

ALUMINUM

INDUSTRY TECHNOLOGY ROADMAP



FEBRUARY 2003

Aluminum is ...

- ◆ Strong and lightweight
- ◆ Repeatedly recyclable for environmental sustainability
- ◆ Resistant to corrosion
- ◆ Good conductor of heat and electricity
- ◆ Tough and non-brittle, even at very low temperatures
- ◆ Easily worked and formed, can be rolled to very thin foil
- ◆ Safe for use in contact with a wide range of foodstuffs
- ◆ Highly reflective of radiant heat
- ◆ Highly elastic and shock absorbent
- ◆ Receptive to coatings
- ◆ Attractive in appearance

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1: ROADMAP BACKGROUND AND OVERVIEW

Aluminum is one of the most versatile and sustainable materials for our dynamic global economy. The North American aluminum industry charted a bold course for the future of this essential material in its 2001 publication *Aluminum Industry Vision: Sustainable Solutions for a Dynamic World*. In 2002, the industry created this updated *Aluminum Industry Technology Roadmap* to define the specific research and development (R&D¹) priorities, performance targets, and milestones required to achieve that vision. By pursuing the ambitious R&D agenda laid out in this *Roadmap*, the industry should secure its place as a world leader in providing innovative, material-based solutions that deliver superior value to users.

Since the industry first embarked on the vision and roadmapping process in 1996, it has prepared several documents that have successfully coordinated basic R&D activities to benefit the entire industry. In addition to the original *Aluminum Industry Technology Roadmap*, the industry has developed five more **sharply focused roadmaps** that address alumina production, bauxite residue, inert anode technology, automotive applications, and applications of advanced ceramics (see Appendix B for details). To date, these roadmaps have helped to generate well over \$100 million in cost-shared R&D projects involving over 75 partners from the industry, its suppliers, universities, private research organizations, and the government.

This update of the roadmap for the new century lays out a strategic R&D plan designed to build on the inherent benefits of aluminum and attain the *Vision's* strategic goals. It focuses primarily on the three goal areas that require technical solutions:

- Products and Markets
- Sustainability
- Energy and Resources

ALUMINUM INDUSTRY VISION

*By 2020, the North American aluminum industry will be universally recognized as a **world leader** in providing innovative, material-based **solutions** that build on aluminum's intrinsic **sustainability** and deliver **superior value** to users.*

(The industry's vision document may be viewed by visiting <http://www.oit.doe.gov/aluminum/pdfs/alumvision.pdf>.)

¹ See Appendix A for a complete list of acronyms.

Attainment of the long-term goals in these areas will position the industry as a universally recognized technology leader. The industry will be widely respected for its use of cutting-edge technology to create innovative products, improve the environment, and contribute to economic growth.

Other industry-wide activities are expected to help achieve the industry's non-technical goals for Education and Human Capital; these activities are beyond the scope of this *Roadmap*.

INDUSTRY-WIDE PERFORMANCE TARGETS

The aluminum industry has now defined a set of performance targets for assessing progress toward and achievement of each of the strategic long-term goals involving technical solutions: Products and Markets, Sustainability, and Energy and Resources (Exhibit 1-1).

To achieve these targets, the industry must pursue an organized, strategic technology agenda. This *Roadmap* outlines that agenda, organized according to the major aluminum processes. It presents detailed, sector-specific performance targets, technical barriers, research and development needs, and R&D priorities for each of these process-based sectors:

- Primary Production
- Melting, Solidification, and Recycling
- Fabrication
- Alloy Development and Finished Products

The highest-priority R&D needs within each of these industry sectors are shown in Exhibit 1-2. These priorities represent technological needs that offer significant opportunity for the industry to improve energy efficiency, productivity, and product quality, or to reduce costs in pursuit of their long-term goals. For each process sector, links to other industry roadmaps are shown to emphasize the role of these supporting documents in the industry's comprehensive approach to technology development.

Exhibit 1-2 also describes the time frames in which these priorities are expected to yield knowledge, tools, and technologies of benefit to the industry. As indicated by the icons, many high-priority R&D needs are in the mid- and long-term time frames; these are also the R&D areas in which pre-competitive collaboration among companies, government, and universities is most appropriate.

Chapters 2 through 5 describe the performance targets for each process-based sector of the industry and the technical barriers that stand in the way of reaching those targets. The chapters also discuss the entire range of identified R&D needs for each sector, organized by topic and stratified by level of priority. Finally, each chapter presents additional details regarding the highest-priority items listed in Exhibit 1-2, including additional technical details, risks and payoffs, and time frame for accomplishments.

Exhibit 1-1. Alignment of Strategic Goals and Industry-Wide Performance Targets

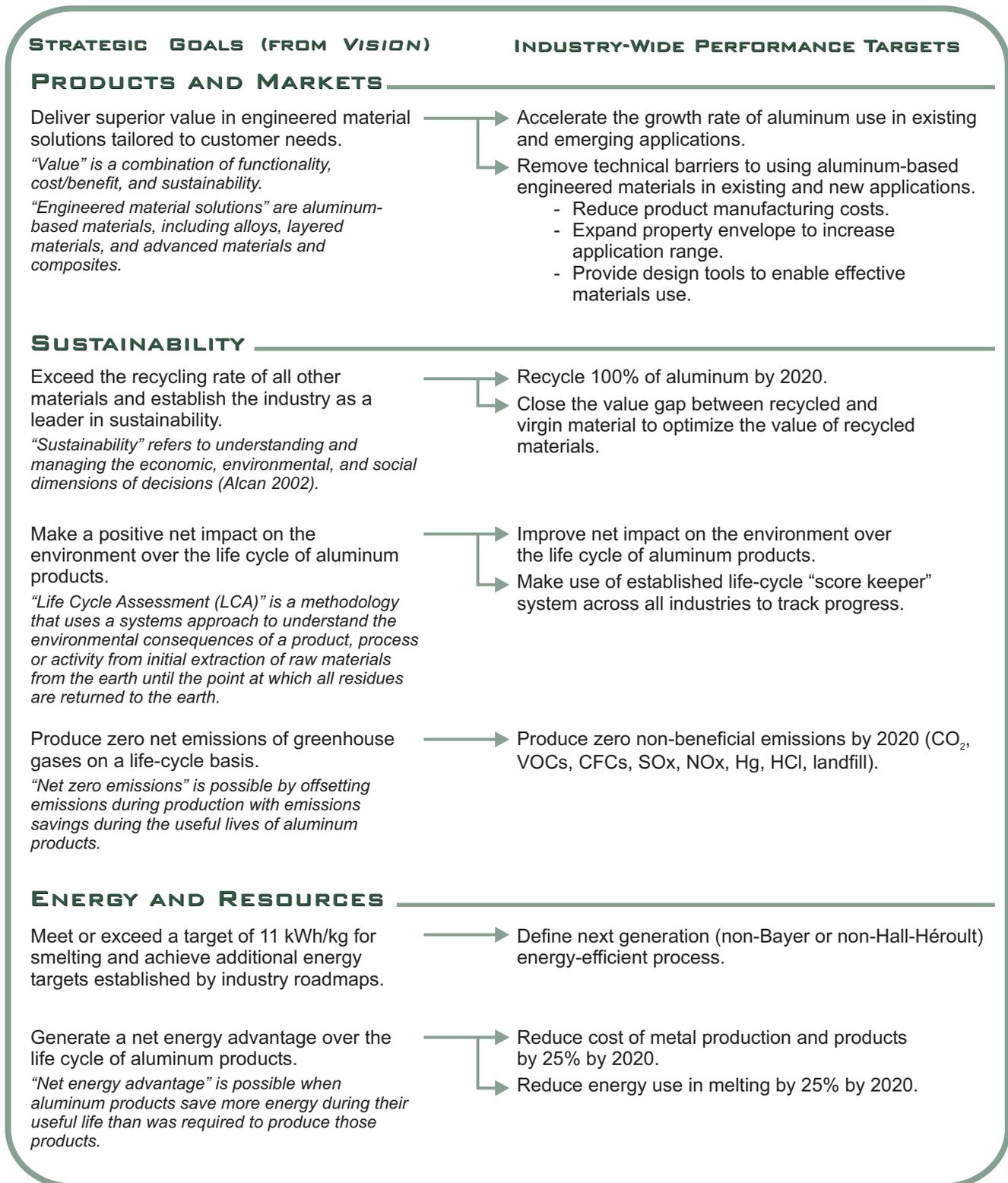
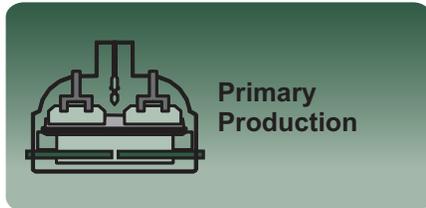


Exhibit 1-2. Top-Priority R&D Needs for Major Aluminum Process Steps

ALUMINUM PROCESS STEPS



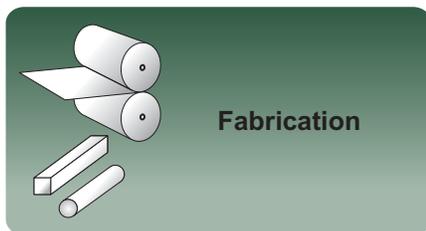
Alumina Refining



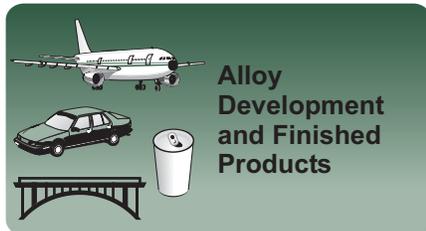
Primary Production



Melting, Solidification, and Recycling



Fabrication



Alloy Development and Finished Products

Recycled Scrap

TOP-PRIORITY R&D NEEDS

N Near Term (0-3 years) **M** Mid Term (3-10 years) **L** Long Term (>10 years)
 § Link to other industry roadmaps

- § *Technology Roadmap for Bauxite Residue Treatment and Utilization*
- § *Alumina Technology Roadmap*

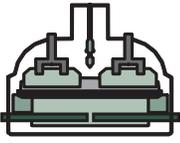
- M** Continue development of wetted, drained cathode technology.
- M L** Develop continuous or semi-continuous sensors to cost-effectively measure alumina, superheat, temperature, and bath ratio.
- L** Develop alternate cell concepts (combination of inert anodes and wetted, drained cathodes).
- L** Develop the carbothermic reduction process on a commercial scale.
- L** Explore other novel, and as yet unidentified, concepts for producing aluminum.
- § *Inert Anode Roadmap*
- § *Applications for Advanced Ceramics in Aluminum Production*
- N** Gather fundamental information on solidification of alloys to predict microstructure, surface properties, stress, and strain.
- N M** Develop an integrated process model to predict metal quality and economics based on first principles.
- M** Develop methods for real-time chemical analysis.
- M** Develop a more complete understanding of oxidation mechanisms.
- M** Develop techniques to determine formability characteristics and associated test methods.
- L** Devise a melting/casting plant and furnace for the future.
- L** Develop strip/slab casting technologies to improve surface control and texture and reduce segregation.
- § *Applications for Advanced Ceramics in Aluminum Production*
- M** Develop new or improved non-contact sensors.
- M** Develop integrated models that relate structural properties to manufacturing processes and the material employed.
- M L** Develop manufacturing processes for scrap-tolerant alloys.
- § *Applications for Advanced Ceramics in Aluminum Production*
- N M** Develop advanced forming techniques to manufacture net shapes without intermediate processes.
- M** Develop integrated numerical methods for analysis and robust design of products, processes, and materials.
- M L** Develop next-generation aluminum alloys by fully understanding the relationship of aluminum alloy composition and processing and their effects on microstructure and properties.
- M L** Develop low-cost joining techniques for similar and dissimilar materials.
- § *Aluminum Industry Roadmap for the Automotive Market*
- § *Applications for Advanced Ceramics in Aluminum Production*
- § *Metalcasting Industry Technology Roadmap*

GOVERNMENT IS A KEY PARTNER

The U.S. Department of Energy (DOE) has been and continues to be a valuable partner to the aluminum industry. For the past seven years, DOE has actively encouraged the industry to define its own future, facilitating the development of industry-wide visions and roadmaps. The government plays several unique and critical roles in stimulating R&D collaboration:

- Provides cost-shared funding for both near-term and long-term, high-risk projects
- Provides specialized expertise through the national laboratories
- Catalyzes collaboration by helping to bring research organizations together
 - Facilitates partnerships among industry, government (DOE and other agencies), and academia
 - Sanctions pre-competitive collaboration
- Provides demonstration test beds
- Acts as an early consumer of new technologies to foster market development

The North American aluminum industry is continuing on the path it began in 1996 with the publication of its first vision document. Recognizing the value of working together toward improved productivity, efficiency, and environmental performance, the industry exhibits a renewed focus, determination, and momentum. By updating its vision and technology roadmap, the industry is reaffirming its commitment to technological innovation through collaborative partnerships. With unified action, and with the help of academia and government, the aluminum industry can most effectively realize its aspirations for the future.



