Department of Chemical Engineering

Thesis Report

Process Optimisation and Intensification Principles and Tools: An Explorative Review for Potential Application in Minerals Processing

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DECLARATION

I declare that this report is my own work except where referenced to other sources, and all statements of fact in this report are true and correct to my best knowledge.

Date: February 10th, 2006
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EXECUTIVE SUMMARY

This project mainly discusses about the application of process optimisation and intensification in mineral industry especially in Bayer Process of Alumina Refinery. Process intensification as a novel invention of developing apparatuses and techniques aims to bring significant improvements in manufacturing and processing as well as decreasing equipment size, energy consumption or waste production. Various applications of process intensification in general process industry are classified based on their strategies followed by an explorative review to determine which strategies could potentially be applied in Alumina Bayer Process.

Those strategies are:

- Miniaturisation
- Combined reaction and separation
- Real time and analysis
- Multifunctional reaction
- Use of alternative/non conventional energy sources
- Novel distillation
- Combined reaction and palletisation
- Filtration/Centrifuging
- Milling and Grinding
- Mixing
- Flow induced phase inversion (FIPI)
- Hybrid Separation

The twelve promising strategies are then considered to offer significant change in Alumina refineries as a sustainable processing industry.

Intensification of grinding process is potential to be applied since grinding is the most power-intensive phase. Innovative technology is required to minimize energy consumption at that stage. This intensification provides active electro-neutralisation of free electric carriers by initiation of depolarisation of the comminuted material which offers the possibility of a new technique for grinding intensification other than ultrasonic grinding. A novel technique known as sonocrystallisation can also be applied in alumina refinery to eliminate oxalate and challenge to remove other impurities which leads to the plant throughput improvement and more advantages. Cross-flow filtration and electronic precipitators are also promising to be applied in Bayer process to replace the conventional apparatuses. In calcination process, technique of enriching O_2 as an additional oxygen for kiln purpose generates a more efficient combustion and gives certain benefits such as higher production and reduction in fuel consumption. Other method such as membrane technology is also mentioned as an alternative to achieve better separation of components in the process.

Intensification in any stage of Bayer process is in fact necessary to have an enhanced alumina refinery process. Better grinding for energy efficiency, sonocrystallisation for

increased refinery output and lower chemical consumption leads to lower environmental impact, oxygen enrichment to improve energy efficiency of calcinations, membrane technology for faster and more efficient separation processes, and many more.

Future research needs to be carried out. This include the possibility of combining digestion and clarification into a single unit operation which will improve the stability of these processes or investigating potential means for improving the thermal energy efficiency of calcination. The alumina industry also needs to establish a strategy for managing its use of resources in the future. Applying the new technology it self is not that easy. Some limitations including specific tools (simulation software) which is not available and lack of literature sources on detailed practical applications since process intensification is relatively new. Enhanced skill an knowledge of the new generation are considered to be essential for further improvement of process intensification in alumina refinery.

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ABBREVIATION

AIChE : American Institute of Chemical Engineers
CPI : Chemical Process Industry
DSP : Desilication Product
ESP : Electrostatic Precipitators
ICI : Imperial Chemical Industries
MF : Microfiltration
NF : Nanofiltration
PI : Process Intensification
RO : Reverse Osmosis
UF : Ultrafiltration

1. Introduction

1.1. Project Background

The minerals processing industry is under increasing pressure to improve the efficiency of its resource use (ore, energy, water, reagents, etc) and contribute to sustainable development. In spite of the common identification that process optimisation and intensification are in principle applicable to minerals processing, there is only limited evidence that such is done in practice. The project research would explore through the literature review, the potential application of process optimisation and intensification principles and tools, as these have been developed for the (chemical) process industry, and assess their applicability in key minerals processing unit operation (size reduction, concentration and separation, and metals extraction (hydro- and/or pyro-metallurgical).

1.2. Objectives

- To identify and summarise key process optimisation and intensification principles and tools from chemical process industry
- To asses the applicability of these principles and tools for core unit operations in minerals processing
- To identify, describe and evaluate the examples of process optimisation and intensification in the Australian minerals processing industry, using Bayer Process of Alumina Refining as a case example

1.3. Expected Outcomes

- Contribution to the application of process optimisation and intensification principles and tools in minerals processing.
- Applicability of proven process optimisation and intensification principles and tools in key minerals processing operations.

1.4. Significance

The significance of this project is to apply the process optimisation and process intensification principles and tools in the mineral processing industry to improve the efficiency of its resource use and contribute to sustainable development.

1.5. Literature Review

Sustainability has become one of the most powerful shapers of industry development in many area including mining, minerals processing and other natural resources (Van Berkel and Narayanaswamy, 2004). The sustainable development of minerals may seem like a contradiction to many people, as they are not renewable resources, as most would define the term. Production processes can have adverse environmental consequences if not properly controlled.

Natural Resources Canada (1997) point out that minerals have become part of human activity. We have been using it for many purposes. In mineral industries, minerals such as mica, silicate, etc., are fundamental components of advanced industrial materials. Even minerals-based fertilizers are essential for agricultural sector. For enzyme and metabolic function, plants and animals, including humans, also require many minerals. Hence, it is almost impossible to imagine life without minerals.

To ensure that society continues to benefit from minerals products, it is important to know and understand the combination of the natural baseline values with human impacts so that appropriate management of human activities can be implemented. Our challenge is to find ways to integrate economic, environmental, and social values in the development and use of minerals. This is not a simple process. The principle of sustainability can however gives bright view and to explore an innovation in mineral processing by reviewing applicable scheme and experiences gained in non-minerals sector.

Stankiewicz and Moulijn (2002) identify that new technological sectors always arise in the society, while the total capacity of the world's production is constant. As a consequence, conventional production sectors have to constantly reduce their share in the natural resources, including land utilization. For any kind of process industry, particularly minerals processing industries, this implies that a decrease in size and an increase in efficiency are a must. Of course, the scale-up in chemicals manufacturing has been impressive. Although the production volumes have increased dramatically, the space used only modestly increased. As we know, many petrochemical industries constructed in the areas which have high natural value and that could be mean a lot to the society. Let us take one example which is the industrial built in harbour areas. If this industry could be scale-up become smaller, both sea life and tourism would benefit a lot as well as the industry, which the investment for the land utilization would also reduce.

Space is not the only criterion in process intensification. That is why the above statement might be a too simple picture. The question is how to move. Chemical engineers are inclined to be realistic and to determine achievable goals. We also believe that by transplanting process intensification lessons learnt from CPIs into minerals processing (with due adaptations of course), the latter could be transformed into one with much less impact on the environment. A logical aim is to replace “big is the best” by “small is beautiful” (Stankiewicz and Moulijn, 2002).

An often used definition of the term process intensification is the strategy for achieving dramatic reductions in the size of the plant at a given production volume. Other researchers active in the field define process intensification in different ways. Two words, however, are common to practically all process intensification definitions. One of these words is *innovative*: process intensification is characterized by the novelty, and in this sense presents a contradistinction to the conventionalism in chemical engineering and process design. The other common word, *substantial,* clearly defines the target of process intensification which is to make quantum leap in process and plant efficiency with respect to space, time, energy, raw materials, environment, etc. (Stankiewicz and Moulijn, 2002).

In recent decades there has been a tremendous increase in the energy efficiency of the process industry by optimisation of unit operations. In many cases the limits of what can be done on a unit-operation scale have been reached. To maintain the trend of increasing energy efficiency, it will be necessary to concentrate the various physical steps and chemical reactions into a single process step that makes only the desired product.

Process intensification is the miniaturization of unit operations and processes where a smaller compact piece of equipment takes the place of a larger one at the same given capacity or mass flow rate. Since 20% of plant costs are in the process equipment and the balance in the structural steel, piping, conduit and wire, smaller unit operations mean smaller installed plant costs (R.C. Costello & Assoc., Inc, 2003).

Process intensification involves the development of new compact devices and techniques that will lead to substantial improvements in the production processes, reductions in the size of production equipment, lower investment costs, lower energy use and waste production, and finally to more sustainable technologies. In particular, process intensification aims at new and compact designs in which two or more classical unit operations or unit processes are combined into one hybrid unit. It is a practical application of a design philosophy that is aimed at getting better product outputs with installations that are an order of magnitude smaller than the conventional equipment (Energy Research Centre of Netherlands, 2003).

Process Intensification refers to the development of radical technologies for the miniaturization of process plants while achieving the same production objective as in bulky conventional processes. The goal is to bring down the plant size by 10-1000 times (Stankiewicz and Moulijn, 2002) by replacing large, expensive and energy-intensive equipment or processes with ones that are smaller, less costly and more efficient (Tsouris and Porcelli, 2003). Hybridization of multiple unit operations and processes into a single compact device is the rule of thumb for process intensification.

Sivakumar, et. al., (2004) stated that Smaller is safer! Therefore, process intensification dramatically increases the intrinsic safety of chemical processes. The aftermath when something goes wrong in process vessels of large volume was evident in the tragedies of Flixborough and Bhopal. Though the philosophy behind process intensification has been in existence for several years, it had a conservative reception from industries due to their unwillingness in taking the risks with a new technology. However, companies like ICI (Ramshaw, 1983 and Ramshaw, 1984), Shell (Taber and Hawkinson, 1959), Sulzer (Meili, 1997), SmithKline Beecham (Oxley, Brechtelsbauer, Ricard, Lewis & Ramshaw, 2000), Eastman Chemical (Siirola, 1995) and Dow (Trent and Tirtowidjojo, 2001) embraced the process intensification philosophy and adopted it in several of their recent processes with great commercial success.

Stankiewicz and Moulijn (2000) have classified the process intensification and its component as stated in the following figure 1.

