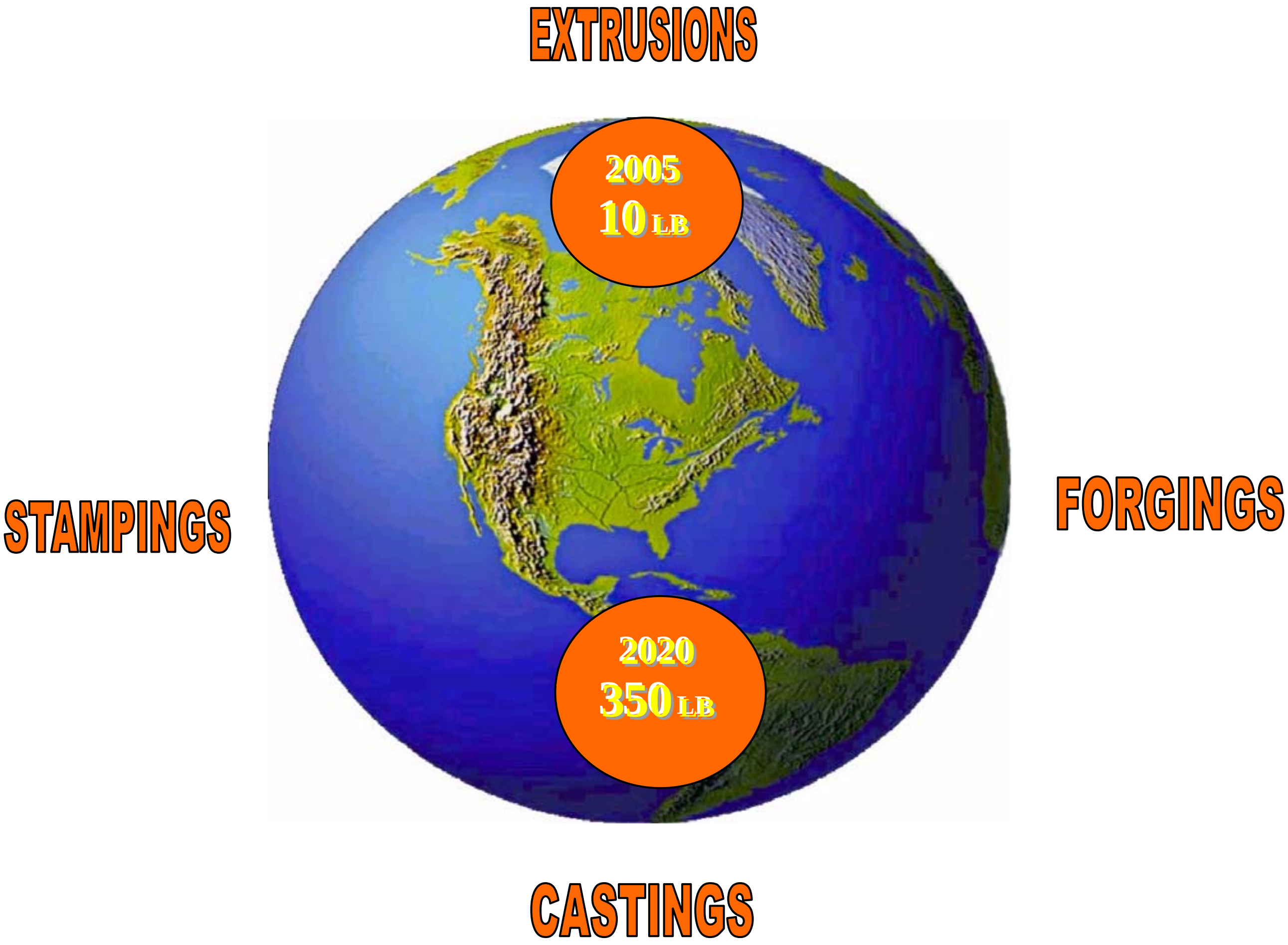
UNITED STATES AUTOMOTIVE MATERIALS PARTNERSHIP

A consortium of the United States Council for Automotive Research

MAGNESIUM VISION 2020:

A NORTH AMERICAN
AUTOMOTIVE STRATEGIC VISION FOR MAGNESIUM



Expanding Potential Automotive Applications

PREFACE

This document, “Magnesium Vision 2020: A North American Automotive Strategic Vision for Magnesium,” originated from a meeting of the United States Automotive Materials Partnership (USAMP) Automotive Metals Division (AMD) at the office of the United States Council for Automotive Research (USCAR) on December 7, 2004. Sixty-one members of the North American (NA) automotive magnesium industry met to discuss the possible effects of global collaboration on the U.S. automakers’ use of magnesium.

The two USAMP-AMD magnesium project teams, Structural Cast Magnesium Development (SCMD) and Magnesium Powertrain Cast Components (MPCC) volunteered to investigate the current use of magnesium within NA and provide a document that would:

- Benchmark the historical use of magnesium;
- Identify the challenges and/or suspected technical problems associated with increasing magnesium use;
- Develop R&D proposals to address the challenges;
- Suggest solutions and estimate timing to resolve roadblocks and advance the large-scale use of automotive magnesium applications;
- Provide a vision to expand potential automotive magnesium applications into metalworking and solidification/casting processes other than high-pressure die casting (which is used to produce more than 99 percent of current automotive magnesium components).

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Why Magnesium? Summary of Magnesium's Benefits in Vehicles

PERFORM

The primary advantage of magnesium is its ability to reduce vehicle weight and enhance:

- ***Performance*****.** Weight reduction improves vehicle performance by enhancing acceleration/ deceleration. Reducing vehicle weight in the front allows the center of gravity to be moved rearward, improving response in steering/cornering.
- ***Fuel Economy***. Vehicle weight reduction improves fuel efficiency.

VALUE

- ***NVH.*** Magnesium parts can be tuned to those critical frequencies where noise, vibration and harshness (NVH) are reduced.
- ***Squeaks & rattles.*** Versus the 30 or so individual elements in a steel component, a single large casting, such as an instrument panel (IP) cross-car beam, allows less room for manufacturing error and misfit, reducing the susceptibility for rubbing and vibration between the elements, reducing squeaks and rattles.

DESIGN

Magnesium can improve vehicle design and add unique customer features:

- ***Design for package improvements*****.** Castings allow package improvements via design/parts consolidation flexibility. Compared to a stamped-welded steel IP cross-car beam, a magnesium beam allows air-bag housings, instrument-cluster housings, etc. to be cast in place, enabling new design features with ease.
- ***Reconfigurable interiors.*** Lighter structures can be removed and/or reconfigured to allow easier egress and ingress; e.g. a 3rd-row magnesium seat is 40 lbs. lighter than a heavier steel fabrication.
- ***More Options Possible.*** With low-weight magnesium components, more and/or heavier options and higher carrying capacity/payload can be made available to customers while maintaining the vehicle axle loading at its allowable GVW (Gross Vehicle Weight).

MANUFACTURE

Magnesium can have reduced manufacturing costs and improved manufacturing value:

- ***Reduced manufacturing cost***. Magnesium castings can have reduced manufacturing cost vs. steel, especially for production volumes of less than 200,000 units per annum. For example, a 30-part steel IP cross-car beam requires 30 expensive tools/gauges; the cast-magnesium version has only 6. Magnesium's improved machinability compared to aluminum and steel and its lower specific heat and latent heat also lower processing costs.
- ***Craftsmanship.*** A one-piece cast-magnesium IP cross-car beam can improve craftsmanship ("fit and finish") and reduce dimensional error vs. stamped/welded steel elements.

PRPS

Magnesium has improved properties vs. other materials (see also Appendix C):

- ***Properties***. Magnesium has higher strength, stiffness, thermal stability and thermal conductivity vs. plastic; higher specific strength, ductility and impact resistance vs. aluminum as well as better damping and dent resistance vs. steel.

Acronyms and Abbreviations

~	Symbol for the word approximately
>	Symbol for greater than
Al	Chemical symbol for aluminum
AM60	Mg HPDC alloy containing 6% aluminum, with <0.5% Mn, used for parts requiring high ductility (>10%)
AMD	Automotive Metals Division, a division of USAMP
ASM	American Society for Materials
ASTM	American Society for Testing Materials
AZ91	Mg HPDC alloy containing nominally 9% aluminum, 1% zinc
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAFE	Corporate Average Fuel Economy, fuel standard set by the U.S. in the 1970s.
CANMET	The science and technology arm of the Minerals and Metals Sector of Natural Resources Canada.
CERP	Casting Emissions Reduction Program, an R&D, prototype and full production foundry in Sacramento, Calif. set up by USCAR in 1995 to help industry develop new low emissions foundry binder materials
Cr	Chemical symbol for chromium
CR	Corrosion Resistance
CRADA	Cooperative Research and Development Agreement, between a federal laboratory and a commercial entity
Cu	Chemical symbol for copper
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EU	The European Union
Fe	Chemical symbol for iron
FEA	Finite Element Analysis
FMEA	Failure Modes and Effects Analysis, a method that defines issues of process and design influencing part quality
FreedomCAR	An R&D program between the DOE and USCAR to reduce the nation's dependence on imported oil, minimize harmful emissions and develop hydrogen-fueled vehicles.
GOR	Grill Opening Reinforcement
GVW	Gross Vehicle Weight, allowable weight on the axles of a vehicle
HIP	Hot Isostatic Pressing, a process that applies very high pressures to reduce discontinuities and improve ductility
HPDC	High pressure die casting, where molten metal is injected at very high rate (>10 m/sec) into a steel die clamped within a press (the die casting machine)
IP	Instrument Panel
ISO	International Standards Organization
LCA	Life Cycle Analysis. A cradle-to-grave analysis of materials, emissions, energy and cost in all areas of a vehicle's life use, from mineral mining to scrap reclamation
M	1 million
MgCOE	Magnesium Center of Excellence, a virtual organization concept that will be a repository of global Mg knowledge and an implementer of new automotive Mg applications
Mg	Chemical symbol for magnesium
mpg	Miles per gallon
Mn	Chemical symbol for manganese
MPCC	Magnesium Powertrain Cast Components program, a USAMP program to produce a Mg-intensive engine using a high-temperature creep-resistant alloy
NA	North America/North American
NDE	Non-destructive examination, a method of examination that does not damage the material being examined
NDT	Non-destructive testing
NIST	National Institute of Standards and Technology, a division of the U.S. Department of Commerce
NFPA	National Fire Prevention Association
Nm	Newton-meters
NSF	National Science Foundation
NVH	Noise, Vibration, Harshness
OEM	Original equipment manufacturer, also the term used for an automaker
ppm	Parts per million
PRP	Properties
RDTs	Research and Development Topics or Themes
SAP	Sintered Aluminum Powder, an aluminum-composite with micron-size oxide particles having improved properties over conventional aluminum at high temperature
SAE	Society of Automotive Engineers
SCMD	Structural Cast Magnesium Development program, a USAMP program whose goal is to expand the knowledge-base of Mg for cast structural components using a lightweight Mg engine cradle as an example
SMC	Sheet Molding Compound, a composite of glass fibers and polymers
SME	Society of Manufacturing Engineers
SPF	Superplastic forming
Sr	Chemical symbol for strontium, a grain refiner in magnesium

SSM	Semi Solid Metal, a description of a metal whose temperature is in the “mushy zone” between solid and liquid and whose metallurgical structure has been refined by mechanical and thermal means
T	metric tonnes (2204 pounds)
T5/T6	Heat treating nomenclature, which defines how a metal is hardened on cooling from the solution treating temperature
Tier One	A full-service supplier of components and sub-assemblies for delivery directly to OEM production lines
TMS	The Metallurgical Society
TRC	Twin-Roll Casting, a process to produce thin (3-15 mm) sheet directly from the molten state by forcing liquid metal between 2 steel rolls
UL	Underwriter’s Laboratory
U.S. automakers	DaimlerChrysler Corporation, Ford Motor Company, General Motors Corporation
USAMP	U.S. Automotive Materials Partnership, one of the 8 consortia of the three U.S. automakers within USCAR
USCAR	U.S. Council for Automotive Research, an umbrella organization of DaimlerChrysler Corporation, Ford Motor Company and General Motors Corporation that facilitates collaborative R&D
V-process	Casting method encapsulating an unbonded sand mold with a thin plastic layer and a vacuum, reducing emissions
Zr	Chemical symbol for zirconium

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EXECUTIVE SUMMARY

Magnesium use in the automotive industry has grown by 10-15 percent per annum over the past 15 years to an average of 10-12 lbs. (range 1-35 lbs.) for an average U.S. automakers' - DaimlerChrysler Corporation, Ford Motor Company and General Motors – (3,360 lbs.) vehicle. This is compared to 260 lbs. of plastics, 280 lbs. of aluminum, and 2,150 lbs. of steel/cast iron. There are two basic questions that need to be answered about magnesium: 1. Why are there only 10-12 lbs. of magnesium per vehicle? 2. How can magnesium be expanded from a specialty metal to a major commodity of automotive construction? This document identifies the major barriers to magnesium use growth and proposes more than 150 research and development topics (RDTs) to overcome them through expanded scientific, engineering and manufacturing knowledge. The 2020 strategic goal is to substitute 340 lbs. of magnesium components for 630 lbs. of current ferrous and aluminum parts (290 lbs. weight saved), bringing total average vehicle magnesium content to 350 lbs.

Cost/Quality Issues: High Pressure Die Casting (HPDC) is the primary production process for automotive magnesium parts. Major use of magnesium will not occur until fully accounted costs for magnesium components (i.e., alloy + tooling + component manufacturing + corrosion protection + fastening + vehicle installation/assembly + repair) become less than current materials/components. Variable quality of HPDC components also is an issue for vehicle engineers. CAE analysis (based on component not test bar properties) can help to reduce weight and imperfections. R&D can improve recycling technology. These are among the 21 RDTs proposed to reduce cost and improve quality.

Engineering/Manufacturing Challenges: Engineers must meet the challenges of magnesium parts corroding in service. Thirty-four RDTs are proposed to overcome these challenges including developing general CAE models that define fastener/washer, materials/geometries and drainage/road-debris bridging. Enhancing bolt-load retention and improving general fastening confidence have an additional 17 RDTs. New applications will require new non-HPDC casting processes. Thirty-six RDTs identify the many issues associated with solidification and casting. They include inventing low-cost alloys, reducing mold-metal reactions and achieving low-cost grain refinement for the low-pressure sand, permanent-mold and foam casting processes. No wrought products are used currently in automotive construction, but there is a great future if the science/engineering knowledge increases and magnesium/component manufacturing prices continue to decrease. Sixty-nine RDTs are presented on wrought technologies encompassing metalworking process capability (10 RDTs), low-cost alloy/continuous-cast sheet development (7 RDTs), stamping (15 RDTs), extrusion (14 RDTs), forging (12 RDTs) and powder processing (11 RDTs).