2. PRIMARY PRODUCTION

As markets expand, finite supplies of recycled aluminum suggest an enduring need for primary aluminum in North America. The location of primary production facilities is contingent to a great extent on the cost and stability of electrical supply. High electrical costs and instability have led to the erosion of primary production in the United States. To endure, domestic primary aluminum smelters may need to explore ways to increase their resiliency to power fluctuations or seek supplements to grid-supplied electricity, such as distributed generation.

Primary aluminum producers are driven to continually improve energy efficiency and reduce costs to better compete domestically with aluminum imports, in global aluminum markets, and against other materials. Radical energy efficiency gains such as those outlined in the *Vision* are likely to require replacement of the Bayer and Hall-Héroult processes over the long term. In the near term, however, techniques to improve Hall-Héroult cells will prove significant to U.S. capacity.

As companies seek to enhance product quality while reducing cost and waste, some companies may increase the degree to which they are vertically integrated as a means to control the cost, quality, and availability of carbon, coke, pitch, and the other raw materials for primary production. Companies that do not vertically integrate will be forced to contend with fluctuations in raw material costs and quality.

CURRENT TECHNICAL SITUATION

Over the past several years, developments in Hall-Héroult cell technology have been overshadowed by major issues, beyond the control of the aluminum industry, in electricity supply, reliability, and cost. Also, significant, game-changing developments in primary production continue to be paced by limitations of available materials that are both sufficiently durable and affordable to warrant implementation of advanced electrode concepts such as drained cathodes and inert anodes.

Advancements in energy efficiency have been steady, but slow. Today, the best cells operate at lower than 13 kWh/kg, and most U.S. production operates at 95 percent current efficiency. With this relatively high current efficiency, long-range research efforts have focused on advanced electrode systems that promise to reduce the anode-cathode distance (the major component of ohmic resistance) and thereby improve the overall energy efficiency of the cell.

Steady improvements in cell performance have occurred through improved plant operations enabled by better instrumentation and control systems, better understanding and control of electromagnetic effects and thus of metal stirring, and through the installation of point feeders, which permit incremental, “just-in-time” alumina feeding. This latter development has enabled significant reductions in the frequency of anode effects, which in turn has increased production and significantly reduced PFC emissions. Generally, cell amperages continue to increase (a 500,000 amp cell has been developed by one company) and overall cathode life is now in the range of 2,500 to 3,000 days, resulting in enhanced productivity and lower overall costs.

Understanding of advanced Hall-Héroult electrode concepts has developed significantly since the original *Aluminum Industry Technology Roadmap* of 1996, and there are many related technology efforts underway both in North America and overseas. As a result, it is now generally conceded that a wetted (TiB₂-containing), drained cathode is feasible, and, in combination with an inert anode, will result in an energy efficiency improvement of about 22 percent while significantly reducing CO₂ emissions. Significant proprietary efforts are attempting to resolve issues of material durability and electrode connectivity, and design concepts involving vertical, multipolar cells are being developed.

The initial roadmap also called for the exploration of reduction processes beyond the Hall-Héroult process –today an area of significant proprietary effort. Carbothermic reduction and kaolinite AlCl₃ reduction processes have been researched for many years. Both processes promise improved energy efficiency, lower overall emissions, and reduced plant footprints. Robust progress has been achieved with several steps in carbothermic reduction through the use of new material containment concepts, yet much remains to be accomplished before any full-scale operation can be considered. For a comprehensive review of the overall topic of cell technology, see the recently published *U.S. Energy Requirements for Aluminum Production, Historical Perspective, Theoretical Limits and New Opportunities*.²

PERFORMANCE TARGETS

Exhibit 2-1 presents the performance targets for primary aluminum production. These targets support the industry’s goals as described in the *Vision*, and quantitatively define the improvements sought in primary production. All targets must be achieved without compromising metal quality or economic competitiveness.

Producing high-purity aluminum from smelters for use as a sweetener can widen the range of scrap that can be recycled into aluminum products. Increasing process flexibility to enable the production of high-purity primary aluminum on demand can increase the scrap available for recycling and help attain the industry goal of eliminating waste.

Carbon dioxide and the high-leverage, global warming perfluorocarbon (PFC) emissions are associated with the use of carbon anodes during primary aluminum production. Reduction of these PFC emissions through control of “anode effects” is a central component of the industry’s approach to sustainability. Reducing the large energy requirements of the Hall-

² Available from the U.S. Department of Energy at <http://www.oit.doe.gov/aluminum>.

Exhibit 2-1. Performance Targets for 2020: Primary Production

<p>PRODUCTS AND MARKETS</p> <ul style="list-style-type: none"> ◆ Achieve energy and carbon targets without compromising metal quality. ◆ Increase process flexibility to support all downstream demands, including higher purities required for use with recycled aluminum.
<p>ENERGY AND RESOURCES</p> <ul style="list-style-type: none"> ◆ Achieve 97 percent average cell current efficiency at a low energy input. ◆ Achieve 13 kWh/kg in the near term using retrofit technology and 11 kWh/kg in the long term in a cost-effective manner which is both environmentally and socially acceptable.
<p>SUSTAINABILITY</p> <ul style="list-style-type: none"> ◆ Make use of a common set of assumptions and definitions among industry, government, and academia in conducting life-cycle analyses. ◆ Reduce net carbon consumption of smelting to 0.4 kg C/kg aluminum for all carbon inside the plant boundary (excludes power generation; includes electricity losses at the plant). ◆ Reduce PFC emissions by achieving 0.02 anode effects or fewer per pot day.

Héroult process is another priority for the industry. Even small efficiency gains in the energy-intensive smelting process can yield large cost savings, emissions reductions, and other benefits. While the most advanced cells can achieve an energy intensity of just under 13 kWh/kg, the industry average is near 15 kWh/kg.

TECHNICAL BARRIERS

Before primary aluminum producers can achieve their performance targets, the industry must develop solutions to several technological and institutional barriers. Exhibit 2-2 presents the technical barriers currently limiting primary aluminum smelting in four main categories:

- Electrolytic Reduction Processes
- Alternative Reduction Processes
- Enabling Technologies
- Institutional Barriers

Technical limitations in existing reduction cells constrain improvements in their energy and production efficiencies, metal quality, and environmental performance. Enabling technologies such as sensors, controls, models, and materials can help to overcome these barriers; however, these enablers are also limited in their accuracy, applicability, or effectiveness. Additionally, the lack of commercially viable alternatives to the Bayer and Hall Héroult processes hinders primary aluminum producers in their efforts to achieve revolutionary advances in cost and efficiency. Less than optimal coordination among industry, government, and academia also limits or slows the rate of technology development. Optimizing these working relationships can help increase the effectiveness of collaborative research and development.

Exhibit 2-2. Technical Barriers: Primary Production (priorities in **bold**)**ELECTROLYTIC REDUCTION PROCESSES**

- **Lack of mathematical models to predict the performance of cell design concepts**
- **Lack of robust bath chemistry (constrained by cryolite-based electrolyte)**
- **Incomplete knowledge of how to raise thermal efficiency of reduction without negatively impacting the process**
- Lack of economical method to retrofit older cells (including buswork)
- Lack of economical technique to remove impurities from alumina in dry scrubbers
- High cost of reduction equipment
- Large gap between theoretical and actual energy efficiency, and high associated power costs

ALTERNATIVE REDUCTION PROCESSES

- **Lack of feasible, economical electrolyte compositions that would require lower voltage without compromising product quality**
- Lack of systems approach to developing overall alternative processes
- Difficulties maximizing use of chemical versus electrical energy in alternative processes

ENABLING TECHNOLOGIES

- **Inadequate process tools, sensors, and controls for reduction cells**
 - ▶ inability to measure cell variables (other than resistance) in real time
 - ▶ lack of non-contact sensors
- Lack of cost-effective metal-purification technologies
- Inadequate process optimization models
- Lack of materials (cathode, anode, and sensor tubes) that can withstand exposure to molten aluminum and cryolite

INSTITUTIONAL BARRIERS

- Government role in research is unclear; collaboration between government, academia, and industry is not optimized; limited cross-institutional communication
- Low researcher awareness of the state of the technology and of previous and ongoing research
- Lack of regulatory cooperation (e.g., spent potliner)

RESEARCH AND DEVELOPMENT NEEDS

The industry can overcome the barriers to improved primary production through research, development, demonstration, and other activities aimed at improving smelting technologies and processes. The R&D needed to achieve the performance targets for primary production can be organized into four areas:

- Electrolytic Reduction Processes
- Alternative Reduction Processes
- Enabling Technologies
- Recycled Materials

Research on the reduction process is needed to reduce costs, lower energy consumption, and improve product yield and quality. In addition to incremental improvements that create steady progress, the industry must pursue more innovative, longer-term advances in reduction technology to dramatically reduce energy consumption. Alternative aluminum production processes must also be developed to dramatically reduce energy consumption. Alternative processes may ultimately hold the key to successful materials competition, but such processes must be developed with zero waste in mind. Enabling technologies like

sensors, controls, and models are needed to better understand and operate reduction processes at optimal efficiency. Finally, exploring ways to recycle process wastes generated during primary production can help primary producers to eliminate waste streams.

Exhibit 2-3 shows a range of R&D needed in primary production. The Exhibit is organized by category; relative priority is shown by the arrows to the left of each R&D need. In addition to these needs, the R&D priorities described in the industry's other roadmaps are critical to the industry's overall approach to technology exploration and development. The needs in the *Alumina Technology Roadmap* are particularly relevant to primary production because alumina is the primary raw material input to the smelting process.

Exhibit 2-3: R&D Needed: Primary Production

N: Near Term (< 3 years) **M:** Mid Term (3-10 years) **L:** Long Term (> 10 years)

ELECTROLYTIC REDUCTION PROCESSES

Priority Level R&D Need

- TOP** Develop alternative cell concepts (including materials development). (L)
 - combination of inert anode/wetted, drained cathode
 - systems approach for designing dimensionally stable cells
- TOP** Continue development of wetted, drained cathode (including materials development). (M)
- HIGH** Improve and decrease cost of alumina purification technologies. (M-L)
- HIGH** Develop technology to run production cells for extended periods of time without an anode effect (minimize anode effects per pot day). (N)
- HIGH** Achieve more robust bath chemistry. (L/ongoing)
- HIGH** Examine alternative carbon sources; learn to cope with new anode materials (high sulfur, ash). (Ongoing)
- HIGH** Develop advanced refractories for the cell. (Ongoing)
- HIGH** Develop a cell capable of performing effectively with power modulations (e.g., off-peak power).
- MEDIUM** Continue development of inert anodes (including materials development). (M-L)
- MEDIUM** Refine method to extract impurities from alumina used in dry scrubbers. (N)
- MEDIUM** Develop cost-effective, low-resistance, external conductors and connections for both the anode and cathode. (M-L)
- MEDIUM** Develop extended-life pot lining (> 5,000-day life). (L)
- MEDIUM** Improve waste heat recovery (from exit gases and from the cathode). (L)
- MEDIUM** Perfect the continuous, pre-bake anode. (M)

ALTERNATIVE REDUCTION PROCESSES

Priority Level R&D Need

- TOP** Develop the carbothermic reduction process on a commercial scale. (L)
- TOP** Develop novel, and as yet undefined, concepts for producing primary aluminum. (L)
- HIGH** Develop solid-oxide, fuel cell-type anode with sodium sulfide electrolyte. (L)
- HIGH** Explore electrolytic production of solid aluminum. (L)
- MEDIUM** Explore chloride reduction for liquid aluminum. (L)

Exhibit 2-3: R&D Needed: Primary Production (continued)

N: Near Term (< 3 years) M: Mid Term (3-10 years) L: Long Term (> 10 years)

ENABLING TECHNOLOGIES

Priority Level R&D Need

TOP

Develop continuous or semi-continuous sensors to cost-effectively measure superheat, alumina, temperature, and bath ratio. (M-L)

HIGH

Improve understanding and models of reduction phenomena. (N-M)

MEDIUM

Develop rapid scan method to determine metal composition. (N-M)

MEDIUM

Develop real-time, feed-forward process control using advances in fuzzy logic and neural networks. (N-M)

- perform signal analysis of cell voltage (noise) to improve control of cell, use fuzzy logic to extract knowledge

MEDIUM

Develop carbon-air burning prevention techniques. (M)

RECYCLED MATERIALS

Priority Level R&D Need

HIGH

Discover techniques to turn aluminum process waste into usable feedstock/products. (M)

MEDIUM

Qualify recycled refractory materials obtained from spent potlining and bake furnaces for possible use. (M)

R&D PRIORITIES

While all the research needs presented in Exhibit 2-3 play an important role in the improvement of primary aluminum production, the five priorities listed below have the greatest potential to enable the industry to realize its vision. Successful research into these priorities promises significant energy savings, cost reductions, environmental performance improvements, and other benefits that will allow primary producers to achieve their performance targets and goals.