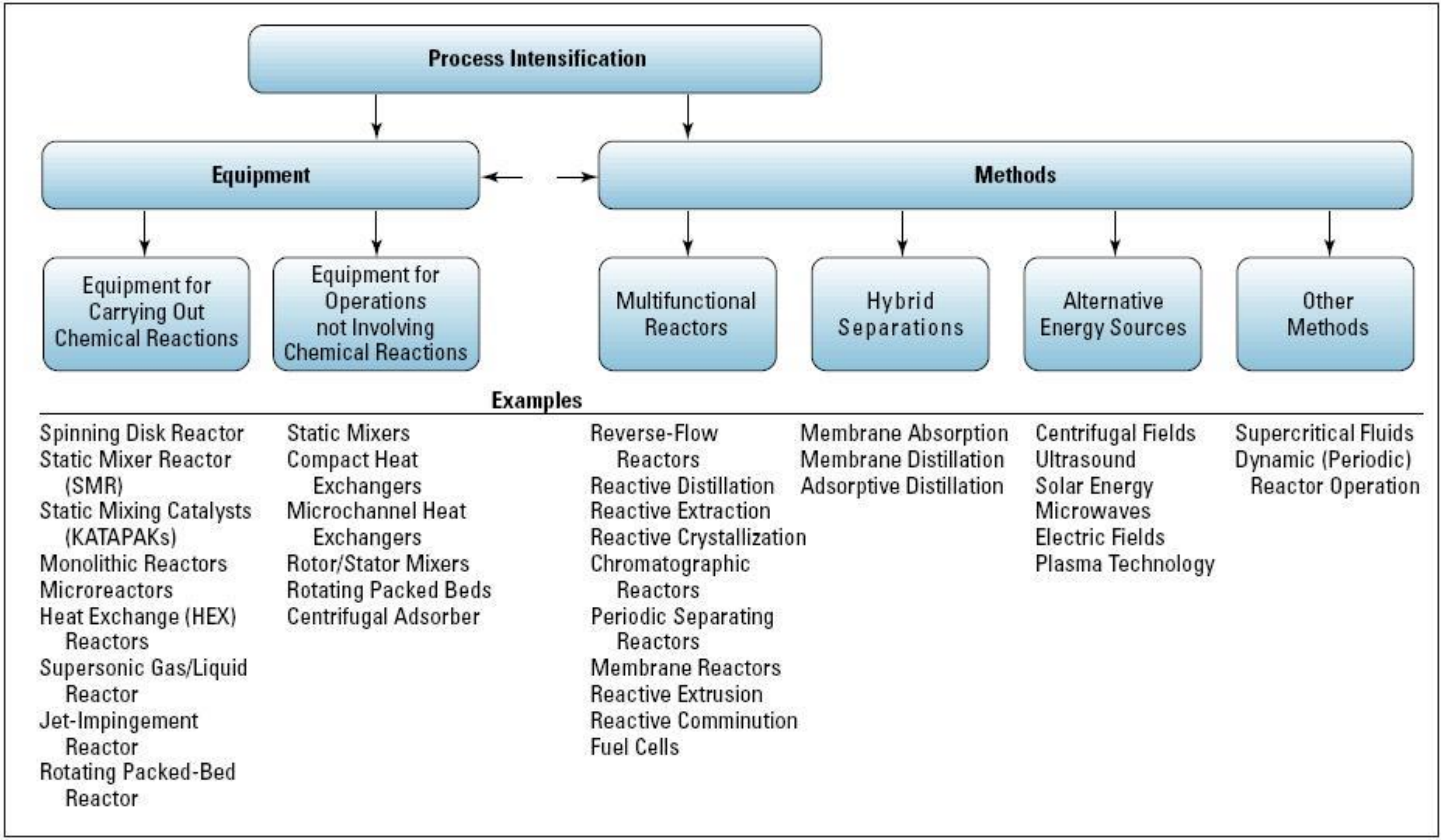


Figure 1: Process Intensification and Its Component (Stankiewicz and Moulijn, 2000)

Bayer Process *(Queensland Alumina Ltd, 2002)*

The Bayer Process is one of the economical methods of producing aluminium oxide. It was invented by an Austrian chemist, Karl Bayer and patented in 1887. The following is broad view about the process description of Bayer Process. For detailed information, please visit www.qal.com.au.

The Bayer Process dissolves the aluminium component of bauxite ore in sodium hydroxide (caustic soda); removes impurities from the solution; and precipitates alumina trihydrate which is then calcined to aluminium oxide.

A Bayer Process plant is principally a device for heating and cooling a large recirculating stream of caustic soda solution. Bauxite is added at the high temperature point, red mud is separated at an intermediate temperature, and alumina is precipitated at the low temperature point in the cycle.

Bauxite usually consists of two forms of alumina which are monohydrate form Boehmite ($Al_2O_3.H_2O$) and trihydrate form Gibbsite ($Al_2O_3.3H_2O$).

As shown in Table 1, Queensland Alumina Ltd uses the Bayer Process to refine two grades of Weipa bauxite, the bulk of which is "monohydrate" grade bauxite.

Table 1: Average analyses of Weipa bauxites (Queensland Alumina Ltd, 2002)

Constituent	Monohydrate Grade %	Trihydrate Grade %
Al_2O_3	55	50
Available Al_2O_3	50*	44#
Fe_2O_3	12	17
SiO_2	5	4
TiO_2	3	3
Other (mainly H_2O)	25	26

*40% from Gibbsite and 10% from Boehmite

Gibbsite only is extractable in sweetening

Digestion of Bauxite

- Grinding:

  To allow better solid liquid contact during digestion, *pisolitic*, monohydrate-grade bauxite (sized to a maximum of 20mm) is ground in mills. Recycled caustic soda solution is added to produce pumpable slurry, and lime is introduced for phosphate control and mud conditioning.

- Desilication:

  This process is carried out by introducing caustic soda to the slurry produced from the grinding process. Slurry afterwards is heated in the pre-treatment tank and held at the atmospheric pressure.

- Digestion:

  The monohydrate slurry is pumped by high pressure through digester vessels. Then it is mixed with steam and caustic solution with the conditions for the reaction are around 250 ^{o}C and a pressure around 3500 kPa produced concentrated sodium aluminate solution.

  Under these conditions, the chemical reactions are rapid:

  $$2NaOH + Al_2O_3.3H_2O \rightarrow 2NaAlO_2 + 4H_2O$$

  $$2NaOH + Al_2O_3.H_2O \rightarrow 2NaAlO_2 + 2H_2O$$

  By sizing the vessel to optimum holding time, about 97% of the total available alumina is extracted and the silica content of liquor is reduced.

Clarification of the Liquor Stream

- Settlers:

  After digestion about 30% of the bauxite mass remains in suspension as a thin red mud slurry of silicates, and oxides of iron and titanium, then it is cooled to atmospheric boiling point. Most red mud waste solids are settled from the liquor stream in single deck 40 metre diameter settling tanks. Flocculants are added to the settler feed stream to improve the rate of mud settling and achieve good clarity in the overflow liquor.

- Washers:

  The mud is washed with fresh water in counter-current washing trains to recover the soda and alumina content in the mud. Slaked lime is added to dilute caustic liquor in the washing process to remove carbonate (Na_2CO_3) which forms by reaction with compounds in bauxite and also from the atmosphere and which reduces the effectiveness of liquor to dissolve alumina. Lime regenerates caustic soda, allowing the insoluble calcium carbonate to be removed with the waste mud.

  $$Na_2CO_3 + Ca\ (OH)_2 \rightarrow CaCO_3 + 2NaOH$$

- Filters:

  Settlers overflow liquor containing traces of fine mud is filtered in Kelly-type constant pressure filters using polypropylene filter cloth. Slaked lime slurry is used to produce a filter cake. Mud particles are held on the filter leaves for removal and treatment in the mud washers when filters are sequentially taken off line.

- Heat Interchange:

  With all solids removed, the pregnant liquor leaving the filter area contains alumina in clear supersaturated solution. It is cooled by flash evaporation, the steam given off being used to heat spent liquor returning to digestion

Precipitation of Alumina Hydrate

- Crystallisation:

  Dissolved alumina is recovered from the liquor by precipitation of crystals. Alumina precipitates as the trihydrate $Al_2O_3 .3H_2O$.

  $$2NaAlO_2 + 4H_2O \longrightarrow Al_2O_3.3H_2O + 2\ NaOH$$

  This is basically the reverse of the extraction process (digestion of trihydrate), except that the product's nature is carefully controlled by plant conditions, including seeding or selective nucleation, precipitation temperature and cooling rate. The hydrate crystals are then classified into size fractions and fed into a rotary or fluidised bed calcination kiln. Undersize particles are fed back into the precipitation stage.

- Classification:

  The finished mix of crystal sizes is settled from the liquor stream and separated into three size ranges in three stages "gravity" classification tanks. The primary classifiers collect the coarse fraction which becomes the product hydrate. The intermediate and fine crystals from the secondary and tertiary classifiers are washed and returned to the precipitation tanks as seed.

- Spent Liquor:

  Spent caustic liquor essentially free from solid overflows from the tertiary classifiers and is returned through an evaporation stage where it is reconcentrated, heated and recycled to dissolve more alumina in the digesters. Fresh caustic soda is added to the stream to make up for process losses.

Calcination of Alumina

- Washing:

  A slurry of coarse hydrate ($Al_2O_3.3H_2O$) from the primary thickeners is pumped to hydrate storage tanks and is filtered and washed on horizontal-table vacuum filters to remove process liquor.

- Calcining:

  The resulting filter cake is fed to a series of calcining units. The feed material is calcined to remove both free moisture and chemically-combined water. Firing-zone temperatures above 1100°C are used. The circulating fluidised bed calciner is more energy efficient than the older rotary kilns. Product sandy alumina particles are 90%+ 45 µm in size.

- Cooling:

  Rotary or satellite coolers are used to cool the calcined alumina from the rotary kilns, and to pre-heat secondary combustion air for the kilns. Fluidised-bed coolers further reduce alumina temperature to less than 90°C before it is discharged on to conveyor belts which carry it to storage buildings where it is stockpiled for shipment.

The schematic description of the Bayer Process can be seen in the figure 2 below.

