Magnesium Casting Industry Technology Roadmap

September 2005

Sponsored by

American Foundry Society

Acknowledgements

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Executive Summary

The North American magnesium casting industry is at a pivotal juncture. Society is growing increasingly mobile, affluent, and environmentally aware. Tremendous technological advances continuously raise consumer expectations for better products and services at ever lower costs. To survive and prosper in these intensely competitive and challenging times, the magnesium casting industry is transforming itself.

The American Foundry Society (AFS) Magnesium Division 6 has sponsored a collaborative effort to examine the future of the magnesium casting industry, determine the highest priority needs to overcome important challenges, and chart a course for successful growth in the next 15 years. At the heart of this effort is a desire to build a consensus among industry and key suppliers, customers, product manufacturers, and researchers about the actions needed to defend existing markets and capitalize on new opportunities. The Magnesium Casting Industry Technology Roadmap outlines the strategic technology agenda for achieving the needs and expectations of the industry and its customers.

The technology strategy of the magnesium casting industry has three principal components:

1. Process Technology – Develop advanced process technologies to improve affordability and competitiveness of magnesium cast components in all markets that value lightweight performance metals.

2. Information Management & Sharing – Accelerate technological innovation by increasing information sharing and technology transfer to attain market growth.

3. Infrastructure Development – Stimulate industry-wide advancement by building shared resources in R&D, auxiliary support, and people.

These three components are closely intertwined and each is critical to ensuring success. Information management and sharing and infrastructure development must occur together to support developments in process technology. The industry is committed to pursuing a robust R&D agenda that recognizes the need for a balance of near-term and long-term research, new technology development and related training, education, and collaboration. The specific R&D needs for each of the above technology strategies are presented in separate sections of this roadmap. An overview of the Roadmap is presented on the following page.

The financial and intellectual resources needed to accomplish the objectives of this Roadmap are beyond the reach of individual companies and even the industry as a whole. Successful technology development usually benefits from a coordinated strategy that engages key suppliers, manufactures, and customers to accomplish mutual technology goals. Government, universities, and nonprofit organizations can also contribute to these goals, provided there are clear public benefits and the activities are

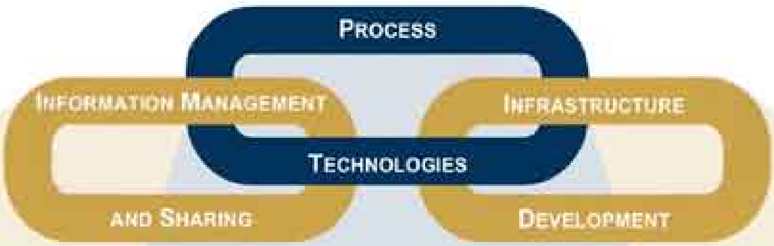
Roadmap Purpose

Promote growth in all areas of the magnesium foundry market, including automotive, aerospace, military, sporting goods, and others through strategic technology development

Grand Challenges

- Relatively small size of the industry limits R&D, auxiliary support, and workforce viability
- Developing affordable, safe, and environmentally friendly corrosion protection strategies
- Expanding the range of casting processes
- Matching desired properties of components with quality levels
- Developing strategies to increase the affordability of casting processes and supporting technologies

Technology Strategy



Priority Activities

	Information Management and Sharing	Process Technologies	Infrastructure Development
2005 – 2010 Near-Term	◦ Develop a database of research and development projects, including previous, ongoing, and future experiments	◦ Develop and implement melt protection technologies for molten metal handling ◦ Develop and validate fluid flow and solidification models to improve prediction of casting properties ◦ Develop methods to affordably reuse in-house scrap without sacrificing quality ◦ Improve existing and develop new magnesium casting processes	◦ Develop an intermediate-scale research, development and demonstration facility with full technical staff support ◦ Establish a clearinghouse for alloy and process information and commercialization guidance
2010 – Mid-Term	◦ Develop an atlas of microstructures, casting defects and mechanical properties of typical magnesium casting alloys and processes ◦ Develop design and process guidelines for non-die cast magnesium foundry products	◦ Develop affordable corrosion protection of components that maintains recyclability ◦ Improve understanding of the effect of heat treatment on casting quality ◦ Develop a versatile casting machine capable of producing permanent mold, lost foam, precision sand, and investment castings by means of pressurized filling (low pressure, counter gravity, vacuum assist, or electro-magnetic systems)	

appropriate to their missions. As this document demonstrates, plentiful benefits are to be found in expanding the use of magnesium castings.

The magnesium casting industry looks to the future with great optimism and determination. New applications in lightweight components, clean transportation and electromagnetic protection are opening up large new markets for magnesium castings that did not exist a decade ago. At the same time, intense competition from alternative metal castings and materials will force the magnesium casting industry to provide exceptional products and services while containing costs. Magnesium foundries must aggressively pursue innovations in technology. By doing so, the magnesium casting industry can seize new opportunities and bring increased value to the changing materials market.

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1. Magnesium Casting Industry Today

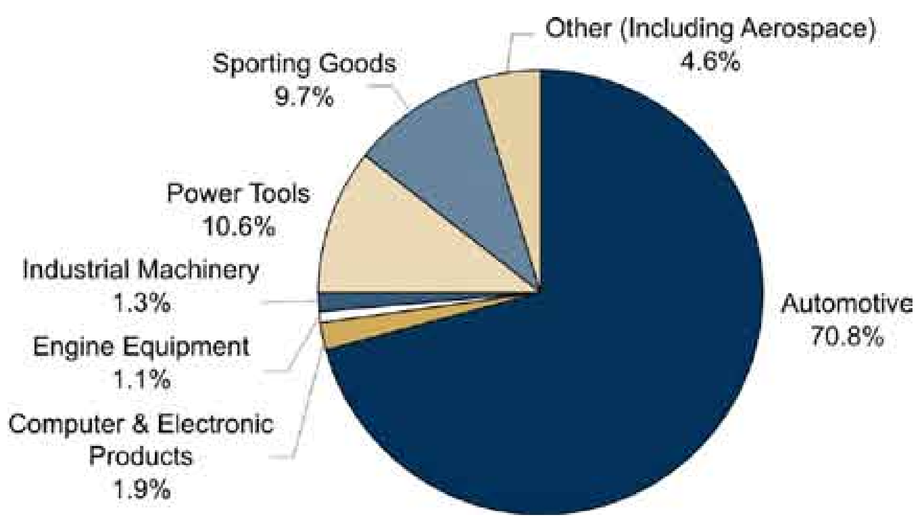
Magnesium Castings: High-Performance Components for Automotive, Aerospace, and other Lightweight Applications

Magnesium castings are light, abundant, and recyclable. The lightest of all commonly used metal castings, magnesium castings dampen noise and vibration, are highly impact and dent resistant, and are easily machined. Perhaps the most important advantage of magnesium castings is found in the environmental performance gains in automotive applications. Lightweight magnesium components have better strength-to-weight ratio than aluminum or steel castings, thereby reducing the total vehicle weight and leading to improved fuel economy, increased safety and handling, significantly lower emissions, and increased recyclability. In addition, there are many other applications for cast components ranging from aerospace, power tools, sporting goods, and computer and electronic products.