- Develop alternative cell concepts (combination of inert anodes and wetted, drained cathodes).
- Continue development of wetted, drained cathode technology.
- Develop the carbothermic reduction process on a commercial scale.
- Explore other novel, and as yet undefined, concepts for producing aluminum.
- Develop continuous or semi-continuous sensors to cost-effectively measure alumina, superheat, temperature, and bath ratio.

These priorities are discussed in greater detail on the pages that follow. Additional technical details, levels of technical risk, potential payoffs, and time frames are also outlined.

R&D PRIORITY
Develop alternative cell concepts (combination of inert anodes and wetted, drained cathodes)

KEY TECHNICAL ELEMENTS

- ◆ Identify or develop materials that fulfill performance requirements, including:
 - longevity
 - manufacturability
 - solubility
 - conductivity
 - thermal shock resistance
- ◆ Revise cell geometry to optimize process.
- ◆ Resolve materials engineering issues created by electric connections.
- ◆ Address scale-up complexities (e.g., 10,000 amps).
- ◆ Develop models (magnetohydrodynamic, process, thermoelectric, etc.) applicable to the new cell (current models are inappropriate).

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>Low Moderate High</p> <p>◆ Difficult to bring together multiple new technologies plus a non-conventional electrolyte</p>	<p>↓ Capital Cost ↓ Footprint</p> <p>↓ Emissions (eliminate CO₂, PFCs, SO₂, NOx, polycyclic aromatic hydrocarbons from process via materials selection)</p>
TIME FRAME	
<p>2003 2020</p> <p>◆ Long Term (> 10 years)</p>	

R&D PRIORITY
Continue development of wetted, drained cathode technology

KEY TECHNICAL ELEMENTS

- ◆ Develop more data on current TiB₂-graphite material (run in a cell ≥10,000 amps for an extended time).
- ◆ Develop and design cell (heat balance) to get protective ledge for the TiB₂-graphite material.
- ◆ Continue to explore other potential cathode materials.
- ◆ Develop accelerated lab tests for material life.
- ◆ Understand long-term cathode erosion mechanisms and how they will impact operations.

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>Low Moderate High</p> <p>◆ Low if only goal is to reduce voltage, moderate when considering lifetime of the cathode</p>	<p>↓ Energy consumption (higher amperage) ↑ Metal production</p>
TIME FRAME	
<p>2003 2020</p> <p>◆ Mid Term (3-10 years)</p>	

R&D PRIORITY

Develop the carbothermic reduction process on a commercial scale

KEY TECHNICAL ELEMENTS

- ◆ Conduct scale-up activities on current processes.
- ◆ Develop metal purification techniques (when starting with a metal with unconventional impurities).

RISK

TECHNICAL RISK

Low Moderate High

◆ High technical risk

PAYOFFS

- ↓ Energy consumption (large savings, but on-site carbon emissions will increase)
- ↓ Capital and operating costs
- ↓ Environmental footprint

TIME FRAME

2003 2020

Long Term (> 10 years)

R&D PRIORITY

Explore other novel, and as yet undefined, concepts for producing aluminum

KEY TECHNICAL ELEMENTS

- ◆ Conduct fundamental research to identify novel concepts.
- ◆ Demonstrate promising concepts at bench scale.

RISK

TECHNICAL RISK

Low Moderate High

◆ High technical risk associated with new concepts

PAYOFFS

Not well defined, but must be significant to be justified

TIME FRAME

2003 2020

Long Term (> 10 years)

R&D PRIORITY

Develop continuous or semi-continuous sensors to cost-effectively measure alumina, superheat, temperature, and bath ratio

KEY TECHNICAL ELEMENTS

- ◆ Identify what additional information can be gathered from the cell.
- ◆ Determine how to "interrogate" cell to collect that information.
- ◆ Develop new sensors.
- ◆ Conduct materials R&D.
- ◆ Conduct lab test, then test in operating reduction cell.

RISK

TECHNICAL RISK

Low Moderate High

◆ Moderate technical risk

PAYOFFS

- ↑ Cell control ↓ Operating costs
- ↓ Energy consumption (payoff is significant with respect to investment)

TIME FRAME

2003 2020

Mid-Long Term (>7 years)



3: MELTING, SOLIDIFICATION, AND RECYCLING

Among aluminum's compelling advantages over competing materials is its ability to be repeatedly recycled with high recovery rates without loss of quality. Secondary aluminum production offers obvious energy and environmental benefits as it requires only five percent of the energy use and emissions associated with primary production. The projected shift in North America toward an increased share of secondary rather than primary aluminum production will consequently improve the industry's overall energy efficiency. The industry faces technical challenges, however, in making further improvements to melter system efficiency and ensuring a steady and reliable scrap stream.

Solidification will continue to play a significant role in productivity, quality, and efficiency of aluminum production. In this *Roadmap*, barriers and R&D needs relative to ingot and continuous casting are considered; shape casting is considered in detail in the *Metalcasting Industry Technology Roadmap* (see references).

New, clean energy sources may enable the industry to meet its energy needs for melting, solidification, and recycling while further minimizing its impact on the environment. Identifying ways to apply advanced energy technologies to aluminum processes would help ensure rapid adoption. Aluminum companies seeking alternative sources of energy may benefit from a variety of technologies as they become available and cost-effective. Examples of such technologies include combined heat and power (CHP), distributed generation (DG), hydrogen fuel, and induction melting using renewable electricity sources.

The growing trend toward engineered material solutions implies that the scrap stream will contain an increased share of aluminum-based composites and other materials with non-aluminum components. In the near term, all internal scrap generated during the processing and manufacture of these new, engineered materials must be captured and recycled. In the coming decades, when these materials enter the post-consumer scrap stream at the end of their service life, they must also be recycled with no waste. By considering the entire life cycle of aluminum-based material solutions and designing them for easy and complete recycling, the aluminum industry can avoid creating products that are not fully recyclable.

CURRENT TECHNICAL SITUATION

The original industry roadmap called for improvements in furnace designs for the future, and furnace improvements in pursuit of this need have been broad and numerous. Flame image analysis has been useful in improving understanding of combustion, optimizing

burner design, and improving temperature uniformity in furnaces. Improved burner designs, including low-NO_x regenerative burners, oxy-fuel burners, and oxy-enriched burners have gained use throughout the industry, and pulsed and oscillating burners are being examined to further extend burner technology. Improved furnace sealing has helped to control the furnace atmosphere, minimize dross formation, and improve overall energy efficiency. Additionally, improved furnace designs, charging techniques, and molten metal pumps all help to increase melt rates and further improve efficiencies.

New heating and melting techniques continue to be developed and demonstrated. The recent demonstration of reliable, high watt-density, immersion heaters that offer high energy efficiencies has pushed this promising technology closer to the market, while flotation, cupola-type melting and delacquering has been demonstrated at a prototype scale.

Advances in filtration techniques and knowledge have gone part of the way to addressing this priority need from the industry's original roadmap. Specifically, a more complete understanding of the role of surface chemistry in inclusion capture, unified depth capture based on computational fluid dynamics (CFD), and flow in reticulated foam media have all led to advances in filtration techniques.

Inclusion sensor development has yielded several promising technologies. The proprietary liquid metal cleanliness analysis (LIMCA™) technology and subsequent refinements of molten metal analysis based on laser-induced breakdown spectroscopy (LIBS) are at or near commercialization, while ultrasonic inclusion sensors and neutron adsorption technologies are being investigated. Scrap identification and sorting technologies have enjoyed similar success, with chemical, color, and LIBS-based sorting all achieving some degree of technical success. X-ray absorption-based scrap sorting and neutron activation-based scrap stream analysis are other areas of ongoing investigation.

Finally, exploration of ways to use non-metallic products resulting from aluminum melting in other applications has yielded some successes. Calcium aluminate, used for iron and steel fluxing, has been commercially produced from non-metallic products (NMP), and a range of other applications have been developed, including low-density concrete formulations with NMP additions, thermal insulation fiber, abrasives, and sand blasting grit.

PERFORMANCE TARGETS

To guide R&D efforts in melting, solidification, and recycling, the industry has set performance targets that support attainment of the industry's long-term goals (Exhibit 3-1). The sector-specific performance targets highlight and, in some cases, quantify improvement through advances in melting, solidification, and recycling technologies that are needed for the industry to achieve its vision.

Exhibit 3-1. Performance Targets for 2020: Melting, Solidification, and Recycling

PRODUCTS AND MARKETS

- ◆ Decrease net energy required to produce aluminum (units energy input per unit of aluminum product).
- ◆ Develop markets for oxide fractions.
- ◆ Maintain pedigree of alloys throughout the recycling process to eliminate value degradation.

ENERGY AND RESOURCES

- ◆ Increase total post-consumer scrap recovery (units of aluminum per unit scrap).
 - Reduce net melt loss by more than 50%.
- ◆ Reduce quantities of internal and OEM scrap generated.

SUSTAINABILITY

- ◆ Eliminate loss of aluminum to landfills (e.g., eliminate losses in dross).
- ◆ Minimize use of diluting metals.
- ◆ Minimize chemical impurity pick-up; maximize the ability to deal with residual impurities in every step.

TECHNICAL BARRIERS

To achieve its performance targets for secondary production and recycling, the aluminum industry must overcome a wide range of technical barriers. Some of the key barriers are shown in Exhibit 3-2, with the highest-priority barriers displayed in **bold** text. These barriers have been organized into the following six process-related categories:

- Melting and Recycling
- Crosscutting Technologies
- Metal Processing and Treatment
- Skim and Dross
- Casting
- Continuous Processes

Achieving the performance targets in this area will require removal of the limitations on efficiency imposed by existing aluminum melting and recycling technologies and systems. Beyond melting and recycling technologies, however, the industry is lacking important crosscutting technologies that could eliminate wastes and improve the economics of recycling. Production and management of skim and dross create additional technical challenges for aluminum melters as the industry drives towards zero waste. Limited understanding of the solidification process and associated technologies hinders casting processes and limits the return secondary aluminum smelters can receive for their products. Additional barriers associated with the processing and treatment of metals center on fluxes, impurities, and fines. Finally, as the industry pushes productivity and efficiency higher, it will increasingly seek continuous operation, which is currently limited by control and processing technologies.

