Alumina Technology Roadmap

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Preface

The origins of this roadmap began with an agreement between The Aluminum Association, acting on behalf of the U.S. aluminium industry, and the U.S. Department of Energy, Office of Industrial Technologies (DOE/OIT), signed in October 1996. Under this agreement, both industry and the DOE/OIT agreed to collaborate on industry-led, government-supported, pre-competitive research and development to increase energy efficiency and reduce wastes in the production of aluminium.

This *"Industry of the Future"* agreement called for industry to develop a vision for its future and a technology roadmap to achieve that vision. The government then agreed to provide cost-shared financial resources to help the industry attain that vision. The program has been sufficiently successful that, following the development of the vision — *Partnerships for the Future* — not one but a series of technology roadmaps has been developed. In addition to a generic roadmap, the industry has developed roadmaps related to inert anodes and advanced smelter technology, the use of aluminium in automotive markets, the handling and treatment of bauxite residue, and the use of advanced ceramics to improve aluminium production and processing. These roadmaps have been distributed globally and have helped spawn similar strategic planning activities around the world. The present alumina roadmap represents the last significant portion of the production chain to be addressed.

Over the past five years, the aluminium industry partnership with the DOE/OIT has been extremely successful. In this time, over 35 cost-shared projects have been initiated with a total of more than 80 technology partners. Assuming all these projects run to completion, a total of some US$100M will have been expended in the development of technology for the aluminium industry. Further, the technology roadmaps have communicated the needs of the industry, focused the efforts of diverse groups such as national laboratories, supplier companies and the universities on critical issues, and aligned the interests of all stakeholders.

Independently in the early 1990s, Australian alumina producers collaborated with joint research projects planned under the auspices of the Australian Mineral Industries Research Association (now AMIRA International). The association coordinated production of the *Alumina Technology Roadmap* which was a joint collaboration between the DOE/OIT, the Australian Department of Industry, Science and Resources and nine alumina companies and was facilitated by Energetics, Incorporated, USA.

1 Introduction

This *Alumina Technology Roadmap* represents a unique global partnership, a partnership that may well signal the future of the aluminium industry. This roadmap partnership has involved the collaborative efforts of industry groups from the major international companies operating on four continents, government representatives from both the United States and Australia, and representatives from the academic community and industry associations (The Aluminum Association and the Australian Aluminium Council). All were drawn together under the auspices of AMIRA International, the mineral industry research association, to consider and develop technology plans for the alumina industry through the year 2020. Given the globalization of the aluminium industry, and the fact that Australia is by far the largest producer and exporter of alumina, it is most appropriate that the input for this *Alumina Technology Roadmap* was developed at a workshop in Fremantle, Western Australia in May 2001.

The alumina industry is facing similar issues as most other global commodity producers: social and environmental reporting, the challenge of sustainable operations, the image of a 'green' industry, and competition from substitute materials. Individually each producer is addressing these challenges. However, it is now evident that some challenges are best dealt with by an industry sector above and beyond the direct competitive environment. One key outcome of a technology roadmap is identifying these collaborative areas and the steps that must be taken to achieve the industry-wide goals.

A steering committee of international technology experts guided the development of the roadmap. An essential first step was the development of critical technology goals to which the industry should aspire. These ambitious goals establish the longterm vision and encompass the challenges for alumina as a commodity — energy efficiency, safety, environmental performance, sustainability issues, and customer expectations — as well as the product challenges of quality, consistency, and performance. The goals reflect the industry's acknowledgment of the growing impact of environmental and social issues on business practices. Improving overall performance on environment, health, and safety, for example, will push the industry beyond current best practice and enhance its long-term competitiveness. The specific industry strategic goals for the year 2020 are shown in Exhibit 1.

The resulting roadmap outlines a comprehensive long-term research and development plan that defines the industry's collective future and establishes a clear pathway forward. It emphasizes twelve high-priority R&D areas deemed most significant in addressing the strategic goals. Both continuous improvement through incremental changes as well as significant advances through innovative step changes will be essential if the industry is going to respond effectively to the challenges in the years to come.

The expected benefits of using the technology roadmap include increasing governments' capacity to build strategic research alliances and enabling industry to capitalize on emerging economic opportunities through early and improved access to leading-edge technology. It is anticipated that the development of this *Alumina Technology Roadmap* will serve to complement other ongoing efforts to enhance the understanding of the industry by government and other stakeholders such as the national laboratories and universities. The Australian industry and Government are currently putting in place a long-term vision for the industry in Australia, under the title of the Light Metals Action Agenda. The technology roadmap approach has been embraced as a key component of this strategy. The development of the *Alumina Technology Roadmap* has also been a major action item under the Government's Energy Efficiency Best Practice program. The participating government agencies of both the United States and Australia are encouraged by the willingness of alumina producers from around the world to collaborate on a strategic plan to guide the industry's growth and enhance its competitiveness in the world economy over the next several decades.

Exhibit 1. Alumina Technology Roadmap Strategic Goals

The Commodity Challenge

Through the application of technology

- Reduce operating costs of existing plants by 3% per annum
- Achieve substantial energy efficiency gains against a benchmark of reducing total energy consumption to 25% below current bauxite specific best practice
- Target capital costs of new plants at <US$500/annual tonne and falling, with major expansion at half this cost, achieved within a framework of return on investment before tax of greater than 18%
- Contribute to improvement of overall performance on environment, health and safety to world's best practice and consistent with global sustainable development principles
- Produce a product that meets all of our customers' current and future needs

This indicates a need to improve over a 5 to 20 year period, with 3 year intermediate goals, through

- Increasing yield by 20% above current bauxite specific best practice
- Reducing DSP caustic consumption to 30 kg/tonne Al_2O_3 and reducing other losses (excluding to product) to best practice
- Achieving a simple capable process by significantly reducing process variability (3 sigma of <5%) through elimination of the effects of scaling and blockages, by more reliable equipment, better materials, process automation, and advanced control
- Reducing total energy consumption through improved methods of calcination, cogeneration and process improvements
- Developing and applying combustion and power generation technology from which waste heat sources can be used for production of alumina, capable of operating at a power generation to alumina ratio that is not significantly less than that for the benchmark of best present technology operated on natural gas, unaffected by bauxite digestion temperature or energy source, other than its net calorific value
- Developing capable processes to achieve a significant reduction and recycling of all other inputs and outputs including water, odours, VOCs, mercury, oxalates, etc.
- Focussing on opportunities with synergistic industries such as caustic soda and power generation
- Developing methods to achieve a 1,000-year ecologically sustainable storage of red mud and other solid wastes in existing storages, and make substantial progress in storage for later reuse as well as achieve substantial progress in the reuse of the red mud