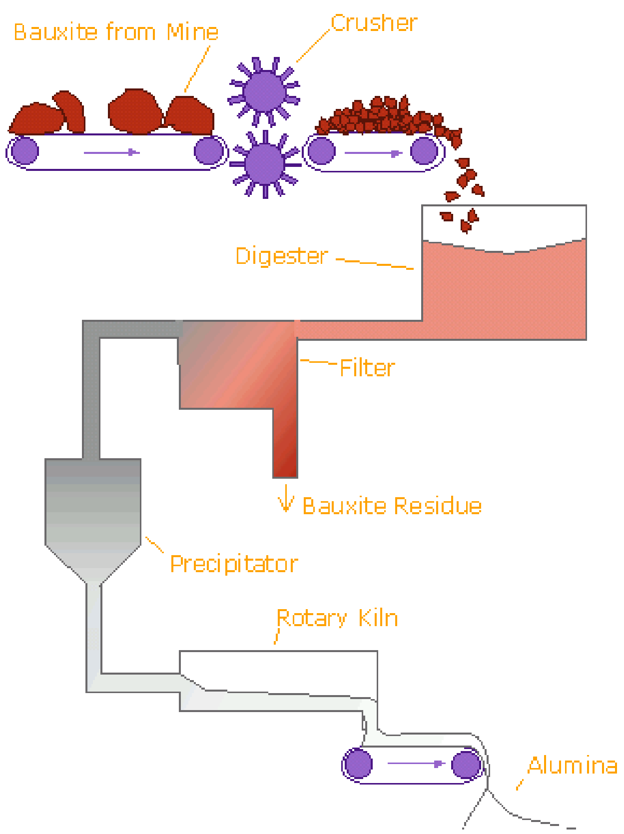


Figure 2: The Bayer Process (Source: http://www.world-aluminium.org/production/refining)

2. Material

Since this project is based on desk-top review, therefore, no particular material is used. However, reviews on books, journals, websites and personal communications have extensively been done.

3. Methods

The activities of this research project are based on literature review of Process Optimisation and Intensification Principles and Tools for Sustainable Mineral Processing, as well as assessing it's applicability for core unit operations in minerals processing and evaluate the example of the process in the Australian mineral industry, in this case the Bayer Process of Alumina Refinery.

By summarizing the forth stages of Bayer Process as explained above, this project attempts to identify and summarize certain possible and promising techniques of process intensification to be applied specifically in alumina refinery and mineral industry in general. The identification is based on writer's intuition which refers to the references obtained.

4. Desk-top Review

Process optimisation and intensification applications have been realized in different types of process industry. Several conventional and new technologies have been developed and applied, whether it's applied alone or in combinations. Although the common identification that process optimisation and intensification are in principle applicable to minerals processing, there is only limited evidence that such is done in practice. Therefore, before starting to find more evidence about it's applicability in minerals processing, it is better to find an example of some applications of process optimisation and intensification in general process industry.

There was no particular experiment has been design and conducted as a part of this research project. This report is mainly based on desk-top research efforts. Reviews on books, journals, websites and personal communications have extensively been done.

The findings of the example applications are described in table 2 shown below, which are differentiated based on the strategy of intensification. All strategies represent novel apparatuses or techniques that are expected to bring dramatic improvements in manufacturing and processing.

Table 2: Process Intensification Strategy and its Application

Strategy	Explanation of how it works and benefits	Application
1. Miniaturisation	**A strategy for making dramatic reduction in the size** of an equipment. These reductions come from shrinking the size of individual pieces of equipment. Benefit: reduce processing volume results in enhance selectivity, thus no need for large space for the equipment which leads to reduction in investment costs for land and equipment	• Intensive mixing • Heat-transfer devices • Mass-transfer devices • Micro bio-reactor • Micro-reactor (chemical reactor of extremely small dimension consisting number of slices with 10 to 100 micro channels)
2. Combined reaction and separation (bioreactor)	**Combining reaction and separation in a single unit operation** has advantages for achieving enhanced conversions and yields in catalysed reversible reactions. Selective absorption, adsorption and permeation, with reaction are all being investigated, as are imposed thermal effects (endothermic-exothermic coupling). Benefits may be obtained from combining reaction and separation in the same operation, both in terms of simplifying plant and improving reactor conversion and selectivity.	• Intensification of the anthraquinone process for production of H_2O_2 (I. Turunen, 1997) • Pressure swing reactors (Alpay, E., et al, 1994) • Rapid pressure swing reactor operation (RPSR) • Temperature - cycled adsorptive reactor (TCAR) • Liquid multiphase reactor systems.
3. Real time analysis and control	**A strategy for making reduction in time of reaction/production** and also making the control of the process much easier to handle. Benefit: Reduce reaction time and retention time in a number of equipment. Controlled process and product.	• Real Time Analysis And Control of Batch Dyeing Processes • Automatic (control) devices/equipment. • Spinning Disc Reactor • Spinning Cone Column
4. Multifunctional reaction	**Combine one or more function (usually a unit operation)** that conventionally would be performed in a separate piece of equipment. Benefits: reduced investment cost and significant energy recovery or savings, improved production selectivity which leads to reduction in raw material consumption and operating costs.	• Reverse-flow reactor (integrating reaction and heat transfer in a multifunctional unit). • Catalytic distillation (combines reaction and distillation in 1 vessel) • Catalytic stripping • Membrane reactor • Circulating fluid bad reactor

5. Use of alternative/non conventional forms and source of energy	**Use of non conventional forms and sources of energy** such as ultrasound/ultrasonic for chemical processing (research on sonochemistry). The use of Solar energy also may play a role in chemical processing. Benefit: reduce operational costs for the use of energy	• Sono chemical reactor • Solar chemical reactor • Microbial fuel cell • Ultrasonic grinding • Ultrasonic for deliquoring
6. Novel distillation	**Combination of all main items of equipment in one unit** with very little pressure drop and small product hold up - no external reboiler and condenser. Climbing wall reboiler connected to the bottom of the column a lamella type separator above this, column provided with structured packings, a direct condenser which allows small temperature differences between process and cooling water, no interconnecting piping needed - all efficient equipment and low liquid content. Benefit: reduce operational costs for material and equipment and enhance the mass transfer with very little pressure drop.	• Hydrogen peroxide distillation system (A. Meili, 1997)
7. Combined reaction and palletisation	Combine rotating packed bed and centrifugal palletiser in a single process unit will improve polymer devolatisation. Benefit: improve product yield and reduce investment cost.	• Polymer devolatisation & palletization in a rotating packed bed (C.J. Cummings, G. Quarderer and D. Tirtowidjojo, 1999)
8. Filtration/Centrifuging	Combining sequential unit operations into one unit The centrifuge combines these operations for a pesticide/herbicide/pharmaceutical product with recycle of the solvent used for crystallization. This saves on floor area, operators, conveying, drying equipment, etc. Benefit: reduce operation time and costs.	• Filtering centrifuge-cum-dryer (M. Mohunta, 2005)
9. Milling and Grinding	Grinding is another area where the traditional ball mill, roll mill etc. in case of fine grinding some times combined with dispersion has been replaced by dispersed media mills. The mills operate in liquid media with small size steel, ceramic or glass balls (beads) which are circulated in a vessel having rotating members inside. Benefit: There are vast reduction in power consumption and civil infrastructure.	• Paint and ink industry, red phosphorus, ferrite powder, pigments, etc. • Intensification of dry grinding • Ultrasonic grinding

10. Mixing	Mixing process involving two or more material which will be mixed becomes a unity expected, whether with the same phase or not. Solid-solid mixing is an invention by a Norwegian company that gives an almost perfect mix with in a matter of minutes. A 250 – 500 kg batch is mixed in 3-5 minutes. Compare this with a traditional ribbon or cone blender which can take hours. Benefit: reduce process time which leads to reduction in power consumption and operation costs.	• Solid-solid mixing in a Norwegian company.
11. Flow induced phase inversion (FIPI)	A dispersion which characterised by its rate and type of deformation state variable (DSV) to invert the dispersion under constant thermodynamic condition. Benefit: to promote phase inversion without changing the thermodynamics of system to obtain higher entropy and to delay phase inversion while reducing system entropy.	• Agglomeration • Micro encapsulation • Latex production from polymer emulsification
12. Hybrid Separation	A method of separation which involve an integration of membranes with another separation technique. Benefit: the system operating conditions can be easily adjusted to accommodate changes in the feed stream or to compensate for changes that occur in the membrane over time, improve the quality of the process yield.	• Membrane Absorption • Membrane Distillation • Adsorptive Distillation • Cross-flow filtration • Powder dispersion • Phase separation

Process intensification has a variety of strategies on its application in general industry. The twelve strategies are listed in table above which are summarised as follows. Some of them might look similar, but actually they have different process and function.

1. Miniaturisation is a strategy for making dramatic reduction in the size of an equipment.
2. Combination of reaction and separation is a strategy for combining reaction and separation in a single unit operation
3. Real time analysis and control is a strategy for making reduction in time of reaction/production and also making the control of the process much easier to handle.
4. Multifunctional reaction is a strategy for combining one or more function that conventionally would be performed in a separate piece of equipment.
5. Use of alternative/non conventional forms and source of energy is a strategy for using non conventional forms and sources of energy such as ultrasound/ultrasonic for processing in unit operation.
6. Novel distillation is a strategy for combining all main items of equipment in one unit with very little pressure drop and small product hold up with no external reboiler and condenser.
7. Combination of reaction and palletization is a strategy for combining rotating packed bed and centrifugal palletizer in a single process.
8. Filtration/Centrifuging is a strategy for combining sequential unit operations into one unit.
9. Ultrasonic grinding or intensification of dry grinding is a strategy in milling and grinding.
10. Mixing is a strategy for mixing process involving two or more material which will be mixed becomes a unity expected, whether with the same phase or not.
11. Flow induced phase inversion is a strategy for dispersion which characterised by its rate and type of deformation state variable (DSV) to invert the dispersion under constant thermodynamic condition.
12. Hybrid Separation is a strategy for separation which involves an integration of membranes with another separation technique.

The above strategies are implemented to provide the best result with the benefits of reducing the equipment/plant size, reducing operational cost, enhance conversion and selectivity, improve the quality of the process yield, and many other benefits could be obtained from them.

5. Result and Discussion

5.1. Process Intensification Strategy and Its Application

The classification of process intensification based on diverse strategies as shown in table 2 in desk-top review section confirms that numerous applications have successfully been achieved. Further review was carried out to analyse which strategy is relevant to be applied in every stage of Bayer Process - alumina refinery. Most of the strategies below, as stated in table 3, are obtained from literature source, but not all of them have actually been applied in Bayer process. In this case, strong consideration of the strategies is made for their promising applicability.

