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SUSTAINABILITY AND ALUMINA REFINERY DESIGN

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1. Abstract

The role of sustainability is becoming more pre-eminent in the development of projects in the mining and minerals industry, including the Bauxite and Alumina industry. However the relationship between sustainability criteria and their applicability to the Bauxite and Alumina industry is not always clear. In addition it may appear at times that implementing sustainability criteria negatively affects project economics. A previous paper addressed sustainability in the Bauxite & Alumina industry, reporting guidelines, sustainable development goals, and corporate sustainability targets [1]. It also discussed bauxite deposit quality criteria and sustainability, and concluded that quality criteria for the evaluation of a bauxite resource span economic, environmental and social aspects, and concluded that economic and environmental aspects (in some cases social aspects) are often intertwined. Put differently: economically more attractive deposits are also more attractive in environmental terms (sometimes in social terms).

The current paper builds on these results and explores the relationship between sustainability and ten key design criteria for alumina refineries in the context of applicable Global Reporting Initiative (GRI) sustainability performance indicators.

2. Refinery Design Criteria and Sustainability

2.1 Refinery Design

Bauxite quality has a profound effect on the design of an alumina refinery – refer [1], i.e. the choice of a specific bauxite feed affects several important refinery design criteria. On the other hand several plant design criteria are chosen independent of the bauxite feed quality or are based on considerations other than bauxite quality alone, in the following areas:

- **Process conditions**: important process conditions such as plant liquor productivity / yield.
- **Equipment technologies and layout** e.g. for digestion, bauxite residue settling, precipitation and overall plant.
- **Plant location specifics** which affect plant design such as annual rainfall, rainfall fluctuations and net precipitation / evaporation impacting on the method of residue disposal, and the overall plant water balance which plays an important in a (bauxite and) alumina project's design; country legal requirements e.g. with respect to emission standards; and local geography e.g. with respect to gravity flow between precipitator tanks.
- **Operating and maintenance philosophies** of the project owners e.g. with respect to outsourcing activities, integration of maintenance and operational activities (multi-skilling), maintenance shop integration, etc. Here too the local conditions may play a significant role.

2.2 Design Criteria

It is not possible to cover all plant design criteria in the context of this paper. However ten of the most important criteria and their sustainability facets are included in Table 1 with references to relevant GRI performance indicators – refer [2], illustrating the relationship between these criteria and sustainability. The rationale behind these design criteria is as follows:

1. **Liquor Productivity / Yield** (refer [3] for details). Figure 1 provides a schematic of the alumina refining process: caustic liquor is used in Digestion to dissolve alumina from bauxite at a temperature of typically 145-150°C for so-called Low Temperature (LT) digestion plants processing Gibbsitic bauxites, and 240-270°C for High Temperature (HT) plants using Boehmitic or Diasporic bauxites – while the dissolved alumina is crystallized from the solution in Precipitation through cooling and seeding. The solution is recycled to the front end (Digestion). In other words, the higher the productivity/yield of the liquor that is pumped around, the more cost effective the use of installed equipment. A key design objective of an alumina refinery is therefore to maximize alumina dissolved in the liquor in Digestion and maximize alumina crystallized from the liquor in Precipitation, i.e. maximize the alumina produced per cubic meter of circulated liquor (liquor productivity / yield). Increasing plant liquor yield has significant advantages:
   - Increased plant capacity, i.e. capex / annual ton production capacity drops for several process areas (e.g. for digestion, decantation, precipitation, steam & power station).
   - Lower consumption per tA of: energy (e.g. digestion steam, overall pumping power), labor, maintenance materials, overheads and other fixed costs.
   - Alumina product quality control. Although not straight-forward, some aspects of product quality control improve when the conditions for yield increase improve (example: increasing the precipitation fill A/C ratio of the mixture of green liquor and spent liquor recycled with the seed charge feeding precipitation).
   - Lower specific energy consumption also means a drop in greenhouse gas emissions per tA and (if applicable) coal ash residues (bottom ash / fly ash) per tA, i.e. an improvement of direct environmental performance. And the potential to improve alumina quality (previous bullet point) enables lowering alumina fines losses during transport and handling, thus improving environmental performance indirectly.