Remarkably abundant, magnesium constitutes about two percent of the Earth's crust and is the third most plentiful element dissolved in seawater. Magnesium metal is produced from seawater, well and lake brines, and magnesium-bearing minerals, which are globally widespread and virtually unlimited. In 2004, U.S. magnesium imports were about 18 percent higher than 2003, with Russia (60%) and Israel (26%) as the principal sources.[1] Exports for 2004 were 42 percent lower than in 2003.[1] Currently, U.S. magnesium metal production consists of a single company in Utah, using an electrolytic process that recovers magnesium from the Great Salt Lake.

Magnesium metal is primarily used as an alloying element to impart strength and rigidity in alloys used in aluminum applications, such as packaging, transportation, and others. The second largest use of magnesium is in the casting of components for product manufacturing. As shown in Figure 1-1, the largest and fastest growing market for magnesium castings is in the automotive market, due largely to increased interest for lightweight components that can improve fuel efficiency.[2]

Figure 1-1. U.S. Magnesium Casting Markets Based on Tons Shipped



Since the 1980's, the aerospace industry has used magnesium castings in stiffness-critical air frames and related drive train structures. The aerospace market has long recognized the benefits of increased fuel efficiency and reduced noise, vibration, and pollution resulting from the use of lightweight magnesium components. The sophisticated and complex needs of the aerospace market demand suitably high performance components, resulting in the highest cost-per-ton of all magnesium markets. Accordingly, while aerospace applications account for less than five percent of annual magnesium casting shipments, those applications generate over 10 percent of total magnesium casting sales.[2]

The second largest market in volume for magnesium castings is in power tools, particularly chainsaws. As a hand-held and potentially dangerous power tool, minimizing chainsaw weight is essential for improved operator safety and handling. While magnesium gear cases and cutting arms are primarily selected for light weight and strength properties, the ease in which these components are assembled is increasingly important. Chainsaw manufactures benefit by using tight tolerance magnesium components that do not require secondary machining.

Sporting goods, such as fishing poles and reel parts, has been a significant market for magnesium castings. A magnesium cast fishing reel frame is lightweight and comfortable, yet durable enough to handle difficult fishing maneuvers. Fishing reel manufacturers use magnesium castings for its excellent surface finish and its ability to achieve tight tolerances of bores and surfaces, enabling fast and simple component assembly. Magnesium castings that improve product appearance and performance and increase manufacturing speeds will continue to foster growth in the sporting goods market.

Magnesium castings are also used in the computer and electronic products market. One of the most critical physical property requirements of an electronic device enclosure is the ability to act as a shield against electromagnetic interference (EMI). EMI impairs the performance of an electronic system through unwanted electromagnetic disturbance which can come from any circuit or device that carries an electrical current. Cast magnesium alloy enclosures for EMI shielding provide significant advantages in weight savings, raw material costs, structural strength, and durability over both plastic and alternative metal housings.[5] As consumer demand for computers and electronic equipment continues to grow along with continued pressures to reduce size, weight, and cost and increase recyclability, magnesium is well positioned to meet these demands.

2. Key Trends and Drivers

Wide Application, Great Potential

In 2004, the U.S. magnesium casting industry culminated ten years of remarkable growth by shipping nearly 100,000 tons of castings (Figure 2-1). Prior to 1995 the previous market high was just over 40,000 tons, reached in 1945.[2] Central to this expansion has been the growing use of magnesium die cast components in automobiles, which more than doubled between 1990 and 2000. Components in which magnesium alloy replaced steel or aluminum includes brake and clutch pedal brackets, instrument panels, cylinder head covers, transfer case housings, intake manifolds, and seat components.

Auto manufacturers initially incorporated magnesium alloys as a means to reduce weight and meet Corporate Average Fuel Economy Standards (CAFÉ) mandated by the U.S. government. Once magnesium castings came into use, however, many other advantages became apparent. For example, parts that had to be made by welding together several stamped steel pieces could be produced as a one- or two-piece magnesium casting, significantly reducing the cost of the finished part. Outstanding fluidity in the molten state allows magnesium components to be cast in thin-walled near-net-shapes, subsequently reducing the amount of material used. Further, magnesium is easily machined, significantly increasing tool life and reducing production time, decreasing costs, and increasing productivity.

Figure 2-1. U.S. Magnesium Casting Shipments 1945-2004

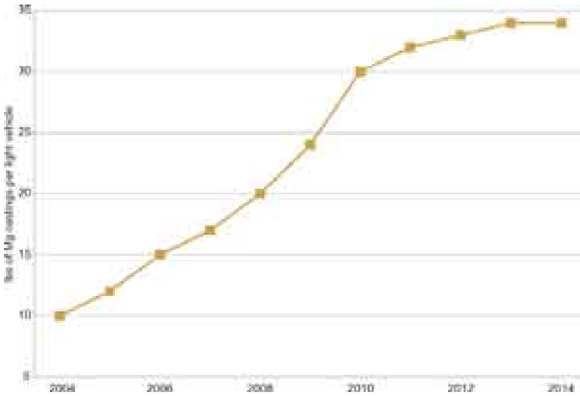
Source: AFS 2004

Automotive Opportunities

During the past decade alone, use of magnesium castings in light vehicles has grown an average of 16% per year and is predicted to continue growing at an annual rate of 11.5% for the next decade.[2]

Automakers are expected to continue to rely on magnesium to reduce the weight of vehicles; the consumption of magnesium castings per light vehicle is forecast to triple by 2014 (Figure 2-2).[2] New applications of magnesium castings are expected to include increased use in instrument panels and brackets, seat frames, steering column components, transmission cases, cylinder head covers, radiator support, and intake manifolds. Magnesium concepts in prototype development include roof panels, structural supports, rear deck lids, reinforcement panels, inner doorframes, engine heads, engine blocks, engine cradles, oil pans, and grill

Figure 2-2. Consumption of Magnesium Castings per Light Vehicle



Source: AFS 2004

reinforcements. Such technologies can reduce U.S. dependence on imported oil, further decrease vehicle emissions, and serve as a bridge from today's conventional powertrains and fuels to tomorrow's hydrogen-powered hybrid fuel cell vehicles.

Aiding these development efforts are the Automotive Lightweighting Materials (ALM) activities of the U.S. Department of Energy's (DOE's) FreedomCAR and Vehicle Technologies (FCVT) Program, which focuses on development and validation of cost-effective lightweighting materials technologies to significantly reduce automobile weight without compromising vehicle cost, performance, safety, or recyclability. The ALM Fiscal Year 2004 Progress Report indicated that magnesium projects will be emphasized over the next few years because they offer the greatest weight-reduction potential. Magnesium components are envisioned to replace an equivalent volume of ferrous material with a mass reduction of 70-75 percent and aluminum with a reduction of 25-35 percent,[3] and two projects are currently underway: the Structural Cast Magnesium Development (SCMD) project and the Magnesium Powertrain Cast Components (MPCC) project. The ability to significantly increase magnesium usage will help the auto industry meet future Federal CAFÉ targets and reduce exposure to CAFÉ penalties. Cast magnesium structures have the potential to reduce vehicle mass by 100 kg, which could reduce emissions and fuel consumption by approximately five percent.[3]

Innovative Process Technologies

The magnesium casting industry has relied heavily on the die casting process for market expansion. The industry has enjoyed enormous growth through the production of die cast components in automotive applications, and many opportunities still exist due to casting process limitations. For example, current investment casting techniques have inhibited magnesium's growth in markets that could consume nearly 300 million additional tons annually.[4] Novel technologies that improve structural integrity of magnesium components for aerospace applications offer the greatest potential in volume and margin for sand cast magnesium components.[2] New uses for magnesium increasingly require properties or cast geometries that are beyond the capabilities of the industry. Expanding the capabilities of the magnesium casting process will help the industry reap the full potential of these opportunities.