The Product Challenge

- Improving consistency of alumina with 3 sigma limits of less than half of the present levels, with emphasis on dust, particle toughness after dry scrubbing, and impurities including sodium and silica
- Developing, in conjunction with the aluminium industry, sufficiently good delivery systems such that adequate dispersion is obtained at the cell, thus allowing the alumina to readily dissolve in conventional and modified reduction cells in the temperature range 840-900C and potentially as low as 750C

2 Alumina Industry Research and Technology Needs

This roadmap represents a concerted look by the global alumina industry at its technology challenges over the next 20 years. While most of the R&D needs themselves are not new, the industry has reached a consensus on the highestpriority issues, creating a vision for the industry as a whole to move forward.

Six major themes encompass the highest-priority research and development needs identified by the industry, as shown in Exhibit 2. These themes are

- Bayer process chemistry and alternatives,
- resource utilization,
- energy efficiency,
- process and knowledge management,
- residue treatment and reuse, and
- safety/human exposure.

Changes in *Bayer process* chemistry can improve refinery productivity and yield, which in turn impact cost and energy efficiency. Major topics include acceleration of precipitation rates, desilication product (DSP) chemistry, scale formation, and the removal and recovery of impurities from the Bayer circuit (either from the liquor or the bauxite itself). Understanding and reducing the variations in alumina quality and consistency is also a key element of improved process chemistry. The development of alternatives to the Bayer process (i.e., direct reduction of alumina or a non-caustic route) must be considered as potential long-term solutions to eliminating problems associated with the Bayer process. Step change approaches are also indicated in changing the process chemistry to eliminate scale.

Resource utilization issues center on bauxite modification or beneficiation and caustic soda consumption. The industry must take further steps to develop technologies and strategies to effectively manage its resources for the future. The capability to use lower quality input materials – including lower grades of bauxite, caustic, and lime – is a key part of this strategy. The challenge of substantially reducing caustic soda consumption is not new but may require a significant process change. Maximizing the use of bauxite reserves is particularly important to the future of the industry; the supply of economical gibbsitic ore is not as large as ores requiring more vigorous treatment. Improvements in resource utilization create benefits that ripple through to plant efficiency and environmental performance. By maximizing the alumina extracted per ton of bauxite, refiners reduce the input of impurities per ton of alumina and also the quantity of residue generated.

The *energy efficiency* of the Bayer process can be improved directly or indirectly through the use of cogeneration, waste heat utilization, and synergies with nearby industries, as well as through equipment advances or process changes.

The non-utilization of waste heat within some refineries represents one of the biggest energy inefficiencies in the industry. Opportunities for utilizing the waste heat of nearby power generators should also be considered. Reducing residence time in the Bayer process equipment also reduces energy consumption, losses, and capital costs while increasing production. Any operating change that increases productivity essentially reduces the unit energy requirements of producing alumina. Improving the thermal efficiency of refinery operations also reduces emissions of greenhouse gases.

The alumina industry is not as advanced as the chemical and some other industries in its use of process management techniques, particularly models and control systems. Refiners often use models that have not been tailored for the specific conditions found in a refinery and therefore do not work particularly well. Increased use of Bayer-specific models and automation reduces process variation while reducing human exposure to the caustic environment. Knowledge management systems are also critically lacking in the alumina industry, leading to repeated mistakes, particularly at the operations level. Benchmarking is a mechanism by which individual refineries can gauge their performance and practices against each other, and the industry can measure itself against other industries. Benchmarking tends to be most successful in those industries where an information infrastructure already exists.

The alumina industry has been investigating options for *residue treatment and utilization* for years with limited success. The economics of using the residue in most applications are not currently favorable. Inventories of this byproduct represent a liability for the industry that extends well into the future, and technology is needed to find economically viable alternative uses.

Reducing human exposure to safety risks can be accomplished through many of the topics already discussed, including reducing scale and increasing plant automation. The push for full automation is a common goal throughout the industry and would promote the awareness of refineries as well-run, modern, and safe. Industry-wide standards and criteria for safety in plant design and operation, as well as standardized training, would help establish a culture of operating safety within the refining industry.

The ensuing pages highlight the twelve priority R&D needs for the alumina refining industry. The details shown include:

- the likely partners to be involved in each research effort
- the technical and economic risk of developing the technology and the potential payoff if successful
- the time frame for usable results to be developed, given that research could begin almost immediately with no funding constraints
- the key challenges that the R&D activity would address
- a list of some of the technical elements that should be considered during project scoping
- the potential impacts of the successful technology on the five main industry goals – operating cost; capital cost; energy consumption; environment, safety, and health; and product quality

Following the highest priority needs is a discussion of thirteen R&D areas that encompass all of the additional research needs identified by the industry. Some of the items are related to those in the priority R&D list but are sufficiently unique to warrant separate mention. As with the priority R&D needs, the key challenges for each R&D area are noted. The individual research needs are organized by the time frame in which results could reasonably be anticipated: near term (1 to 3 years), mid term (3 to 7 years), and long term (>7 years).

Strategic Goal Legend

Exhibit 2. Relationship Between Priority R&D Needs and Major Roadmap Themes

Priority R&D Need	Major Themes					
	Bayer Process Chemistry and Alternatives	Resource Utilization	Energy Efficiency	Process and Knowledge Management	Residue Treatment and Reuse	Safety/Human Exposure
Alternative Methods to Accelerate Precipitation Rates	✔		✔			
Bauxite Residue: Cost-Effective Inerting and Alternative Uses		✔			✔	
Conversion of Monohydrate Bauxite to a More Beneficial State	✔	✔	✔			
Direct Reduction of Bauxite or Other Aluminium Materials	✔	✔	✔			
Full Automation/Improved Control Strategies				✔		✔
Impurity Removal: Bauxite and Bauxite Beneficiation	✔	✔	✔			
Impurity Removal: Bayer Liquor	✔					
Knowledge Management and Best Practices Benchmarking				✔		
Major Reduction in Caustic Consumption	✔	✔				✔
Scale Management	✔	✔	✔			✔
Technical Solutions for Refinery Releases						✔
Waste Heat Recovery		✔	✔			

Alternative Methods to Accelerate Precipitation Rates

Dissolved alumina is recovered from liquor in precipitation tanks seeded with alumina trihydrate crystals. The rate of precipitation depends on the temperature of the process, the concentration of the alumina hydrate and the caustic soda, the seeding process, impurities in the liquor, and other factors. Precipitation is typically very slow, necessitating the use of many large tanks.