Exhibit 3-2. Technical Barriers: Melting, Solidification, and Recycling (priorities in **bold**)**MELTING AND RECYCLING**

- **Sub-optimal scrap melt rates**
- **Low fuel efficiency in melting and holding furnaces; furnaces are not optimized for scrap heating and waste heat recovery**
- **Lack of methods to recycle new types of scrap that will result from new product mix (e.g., engineered material solutions)**
- High contaminant levels in purchased scrap, including toxics; difficulties detecting non-metallic impurities in scrap
- Lack of economic incentive to separate scrap by alloy
- Inability to meet OSHA and other standards while using low-grade scrap
- Some secondary specifications are based on scrap availabilities that no longer exist or are otherwise outdated
- Temperature stratification and alloy segregation
- Lack of economical alternatives to chlorine fluxes for magnesium and alkali removal

CROSSCUTTING TECHNOLOGIES

- **Inability to control quality and metallurgical structures in real time**
- **Inability to predict metal quality and economics based on "first principles"**
- Segmented, operation-specific thinking; too many non-value added, repetitive process steps (e.g., remelting, transportation, multiple cleanings)
- Limited information and best-practice sharing to improve competitive position relative to other materials

METAL PROCESSING AND TREATMENT

- **Lack of environmentally friendly reactive flux gases for metal treatment**
- Inadequate impurity removal methods
- Generation and loss of fines during shredding and subsequent processing

SKIM AND DROSS

- **Limited knowledge of, and lack of methods to prevent or control molten aluminum-oxygen reactions to create desired oxides**
- **Lack of applications for non-metallic products**
- Lack of methods to minimize oxidation of 5xxx alloys without using beryllium
- Lack of alternative dross treatments; processes that require skimming are inherently limited

CASTING

- **Lack of closed-loop control for casting**
- Poor water quality and uniformity around the mold
- Poor metal quality in ingot head and tail during casting
- Too many cavities and voids in the sows; inability to practically determine sow soundness
- Inadequate means of detecting bleedouts in billet casting
- Lack of understanding of cracking mechanisms as a function of alloy
- Incomplete control of surface quality for all types of casting
- Incomplete understanding of the conditions that trigger aluminum-water explosions and why certain coatings prevent explosions
- Insufficient understanding of the aluminum solidification process

CONTINUOUS PROCESSES

- **Inability to change or control metal composition in real time**
- Inability to continuously cast strip with a wider range of high-alloyed compositions
- Limited ability to control degree and uniformity of heat extraction

RESEARCH AND DEVELOPMENT NEEDS

To address the barriers and realize its long-term goals, the industry must conduct research, development, and demonstrations in a wide range of melting, solidifying, and recycling technologies. These R&D needs have been grouped into six areas:

- Process Fundamentals
- Energy-Efficient Technologies
- New Manufacturing Concepts
- Sensors and Controls
- New Products
- Safety

Conducting research into process fundamentals will allow the industry to better understand the physical phenomena that occur during melting, solidification, and recycling, thereby creating a knowledge base for aluminum producers to better control their processes. However, to make meaningful advances toward some long-term goals such as sustainability, zero waste, and net positive energy impact, the industry will also need advanced, energy-efficient technologies and new manufacturing concepts. Secondary aluminum producers will also need intelligent online sensors and controls that ensure their processes run at optimum productivity and efficiency.

In addition to technological enhancements, the industry needs to develop new products and markets to strengthen demand for recycled aluminum. A two-part approach will be most effective: develop new secondary alloys and products from recycled scrap and seek ways to create products from non-metallic fractions rather than wastes.

Finally, safety concerns permeate all aspects of the industry and are inherent in all areas of the *Roadmap*. The industry can pursue activities aimed directly at ways to improve the safety of their processes and better protect their workers. Exhibit 3-3 presents a range of research and development needed in melting, solidifying, and recycling.

Exhibit 3-3. R&D Needed: Melting, Solidification, and Recycling

PROCESS FUNDAMENTALS

Priority Level R&D Need

TOP

Gather fundamental information on solidification of alloys to predict microstructure, surface properties, stress, and strain.

- develop computer model capable of real-time process control
- increase fundamental research on macro-segregation
- conduct fundamental study of intermetallic phase formation as a function of alloy chemistry and cooling conditions

TOP

Develop an integrated process models to predict metal quality and economics based on first principles.

TOP

Develop a more complete understanding of oxidation mechanisms.

- identify a non-toxic, non-carcinogenic substitute for beryllium
- explore new, potentially beneficial oxide species

TOP

Develop techniques to determine formability characteristics and associated test methods.

- plane strain testing
- quicker/cheaper forming limit diagrams (FLD)
- superplastic forming (SPF) test methods

HIGH

Increase understanding of metal treatment to increase efficiency and reliability while lowering costs.

ENERGY-EFFICIENT TECHNOLOGIES

Priority Level R&D Need

TOP

Develop and design furnace for the future that:

- minimizes melt loss
- increases safety
- improves melt rates
- improves cost-effectiveness
- improves fuel/energy efficiency
- reduces emissions

HIGH

Develop methods or models that evaluate life cycle of components (e.g., refractories).

HIGH

Consider methods to allow for fuel versatility or hybrid systems.

MEDIUM

Explore recovery of useful energy in solidification.

NEW MANUFACTURING CONCEPTS

Priority Level R&D Need

TOP

Develop a melting/casting plant for the future.

TOP

Develop strip/slab casting technologies to improve surface control and texture and reduce segregation.

HIGH

Develop ways to minimize oxidation of metal during transport.

HIGH

Develop low-cost process for alloy/scrap purification.

HIGH

Produce high-quality metal from mixed scrap.

HIGH

Develop means to remove specific impurities from the melt (e.g., Mg, Fe, Pb, Li, Si, Ti).

HIGH

Develop continuous, high-productivity, thin-strip casting process at lower gauge (0.020 inch).

HIGH

Develop near-net shape ingot casting capabilities.

MEDIUM

Develop ways to maintain surface quality.

MEDIUM

Develop methods to continuously maintain surface quality control.

MEDIUM

Pursue in-situ composite production in non-traditional processes and ensure products are recyclable.

MEDIUM

Develop model to evaluate and predict how process changes impact net value throughout the entire system.

MEDIUM

Develop processes that more effectively separate metal from dross/salt cake.

Exhibit 3-3. R&D Needed: Melting, Solidification, and Recycling (continued)

SENSORS AND CONTROLS

Priority Level R&D Need _____

- TOP** Develop methods for real-time chemical analysis.
- HIGH** Develop more extensive closed-loop control of casting process.
- HIGH** Develop low-cost inclusion meter to achieve 100% metal inspection at less than ten microns.
- HIGH** Develop an in-line, real-time, operator-friendly, continuous non-contact sensor and method to identify and separate scrap.
- MEDIUM** Develop non-contact sensors to use in direct-chill (DC) casting that measure shell thickness and surface temperature in ranges of 1,000 - 1,200°F and 0.1 to 3.0 mm.
- MEDIUM** Develop incipient crack sensor.
- MEDIUM** Develop method for predictive macrostructure characterization.
- MEDIUM** Develop fast methods to analyze bulk characteristics (not just surface).

NEW PRODUCTS

Priority Level R&D Need _____

- HIGH** Conduct research on how to produce primary alloys using recycled scrap.
- HIGH** Develop products that use the non-metallic fraction of dross.
- HIGH** Determine the effect of variations in composition on properties.
- MEDIUM** Develop new secondary alloys that better match scrap to specifications for increased utilization and enhance alloy characteristics based on current alloy technology.
- MEDIUM** Establish customer guidelines for alloy selection based on their needs (properties, corrosion, etc.).
- MEDIUM** Develop high-modulus alloy.

SAFETY

Priority Level R&D Need _____

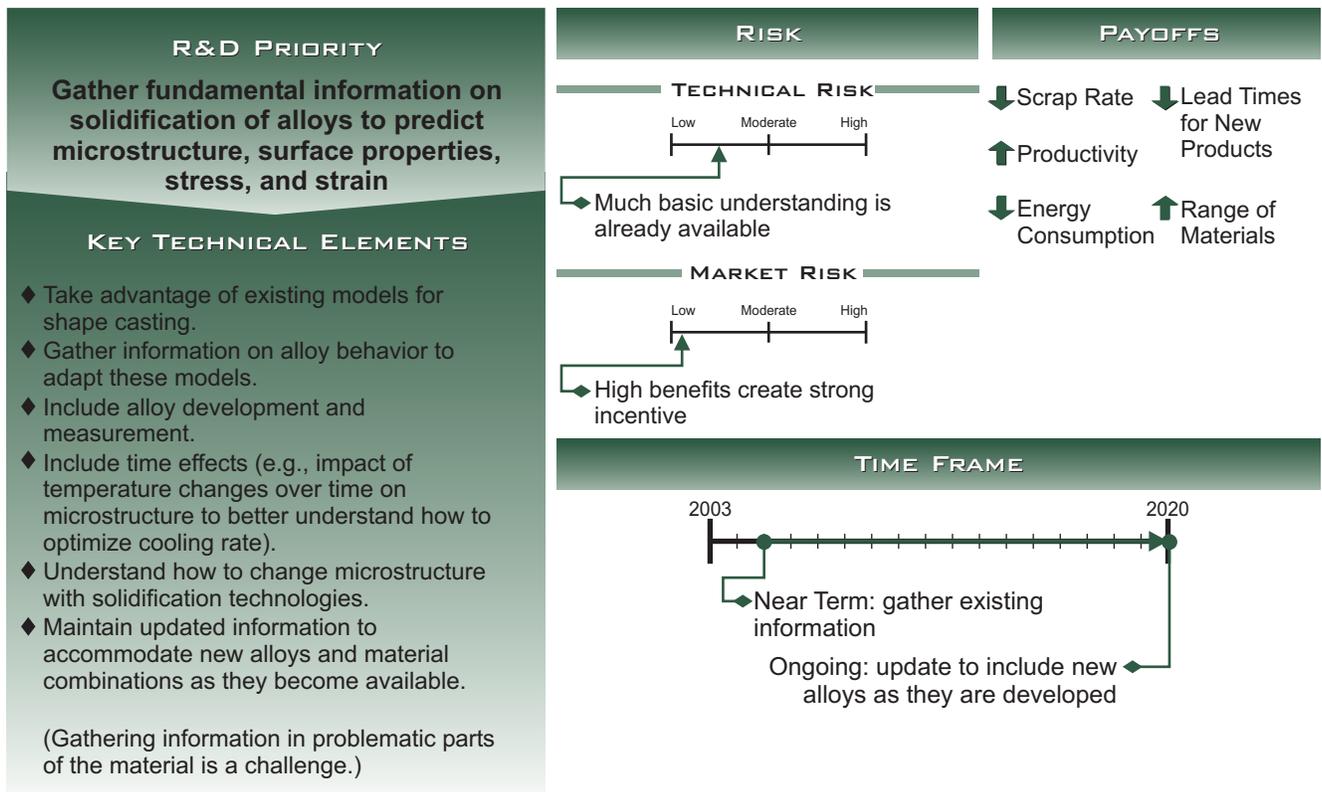
- HIGH** Develop methods and sensors to quantify presence of moisture and non-metallic impurities (e.g., phosphates, nitrates) in charge to furnace to prevent explosions.
- MEDIUM** Continue efforts to understand mechanisms of water-aluminum explosions.
- MEDIUM** Conduct research into materials for protective clothing for casting operators.
- MEDIUM** Explore methods to prevent dust formation.

R&D PRIORITIES

Seven priorities have emerged as most critical to advancing melting, solidification, and recycling technology. While all of the R&D needs described in Exhibit 3-3 are important to fully realizing the vision, the seven following needs hold the most promise for creating significant gains towards the sector-specific performance targets and, ultimately, the industry’s long-term goals.

- Gather fundamental information on solidification of alloys to predict microstructure, surface properties, stress, and strain.
- Develop an integrated process model to predict metal quality and economics based on first principles.
- Develop a more complete understanding of oxidation mechanisms.
- Develop techniques to determine formability characteristics and associated test methods.
- Devise a melting/casting plant and furnace for the future.
- Develop strip/slab casting technologies to improve surface control and texture and reduce segregation.
- Develop methods for real-time chemical analysis.

These priorities are described in further detail on the following pages. The graphics present additional technical details, levels of technical and market risk, potential payoffs, and time frames in which the results are expected.



R&D PRIORITY
Develop an integrated process model to predict metal quality and economics based on first principles

KEY TECHNICAL ELEMENTS

- ◆ Base model on science and physics and verified by empirical data/fuzzy logic.
- ◆ Start by understanding fundamental relationships, then apply to control.
- ◆ Develop sensor for real-time analysis for real-time control.
- ◆ Use model to understand process options.
- ◆ Develop equations of what goes on in the furnace, and understand how to utilize these equations in terms of algorithms. (Much information exists in pieces at various companies, key is assembling it.)
- ◆ Predict inclusions, composition.
- ◆ Consider removal of H, Li, Na.
- ◆ For each piece of model, show how it can be used and develop software for its use.

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>Low Moderate High</p> <p>◆ This is a major challenge, as is creating a useable model</p>	<p>↓ Cost</p> <p>↑ Productivity</p> <p>↓ Energy Consumption</p> <p>↓ Environmental Impact</p> <p>↑ Quality</p>
<p>MARKET RISK</p> <p>Low Moderate High</p> <p>◆ Model is fundamental, so relevant to all processes</p>	
TIME FRAME	
<p>2003 2020</p> <p>◆ Near Term: assemble existing information</p> <p>◆ Mid Term: fill gaps, develop model</p> <p>Ongoing: refine model with most recent advances</p>	

R&D PRIORITY
Develop a more complete understanding of oxidation mechanisms

KEY TECHNICAL ELEMENTS

- ◆ Prevent spinel formation with blocking medium.
- ◆ Avoid runaway oxidation.
- ◆ Develop new oxide products.
- ◆ Reduce oxidation rate and create oxides that are products rather than wastes.
 - include carbobases, carbofluxes, fuming
 - enable the elimination of beryllium

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>Low Moderate High</p> <p>◆ Low to moderate risk</p>	<p>↓ Dross</p> <p>↓ Energy Consumption</p> <p>↑ Yield</p> <p>↑ New Products</p>
<p>MARKET RISK</p> <p>Low Moderate High</p> <p>◆ Much work is ongoing</p>	
TIME FRAME	
<p>2003 2020</p> <p>◆ Near Term: Improve understanding with basic science</p> <p>◆ Mid Term: create commercially available technology to manage oxides</p>	

R&D PRIORITY

Develop techniques to determine formability characteristics and associated test methods

KEY TECHNICAL ELEMENTS

- ◆ Develop set of standard test methods.
- ◆ Develop tools for high-resolution process and alloy development.