Expand industry capabilities to reap the full potential of new market opportunities.

While magnesium castings offer plentiful benefits, costs must be contained to stay competitive with alternative metal castings and materials. Reducing manufacturing costs by improving recycling capabilities, is one strategy that could make magnesium components less expensive. For example, scrap generated during die-casting can exceed the final component weight. In fact, metal losses during the casting process can be as high as 60%.[7] In North America, the high cost of recycling magnesium scrap can be attributed to expensive quality assurance procedures and lack of sufficient volume (about 70,000 tons in 2003)[6] to substantiate a secondary market for magnesium. However, the volume of magnesium recyclables is predicted to grow enough over the next decade to achieve economies of scale and significantly impact the affordability of magnesium castings.

Increasingly Environmentally Friendly

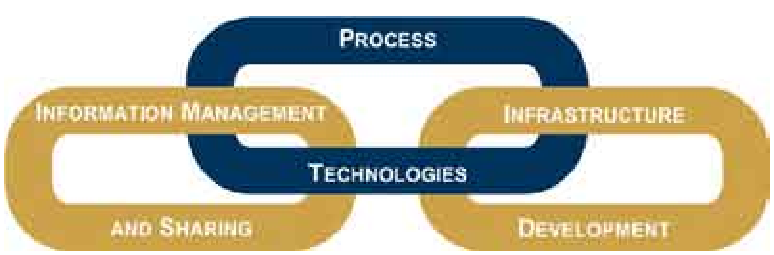
In 1999, the U.S. Environmental Protection Agency and the U.S. magnesium industry, with the support of the International Magnesium Association (IMA), launched a voluntary partnership to promote technically feasible and economically attractive actions aimed at minimizing emissions of sulfur hexafluoride (SF_6), a greenhouse gas with a strong global warming potential. Magnesium producers, casters, and recycling companies use a cover gas of dilute SF_6 in dry air and/or carbon dioxide (CO_2) to protect the molten metal from oxidation. Without protection, molten magnesium will oxidize in the presence of air and form magnesium oxide (MgO) inclusions that greatly reduce the quality and strength of the final product. In contrast, an effective cover gas, such as SF_6, modifies and stabilizes the MgO surface film to form a protective layer that prevents further oxidation.

In just a few short years, EPA and its magnesium industry partners have made tremendous progress, reducing emissions intensity by more than 40% between 1999 and 2002. Cost-effective pollution prevention is being realized through optimized equipment designs and operation and improving SF_6 gas management practices. These activities and technological innovations have directly contributed to the partnership's success and provided both economic and environmental benefits. In February 2003, EPA's partners and the IMA added their support to the President's Climate VISION initiative by establishing a goal to eliminate SF_6 emissions by the end of 2010. To meet this technically aggressive commitment, the industry will need to further evaluate and implement alternative cover gases.

3. Technology Strategy

Never before has the magnesium casting industry faced such a wealth of opportunities and challenges, and now is entering a period of transformation. Economic globalization, environmental issues and new technologies have forced magnesium foundries to reevaluate their existing business strategies and identify new business models for future success. To ensure future viability, the magnesium casting industry is forging strategic alliances, providing innovative products and services, offering unique technology solutions, delivering superior value to customers, setting new standards of safety and environmental protection, and maintaining competition and profitability.

New technologies and practices will bring innovative products and services to customers and improve the productivity and profitability of the industry. However, technology alone is insufficient to fully ensure industry-wide growth. A well-grounded research and technology agenda is the cornerstone for future success. The industry is committed to pursuing a robust research and development agenda and recognizes the need for a mix of near- and long-term research, new technology development and related training, education, and collaboration. The technology strategy of the magnesium casting industry has three principal components:



- Process Technology – Improved productivity, efficiency, and operational environment while delivering consistent, high-quality castings at competitive costs has long been a pursuit of the industry. Progress in advanced process technologies to increase the range of cast geometries and properties and related enabling technologies that support them is essential in increasingly competitive lightweight components markets.

- Information Management & Sharing - Accelerating technological innovation requires that information be shared and technology transferred. Effective sharing allows industry to more readily adopt developing technologies in the near term and maintain a sustainable competitive advantage of the industry in the long term.

- Infrastructure Development - The small size of the industry limits its ability to allocate major capital for unproven technologies, grow a network of auxiliary support, and attract a viable workforce. As a result, only incremental improvements to alloys and processes have been made. Infrastructure development must include major research and development investments in manufacturing process and casting techniques and influence auxiliary groups and potential employees to become more involved in magnesium in order to ensure the viability of the industry for years to come.

While process technology developments lead the R&D agenda, coordinated improvements in information management & sharing, and infrastructure development are fundamental to supporting progress in the process technology area and crucial to achieving the technology goals of the industry. The specific R&D needs for each area are detailed in the following pages.

3a. Process Technology

The magnesium casting industry must improve productivity, efficiency and operational environment while delivering consistent, high-quality castings at competitive costs. As such, advanced process technologies are essential to the continued success of the industry in increasingly competitive markets. The process technology area is extremely diverse and includes die casting, sand casting, semisolid processes, permanent mold casting, low pressure casting, lost foam casting, squeeze casting, and investment casting.

In order to fully realize emerging market opportunities, alternative metal casting methods must be developed. The demand for magnesium die castings has risen significantly in automotive applications, and current die-cast methods alone cannot meet future demands; applications increasingly require properties or cast geometries that cannot be produced using current magnesium casting techniques. For example, the aluminum industry has exploited the investment casting process to capture almost $390 million in annual sales,[4] while application in the magnesium industry has been limited due to current capabilities. The development of new magnesium casting process technologies and related enabling technologies are essential to encouraging new magnesium component applications in all markets.

Critical Challenges

Critical process technology challenges, as highlighted in the following chart, can be divided among three key issues:

- Process optimization – Magnesium casting companies must be efficient and agile to respond to customer expectations and market changes. The magnesium casting industry must continue its efforts to cost-effectively develop and produce castings faster while improving casting quality and consistency. While reducing lead times and increasing productivity are essential to the financial success of the industry, continued progress in effectively increasing the range of magnesium cast geometries and properties is paramount to determining how competitive the industry will be in the future.

- Product quality – Lightweight components of the future will be revolutionized by new materials as technological breakthroughs improve component manufacturability and environmental friendliness. New product applications are driving process developments that enable lightweight materials to consistently meet desired component performance characteristics. However, competitive materials, such as steel, cast iron, aluminum, and plastics have made great strides in this regard while magnesium's progress has been slow due to its limited capability to predict casting properties.

- Environmental and safety performance – Magnesium castings produced in North America compete in the international market with castings produced in countries with less demanding environmental standards and where the cost of environmental control is significantly lower. To stay competitive and cope with the rising cost of environmental compliance, the industry must examine ways to reduce or reuse waste during processing as well as methods to increase the reuse of old consumer components. Technologies that reduce or eliminate waste and improve performance will greatly enhance the future success and world-wide competitiveness of the industry.