   The focus for maximizing liquor productivity in a refinery is mostly but not solely on precipitation yield because the reaction kinetics of precipitation (alumina tri-hydrate crystallization) are more difficult to control and enhance than those of the digestion reaction (dissolution of alumina from bauxite).

   Figure 1 also illustrates that heat recovery occurs extensively throughout an alumina refinery by recovering heat from streams requiring cooling down to streams that require heating up. Examples: heat exchanger (HX) / flash vessel combinations in digestion and evaporation, heat exchanged between liquor to precipitation and spent liquor returning to digestion in the heat interchange area, and the water used in the bauxite residue wash circuit being used first for cooling purposes in a barometric condenser for instance in the evaporation area, thus recovering heat and optimizing energy consumption.

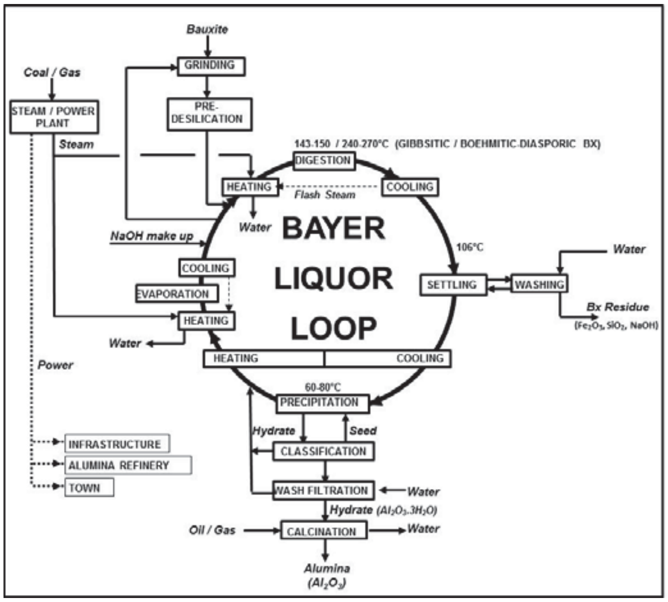

Figure 1 – Alumina Refinery Process Schematic

Precipitation yield increases are feasible (refer Table 2) of ~9-20 kg/m^3 (or g/l) for LT resp. 15-30 kg/m^3 for HT digestion plants raising typical current precipitation yield levels of ~65-75 kg/m^3 to a benchmark level of ~90 kg/m^3 and beyond, by implementing plant design adaptations – refer [3]. These yield increases are equivalent to ~13-31% production capacity increases for LT resp. 23-46% for HT digestion plants, and to steam & power energy savings of ~0.8-1.9 GJ/tA for LT resp. 1.8-3.5 GJ/tA for HT digestion plants. These energy savings are significant compared with typical total steam and power energies of ~6-9 GJ/tA for LT resp. 8-11 GJ/tA for HT plants.

Increasing precipitation yield through extra liquor dilution (instead of or in addition to the plant adaptations indicated in Table 2) requires additional evaporation i.e. additional energy consumption. The overall economic and environmental gains are not clear-cut especially for LT digestion plants. A similar argument applies to increasing precipitation yield by just increasing precipitation holding time. These options have therefore not been included. Some proposed new technologies are also shown in Table 2. Maximum achievable yield may be constrained by liquor impurities originating from the bauxite feed such as oxalate, carbonate and sulphate. Various liquor removal options may be considered to offset their effects.

2. **Digestion Temperature.** Mainly the consequence of bauxite quality – refer [1], Table 1, item 5. Other process considerations may play a role as well e.g. related to the water balance.

3. **Digestion Technology:** benchmark digestion technology is Slurry Heating (also termed "single streaming") comprising heating of a combined bauxite/liquor slurry rather than heating the bauxite slurry separately and in parallel with the liquor which are mixed only in the digester vessel (liquor heating or "double streaming").