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>Low Moderate High</p> <p>◆ Low technical risk</p>	<p>↓ Development Time ↑ New Applications</p> <p>↑ Accuracy of Predictions and Performance ↑ Productivity</p>
<p>MARKET RISK</p> <p>Low Moderate High</p> <p>◆ Low market risk</p>	<p>↑ Reproducibility</p>
TIME FRAME	
<p>2003 2020</p> <p>◆ Mid-Long Term (>7 years)</p>	

R&D PRIORITY

Devise a melting/casting plant and furnace for the future

KEY TECHNICAL ELEMENTS

- ◆ Key features of future plant:
 - flexible, on-demand processing
 - zero waste, environmentally benign
 - safe
 - energy efficient
 - cost effective
 - high product quality
- (Analysis to define characteristics (capacity, melt rate, etc.) is first step.)
- ◆ Identify suitable heating methods.
- ◆ Explore methods to increase melt rate.
- ◆ Control oxidation.
- ◆ Develop ability to change alloy quickly and easily.
- ◆ Develop improved heat transfer techniques (e.g., furnace shape); consider entire energy and emission balance.
- ◆ Increase life for refractories.
- ◆ Explore use of cogeneration.
- ◆ Minimize melt loss.
- ◆ Develop methods for closer compositional control.
- ◆ Explore halide-free fluxing.

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>Low Moderate High</p> <p>◆ New concepts are inherently risky; uncertainty on capacity and melt rates creates technical risk</p>	<p>↑ Quality ↓ Emissions</p> <p>↑ Energy Efficiency ↑ Production Rate</p> <p>↓ Operating Costs ↓ Footprint on Floor Space</p>
<p>MARKET RISK</p> <p>Low Moderate High</p> <p>◆ Existing units must expire first, but concepts may be applicable to older furnaces; power source uncertainty adds economic risk</p>	
TIME FRAME	
<p>2003 2020</p> <p>◆ Near Term: develop refractories that perform better than currently available ones</p> <p>◆ Mid Term: conduct pilot operations</p> <p>◆ Long Term: commercially available plant</p>	

R&D PRIORITY

Develop strip/slab casting technologies to improve surface and texture and reduce segregation

KEY TECHNICAL ELEMENTS

- ◆ Achieve more complete understanding and control of thermal reaction at surface (interaction with mold).
- ◆ Develop new alloys for continuous casting.
- ◆ Gather process data.

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>Low Moderate High</p> <p>High technical risk</p>	<p>↓ Costs</p> <p>↓ Energy Use</p> <p>↓ Lead Times</p> <p>↑ Productivity</p> <p>↑ New Products/ Markets</p>
<p>MARKET RISK</p> <p>Low Moderate High</p> <p>Low market risk due to potential demand</p>	
<p>TIME FRAME</p> <p>2003 2020</p> <p>Long Term (> 10 years)</p>	

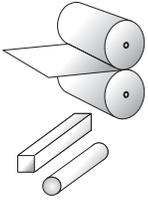
R&D PRIORITY

Develop methods for real-time chemical analysis

KEY TECHNICAL ELEMENTS

- ◆ Develop rapid elemental analysis with required precision at affordable cost.
 - one reading per second
 - ability for real-time adjustments
 - effective in solid and liquid phases
 - ability to analyze trace elements
 - applicable to batch or continuous processes
 - robust in molten metal environment
 - no operator exposure while taking samples
 - eliminate opening furnace to sample
- ◆ Identify optimal approach and limitations.
- ◆ Develop sampling and analytical technique.
 - surface provides difficulty for sampling and analysis
- ◆ Laser-induced breakdown spectroscopy (LIBS) is close, but limited.

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>Low Moderate High</p> <p>Complicated by trace elements</p>	<p>↑ Productivity</p> <p>↑ Yield</p> <p>↓ Energy consumption</p> <p>↓ Emissions</p>
<p>MARKET RISK</p> <p>Low Moderate High</p> <p>Operations do not have to be interrupted to incorporate technology</p>	
<p>TIME FRAME</p> <p>2003 2020</p> <p>Near Term: demonstrate prototype concept</p> <p>Mid Term: technology is commercially available, ongoing improvements</p>	



4. FABRICATION

To meet heightened customer expectations for product functionality, aluminum companies of the future will work with their customers more closely than ever before to develop engineered and fully recyclable material solutions. This shift will require fabricators to adopt new technologies and to rethink or adapt their business approach, supply chain, design, materials, and decision making throughout the manufacturing process. A key part of this process will include constant improvements to aluminum fabrication techniques, such as rolling, extrusion, forging, and others.

By taking a stronger role in the downstream supply chain, aluminum companies will better position themselves to incorporate fabrication choices with product design, thereby improving supply chain efficiency, reducing product lead times, and bringing higher value to customers. Such integration will enhance flexibility and the ability of aluminum companies to create unique material solutions tailored to specific customer requirements.

The industry's long-term goal of zero waste will demand increased consideration of a product's recycling potential during the design and fabrication process. Products that are "designed for recycling" will facilitate growth in aluminum recycling and fortify the industry's ability to conserve energy and resources.

Many of today's fabricated aluminum products are designed for manufacture using alloys made from primary aluminum. More semi-finished products will need to be designed for manufacture using secondary alloys to accommodate the shift toward increased secondary production and recycling. As mentioned in Chapter 2, high-purity primary aluminum may sometimes be used as a sweetener to extend designs from primary to secondary aluminum alloys.

CURRENT TECHNICAL SITUATION

The 1997 *Aluminum Industry Technology Roadmap* highlighted the need for predictive models relating alloy microstructure and properties to specific forming processes. While proprietary and academic efforts have yielded considerable technical progress in this area, predictive modeling remains an area of need within the industry.

Continuous casting (direct conversion of molten metal to strip) has continued to gain use throughout the industry because it eliminates several process steps, saving time, conserving energy, and reducing cost. While this process is now widely used to roll simpler alloys (e.g. 1xxx, 3xxx, and some 5xxx alloys), continuous casting has not yet broken the barrier to

processing the more complex 5xxx and 6xxx alloys for automotive applications due to issues of market size, formability, surface quality, and financial risk.

Significant progress has been made in the general area of sensor development and application. Some noteworthy developments are the use of refractory-coated tubes to enable more robust, continuous monitoring of molten metal temperature, the advent of LIBS for rapid, in-situ molten metal analysis, and the online use of non-contact laser ultrasonics to monitor the recrystallization of continuously cast strip prior to coiling. This application of laser ultrasonics is especially innovative and practical in that both the laser probe and analyzer are remote from the metal strip under evaluation.

Lastly, the call for more advanced forming technologies has been partially satisfied by the pilot demonstration of electromagnetic forming (EMF) of automotive components. The high-speed deformation that occurs during EMF overcomes some limitations of the forming limit diagrams for stronger, more complex alloys. Work is now focusing on making the equipment more robust for the industrial environment.

PERFORMANCE TARGETS

Each of the performance targets supporting the Products and Markets goals focuses on one aspect of overall cost to increase the value of semi-finished aluminum products. Attainment of these ambitious targets will help aluminum compete more effectively with other materials and provide higher customer satisfaction.

Aluminum fabricators will take a multi-pronged approach to enhance sustainability. They will strive to reduce overall process emissions, including gaseous and liquid emissions such as solvents and lubricants; facilitate increased recycling through material and alloy design; and eliminate lost-time accidents.

Exhibit 4-1. Performance Targets for 2020: Fabrication

PRODUCTS AND MARKETS

- ◆ Decrease customer returns by one order of magnitude.
- ◆ Reduce development cycle time and associated costs by 50%.
- ◆ Increase productivity by 50% (shorten the production path).
- ◆ Increase product recovery to 90% by minimizing planned and incidental process scrap.

ENERGY AND RESOURCES

- ◆ Reduce thermal process energy by 30% (conserve heating/cooling energy) .
- ◆ Increase reliability of manufacturing operations to 95%.

SUSTAINABILITY

- ◆ Reduce emissions by 90% (including solvents, lubricants, etc.).
- ◆ Create new alloys that are compatible with recycling.
- ◆ Improve/increase scrap-tolerant processing and alloys.
- ◆ Achieve zero lost time accidents.

By improving the reliability of their operations, aluminum fabricators can improve process efficiency and minimize downtime, thereby conserving resources and increasing productivity. Reducing the thermal cycles of fabrication processes offers an opportunity to further reduce energy consumption and lower costs.

TECHNICAL BARRIERS

If fabrication technologies are to reach the performance levels described above, the industry must address many technical barriers that hinder the fabrication of aluminum products (Exhibit 4-2). These barriers can be grouped into four main areas:

- Sensors and Measurement
- Predictive Capabilities
- Manufacturing Efficiency
- Manufacturability

Limitations in sensors and other measurement capabilities currently restrict aluminum fabricators' knowledge of process specifics, in turn limiting the precision with which they can control processes to optimize productivity, quality, and efficiency. Inadequate predictive capabilities and data also limit fabricators' ability to design and optimize processes to achieve desired microstructures, alloy chemistries, or other product characteristics. Other technical barriers further constrain manufacturing efficiency, such as inadequate, expensive tools and equipment and inconsistencies in raw materials. Finally, difficulties associated with manufacturing aluminum stem from current formability limits, which restrict or inhibit fabrication choices and flexibility.

RESEARCH AND DEVELOPMENT NEEDS

Overcoming the barriers to achieve the fabrication performance targets will require the industry to pursue research, development, and demonstration activities in four major areas:

- Manufacturing Efficiency
- Predictive Capabilities
- Sensors and Measurement
- Improved Alloys

Manufacturing efficiency is the most important area of research in the fabricated products sector. Developing methods to fabricate products without waste (e.g., net-shape manufacturing) can help the industry improve yields and reduce costs. Research leading to the consolidation or elimination of processing steps will streamline fabrication, saving time, energy, and money. Technologies that improve product quality (e.g., improved extrusion surface quality techniques) will help increase customer satisfaction.

Exhibit 4-2. Technical Barriers: Fabrication (priorities in **bold**)**SENSORS AND MEASUREMENT**

- **Lack of methods to relate surface quality measurements to the processing history of the material**
- **Lack of commercial tools to segregate scrap for both in-line processing and returned material**
 - ▶ characterization
 - ▶ sensitivity
 - ▶ high resolution
- **Lack of automatic microstructure and texture measurement methods**
- **Lack of technology to measure dimensional control**
- Inability to measure thermal gradients in the process for temperature control
- Lack of cost-effective methods to detect and classify surface defects online

PREDICTIVE CAPABILITIES

- **Lack of models capable of relating structural properties to manufacturing processes and the materials employed (constitutive models that are also capable of addressing alloy chemistry)**
- **Lack of accurate material data, including elemental data by alloy type**
- Lack of accurate process design data and integrated process models
- Lack of modeling to design process flowpath to meet final customer product requirements
- Lack of life-cycle design methodologies; limited understanding of the performance of aluminum products over long-term use (10-15 years)
- Insufficient understanding of aluminum rheology, including liquid and plastic deformation characteristics
- Lack of tools for alloy design
- Lack of models that allow reverse engineering

MANUFACTURING EFFICIENCY

- Lack of information on surface chemistry (lube/tool/metal)
- Capital investment too high for new processing methods
- Insufficient tooling
 - ▶ tool life too limited
 - ▶ lack of tested way to design and implement tooling that works properly the first time
 - ▶ current tool/die steels and their material development do not satisfy industry needs
- Inconsistent incoming raw material
- High cost of lubricant disposal

MANUFACTURABILITY

- **Limitations in advanced forming technologies for new markets**
 - ▶ lack of non-traditional forming methods
 - ▶ lack of alloys whose design permits increases in modulus compared to conventional alloys
- Lack of dimensional stability (customer requirements for shape and residual stress levels)
- Corrosion problems between aluminum and other materials (customer requirements)
- Ineffective machinability tests

Improved predictive capabilities will help aluminum fabricators optimize their operations while achieving desired bulk material and surface properties. Such capabilities also have the potential to further reduce waste and greatly enhance overall efficiency. Improved sensors and other measurement techniques are important enabling technologies for expanding the knowledge of fundamentals and how those processes can be manipulated to achieve desired outcomes.