Table 3: Application of Process Intensification in Mineral Industry

Process Intensification Strategy	Aluminium Refinery			
	Digestion of Bauxite	Clarification of the Liquor Stream	Precipitation of Alumina Hydrate	Calcination of Alumina
Miniaturisation				
Combined Reaction and Separation				
Real Time Analysis and Control				
Multifunctional Reaction				
Use of non-Conventional Energy	Ultrasonic grinding		- Sono crystallisation - Electro static precipitation	
Novel Distillation				
Combined Reaction and Palletisation				
Filtration/ Centrifuging				
Milling and Grinding	Depolarisation of comminuted material			
Mixing				
Flow Induced Phase Inversion				
Hybrid Separation	- Membrane Technology - Cross-flow filtration			- Membrane Technology - Oxygen enrichment
Other	Bayer-Sinter Combined Method			

The following are detail explanations of potential intensification in alumina refinery as described in the table above:

Ultrasonic Grinding

The ultrasonic grinding mill is designed and applied. The three mechanisms of effect on powders can be realized in ultrasonic grinding mill which are the effect of ultrasonic vibrations, the mechanism of shock ultrasonic treatment (with free working elements), and the effect of ultrasonic cavitation. (Prokopenko, 2002).

This process allows to make accelerated mincing, mixing and mechanical alloying of powder mixtures. Ultrasonic grinding technology provides a fully automated mill roll inspection system. The system is integrated into large grinding machines used for resurfacing large milling rolls. It allows on-line monitoring of the grinding operation, guaranteeing defect-free surfaces, minimizing process time and optimizing roll life. The figure 3 below shows the illustration of hardware interface in ultrasonic grinding.

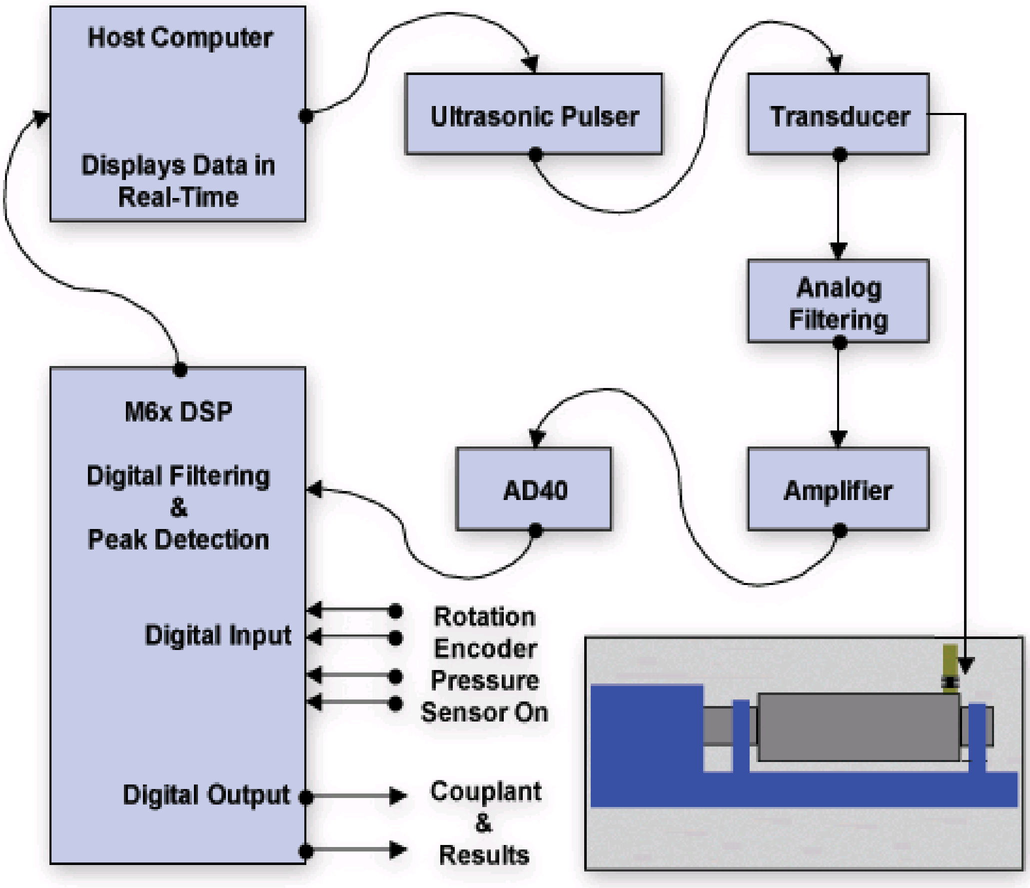


Figure 3: Illustration of hardware interfaces in ultrasonic grinding (source: http://www.innovative-dsp.com/products/images/umiappfig4.gif)

Innerspec Technologies Inc. (2005) provides the benefits could be obtained from ultrasonic grinding, which are:

- Rapid identification of surface breaking and sub-surface defects
- Immediate presentation of roll defects on a detailed colour defect map indicating the number, location and relative severity of defects detected.
- Detection of both circumferential and axial defects
- Ability to inspect during the grinding process
- High-speed sampling rate
- Simple implementation of repeated burst capture on external gate signal
- Low cost

Intensification of Grinding: Depolarisation of comminuted material

Grinding is defined as the size reduction process of particles which is also called as comminution. It describes desirable size reduction while attrition is used to describe accidental or unwanted size reduction. In addition to grinding is classification or particle size separation.

Since 1999, the intensification of grinding process has been applied in cement industries. The grinding is the most energy-intensive phase in the production of cement. Many sell-known companies did the research in the grinding stage in order to be able to minimise the energy consumption. This new technology (ECOFOR) offers the achievement of additional result not by using increased input force, but by decreasing the comminuted material's reaction to the force.

As a consequence of mechanical actions inside the mill, the comminuted dry non-electrically conductive material becomes charged or polarised. A multitude of free electric carriers appears. Their interactions result in the closing of some part of cracks inside the pieces of material after the blows, in the aggregation of ground particles and very often in the formation of coating on grinding media. Thus, the free electric carriers decrease the efficiency at grinding. Their appearance is a symptom of an electrostatic component of the comminuted material's resistance to the force action. The technology for intensification of grinding by special depolarisation of comminuted material is supported by European Patent Application. The device is named as ECOFOR, which realizes the forced decrease of electrostatic level at production. The methods of powder material electromagnetic conditioning by the use of passive electro-neutralisation are known from patent publications (Glukarev, 2001). Structure of ECOFOR method and process on the level of grinding media are shown in figure 4 and figure 5 below.

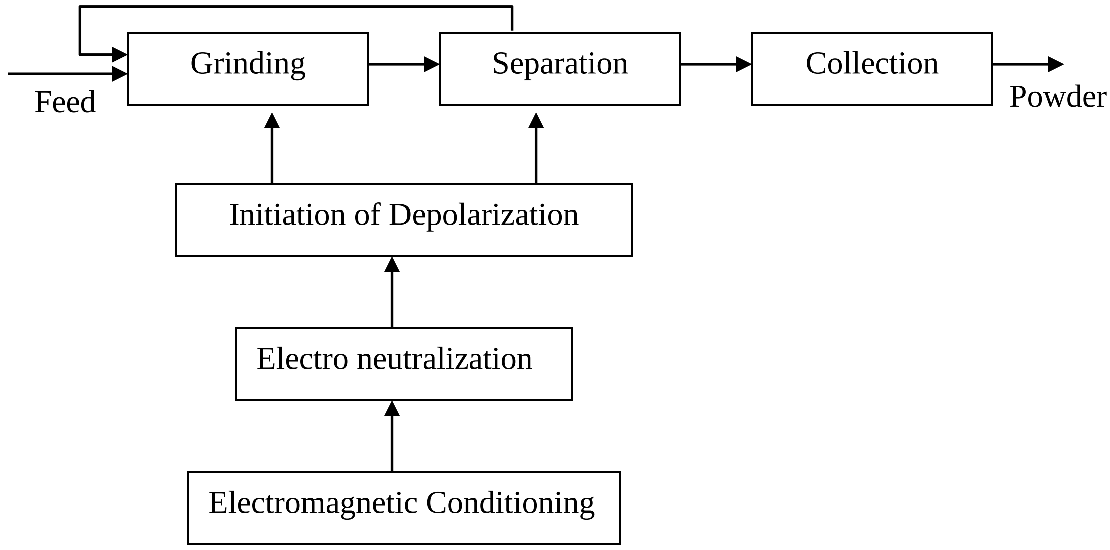


Figure 4: Structure of ECOFOR Method (Glukharev, 2001)

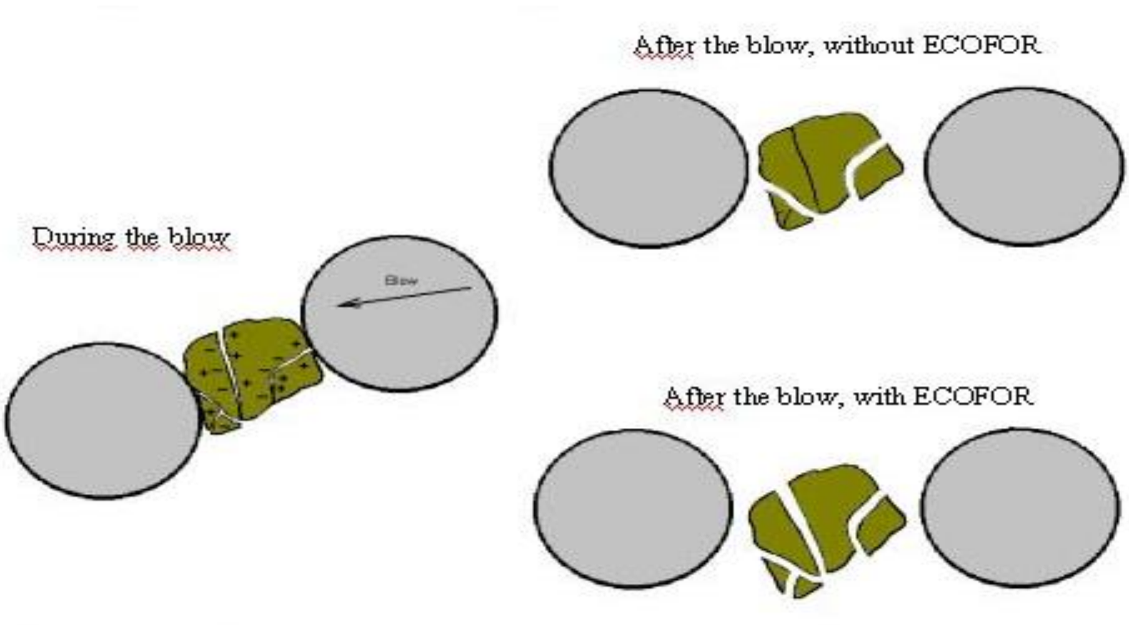


Figure 5: Process on the Level of Grinding Media (Glukharev, 2001)

Membrane Technology

Membrane filtration is the separation of the components of a pressurized fluid performed by polymeric membranes (GE Infrastructure, 2005). Membrane separation processes driven by pressure which is varies depending on the size of the pores, like microfiltration (MF) which has largest pores, ultrafiltration (UF), nanofiltration (NF) or reverse osmosis (RO) which has smallest pores, hence, require the biggest pressure. Those kind of filtration have aimed namely at purification of diluted solutions with low concentration of solid and dissolved particles, with low viscosity and at lower temperature. Cross-flow ultrafiltration and microfiltration (pore size 100 nm) on ceramic membranes can be implemented into the refining process to replace conventional refining techniques, such as cartridge filtration using filtration aids (diatomaceous earth, activated carbon, bone black), and/or decolourising ion-exchange separation. Particularly in Bayer Process, membrane technology could be implemented in digestion and calcination stages. The use of the membranes in those stages basically replaces the use of conventional filters. As its separation driven by pressure, application of membrane separation processes is usually much faster, more efficient and has lower energy requirements in comparison with traditional separation processes, such as crystallization, extraction, absorption, distillation or conventional filtration.