   Slurry heating has significant advantages over Liquor Heating: **1.** Improved recovery of heat exchanged in the train of flash vessels / HX's between the slurry ex the digester vessel being cooled down and the slurry to the digester vessel being heated up (put differently: a better heat balance between the flows being heated up and cooled down), i.e. lower energy consumption and lower capex per tA produced; **2.** The slurry flow through the heater tubes keeps them clean from scaling for a longer period time due to the erosive effect of the slurry (scaling inhibitors may have a similar effect) – especially the HX's operating at higher temperatures, i.e. plant on-line time improves (improving plant efficiencies) and less heater cleaning is required (i.e. lower steam consumption due to an overall improvement in heat transfer rates, and less waste, maintenance materials); and **3.** An improved digestion yield potential as there is no Free Caustic (FC) constraint because the Gibbsite in the combined bauxite/liquor slurry rapidly dissolves during the passage through the heater tubes (typically more than 75% of the extractable alumina) thus reducing the extraction liquor's FC (at elevated liquor FC concentrations the risk of stress corrosion cracking – caustic embrittlement – of steel in the heating equipment becomes prohibitive while the allowable liquor FC concentration decreases with increasing liquor temperature – refer e.g. [4]). This means that the caustic concentration of the liquor to digestion and therefore the digestion liquor productivity can be significantly increased impacting positively on opex, capex and environment as discussed in section 1 above.

   Despite their slightly smaller heat transfer coefficient, vertical HX's are overall more attractive for slurry heating than horizontal heaters because they prevent solids blocking up the tubes and they are easy to maintain using an overhead crane. An alternative, notably in the case of HT digestion, is the use of tube digestion employing jacketed pipes for heat transfer [5].

   Although not mentioned as separate item the technology selection for bauxite crushing and grinding should be driven primarily by the requirements to handle the range of expected bauxite feed ore characteristics (e.g. top size ROM ore, ore "stickiness", strength, targeted grind size, etc). With single streaming digestion, closed circuit grinding would be preferred whereas open circuit grinding is more suited to double streaming digestion. Pre-desilication of the slurry ex the grinding mills at high solids density (50-55% m/m) and ~100°C is benchmark.

4. **Bauxite Residue Settling and Washing Technology** (refer also [1], section 3.2, criterion 4B): Bauxite residue slurry discharging from Digestion is subsequently separated in a Solid/Liquid separation/decantation step and the residue ("red mud") is washed counter-currently with water to recover dissolved alumina and caustic soda values in the solution adhering to the residue solids. High rate thickening / washing technology (incl. the use of appropriate flocculants, and the recycle of thickener overflow to dilute the tank feed) is benchmark and has the following advantages over conventional large-diameter thickeners: **1.** Greatly increased mud throughput per m^2 thickener area, i.e. lower capex and opex (e.g. maintenance costs of thickeners and pumps); **2.** Increased underflow densities, i.e. more effective washing and thus reduced soda and alumina losses with liquor adhering to the residue at the same wash water requirement (or less wash water required at the same soda and alumina losses), and a smaller acreage requirement for the residue (lower capex, opex and environmental burden); **3.** Reduced contact time between liquor and mud and hence less potential of alumina reversion / auto-precipitation occurring in the tanks (premature gibbsite crystallization from the super-saturated alumina liquor on non-extracted gibbsite and on goethite in the bauxite residue), i.e. further reducing alumina losses; and **4.** These tanks can handle "sands" (coarser fraction of the bauxite residue), saving capex and opex for separate