Enabling Infrastructure: Unlike other materials, engineered magnesium components have few industrial champions and a very limited number of full-service Tier One suppliers to develop, produce and promote low-cost automotive designs/applications. In the absence of this support, three concurrent approaches are proposed that could help retain NA competency in magnesium technology and grow NA automotive magnesium components from 12 to 350 lbs. by 2020.

- Continue and expand industry-U.S. automakers USAMP-sponsored magnesium projects (such as the SCMD engine cradle and the MPCC engine block).
- Create a virtual technical center, with multidisciplinary participation of the U.S. automakers, suppliers, academia and governments. It will focus on research and engineering, developing implementation ready designs and processes and educating participants.
- Collaborate with global experts to develop the science and engineering required for growing automotive-relevant technology. These specialists would share information via joint Web sites, meetings and programs in the search for new ways to lighten vehicles with magnesium.

1. Enablers for Large Volume Usage of Magnesium

Magnesium Vision 2020 proposes to reduce the weight of an average 3,360 lbs. NA vehicle by 290 lbs. by replacing 630 lbs. of current aluminum, iron and steel with 340 lbs. of magnesium. This major materials realignment will not take place without significant drivers for change, as shown below:

Exhibit 1-1.

Economic Drivers for Materials Change

For OEMs to defray the costs associated with Mg substitution, Mg components have to provide either equal function at a reduced cost and/or improved function (lighter weight) at an equal cost, or be able to justify any increased price premium per pound of weight saved.

Exhibit 1-2.

Technical Drivers for Materials Substitution

Hundreds of magnesium products have demonstrated implementation readiness over the past 75 years, but the average U.S. automaker's vehicle still utilizes only 10-12 lbs. A major reason is that there still are several technical barriers to be overcome:

- Cost-effective solutions to prevent bi-metallic/galvanic corrosion;
- Low cost mechanical fastening to vehicle without bolt-load-retention/corrosion issues;
- Improved quality (low porosity) and higher/more uniform ductility HPDC parts;
- Alternate casting methods to HPDC;
- Low-cost wrought alloys, coupled with low-cost stamping, extrusion and forging.

Exhibit 1-3.

Infrastructure Requirements for Promoting Technological Change

In recent years, Tier Ones have dominated the implementation of new technology in the NA automotive industry. They perform R&D, product engineering, manufacturing and marketing, while developing implementation-ready components for and with OEMs. But there are almost no Tier One champions of magnesium components and processes. Consequently, a new paradigm is needed to promote magnesium innovation and substitution in NA:

- Collaboration/cooperation among global individuals/organizations that both perform R&D and develop new products and processes.
- Creation of a NA technical center of excellence to take a leadership role in developing implementation-ready magnesium technology for the automotive industry.

Exhibit 1-4.

Social/Political Drivers for Promoting Materials Change

There are significant political and/or societal pressures associated with using gasoline in transportation, i.e., foreign oil imports, gasoline costs at the pump, CAFE, taxation, and emissions. All can influence technological change. Increased fuel efficiency in vehicles will become even more important if, as expected, oil prices continue to rise.

2. Weight Reduction Strategy of Magnesium Vision 2020

Vehicle Materials Distribution

There are many examples of how materials are distributed in a vehicle. This document uses an analysis originated by American Metals Market (1), based on an average 3,360 lb. 2005 vehicle.

Exhibit 2-1.
Current Materials Distribution for a 3,360 lb. (average) NA Vehicle

	MATERIAL	WEIGHT (lb.)	VEHICLE %
▪	**Steel + Cast Iron**	**2,145**	**63.8%**
▪	**Aluminum**	**278**	**8.3**
▪	**Polymer/composites**	**255**	**7.6**
▪	**Others**	**423**	**12.6**
▪	**Rubber and Glass**	**249**	**7.4**
▪	***Magnesium***	***10-12***	***0.3***

The Magnesium Vision 2020 goal is to obtain a substantial weight reduction for this particular vehicle. The following scenario was considered: 290 lbs. by substitution (250 lbs. of magnesium replacing 500 lbs. steel/cast iron at 50 percent weight reduction and 90 lbs. of magnesium replacing 130 lbs. aluminum at 31 percent weight reduction). (500-250) + (130-90) = 290 lbs.

When weight is reduced by 290 lbs., chassis, suspension and powertrain components may also be reduced, allowing a secondary weight savings or weight compounding. The amount of this reduction is highly controversial, but if it could reach an additional 210 pounds, then the total weight of the vehicle might be reduced by 15 percent.

(1) American Metals Market 2003

Exhibit 2-2.
New Materials Distribution for a 500 lb. Weight-reduced Vehicle (to 2860 lb.)

NEW MATERIALS DISTRIBUTION				**MATERIALS CHANGE (lb.)**							**WEIGHT SAVE**
	MATERIAL	**WT. (lb.)**	**%**	**Original**	**Final**	**TOTAL**	**Substitution**	**Downsize**	**Mg**		**TOTAL (lb.)**
▪	**Steel + Cast Iron**	**1,513**	**53.0**	**2,145**	**1,513**	**-632**	**-500**	**-132**	**+250**		**-382**
▪	**Aluminum**	**130**	**5.2**	**278**	**130**	**-148**	**-130**	**-18**	**+ 90**		**- 58**
▪	**Polymer/composites**	**255**	**8.6**	**255**	**255**						
▪	**Others**	**380**	**13.5**	**423**	**380**	**-43**		**-43**			**-43**
▪	**Rubber and Glass**	**232**	**8.2**	**249**	**232**	**-17**		**-17**			**-17**
						-840	**-630**	**-210**	**340**		**-500**
▪	***Magnesium***	***350***	***12.2***	**10**	**350**						
	TOTAL	**2,860**		**3,360**	**2,860**						

3. Production of Current Magnesium Components

3.1. Historical Experience with Magnesium

Since the 1930s, the global automotive industry has used a wide range of magnesium components on vehicles – in pistons, oil pumps, mounts, brackets and housings. In the late 1930s to ‘60s, the VW Beetle was the first (and only) vehicle to use more than 40 pounds of magnesium; primarily in its transmission and air-cooled engine. The 1952 Chrysler had more than 15 die cast parts, most converted from heavy zinc. Ford Motor Company's 1998 Partnership for a New Generation of Vehicles (PNGV) demonstration vehicle contained 87 lbs. of magnesium components.

European and U.S. automakers have different criteria for utilizing magnesium. In the EU, weight reduction is used both to increase fuel efficiency (Consumers have to cope with gasoline prices that are two to three times those in NA.) and to reduce emissions (Impending EU 2006 regulations significantly reduce CO_2 tailpipe emissions). Mg in NA has been used at times to address CAFE requirements. European OEMs also use magnesium in their more expensive vehicles to improve drivability and performance by reducing weight in the front (which moves the center of gravity aft).

Cast magnesium wheels appeared first on a 1967 Fiat and later on a 1978 Alpha Romeo. Porsche introduced a 6-cylinder crankcase in 1968. The first instrument panel cross-car beam appeared on a 1989 Audi, later migrating to NA and appearing on a General Motors Corporation vehicle in Model Year 1995. Audi introduced the first magnesium automatic transmission in 1999; in 2003, DaimlerChrysler Corporation introduced a larger version in the Mercedes. The first large Mg radiator support/carrier was introduced into a NA vehicle (Ford F-150) in 2003. In 2004, BMW introduced a composite Mg/Al-Si I-6 crankcase. In 2005, for the first time, European OEMs were projected to have surpassed the Big 3/NA utilization with ~ 85,000 T of automotive products.

Regarding wrought products, Dow Chemical Company produced demonstration trucks in the 1920s with sheet and extruded components. GM produced a limited number of stamped Mg hoods for the 1952 Corvette. International Harvester successfully produced 6,300 Metro-Light trucks containing magnesium sheet and extrusions in the 1955-1965 time frame. Currently, the only automotive wrought products are forged road wheels and an interior trim panel on the 2005+ Porsche.

3.2. Production of Current Magnesium Components

Historically, the United States automakers used more magnesium than the EU until 2004. The 2004 average was ~ 55,000 T or ~12 lb./vehicle, based on U.S. automakers 2004 sales of 9.9 M vehicles (58.6 percent of 16.9 M total NA sales), primarily on the larger vehicles. The magnesium components cover a broad range of non-Class A surface applications in all parts of the vehicle interior, body, chassis and powertrain. See Exhibit 3.2.1.

The primary motivation for the NA applications has been for weight reduction. However, there are several U.S. automakers’ examples where Mg components have displaced current materials for noise, vibration and harshness (NVH) improvements and even cost reductions; e.g. for some low-volume IP cross-car beams. The general NA experience has been that the Mg design is discarded when a lower-cost solution for a particular weight problem becomes available.

Exhibit 3.2.2. lists the weights of powertrain, interior, chassis and body components in terms of the initial weight, the weight in Mg and the weight reduction obtained. On converting from steel/cast iron, typically a 50-55 percent weight reduction is achieved; converting from an Al design yields an approximate one-third reduction. Photographs of the more common components are shown in Exhibit 3.2.3.

Exhibit 3.2.1. Magnesium Components in U.S. Automakers' Vehicles

The variety and quantity of the ~ 55,000 MT of magnesium components used by the U.S. automakers' include the following, with the number of nameplates/platforms in ( ).

Chassis:

Brake bracket and bracket assembly (4), brake/clutch pedal bracket (3), clutch pedal bracket and assembly (3), brake pedal bracket (2), air bag housings (2), engine cradle/subframe (1)

Interior:

Seat base (3), bench seat riser (1), console bracket (1); instrument panel cross car beam (7), IP reinforcement (2), IP console support bracket (2), IP support beam (5), IP support bracket assembly (2), ABS housing (1); steering wheel armature (33), steering column bracket (11) and hub (3), jacket assembly and housings (8), lock housing (7), actuator housing and retainer (7)

Exterior:

Sunroof cover/cap assembly (4), outside mirror armature (1), roof frame (3)

Powertrain:

Alternator/A/C bracket (3), alternator bracket (1), alternator/idler bracket (1), valve cover (9), cam cover (5), EGR valve plate (4), transfer case (6)

Additional applications in the EU:

Chassis: Road wheels (3), Front end carrier (1). **Interior**: Seat cushion/back (2)
Powertrain: Manual transmission case (2), automatic transmission case (4), engine block (3)

Why There Are Only a Limited Number of Mg Components on Vehicles

There would be ~ 380 lb. of Mg parts if all the various components were installed on a single vehicle (somewhat more than that proposed in this Vision 2020 report). Given that these parts have passed implementation readiness could lead one to question why does the average U.S. automaker's vehicle today have only ~ 12 lb.? There are several reasons, such as:

- Cost.
- Inconsistent properties in High Pressure Die Cast (HPDC) parts.
- Technical challenges in fastening and protecting against corrosion.
- The perception that Mg is flammable.
- The replacement of Mg parts with lower cost and alternate materials and designs.
- Limited Mg infrastructure unable to develop and market competitive solutions.

Solutions to these hurdles are proposed in the following sections.

Exhibit 3.2.2.
Magnesium Components Used in Vehicles (lb.)

	Original Weight	Original Material	Mg Weight	Weight Saved
CHASSIS				
4 Wheels	65	Al	39	26
1A Frame Cross Member	20	steel	10	10
Engine Cradle	34.8	Al	23.7	11.1
Fuel Tank Barrier	8.7	steel	5	3.7
Brackets - Adjustable Pedal	2	steel	1	1
Brake/Accelerator	2.5	steel	2	0.5
Steering - Wheel	2.5	Al	1.5	1
Columns	4	Al	3	1
Column Brackets	2	steel	1.5	0.5
ABS Mounting Bracket	1.3	iron	0.9	0.4
INTERIOR				
Seats - Frames (4)	44	steel	16	28
Stanchions (2)	24	steel	13	11
IP - X-car beam	25	steel	15	10
Knee Bolster	10	steel	6	4
Console	8	steel	5	3
Brackets	1	steel	0.5	0.5
Glove Box Door	1	steel	0.7	0.3
POWERTRAIN				
Engine Block I 6	56	Al	33	23
Engine Block I 4	42	Al	23	19
Automatic Transmission	42	Al	30	12
Intake Manifold	22	plastic	12	10
Transfer Case	25	Al	15	10
Clutch Housing	14	Al	7	7
Oil Pan	9	Al	6	3
Engine Mounting Brackets	6	iron	3	3
Alternator Bracket	5	Al	2.5	2.5
Cam Cover (2)	7	Al	5	2
Cylinder Head Cover	7	Al	5.7	1.3
Air Intake Housings	6	plastic	4	2
Oil Pump Housing	3	Al	2	1
Power Steering Pump Bracket	1.5	Al	1.2	0.3
BODY STRUCTURE				
Door Inner Panels (4)	86	steel	39	47
Radiator Support/GOR	32	steel	12	20
Front of Dash Structure	40	steel	22	18
Lift gate Inner	22	steel	12	10
Windshield Surround (frame)	22	steel	12	10
Targa Roof Frame Opening	11	steel	6	5
Wiper Motor/support Assembly	3.5	Al	2	1.5
Mirror Housing	3	zinc	2	1
Headlight Retainer	1.5	steel	1	0.5
TOTAL	680*		**380***	300*

All parts on a single vehicle with an I-6 engine

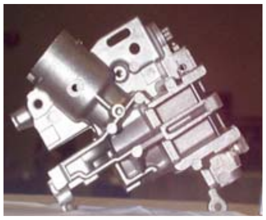
* Rounded to 2 significant figures

Exhibit 3.2.3. Examples of Typical Cast Mg Components

Steering Wheel Armature

Steering Column

Lock Housing

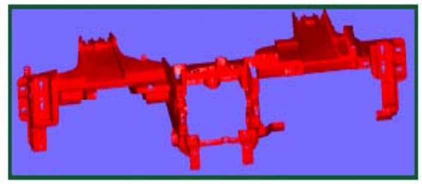


GM Corvette, Z06 Front Cross Member (or Cradle)

DCX Third-Row Seat Frame

Jaguar Seat Frame

Jaguar IP Cross-Car Beam

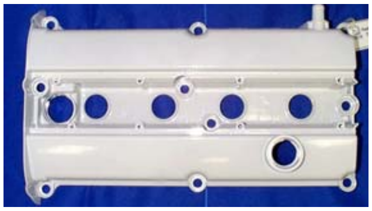


GM Front Console

Engine Accessory Mounting Bracket

Door Inner Module Aston Martin

Cam or Valve Cover

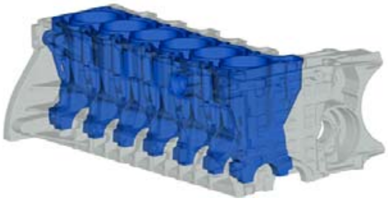


Transfer Case for 4x4 Transmission

Intake Manifold, BMW

DCX 7 Speed Transmission Case

BMW Block with Cast in Al-Si Liners



Front-End Assembly for Ford F-150 Truck

4. Challenges to Using Large Amounts of Magnesium in Vehicles

There are four major technical challenges to using more Mg on U.S. automakers' vehicles:
1. Perception that High Pressure Die Casting (HPDC) cost is too high and its quality is too variable. 2. Concerns about general corrosion. 3. Concerns about galvanic corrosion. 4. Concerns that fastening Mg components to ferrous structures is not a durable process.