Critical challenges to improving process technology

Process Optimization

Corrosion
- **Limited number of affordable, safe, and environmentally friendly corrosion protection strategies**
- Limited ways to prevent long-term galvanic corrosion (e.g., lack of affordable washers for alloy separation)

Casting
- **Limited range of casting processes for magnesium**
- **Affordable casting process and supporting technology strategies are limited** (e.g., lack of fully contained melting and pouring processes and limited rapid solidification capabilities)
- Few strategies to introduce and develop magnesium castings in the investment casting market
- Lack of understanding of current casting process stability for large structure components
- Inability to produce sand castings at high volumes

Post casting
- Inadequate development and application of thermal processing
- Limited capabilities to weld at required tolerances during salvage repair
- High cost of fire protection and waste treatment systems during machining processes
- High overall costs of the post-casting process

Molten metal handling
- Lack of affordable, low environmental impact melt protection technologies to prevent oxidation
- Limited understanding of molten magnesium cleanliness
- Limited knowledge of molten metal oxidation and inclusion characterization
- Lack of molten magnesium alloy reactivity data

Modeling
- Lack of affordable rapid prototyping capabilities
- Lack of physical property data for Mg alloys limits solidification modeling and porosity prediction
- Limited computer modeling (software, tool suites) for prediction of properties
- Limited understanding of interfacing modeling, designing and processing of a component

Joining
- Limited joint design capabilities
- Limited techniques for joining dissimilar metals
- Limitations in spot welding procedures decrease reliability of welded joints
- High bonding and sealing costs

Process Quality

Fundamental properties
- **Limited capabilities to predict casting defects and properties**

Alloys
- Lack of grain refining techniques limits property improvements
- Lack of alloy standardization to ease alloy selection for applications such as creep resistance or high temperature performance
- Lack of classical modeling approach and available data limit alloy development
- Limited understanding of fundamental alloy properties
- Lack of non-destructive techniques for testing porosity and micro-shrinkage in magnesium alloys

Environmental and Safety Performance

Limited capability to close the recycling loop within the casting cell

Limited capabilities in plant-wide magnesium fire inhibition systems

Bold indicates highest industry challenge

Research and Development Needs

To meet the process technology demands of the next fifteen years, the magnesium casting industry must undertake near-term (0-5 years), mid-term (5-8 years), and long-term (>8 years) research and development activities. These activities can be divided among seven areas of research:

- Alloy Optimization – Understanding magnesium quality and consistency issues is paramount to increasing the use of magnesium castings. Alloy property and defect data availability and access must be improved to enable the design and development of new magnesium components. Notably, improved understanding of heat treatment methods and their effects on alloy properties will allow magnesium casters to develop alloys that exploit magnesium's advantages as a lightweight structural material.

- Corrosion Mitigation – Affordable and reliable corrosion prevention strategies must be developed to maintain magnesium's favorable position in aerospace applications and to increase the use of magnesium in all markets. Components designed for exterior and harsh environment applications must display corrosion resistance, particularly in the aerospace industry where concerns about structural degradation in airplane and helicopter components due to in-service corrosion are highest.

- Modeling – Developing modeling and prototyping capabilities will allow the industry to rapidly design new components, control final product properties and reduce scrap and rework. A growing trend toward product customization, low-volume production, and quick turnaround time has boosted the importance of rapid prototyping. Although several rapid prototyping technologies already exist, these systems need to become more affordable to encourage wide spread use in the industry.

- New Casting Technologies – Current magnesium casting capabilities limit the range of geometries and properties that can be used in new applications. The development of new magnesium casting process technologies and the related enabling technologies are essential to encouraging the use of magnesium in new component applications.

- Molten Metal Handling – Due to the high global warming potential of SF_6, the industry recognizes the need to develop and implement alternative melt protection technologies that prevent metal losses and oxide contamination prior to casting. Also, improved methods of transferring liquid metal must be developed to reduce dross and improve operator handling.

- Data Generation – Despite the increases in available data on the mechanical, physical, performance, and design properties of magnesium castings, wide variation in data and numerous information gaps still exist. For example, low confidence in test bar databases requires thicker than necessary component sections to ensure in-service safety. An improved understanding of test specimens is needed to improve the accuracy of property databases, allow components to be designed with thinner walls without compromising component function and durability, and reduce costs.

- Recycling – Recycling of high quality magnesium scrap from the casting process demands only five percent of the energy required to manufacture the primary metal. As such, recycling is a key element in increasing the affordability of magnesium cast components. Because magnesium oxidizes so readily, new recycling technologies that can minimize oxidation of in-house scrap are needed to reduce metal losses and contamination.

Specific research and development needs for each area are presented on the following page.

Process Technology R&D Needs

	Near-Term (0-5 years) 2005	Mid-Term (5-8 years) 2010	Long Term (>8 years) 2020
Alloy Optimization		▸ **Improve understanding of the effect of heat treatment on casting quality** ▸ Develop new microstructure control procedures and materials ▸ Characterize defects specific to Mg alloys for more accurate designs ▸ Develop new foam structure for lost foam casting ▸ Characterize microstructures and relate to properties	▸ Update thermodynamic database on multi-component systems for alloys
Corrosion Mitigation		▸ **Develop affordable corrosion protection of components that maintains recyclability** ▸ Develop better anodic treatment and coatings	▸ Increase capabilities to manipulate magnesium oxide film to increase corrosion protection
Modeling	▸ **Develop and validate fluid flow and solidification models to improve prediction of casting properties** ▸ Develop simulation of complex casting to improve repeatability and lead time	▸ Develop rapid prototyping methods to shorten time to market ▸ Develop modeling capability for prediction of hot tearing magnesium alloys	
New Casting Technologies	▸ **Improve existing and develop new magnesium casting processes** ▸ Develop new mould technologies to enable investment casting ▸ Develop intricate core technology to enable more complex castings	▸ **Develop a versatile casting machine capable of producing permanent mold, lost foam, precision sand, and investment castings by means of pressurized filling (low pressure, counter gravity, vacuum assist, or electro-magnetic systems)**	▸ Develop advanced manufacturing equipment that is fully contained for melting and pouring and provides rapid solidification of Mg alloys
Molten Metal Handling	▸ **Develop and implement melt protection technologies for molten metal handling** ▸ Improve in-plant liquid metal transfer (Central Breakdown)		
Data Generation	▸ Collect and generate missing thermo physical data for improved computer modeling and design of magnesium components	▸ Increase understanding of metal flow-fronts and oxide films in magnesium gravity and low pressure casting ▸ Develop basic physical metal/mould properties for effective modeling ▸ Increase understanding of interactions between foam density, foam coating alloy superheat and applied pressure or vacuum ▸ Improve understanding of test specimens by using standard procedures for reproducible data ▸ Develop process capability indices for various casting processes	
Recycling	▸ **Develop methods to affordably reuse in-house scrap without sacrificing quality**	▸ Design alloys to improve recyclability of scrap, reduce dross, and improve dross handling ▸ Develop methods to separate Mg from Al for recycling (shredded material)	

Bold indicates highest industry challenge

3b. Information Management & Sharing

Advancing scientific research and development into technological innovation require that information be shared, knowledge exchanged, and technology transferred. Despite a wealth of new information management tools created by progressive computer technologies, the magnesium casting industry has yet to fully engage their potential for disseminating information about magnesium alloy quality and performance, research and development programs, and industry news. Computer-based information tools could lower design costs by linking designers and foundries together, thereby increasing the accuracy of new component construction. Improved communication from design to production would allow product designers to better understand the process capabilities of a foundry, and foundries to develop processes to meet the performance requirements of a design.