Cross-Flow Filtration

Most of conventional particle filtrations are run in perpendicular flow, with the solution to be filtered approaching the filter media in a perpendicular direction. We can barely find the particle filtration that run in a cross-flow design. In the perpendicular flow design, there are only two streams, the influent and the effluent. Separation is effected in the micron range or greater; with certain depth filter media achieving as low as a nominal one micron separation. Cross-flow filtration is fundamentally different in design, in that the influent stream is separated into two effluent streams, known as permeate and concentrate. Permeate is that fraction which has passed through the "semi-permeable" membrane while the concentrate is that stream which has been enriched in the solutes or suspended solids, which have not passed through the filter. The advantage of this design approach is that the membrane media is operated in a continuously self-cleaning mode, with solutes and solids swept away by the concentrate stream, which is running parallel to the membrane. This principal is basically similar with conventional filtration but different in its technology. Hence, the implementation in the Bayer Process is also basically replaces the conventional filtration.

Figure 6 below show the conceptual view of cross-flow filtration. The feed solution flows under pressure between the two membranes depicted, and as it flows over the membranes, permeate passes through. The rate of permeation is known as flux. The concentrated fraction of the stream exits through the same flow channel as the feed enters, carrying away concentrated solutes and particles (GE Infrastructure, 2005).

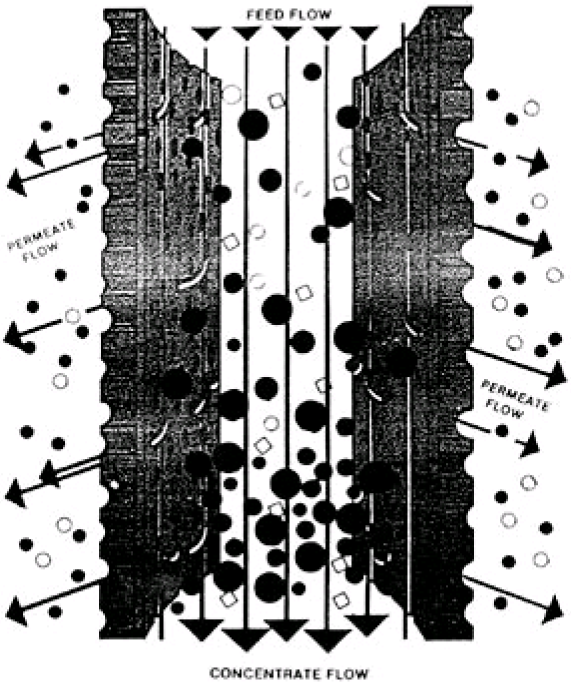


Figure 6: Conceptual view of cross-flow filtration (source: http://www.gewater.com/images/osmonics/771-a.jpg)

Bayer-Sinter combined method

The combined method of Bayer-Sinter is based on the fact that alumina refinery is an energy intensive industry. Traditional energy saving methods employed have been single-equipment-orientated. Based on two concepts of 'energy carrier' and 'system', this novel method analyses the effects of unit process energy intensity (e) and product ratio (p) on overall energy intensity of alumina. The important conclusion drawn from this method is that it is necessary to decrease both the unit process energy intensity and the product ratios in order to decrease the overall energy intensity of alumina, which may be taken as a future policy for energy saving. Energy savings can be made (1) by increasing the proportion of Bayer and indirect digestion, (2) by increasing the grade of ore by ore dressing or importing some rich gibbsite and (3) by promoting the advancement in technology. The result shows that the overall energy intensity of alumina decreased by 7.36 GJ/t-Al2O3, 49% of total energy saving is due to direct energy saving, and 51% is due to indirect energy saving (Liu, et. al., 2005).

The hybrid Bayer-sintering process extracts alumina from a quality bauxite in a Bayer plant and then extracts alumina from another diasporic bauxite plus the red mud from the Bayer process in a sintering plant. The residual alumina and soda in the Bayer red mud can be extracted when the red mud is transferred to the sintering process for further treatment. Only mud from the sintering process is disposed of in waste storage ponds. A portion of the pregnant liquor from the sintering process is carbonated to produce sodium carbonate for recycling to the kiln feed mixture. The rest is added to the pregnant liquor from the Bayer process and precipitated as described above (Price Water House Coopers, 2001). The following figure 7 describes the Bayer-Sinter combined method process.

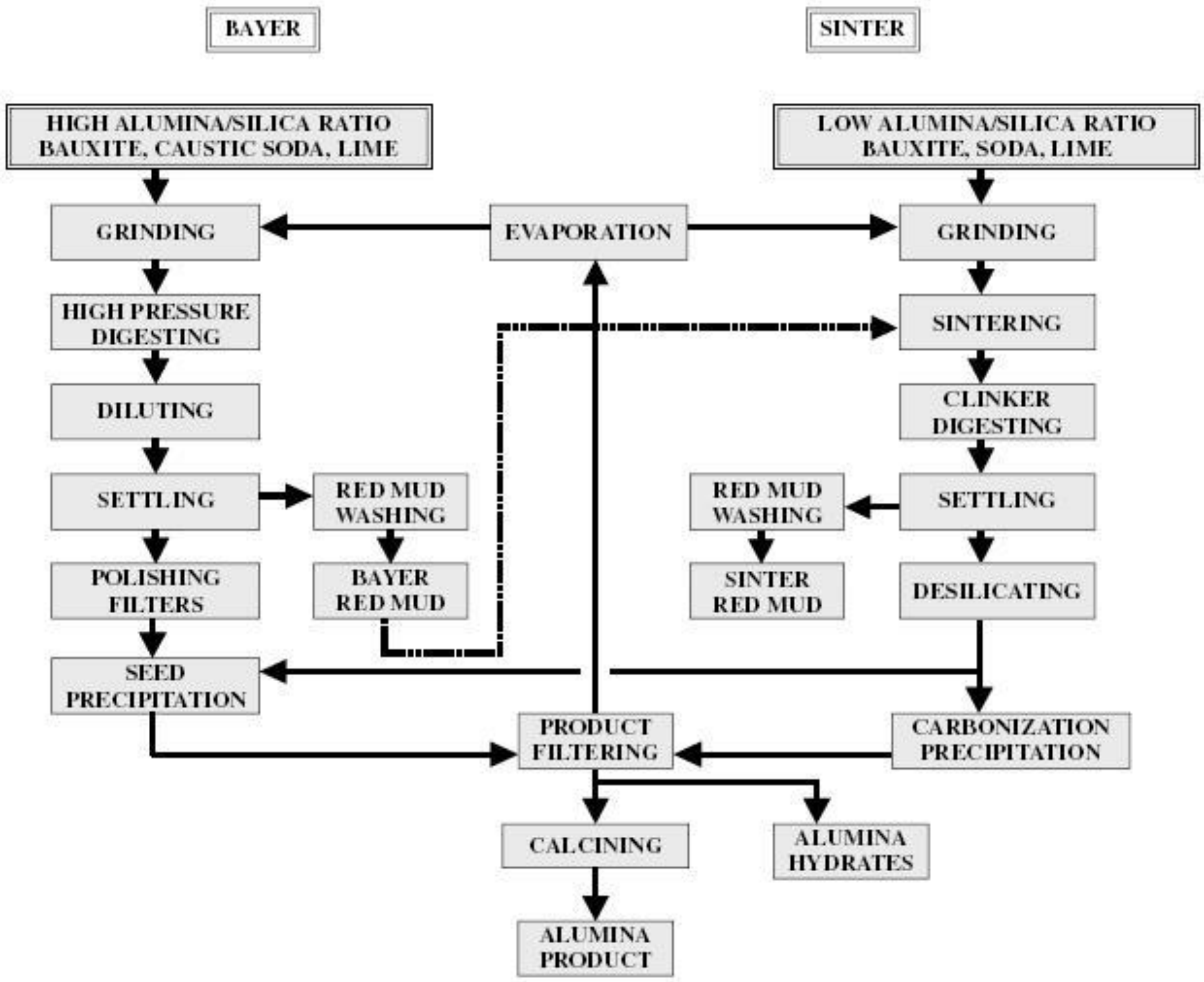


Figure 7: Bayer-Sinter Combined Method Process Diagram (Price Water House Coopers, 2001)

Sonocrystallisation

Among numerous attractive effects on physicochemical processes, one of the most promising applications of power ultrasound is sonocrystallisation. Ultrasound has been used in crystallization to initiate primary nucleation by narrowing the metastable zone width. It influences secondary nucleation and crystal growth. It has beneficial effects on crystal habit and crystal size distribution. It can also reduce or modify agglomeration and the subsequent liquid inclusions and improve product handling (Ratsimba, et. al., 2003).