4.1. Higher Perceived Cost for Current HPDC Components

A Mg part (at two-thirds the weight of Al) costs less than an Al part cast in the same die (in early 2006, Al ingot prices ~ Mg). The most important issue for expanding automotive Mg applications is that Mg components have perceived higher fully accounted costs vs. Al, (alloy ingot+ tooling + component manufacturing + corrosion protection + fastening+ vehicle installation/ assembly + repair). Costs have to be even lower to counter negative perceptions by auto engineers and concerns about potential additional costs associated with converting Al production lines to Mg.

Exhibit 4.1.5 describes 21 RDTs that could reduce the cost of cast Mg components:

1. Reduce cost of primary and recycled/secondary feedstock (Exhibit 4.1.1)
2. Reduce component cost via improved lightweight designs (Exhibit 4.1.2)
3. Reduce manufacturing cost by improving process and quality (Exhibit 4.1.3)
4. Reduce prototype costs (including time-to-delivery) (Exhibit 4.1.4)

Exhibit 4.1.1 Reduce Cost of Feedstock (Recycling)

The internal cost to remelt/refine scrap/returns is lower than the cost of virgin ingot and is less costly than hiring external recyclers (who charge from $0.25-$0.40 per lb. depending on metal loss) to toll scrap back into ingots. Many Mg foundries perform some internal recycling of their clean returns, but they have neither the technical capability nor facilities to certify that recycled ingot is equivalent in quality to primary. Non-metallic inclusions/impurities in an ingot potentially can contaminate the metal and damage component functionality; low cost technology is required to statistically ensure recycled quality.

Exhibit 4.1.2 Design for Lightweight (Reduce Cost of Metal in Part)

Because of low confidence in test-bar data and limited engineering experience with Mg, high factors of safety are commonly used in part design. This increases section thickness, component weight and cost. Using properties from actual components, designs specifically for Mg can use lower factors of safety and allow components to be designed with thinner walls, without compromising component function/durability. Less metal will be used and thereby lower costs.

Exhibit 4.1.3 Manufacture for Low Cost

HPDC castings must be produced as efficiently as possible; this requires CAE designs to optimize filling and feeding so that gate, runner and overflow designs minimize the amount of melted/cast/recycled metal. A CAE-designed die will rapidly achieve operating temperature and have reduced scrap. A die optimized for velocity and pressure vectors will show where/how vents/vacuum ensure proper filling, reducing porosity/shrinkage and increasing cast quality.

Exhibit 4.1.4 Minimize Time to Deliver New Concepts to Customers

Time is an important economic variable in deciding materials and processing strategy. Product cycles are becoming shorter and designs must be completed in a shorter time period. Materials/ components that can be prototyped and validated quickly, with “make-like” production functionality and at low cost, have an advantage over slower more costly procedures. HPDC components currently take too long to deliver, requiring several months to prototype and fabricate. CAE modeling of the casting process and material properties could reduce time, but the models need development. Development of alternative, representative casting methods may also speed the process.

Exhibit 4.1.5. Major Research Needs to Reduce Cost/Quality Challenges

N=Near Term (1-3 years), M =Mid Term (4-8 years), F=Far Term (9-15 years)

Time Line	Strategic Framework	Research Objectives	Perceived Needs
N	1. Reduce cost by improving HPDC design capability.	. Collect Mg property database from actual field-run castings and not test bars. . Compare laboratory, proving-ground and field customer for 10-year lifetime requirements.	. Develop databases so that components are appropriately designed. . Determine if there is degradation with exposure to the environment; develop design and assembly practice to address issues. . Optimize modeling protocol.
N	2. Reduce cost and increase quality by improving HPDC manufacturing capability.	. Minimize waste in casting processing. . Minimize waste in casting start-up of HPDC dies. . Reduce casting defects, improve casting quality.	. Determine process control algorithms for HPDC so that heating and cooling lines and procedures can be designed into the tool to produce a first-off good casting. . Reduce porosity and inclusions with overflows and porous plugs. . Demonstrate improved mechanical properties. . Show that heat treatment can improve properties. . Use sequential injection to improve quality.
N	3. Demonstrate implementation-readiness for a wider range of parts.	. Develop technical cost models for magnesium HPDC.	. Perform life-cycle analysis. . Demonstrate implementation-readiness capability and cost competitiveness vs. aluminum and steel/cast irons.
M	4. Reduce development costs and development time for producing prototypes.	. Rapid prototyping.	. Develop rapid prototyping that simulates HPDC but is low cost and takes 1 week in lieu of 1 month.
F	5. Reduce cost of magnesium feedstock. Support a secondary magnesium industry. Understand issues involved in recycling in-plant (2020) and returns from the field (in 2030).	. Reduce cost of primary ingot. . Reduce cost for producing magnesium alloys. . Reduce cost of recycling and increase quality of recycled magnesium. . Develop understanding of how recycling affects quality	. Develop new low-cost alloys that have improved properties for structural applications. . Develop low-cost method to measure inclusions on-line during secondary remelting/refining. . Improve procedures for reducing inclusions in magnesium using fluxless melting. . Develop low-cost procedure to measure oxide content of ingot (w/o expensive neutron activation analysis). . Develop low-cost methods to recycle wet chips. . Develop low-cost/improved filtering methods.
F	6. Reduce social costs in using magnesium.	. Reduce emissions. . Reduce concerns about fire.	. Develop low-cost non-global-warming cover gas that does not corrode equipment to replace SO_2/SF_6. . Develop melting/casting procedures that preclude need for cover gas. . Perform marketing and education to show that magnesium components do not burn like Mg ribbons.
F	7. Reduce warehousing and shipping costs.	. Shipping and storing.	. Work with local fire agencies, NFPA, NIST and UL for shipping/storing castings, scrap and chips.

4.2. General Corrosion

Modern HPDC Mg alloys have almost the same general corrosion resistance (CR) to normal environmental exposure as mild steel and considerably better than HPDC Al which contains 2 percent Fe and 2-4 percent Cu (1). Older Mg alloys rapidly corroded in a vehicle environment since they contained copper, iron and nickel impurities at levels greater than the new 1980 standards (80-300, 40-50 and 10-20 ppm, respectively). For most applications, the CR of HPDC Mg alloys is adequate without any protective treatments. However, under certain service conditions (such as marine environments), surface protection is required and a series of 13 RDTs is presented to elucidate the challenges and address concerns (see below, in Exhibit 4.2.1.).

Effect of solidification (phase size and concentration), porosity and material quality

The size and distribution of impurity-rich phases (i.e. the phases that cause Mg to corrode) and the $Mg_{17}Al_{12}$ beta phase (the more corrosion-resistant high Al phase) have a large influence on corrosion. Slow solidification and heat treatment both increase precipitate size and shape and potentially add porosity and other imperfections that decrease CR. HPDCs freeze rapidly, have finer structure, smaller inclusions and a higher tolerance to impurities than do sand castings which freeze several orders of magnitude slower. With adequate Al, the $Mg_{17}Al_{12}$ phase in HPDC presents a continuous network and provides a protective oxide layer. In slowly solidified castings, the beta phase is uniformly dispersed and does not provide surface coverage or protection.

(1) In ASTM B117 salt spray tests, Al A380 corroded at 0.3 mg/cm^2/day, or 6X the rate of AZ91D and 3X AM60.

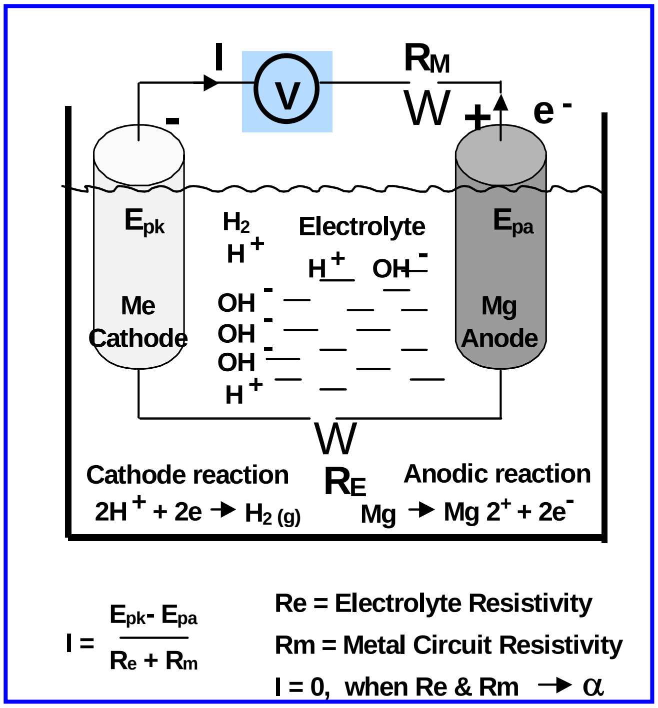
Exhibit 4.2.1. Major Research Needs to Reduce General Corrosion Challenges

N=Near Term (1-3 years), M =Mid Term (4-8 years), F=Far Term (9-15 years)

Time Line	Strategic Framework	Research Objectives	Perceived Needs
N	1. Increase confidence in general corrosion performance.	. Compare corrosion testing of laboratory, proving ground and actual road experience.	. Understand relationship between accelerated corrosion testing and actual lifetime on-vehicle/on-road experience. Verify observations with correlating laboratory and vehicle tests.
N	2. Protect Mg surface from corroding. Expand Mg use with new surface technology.	. Adapt aerospace and military coating technology. . Develop low-cost corrosion-resistant coatings. . Develop coatings with lasting and self-healing effects.	. Develop fundamental understanding of surface chemistry and reaction kinetics for low-cost Cr-free protection. . Develop very low-cost thin organic coatings for protection during ocean transportation. . Develop low-cost shiny, hard, wear-resistant surfaces for Class A applications. . Examine use of nano-particles in solutions and electrolytes to impart self-healing. . Develop coatings with colors and textures for unique design effects.
M	3. Protect chassis parts.	. Protect from stones/abrasion.	. Develop peck-resistant (e.g. urethane) coatings.
M	4. Effect of recycling on corrosion.	. Determine how recycling affects corrosion.	. Examine melt/treat/purify cycle to ensure no pick-up and no corrosion problems.
F	5. Alloys and corrosion.	. Identify low-cost effective alloying.	. Examine use of micro-alloys.
F	6. Effects of corrosion on fatigue .	. Examine stress-corrosion cracking.	. Study effect of cyclic strain which ruptures protective films & exposes new, unprotected metal.
F	7. Corrosion of slow freezing processes.	. Corrosion of sand, low-pressure and gravity castings.	. Define fundamental corrosion properties of alloys used in sand castings vs. HPDC. . Determine effects of foundry variables and inoculants on corrosion.
F	8. Continuous casting.	. Corrosion of fine structure.	. Examine corrosion on sheet produced from slow solidification (ingot) vs. rapid (continuous casting).

4.3. Galvanic Corrosion

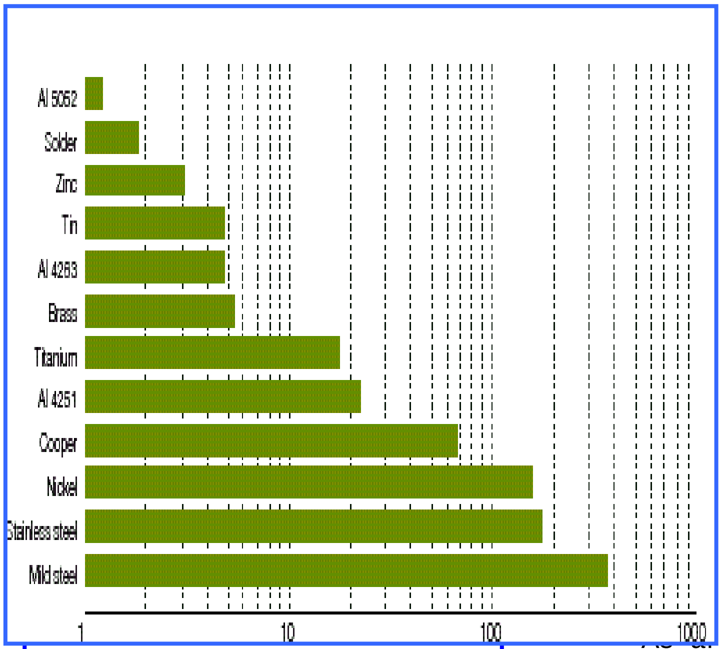
Exhibit 4.3.1. Schematic of Corrosion



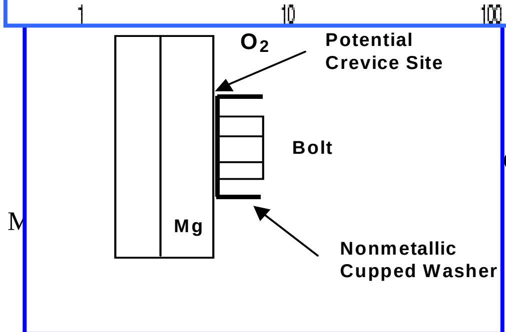
Galvanic corrosion is one of the most pressing technical and economic issues that limit Mg use in vehicles. Mg is subject to galvanic corrosion when it is electrically connected to another metal, immersed in the same conducting liquid (electrolyte); i.e., when there is an electrochemical potential difference plus a liquid electrolyte so that current can flow from one to the other. This is a serious problem for Mg and must be guarded against in any design. Galvanic corrosion is worse in the presence of acidic water, chloride-containing water or moisture condensate; removal of either the metallic connection, or the electrolyte, eliminates the corrosion, see Exhibit 4.3.1.

The resistance, R, current, I, and electrochemical potential, E [for the Mg anode and other metal cathode (k)], define the circuit and ion flow.

Exhibit 4.3.2.
Relative Galvanic Corrosion of AZ91D.