Alloys that are more conducive to recycling or that offer increased formability, higher modulus, or other enhanced properties could open additional market opportunities for aluminum. Exhibit 4-3 presents a range of R&D needed in fabrication.

Exhibit 4-3. R&D Needed: Fabrication

N: Near Term (< 3 years) M: Mid Term (3-10 years) L: Long Term (> 10 years)

MANUFACTURING EFFICIENCY

Priority Level R&D Need

- HIGH** Reduce/eliminate homogenization. (M)
- HIGH** Develop alternative/different manufacturing process for optimized product applications.
- HIGH** Develop better understanding of the factors affecting metal flow in hollow extrusions, thereby enabling the development of computerized extrusion die designs. (N)
- HIGH** Develop methods that eliminate processing steps currently needed to produce end products. (M)
- HIGH** Develop surface treatment technologies.
 - surface chemistry and tribology
 - develop environmentally friendly lubricants and coolants
- HIGH** Develop technologies to reduce residual stress.
- HIGH** Develop more complete understanding of the relative strength and formability of alloys as a function of thermomechanical processing and chemical composition. (M)
- MEDIUM** Develop isotropic properties in thick plate.
- MEDIUM** Enhance the surface quality of extruded products. (L)
- MEDIUM** Acquire a more complete understanding of alloy behavior including crystallographic texture changes during thermomechanical processing. (M)

PREDICTIVE CAPABILITIES

Priority Level R&D Need

- TOP** Develop integrated models that relate structural properties to manufacturing processes and the materials employed. (M)
- HIGH** Develop material property database for predictive capability.
- HIGH** Develop model relating surface evolution to prior processing history.
- HIGH** Develop real-time, more accurate process engineering models that can be used for process control. (M)

SENSORS AND MEASUREMENT

Priority Level R&D Need

- TOP** Develop new or improved non-contact sensors. (M)
 - microstructure
 - dimensions
 - texture
 - speed
 - temperature
 - pressure
 - residual stress
- HIGH** Develop surface inspection devices for high speed manufacturing capable of operating in industrial environments. (N)

IMPROVED ALLOYS

Priority Level R&D Need

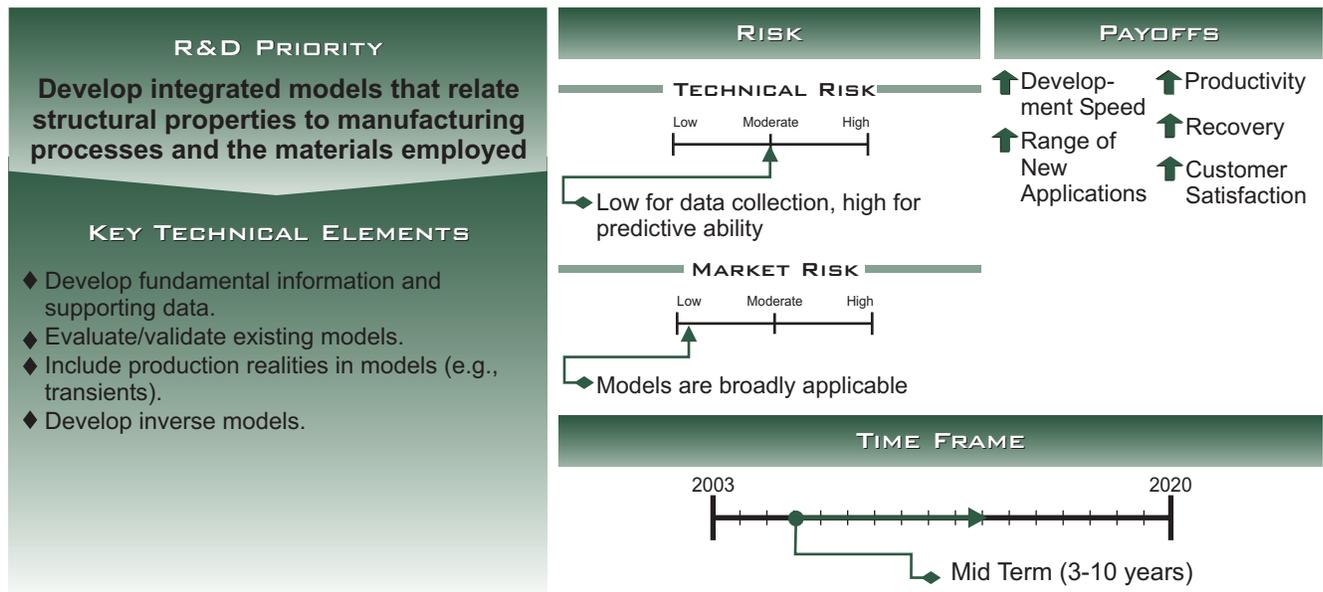
- TOP** Develop manufacturing processes for scrap-tolerant alloys. (M-L)
- HIGH** Develop aluminum alloys with the same properties as competitive materials (e.g., formability, end-product performance). (N-M)
- HIGH** Conduct fundamental science and engineering work on the machinability of aluminum alloys. (M)
- MEDIUM** Acquire a more complete understanding of meta-stable phase transformation kinetics and impact on mechanical properties. (N-M)

R&D PRIORITIES

Although all of the R&D needs presented in Exhibit 4-3 are important for the industry to achieve its performance targets, three needs have emerged as the highest priorities for the aluminum fabrication sector. Successfully addressing these three needs promises to significantly reduce fabrication costs, improve energy efficiency, and provide other benefits to the aluminum industry.

- Develop integrated models that relate structural properties to manufacturing processes and the materials employed.
- Develop new or improved non-contact sensors.
- Develop manufacturing processes for scrap-tolerant alloys.

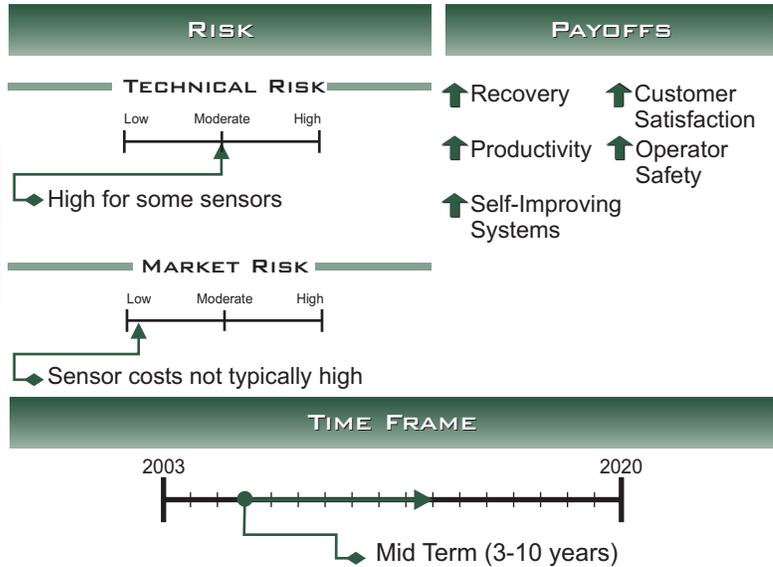
The following graphics provide additional details with regard to each of these priorities. Additional technical details, risks and payoffs, and expected time frames for results are presented.



R&D PRIORITY
Develop new or improved non-contact sensors

KEY TECHNICAL ELEMENTS

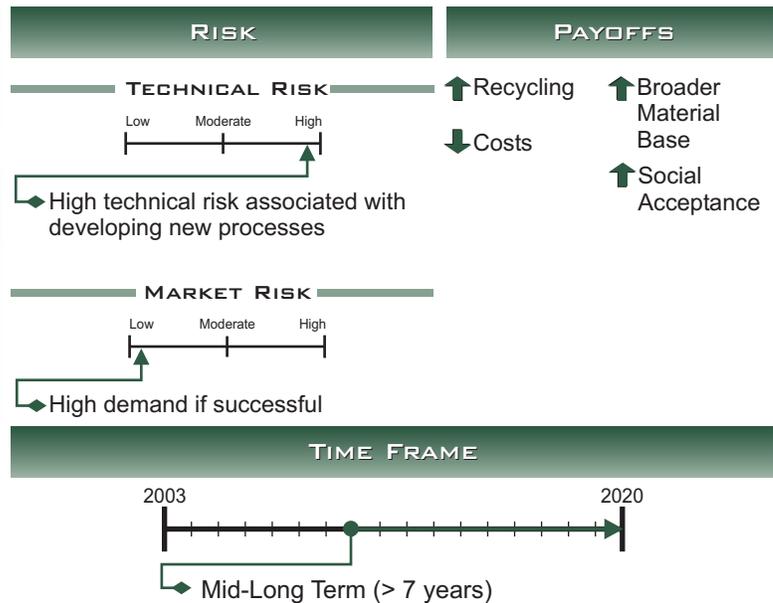
- ◆ Transition from lab scale to commercial.
- ◆ Integrate with control systems.
- ◆ Reduce cost for specialized equipment.
- ◆ Reduce necessity of sensor proximity to process.

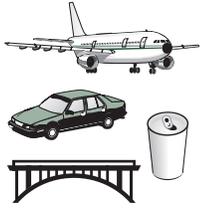


R&D PRIORITY
Develop manufacturing processes for scrap-tolerant alloys

KEY TECHNICAL ELEMENTS

- ◆ Refine understanding of interactions between elements in alloys.
- ◆ Understand trends in scrap composition (elemental) and impact on manufacturing process.
- ◆ Develop impurity removal methods.





5. ALLOY DEVELOPMENT AND FINISHED PRODUCTS

The industry's goal of providing engineered material solutions tailored to customer needs most directly impacts the finished products sector. The need for close interaction with customers in order to identify, understand, communicate, and address their material requirements will place the finished products sector at the forefront in realizing this aspect of the vision. For the purposes of this *Roadmap*, the finished product sector includes joining and finishing technologies along with end-use applications, as these technologies are typically determined by customer requirements.

Close collaboration will allow customers and material providers the opportunity to assess materials substitution and integration possibilities. This collaboration should yield engineered material solutions that combine alloys and different material types in the most effective way for each end-use application. New material combinations will create new disassembly needs as multi-material components reach the end of their useful lives and enter the scrap recycling stream. Material providers will have to keep recyclability in mind when developing these new material solutions.

Competing materials are vigorously pursuing advances that threaten aluminum markets if the aluminum industry does not keep pace. By focusing on the distinct competitive advantages of aluminum, including aluminum's life-cycle benefits, the industry can fortify its position in existing markets and open doors to new ones. Life-cycle analyses will gain particular attention in automotive markets because of the significant energy savings associated with lightweight materials. Successes in transportation markets –aluminum's largest market sector –will likely cascade into other market sectors as well.

Finally, with the increasing globalization of aluminum companies and their customer industries, rapid adoption and global distribution of advanced technologies will increasingly become standard business practice. Innovations developed in North America will be disseminated throughout corporate structures to achieve maximum benefit, and technologies developed abroad will similarly flow into North American aluminum facilities to improve domestic capabilities.

CURRENT TECHNICAL SITUATION

The growing awareness of the concept of total LCA and overall product sustainability ranks among the most significant developments in the application of aluminum products. The concept of process and product sustainability plays to one major strength of aluminum: easy and energy-efficient recycling. Recycling of aluminum only requires about five percent of

the energy needed to smelt the metal from its ore. Exhibit 5-1 illustrates the dramatic impact of recycling on the total energy required to produce the combined primary and secondary U.S. metal supply. As the proportion of recycled aluminum has grown over the past four decades, the total weighted-average energy required has decreased from 19.2 to 8.2 kWh/kg, a reduction of 57 percent. While some of this decrease is due to technology advancements in the primary smelters, the bulk is due to the growth of recycling.

The importance of recycling and sustainability is expected to continue to increase in the near future. The application of lightweight aluminum to improve the fuel efficiency of automobiles has led to a significant increase in the amount of aluminum per average vehicle: from 183 pounds in 1991 to 274 pounds in 2002. Given that the average vehicle life is now about 15 years, this material will start to enter the recycling loop in the middle of this decade. The use of auto shredders that take advantage of recent advances in scrap sorting technology, permitting not only the segregation of aluminum from other metals but also the separation of cast from wrought alloys and the separation of material by alloy family, will enable this material to be captured for recycling. Furthermore, unlike the recycling of beverage cans, the industrial auto shredder will override the individual decision of whether or not to recycle. Eliminating these decisions can explain the contrast between the low can recycling rate, which has now dropped to around 50 percent, and auto shredders that capture approximately 90 percent of the aluminum in vehicles.