Table 1 – Alumina Refinery Design Criteria & Sustainability Facets

Refinery Design Criterion	Target / Benchmark	Related GRI Performance Indicator		
		Economic	Environmental	Social
1. Liquor Productivity / Yield	90^{+} kg/m^3	EC1	EN1, EN3/EN5, EN4/EN7, EN6, EN16, EN20, EN22-MM3	MM11
2. Digestion Temperature	Refer [1], Table 1, item 5	EC1	EN3/EN5, EN16, EN20	
3. Digestion Technology	Slurry heating ("Single Streaming")	As 1 (Precip. Liquor Yield)		
4. Bauxite Residue Settling & Washing Technology	High rate Thickeners (Settlers)/Washers	EC1	EN1, EN4/EN7, EN8, EN12-MM1, EN21, EN22-MM3	SO1, SO1-MM9, SO1-MM10
5. Heat Interchange Technology	Direct Heat Transfer	As 1		
6. Precipitation Technology	High solids tanks; Seed filtration; Interstage cooling; Green liquor split; Split seeding; Classification by hydrocyclones	As 1		
7. Power and Steam Generation	- Gas as energy carrier (if available)	EC1	EN1, EN3/EN5, EN16	SO1
	- Refer [1], item 5	EC1	EN3/EN5, EN16, EN20	
	- Off-gas de-sulphurisation		EN16, EN20	SO1
8. Calcination Technology	Stationary Calciners	EC1	EN1, EN3/EN5, EN16, EN20	MM11
9. Bauxite Residue Disposal Technology	Dry disposal in areas lined with clay or HDPE/PP seal with underdrains; rehabilitation / re-vegetation afterward; sea water neutralization if applicable	EC1	EN4/EN7, EN12-MM1, EN21, EN22-MM3	SO1, (SO1-MM9), SO1-MM10
10. Overall Plant:				
10A Design & layout	Conventional: design accommodates future digestion / process units. New approach: dedicated design & layout for a specified prod. capacity Design for disassembly	EC1	EN1, EN3/EN5, EN4/EN7, EN12- MM1	LA1, SO1, (SO1-MM9), SO1-MM10
10B Production Capacity	General: depends on deposit size, plant considerations, economies of scale, infrastructure requirements, and market economics; New approach: compact capacity ~300-600 ktpa alumina	EC1, EC4	EN1,EN3/EN5, EN4/EN7, EN12- MM1, EN16, EN22 EN22-MM3	LA1, SO1, (SO1-MM9), SO1-MM10
10C Equipment and Additives	- Mechanical Seal Pumps - Low-NOx burners - Mechanical vapor compression - Anti-scaling chemicals	EC1	EN1, EN3/EN5, EN20, EN22	
10D Control Equipment	Variable Speed Pump Drives	EC1	EN1, EN3/EN5, EN4/EN7, EN16	

sands separation and washing systems.

To maximize recovery of caustic soda and alumina values and to further increase solids in the residue to disposal, thus minimizing residue disposal acreage, the inclusion either of bauxite residue filtration downstream of the wash train or of a "super-thickener" / "deep thickener" at the storage disposal site may be considered. Although not mentioned separately here, a proposed plant design modification encompasses by-passing or excluding the Security Filtration process area (refer [6]) which has economic (capex, opex) and environmental (scale, cleaning liquor, etc) advantages.

5. **Heat Interchange Technology:** direct heat transfer (e.g. plate HX's) rather than indirect heating (e.g. by vacuum flash steam) in the Heat Interchange area. Advantages: **1.** Avoids the liquor concentrating effect from flashing, i.e. Digestion can operate at a higher caustic concentration without changing precipitation

Table 2 – Precipitation Yield Improvement Options vs. Capacity Increases & Energy Savings (refer [3])

Plant Adaptation①	**Yield Increase**① **kg/m^3**	**Capac. Increase**② **%**	**Energy Savings**③ **GJ/tA**
Plants using Gibbsitic bauxite			
Seed filtration in Precipitation	5-10	7-15	0.4-0.9
I'stage cooling in Precip. – 5 units	2-5	3-8	0.2-0.5
Direct cooling in Heat Interchange	1-3	1.3-5	0.1-0.3
High rate thickeners in decantation	1-2	1.3-3	0.1-0.2
Total (proven technology)	**~9-20**	**~13-31**	**~0.8-1.9**
Plants using Boehmitic bauxite			
Sweetening in Digestion	6-10	9-15	0.7-1.1
Seed filtration in Precipitation	5-10	8-15	0.6-1.1
I'stage cooling in Precip. – 5 units	2-5	3-8	0.3-0.6
Direct cooling in Heat Interchange	1-3	1.5-5	0.1-0.4
High rate thickeners in decantation	1-2	1.5-3	0.1-0.3
Total (proven technology)	**~15-30**	**~23-46**	**~1.8-3.5**
Proposed New Technologies④	**Yield Increase**④ **kg/m^3**	**Capac. Increase**② **%**	**Energy Savings**③ **GJ/tA**
Plants using Gibbsitic bauxite			
Fines destruction in Precipitation	4-8	5-12	0.3-0.7
Bauxite residue re-digestion at high solids density	4-5	5-8	0.3-0.5
Plants using Boehmitic bauxite			
Fines destruction in Precipitation	4-8	6-12	0.5-0.9
Bauxite residue re-digestion at high solids density	not applicable	n. a.	n. a.