The current through the electrolyte is accomplished by a flow of ions. One of the metals dissolves in the electrolyte to provide the ions; this is called the anode. The non-dissolving metal is the cathode. Because of its position in the galvanic series, Mg is anodic to almost all other metals. In general, the greater the electrochemical potential difference, the greater the corrosion; thus, a Mg-iron couple is more serious than a Mg-Al one. This is the case for bare metals in contact. However the situation is more complex; protecting films can sometimes build up on both the Mg part and a cathode, increasing the resistance of the galvanic current and reducing the corrosion rates; e.g., tin can be cathodically polarized to reduce attack of other metals.



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narrow gap, its composition changes as a result of releasing dissolved elements. Since the electrolyte cannot be replenished, a concentration difference is set up causing a voltage difference. This causes a flow of ions and leads thereby to corrosion. Even in the same alloy, cold worked surfaces can be anodic to unworked areas, leading to corrosion (Busk, loc cit).

Surface Contamination

Another form of galvanic corrosion is from surface contamination with small particles of a dissimilar metal, causing severe pitting. This can occur from die lubricants that contain molybdenum disulphide and carbon, from iron particles transferred from dies during casting, forging, extrusion, rolling and stamping, or from heavy metals present in shot-blasting media. Pickling solutions can also cause problems if they contain heavy-metal salts.

Corrosion From Fastening

The most common source of galvanic corrosion occurs from fastening. The most effective remedy is to select compatible joining materials and reduce the cathodic surface area. Hydro Magnesium has published an extensive design brochure on the subject. When implemented, the guideline defines how to prevent most joints from corroding. However, there are situations where unique designs have to be invented. Two recent examples are the front end assembly bracket for the Ford F-150 truck and the engine cradle for the GM Corvette (developed under the USAMP-SCMD project). These components required significant field design work for the joint designs and materials (washers, spacers, bolts, etc.).

The recent EU development of high-strength Al bolts is encouraging, but NA OEMs require higher assembly torque loads than does Europe. Since the Al bolts will only work at assembly loads of less than 50 Nm, they are not approved in NA. RDTs to reduce galvanic corrosion barriers are listed in Exhibit 4.3.5.

Exhibit 4.3.4. Protecting Against Corrosion at a Fastener

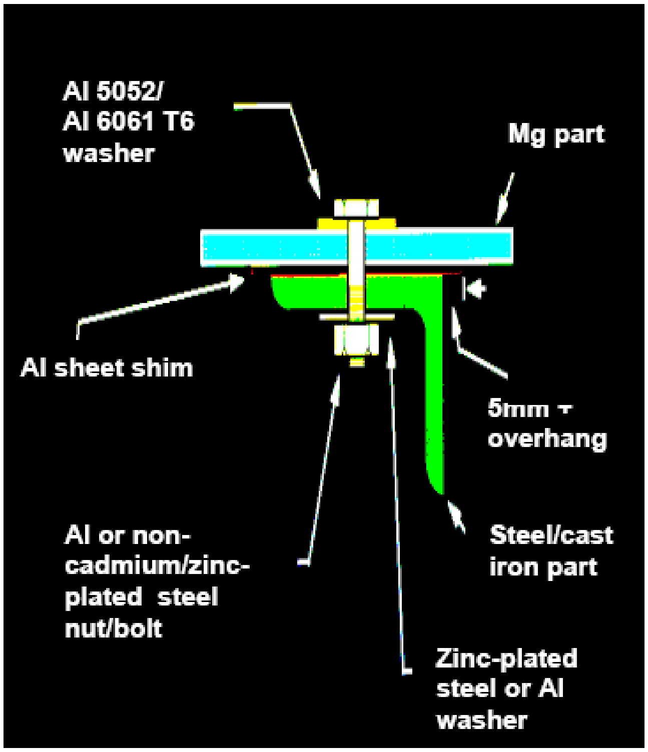


Exhibit 4.3.5. Major Research Needs to Reduce Galvanic Corrosion Challenges

N=Near Term (1-3 years), M =Mid Term (4-8 years), F=Far Term (9-15 years)

Time Line	Strategic Framework	Research Objectives	Perceived Needs

N	1. Mitigate galvanic corrosion from influencing the durability of mechanical fasteners.	. Develop suitable washer designs and washer separation protocols that prevent galvanic corrosion.	. Develop design rules for drainage to eliminate sites/pockets for moisture build-up. . Develop designs defining spacing/overlap among washer/bolt/Mg part via general FEA models. . Develop Al fasteners. . Develop creep-resistant plastics or Al/Mg composite washers that maintain clamp load in service. . Develop plastic and metallic coatings or washer shapes (cups) that cover steel bolts and nuts, have an electrochemical compatibility with Mg but still allow a central driver for torquing the fastener. . Develop process to affix washer to part so that it remains in place during transport to assembly plant.
		. Determine effects of road debris and salts on corrosion.	. Road debris can bridge & connect Mg with a ferrous conductor. Model the dimensions and geometry of the electrolytic effects associated with the fluctuating (dry-wet) conditions.
N	2. Eliminate galvanic corrosion that results from local (micro) surface contamination.	. Prevent contamination from microscopic metallic particle contamination at the surface of magnesium.	. Develop fast-screening procedures to ensure lubricants/pickling solutions and contact with HPDC die surface leave no metal residues. . Develop new (hydrophobic) die lubricants. . Find ways to eliminate and/or cover the particles. . Sand, glass or Al oxide shot blast can leave iron residue; develop new ways to provide similar surface alteration but with non-contaminating media. . Determine if contamination remains on component surface from stamping/forging/ extrusion dies/rolls.
N	3. Contact Corrosion	. Eliminate galvanic corrosion from Mg contacting other metals.	. Develop designs for specific applications, e.g., a Mg wheel with Al or steel bushings or contact with iron brakes and HPDC Al components.
M	4. Cathodic coatings	. Develop impermeable coatings on cathode rather than protecting Mg.	. Develop low-cost cathodic coatings that are impermeable to corroding environmental elements.
F	5. Interaction with properties	. Determine the effect of corrosion on mechanical properties.	. Study effect of coatings and corrosion on mechanical (fatigue) properties of structural parts.
F	6. Non mechanical fastening	. Determine how to deal with corrosion from other fastening procedures.	. Determine if corrosion occurs with adhesive bonding Mg to Mg, Mg to Al & Mg to steel, and develop solutions to prevent it.
F	7. Engine applications	. Characterize corrosion in the presence of engine coolants. . Develop standardized testing procedures.	. Understand effects of commercial/novel engine coolants in contact with engine materials . Determine if/how inhibitors (such as fluorides) reduce corrosion without being degraded during vehicle operating temperatures and times. . Develop techniques to characterize corrosion of Mg in contact with head gasket, cylinder liner, etc.
F	8. Basic R&D	. Develop accelerated testing protocols . Develop thermodynamic understanding	. Develop new accelerated methods to predict corrosion in various vehicle locations. . Close gaps in understanding corrosion/ passivation/hydride formation.

4.4. Fastening and Joining

Mg can be joined by most of the bonding, mechanical-fastening and welding methods common to the metalworking industries: arc, gas, laser, electron-beam, ultrasonic, plasma-arc, electric-resistance (spot, seam), friction-stirring and hybrids. Mechanical-fastening technologies, (rivets/

self-piercing rivets, bolts, screws, crimping, overmolding and self-fastening devices) require unique materials/processing to eliminate corrosion/damage. Mg can be brazed, soldered and adhesively bonded. All processes must be optimized to account for Mg's reactivity and material properties that differ from other metals. The process selection is based on consideration of material type (cast or wrought, bare or coated, etc.), alloys and materials to be joined, operating environment (temperature, humidity, salinity, etc.) design flexibility and cost. NDE methods must be made available to determine joint integrity.

Design to Enhance Bolt-Load Retention

Depending on the Mg alloy, bolt material, temperature and applied loads, the Mg part can relax sufficiently that clamp loads can reduce to below a desirable level when using mechanical fasteners. Acceptable clamp loads can be maintained throughout the vehicle life by spreading the loads with washers and shims, by using Mg alloys with higher temperature capability and by using Al alloy fasteners. A component sometimes experiences the greatest fatigue stresses at a fastener and may have to be redesigned to eliminate potential fatigue conditions. Exhibit 4.4.1. lists RDTs that can provide critical information for reducing fastening/joining concerns.

Exhibit 4.4.1. Major Research Needs to Reduce Fastening and Joining Challenges

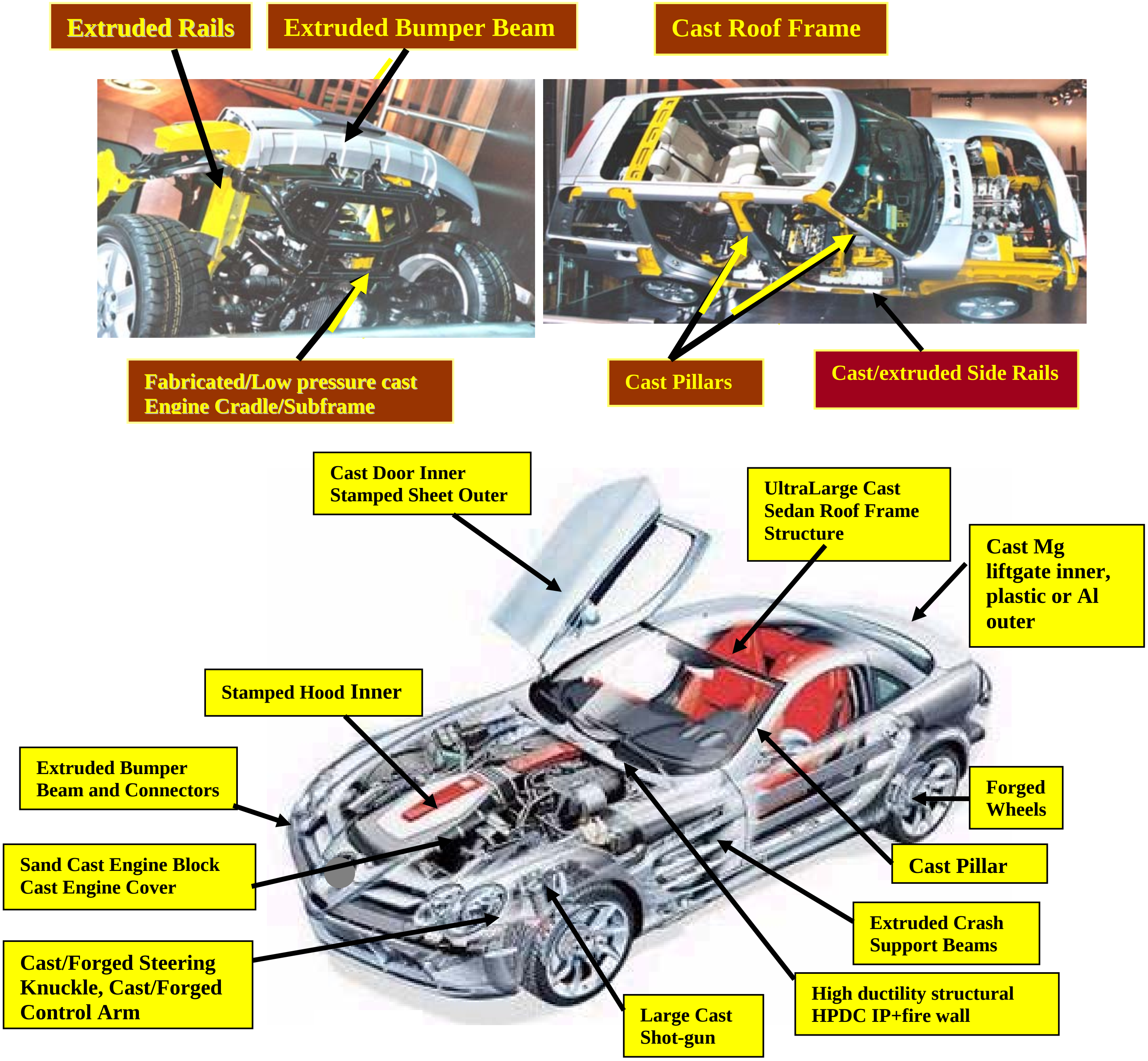
N=Near Term (1-3 years), M =Mid Term (4-8 years), F=Far Term (9-15 years)

Time Line	Strategic Framework	Research Objectives	Perceived Needs
N	1. Mechanical Fastening	. Develop unique design guidelines based on laboratory, proving ground and field testing.	. Develop CAE/CAD design guideline defining the shim/washer requirements and critical distances between Mg and a ferrous component. . Develop design rules to ensure no liquid can seep into the joint which could lead to corrosion. . Develop guidelines for clamp loads, joint design and rapid/robust test methodologies for use with threaded fasteners. . Develop criteria for riveting, crimping and thread forming without cracking the Mg part. . Examine global development of new fasteners.
N	2. Compatibility	. Ensure joining process compatible with assembly and service operations.	. Ensure no joint damage by body-in-white processing. . Ensure in-plant and in-service serviceability.
M	3. Welding/brazing	. Develop robust welding/brazing processes for joining Mg-Mg, Mg-Al, Mg-steel.	. Survey/assess state-of-art/limitations. . Determine/develop best practices. . Develop process parameters/CAE predictive tools for spot/continuous sheet welding. . Determine corrosion & metallurgical issues when joining dissimilar materials. . R&D joining methods (e.g. friction-stir welding). . Develop understanding of brazing capabilities.
M	4. Non-Destructive Evaluation (NDE)	. Ensure load performance (dynamic/static) over time (short/long)	. Develop NDE methods and criteria for ensuring fastener functionality, load history and integrity.
F	5. Adhesive Bonding	. Develop durable adhesive-bonding technology for Mg-Mg, Mg to steel/cast iron, Mg-Al.	. Define optimum surface conditions/adhesive criteria for Mg-Mg, Mg-Al, Mg-steel. . Develop full database of adhesive bonding for joining castings/stampings/forgings (primers, design, curing conditions, etc.). . Determine needs/best fixturing methods for assembly and processing.

5. Expanding Applications of Magnesium Via New Components

The large range of Mg components that has been produced (by HPDC processing) was shown earlier, but there are still only ~12 lb. on a typical NA vehicle. Reducing the high cost and variability in HPDC and eliminating corrosion/fastening challenges will help grow applications. But to achieve the 350-lb. Mg-component utilization target, new products are required, based on new manufacturing (non-HPDC, extrusion, forging, sheet stamping/superplastic forming) and assembly processes (welding/riveting/adhesive bonding) of hybrid Mg-steel, Al, polymer composite and plastic materials. Lightweighting in the front of a vehicle is especially important for performance and handling; reducing weight in the upper part of a vehicle can contribute to vehicle stability. Examples of typical applications are shown below.