Potential Partners Alumina companies, academia, research organizations

Potential Payoff High

Technical / Economic Risk

Time Frame

2001 2005 2010 2020

Challenges

- Increase precipitation rate
- Improve seed management
- Understand fundamental precipitation chemistry

Description

Investigate alternative methods (both chemical and physical) to accelerate precipitation rates while maintaining product quality. Develop a full understanding of the precipitation mechanism. Develop cost-effective catalysts.

Key Technical Elements

- Examine process kinetics / activation energy
- Examine supersaturation / solubility
- Study alternative (non-sodium) solvents

Comments

- Significant previous work; focus should be on new methods
- May be a challenge to maintain product quality

Impacts

- Lower energy costs; lower maintenance costs
- Fewer precipitators; lower capital cost per ton of alumina for brownfield and greenfield projects
- Increased yield is equivalent to lower unit energy requirements
- Fewer energy-related emissions per ton of alumina
- See comments under "Description"

Bauxite Residue: Cost-Effective Inerting and Alternative Uses

The sheer volume of bauxite residue generated at refineries, combined with its alkalinity and the cost of treatment and handling, are major constraints in finding economical applications for this byproduct. Rendering the residue inert would make it easier and cheaper to store in a sustainable form and would facilitate its use in many applications.

Potential Partners Alumina companies (corporate level), government, industry associations, academia, research organizations, potential customers

Potential Payoff Moderately high

Technical / Economic Risk

Time Frame

2001 **2005** **2010** **2020**

Challenges

- Improve bauxite residue management
- Increase focus on corporate social responsibility

Description

Conduct expert brainstorming session or workshop to scope out potential solutions. Investigate inerting options. Coordinate with other sectors and industries on potential uses of the residue.

Key Technical Elements

Inerting
- Inorganic polymers or other new chemistries
- Use of sea water

Alternative Uses
- Metal recovery
- Absorbent for CO2
- Road base / levee construction
- Soil amendment
- Treatment for acid-generating materials / acid mine drainage
- Cement kiln additive
- Effluent treatment
- Bricks / building products

Comments
- Additional information found in Bauxite Residue Technology Roadmap (The Aluminum Association, February 2000)

Impacts

- Small reduction in refinery operating costs
- Reduced residue storage requirements
- No impact
- Large reduction in residue stockpiles; improved sustainability and environmental responsibility
- No impact

Conversion of Monohydrate Bauxite to a More Beneficial State

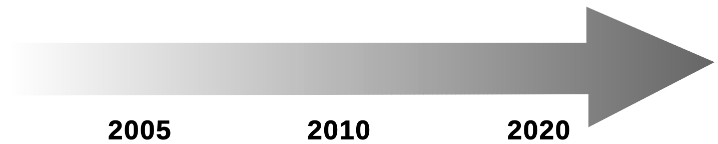
A significant fraction of the bauxite being refined in the world today is monohydrate bauxite (boehmite or diaspore) that requires high-temperature digestion. Bauxite in the form of some intermediate state between monohydrate and trihydrate (gibbsite) could be digested at lower temperatures and would require less caustic and energy.

Potential Partners Alumina companies, academia, research organizations

Potential Payoff Moderate

Technical / Economic Risk

Time Frame



2001 2005 2010 2020

Challenges

- Reduce caustic consumption
- Reduce impurity content of liquor
- Modify bauxite properties
- Eliminate unit operations
- Increase cogeneration

Description

Estimate direct and spin-off benefits of converting monohydrate to trihydrate or some intermediate state. Identify intermediaries and investigate thermally efficient process options for conversion.

Key Technical Elements

- Perform cost/benefit study
- Study mineralogy
- Investigate thermal processing options

Comments

- New conversion process(es) will consume energy; overall net effect must be positive
- Elimination of oxalate and other impurities from the process could indirectly lead to accelerated precipitation rates
- Not appropriate for all refineries

Impacts

Large reduction in energy requirements

Eliminates need for causticization, oxalate destruction, sweetening, and seed wash; fewer heaters required

Energy savings associated with moving to low-temperature digestion

Fewer energy-related emissions; reduced odor

Improved alumina properties with fewer impurities

Direct Reduction of Bauxite or Other Aluminium Materials

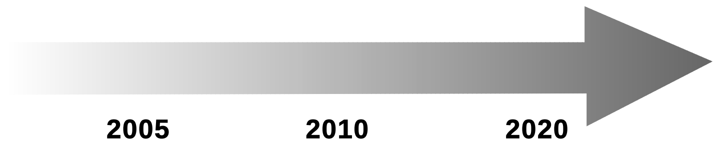
The development of a direct reduction process for producing aluminium from bauxite or other aluminium-bearing minerals could eliminate many of the problems associated with alumina production. Direct reduction could be combined with an aluminium refining process to produce aluminium with the desired quality. This new process would be a radical change from the current alumina/aluminium production route with major impacts on costs and energy consumption.

Potential Partners Alumina companies, government, academia, research organizations

Potential Payoff High

Technical/Economic Risk High

Time Frame



2001 **2005** **2010** **2020**

Challenges

- Develop alternatives to the Bayer process
- Eliminate unit operations
- Encourage management to adopt long-term view

Description

Examine the limits of the process and establish a baseline of fundamental data. Identify and evaluate reduction process options. Determine the material requirements of the reaction vessel.