A culture change to facilitate the sharing of information among equipment manufacturers, foundries, national laboratories, consultants, universities, and government will help the industry develop magnesium casting technologies for market growth in the near term and ensure viability of the industry for years to come.

Critical Challenges

Critical challenges to information management and sharing, as highlighted in the following chart, can be divided among three key issues:

- Knowledge Exchange – Limitations in the accuracy and availability of data on material and design properties have hindered demand for cast magnesium components. Coordination within the magnesium casting industry, with other industries, and internationally must occur to facilitate knowledge and technology transfer as well as accelerate technology development and deployment.

- Technical Resources – In spite of the increases in available data on the mechanical, physical, performance, and design properties of magnesium castings, there remains a wide variation in the data and few sources of information exist. The development of a solid base of technical resources will help improve existing products and develop new applications to better compete with alternative materials, metal-forming techniques and foreign castings. Further enhancement and increased availability of the industry knowledge base is needed to increase user confidence and help magnesium castings penetrate new markets.

- Public Perception – The magnesium casting industry must position itself as a safe, user friendly, reliable and affordable mate-

Critical Challenges to Information Management & Sharing

Knowledge Exchange	
• Limited end-user education; particularly in machining and hazardous waste disposal and storage • Lack of design engineering knowledge on magnesium use limits component design development	• Magnesium safety education is needed to increase the use of magnesium in component design

Technical Resources	

• Limited design guidelines need refinement, updating and enhancement
• Lack of technical knowledge due to minimal publishing of technical information has put the industry at a disadvantage compared to other casting industries (e.g., the aluminum casting industry)
  • Lack of a robust magnesium alloy database due to gaps in alloy property and performance information or proprietary issues
  • "The book" for magnesium does not exist
	• Limited inspection guidelines need refinement, updating and enhancement
	• Limited publishing of lessons learned allows mistakes to be repeated

Public Perception	
• Misconceptions by the general public and manufacturing companies in the safe handling and processing of magnesium • Lack of consumer and producer awareness of the benefits of using magnesium cast components	• Fear of using magnesium • Low industry profile; limited promotion of industry developments

Bold indicates highest industry challenge

rial for a variety of applications. Consumer choices for competing lightweight materials continue to expand as government regulations tighten and cost pressures increase. Consumer and producer education about the uses and advantages of magnesium castings for a variety of applications will ensure existing and potential customers consider magnesium when evaluating component materials.

Research and Development Needs

To meet the information management and sharing demands of the next fifteen years, the magnesium casting industry must undertake near-term (0-5 years), mid-term (6-8 years), and long-term (>8 years) research and development activities. These activities can be divided among four areas of research:

- Technical Resources – Mechanisms for information exchange will foster reproducibility, allow quantitative comparisons of experimental and production methods, promote communication between process and design communities, and facilitate the development of a comprehensive database of magnesium casting alloys and processes. Given the breadth of the research and development challenges, numerous technical resources are needed so researchers, casters and designers can collaborate, improve the lessons learned by others, and improve the cost effectiveness of research. Results from all pre-competitive, government-funded research will be the primary information source, which must be easily accessible to the research and development community, and require data sharing from basic research through full-scale manufacturing.

- Benchmarking – Benchmarking industry performance is critical to successful development of magnesium casting technology. Collection and analysis of data about magnesium components, the aluminum casting industry and other competitors, and magnesium casting processes will provide industry benchmarks and set performance metrics.

- Knowledge Exchange – Mechanisms that encourage knowledge sharing and transfer are crucial to fostering innovation and commercialization. The magnesium casting research network is complex and expanding. To facilitate technology transfer, communication among researchers, government and industry must increase dramatically. Companies, both large and small, must gain a better understanding of funding resources, such as government programs, and how to work together toward building the research foundation for the magnesium casting industry.

- Outreach – The general public and student population lack an understanding of emerging magnesium casting technologies and their potential benefits to society and the economy. Steps must be taken to ensure that consumers and future workers are informed about magnesium casting technology and magnesium cast components. For example, a road show of presentations targeted at end users and college students is needed to increase interest in magnesium and drive the future advancement of R&D programs. Effective communication of magnesium information will foster confidence in the use of magnesium cast components.

Specific research and development needs for each area are presented on the following page.

Information Management R&D Needs

	Near-Term (0-5 years) 2005	Mid-Term (5-8 years) 2010	Long Term (>8 years) 2020
Technical Resources	▸ **Develop a database of research and development projects, including previous, ongoing, and future experiments, studies and other evaluations**	▸ **Develop an atlas of microstructures, casting defects and mechanical properties for typical magnesium casting alloys and processes** ▸ **Develop design and process guidelines for non-die cast magnesium foundry products** ▸ Develop summaries of prior research to prevent repetitive studies ▸ Proprietary concerns typically prevent sharing research data ▸ Discretion is necessary to protect technological resoucres from competitive international companies ▸ Encourage newcomers to Mg to share knowledge ▸ Age data (share "old" data that may no longer need protection) ▸ Generate on-line database for properties and defects of magnesium alloys ▸ Develop magnesium casting handbook of design and production guidelines ▸ Develop a new model for sharing best practices ▸ Develop methods for sharing new technologies in processing and refining	▸ Develop an expert information system for designers and producers
Benchmarking	▸ Develop benchmarks of casting processes for a particular component ▸ Investigate aluminum casting successes ▸ Develop baseline profile of existing processes and environmental issues ▸ Identify producer cost competitor process opportunities ▸ Identify high cost portions of industrial-scale casting processes		
Knowledge Exchange	▸ Develop alliance between researchers, educators, and foundry persons and technical societies ▸ Increase International technical exchange and collaboration ▸ Collaborate with computer, mathematics, and materials specialists to review existing computational models and to develop useful and suitable modeling capabilities for foundries	▸ Increase technical knowledge by having technical trade organizations seek papers and other types of information to fill specific information gaps, target AFS, The Minerals Metals, & Materials Society (TMS), International Magnesium Association (IMA), North American Die Casting Association (NADCA,), and others	
Outreach	▸ Develop promotional materials ▸ Promote successes with magnesium to establish demand-driven processes and increase base		

Bold indicates highest industry challenge

3c. Infrastructure Development

The relatively small size of the magnesium casting industry limits its ability to allocate major capital for unproven technologies. Small foundries seldom have the resources to implement new technologies that support the casting process, such as improvements in molding or core making, which has hampered the rate of change in the industry. As a result, incremental improvements to alloys and processes have been seen rather than revolutionary new technologies. Additionally, a smaller pool of employees at all levels makes attracting skilled employees very important; engineers, chemists, metallurgists, technicians, and craftsmen are needed throughout the industry to meet the challenges presented by advanced equipment, new processes, and the production of complex cast parts. Affordability will continue to put major pressure on magnesium casters, especially when competing with regions of the world where labor is inexpensive.