Exhibit 5.1 Possible Applications of New Mg Parts in Front and Upper



6. Expanding Applications of Magnesium via Non-HPDC Manufacturing

6.1. General Technology in Casting and Solidification Processing (Ex 6.1)

Methodology for approving non-HPDC processes – There is no experience with sand-based processes that can produce large, high-quality castings for automotive applications, which are competitive with HPDC in cost, surface appearance/finish, wall thickness and dimensional tolerances. Sand processes are used currently with expensive, low-volume, high-alloy aerospace castings. But for high-volume automotive production, low-cost versions are required. Since tooling costs are reduced, such castings can be more easily and rapidly prototyped prior to large-volume/low-cost automotive production. For small-volume production (say 20,000 units) they should be less costly than HPDC, which requires large machines, large and expensive metal dies and costly controls to rapidly fill the dies in a fraction of a second with high-pressure molten metal.

Structure/property control – Non-HPDC processes include counter-gravity/gravity filling into semi-permanent/sand molds, gravity/counter-gravity/pressurized filling of Styrofoam molds and utilizing the V-process. All produce slowly solidified castings at very low (~ 0) temperature gradients. In the absence of grain refinement, large (~ 5 mm.) inhomogeneous grain structures are formed that can lead to cracks and thereby reduce mechanical properties. This is not the case with HPDC castings where the thermal gradients are very high (~10^4 ^oC /cm.), the freezing rates are also high and grains are correspondingly 100-500 times smaller. In sand castings, positive temperature gradients have to be forced on the system, such as by using high thermal conductivity sands (steel granules, zircon, etc.) or shaped-chills. In addition, grain refinement is needed to obtain the fine-grained structure that is required to obtain high mechanical properties. Low cost grain refiners are available for Al alloys, but not for Mg alloys, especially if they contain Al. Also, the most appropriate method for inoculant-introduction needs to be developed (such as via gas injection, mold coating, plunging, in-mold inoculation, etc.) that does not introduce either oxides or potential corrosion/strength-reducing impurities. Non-HPDC castings require heat treatment to develop viable mechanical properties for automotive applications. Low-cost procedures, such as fluidized-bed technology, have considerable promise for improved property control at lower cost.

Casting filling – Molten magnesium is very reactive. Sand core/mold additives and coatings must be developed that will produce a smooth casting surface; will not react with the melt; and will collapse after solidification and shake-out without cracking the casting. Filling a mold without oxidation-induced turbulence is required for high-quality structural aluminum castings; it is also required for magnesium. Mechanical/electrical pumping systems can provide controlled/slow fill with no turbulence and thus no inclusion-generation. But obtaining a long pump life in molten Mg requires new materials and designs. Filling ultra-large thin-wall castings without defects may require a multitude of pouring sprues that can be filled sequentially.

New technology – There is a need to invent new alloys that are appropriate for automotive applications and can be processed using the non-HPDC technology described above. New approaches to improving properties might include composite materials containing macro- and nano-particulates, fibers and composite preforms. The issue of molten Mg compatibility must be taken into account since Mg will react with almost all non-metallics to form spinels and potentially corroding reaction products.

Growth of the Mg casting industry will require improved quality of secondary/recycled metal. There is currently limited ability to economically remove and quantitatively detect non-metallic/gas inclusions at low concentrations. All processing should ensure that the resulting magnesium castings are produced with zero emissions, as verified by life-cycle analysis.

Exhibit 6.1. General Issues in Casting and Solidification Processing

Rapid Prototyping	Non HPDC Casting	Casting Design	Infrastructure	New Applications
Expensive and slow with metal tooling. Plaster & sand do not represent permanent mold thermal & metal flow conditions. Limited experience with foam and V-process casting.	Current aerospace processing experience is expensive. No high production/auto applications have been developed...need new processes. Molding/core media require special protection to prevent sand/metal reactions. Need to increase temperature gradient (such as with higher conductivity sands) since non-HPDC processes form coarse grains at low thermal gradients. Need low-cost grain refiners; current Zr grain refinement is expensive. Not possible to grain refine Al-containing alloys. Need low-cost, robust inoculant-introduction methods. Need low-pressure pumps that don't react with molten magnesium. Need low-cost heat treating to optimize properties. No information on whether forging/Hot Isostatic Pressing (HIPing) can improve properties of castings to compete with forgings. Limited information on semisolid technologies; current use is limited but there is potential for improved properties, heat treat ability and thinner sections.	Limited database from castings that have been on test track or in the field. Inability to predict mechanical properties throughout casting geometry. Database not sufficient to optimize component shape for least-weight design. Inability to predict microstructure throughout casting geometry.	Recycling quality insufficient. Unable to measure, predict and control melt quality during remelting and recycling. Supply base has few resources to support new product/process development as Alcoa/Alcan did for automotive Al applications in the 1950s. Need funding and support for a technical center that can develop new Mg technology & provide technical support to OEM's and suppliers. Develop collaboration & cooperation links around the world to leverage limited NA capabilities in R&D and Mg product/ process development.	Need to qualify new non-HPDC processes and components for implementation readiness. Require new alloys for low-gradient freezing processes that can respond to heat treatment.

Exhibit 6.1.2. Major Research Needs of Non-HPDC Casting/Solidification Processes

N=Near Term (1-3 years), M =Mid Term (4-8 years), F=Far Term (9-15 years)

Time Line	Strategic Framework	Research Objectives	Perceived Needs
M	1.Develop new casting processes for large castings that produce less stress on the solidifying metal vs. HPDC, and that can produce 2-mm-thin sections with smooth surfaces.	. Produce large sand and semi-permanent -mold castings using counter-gravity/low-pressure filling with no turbulence to produce high-quality castings.	. Develop multiple ingate, low-pressure permanent-mold/sand-mold processing. . Examine use of vacuum/V-processing with low-pressure fill. . Study use of foam/counter-gravity-pressurized foam processing. . Develop immersion pump system for low-pressure filling that does not foul because of Mg reactions.
		. Develop high-volume processes that can produce thin walls (in the 1-3 mm range) in sand/ permanent-mold castings without extensive tooling cost (as HPDC).	. Develop green-sand molding for magnesium. . Develop mold/core media to produce smooth surfaces that do not react with molten Mg.
		. Maintain a positive temperature gradient inside a sand mold to control as-cast grain structure.	. Examine process of water spray on casting while still in the mold. . Develop thermally conductive sands that have an ultra-fine surface and do not react with magnesium. . Study economics of iron and metal-matrix inserts to increase local thermal gradients, reduce porosity & locally improve function.
		. Develop methodology for preventing sand "burn-on."	. Examine mold/metal chemical reactions. . Develop molding and core making media (e.g. non-silica media such as synthetic ceramics, solid CO_2), and additives (e.g. S-bearing) to prevent Mg-reaction.
		. Develop inoculants that can promote fine-grained structures in magnesium castings that are solidified slowly in zero- or low-temperature gradients.	. Study heterogeneous nucleation in sand casting. . Develop non-Zr inoculants for new alloys. . Develop low-cost effective grain refiners for Al-based Mg alloys (where Zr is ineffective).
		. Develop additional methodology to ensure reliable fine-grained structures.	. Study gas injection, plunging, tablets, magnetic/ultrasonic/acoustic vibration, and in-mold inoculation.
M	2. Expand applications of Mg with new alloys.	. Invent new alloys that can develop the appropriate properties when solidified slowly.	. Develop alloys that are suitable for slow solidification at low temperature gradients that have good mechanical properties and corrosion resistant chemistry.
M	3. Improve quality of cast components by post processing.	. Develop heat-treatment procedures to improve the properties of non-HPDC castings.	. Develop models for metallurgical structure-control by heat treatment. . Develop low-cost heat-treatment methodology using fluidized beds to reduce thermal stresses and enhance properties. . Develop new quench media/quenching process that ensures no thermal cracking.
Time	**Strategic**	**Research Objectives**	

Line	Framework		Perceived Needs
F	3. (Cont.)	. Reduce cast component porosity after casting.	. Develop cast-forge processing capability. . Measure properties. Ensure benefit and cost targets are maintained. . Adapt Fiat's low-cost liquid hydrostatic (HIP) squeeze process from aluminum.
F	4. Composite casting methods	. Develop local and global improvement in casting properties using metal matrix composites preforms, and nano-composite additions.	. Develop metal-matrix composite and nano -composite additions that do not form spinels with magnesium.
F	5. Semi-solid processing	. Develop better understanding of semi-solid processing. . Optimize metal filling.	. Develop liquid metal on-demand semi-solid processing systems for sand and semi-permanent mold processing. . Develop alloys that respond to SSM processing. . Measure properties throughout component geometry from parts that have been field-tested. . Measure microstructure (porosity, inclusions, oxide films and cracks).
F	6. Improve component properties.	. Develop design rules for cast components; develop CAD/CAE capability. . Predict microstructure and properties from melting/casting process and the design of the component.	. Correlate microstructure to process and component design . Perform cradle-grave-cradle analysis to predict microstructure and properties from first principles. . Optimize component design vs. process design for new processes.
F	7. Ensure magnesium castings are "greener" than parts produced by other processes and other materials.	. Examine OSHA and EPA issues for Mg foundries.	. Perform LCA on the residual wastes, sludges, drosses, and gaseous emissions (non-SF_6 cover gases). . Develop processes that do not require cover-gas protection.
F	8. Improve quality of recycled magnesium.	. Develop capability to measure, predict and control melt quality.	. Determine effect of trace impurities and inclusions on solidification and component properties. . Develop standards and non-destructive testing capability to quantify quality (e.g., inclusions and films) in recycled melts. . Develop filtering and liquid-metal processing techniques to reduce inclusions. . Develop techniques to recycle wet magnesium chips from machining large sand castings.

6.2. Metalworking Technologies

Wrought technology offers significant opportunities to expand the use of Mg in the automotive industry. Stamping, extrusion, forging, brake/hydrostatic forming, spinning, stretch forming, deep drawing, bending and superplastic forming are all possible. Metalworking costs are more expensive than HPDC; however cost reductions are probable in all areas (1). Whereas Mg sheet by conventional ingot-rolling is almost five times more expensive than Al sheet, new continuous-casting technology could potentially reduce prices to be only ~ 20 percent higher (2). This would make components from Mg sheet economically realistic.

There are many scientific/technical problems including developing new low-cost alloys that need to be addressed for Mg to compete with steel and Al-based wrought materials. (Exhibit 6.2.1) The Russians seem to be the most aggressive in developing new wrought Mg alloys (3). Unlike most metals that are stronger in compression than tension, Mg is ~ two times weaker in compression than tension. Mg also demonstrates a strong preferred structure-orientation, with extensive twinning and with properties changing in the working direction. Both these issues require unique designs to compensate for the asymmetrical properties developed by the fabrication process. Importantly, since the Mg crystal structure is hexagonal closed-packed, room-temperature deformability is considerably lower than steel and Al; not until the temperature is ~ 230°C, (450°F) is there enough ductility to form complicated shapes.

Exhibit 6.2.1. Major Research Needs for Overcoming Metalworking Process Challenges

N=Near Term (1-3 years), M =Mid Term (4-8 years), F=Far Term (9-15 years)

Time Line	Strategic Framework	Research Objectives	Perceived Needs
N	1. Expand metalworking applications through developing new alloys.	. Develop new alloys with improved mechanical properties that are cost-competitive with Al. . Develop procedures to refine grains and improve ductility at lower temperatures.	. Develop new alloys and metallurgical structures that can allow ductile forming at temperatures near 90-150 °C. . Examine effects of small alloy additions on grain refinement, e.g., Sr. . Develop thermomechanical processing strategy to get warm-forming ductility.
N	2. Improve understanding of microstructure/ process/ property relationships	. Develop capability for superplasticity.	. Determine structure required to obtain superplastic behavior. Develop process routes to utilize superplasticity in forming shapes.
		. Study effects of process and product design on microstructure.	. Determine influence of microstructure on mechanical properties vs. alloy composition. . Determine influence of process parameters on part microstructure. . Develop heat-treatment procedures coupled with alloy/micro-alloy/nano-alloy materials.
		. Collect materials property database to allow accurate design of wrought automotive components.	. Develop property database from testing wrought products. . Predict static/dynamic behavior as a function of testing/working direction vs. starting material orientation/temper. . Develop design rules that take into account the lower compressive yield vs. tensile strength.
F	3. New generation computer modeling.	. Develop ability to simulate and model wrought structures for automotive applications.	. Develop multi-scale modeling methodology that includes history effects; validate models with experiments.

(1) A. Luo, Publication # SP1947, Transactions SAE 2005, p 161-171

(2) Cost Assessment of Emerging Magnesium Sheet Production Methods, W. Hunt and D. Herling, PNNL-15368, September 2005

(3) C. Bettles and M Gibson, JOM, p 46-49, May 2005

6.2.1. Sheet Production and Automotive Stamping

In the 1930s, Dow Chemical Co. showed that sheet Mg products could be used to produce lightweight tractor-trailers. By 1942, almost 300 T/mo. of AM503 sheet was being used in Germany to make aircraft (1). After the war, price increases and lower cost/improved Al alloys essentially eliminated Mg sheet use for structural applications; however, a great deal of data is available (2, 3).

Low-cost sheet production

Current processing methods to produce Mg sheet from ingot are more expensive than Al. The twin-roll casting method has great promise and could make Mg sheet more cost-competitive and a viable automotive material. It is being studied and developed in China, Korea, Germany, Norway and Australia, as discussed in the Hunt and Herling review (loc cit). Sheet and automotive-stamping technology requires a great deal of development, but at the right price, automotive Mg sheet stampings could see wide applications, see Exhibit 6.2.1.1.

Conventional Stamping

Alloy composition, cast grain structure and thermomechanical processing are important variables in automotive sheet and stamping. Magnesium's hexagonal close-packed crystal structure requires higher processing temperatures (225^{o}C) vs. Al or steel which can be stamped near room temperature. Ultra-fine grain continuous-cast sheet might be warm formable (90-150^{o}C), which could significantly reduce process cost. Tooling designs that compensate for Mg's unique attributes require development, as do rules for hemming, inner/outer joining and lubricants/coatings to improve stamping, drawing and bead formation.