Key Technical Elements

- Explore pyrometallurgy options
- Investigate chlorination process
- Investigate hydrate reduction
- Develop aluminium metal refining process
- Develop materials technology for reaction vessel

Comments

- Additional details on technical options to be developed in cooperation with the aluminium industry

Impacts

- Elimination of caustic; reduced energy requirements; reduced manpower requirements
- Elimination of Bayer process equipment
- Substantial reduction in energy requirements of producing aluminium
- Unknown
- Unknown

Full Automation / Improved Control Strategies

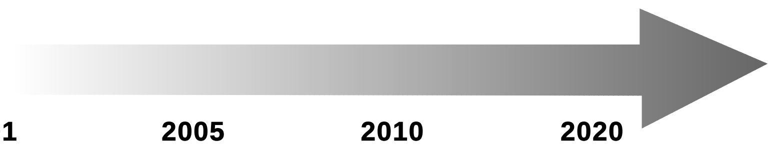
The motivating factors for increased automation in the refinery are improved efficiency and productivity as well as reduced manpower requirements. Safety considerations also represent a key driver; automation reduces process upsets requiring human intervention in potentially dangerous environments. Automation can also lead to better product quality and consistency.

Potential Partners Alumina companies, academia, research organizations, equipment and instrument suppliers

Potential Payoff Moderate

Technical / Economic Risk

Time Frame



Challenges

- Improve process automation and control
- Use more capable processes and elegant design
- Improve seed management
- Minimize human exposure

Description

Benchmark status of the alumina refining industry versus other industries.
Develop more reliable sensors and instrumentation capable of surviving in caustic environments.
Develop predictive models for the Bayer process.

Key Technical Elements

- Develop new sensors and control software (e.g., for precipitation)
- Conduct dynamic modeling
- Investigate low-cost, online precision control (e.g., liquor analyzer)
- Develop expert systems and neural networks

Comments

- Some sensing methods don’t work well in the refinery environment
- Continuous advances will be needed to achieve the long-term goal of full automation

Impacts

Incremental improvements in productivity and energy efficiency; reduced labor requirements

Negligible impact

Small savings from better control of digestion and calcination

Reduced human interaction in potentially dangerous environments

Better product quality and consistency through improved process control and predictive modeling

Impurity Removal: Bauxite and Bauxite Beneficiation

Efficient use of the world's bauxite resources requires maximizing both the quantity and quality of the alumina that is extracted. A major cause of Bayer process inefficiency is the introduction of impurities contained in the bauxite. The industry lacks technically and economically viable methods for controlling and removing these impurities. The trend toward lower grades of bauxite available in the future will only exacerbate this problem.

Potential Partners Alumina companies, research organizations, government, suppliers

Potential Payoff High

Technical / Economic Risk Moderate

Time Frame

2001 2005 2010 2020

Challenges

- Conduct economic bauxite beneficiation
- Address declining grades of bauxite reserves
- Reduce impurity content of the liquor
- Reduce scale

Description

Develop a better understanding of bauxite and estimate future requirements. Develop methods to modify bauxite in order to increase the percentage of extractable alumina. Explore chemical and biological means for removing impurities from bauxite.

Key Technical Elements

- Develop technologies to extract organics from bauxite
- Investigate thermal treatment to remove carbon and change the mineralogy and chemistry of the bauxite
- Develop cheaper, cleaner liquor burning technologies
- Explore in-situ heap leaching of bauxite to remove certain organic and inorganic impurities
- Explore bauxite beneficiation options, including biological methods
- Develop selective mining techniques

Comments

- Alternative is to remove organics from the Bayer liquor (see "Impurity Removal: Liquor")

Impacts

- Increased liquor productivity (lower caustic consumption)
- Increased refinery output and a lower capital cost per ton of alumina
- Better energy efficiency from increased caustic concentration
- Maximized use of bauxite reserves
- Less degradation of alumina quality

Impurity Removal: Bayer Liquor

Almost all organic compounds enter the Bayer circuit with the bauxite. Inorganic impurities also are introduced via bauxite as well as caustic and makeup water. The presence of significant concentrations of impurities in the liquor has a detrimental effect on almost every aspect of the Bayer process, including digestion and precipitation capability, liquor productivity, and product quality.

Potential Partners Alumina companies, academia, research organizations, government

Potential Payoff Moderately high

Technical / Economic Risk

Time Frame

2001 2005 2010 2020

Challenges

- Reduce impurity content of the liquor
- Improve understanding of how organics affect alumina quality and yield
- Reduce scale

Description

Develop a better understanding of various organics and determine their relative impact. Examine various options for removing impurities, including techniques to specifically attack the worst offenders.

Key Technical Elements
- Explore alternative chemistries
- Investigate organic destruction technologies
- Develop improved wet oxidation techniques
- Explore specific surfactants to target impurities
- Consider double-layer, hydroxide, ion exchange, electrolysis, molecular sieve technology, and physical techniques
- Investigate biological impurity reducers

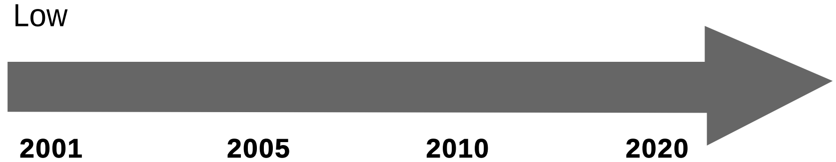
Comments
- Alternative is to remove organics from the bauxite before it enters the Bayer process (see "Impurity Removal: Bauxite")

Impacts

- Increased liquor productivity (lower caustic consumption)
- Increased refinery output and a lower capital cost per ton of alumina
- Better energy efficiency from increased caustic concentration
- Fewer residues, increased use of lower-grade bauxites
- Less degradation of alumina quality

Knowledge Management and Best Practices Benchmarking

The alumina industry lags behind the chemical and some other industries in terms of its use of process modeling to optimize operations, the sophistication of its control systems, its handling and treatment of raw materials and byproducts, and its safety culture. Poor knowledge management, particularly at the operations level, inhibits the industry's ability to improve its performance. Benchmarking may help the refining industry identify potential solutions to some of its key problems by learning from other industries.

Potential Partners	Alumina companies, government, suppliers
Potential Payoff	Moderately high
Technical/Economic Risk	Low
Time Frame	

Challenges

- Improve process design
- Improve process automation and control
- Reduce scale
- Minimize human exposure

Description

Benchmark operating practices in the alumina industry versus other industries (e.g., chemicals and petrochemicals, power). Develop information management tools and knowledge management techniques. Establish industry-wide cooperative standards and criteria for engineering design.