Sonocrystallisation or widely defined as C3 core proprietary technology competence, has the high intensity of application (100 W/L) and low-frequency (20 - 100 kHz) ultrasound to promote and control crystallization. Benefits of sonocrystallisation can include controlled initiation of nucleation, enhanced yield, improved crystal habit, improved filtration characteristics, improved product properties including handling, bulk density and appearance, reduced agglomeration crystals with fewer imperfections and increased process reproducibility.

In the case of Bayer process, sonocrystalliation is applied to remove the impurity which is oxalate. The C3 technology works by significantly increasing the frequency of nucleation events. Each of those nucleation events gives rise to a site for an impurity crystal to form. The rate of impurity crystal formation and subsequent removal via further temperature and supersaturation management is greatly enhanced. (Ruecorft, et. al., 2005) .The simplified Bayer alumina process using sonocrystallisation for oxalate removal could be seen in figure 8 bellow.

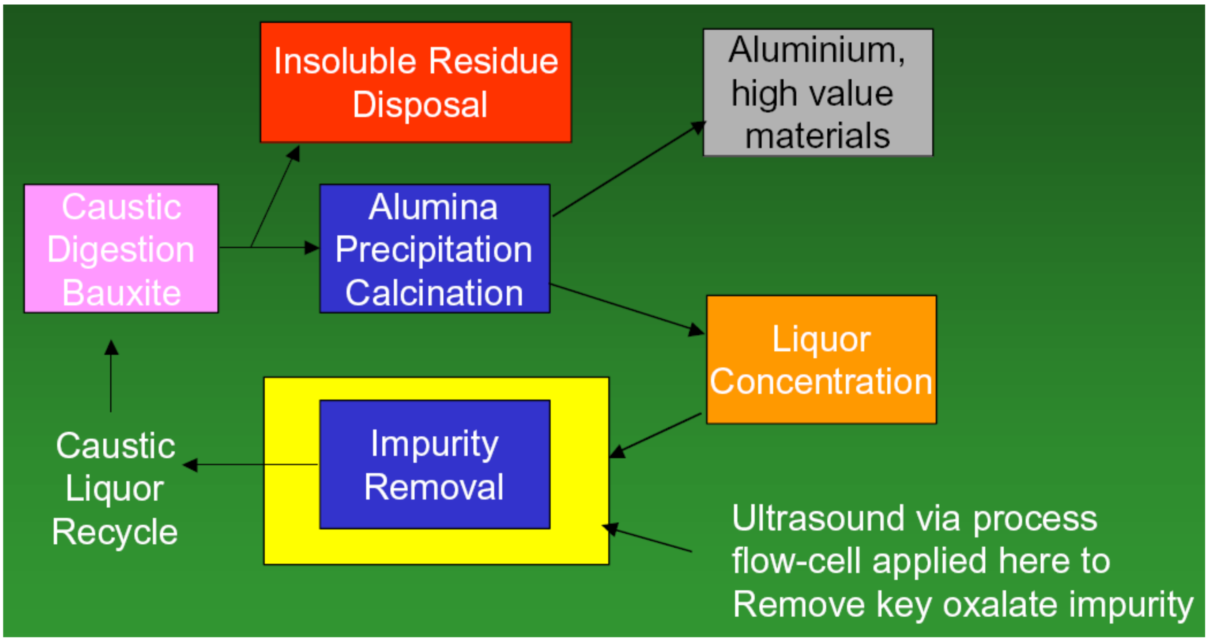


Figure 8: The Simplified Bayer Alumina Process using Sonocrystallisation for oxalate removal (Ruecorft, et. al., 2005)

Early results indicated that there was potential to significantly increase the plant throughput, by introducing a continuous sonocrystallisation system into the current plant arrangement for oxalate removal enhanced.

The overall benefit of C_3 technology in alumina Bayer Process includes:

- Increased liquor productivity
- Lower consumable chemical consumption
- Increased refinery output
- Lower capital cost per tonne of product
- Better energy efficiency from increased concentration
- Fewer residues, lower environmental impact
- Less degradation of alumina quality
- Increased profitability of plant
- Crystallization without crystal modifiers
- Co-precipitation of other impurities (carbonates, sulphates, silicates etc)

Electrostatic Precipitation

This process has been modified by some companies as part of waste minimisation efforts. Lime slurry is added to the slurry pot to control the pH of the slurry to a set point of pH 12. The lime reacts with the phosphorus to form phosphites and phosphine gas, thus reducing the concentration of phosphorus to below 1000 ppm. The lime also prevents the metals from becoming leachable.

Furnace off-gas may contain elemental phosphorus, carbon monoxide, and particulates. Electrostatic precipitators (ESP) are used to remove the particulates. Dust slurry from the four ESPs is discharged to ponds that are dredged. Furnace off gas is not considered to be hazardous (US Mining Industry, 2003). Hence, the process benefits mainly concern on environmental impact which is should also be considered.

Two stage electrostatic precipitators are composed of two sections, a charging section and a collection section. The charging section uses ionizer wires to impart a positive charge to the incoming smoke, fume, and dust particles. The charged particles are then drawn into a secondary electric field where they are collected on a series of metal plates. Clean air is then recirculated back into the general air stream (Peak Pure Air, 2001). The following figure 9 is illustrating the electrostatic precipitation process.

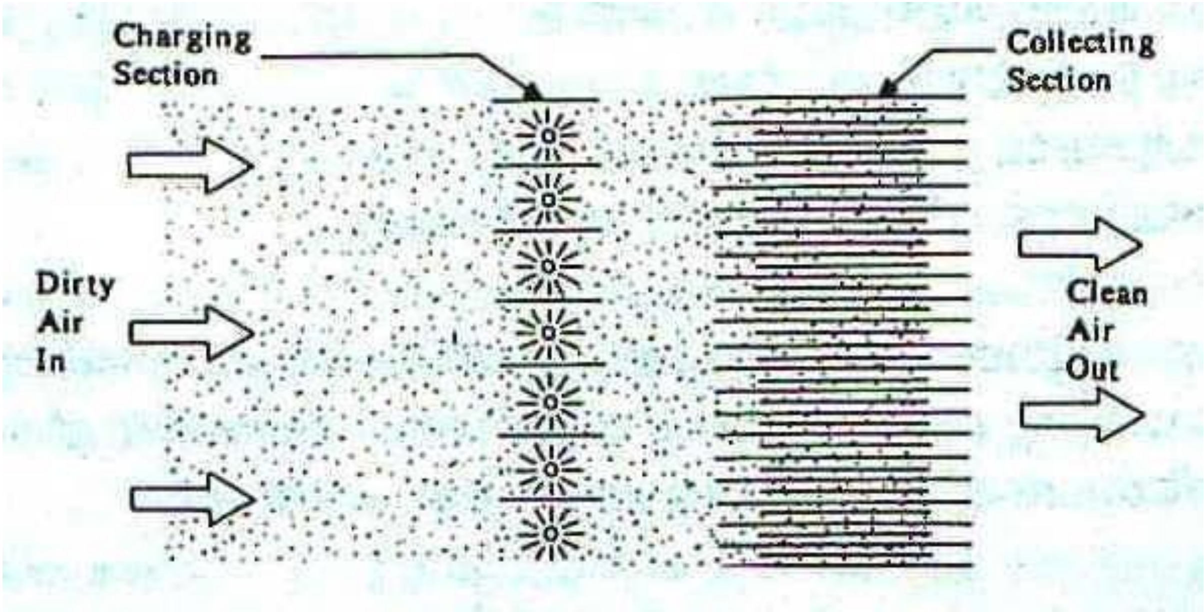


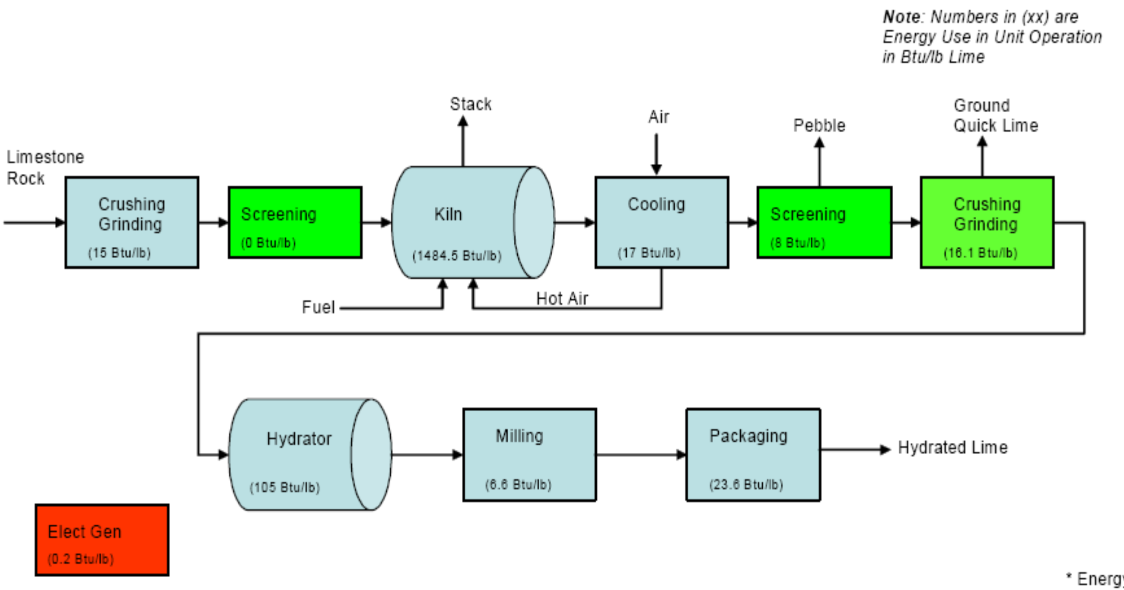
Figure 9: Illustration of the electrostatic precipitation process (Peak Pure Air, 2001)

O_2 enrichment of the air to the kiln by the use of membrane

Calcination is a heating process of removing the chemically combined water from the alumina hydrate which represents one of the most expensive and energy-consumptive operations in alumina refining. A strategy to improve thermal energy efficiency of calcinations for finally reducing the higher cost of calcination process becomes essential to develop.

A novel technology of Oxygen Enrichment in Lime Kiln has attested to be an economical alternative for increasing lime kiln capacity as well as reducing emissions from this recovery process, since the supplemental oxygen is introduced into the kiln burner section to promote more efficient combustion. Advantages such as higher lime production, reduction in average fuel consumption, lower total reduced sulfur emissions, and removal lime mud disposal has significantly confirmed.