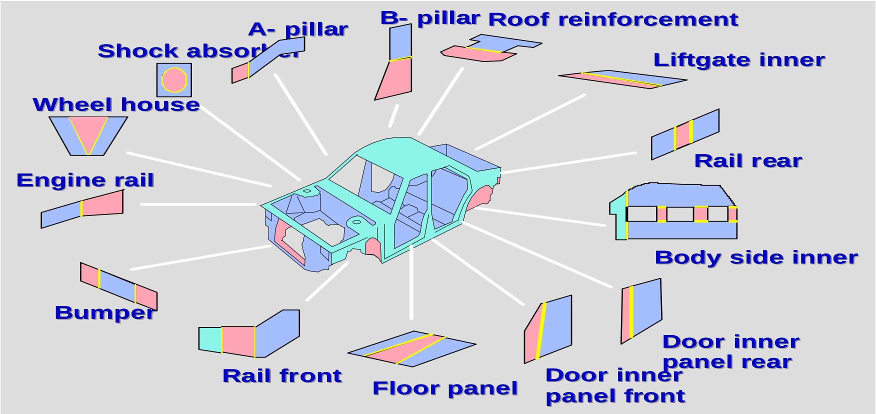
Superplastic Forming (SPF)

SPF can produce body shapes without the concerns of conventional stampings that stretch, tear and crack under unfavorable stamping loads, shapes and temperature. SPF requires unique grain structure, temperature and shape-forming/deformation process development.

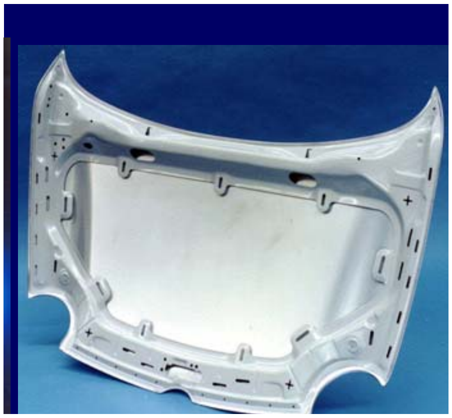
Surface Preparation / Protection

The surface of a stamped sheet may become coated with potentially deleterious particles as a result of the rolling and stamping processing and requires that the sheet be carefully cleaned. This will produce an active surface that requires protection. Coatings also need to be developed to improve their wear resistance. These may include 2-sided, co-rolled, bonded plastic layers, shiny/diamond-hard coatings, Cr-free conversion coatings or other chemical passivation coatings. The ultimate goal is to produce a class A surface using a sheet stamping process.

Exhibit 6.2.1.1. Potential Vehicle Sheet Applications



Stamped VW Lift Gate



(1) Bob Brown, Magnesium Monthly Review, private communication
(2) H. Friedrich and S. Schumann, Transaction IMM, p. C65-71, May 2002
(3) R. S. Busk, Magnesium Products Design, Marcel Decker, ISBN 0-8247-7576-7, 1987

Exhibit 6.2.1.2. Major Research Needs of Sheet Production and Stamping Processes

N=Near Term (1-3 years), M =Mid Term (4-8 years), F=Far Term (9-15 years)

N	1. Reduce cost of magnesium sheet.	. Develop capability for continuously-cast sheet that is competitive with aluminum. . Perform R&D on all aspects of TRC process.	. Set up in NA, or support, a global twin-roll casting (TRC) facility for R&D development. . Develop a process database for TRC. . Produce 3-15 mm thick x 1.8 m sheet with uniform/refined microstructure that can be cold/warm rolled with structural homogeneity suitable for cold/warm stamping. . Develop rolling process to produce required sheet thickness and fine grain microstructure. . Determine if high-intensity heating (e.g. plasma-arc lamps) can provide a low-cost continuous anneal to give the required microstructure.
		. Develop new alloys for TRC automotive sheet applications.	. Develop unique alloys that are responsive to continuous sheet casting processing and automotive stamping. . Determine whether alloying can improve texture via grain-boundary sliding and shearing or via twinning.
N	2. Produce stamped automotive sheet products.	. Develop processing know-how to produce magnesium sheet suitable for automotive stamping applications.	. Develop rules for stamping auto-body components: microstructure, tool heating, joining inner/outer sections, lubricants, coatings. . Determine how TRC sheet compares with conventional ingot-processed sheet for corrosion and properties. . Study response of stamping to dent resistance, stone pecking, weld/adhesive repair. . Develop mechanical property database for stamped body designs. . Determine thermo-mechanical/alloy process to produce ultra-fine grained sheet for warm forming.
M	3. Superplastic forming	. Develop design/manufacturing capability for superplastic forming (SPF).	. Develop alloys and microstructure required to produce SPF sheet products. . Develop processing procedures for SPF; characterize the deformation behavior. . Determine whether modified thixomolding could produce the required SPF microstructure.
F	4. Improve surface of magnesium sheet.	. Improve surface protection and finishing of stampings.	. Study cleaning procedures. . Develop coatings for improved scratch/ corrosion resistance, e.g., 2-sided bonded plastic films. . Study stamping behavior with coatings. . Develop shiny, diamond-hard coatings to improve magnesium sheet scratch resistance. . Study continuously-applied spray/dipped coatings to protect surface...galvanizing, Cr-free conversion/chemical passivation coatings. . Develop embossing procedures to produce unique designs.
F	5. Use sheet to produce other shapes.	. Form tubes from sheet.	. Determine the processes for rolling and welding sheet into tubes. Determine whether tubes can be hydrostatically formed into engineering shapes.

6.2.2. Extrusion

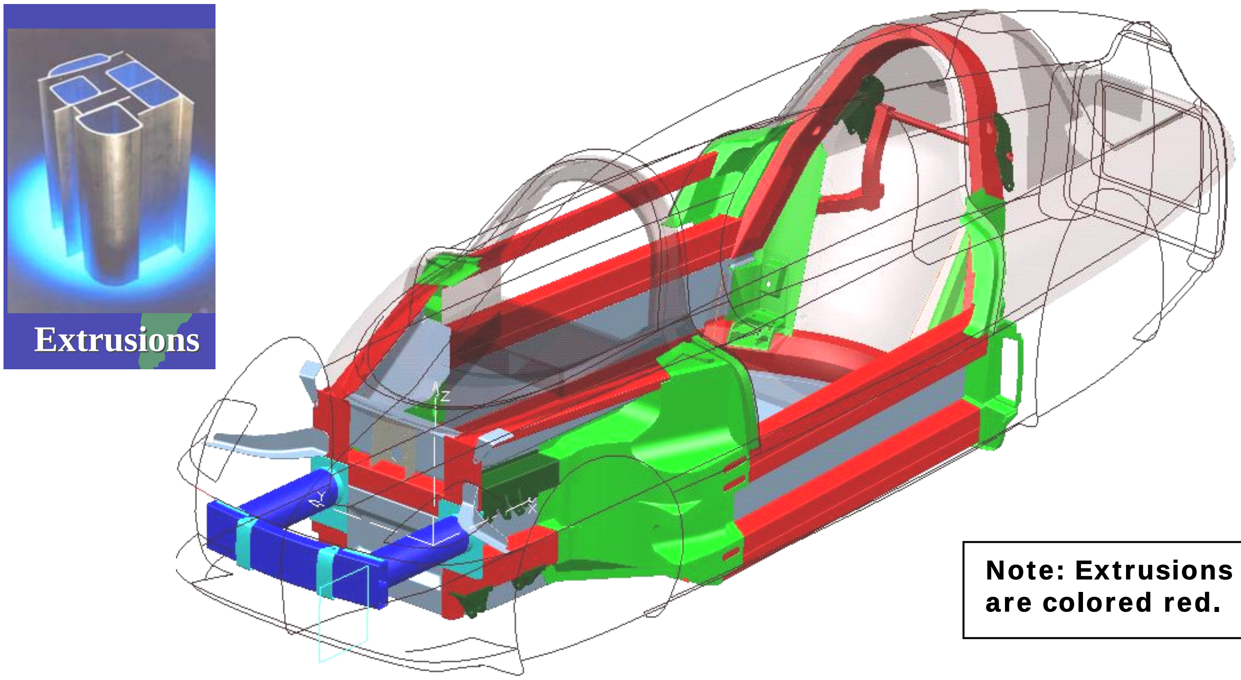
Automotive applications of Mg extrusions depend on the ability of Mg alloys to support the stresses to which the component is subjected. Mg appears to offer weight-saving potential in single-axis tensile and bending-stress applications where thin walls and component cross-sections can be correspondingly enlarged. The fundamental advantage of Mg extrusions lies in their better mechanical properties compared to cast components...up to 15 percent elongation at fracture (Friedrich and Schumann, loc cit). The VW researchers noted that the energy absorption capabilities of Mg were lower under dynamic axial stress; with dynamic transverse and diagonal loading, the differences were less marked. The authors also reported that new alloys had an increased potential for higher specific-energy-absorption compared to Al or steel.

General Technology Issues

Alloy/Process Development

Newer alloys such as AM10, AZ21 and ZM21 extrude at least twice as fast, at 2 m/min., as the common AZ31 alloy. In turn, this is 10 times faster than the common AZ61 alloy; i.e., when the ram speed is increased with the older alloy families, the temperature increases too high causing hot cracking. The equipment and tooling for extruding Mg tubes differ from Al in terms of tooling geometry, thickness, tube diameter, ribbing and tolerances (1). The processing procedures (temperatures, rates, forces, lubrication, etc.) have not been optimized and at one-half the rate of the hard-to-extrude Al A6063, even the fastest Mg extrusions are not cost competitive. There is limited production in NA and Europe and the processing procedures and alloys that would allow increased extrusion rates require further study. There has been some indication that hydrostatic extrusion could increase the extrusion speeds five-fold, but the knowledge base is limited.

Exhibit 6.2.2.1. Example of Mg Extrusions in an Advanced Vehicle



Note: Extrusions are colored red.

The extrusions are part of a 1 L/100 km (240 mpg) vehicle built by VW in 2003 to show the advantages of lightweight engineering for fuel reduction. In addition to extrusions the vehicle also contained magnesium castings (green), magnesium sheet (grey) and Al (blue). H. Friedrich, (private communication).

1) C. Davies and M. Barnett, "Expanding the extrusion limits of wrought magnesium alloys" JOM p 22-243, May (2004)

Exhibit 6.2.2.2 Major Research Needs for Extrusion Processing

N=Near Term (1-3 years), M =Mid Term (4-8 years), F=Far Term (9-15 years)

Time Line	Strategic Framework	Research Objectives	Perceived Needs
N	1. Reduce cost of producing magnesium extrusions.	. Increase extrusion rates.	. Develop capability to increase extrusion rates from 10 to 100 m/min. . Develop new alloys to produce a billet that can be heated and remain grain refined (no grain growth), will not be "hot short" (have too low a solidus temperature) at the temperatures required for high speed extrusion, and will have minimized property anisotropy. . Optimize processing procedures (temperatures, rates, forces, lubrication) to increase the extrusion rates, while maintaining high mechanical properties.
		. Develop new technology.	. Develop the hydrostatic extrusion process, which has the potential for 5x increase in extrusion rates. . Develop capabilities for thixo-extrusion and determine if starting microstructure can influence extrusion rates.
M	2. Apply extrusions to automotive applications.	. Produce automotive components with extruded members. . Develop new applications for magnesium extrusions.	. Develop mechanical property database for extrusions for modeling and component development; characterize microscopy and properties as function of processing. . Study the anisotropy in tensile vs. compressive properties; determine whether microstructural modifications can reduce the anisotropy.
		. Develop tube-bending capability. . Characterize the applications.	. Develop design rules that encompass the data. . Examine mechanical/physical properties and processing requirements for automotive applications in bumper beams, rails, space frames, sub-frames, seats & window frames. . Determine bending process characteristics for hydroforming technology: temperature, bend radius and wall thickness . Develop understanding of stretch-bending. . Determine if welded-sheet tubing has the same properties as extruded tubes.
		. Characterize crash capability of extrusions.	. Develop full understanding of crash (strain rate) and damage response of different extrusion geometries and microstructure. . Understand the effect of straightening and weld repair on function.

6.2.3. Forging

Typical

General Technology Description (Exhibit 6.2.3.2)

Forgings are used where castings either have too much variability in properties or are too weak. Forged Mg parts have seen limited automotive use (1) because of high cost and a limited knowledge base. Elevated temperature forging is required to force metal into the die cavity. The resultant metal flow causes the part to develop a crystallographically preferred orientation, with second-phase particles and grain axes lining up in the strain direction. The mechanical properties mirror this asymmetry, being higher parallel to the flow direction and lower in the transverse. An important part of the forging design process is to ensure that metal flow is directed to where maximum properties are required (2). The strong interaction among component design, forging process, mechanical properties and application loading requires much development in Mg. Potential Mg forging applications include steering knuckles, control arms and high-strength road wheels.

Forged Road Wheel

Exhibit 6.2.3.2. Major Research Needs for Producing Magnesium Forgings

N=Near Term (1-3 years), M =Mid Term (4-8 years), F=Far Term (9-15 years)

Time Line	Strategic Framework	Research Objectives	Perceived Needs
N	Develop forging process for Mg.	. Develop new alloys. . Develop understanding of forging processing; characterize material properties of new alloys.	. Determine whether current alloys meet the competitive requirements of aluminum, ductile iron, and compacted iron components. . Develop improved low-cost alloys that have better heat treating and forging response. . Develop forging practice and heat treatment procedures; measure properties as a function of loading, temperature and alloy composition. . Develop appropriate die lubricants. . Determine the effect of starting structure of blank (direct chill-cast stock or pre-extruded stock) on forging properties. . Determine how to prevent recrystallization and grain growth during forging and heat treating. . Develop non-destructive-testing (NDT) procedures on blank to ensure no second-phase intermetallic or oxide particles.
M	Use forging technology to produce automotive components.	. Develop new automotive applications for forged magnesium.	. Examine applications for forged components in chassis applications where castings have either too much variability in properties or are too weak. . Determine the effect of various forging steps vs. reduction and temperature on structural/property directionality throughout the part.
F	Improve durability of Mg forgings.	. Determine issues that influence durability of Mg forgings.	. Examine corrosion/rotary fatigue/impact conditions. . Perform FMEA on selected designs. . Develop NDT strategy.

REFERENCES:

1) R. Brown "Developments in Magnesium Wrought Products", Magnesium Technology 2002, H.I. Kaplan Ed, TMS p 156-64 (2002)
2) E.F. Emley, Principles of Magnesium Technology, Pergamon Press, (1966)

6.2.4. Magnesium Powder Processing

There is interest in using magnesium powders because of the ability to get very rapid solidification and utlra-fine (perhaps nano-scale) structures, thereby allowing non-equilibrium phases and very hard/strong particle compacts. Conventional magnesium alloys display grain growth problems (coarsening) that powders do not have. Extruded Mg powders may have valuable mechanical properties at very high temperature, analogous to sintered aluminum powder (SAP). Emley (loc cit) reports that extruded powders have high reduction ratios, higher extrusion speeds and can be formed at higher extrusion temperatures, near the solidus. Lavernia (1) is developing new spray procedures to produce Al powders and to build up structures directly from powder spray; this process could be applied to Mg and might provide interesting products.