Key Technical Elements

Benchmark the following:
- Scale control
- High-solids material handling
- Particulate chemistry
- Beneficiation processes
- Process control
- Reliability
- Maintenance practices
- Safety

Comments
- Implementation of existing technologies from other industries in the alumina industry may be risky

Impacts


Potential for lower maintenance costs, reduced manpower requirements


Potential for more elegant processes, fewer unit operations


Potential for more efficient operation


Potential to reduce human exposure for descaling


Potential to improve product through better process control and predictive modeling

Major Reduction in Caustic Consumption

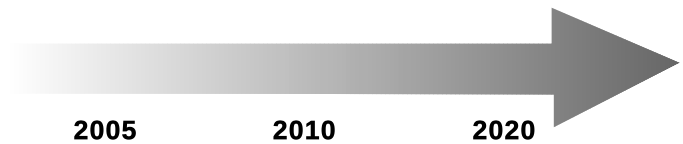
The caustic soda used in Bayer liquor represents one of the largest operating costs in an alumina refinery. Major factors influencing caustic requirements are the composition of the bauxite being processed and the chemistry of the desilication product (DSP) formed during digestion. Much of the caustic soda content of DSP is currently unrecovered.

Potential Partners Industry, academia, research organizations, government

Potential Payoff High

Technical / Economic Risk

Time Frame



2001 2005 2010 2020

Challenges

- Promote caustic selfsustainability
- Conduct economic bauxite beneficiation
- Address declining grades of bauxite reserves
- Alter the chemistry of DSP

Description

Benchmark current caustic consumption in terms of locations and quantity. Develop methods to alter the chemistry of bauxite so that less caustic is required. Develop a better understanding of DSP and investigate ways to alter its chemistry so that less caustic is lost.

Key Technical Elements

- Further develop the Sumitomo process
- Develop improved bauxite characterization and separation technologies
- Examine silica dissolution
- Investigate alternative DSP structures
- Develop methods to recover soda and valuable by products from DSP
- Develop high temperature separation technologies
- Improve mud washing techniques

Impacts

Large cost savings from reduced caustic requirements

No impact

No impact

Reduced handling of a dangerous substance, less likelihood of spills

No impact

Scale Management

The precipitation of sodium aluminosilicate crystals from spent Bayer liquor leads to scaling of heat exchanger vessels and piping. Other types of scale can occur elsewhere in the plant (e.g., calcium titanate-containing scale and alumina trihydrate scale). Maintenance personnel are required to remove scale manually, presenting a serious risk for injury because of the corrosive environment and enclosed space. Scale leads to a significant reduction in heat transfer efficiency and liquor throughput, resulting in increased energy and caustic soda consumption and loss of productivity.

Potential Partners Alumina companies, academia, research organizations, suppliers, government

Potential Payoff High

Technical / Economic Risk Moderately high

Time Frame

2001 2005 2010 2020

Challenges

- Reduce scale
- Minimize human exposure
- Use more capable processes and elegant design

Description

Perform scoping study of the scale issues, including industry benchmark comparison. Conduct fundamental research to eliminate scale and prevent scale initiation and formation. Investigate chemical, biological, mechanical, and material solutions as well as new process designs.

Key Technical Elements

- Study surface chemistry fundamentals
- Optimize hydrodynamics and use CFD modeling to eliminate dead spots
- Investigate scale-resistant construction materials and surface coatings
- Develop chemical solutions such as additives or smart reagents
- Develop robotic cleaning technology
- Investigate technologies to remove silica and other impurities that cause scale

Comments

- Future regulations may restrict manual removal of scale

Impacts

- Large reduction in maintenance requirements, improved productivity; lower energy requirements
- Fewer heaters required
- Savings from higher heat transfer efficiency in the heat exchangers
- Reduced human interaction in descaling (enclosed space, caustic environment)
- Small benefit through better control of silica

Priority R&D Needs

Technical Solutions for Refinery Releases

The issue of refinery releases (including air emissions, effluents, and solid wastes) is becoming more prominent and must be viewed from a broader perspective than in the past. Cost-effective solutions are needed to deal with caustic, organics, trace metals, particulates, and other releases. Insufficient attention has been given to groundwater contamination in particular.

Potential Partners Research organizations, government, refineries, industry trade associations

Potential Payoff Moderately high

Technical / Economic Risk High

Time Frame

2001 2005 2010 2020

Challenges

- Reduce groundwater pollution
- Minimize water usage
- Minimize human exposure
- Increase focus on corporate social responsibility

Description

Conduct scoping study to determine possible next steps. Investigate technical options. Share industry best practices.

Key Technical Elements

- Determine environmental impact at the boundary of the refinery
- Develop non-end-of-pipe removal of trace metals (e.g., selective mining)
- Conduct mixing zone estimation (e.g., toxicology studies, generic models)
- Develop better instrumentation and standardize design and practices to minimize spills
- Develop caustic spill management techniques other than concrete technology
- Model full mass balance to track all constituents

Comments

- Solutions are a mix of best practices and research activities
- May be needed for future operation / expansion

Impacts

Small reduction in caustic consumption

No impact

Small opportunity to recover low-grade waste heat from flue gas

Reduction in air pollutant emissions, spills, and groundwater contamination

Provide “green” alumina to customers

Waste Heat Recovery

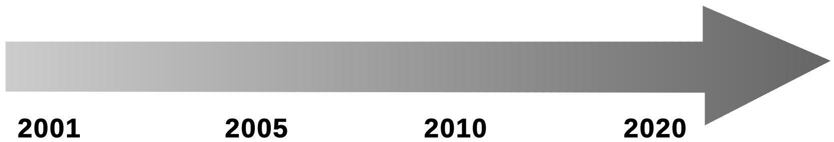
The alumina industry is a large sink for low-grade heat and presents significant opportunity for cogeneration. The industry is currently not taking advantage of available waste heat, mainly because of economic and regulatory reasons. The initial focus should be on recovering waste heat generated in the refinery.

Potential Partners Alumina companies, adjacent industries, government

Potential Payoff Moderate

Technical / Economic Risk Low

Time Frame



Challenges

- Eliminate unit operations
- Increase cogeneration
- Integrate with nearby industries

Description

Recover and use the waste heat in the Bayer circuit. Utilize waste heat from nearby power plants or other primary energy users.