This technique is highly recommended for alumina refinery to improve energy efficiency in calcination process as well as enhancing plant capacity. Generally, all fuel combustion processes use oxygen, and normally the 21 percent concentration in air is sufficient. Oxygen enrichment of the combustion air to the kiln was considered to reduce the mass of nitrogen heated and released to the stack. In lime industry, where this technique has been applied recently, the significant advances to membrane technology for O_2 enrichment my allow decrease in N_2 to kiln or 5% reduction in energy to kiln. The following figure 10 is the lime production diagram using oxygen enrichment.



* Energy in Btu/lb

Chemical	Annual Production (lbs/yr)	Total Energy Required	Process Energy Input	Reaction Operations	dHrxn	Separation Operations	Energy Conversion	Separation Energy (Btu/yr)	Alternative Technology (Savings)	Potential Savings (Btu/yr)
Lime	4.06E+10	2892.1*	2892.0*	1651.7*	1208*	32.1*	0.2*	1.30E+12	Significant advances to membrane technology for O_2 enrichment may allow decrease in N_2 to kiln (5% reduction in energy to Kiln)	3.01E+12
% of Input				57.1%	41.8%	1.1%	0%			

Figure 10: Example of Lime Production using O_2 enrichment kiln

(Source: www.eere.energy.gov/industry/imf/pdfs/separations_report.pdf)

5.2. Motivation, Barriers and Recommendation on Process Intensification

Motivations for Considering a Process Intensification Solution

The panel at the AIChE Spring National Meeting on March 30 - April 3, 2003, New Orleans, with title of Process Intensification, identified the following motivations which many of them have been noted before in the above-referenced process intensification article by Stankiewicz and Moulijn and the paper by Protensive Ltd (Tsouris and Porcelli, 2003). The explanation of each point is made in the case of potential application process in aluminium refinery.

- Novel or enhanced products

  The strongest driver for process intensification may well be the possibility of producing novel products that cannot safely or successfully be produced by any other means.

Enhanced alumina product is possible to be obtained by sonocrystallisation which removes oxalate impurity generating a less degradation of alumina quality. No specific method in aluminium refinery has yet been found which could produce significant improvement in alumina product.

- Improved chemistry

  Improvements in chemistry may offer some or all of the following advantages: reduction in raw materials losses, reduced energy consumption, reduced purification and waste disposal costs. A challenge to improved Bayer Process chemistry involves a conversion of monohydrate bauxite to a more beneficial state. Significant fraction of bauxite refined is monohydrate bauxite (boehmite or diaspore) necessities high digestion temperatures. By converting monohydrate bauxite to the form of some intermediate state between monohydrate and tryhydrate (gibbsite), digestion process at lower temperature can be carried out which benefits less caustic and energy. This new challenge entails an investigation of a thermally efficient process options for conversion. (Energetics Inc. of Columbia, 2002)

- Enhanced safety

  Process intensification may improve safety, both by reducing the total volume of potentially hazardous materials, and by possibly improving control of a very fast and/or dangerous reaction. Improved full automation and control strategies are considered to enhance safety in refinery which leads to improved efficiency and better product quality as well as reduced manpower requirement. Automation reduces process upset requiring human intervention in potentially hazardous environments which will minimise the risk of human exposure. Future challenge is to generate more reliable sensors and instrumentation capable of surviving in caustic environments.

- Improved processing

  The improvement of a direct reduction process for producing aluminium from bauxite or other aluminium-bearing minerals could eliminate many of the problems associated with alumina production. An improved processing suggested is therefore a direct reduction which could be combined with an aluminium refining process to produce aluminium with desires quality. This new process would be a radical change from the current alumina production route with major impacts on costs and energy consumption.

- Energy and environmental benefits

  Some applications of process intensification may offer opportunities for energy savings and environmental benefits. Energy savings in Bayer process can be made by either (1) by increasing the proportion of Bayer and indirect digestion, (2) by increasing the grade of ore by ore dressing or importing some rich gibbsite and (3) by promoting the advancement in technology (Liu, et al, 2005). However, other method such as waste heat recovery is important to be analysed. Alumina industry is a huge sink for low-grade heat and presents significant opportunity for cogeneration. Focus in recovering waste heat generated in refinery by utilising waste heat from nearby power plants or other primary energy users. (Energetics Inc. of Columbia, 2002)

- Capital cost reduction

  Process intensification which involves an improvement of equipment will lead to capital cost reduction. Precipitation as one of essential processes in alumina refinery can be modified with aims to accelerate the precipitation rates. From Bayer process can be understood that dissolved alumina is recovered from liquor in precipitation tanks seeded with alumina try hydrate crystals. The rate of precipitation depends on the process temperature, alumina hydrate and caustic soda concentration, impurities in liquor and many others. Precipitation is typically slow which requires the use of larger tank. Alternative method to accelerate precipitation rate will lead to lower capital cost per ton alumina since the precipitators required are only a few. (Energetics Inc. of Columbia, 2002)

Barriers or Deterrents to the Implementation of Process Intensification

On the other hand, there are barriers or deterrents to the Implementation of process intensification (Tsouris and Porcelli, 2003):

- Dynamics of most chemical and pharmaceutical industries
- Conservativism of plant operators
- Batch processors will not easily accept continuous processing solutions
- The current portfolio of process intensification unit operations and processes is limited
- Different process intensification solutions are needed to satisfy each “driver”
- New design codes are needed for novel equipment
- For some process intensification solutions, fouling may be an issue
- There is inadequate education and publicity regarding process intensification in many countries.

If all of those points are to be reflected in alumina refinery or mineral industry in general, the most concerning barrier would probably be the limitation of current portfolio of PI unit operation and process. It is not easy to achieve an entirely effective process intensification in industry. Broad range of technology must be developed for many unit operations for PI to be successfully accomplished. In the case of mineral processing, many solutions of industrial problems have been established but only fewer have actually been applied in industry itself.

Recommendations for Accelerating the Adoption of Process Intensification (Tsouris and Porcelli, 2003)

Increased efforts must be made to strengthen the motivators for process intensification adoption and to reduce the barriers described above. One can explain the scarcity of cases where process intensification has been implemented with the facts that:

- Few of the technologies developed to date offer a clear economic incentive (or other compelling advantages) to justify implementation, whether for a new plant or for a retrofit situation. In other words, an appropriate technology for most applications has not yet been developed.
- If there is a substantial advantage to a process intensification technology for a particular application, the potential user may be either unaware of the technology or not able or willing to evaluate the technology because of its novelty and/or the user's unfamiliarity or distrust of the technology.

These considerations suggest the need for a multi-pronged approach, with pro-active cooperation among industry, academia and government and the engagement of the worldwide process intensification community. The following needs and actions are recommended:

- Identify and communicate the critical needs for process intensification solutions
- Publicize examples of successful development and implementation of process intensification
- Encourage the education of chemical engineers in the science and technology of process intensification
- Encourage the development, testing and commercializing of valuable but risky new technologies
- Vendors of equipment should be encouraged to develop lab and pilot scale versions of process intensification technologies

5.3. Future Research on Process Intensification Challenges in Alumina Refinery

The following table 4 is adapted from Alumina Technology Roadmap (2002) which outlines challenges of comprehensive long-term research and development particularly for Bayer Process in alumina refinery. However, considering there is a similarity of some process between mineral industries, some challenges might be able to be applied in other mineral industries, such as nickel refinery, etc.

Table 4: Process Intensification Research Challenges in Bayer Process (Alumina Refining), (adapted from Energetics Inc. of Columbia, 2002)

Unit Process/Operation	**Challenges**
Digestion	• Achieve higher alumina extraction efficiency • Alter the chemistry of desilication product (DSP) • Sustain higher supersaturation in the digester • Reduce embitterment in the digester • Lower temperatures in Bayer operations • Reduce caustic consumption • Increase use of biotechnology • Address declining grades of bauxite reserves
Clarification	• Achieve better separation of components in the process • Combine unit operations to reduce capital intensity • Use more capable processes and elegant designs • Reduce wash water requirements • Reduce energy consumption
Precipitation	• Increase precipitation rates • Use more capable processes • Improve seed management • Reduce equipment residence time • Increase use of lower-grade reagents • Understand fundamental precipitation chemistry and physics

Calcination	• Improve energy efficiency of calcination • Lower the overall temperature in Bayer operations • Increase use of waste products
New Process Chemistries and Alternative Raw Materials	• Develop alternatives to the Bayer process • Understand other process chemistries that may supplant Bayer • Use more capable processes and elegant design • Reduce scale • Find cheaper sources of raw materials • Address declining grades of bauxite reserves • Encourage management to adopt long-term view
Controls and Instrumentation	• Improve process control and develop more on-line instrumentation and • measurement techniques • Increase process automation • Reduce manual labor requirements • Develop more process optimization tools and techniques • Improve knowledge management at the operations level • Develop efficient isolation valves • Use more capable processes and elegant design
Energy and Fuels	• Consider thermal efficiency on a system basis • Optimize the efficiency of the overall process • Achieve 16 MW/petajoule of cogeneration industry-wide • Reduce greenhouse gas emissions from energy use • Overcome the difficulties and cost associated with demonstrating • new technology
Bauxite Residue	• Improve bauxite residue management • Develop economic applications for bauxite residue • Increase focus on corporate social responsibility

Digestion

The alumina contained in the bauxite is dissolved in the Bayer liquor become sodium aluminate during the digestion process. In future research, R&D needs more focus on reducing the energy requirements (e.g., by carrying out the process at lower temperature or using biotechnology), facilitating the use of different grades of bauxite such as those with more reactive silica and also reducing caustic requirements.

The use of desilication technologies that reduce sodium consumption may also play role for the future research and development. This technology was developed using CaO and CaO + Na_2SO_4 as additives (Solymár, et. al., 1977). The latter process is protected by Hungarian Patent No. 166.061. According to this technology, addition of 3% CaO calculated on the dry weight of the Bauxite, reduce the loss of bonded NaOH by 10 to 12%. The simultaneous addition of Na_2SO_4 to the digestive liquor in quantities of 3 to 5 g/litre compensates for 5 to 7% of the NaOH loss. The success of this effort would also significantly increase usable bauxite reserves. A true counter-current digestion process for extracting monohydrate grades of bauxite at low temperatures may be developed by using a vertical upflow vessel where the monohydrate is introduced at the top and the spent liquor at the bottom. It would be a valuable progression of the counter-current technology currently used. The use of “free” evaporation should also be considered where entropy is used as a replacement for additional live steam.