Since 1990, the supply of magnesium metal imports to U.S. foundries has been increasing, while U.S. ingot production capacity has decreased. At the end of 1998, The Dow Chemical Co. closed its 60,000 t/yr plant, and in 2001, Northwest Alloys closed its 43,000 t/yr plant, leaving the U.S. with one supplier with a 2003 capacity of 45,000 t/yr.[1] Meanwhile, the demand for magnesium has increased significantly for the production of cast components. These supply/demand issues have created uncertainties about the reliability of magnesium metal supply.

Auxiliary support organizations provide engineering, information technology, and supply chain products and services throughout the magnesium cast component life cycle, from raw materials extraction to final reuse or disposal.

Critical Challenges

Critical infrastructure development challenges, as highlighted in the following chart, can be divided among two key issues:

- Industry Size – The relatively small size of the industry creates numerous challenges with R&D, auxiliary support, and workforce viability. For example, lack of strategic direction and limited resources for research and development has constrained technology development and inhibited growth. The perception that other larger industries provide higher returns on investment have constrained developments in auxiliary support in supply, production, marketing, engineering, distribution, and waste issues. Finally, the unsophisticated image of the industry has hurt its ability to attract young people.

- Environmental and Safety Issues – While individual companies continue to strive to improve process efficiencies

Critical Challenges to Infrastructure Development

Industry Size

- **Relatively small size of industry limits R&D, auxiliary support, and workforce viability**
- Lack of strategies to implement new technology transfer, including adoption of new magnesium process technologies; unknowns include identifying aluminum foundries that will convert existing casting processes from aluminum to magnesium and identifying magnesium foundries that will adopt new casting technologies
- Limited capabilities to demonstrate process feasibility (technically and ecologically) on an industry scale
- Limited implementation of high production, low cost technologies (e.g. permanent mold casting) due to lack of awareness and strategic planning
- Limited human resources, particularly small size of workforce
- Few resources limit effectiveness of magnesium industry lobbying efforts to government policy makers
- Reliability of magnesium primary metal supply is uncertain due to fluctuations in supply and demand
- Long lead times from supplier base
- Few foundries are located in the United States
- Education is not part of core curricula in academia due to lack of student interest and limited industry exposure and visibility

Environmental and Safety Issues

- High environmental compliance costs across all magnesium casting disciplines
- Incomplete understanding of full life-cycle environmental footprint of magnesium casting products
- Limited magnesium safety education

Bold indicates highest industry challenge

and reduce waste, the industry as a whole must unify itself to improve its image as an environmentally friendly and safety conscience community. Even with safe handling procedures in place, the industry realizes it must continue to improve safety. Safety concerns, both real and perceived, present a real challenge for magnesium foundries as they expand their markets

Research and Development Needs

To meet the infrastructure development demands of the next fifteen years, the magnesium casting industry must undertake near-term (0-5 years), mid-term (6-8 years), and long-term (>8 years) research and development activities. These activities can be divided among three areas of research:

- Research Development and Demonstration Capabilities – The lack of research facilities focused on magnesium casting applications limits the industry's ability to demonstrate feasibility and affordability of new technologies. In order to ensure industry growth, new research centers are needed to evaluate new, potentially low-cost magnesium alloys; design several pre-competitive components for the best alloy properties; and cast and test magnesium components in assembled products. To complement these, a central location for magnesium alloy and process information is needed, along with education resources that promote the commercialization of improved magnesium alloys and casting processes.

- Strategic R&D Planning – To assure U.S. magnesium industry competitiveness and future growth, strategic planning for R&D investment is needed in the following areas:

    - Application-Driven Support - Magnesium cast components must be incorporated into more diverse materials, products, and systems while retaining their novel attributes. A key challenge is to develop application-driven support, especially in markets where aluminum cast components have achieved great success. Several programs are already in progress for the promotion of magnesium cast components. Increasing access to information about these programs is essential to expediting progress in all market areas.

    - Recyclability – Life-cycle assessments are needed to promote the environmental benefits of magnesium. Reliable and affordable separation and identification techniques are needed to easily sort materials into the appropriate recycling process, thereby improving the overall efficiency of recycling magnesium.

    - Safety – Magnesium casting companies are tied together by their collective safety performance and all benefit from improvements in industry safety. The expertise and resources of all segments of the magnesium community – foundries, associations, universities, national labs, regulators, trainers, federal, state, and local governments, and equipment manufacturers – are required to accomplish safety initiatives. Safety programs must be enhanced to increase consumer and producer confidence in magnesium cast components.

- Collaborative Partnerships - Success in the race to implement light weight materials requires a large highly integrated, multidisciplinary, national effort focused on highly interwoven activities oriented toward commercialization. Bringing all of these resources together necessitates unprecedented levels of integration of multidisciplinary expertise. The R&D effort must coordinate developments in magnesium cast properties, new casting technologies, and new modeling and prototyping tools while improving understanding of product performance, safety, environmental impact, and costs.

Infrastructure R&D Needs

	Near-Term (0-5 years) 2005	Mid-Term (5-8 years) 2010	Long Term (>8 years) 2020
Research Development and Demonstration Capabilities	▸ **Develop an intermediate-scale research, development and demonstration facility with technical staff support** ▸ **Establish a clearinghouse for alloy and process information and commercialization guidance**	▸ Continue development of magnesium casting facility to become a center of excellence in melting, heat treatment, and corrosion technologies	
Strategic RD&D Planning	▸ Increase understanding of technology developments by reviewing outcomes of Magnesium Powertrain Casting Components (MPCC) and Structural Cast Magnesium Development (SCMD) projects for gaps and next steps ▸ Develop and support application-driven R&D such as the United States Automotive Materials Partnership (USAMP) projects ▸ Increase awareness of magnesium casting activities worldwide by keeping active eyes on international publications ▸ Develop safety programs to improve employee protection, enhance the magnesium casting workforce, and increase consumer and producer confidence ▸ Develop alloy identification system to improve recyclability	▸ Develop studies of environmental effects of using magnesium casting components; including life cycle assessments and recycling of process waste and post consumer scrap	▸ Identify an industry pioneer who is unafraid to take the risk of investing and implementing new technologies and willing to share pre-competitive information for the benefit of the entire industry
Collaborative Partnerships	▸ Increase AFS involvement for education and marketing ▸ Generate greater industry support and funding ▸ Increase awareness of U.S. and Canadian national labs, universities, and other research centers as resources for foundry research and collaboration	▸ Improve western partnerships to maintain technical advantage ▸ Develop technical/academic vendor/supplier foundry participation synergy ▸ Develop academic and university partnerships by including them in projects of specific interest	

Bold indicates highest industry challenge

4. Top Priority Activities & Action Plans

The magnesium casting industry is pursuing a balanced portfolio of research, development, and demonstration (RD&D), education, information management, and other activities to support its efforts to promote industry growth. Process technology activities that are central to the R&D agenda must have simultaneous efforts in information management and sharing and infrastructure development to support the success of the industry technology strategy. The portfolio will be comprehensive and robust to take advantage of rapid changes in markets, technologies, and environmental regulations, though limited resources require that the portfolio focus on the most critical technology priorities to propel growth over the next 15 years. This chapter identifies the most important research and development priorities and indicates how they can be implemented. The following information is examined for each priority listed in the following pages:

- Description of the need
- Key challenges to be addressed
- Time frame
- Potential benefits
- Implementation steps

By emphasizing the top-priority activities described in this chapter, the industry will focus on those areas of the magnesium casting market where the opportunities to increase consumption and production are the greatest.