Key Technical Elements
- Examine existing technologies in energy storage or conversion that are applicable to refineries
- Investigate if any Bayer process reactions can be done using waste heat (e.g., calcination alternatives)
- Study waste heat from other sources

Comments
- Linkages with other primary energy users is site-specific
- Will the use of waste heat have an associated greenhouse gas credit?

Impacts

- Moderately lower energy costs
- Recovery of refinery waste heat–no net impact (fewer boilers but more heat recovery equipment) Recovery of outside waste heat–large savings from fewer boilers
- Moderate to high savings (higher if cogeneration is used)
- Fewer combustion-related emissions
- No impact

Digestion

During the digestion process, the alumina contained in the bauxite is dissolved in the Bayer liquor in the form of sodium aluminate. R&D needs in digestion 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 reducing caustic requirements. A specific activity would be research into altered desilication technologies that reduce sodium consumption, which would have a substantial payoff for refiners processing high-silica bauxite. The success of this effort would also significantly increase usable bauxite reserves. A true countercurrent digestion process for extracting monohydrate grades of bauxite at low temperatures (using a vertical upflow vessel where the monohydrate is introduced at the top and the spent liquor at the bottom) would be a valuable progression of the "best practice" countercurrent technology currently used. The use of "free" evaporation (where entropy is used as a substitute for additional live steam) should also be investigated.

Challenges

- Achieve higher alumina extraction efficiency
- Alter the chemistry of DSP
- Sustain higher supersaturation in the digester
- Reduce embrittlement in the digester
- Lower temperatures in Bayer operations
- Reduce caustic consumption
- Increase use of biotechnology
- Address declining grades of bauxite reserves

R&D Activities

Near Term

- Flexible digestion technology to accept variable grades of bauxite
- Free evaporation using entropy
- Design of a real countercurrent digestion process to extract monohydrates at low temperatures

Mid Term

- Non-milling digestion technology
- Altered desilication technology with lower soda consumption
- Technology for high alumina extraction at low temperature
- Selective bauxite biodigestion
- New digestion system for high-silica bauxite
- Methods to eliminate coarse particles from the digestion circuit

Long Term

- Continuation of near- and mid-term activities

Clarification

Bauxite residue is separated from the liquor containing the dissolved sodium aluminate in a settling process, 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.

Challenges

- 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

R&D Activities

Near Term	Mid Term	Long Term
◆ Pressure decanter to carry out both digestion and clarification at elevated temperature	◆ Low-wash soda recovery	◆ Alternative liquid-solid separation process for residue from liquor ◆ Alumina stabilizer that can be easily removed from pregnant liquor ◆ Elimination of security filtration

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 (as well as other Bayer process steps) could significantly improve productivity. Computer modeling 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.

Challenges

- 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

R&D Activities

Near Term	Mid Term	Long Term
◆ Continue ongoing projects aimed at incremental improvements	◆ Better seed management ◆ Molecular simulation of new reagents to promote rapid crystallization ◆ Highly energy-efficient agitators	◆ Identification of a gibbsite precipitation catalyst ◆ Accelerated precipitation technology ◆ Computer modeling to design additives ◆ Countercurrent precipitation ◆ Methods to make quality after precipitation

Calcination

Calcination represents one of the costliest and most energy-intensive operations in alumina refining. In calcination, 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 R&D is investigating potential means for improving the thermal energy efficiency of calcination. These efficiency gains must be sufficient to offset the high cost of retrofitting the calciner. Refiners and smelters need to collaboratively examine whether the trend toward decreasing smelting temperatures would affect calcination requirements. The quality of reprocessed calciner dust and technologies that activate it for use in the Bayer process also merit more research.

Challenges

Improve energy efficiency of calcination

Lower the overall temperature in Bayer operations

Increase use of waste products

R&D Activities

Near Term	Mid Term	Long Term
◆ Determination of effect of lower Al smelting temperatures on calcination	◆ Study of oxygen-enrichment benefits of calcination ◆ Methods to reduce the temperature of calcination ◆ Technology that activates calciner dust for use	◆ Continuation of near- and mid-term activities

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. 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 needed. 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.

Challenges

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

R&D Activities

Near and Mid Term	Long Term
◆ Study of simpler systems and analogy to the Bayer process	◆ Dry particle separation for bauxite ◆ Physical separation of mono- and tri-hydrate ◆ Use of low-alumina laterites ◆ Economic use of trona ◆ Mechanical and chemical fine grinding technology and kaolin immobilization ◆ Kaolin complexation technology process agent ◆ Process for converting kaolin to absorbents ◆ Viable alternative caustic source ◆ Use of other caustic salts as solvents ◆ Solvent extraction technology for Bayer liquors ◆ Investigation of a chloride route (production of aluminium trichloride) ◆ Alternate means of inducing reactions (e.g., microwave)

Product Characteristics and Quality

Alumina refiners and aluminium smelters need to work cooperatively on a number of issues related to alumina quality and properties. A solid fundamental understanding of alumina's chemical and physical properties and their variations will provide the framework for achieving consistent product quality. This will also enable refiners to tailor product characteristics to better meet their customers' needs. Better data on product characteristics may also indicate the potential use of beneficial process changes (e.g., calcining at lower temperatures) while still producing an acceptable alumina. New or revised product classification technologies are also needed, as are new measures for product quality itself. The refining industry could also work with smelters to redesign pot feeders capable of handling variable density alumina and to redesign dry scrubbing systems.

Challenges

- Better rationalize product strength
- Develop better measures of product physical quality
- Improve fundamental understanding of product quality
- Develop better understanding of alumina's properties
- Increase cooperation with experts from other industries
- Improve coordination between suppliers and customers

R&D Activities

Near Term	Mid Term	Long Term
◆ Improved method for attrition index/alumina dustiness ◆ Scrubbing technology that uses weak alumina ◆ Studies of alumina dissolution at low temperature ◆ Study of product variability	◆ Cooperative effort with customers to redesign pot feeders to handle variable bulk densities of alumina and fines	◆ Continuation of near- and mid-term activities

Controls and Instrumentation

Advances in process controls, instrumentation, and measurement techniques are key to the long-term goal of full refinery automation. Achieving a high level of process control without significant human labor 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 on-line measurement techniques and robust sensors are also needed for parameters specific to the Bayer process such as A/C and caustic analysis. The use of "at-line" instrumentation — a variation of on-line instrumentation that is not in continuous use (and therefore not constantly subjected to the corrosive stream) — could add operational flexibility by providing the feedback needed to make corrections without the delay associated with lab results. 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, nonscaling, and reliable for use in liquor and slurry applications.