① Based on proven technology; refer [3] for further details
② Using a base case precipitation yield range of 65-75 kg/m^3 for LT plants (digestion typ. 143-150°C) using Gibbsitic bauxite; and a precipitation yield of 65 kg/m^3 for HT plants (digestion typ. 240-250°C) using Boehmitic bauxite.
③ Using a steam & power energy requirement of 7.6 GJ/tA for plants using Gibbsitic bauxite (all required power required generated in a co-generation facility); and 9.7 GJ/tA for plants using Boehmitic bauxite (part of the power required generated in a co-gen facility, and 0.5 GJ/tA of imported power required to meet remaining power needs). In other words in both cases alumina calcination energy is not included.
④ Refer [3] for further details

caustic concentration, enabling an increased digester discharge A/C ratio and thus also LTP A/C ratio (i.e. potential for higher precipitation yield and thus lower capex, opex, energy consumption, and greenhouse gas emissions per tA produced); and **2.** Plate HX's are inexpensive and simple to operate and maintain (low capex and opex).

6. **Precipitation Technology:** in addition to the process adaptations indicated in Table 2, the following features are included in the design of a benchmark precipitation area:
   - For yield increase reasons (high surface area):**1.** Precip tanks designed for 600-800 kg/m^3 solids and more (current typically ~400-600 kg/m^3), including appropriate agitators; and **2.** Use of additives (e.g. crystal growth modifiers).
   - For improved product quality control: **1.** Pregnant / green liquor feed split (control of soda inclusion) and split fine / coarse seeding (control of particle size and strength); and **2.** Agglomeration (mainly quality control) and growth (mainly yield increase) sections.
   - Product / seed classification by hydrocyclones rather than gravity classifiers for reasons of both yield and product quality control improvement.

   The advantages of benchmark technology in the precipitation area are covered in point 1 above (Liquor Productivity/Yield).
7. **Power and Steam Generation** (refer also [1], section 3.2, criterion 5)**:** using gas as energy carrier enables the use of gas turbines in combination with co-generation of steam and power. A gas-fired co-generation facility comprises a gas turbine linked to an electrical generator (producing power required by the alumina refinery), and heat recovery steam generator recovering waste heat from the gas turbine exhaust which is used to produce steam for the refinery, with surplus electricity exported to the local power grid. This electricity has about one-third the emissions intensity of coal-fired electricity. This type of co-generation technology or 'combined heat and power' technology provides greater conversion efficiencies than conventional generation methods, harnessing heat that would otherwise be wasted and reducing greenhouse gas emissions. End result: a reduction of about 26% in the operation's greenhouse gas intensity compared with electricity and steam generated from coal (Yarwun – refer [7]). When applicable: off-gas de-sulphurisation to be included to reduce SO_2 emissions.

8. **Calcination Technology:** alumina hydrate crystals from precipitation are washed and calcined to smelter grade ("sandy") alumina for benchmark performance of aluminium smelters. Calcination in stationary calciners is benchmark, incorporating effective heat recovery from combustion gases (i.e. improved opex and less greenhouse gas emissions per tA produced), and improved product quality control over rotary calciners. Energy consumption is ~2.7 GJ/tA [8]. The selection of energy carrier (natural gas, coal gas, heavy fuel oil) should be based on: 1.An economic evaluation of availability, price and capital cost (coal gas fired calciners require coal gasification and modifications to the calciner); 2. The related environmental footprint (CO_2 emission, coal fly ash); and 3. Alumina product quality (e.g. with respect to coal impurities ending up in the alumina).
9. **Bauxite Residue Disposal Technology:** although both so-called "wet" and "dry" residue disposal technologies are applied worldwide, thickened tailings / "dry" disposal (deposition of bauxite residue layer by layer) is benchmark. Depending on residue characteristics and local conditions (e.g. rainfall), dry stacking (residue slope formed "naturally") or slope deposition (discharge onto a slope with an angle equal to the residue's natural angle of repose) may be more appropriate. Dry stacking requires the formed layer of residue to consolidate by solar drying (assisted by so-called amphirolls to plough the residue to promote the drying process) prior to the deposition of the next layer on top. Rotating between residue discharge points with intervals achieves this. Perimeter dikes of a Residue Disposal Area (RDA) prevent contamination of the surrounding environment; when an area is filled up a next lift is created on top. An RDA is clay- or HDPE/PP lined to prevent seepage of alkaline solution into the ground water. The lining is covered with a layer of sand housing a network of porous pipes to collect the alkaline drainage from the residue which is returned to the refinery. Once an RDA has been totally utilized, it may be capped with clay and covered with top soil for re-vegetation. The run-off from a de-commissioned RDA is returned to the process until its composition is acceptable for return to the environment. Thickened Tailings Disposal of bauxite residue is more attractive than wet mud disposal because **1.** It requires less surface area and results in less rain water runoff requiring treatment; **2.** It provides the potential for more controlled residue disposal management; and **3.** It is aesthetically more acceptable. Several variations are in use in the world e.g. in Brazil (Alunorte), Australia (Worsley, Gove), Jamaica (Ewarton) and Ireland (Aughinish).