The top priority activities for the magnesium casting industry are listed on the next page; those marked with ❖ are described in detail in the following pages.

Top-Priority Activities for the Magnesium Casting Industry

- Develop an intermediate-scale research, development and demonstration facility with technical staff support
- Develop a database of research and development projects, including previous, ongoing, and future experiments, studies and other evaluations
- Develop an atlas of microstructures, casting defects and mechanical properties for typical magnesium casting alloys and processes
- Develop and implement melt protection technologies for molten metal handling
- Develop and validate fluid flow and solidification models to improve prediction of casting properties
- Develop a versatile casting machine capable of producing permanent mold, lost foam, precision sand, and investment castings by means of pressurized filling (low pressure, counter gravity, vacuum assist, or electro-magnetic systems)
- Establish a clearinghouse for alloy and process information and commercialization guidance
- Develop affordable corrosion protection of components that maintains recyclability
- Improve understanding of the effect of heat treatment on casting quality
- Develop design and process guidelines for non-die cast magnesium foundry products
- Develop methods to affordably reuse in-house scrap without sacrificing quality
- Improve existing and develop new magnesium casting processes

Top Priority — Infrastructure Development

Develop an intermediate-scale research, development and demonstration facility with technical staff support

The magnesium casting industry can benefit from an intermediate-scale research, development and demonstration facility to evaluate new, potentially low-cost magnesium alloys; design several pre-competitive components for the best alloy properties; cast and test the components in assembled products; and promote the use of improved magnesium alloys and casting processes.

Expanding demonstrations of magnesium casting applications will enable the industry to determine technical issues, develop operating experience, and expand awareness. The promotion of design concepts that take advantage of the unique properties of magnesium alloys as well as the development of advanced alloys suited to challenging conditions will further enhance magnesium as an exceptional component material.

An important long-term goal of the facility is to evolve into a magnesium center of excellence by supporting industry capabilities in melting, heat treatment, and corrosion protection technologies.

Challenges Addressed

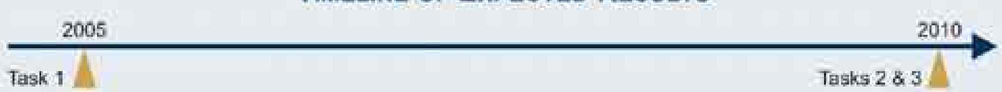
- Limited education in casting process development
- Need to expand infrastructure

Benefits

- Development of full scale industrial research
- Development of industry infrastructure

Action Plan

Timeline of Expected Results



Tasks

1. Develop business plan for RD&D facility
   a. Perform market study
   b. Identify funding resources
   c. Determine personnel and equipment needs
   d. Define long-term goals

2. Define facility capabilities
   a. Rapid prototyping
   b. Preproduction
   c. R&D

3. Implement facility

Top Priority — Information Management and Sharing

Develop a database of research and development projects, including previous, ongoing and future experiments, studies and other evaluations

Sharing information on previous, ongoing and future R&D experiments, studies and other evaluations is critical to future industry success and will help optimize and accelerate R&D efforts. Additionally, increased awareness of R&D efforts will facilitate collaborative efforts and increase funding opportunities by promoting technology, process, and product developments of the industry.

The R&D database will document research activities related to magnesium casting; provide ready access to information about the latest developments in magnesium research; aid the planning of future research activities; avoid costly duplication of research; and establish valuable contacts within the research community, government organizations, industry and the general public.

Challenges Addressed

- Lack of awareness on developments in process control
- Limited range of casting processes for magnesium
- Limited design guidelines

Benefits

- Save time, effort and resources by not reinventing the wheel
- Define process capability limits
- Increased accountability of funded experiments

Action Plan

Timeline of Expected Results

2005	2006	2007	2008	2010
	Task 1	Tasks 2 & 3	Task 4	Tasks 5 & 6

Tasks

1. Identify funding opportunities for this effort
2. Determine contributors
3. Establish a taxonomy of terms and protocols
4. Organize previously collected data
5. Collect additional data through literature search and interviews
6. Identify gaps and inconsistencies

Top Priority — Information Management and Sharing

Develop an atlas of microstructures, casting, defects, and mechanical properties of typical magnesium casting alloys and processes

Microstructures, casting, defects, and mechanical property data relevant to magnesium alloy selection in various applications are needed to enable product designers to determine optimal designs for each alloy to a performance specification. Particularly important is the prediction of alloy defects and properties. This atlas will enable producers to identify potential problems of typical magnesium casting alloys and processes and make continual improvements.

The increased ability to access thermo and physical property data will enable industry to develop models, designs, and processes with accurate, consistent data that will significantly shorten development time.

Challenges Addressed

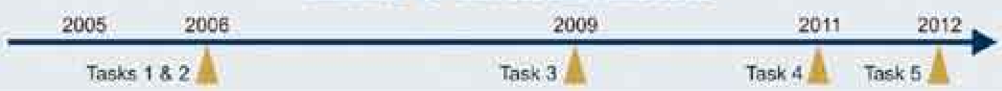
- Limited time
- Information spread among several sources
- Lack of agreement on gaps and unknowns
- Limited cooperation and commitment from government, research and standards organizations, and industry
- Lack of funding
- Complex bureaucracy of American Society for Testing and Materials (ASTM)

Benefits

- Develop one source of all data in CD, book, etc. to improve access and ease of use
- A centralized resource for reference and product design
- Identify potential problem areas
- Identify new developments in alloy or process research
- Develop an industry standard to eliminate conflicting information

Action Plan

Timeline of Expected Results



Tasks

1. Perform a literature review of existing data on microstructures casting defects and mechanical properties
2. Identify the gaps and how they should be filled
3. Gather missing data (producing alloys with different composition, microstructure and defects)
4. Complete atlas
5. Achieve ASTM accreditation of casting defects

Top Priority — Process Technologies

Develop and implement melt protection technologies for molten metal handling

Magnesium's reactivity and significant vapor pressure in the molten state require the use of film-forming inhibitors that limit metal losses due to oxidation and prevents oxide contamination of alloys prior to casting. For over 20 years the inhibitor of choice has been SF_6, blended at low levels with air or carbon dioxide. The use of SF_6 improved melt protection and eliminated toxicity and irritant issues associated with the formation of SO_2. However, due to high metal loss rates, quality issues, and the high global warming potential of SF_6, the industry recognizes the need to identify new alternatives with both low environmental impact and low toxicity. While successful commercial implementation of one of these alternatives will allow the magnesium industry to reduce its impact on global warming, they must also increase yields without sacrificing quality.

The timeline below indicates that results from the implementation of this priority will take approximately three years.