Challenges

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

R&D Activities

Near Term

- Better plant sampling methodologies and techniques
- Use of new developments in chemometrics
- Bayer-specific sensors for particle size, caustic, A/C
- In-situ techniques that will survive in sodium chemistry
- Remote sensing (e.g., ultrasonics) to examine material or scale thickness

Mid Term

- Industry-specific control valves, isolation valves, and pumps for liquor and slurry
- At-line instrumentation (simple, robust, real-time, operator-controlled)

Long Term

- Specifications for sensing of common parameters (i.e., temperature, pressure, density, flow) reliably and accurately

Models and Tools / Process Management

Accurate, validated models can allow more effective management of the refinery from both a process and an economic point of view. Better understanding of what is happening in each process step will help refiners optimize operations and increase throughput. The industry needs to create tailored tools that will allow alumina companies to achieve "best practice" status. Models that incorporate economic factors are also needed; capital efficiency is an area where the refinery industry suffers in comparison to other industries. A refinery tool for capital process optimization could offer the potential for large savings by sharing knowledge between companies. In addition, the industry could develop an alumina/aluminium process model to determine whether certain process steps could be shifted from refineries to smelter operations in order to reduce overall costs, energy use, or waste generation.

Challenges

Develop more process optimization tools and techniques

Increase process automation

Improve knowledge management at the operations level

Optimize the efficiency of the overall process

Improve accounting of full product life cycle

Use more capable processes and elegant design

R&D Activities

Near Term

- Industrial process model (continuously updated; contains equipment reliability data)
- Capital process optimization tool
- Use of lean manufacturing technology
- Methodology to convert process parameters to key performance indicators
- Methodology to maximize equipment up-time

Mid Term

- Life-cycle modeling (including environmental factors and cost)
- Process model (including energy and waste data) to define optimal break points
- Modularization and optimization of plant layout

Long Term

- Techno-economic model of the Bayer process (validated computational modeling of process steps)

Knowledge Management

Gathering and managing information on developments within the alumina industry as well as those in related industries is critically important to improving competitiveness. The alumina industry tends to be quite insular and does not typically look for solutions from other industries, even those facing the same issues as refiners. The development of an information infrastructure for the industry will allow companies to avoid duplication of efforts and take advantage of shared knowledge. Suggested actions include developing a Bayer-sector data base with common units and finding ways to utilize the wealth of Bayer plant knowledge (particularly on instrumentation) in the Eastern Block. A potentially major event would be an examination of the Bayer process by world-class organic chemists and separations technologists, who would be asked to recommend improvements or even entirely new ways of producing alumina. Finally, the industry needs a guide on how to approach local communities when moving into new countries to find bauxite reserves.

Challenges

Improve knowledge management at all levels, particularly operations

Work with all levels of plant personnel to develop solutions to problems

Develop new processes and technologies for producing alumina

Keep alumina industry ahead of the curve on dealing with new issues (e.g., environmental)

Increase focus on corporate social responsibility

R&D Activities

Near Term	Mid Term	Long Term
◆ Cooperative efforts with other industries to look for ideas and synergies ◆ Invitation to world-class scientists to evaluate Bayer process ◆ Industry-wide process model to manage knowledge ◆ Expert systems that capture existing knowledge ◆ Techniques to utilize knowledge in the Eastern Block ◆ Guide on how to approach communities on exploration and mining	◆ Study of the theoretical and technical limits of existing processes ◆ Bayer-sector common data base	◆ Continuation of near- and mid-term activities

Energy and Fuels

Energy use and process efficiency are key drivers 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 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.

Challenges

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

R&D Activities

Near Term	Mid Term	Long Term
◆ Improved condensate and steam balance ◆ Full model of plant-wide energy balance	◆ Use of geothermal and solar power to supplement energy requirements ◆ Methods to improve the efficiency of power houses ◆ Methods to build power interruptability into the plant (e.g., different levels of gas turbine output) ◆ Methods to apply combined cycle system and still use coal efficiently	◆ Utilization of organics in bauxite for energy ◆ Coal combustion technologies that give cogeneration capabilities (e.g., low-capital coal gasification)

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. This may include development of processes to extract valuable materials such as titanium or even organics from the residue. (Note: more detailed information can be found in the Technology Roadmap for Bauxite Reside Treatment and Utilization.)

Challenges

Improve bauxite residue management

Develop economic applications for bauxite residue

Increase focus on corporate social responsibility

R&D Activities

Near and Mid Term

- Methods to produce a residue with high solids content and the required rheological properties
- More efficient fine particle classification
- Further development of high-temperature separation technology
- Process for extracting useful components from residue
- Examination of land reclamation alternatives

Long Term

- Viable technology to neutralize residue
- Single-stage washing of residue
- Separation of residue into components to facilitate neutralization

Releases

Refinery odours are an issue for on-site personnel as well as refinery neighbors. Most odours are a consequence of the emission of low-grade heat in the form of vapor, which also represents a direct energy loss. An industrywide database defining the origins of organic vapors should be created for the worst compounds contributing to plant odours. The toxicological effects of emissions of mercury and other compounds are not often clearly understood, creating the need for a health assessment of all refinery emissions. Refineries consume large amounts of water; new effluent treatment technologies and techniques to reduce groundwater pollution can help the industry minimize its water use. Better technologies for reducing flue gas emissions are critical for those refineries burning oil or coal.