Clarification

In a settling process, bauxite residue is separated from the liquor containing the dissolved sodium aluminate, after which the residue is washed to recover caustic soda and any remaining aluminate liquor. Potential improvements to this process could include the elimination of security filtration, which would improve safety while decreasing capital and operating costs. Combining digestion and clarification into a single unit operation would improve the stability of these processes. If the combination process is continuous, it would represent a step change in current operations. An alternative to pressure decanter technology for the combined process would be a liquid/solid separation process utilizing membrane technology.

Precipitation

Alumina hydrate crystals are precipitated from Bayer liquor in a series of tanks seeded with gibbsite. The development of catalysts for reducing the activation energy for precipitation could significantly improve productivity. Computer modelling techniques should be developed to improve the efficiency of designing these catalysts as well as other additives. An alternative to current precipitation operations would be to focus on the yield of the precipitation process and adjust the quality of the product afterwards.

Calcination

Calcination is one of the costliest and most energy-intensive operations in alumina refining. The precipitated alumina hydrate crystals are sent to calciners or kilns where the water is removed. Several properties of the alumina product are very dependent on the conditions of the calcination process. The main focus of future research is investigating potential means for improving the thermal energy efficiency of calcination. Study of oxygen-enrichment benefits of calcination should also be considered.

New Process Chemistries and Alternative Raw Materials

The development of new process chemistries could eliminate many of the problems associated with alumina production (e.g., scale, impurities). Some options (the use of trona, for example) have been considered in the past but were unsuccessful (Aitala, R. & M. Aitala, Isonex, Inc, 1997). Other options include an aluminium chloride route to alumina production and the physical separation of monohydrates and trihydrates. New physical or chemical methods to reduce the amount of reactive silica that is dissolved or to remove kaolin from Bayer liquor before dissolution is complete are also considerable. The alumina industry also needs to establish a strategy for managing its use of resources in the future. The trend toward lower grades of bauxite and higher raw material costs will require the industry to maximize the use of its bauxite reserves, possibly through the use of alternative raw materials.

Controls and Instrumentation

Advances in process controls, instrumentation, and measurement techniques are solution to the long-term goal of full refinery automation. Achieving a high level of process control without significant human labour requires instrumentation that is precise, reliable, and robust. Reliable instruments that are specific to alumina refining are needed to measure common parameters such as temperature, pressure, density, and flow. New specific sensor such as robust sensors, particle size sensor, and caustic analysis could apply operational flexibility by providing direct feedback if needed without any delay associated with lab result. Other research needs include the development of new in-situ techniques that will survive in sodium chemistry; remote sensing technology (e.g., ultrasonics) that can evaluate material thickness and defects without opening up equipment; and industry-specific control valves that are cheap, low pressure-drop and reliable for use in liquor and slurry applications.

Energy and Fuels

Energy use and process efficiency are the most important thing for many process-related issues in the refinery. Reducing the time spent on unit operations such as digestion and precipitation, increasing product yield, and adopting on-line instrumentation (like mentioned before) all make the overall refining process more efficient. The lack of plant-wide energy balance models makes it difficult to optimize plant thermal efficiency and use of waste heat. The development of process-specific models for condensate and steam balance would reduce water consumption in addition to energy requirements. In terms of power generation, on-site cogeneration is more efficient and has fewer associated greenhouse gas emissions than purchasing power. One of the most efficient and environmentally friendly options would be the use of a coal-gasification combined-cycle system to cogenerate electricity and process steam.

Bauxite Residue

Bauxite residue, or red mud, is the largest environmental concern of alumina refineries mainly because of the size of this waste stream and its causticity. Much effort has already been put into developing improved dewatering techniques, disposal technologies, and alternative uses. The alumina industry recognizes that it has a cradle-to-grave responsibility for the residue and that more work is needed to develop reuse opportunities and sustainable storage options. One option may be to neutralize the residue in-situ rather than build up large inventories. Improved methods of separating the components of the residue may ease neutralization and reduce the need for future remediation.

Recent project has been developed by Alfa Laval and Alcor (Alfa Laval Benelux, 2005). Alfa Laval's equipment combined with Alcor's alumina process know-how has resulted in a new technology. The co-operation has resulted in the development of a new technology package for the production of alumina from bauxite, combining Alfa Laval's equipment technology with Alcor's process technology.

Implementation of the technology reduces the amount of mud produced, a serious environmental liability in alumina refining, and in turn generates an attractive revenue stream, hence it has been given the acronym Mud-to-Money. With today's demand for alumina the production increase, albeit modest, and the short implementation time and outstanding project economics will be most welcome for the industry.

6. Conclusions and Recommendations

6.1. Conclusions

Inherent in the concept of process optimisation is the reduction and control process variability. Maintaining the process variable as close as possible to the set point will allow the process to operate closer to the plant's constraints and can have a tremendous impact on the bottom-line results due to increased throughput, yield, and quality, as well as a reduction in waste. Process Intensification refers to the development of radical technologies for the miniaturization of process plants while achieving the same production objective as in bulky conventional processes.

The improvement of process intensification in mineral industry is not as vast as that on general chemical industry. The key of intensification principle are summarised in the twelve strategies which are assumed to be the accurate way in classifying various applications in process intensification. Some of those strategies are however quite promising to be applied in refinery, which are:

- Non conventional energy utilization: ultrasonic grinding, sonocrystallization and electrostatic precipitation
- Milling and grinding : depolarisation of comminuted material
- Hybrid separation : membrane technology, cross flow filtration and oxygen enrichment
- Other strategies : Combined Bayer-Sinter Method

The above applications offer numerous advantages including reduction in operational cost, enhancement in conversion and selectivity, improvement in quality of the process yield, time efficiency, improved separation process, lower energy consumption, and increased refinery output. Therefore, process intensification as a well-known issue in process industry can also successfully be implemented in one or few stages of alumina refinery which is expected to generate a more sustainable mineral processing

The findings also include the comprehensive long-term research and development for Bayer Process. Advance research is necessitated on every stage of alumina refinery includes digestion, clarification, precipitation, calcination, as well as various challenges in new process chemistries, alternative raw materials, controls and instrumentation, energy and fuels which will develop a more intensified alumina refinery in the future.

6.2. Recommendations

Process optimisation and especially process intensification should widely be used, particularly in mineral processing industry which its application can be barely found, in order to achieve efficient and substantial improvements in the production processes, lower investment costs, lower energy use and waste production, and especially reductions in the size of equipment which has not been applied in mineral industry, to eventually achieve a more sustainable technologies.

Achieving sustainability of those aims requires a new generation of engineers that are trained to adopt a holistic view of processes as embedded in larger systems. Therefore, it might be useful if process optimisation, process intensification and sustainable development are widely and early introduced to the high education of (chemical) engineer.

As process intensification is relatively new, any research experiment concerning this topic should be fully supported in many aspects in order to attain satisfaction outcome for process intensification progress. Tools (lab experiment) and software (modelling) are two of many aspects that could be very supportive to obtain real and accurate findings to be implemented in mineral industries. Suggestions for various mineral problems are frequently end up with no actual application involved. Conservativism of plant operator, limitation of the current portfolio of process intensification unit operations and processes, etc., are considered as barrier in process intensification improvement.

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GLOSSARY

Term	**Definition**
Alumina	The compound Al_2O_3. The calcined product from an alumina refinery at > 98% Al_2O_3.
Alumina hydrate	The compound $Al_2O_3,3H_2O$. Mineral name is gibbsite. Frequently referred to as hydrate. This is the white solid that is precipitated in the refinery process and is calcined to form alumina.
Bauxite	The principal ore of aluminum, composed mainly of hydrous aluminum oxides and aluminum hydroxides
Bayer Process	The process invented by Dr. Karl Bayer, wherein alumina content of bauxites is dissolved in hot caustic solutions, clarified, cooled and alumina hydrate added as seed to precipitate alumina hydrate for classification and calcination to alumina.
Boehmitic	Containing the mineral boehmite, AlOOH
Calcination	The process of heating alumina hydrate in rotary or stationary calciners to remove all the water of crystallization except the last 0.5-1.0%.
Caustic Soda	The compound sodium hydroxide, NaOH. Frequently supplied as 50% solution.
Desilication	The process for removing silica from a process stream, usually by seeding and precipitation.
De-bottlenecking	Process of eliminating plant restrictions by improving operations or equipment.
Diasporic	Containing the mineral diaspore, Al_2O_3,H_2O in a very tight lattice structure.
Digestion	The process of dissolving compounds of interest from an ore at temperature with an appropriate solution.
Gibbsitic	Containing the mineral gibbsite, $Al(OH)_3$. Also referred to as alumina hydrate or aluminum hydroxide.
Grinding	To crush, pulverize, or reduce to powder by friction, especially by rubbing between two hard surfaces
Kiln	An item of equipment for heating materials to remove volatiles or to decompose a compound. In reÑneries to convert limestone to lime, sintering kiln feed to clinker, or alumina hydrate to alumina.
Liquor, pregnant	A solution of alumina in a caustic liquor with a high ratio of alumina to caustic.

Liquor, spent	A solution of alumina in a caustic liquor with a low ratio of alumina to caustic.
Membrane	A thin sheet of natural or synthetic material that is permeable to substances in solution.
Monohydrate	A compound, such as calcium chloride monohydrate, $CaCl_2 \cdot H_2O$, that contains one molecule of water.
Precipitation	The process of a compound coming out of a solution; usually promoted by cooling and seeding of a supersaturated solution.
Red Mud	The waste solids from the Bayer process after the extraction of alumina from a bauxite; consists mainly of iron oxides and desilication products.
Sintering Process	The process for extracting alumina from diasporic ores by mixing with lime, soda, and strong caustic solution in the required ratios and burning in rotary kilns at 1200-1300™C to produce a clinker, containing the required Na2O,Al2O3, which is dissolved in liquor after grinding, then clarified, desilicated and carbonated to produce alumina hydrate for calcination into alumina.
Slurry	A slurry is a suspension of solids in a liquid.