Challenges Addressed

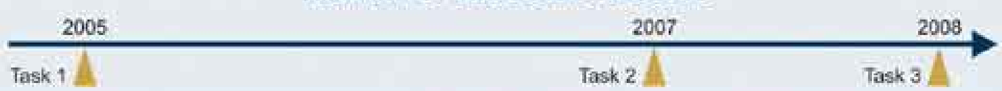
- Limited metrics knowledge of melt loss at given throughput; shot casting parameters, furnace termperature variation, dross production, and cost
- Lack of willingness to share data
- Lack of a comparative procedure
- Limited prediction capability

Benefits

- Clarity of performance parameters
- Increase knowledge of current options
- Improve consistency of data for comparison of current technologies
- Dramatically improve melt protection
- Reduced production costs; shorter lead time; and yields based on improved computer based modeling

Action Plan

Timeline of Expected Results



Tasks

1. Survey existing technologies
   a. Contact parties who have proposed solutions
   b. Document state of maturity of technology (i.e., extent to which demonstrated)
   c. Include performance studies of comparative technologies
2. Perform (if needed) validation studies to complete comparative database
3. Develop new procedures and materials for effective, environmentally sound protection that is cost competitive (if needed)

Top Priority — Information Management and Sharing

Develop and validate fluid flow and solidification models to improve prediction of casting properties

Increased understanding of the microstructures developed during the solidification process is important for precise control of final product properties. Refinements in process control should increase the quality of components without increasing product costs and development times. Although some fluid flow, solidification and heat treatment information is available, this knowledge is generally kept as a trade secret by individuals or companies who possess generations of experience. Solidification expertise has not been communicated throughout the industry, which in turn has hampered property and defect prediction capabilities of magnesium castings.

The development and validation of fluid flow solidification models will allow magnesium casters to consistently, accurately, and rapidly design new components to achieve specific performance characteristics. Magnesium casters will be able to lower production costs by reducing scrap and rework and obtaining higher yields.

Challenges Addressed

- Limited prediction capability-existing models and thermo physical data do not accurately predict casting defects in magnesium alloys

Benefits

- Reduced production costs
- Shorter lead time
- Increased yields from improved computer based modeling

Action Plan

Timeline of Expected Results

Tasks

1. Develop Modeling Software
   a. Create team of software suppliers, universities, national labs and end users
   b. Run existing software on simple casting geometries
   c. Identify shortcomings, data needs

2. Develop Thermo Physical Property Data
   a. Collect available property data from literature
   b. Generate mission data

3. Validate Modeling
   a. Cast simple geometries to confirm model predictions
   b. Cast complex geometry to confirm model predictions

Top Priority — Process Technologies

Develop a versatile casting machine capable of producing permanent mold, lost foam, precision sand, and investment castings by means of pressurized filling (low pressure, counter gravity, vacuum assist, or electro-magnetic systems)

Magnesium producers must be efficient and agile to respond to customer expectations and market changes. The magnesium casting industry must accelerate the integration of improved casting technologies to stay competitive under these conditions. The development of new casting equipment is one strategy that could expand the range of geometries and quality levels of magnesium cast components.

A versatile magnesium casting machine will increase the affordability of magnesium components by reducing defects, improving consistency, increasing productivity, and reducing lead times.

Challenges Addressed

- Lack of capability to produce consistent quality parts
- High cost per product
- Modernization of casting facilities

Benefits

- Provide best quality castings
- Provide best cost per product
- Increase market share

Action Plan

Timeline of Expected Results

2005 — 2010 — 2013

Tasks 1-3 (2010); Task 4-5 (2013)

Tasks

1. Review current best practices by process and material
2. Determine best "package" for casting magnesium
3. Design and build a versatile RD&D magnesium casting machine to produce permanent mold, lost foam, precision sand and investment prototype castings
4. Develop and define mould technology for investment casting and lost foam casting
5. Make the technology available to North American Foundries

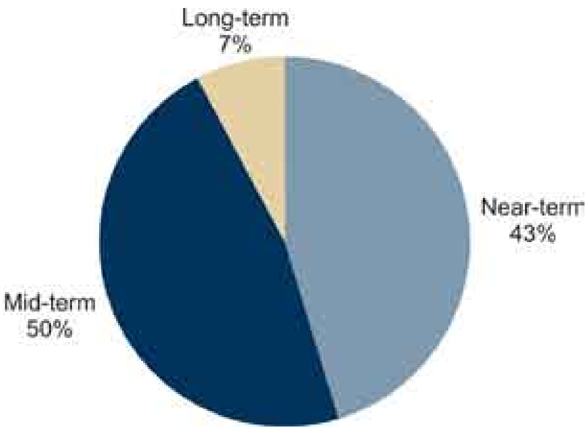
5. Portfolio Development

Uncertainties in markets, regulations, technology advancement, and competition require that the magnesium casting industry maintain a robust portfolio that can respond effectively to a variety of futures. As the industry funds R&D projects and pursues the strategies contained in this roadmap, it will continually review and assess the mix of projects that will lead to success both today and in the future. In addition, the magnesium casting industry will work with partners in industry, government, and other organizations to ensure that funded activities are complementary and contribute to a balanced North American magnesium casting portfolio. The initial portfolio includes a mix of R&D investments by time frame and by strategic emphasis.

Time Frame Analysis

The magnesium casting industry portfolio should contain a mix of R&D projects that will come to fruition in the near (0-5 years), mid (5-8 years), and long term (over 8 years). Near-term activities are needed to infuse the industry with technologies that immediately improve productivity and expand new applications. Mid-term activities ensure that the technical and cost challenges of emerging technologies are resolved so these technologies can be deployed within eight years. Long-term technologies usually have the potential for big payoffs but are higher risk. These technologies help position the industry for long-term growth in existing and new market areas.

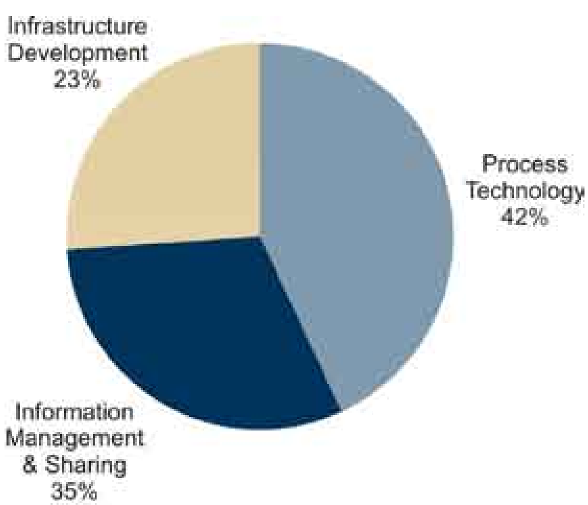
Figure 5-1 Time Frame Portfolio Mix



Strategic Emphasis

The most important technology strategy for the magnesium casting industry is to develop process technologies that improve the value of magnesium cast components and thereby expand markets and generate new magnesium casting sales. As such, about 42% of the magnesium casting industry R&D portfolio should consist of process technologies and information management and sharing invest-

Figure 5-2 Technology Strategic Areas



ments should comprise 35% of the portfolio. Research that develops industry infrastructure should make up about 23% of the investments.

This investment strategy should be used as a general guide for initial investments but not as a strict formula. The relative benefits and cost of specific R&D projects must be used as the most important criteria for investment.

Implementation

The magnesium casting industry will use this Roadmap to ensure industry investments address the most strategically important needs as it seeks to improve its position as the choice material for components in automotive, aerospace, power tools, sporting goods, and computer and electronic equipment. Through active, engaged partnerships within the industry, the individual magnesium casters and the industry as a whole will achieve mutual gain. Extending this coordination to suppliers, universities, and government agencies will allow the industry to leverage its investments with additional financial and technical resources, stimulating even greater innovation and progress towards achieving industry growth.

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