Developments in joining have been significant since 1996. Laser welding of automotive sheet, weld bonding (the combination of spot welding with adhesives), and the use of friction stir welding (FSW) have advanced rapidly. Since its invention in the early 1990s, FSW of metals has been utilized most rapidly with aluminum and is now being used in advanced aerospace and aircraft applications such as the external tank of the space shuttle and the Eclipse business jet. FSW has enabled the joining of previously difficult-to-weld alloys, often with improved mechanical properties in the joint, and aided the competitiveness of aluminum versus other materials. The advent of FSW has also facilitated the application of aluminum in the fabrication of fast ferries and bridge decks, where the industrial process has improved dimensional tolerances, reduced residual stresses and lowered manpower needs.

Exhibit 5-1. Impact of Secondary Metal Production on the Energy to Produce Aluminum in the United States.

	Year				
	1960	1970	1980	1990	2000
U.S. Primary Production (thousand metric tons)	1,828	3,607	4,653	4,048	3,668
Primary Energy Requirements (kWh/kg)	23.1	21.4	17.5	16.1	15.1
U.S. Secondary Production (thousand metric tons)	401	937	1,577	2,393	3,450
Market Percentage of Secondary (%)	18	20	25	39	47
Effective Energy Combined Metals (kWh/kg)	19.2	17.3	13.3	10.5	8.2

Source: U.S. Energy Requirements for Aluminum Production: Historical Perspective, Theoretical Limits, and New Opportunities, U.S. Department of Energy, 2003.

PERFORMANCE TARGETS

Exhibit 5-2 presents the specific performance targets for the finished products sector. These targets collectively support the industry-wide performance target of increased aluminum use in existing and emerging applications. Several targets have been established to quantify the magnitude of improvements sought in joining, design tools, finishing, material properties, and other technical areas. Additional application-specific targets have also been established for several of aluminum's key markets.

TECHNICAL BARRIERS

For the aluminum industry to achieve the specific performance targets for finished products, it must develop technological solutions to several barriers that currently limit capabilities. Exhibit 5-3 presents the range of technical barriers currently limiting the production and performance of finished aluminum products. The barriers can be organized into four categories:

- Enabling Technologies
- Design Tools, Models, and Property Data
- Aluminum Properties
- Processing Technologies

To be successful, material providers require technologies and processes that allow them to design products efficiently, manufacture them quickly with minimal waste, and join them to one another for end-use applications. The enabling technologies currently available to the aluminum industry constrain the applications in which its material can be used. Aluminum providers and users also require improved design tools, models, and numerical methods for the design and manufacture of finished products to expand the applicability and effectiveness of their products.

The current limitations on both aluminum properties and the understanding of those properties narrows the product functionality of today's aluminum finished products. Research to establish material properties based on microstructures could significantly expand product offerings. In addition, the industry must improve processing technologies to improve levels of control, quality, and production.

Exhibit 5-2. Performance Targets for 2020: Alloy Development and Finished Products

<i>Industry-Wide Performance Target: Accelerate growth rate of aluminum use in existing and emerging applications.</i>	
TECHNOLOGY AREAS	
Joining	Reduce scrap/waste from joining by 50% via real-time joint inspection. Reduce by 50% the cost, waste, and hazards of joining consumables and airborne byproducts. Use lower melt temperature with alternative joining procedures. Develop full potential of friction-stir welding.
Design Tools	Establish guidelines for lifetime performance predictions (environment, degradation). Develop accurate and reliable specifications and standards for buildings, infrastructure, packaging, and tools for structural design. Establish aluminum durability design rules.
Finishing	Develop alternative aluminum finishing processes that decrease total scrap generation by 50%.
Properties	Define the microstructure property relationships needed for design prediction. Expand property envelope with respect to operating temperature, corrosion resistance, and formability.
MARKET APPLICATIONS	
Aerospace/ Defense	Reduce the assembled cost of aluminum aerospace structures by 30% per equivalent performance unit. Reduce the weight of aluminum aerospace structures by 20% with no cost increase.
Automotive	Develop unified body sheet alloy for inner and outer applications. Produce predictable, consistent, reliable product. Eliminate premium over steel on an application basis.
Building and Construction	Increase aluminum usage in building and construction by 50% by 2010. Develop and promote "cost effective" structural alloys with 50% higher strength than 6061-T6. Ensure aluminum is included in design codes.
Energy	Promote aluminum for hydrogen containment.
Infrastructure	Establish aluminum as 20% of the total structural value of upgrades to U.S. infrastructure (i.e., bridge deck/support). Use aluminum in smart structures.
Packaging	Reduce can tear-offs to 1 per million cans. Develop uni-alloy cans to facilitate recycling. Reduce the need for multiple coating types by 50%. Achieve 100% use of aluminum for food packaging and 100% recyclability of food packaging.
Other Transportation	Achieve 50% aluminum in freight transportation containers. Increase aluminum use in fast ferries. Eliminate premium for aluminum body-in-white over steel in alternative-fuel vehicles.
Other Applications	Eliminate chromate coatings. Develop end-use for "waste" products from upstream processes.

Exhibit 5-3. Technical Barriers: Alloy Development and Finished Products (priorities in **bold**)**ENABLING TECHNOLOGIES**

- **Lack of integration between process and product design**
- **Inadequate scale and cost-effectiveness of near-net shape technology**
- Inadequate material joining technology development
 - ▶ dissimilar materials
 - ▶ limited methods for joining high-strength alloys
 - ▶ too slow and costly
 - ▶ real-time non-destructive evaluation (NDE)
 - ▶ structural design rules for “stir welded” members
- Inadequate lubrication systems for forming processes and component use
 - ▶ lubricants are not environmentally friendly
 - ▶ lack of biolubricants for ultra-low emissions vehicles
- Inadequate, slow tests to predict long-life performance (tests for fracture toughness, degradation, environmental performance, corrosion)

DESIGN TOOLS, MODELS, AND PROPERTY DATA

- **Inadequate computer design and simulation tools to link product design and optimized manufacturing**
- Lack of design rules for aluminum-concrete composite design (for bridge applications)
- Inadequate numerical methods and performance databases for analysis and design of products; inadequate design codes
- Too few demonstration products or prototypes being tested

ALUMINUM PROPERTIES

- **Limited understanding of relationships between microstructure and material performance**
- Poorly defined targets (standards) for strength versus dent resistance and durability
- Insufficient knowledge of composites and metal hybrids
- Lack of high-temperature aluminum alloys with good fracture toughness
- Inadequate corrosion performance, surface durability, hardness, and modulus of elasticity
- Thermal conductivity of aluminum is high
- Tendency to alloy with resistance-welding electrodes

PROCESSING TECHNOLOGIES

- **Inadequate process control technology**
 - ▶ inability to conduct real-time monitoring and control or link process models with product models
 - ▶ inadequate sensors/process feedback for control
- **Limited advanced forming technologies for new markets**
- Inadequate dimensional stability and consistent formability of aluminum components
- Lack of a continuous process from melting to final product
 - ▶ problems with surface-critical products from continuous cast processes
- Limited process technologies to produce advanced materials

RESEARCH AND DEVELOPMENT NEEDS

The aluminum industry can overcome technical barriers through research, development, demonstration, and the controlled evolution of technologies and processes. The R&D needed to achieve the performance targets for finished products can be organized into four areas:

- Finished Product Technologies
- Processing Technologies
- Aluminum Properties
- Sustainability and Life-Cycle Analysis

Aluminum companies need technologies that will allow them to produce easily recyclable, finished aluminum products more efficiently, consistently, and with less waste. Establishing clear linkages among structural properties, performance, material properties, and process choices is an important priority for aluminum companies seeking to satisfy customer requirements quickly and efficiently.

Another priority involves the joining of aluminum to other metals and materials. The industry faces significant challenges in achieving optimal product performance during end use while also facilitating easy disassembly and recycling at the end of the product's service life.

Processing technologies, particularly net-shape and near-net-shape forming technologies, represent major opportunities to reduce waste and cost during finishing operations. A range of emerging technologies offer various levels of promise for near-net shape forming, and identifying which net-shape technologies are most effective for specific market sectors and applications is an important priority for the industry. Process sensors, controls, and simulations are also needed to optimize finishing operations.

Cultivating a more complete understanding of aluminum properties and how they relate to processing options demands significant research. The industry needs new alloy designs and other material solutions with enhanced properties to expand markets and applications. Finally, tools for life-cycle analyses need to be applied across all industries for the aluminum industry to accurately measure and take full advantage of aluminum's life-cycle benefits.

Exhibit 5-4 illustrates a range of R&D needed in the finished products sector. In addition to these needs, the R&D priorities described in the aluminum industry's other roadmaps are critical to the industry's overall approach to technology exploration and development.

Exhibit 5-4. R&D Needed: Alloy Development and Finished Products

FINISHED PRODUCT TECHNOLOGIES

Priority Level R&D Need

TOP

Develop integrated numerical methods for analysis and robust design of products, processes, and material.

- improve design of extrusions
- establish design specifications
- develop accurate and reliable structural design specifications

TOP

Develop low-cost joining techniques for similar and dissimilar materials.

- e.g., FSW, adhesives, joining methods for high-volume structures
- investigate and publish joining performance guidelines by process/alloy/geometry
 - link process to product design
 - material joining development
 - multi-material
- eliminate pre-treatment for joining
- include real-time NDE

HIGH

Develop simulations of finished product fabrication processes, including material variability.

- develop models linking process parameters to property/material performance (through process modeling)
- develop integrated process/ product models for cost and quality optimization

HIGH

Translate product requirements into material properties and test standards.

MEDIUM

Reduce process waste in finished production.

MEDIUM

Develop advanced joining techniques that do not impact material properties.

MEDIUM

Develop advanced forming process for subassemblies.

PROCESSING TECHNOLOGIES

Priority Level R&D Need

TOP

Develop advanced forming techniques to manufacture net shapes without intermediate steps.

- semi-solid casting
- spray forming
- powder metallurgy
- aluminum deposition processes with less than 0.01% porosity
- physical vapor deposition
- rapid solidification
- eliminate intermediate processes

HIGH

Develop and apply computational methods for process simulation.

HIGH

Develop methods to purify alloys for recycling.

MEDIUM

Develop alternatives to chromate coatings.

MEDIUM

Develop better online, real-time sensing for process control.

MEDIUM

Develop processes to fabricate multi-material products (non-aerospace laminates, MMCs).

- metal composites for engines
- develop economical, high-performance laminate structures

MEDIUM

Develop in-line, surface-inspection systems for hot mill.

MEDIUM

Develop processes to improve wear resistance of aluminum.

Exhibit 5-4. R&D Needed: Alloy Development and Finished Products (continued)

ALUMINUM PROPERTIES

Priority Level R&D Need

TOP

Develop the next generation of aluminum alloys by understanding the relationship of alloy composition and processing and their effects on microstructure and properties (including nano-structures).

HIGH

Develop tools for alloy design with improved physical properties.

- higher modulus
- lower density
- corrosion resistance
- fracture toughness
- surface durability
- ability to input properties of competitive materials to determine aluminum requirements

HIGH

Develop superior marine alloys.

MEDIUM

Develop “structural” alloy with 50% more strength than 6061-T6.

MEDIUM

Improve quantitative, microstructural characterization techniques.

MEDIUM

Enhance surface chemistry of aluminum alloys to improve corrosion and joining issues.

MEDIUM

Develop statistical information on material properties and fabricating tolerances.

MEDIUM

Develop multi-purpose packaging alloys.

SUSTAINABILITY AND LIFE-CYCLE ANALYSIS

Priority Level R&D Need

HIGH

Universally implement “rules” for LCA (led by transportation).

HIGH

Enhance sustainability of key products with respect to greenhouse gases on life-cycle basis.

MEDIUM

Eliminate recycling incompatibility on all key products.

R&D PRIORITIES

While all the research needs presented in Exhibit 5-4 play an important role in the improvement of finished aluminum products, the four priorities listed below have the greatest potential to propel the industry forward. Successful research in these areas promise significant cost reductions, decreased energy consumption and waste, and market expansion in a variety of sectors.

- Develop integrated numerical methods for analysis and robust design of products, processes, and materials.
- Develop low-cost joining techniques for similar and dissimilar materials.
- Develop advanced forming techniques to manufacture net shapes without intermediate processes.
- Develop next-generation aluminum alloys by fully understanding the relationship of alloy composition and processing and their effects on microstructure and properties.