   Sea water neutralization followed by dry stacking may be applicable in case of a refinery location close to the sea (requires confirmation by test work). Magnesium and calcium in the sea water neutralize the alkaline components in the bauxite residue. The neutralized slurry is subsequently thickened to a high solids concentration; the saline overflow is returned to the sea. The thickener underflow is discharged to a conventional dry stacking area. Control of the rain water runoff from the storage area (solids, pH, heavy metals) would be required because this cannot be recycled to the refinery and needs discharging into the sea. Advantages of sea water neutralization: **1.** Long term liability and management issues related to a storage area and its rehabilitation are significantly reduced; and **2.** The storage area may not require a lining, depending on local ground conditions.
10. **10A. Overall Plant Design & Layout:** conventional designs aim at accommodating additional future digestion and other process units, i.e. plant design incorporates provisions for future expansions which results in significantly increased capex of the design / initial production capacity negatively affecting economics (refer [9]). A new approach is based on a dedicated refinery design and layout for a specified production capacity, i.e. tailored to the equipment and infrastructure requirements of the selected production capacity (earth works, power, water supply, piperacks, roads, cable trays, etc) (refer [10] and [11]). This enables optimizing plant layout e.g. with respect to positioning similar equipment close to each other; and the use of common spare equipment. The approach results in a focus on a "lean" design positively impacting on commodity volumes: for the same production capacity commodity volumes for steel, concrete, piping, etc for a greenfield plant designed this way are similar to that of a brownfield expansion of an existing refinery. In other words per annual tA production capacity significantly lower amounts of commodities are required for greenfield projects compared with conventional designs. The dedicated design excludes therefore provisions for future expansions (these require their own economic justification). And because commodities represent a significant element of refinery capex, the consequence is a drop in capex (indicatively by ~10%) and opex, more effective use of available space for the plant, and avoidance of unnecessary energy consumption (e.g. pumping power) and maintenance costs.

    This approach is independent of preferred / selected refinery technologies, and includes the following main design and layout elements (refer [11] for details): **1.** Digestion and Evaporation areas positioned next to each other, using similar equipment and sharing a common spare bank of HX's; **2.** Bauxite residue settler and washers placed in a horseshoe shape; **3.** Bauxite residue discharging from the residue wash train containing less than ~8 g/l caustic soda in the adhering liquor; **4.** Filters for hydrate to calcination, for fine seed to precipitation and for oxalate removal located in one building; **5.** Last two on-line precipitators operating with agitators allowing varying slurry levels; **6.** Facility in the center of the plant accommodating plant control room, operations office and plant laboratory; **7.** Key role for equipment cleaning / de-scaling, including mechanical cleaning of the precipitators. Advantages: no major plant volume / plant liquor caustic concentration changes required, i.e. better control of both, allowing a smaller "safety range" for liquor super-saturation target; or put in another context: the controls of precipitator cleaning and plant volume / liquor concentration have been separated; other advantages: no further spare precipitators are required (or tanks of similar size), and steam required for C/C purposes is saved; **8.** Extensive use of common spare equipment; and **9.** Hydrate storage facility between the precipitation and calcination areas to ensure that hydrate production (Bayer Loop) operates independently from the subsequent calcination operation (hydrate is stored when calcination capacity is constrained).

    The operational period of an alumina refinery is generally substantial (50^+ years). Its disassembly costs are significant and in some countries project owners are legally obliged to build up financial reserves for a refinery's final disassembly. If an alumina plant is designed for disassembly right from the outset, disassembly costs could be significantly lowered with conceptually little effect on the project's initial capex. In addition this approach is environmentally more attractive as it will be easier to return the area to its original situation.