Exhibit 6.2.3.2. Major Research Needs for Producing/Using Magnesium Powders

N=Near Term (1-3 years), M =Mid Term (4-8 years), F=Far Term (9-15 years)

Time Line	Strategic Framework	Research Objectives	Perceived Needs
N	1. Produce low-cost powders.	. Develop processes for producing powders. . Characterize magnesium powder properties.	. Adapt current aluminum powder processing methods to magnesium. . Determine whether experience with high-strength sintered aluminum powder (SAP) can be applied to magnesium.
N	2. Increase application temperatures for Mg components produced from powders.	. Develop new alloys.	. Examine mixtures of magnesium alloy powders and other ceramic/metal powders either as micro- or nano-composites. . Design alloys that optimize the high-temperature application of compacted powders. . Determine if heat-treatment protocols can allow powder compacts to have enhanced ambient and high-temperature mechanical properties.
		. Develop heat-treatment databases.	. Develop database of properties and costs.
M	3. Produce powder compacts.	. Develop extrusion processes and forging processes for auto application.	. Determine cost and functional component benefit of powder forgings and extrusions.
F	4. Develop metal injection molding	. Study technology to perform metal injection molding with Mg-based alloy powders.	. Determine effect of powder size on properties. . Characterize ability to extrude base powders or powders coated/mixed with polymers.
F	5. Produce powders by new processes.	. Consider spray atomization. . Consider splat cooling.	. Determine whether spray atomization (1) can be used to economically produce powders for automotive parts. . Determine if splat-cooled powders have value to produce interesting structures.

(1) E.J. Lavernia , J. Baram, and E.Gutierrez, Materials Science and Engineering A 132, (1999) p. 119-133

7. Enabling Infrastructure

Background

Tier One Evolution

There has been a considerable shift in the U.S. automotive industry over the past 30 years with the automotive Original Equipment Manufacturers (OEMs) outsourcing a large portion of their activities to (fewer and fewer) Tier One assemblers. The Tier Ones have become multibillion-dollar entities that design and manufacture steel, plastic and Al components from purchased/in-house manufactured sub-components, and then ship these larger assemblies to OEM production lines for direct installation into vehicles. Tier Ones are responsible for much of the new product development and technology used on U.S. automakers' vehicles.

There seems to be little commercial interest in weight reduction as a major attribute that can add customer value. At 12 lb./vehicle, magnesium is only a minor attribute of the design envelope and is below the radar screen of the U.S. auto industry design engineers and program managers.

Currently, only one Tier One has the infrastructure to design, produce, assemble and develop implementation ready Mg components; for most Tier Ones, Mg parts compete with their current suite of manufactured components. With this limited Tier One competency, the success of a 350 pound Magnesium 2020 vision requires a major change in how Mg components are developed, manufactured, sub-assembled and installed on vehicles.

History of NA Aluminum Developments

The Al, plastics and steel industries have historically poured billions of dollars into supporting their current and potential customers with unique designs, and developing the manufacturing processing to achieve those designs. For example, when the Al industry began its growth spurt in the 1950s, Alcoa, Alcan, Reynolds and others provided hands-on, 24/7, engineering and managerial support to convert components from steel and cast iron. Auto designers were supported with unique Al products that improved function while reducing cost. At the same time the laboratories of General Motors Corporation, Chrysler Corporation and Ford Motor Company provided reciprocal support with funding, facilities and manpower to further leverage their foray into lightweight automotive components. Now the Al and auto laboratories have consolidated, many metallurgical specialists have retired, and engineering staffs are now focused more on cost reduction.

North American Manpower

Compared to the institutional effort that nurtured Al industrial growth in the 1950s-80s, the manpower to develop a new metallurgical industry based on Mg no longer seems available. Fewer students are studying metallurgy and manufacturing in NA institutions of higher learning. In addition, since the 1970s, NA has seen a gradual deindustrialization with many manufacturing jobs moving off-shore. According to the Bureau of Labor Statistics, in 2002 less than 10 percent of the workforce (130M workers) were involved in manufacturing vs. 33 percent 50 years ago. Without governmental support, there may not be enough manufacturing-metallurgical expertise to support Mg component development.

New Paradigm for Materials Technology

Three-hundred-fifty pounds of implementation-ready magnesium components on a vehicle could not occur by 2020 with the limited technical, corporate, academic and governmental infrastructure currently available in NA. That is why this document proposes 3 strategies... continuation/expansion of existing industry-U.S. automaker magnesium projects (such as SCMD and MPCC), creation of a virtual magnesium technical center and extensive cooperation/collaboration with global organizations under the auspices of USAMP.

7.1. Magnesium Center of Excellence (MgCOE)

Definition

A virtual organization to coordinate the acquisition of Mg knowledge, outsource implementation readiness and provide design and manufacturing support for automotive Mg products.

Background

There are as many, if not more R&D problems that require resolution with Mg as there were with Al when it entered the automotive industry 50 years ago. However, as discussed previously, the world has changed and the Al model cannot be replicated.

Objective

The Magnesium Center of Excellence (MgCOE) will supply design, manufacturing, testing and general implementation readiness capability. It will provide marketing and educational support functions, incubate the technology required for the Magnesium Vision 2020 to succeed and perform multidisciplinary engineering/manufacturing research. OEMs and Tier Ones will use the Center to develop and prototype new processes, develop manufacturing feasibility data, design and produce prototype products, perform implementation-ready protocols and develop cost models. This is not a conventional “brick and mortar” structure. Rather it is a networking of global resources into a command center that will manage the required information to implement new products and processes. It would support the vision of Dr. Jenny Jackman, Department of Natural Resources Canada:

> Magnesium is a new and strategic material. In terms of technology development, it is where steel was a little over a century ago. It is a challenging material and likely to become quite significant to society over the next century because of its high strength-to weight ratio, abundance and other useful properties. A lot of knowledge on this material is emerging now all around the world - all supported by government funding. If we pull out now, that knowledge will reside in other countries. I think that magnesium is too strategically important to our society to pull out public funding at this point and allow other countries to have a monopoly on the knowledge.
>
> If magnesium does become an important metal in society, and given that its use is dependent on a high degree of knowledge, then we would be well advised to ensure that a fair share of that knowledge is resident in the minds of North Americans.
>
> Dr. Jenny Jackman, private communication July 25, (2005), as edited by Dr. Gerald Cole

Examples of Possible Programs

- Work virtually with engineers from supplier companies to optimize current products and processes and/or develop new product designs and processing.
- Provide assistance to existing and new AMD/USAMP Mg R&D programs with NA academic institutions, NA automotive casting and metalworking industries and the NA automotive OEMs/supply base.
- Obtain automotive-relevant engineering data, similar to that provided by Alcoa and Alcan and the automotive laboratories of the past 50 years.
- Develop marketing and outreach programs for OEMs and Tier Ones.
- Provide a central information resource for automotive design, engineering and manufacturing.
- Be able to perform component and system testing of Mg.
- Supply Mg activities similar to a university agricultural extension program or for example, a Georgia Institute of Technology local industry extension program.
- Provide information and/or facilities for educational outreach to educators/students (from K-12 through graduate school) and to consumers, OEMs, suppliers and government including authoritative information addressing misconceptions about magnesium’s flammability.

- Assemble a cost-effective, ultra-lightweight Mg-intensive vehicle and demonstrate its durability/crash functionality via CAE, laboratory and proving ground testing.

Facilities and Manpower

The center will have limited physical assets. It will contract R&D and implementation readiness until the Mg suppliers are sufficiently capable to provide the requisite support for growing their own Mg applications.

Funding

It is proposed that funding will initially come from federal and state governments and USAMP through direct funding, cooperative agreements, and/or Cooperative Research and Development Agreements (CRADAs). Suppliers and OEMs will use the center to develop cost-effective Mg applications for which they will pay via some appropriate industrial fee-structure.

7.2. Global Collaboration in Magnesium Technology

Why Collaboration?
There is an unknown storehouse of R&D knowledge held by global researchers that could be applied to meet the Vision 2020 goals. For Magnesium Vision 2020 to succeed, worldwide cooperation and collaboration will be required among industry, academia and state/federal governments.

How Will It Work?
Significant automotive conversions by U.S. automakers to Mg are unlikely to occur with the current infrastructure. The MgCOE would be an important vehicle to promote a Mg mindset in the academic, government, OEM and supplier network. NA professionals would design, develop and distribute Mg-relevant automotive information in cooperation with NA and foreign scientists/ engineers. This information would be organized into product/process programs that together with laboratory/proving ground test activities would lead to implementation-ready components.

Resources, Funding and Program Elements of the Collaboration Plan

Governmental Level – Government resources are required for funding and policy development. Cooperative funding will be developed among federal/state/provincial government officials in the U.S., Canada and abroad to support the initiative. (Most of the global Mg R&D is managed currently via government resources.) A global cooperative program will leverage the limited amount of individual national funds, currently employed in Mg research, into major global programs for weight reduction, supporting the fuel and emissions reductions desired by all governments.

Scientific Level – Programs will be arranged by U.S. science officials (at NSF, DOE, DOD, NIST, etc.), with their Canadian counterparts (such as CANMET) and other interested foreign science organizations, to be performed at universities, technical colleges, state and provincial science and technology facilities, and national laboratories.
Two goals have been identified:
1. To capture a global Mg microstructural engineering knowledge base in: integrated computational materials engineering tools; integrating process/materials/performance; integrating microstructural evolution and property prediction; integrating experiments/models; and establishing a collaborative infrastructural tool for data and models. Additional objectives are to identify/promote a microstructural engineering network list of experimental/analytical global research activities, personnel and facilities for materials engineering, manufacturing processes and part properties.
2. To understand the fundamentals of microstructure formation during solidification, from HPDC to sand castings, in billet production to continuous cast sheet; and to understand how the microstructure of Mg can be manipulated to improve formability through identification, quantification and control of critical microstructural parameters.

Engineering Level – Technical organizations such as SAE, SME, TMS, ASTM, ISO and ASM will detail the manufacturing and technical infrastructure cooperation for automotive parts requirements including manufacturing, chemical/physical/mechanical properties and automotive part standards in the NA and off-shore markets.

Educational Level – Develop a NA infrastructure for educating and fostering the next generation of Mg technologists.

Commercial Level – Develop cooperation among U.S. and Canadian commercial entities and foreign counterparts, to produce components and validate implementation-ready solutions.

8. Summary and The Path Forward

Magnesium's main automotive advantage is its ability to enable lightweighting. The Magnesium Strategic Vision proposes reducing vehicle weight by 15 percent (500 lbs.), substituting 340 lbs. of magnesium components for 840 lbs. of steel, aluminum and plastic parts (assuming 210 lbs. of secondary weight reduction/powertrain resizing). Weight reduction provides customer value and is complementary to diesels, alternate fuel/hybrids and fuel cells for increasing performance and/or reducing fuel consumption. It is thus an enabler for the FreedomCAR hydrogen-fueled vehicle. Gasoline prices have risen recently to a level where consumers are beginning to demand and purchase more fuel efficient vehicles. By 2020, automotive growth in India and China will add further pressures to increase NA fuel efficiency.

While over 350 lbs. of magnesium parts have been approved in the past, there are only ~ 12 lbs. on the average U.S. automaker’s vehicle. The challenges that limit growth have been examined in this document based on concerns that magnesium burns easily, that magnesium parts are too costly, and that they have variable quality, poor corrosion and fastening durability. USAMP currently supports several magnesium research and development (R&D) initiatives to address these concerns. This document suggests that expanding the R&D to over 150 R&D themes (RDTs) could overcome the challenges and promote more Mg applications in the NA automotive industry.

Cost Reduction/Quality Improvement – The most formidable challenge to using more Mg in NA is higher cost vs. other materials; i.e., the cost of the base Mg parts, plus anti-corrosion and fastening. In a fully accounted sense, current Mg components are only slightly more costly than components produced from Al, plastics and steel. 21 RDTs are proposed that could reduce cost: through improving recycling, reducing magnesium used in the component via optimal CAE designs and by reducing waste through improved quality/reduced rejects.

Corrosion and Joining – The scientific and technical barriers associated with corrosion and joining are addressed in this document via 34 RDTs in corrosion and 17 in joining. Successful data will increase auto industry confidence that corrosion can be prevented and that magnesium can be securely fastened to a vehicle in a robust/cost-effective manner.

New Products – New, smaller magnesium applications are proposed. Also, two large magnesium-integrated vehicle concepts are presented (in the Appendix A) that could expand magnesium beyond the 350 lbs. of individual applications required to achieve a 15 percent weight reduction goal.

New Manufacturing – High Pressure Die Casting (HPDC) is used for over 99 percent of the magnesium components currently in global use. To provide the range of products proposed in this study, newer cast as well as wrought technologies are required. The document examines technical issues associated with new solidification and casting processes via a series of 36 RDTs that address open issues in producing large, thin-wall, low-cost, non-HPDC castings. Wrought technologies are not used currently to produce magnesium components because of cost and technical (mainly formability) issues. Almost 70 RDTs are presented that address concerns in manufacturing components via sheet/stamping, extrusion, forging and wrought powder routes.

New Analytical Technology – New multi-scale modeling and simulation-specific capabilities need to be developed for casting/metalworking magnesium alloys that include the history effects associated with stamping, extrusion, forging, casting and heat treatment. The objective is to develop cradle-to-grave-to-cradle simulation tools that cover different alloys and various material scales of analysis (electronic, atomistic, macro-scale, etc.). Experiments will validate the models and allow future designs to be developed without expensive and lengthy trials.

International Collaboration – For this magnesium strategic vision to succeed, cooperation and collaboration will be needed among industry, academia and state/federal governments from all corners of the world. Many countries are expending money and acquiring fundamental information about magnesium. There is a storehouse of R&D knowledge held by researchers around the world that could be applied to promote the 2020 goal of 350 lbs. magnesium parts on U.S. automakers' vehicles. If we developed access to that information, we could leverage our North American efforts.

Enabling Infrastructure/Magnesium Center of Excellence – Achieving the Magnesium 2020 Vision requires developing NA R&D via an infrastructure that could engineer/design, manufacture, and test/approve/certify magnesium components for automotive use. A virtual Magnesium Center of Excellence is proposed that could integrate global magnesium scientists, engineers, and automotive manufacturing/product development specialists. They would collect global information and develop implementation-ready magnesium products and processes. This approach could provide for magnesium much of the automotive-aluminum industrial R&D/support/marketing infrastructure that sponsored aluminum's growth over the past 50 years. The magnesium center will be a repository for the knowledge required to support a NA lightweight vehicle architecture.

Next Steps.