These priorities are discussed in greater detail below. Additional technical details, levels of technical and market risks, potential payoffs, appropriate government roles, and time frames are also outlined.

R&D PRIORITY

Develop integrated numerical methods for analysis and robust design of products, processes, and materials

KEY TECHNICAL ELEMENTS

- ◆ Develop accurate and reliable structural design specifications.
- ◆ Understand relationships of material structure to mechanical behavior.
- ◆ Develop guidelines for using numerical analysis methods as tools.

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>◆ Low technical risk</p>	<p>↑ Provides base for optimum designs</p> <p>↑ Structural analysis base</p>
<p>MARKET RISK</p> <p>◆ Understanding relationship of material structure to structural behavior will require significant resources</p>	<p>↑ Design of alloys for applications</p>
TIME FRAME	
<p>2003</p> <p>◆ Near Term: up-to-date specifications (extrusions or cold-rolled products at a minimum)</p> <p>◆ Near Term: guidelines for using numerical analysis methods are established</p>	<p>2020</p> <p>◆ Long Term: ongoing updates to guidelines</p> <p>◆ Long Term: constant advances towards understanding relationship of structure to mechanical behavior</p>

R&D PRIORITY

Develop low-cost joining techniques for similar and dissimilar materials

KEY TECHNICAL ELEMENTS

- ◆ Joining of aluminum to aluminum, steel, plastics, and advanced composites.
- ◆ Environmentally friendly pretreatment (or elimination of pretreatment).
- ◆ Inspection and quality assurance techniques.

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>◆ Moderate technical risk</p>	<p>↓ Design constraints in developing material solutions</p> <p>↑ Markets and applications</p>
<p>MARKET RISK</p> <p>◆ Low market risk</p>	
TIME FRAME	
<p>2003</p> <p>◆ Near Term: develop analysis method for inspection</p> <p>◆ Mid Term: established quality assurance strategies and practices</p> <p>◆ Mid Term: joining processes developed</p>	<p>2020</p> <p>◆ Mid Term: standards and codes for newly developed processes</p> <p>◆ Long Term: new processes applied</p>

R&D PRIORITY

Develop advanced forming techniques to manufacture net shapes without intermediate processes

KEY TECHNICAL ELEMENTS

- ◆ Rapid solidification (spray casting, PM, emerging technologies).
- ◆ Deposition processes [i.e., laser, chemical, physical vapor deposition (PVD)].
- ◆ Sheet forming (EMF, SPF).
- ◆ Extrusion forming [analysis of residual stress, development of extrusion computer-aided engineering (ECAE)].
- ◆ Eliminate thermal treatments.
- ◆ Recover process energy.
- ◆ Continuously cast high-value products.
- ◆ Investigate innovative processes.

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>Low Moderate High</p> <p>Moderate to high for rapid solidification techniques, low for others</p>	<p>↓ Energy consumption</p> <p>↓ Processing costs</p> <p>↑ Advanced materials selection</p> <p>↓ Cost of structures</p> <p>↓ Lead Times</p> <p>↑ Productivity</p> <p>↑ New Products/ Markets</p>
<p>MARKET RISK</p> <p>Low Moderate High</p> <p>High for emerging technologies, deposition processes, moderate for others</p>	
TIME FRAME	
<p>2003 2020</p> <p>Near Term: complete proof-of-concept, move to pilot plant for rapid solidification</p> <p>Mid Term: pilot scale demonstration for rapid solidification</p> <p>Near Term: demonstrate suitability of deposition processes for aluminum</p>	

R&D PRIORITY

Develop next-generation aluminum alloys by fully understanding the relationship of alloy composition and processing and their effects on microstructure and properties

KEY TECHNICAL ELEMENTS

- ◆ Challenge paradigms of alloy application to specific products.
- ◆ Develop higher-strength structural alloy with good formability and weldability.
- ◆ Understand potential for altering physical properties with same mechanical properties (density and modulus).
- ◆ Continue efforts to understand effects of thermomechanical properties on product properties.
- ◆ Develop new scrap-tolerant alloys.
- ◆ Develop marine alloy with higher strength and good corrosion resistance.

RISK	PAYOFFS
<p>TECHNICAL RISK</p> <p>Low Moderate High</p> <p>Low, particularly for incremental gains</p>	<p>↑ New or expanded markets</p> <p>↓ Energy consumption</p> <p>↑ Expanded aluminum usage improving efficiencies of LCA/recycling</p> <p>↓ Material needed</p> <p>↓ Energy use in application (e.g., transportation)</p>
<p>MARKET RISK</p> <p>Low Moderate High</p> <p>High (high cost associated with this priority)</p>	
TIME FRAME	
<p>2003 2020</p> <p>Near Term: new marine/ structural alloys</p> <p>Mid Term: new thermomechanical property approach for alloy processing</p> <p>Mid Term: new applications/markets from increased understanding</p> <p>Long Term: new alloys with modified physical properties</p>	

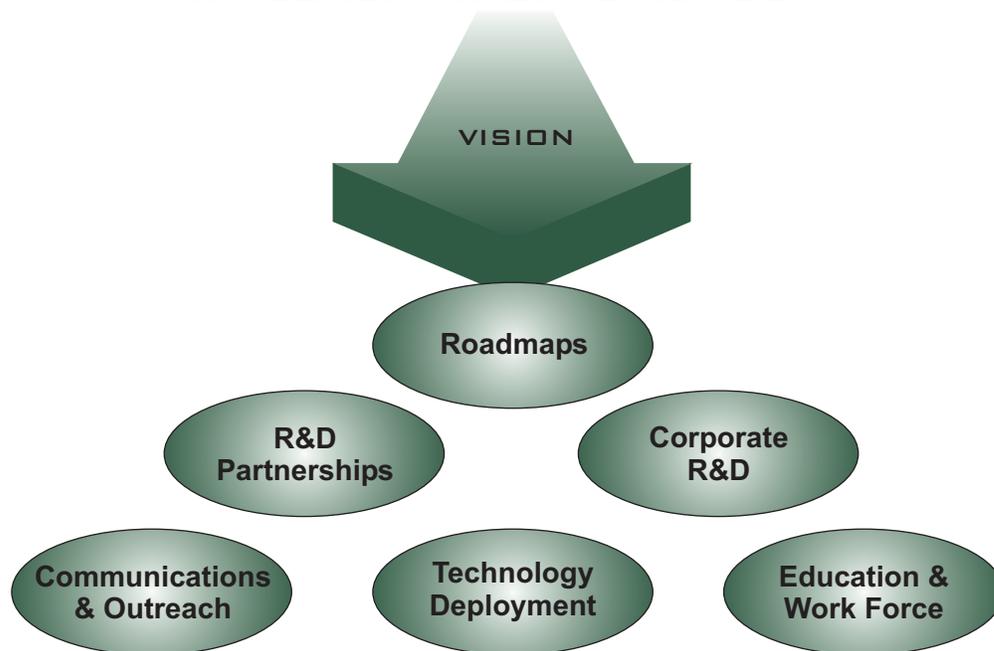
6. LOOKING FORWARD: IMPLEMENTATION

The success of the aluminum industry's technology roadmapping efforts can be measured by the dozens of technological innovations that have entered the industry since the industry's first roadmap in 1997, or by the \$100 million that the research partners have leveraged to address industry-defined R&D priorities. Such success is only possible through the industry's committed, strategic approach to implementing its vision and suite of technology roadmaps.

The *Aluminum Industry Vision* outlines the industry's strategy for implementing its vision and roadmaps. This strategy centers around six important elements:

- **Roadmaps** that identify specific technology issues and barriers and set priorities for achieving industry goals will continue to be used to attract and influence technical, intellectual, and financial resources.
- **Collaborative partnerships** will leverage resources and capabilities among aluminum producers, customers, and supplier groups, equipment manufacturers, universities, national laboratories, government, and other stakeholders to accomplish R&D that will yield broad benefits to the entire industry and to the nation.
- **Corporate R&D** continues to play an important role in pursuing corporate R&D interests and in commercializing new technologies. Corporate R&D is carried out independently or in conjunction with other entities, including members of the supplier and customer industries, in a manner consistent with all applicable antitrust laws.
- **Communications and outreach** efforts to promote public and regulatory policies will yield broad benefits to the entire industry, including recognition of the unique value of aluminum with respect to sustainability, recycling, and life-cycle energy and resource efficiency.
- Rapid **technology deployment** of efficient technologies throughout the industry will ensure the benefits of collaborative partnerships (i.e., efficient technologies) will broadly benefit the industry and the nation.
- **Education and work force** efforts that address student outreach and education, combined with effective, multi-lingual training materials, will ensure the industry's continued access to a highly skilled work force.

IMPLEMENTATION STRATEGY



R&D PARTNERSHIPS: A KEY TO SUCCESS

As called for in the *Vision*, collaborative partnerships that engage all stakeholders in the North American aluminum industry will continue to be a key element for successful roadmap implementation. While many of the industry's goals build on the beneficial properties of aluminum, the attainment of many of the most challenging technological goals will require large, costly, multi-disciplinary, and carefully orchestrated R&D efforts. Since the U.S. aluminum industry's first roadmap was published in 1997, aluminum producers, equipment suppliers, research laboratories, government programs, and others have proceeded to undertake collaborative R&D projects and accelerate progress toward long-term goals.

The aluminum industry's long-standing partnership with the U.S. Department of Energy's Industrial Technologies Program will continue to be vital for success. By partnering on both near-term and higher-risk, longer-term R&D efforts, DOE and the aluminum industry will continue to work together to secure near-term efficiency and productivity gains while laying the foundation for sustained progress over the long term. Partnerships with other parts of the government have brought additional resources to bear on industry-defined R&D priorities. Examples include industry partnerships with several other programs within DOE, the National Science Foundation, the National Institute of Standards and Technology, the Navy's Manufacturing Technology Division, Army TARDEC, the Office of Naval Research, and the Air Force Office of Scientific Research.

Based on the success of these past efforts, collaborative R&D partnerships will continue to be one of the cornerstones of the industry's pursuit of efficient technologies that yield far-reaching benefits to the entire industry while also helping to create a globally sustainable quality of life.

A. ACRONYMS

ASTM	American Society for Testing and Materials
BIW	body-in-white
CFD	computational fluid dynamics
CHP	combined heat and power
CFC	chlorofluorocarbons
DC	direct chill
DG	distributed generation
DOE	U.S. Department of Energy
ECAE	extrusion computer-aided engineering
EMF	electromagnetic forming
FLC	forming limit curve
FLD	forming limit diagrams
FSW	friction-stir welding
HCl	hydrochloric acid
kWh/kg	kilowatt-hour per kilogram
LCA	life-cycle analysis
LDH	limiting dome height
LIBS	laser-induced breakdown spectroscopy
LIMCA™	liquid metal cleanliness analysis
MHD	magnetohydrodynamic
MMC	metal matrix composites
NDE	non-destructive evaluation
NMP	non-metallic products
NO _x	nitrous oxides
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
PAH	polycyclic aromatic hydrocarbons
PFCs	perfluorocarbons
PM	powder metallurgy
PVD	physical vapor deposition
SO _x	sulfur oxides
SPF	superplastic forming
TARDEC	tank automotive research, development, and engineering center
TiB ₂	titanium diboride
TMS	The Minerals, Metals & Materials Society
ULEV	ultra-low emissions vehicles
VOCs	volatile organic compounds

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³ Available at the Aluminum Association's Bookstore at www.aluminum.org.

⁴ Available at www.oit.doe.gov/aluminum.

C. ROADMAP CONTRIBUTORS

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Did you know?

- ◆ The U.S. aluminum industry provides over 145,000 jobs paying an average of \$36,100 per year, and shipped \$39.1 billion in products in 2001. — *The Aluminum Association, Inc.*
- ◆ Using recycled aluminum instead of raw materials reduces air pollution by 95%, water pollution by 97%, and energy use by about 95%. — *DHEC Office of Solid Waste Reduction & Recycling*
- ◆ Used aluminum cans are recycled and returned to store shelves as new cans in as few as 60 days. — *Cancentral.com*
- ◆ The U.S. aluminum industry supplies material enabling the production of 100 billion cans annually or about one can per person per day. — *Subodh Das, Secat, Inc.*
- ◆ Each pound of aluminum replacing two pounds of steel can save a net of 20 pounds of CO₂ equivalents over the typical lifetime of a vehicle. — *Auto Aluminum Alliance*
- ◆ A 6-8% fuel savings can be realized for every 10% weight reduction by substituting aluminum for heavier materials. — *Auto Aluminum Alliance*

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