wai'ale'ale? Some simple mathematics confirms that it would not:

- Assume refinery water demand is 2.5 t/t, a typical figure for a modern refinery.
- For a 1 Mtpa refinery, that would mean ability to consume 2.5 Mtpa water, or 0.2 million cubic metres per month.
- Although annual rainfall is 9.5m, the peak monthly rainfall is a more relevant design parameter since there is generally little capacity for storing wet-season contaminated runoff for use during the dry season. Peak monthly rainfall at Mount Wai'ale'ale is 1.2 metres (the April average). So 0.2 million cubic metres corresponds to the rain falling on an area of 170 000 square metres (200 000/1.2), ie 0.17 square kilometres.
- Contaminated run-off water can come from both refinery process areas and residue storage area. Allocating (say) 25% of the available footprint to the refinery and 75% to the residue area, that allows for about 0.04 km^2 maximum area for the refinery.
- A 1Mtpa refinery typically has a process area footprint of 0.1 to 0.3 km^2. Shrinking the process area to below 0.04 km^2 is not feasible without a paradigm shift in refinery design

Instead, a re-think of process area slab management is required, along the lines of the discussion in 3.2 above.

Our Wai'ale'ale refinery will feature covered process areas and an elaborate drainage system. Bauxite stockpiles and handling facilities will be covered.

The Wai'ale'ale refinery would also face some altitude-related challenges. At 1569m elevation, atmospheric pressure is about 85 kPa and water boils at about 95°C. If using a conventional design, security filtration temperature will be around 100°C instead of the more typical ~105°C. A refinery that might otherwise have achieved a pregnant liquor A/C of 0.740 will instead have to settle for 0.697, a 10 g/L yield decrease.

To avoid this loss, our refinery will employ Pressure Decanters for mud settling. These will operate at ~2 bar and ~125°C, as too will the Security Filters. Special filter fabrics will be required, to overcome the temperature limitations of conventional polypropylene. Pregnant liquor ratio will be maintained at ~0.780; despite this high ratio, there will be virtually no alumina loss to reversion in settlers or security filtration, due to the high temperatures employed.

Clear filtrate will be cooled to ~90°C, at which point the supersaturation is suitable for agglomeration. Precipitation yield will be in the mid-90's (depending on liquor purity).

Residue management is particularly challenging in this case. Assuming that downstream applications for the residue can not be found, and that it is not acceptable to send the residue elsewhere for disposal, then a residue storage method needs to be developed which can achieve a storage intensity of 0.1 km^2/Mtpa or lower.

Simple calculations on drying time requirements quickly show that thickened paste stacking (the technology of choice in many refineries) is not going to succeed. This approach typically needs 0.2 to 1 square km per Mtpa of alumina production.

Instead, residue will be pressure-filtered to produce a dry mud cake which will be manually stacked using trucks and earth-moving equipment. The active residue area will be kept at about 0.05 km^2. As soon as an area is filled (~100 days), capping and revegetation will commence and residue storage will move to the next area.

Rainfall falling on the active residue area will be collected and re-used in the process. Bunded areas under the roofs will have sumps directed back to the refinery process. All other rainfall run-off will be either used for alumina transportation (see below) or discharged to the environment (after an elaborate system of intermediate storage ponds with contamination detection and diversion capability).

Washed alumina trihydrate slurry will be transported to the Port via pipeline; generating around 400MW power due to the elevation difference. The hydrate will be filtered and calcined at the Port.

6.2 LAL Case Study

Lunar Alumina Limited (LAL) has its Redside and Calcination facilities housed in a pressurised bubble at ~5 bar. Whiteside facilities are housed in a second bubble at 1 bar. A third vacuum / cooling / utilities bubble operates at ~0.5 bar.

Refinery feedstock is sintered anorthite ore from the lunar highlands. Refinery residue is mainly calcium silicate and is used to make the valuable LunaCrete™ by-product.

Digestion is carried out in open-top "atmospheric" (5 bar) digestion tanks. Predesilication and causticisation also take advantage of the elevated pressure and both operate at around 140°C.

The vacuum / cooling / utilities bubble features large absorber arrays to capture moisture in gases leaving the higher pressure bubbles. By capturing calciner vapour, the refinery operates as a net water generator and sells its excess water to the nearby lunar colonies (in fact the profit on this water is more than the profits from alumina sales!).

Vessel agitator power requirements are very low relative to Terran counterparts, and blockages due to settled solids are virtually non-existent. However, after a particularly embarrassing start-up period, the originally installed gravity thickeners have been converted to additional precipitation vessels. All solid-liquid separations are now by centrifuge, cyclone or filters.

Large solar arrays provide energy requirements for digestion, calcination, power generation and absorber regeneration. Solar-thermal compressors pump air back from the Utilities bubble to the Digestion bubble.

Capital costs during construction were generally high due to the remote site but there were some offsetting savings for gantries, cranes, ladders and vacuum pumps.

Operating costs of $2 000/t are many times lower than the freight costs to bring finished aluminium products up from the Earth, and LAL's investors are very happy with their returns. About half of LAL's alumina goes to the nearby smelter and half is exported to the Martian colonies. Key aluminium products include solar reflectors, solid booster rocket fuel and orbiting space stations.

7. Conclusions

Climatic conditions can significantly influence refinery design.

High rainfall areas require a rigorous approach to water balance and run-off management. With appropriate design, even the most extreme rainfall levels can be accommodated.

Applying the same high-rainfall design discipline to refineries in lower rainfall areas may also provide significant benefits.

Arid regions warrant a number of water conservation features, and additional dust control measures against both dust egress and dust ingress.

Refinery elevation can significantly impact on precipitation yield, impacting on capital cost by around $10/tpa for a refinery at 1 000m elevation.

There is potential for solar energy to emerge as a viable supplement for alumina refinery energy requirements in the near future.

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