    10B. Plant Production Capacity: key selection criteria to decide on the capacity of an alumina refinery typically include: **1.** Bauxite deposit size; **2.** Plant considerations e.g. one or more "trains", and project complexity; **3.** Economies of scale; **4.** Infrastructure requirements (both "external" e.g. port (extension), consumables and alumina transport, personnel housing; and "internal" e.g. piperacks, power distribution, water supply, buildings), representing a significant part of project capex; and **5.** Market economics.

A new **DCS**-approach (**D**edicated **C**ompact **S**ustainable) applies a dedicated and sustainable design to a compact refinery of ~300-600 ktpa alumina, resulting in a project with a simple and limited scope. As a result plant capex decreases significantly (indicatively by another ~10% on top of the capex decrease from the dedicated-design approach – refer [10]). To ensure acceptable economics for the overall project, infrastructure capital should be limited. At the same time such a project has few infrastructural requirements, especially if located close to an existing port. Advantages:

- The smaller project capex (lower risk) enables development of bauxite & alumina projects by smaller companies without a need to form (complex) joint ventures, thus increasing the number of companies potentially interested in developing bauxite deposits. Competition increases, resulting in a more efficient use of (capital and bauxite) resources.
- Small and simple projects carry less risk; require less time to develop, construct & start up, positively impacting economics.
- Long term alumina refining projects based on this approach require a small deposit (~40 Mt would support a 400 ktpa project for 30 years), i.e. worldwide the number of deposits lending themselves to development increases, improving the use of resources and employment opportunities.
- This approach may also be applied to the development of part(s) of a large deposit.
- In some cases this approach would enable value creation through alumina refining rather than being limited to bauxite export sales (attractive to the host country and to companies developing bauxite & alumina projects).
- An adapted version of the approach may in some cases enable bauxite deposit development even in locations with little existing infrastructure, albeit at a larger than compact scale (e.g. ~1.5 Mtpa alumina).
- Approach is independent of selected refinery technologies.

An overall process plant layout for a compact 400 ktpa alumina refinery based on the dedicated design approach illustrates that the approach leads to a compact, simple and efficient layout with a small Bayer loop, illustrating that the goal to tailor the design to the equipment and infrastructure requirements of the specified production capacity is achievable: most of the infrastructure is integrated in the process areas and only limited infrastructure is required outside those (refer [11]).

10C. Equipment and Additives: equipment related design criteria include: **1.** Mechanical seal pumps instead of pumps with water-purged glands (less process dilution, less infrastructure, lower water consumption); **2.** Low-NO_x burners in power & steam generation (improved NO_x emissions); and **3.** Mechanical vapor compression in case of low-cost power from cogeneration (if there is no excess steam to be condensed in condensing turbines). Additives related design criteria include using appropriate chemicals e.g. anti-scalants in Liquor Evaporation.

10D. Control Equipment: variable speed pump drives instead of control valves for level control, flow control, etc. This reduces pumping energy, improves erosion and cavitation (i.e. less wear). In other words lower opex, capex and greenhouse gas emissions.

2.3 Conclusions

Table 1 and its rationale illustrate that some of the key criteria for the design of an alumina refinery comprise the three pillars of sustainable development: economic, environmental and social aspects. In other words sustainability in the context of refinery design can be qualified and quantified once bauxite characterisation test work has been completed and project size decided. Table 1 also illustrates that economic and environmental aspects are in fact two sides of the same coin, while social aspects are often also integral to refinery design. Putting it differently optimum refinery design in economic terms is (long term) often also the most attractive environmentally (and to some extent socially).

Most if not all of the criteria included in Table 1 are consistent with the issues for the upstream steps of the aluminium value chain from the Responsible Aluminium Scoping Phase RASP (e.g. bauxite residue management; SO_2, CO_2, and NO_x emissions; energy efficiency, and caustic soda management for alumina refining – refer [12]). And most are also consistent with the long-term / strategic company targets of the industry majors (refer [1], section 2.4).It seems likely that sustainability will play a growing role in future decisions on the design of brownfield and greenfield alumina refinery projects. Elements of that trend include: a continuing push to increase precipitation liquor yield (item 1 of Table 1); finding new approaches and technologies to improve plant and process efficiencies (e.g. item 10), including a growing thrust to improve on bauxite residue disposal (items 9 and 10); and developing a more sustainable energy supply (e.g. Integrated Solar Combined Cycle).

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