Challenges

Reduce or eliminate groundwater pollution

Minimize water usage

Better understand and control toxic emissions

Reduce mercury emissions

Eliminate refinery odours

Increase use of waste products

R&D Activities

Near and Mid Term

- Health assessment of all emissions
- Inexpensive way to completely detect organic vapors
- Identification of specific compounds with high levels of odour
- Flue gas emission reduction technology
- Bioremediation to address groundwater problems
- In-situ barrier technology to control groundwater
- Downstream uses for oxalate

Long Term

- Low-cost effluent treatment technologies

Minimization of Human Exposure and Improved Safety: Technology and Training

Improved materials of construction and processes that are designed with a focus on eliminating human exposure are particularly important in improving the safety of alumina refineries. Techniques to reduce workforce requirements for maintenance will also reduce human exposure to potentially harmful conditions. Training and education programs on safety and the development of systems for housekeeping and health will help establish a safety culture within the alumina refining industry. The acceptance and adoption of behavioral-based safety by plant personnel will be key. Based on the petrochemical industry model, for example, refiners can establish industry-wide cooperative standards for ES&H in engineering design.

Challenges

Reduce human exposure

Create better safety systems and supporting culture

Reduce manual labor

Establish standards for hazardous operations

Increase focus on corporate social responsibility

Technology R&D Activities

Near Term	Mid Term	Long Term
◆ New materials for conveyor belts to reduce noise	◆ Designs to eliminate human exposure ◆ Improved materials for piping and tanks to reduce exposure ◆ Scale removal techniques	◆ Safer heat transfer medium than steam

Training R&D Activities

Near Term	Mid Term	Long Term
◆ Virtual reality for safety and hazard training ◆ Education programs on safety procedures	◆ Behavior-based safety (education and standards) ◆ Uniform industry cooperative standards for ES&H ◆ Standardization of pressure vessel design and release system criteria	◆ Continuation of the near and mid-term activities

3 Moving Forward

The *Alumina Technology Roadmap* is intended to be a dynamic document. The industry will face significant and varied challenges over the next 20 years. During this period some challenges may diminish in importance while others — particularly social and environmental issues — may become more prominent. By aggressively pursuing innovative solutions to its long-term problems, the alumina industry can favorably position itself to meet these challenges as they arise.

A major objective of this roadmap is to help alumina companies align their pre-competitive research programs with the needs of the global alumina industry. The research agenda described in the roadmap can be pursued by both individual companies and collaborative partnerships within the industry, as well as help guide government participation. Individual companies can develop a better understanding of how their own strategic plans mesh with the priorities of the industry as a whole. The roadmap can also serve as a mechanism to better educate suppliers to the alumina industry about its needs and integrate them into collaborative R&D activities in areas such as process sensors and materials of construction.

Solutions to some of the needs identified in the roadmap already exist but are limited in their application or are not commercially viable. Additional research or demonstrations may be indicated in these instances. Many of the needs have been the subjects of earlier unsuccessful investigations and may require a fresh approach in order to find a solution.

A large portion of the needed R&D is precompetitive and would benefit all refiners. Some activities — bauxite modification or beneficiation, in particular — would be limited to the point at which they become site-specific. Likewise, the grade of bauxite used at a plant may also dictate the extent of the benefits of some activities, such as thermal preprocessing of bauxite to remove impurities.

Scoping projects may provide a low-risk mechanism for defining potential solutions and outlining possible research pathways for moving ahead on many problems. Step changes in existing processes would likely be recommended for many of the high-risk, potentially high-payoff technical needs. A step change innovation typically requires significant fundamental R&D involving the entire research community. These activities are most appropriate for collaboration between multiple companies because individual ones do not have the resources to perform the research themselves.

The alumina industry can greatly improve the efficiency of its research efforts by sharing the costs of mechanisms already in place. Individual companies can benefit by sharing research results, thereby increasing the industry's collective knowledge and avoiding duplication of efforts.

Similarly, the sharing of best practices among refiners can benefit all areas of plant operation as well as environment, health, and safety aspects. In many cases technologies existing in other industries may offer solutions to alumina industry problems. Examining other industries' responses to scale management, ore beneficiation, and waste heat recovery, for example, could help refiners develop their own solutions to these problems.

Sharing of best practices within the industry or application of best practices from other industries may represent the best pathway for industry needs that are considered low risk yet have potentially high payoff. It should be noted, however, that even though a technology may be successfully applied in another industry does not ensure its success in the alumina industry.

As part of its strategy for implementing the roadmap, the industry has formed the Alumina Technology Committee consisting of representatives from major refining companies. The committee will

- advance initiatives from the roadmap
- identify appropriate subgroups to sponsor research projects and other initiatives and monitor their progress
- establish and maintain an ongoing review of the long-term goals of technology development for the alumina industry and benchmark technical progress towards these goals
- monitor and enhance the alumina research infrastructure to facilitate delivery of leadingedge, pre-competitive research and suitably trained personnel for the industry
- inform key decisionmakers within companies and governments to ensure adequate understanding of the priorities in alumina technology development and commitment to necessary research funding
- engender a long-term perspective for research needs and delivered outcomes
- leverage industry research funds with successful applications to relevant government funding programs
- provide a concerted technical focus for dealings with suppliers (chemical, equipment, engineering) to the industry
- act in a referral role in dealings with the industry associations on technical issues
- provide an appropriate framework for discussion of the future technology goals of the alumina industry and wide dissemination of information.

Implementing the research activities in this roadmap will require a substantial effort on the part of the alumina industry to increase corporate spending on R&D, handle complex intellectual property issues, and overcome other difficulties and costs involved in developing and demonstrating new technology. Historically, companies have been reluctant to embrace the outcome of R&D because of the perceived risk and the push for a quick payback on investments.

Implementation of this inherently collaborative technology roadmap may be complicated by the competitive nature and historic secretiveness of the refining industry. While researchers at one company may develop information that would benefit other companies, sharing this knowledge may eliminate the competitive advantage gained by the company spending the money on the research in the first place. Strategies to reconcile the competitive versus collaborative nature of alumina companies will be needed early in the roadmap implementation phase.

The alumina industry should make every effort to move forward with the research priorities in the roadmap so that it can begin to reap the benefits. New technologies that can lower costs, decrease energy consumption, reduce environmental impact, and improve worker health and safety will help ensure the industry's continued health and prosperity well into the 21st century.

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Appendix B
List of Acronyms

A/C	Ratio of alumina to caustic
CFD	Computational fluid dynamics
DISR	Australian Department of Industry, Science and Resources
DOE/OIT	U.S. Department of Energy, Office of Industrial Technologies
DSP	Desilication product
ES&H	Environment, safety and health
MW	Megawatt
R&D	Research and development
U.S.	United States
VOCs	Volatile organic compounds