It is proposed that USAMP take the lead in implementing the strategy described here and to manage the process of overcoming the challenges to magnesium implementation by undertaking the following proposed actions:

1. Create and program the activities of a Magnesium Center of Excellence concept.
2. Determine the protocol for working with global experts.
3. Determine the best way to organize, fund and perform the over 150 R&D activities described.
4. Manage a magnesium-intensive demonstration vehicle.
5. Market the value of magnesium for vehicle lightweighting to government, academia, OEMs and suppliers.

EPILOGUE

Lightweighting with magnesium can improve fuel efficiency and emissions reduction and will excite customers with innovation and performance. The research and development activities identified in this Magnesium 2020 document represent a key for overcoming the cost, technical, and infrastructure challenges that will lead to increased magnesium automotive applications. Success will come from the simultaneous involvement of a variety of stakeholders to address automotive magnesium design and manufacturing opportunities. Successful completion of the Magnesium Vision 2020 strategy will give NA OEMs and suppliers confidence that magnesium components will add function, value and competitiveness to NA vehicles.

APPENDICES

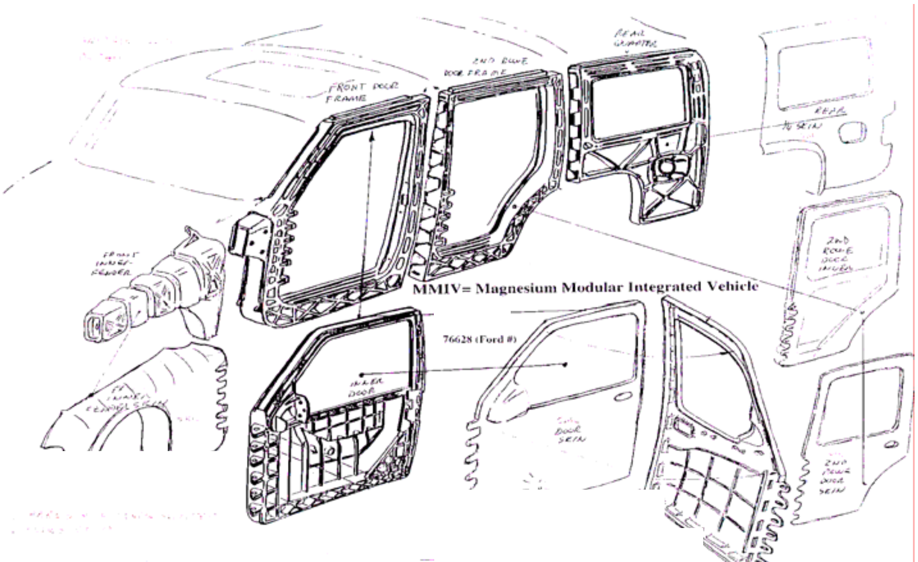
Appendix A

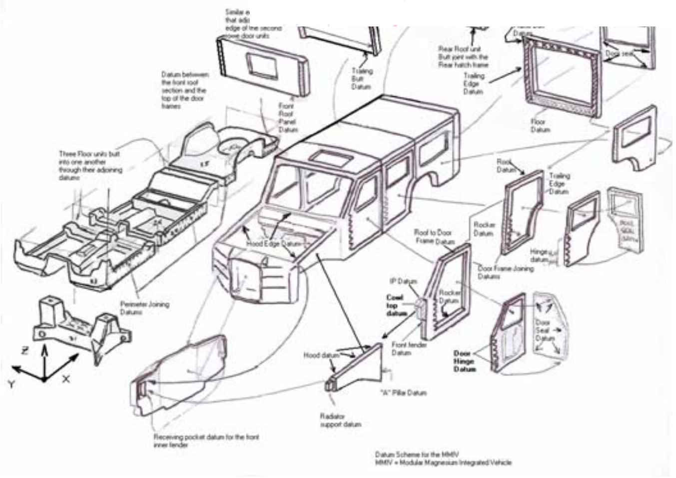
Paradigm Shift …. Using Large Connected Magnesium Structures

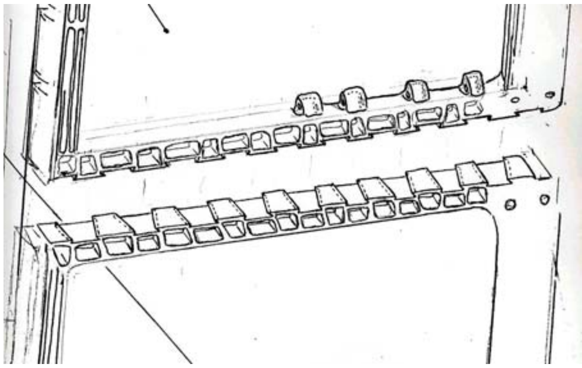
There are possibilities to use magnesium in ways that can make a paradigm shift in how vehicles are conceived and assembled. Because these structures are so extreme, they are included in the Appendix rather in the main body of the text. Two examples are shown below.

The first design conceives of a vehicle concept composed of 25 building blocks of ultra-large HPDC magnesium castings that will allow an OEM to make a variety of vehicles. The individual elements are locked in place to create an integrated skeleton. The outside primary surface is covered in SMC (polymer) color impregnated thin skin which does not take load and does not have to provide crash/crush contribution. All vehicles using the system can be built in any plant; the assembly line doesn't care. The integrated skeleton reduces the number of sub-component parts, variability, labor and weight and pays for the lightweight metal. This system eliminates plant changeover for new models since it is only the skin that varies, thus reducing assembly plant capital equipment costs. The integrity and load transfer mechanism of the HPDC Mg elements is based on their being assembled into lock-in-place dove-tail joints bonded by unique high strength adhesives.

Proper execution of the system could result in approximately 25% weight reduction.

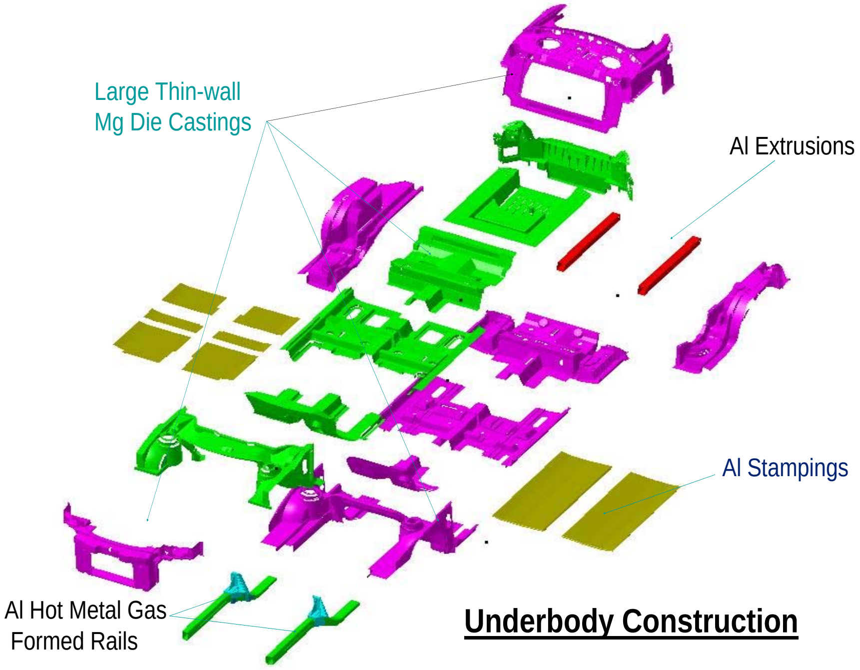




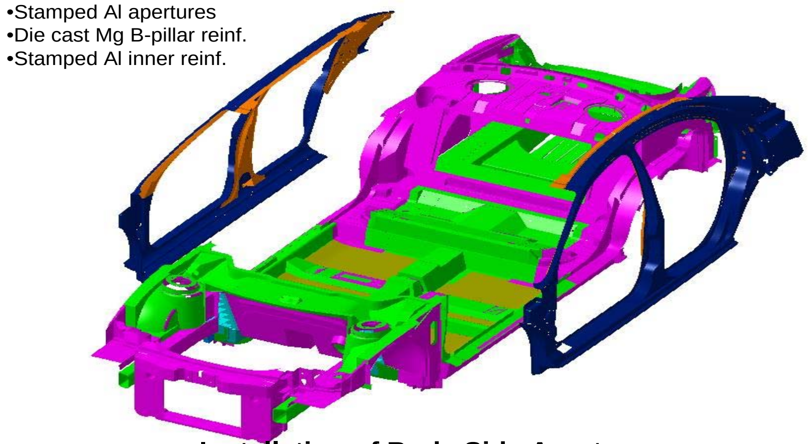


The second model was developed by engineers at DaimlerChrysler Corporation (1). It is a hybrid of Mg, structural foam and Al (which could be fabricated in the future from Mg). It reduces weight while also improving function.

Exhibit A.2. Hybrid Mg/Al/Foam 49% Weight Reduced Body-in-White



Underbody Construction



Installation of Body Side Apertures
on Underbody

The advantages to this design include

- Reduced part count: (-78%), Bending frequency improvement: (+3 Hz or 8.5%)
- Torsion frequency improvement: (+10 Hz or 25%)
- Meets or exceeds all NVH and energy management goals:Better than current vehicle on current standards and meets new 50 mph offset rear impact standard
- Variable cost: (+3%), Investment cost: (-46%)
- **Reduced weight: (-356 lbs. or 49%)**

(1) Stephen Logan, David Gostovich,William Doolittle, Suresh Nagesh, DaimlerChrysler Corporation

Appendix B

Background to Magnesium Ingot Production

Currently, there are two commercial Magnesium production processes employed; the electrolytic process (used by Hydro-Canada, US Magnesium-Utah, Dead Sea Magnesium - Israel and the several Russian/Ukrainian operations) and the Pidgeon process used by producers in China. Each process has its advantages and disadvantages. The electrolytic process is very capital intensive and requires significant amounts of electrical energy. As a result, like aluminum smelting, it is frequently located in areas with abundant low-cost hydroelectric power in North America. Since there is not a terminal market for magnesium as the London Metal Exchange is for aluminum, long term price hedging is accomplished contractually between buyer and seller based on the relative predictability of future cost inputs.

The Pidgeon process in China by comparison requires about one-tenth the capital cost but uses more energy, typically in the form of coal. It also is significantly more labor intensive. The challenge for the smaller Chinese magnesium producers is the lack of price stability for the primary inputs. Supply disruptions have occurred, related to weather, mine closures (because of poor safety practices), or electricity availability. Supply contract terms are short, typically 3-6 months. At the current costs of coal, ferrosilicon, dolomite and labor, the Pidgeon process is about 25 percent less costly than the electrolytic. By the early 2000s, China was supplying about 70 percent of the world's demand for magnesium, exporting 70 percent of its 600,000 T capacity at prices ~ $0.80/lb. This forced the closure of over 300,000 T of higher cost NA and European production.

The magnesium market benefits from the existence of both forms of production. Automotive companies and their suppliers are able to obtain long-term stable pricing and supply from Western suppliers for new applications. Chinese supply on the other hand can offer lower pricing, though it may fluctuate significantly during any 12-month period. The institution of anti-dumping procedures in April 2005 against Russian and Chinese magnesium caused significant instability in the supply chain and prices increased soon afterwards to $1.40-$1.50/lb. However, as a result of increased competition between Western producers, US prices have begun to decrease. The US market clearly is not entirely isolated from the effects of Chinese production.

Ongoing R&D in China continues to improve the Pidgeon process. Even with revaluation of the Chinese currency and increasing costs for transportation, emissions-reduction and coal, Chinese ingot should continue to remain in the $0.90-$1.00/lb. level outside the United States.

Appendix C

Properties of Magnesium Alloys vs. Plastics, Aluminum and Steel

Exhibit C. 1. PHYSICAL PROPERTIES OF MAGNESIUM

PROPERTY	Units	AZ91D	AM 60B	AE44 (1)	AJ62A (2)	Al A380 HPDC	Al A356 T6	Nylon + 30% Glass	ABS	Steel
Sp Gravity	g/cm^3	**1.81**	**1.79**	1.82	1.80	2.74	2.69	1.4	1.05	7.8
Th Conductivity	W/mK	**51**	**61**	84*	62	96	159	0.33	0.28	14
Coeff Th Expan	μm/mK	**26**	**25.6**	26.1	28	22	21.5	34.5	76.5	12
Damping Capacity	% @ 35 MPa	**29**	**52**	?			1.2			
Specific Heat	J/LK	**1120**	1090	750-1050*	1150	2,640	2,590			1,200
Heat of Fusion	KJ/L	**673**	same	Same	Same	1,066				
Freezing Range	^{o}C	420-598	420-615	572-620	515-611	540-595	555-615			
Corrosion Wt. loss 3 days in 5% NaCl ASTM B117	mg/ cm^2/d	**0.1**	**0.25**	0.2 *	0.04	0.33				0.5

* AE42 data

(1)Alloy used in SCMD project to produce the GM Corvette engine cradle

(2)Alloy used by BMW to produce the world's first Mg HPDC engine block

Exhibit C. 2. MECHANICAL PROPERTIES OF MAGNESIUM

Property	Units	Condition	AZ91D	AM60	AE44	AJ62A	Al A380 HPDC	Al A356 T-6	Nylon + 30% Glass	ABS	1010 Steel
UTS	MPa	Amb	230	220	245	234	320	262	195	45	~330
YS (tensile)	MPa	Amb	150	130	142	140	160	185	170	40	~200
(comp)	MPa		165	130	103*	105		186			
Shear Str	MPa		140				214	205			
RB Fatigue St	MPa	5 x 108 c	82	60		92	145	90			
0.1% Creep St after 100 hrs	MPa	125^{o}C	34	34		59^	135				
Impact St Unnotch	Joules		6	22	15	13	3.5	11			
Notched	Joules		1.5	3.2		4.2					
Elongation	%		3	~10	10	7	4	5	8	17	30-50
Elastic (Young's) Modulus	GPa	Amb	45	Same	same	same	72	73	8.9	2.1	207
Shear Modulus	GPa	Amb	14				27	28			83
Brinell Hardness			65	60	62	61	80	80			140
Poisson's Ratio			0.35	0.35			0.33				0.3

^ After 200 hours at 120 C

Magnesium is not as strong or as hard as steel, and has a lower ultimate tensile strength and fatigue strength than aluminum. However its relative properties (property/density) are equal to or better than most competitive materials. Magnesium has twice steel's relative yield strength and is almost equal in relative modulus. Magnesium components can be designed and cast with cross-sections, ribbing and surface features that can ensure functional viability (stiffness, strength), and durability.

Appendix D
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Appendix E
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