Magnesium: Where Have We Been, Where Are We Going?

A 65 Year Retrospective on the Use of Magnesium

By Joseph C. Benedyk, Editor, *Light Metal Age*

Abstract

Since its first publication in May 1943, *Light Metal Age* magazine has been collating the progress and the economic ups-and-downs of magnesium, the lightest of the commodity light metals. Starting with the first issue of *Light Metal Age,* its founder, Roy Fellom Jr. wrote about the magnesium production processes of the times (much the same today). This article summarizes the progress made in magnesium technology through the decades, with emphasis on the use of magnesium. The year 1943 was a watershed year for magnesium production, with worldwide production peaking that year due to the war effort and then falling precipitously at the end of WWII by a factor of 50 times. It took decades for the market to recover to where it is today—some four times the worldwide production level during its peak in WWII—with credit due in large part to the remarkable properties of this light metal and to the outstanding work of magnesium technologists in creating alloys and processes that offer advantages and value in commercial applications. These trends in magnesium technology as well as the uses of magnesium have been documented in *Light Metal Age.* Upon cursory examination of the many decades of magnesium usage, we at first sense a case of "history repeating itself" but, digging deeper into the magnesium archives, we see how critical the progress made by magnesium technologists has been in expanding its use in a wide variety of markets.

Introduction

The first issue of *Light Metal Age* was dedicated to the new age of metals—the Light Metal Age—that as its first publisher Roy Fellom Jr. (1913-1993) duly noted then in his editorial:

"Out of the crucible of wars throughout history have been born the great ages of man – the Stone Age, the Bronze Age, the Iron Age, the Steel Age … History is again repeating itself.…Light Metal (magnesium, aluminum, and their alloys) is the child of the present war.…It will be an era of Peace wherein Light Metal will be the dominant metal in the field of applied manufacture.…A truly miracle metal that will become the structural material of industry for automobiles, trucks, trains, tractors, ships, engines, tools, business machines, cranes, bridges, and skyscrapers, and will mark the arrival of the LIGHT METAL AGE."

Supporting his view of the future laid down 66 years ago, Roy would have been pleased to see the progress made in applications of magnesium and its alloys today, albeit in industries developed since then—cases for cell phones and laptop computers, components for satellites and space probes, advanced vehicle powertrains, and many other magnesium applications described at the 65th Annual World Magnesium Conference of the International Magnewium Association (IMA), May 18th - 20th, 2008 in Warsaw, Poland. All of the advancements made in the wider usage of magnesium and its alloys have benefited over the years from the advancements made in development of better magnesium alloys, improvements made in structural designs with magnesium alloys, casting and semisolid process innovations, worldwide magnesium R&D networking, and widespread dissemination of information about the advantageous properties of magnesium and its alloys.

In summarizing decades of magnesium progress, including the "ups and downs," the questions to be answered—where have we been, where are we going?—are perhaps best answered by starting with the present, i.e., where are we now?

Magnesium: Where Are We Now?

Describing the present situation in the world of magnesium, it is apt to paraphrase Charles Dickens in capturing the essence of an environment in the midst of turmoil and change:

These are the best of times; these are the worst of times.

The positive side of the present magnesium scenario has many facets, many of which are made apparent at the 65th Annual World Magnesium Conference; the negative side of the present magnesium scenario, as it should, is voiced here as well.

In the context of the present global environment for magnesium, optimists may believe "the crucible is half full" and these are the *best of times.* Indeed, the following positive aspects for the magnesium industry may be cited:

☺ On a worldwide basis, magnesium production set a record in 2007

☺ New magnesium production processes have been developed that can significantly improve efficiency and reduce capital costs

☺ The focus of vehicle manufacturers on lightweighting augurs well for increasing use of magnesium alloys in structural and powertrain applications, thereby expanding the potential market for magnesium significantly

☺ R&D programs that have been in place since the 1990s are bearing fruit in meeting the challenges magnesium faces from competing materials in lightweighting vehicles

☺ New magnesium alloys have been recently developed that have the properties and requirements to displace competitive lightweight materials in powertrain applications

☺ The lightweight composite aluminum-magnesium engine block developed by BMW was available on all their automobiles in 2007 and received high ratings

☺ Advances have been made in magnesium processing to create large size, thin wall, high integrity structural castings

☺ Magnesium alloy casting and semisolid forming processes and technologies are at an advanced state of development and production efficiency

☺ Continuously cast magnesium alloy sheet and strip are now being produced commercially by twin roll casting and rolling offering advantages over direct chill (DC) cast ingot and rolling and opening the door wider for magnesium sheet applications

☺ Options are now available for magnesium producers to address global warming concerns and reduce energy consumption and CO_2 emissions

☺ Collaboration and networking among peers worldwide in magnesium R&D and technology transfer has never been better, empowered by country and international based forums such as IMA conferences, of course, and by worldwide web resources

☺ Optimists (you know who you are) can add to the list

There are some negative aspects as well in the present global environment for magnesium, and pessimists may believe the "crucible is half empty" and that these are the *worst of times*:

☹ In spite of record worldwide production, the cost of magnesium spirals upward

☹ U.S. antidumping laws have curtailed imports of magnesium from China, the world's largest primary magnesium producer

☹ North American magnesium die casters are struggling due to the imposed antidumping laws in the U.S. and to changes and problems in the U.S. automotive industry, which has traditionally been the largest user of magnesium die castings

☹ For the first time since 1941, there is no magnesium production in Canada, and magnesium production has ceased recently in Ukraine and Serbia as well

☹ The present high cost and low availability of magnesium and its alloys are hampering commercial projects and opening doors for competing materials

☹ The competitive pressure from other metals, plastics, composites, and even wood has never been greater

☹ As are others, the magnesium industry is facing challenges posed by global warming and environmental concerns

☹ Most primary magnesium is produced in China utilizing a thermal process (Pidgeon) that is now faced with emission reduction requirements by the Chinese government

☹ Magnesium was rejected by the London Metal Exchange in 2007 as a traded commodity metal due to the small size of the industry and the control of production by China

☹ In a new European Community program, magnesium will be classified as a potentially hazardous chemical, and magnesium imported in the countries under the jurisdiction of the program will face more scrutiny

☹ Compared with competitive materials, magnesium marketing/sales/engineering infrastructure and support is lacking in the West and some of the other largest potential regional markets for magnesium

☹ Know-how and training of engineers and technologists in working with magnesium and its alloys appears to be declining in the West, a process made worse by lack of availability of the metal

☹ Pessimists (you know who you are) can add to the list

Magnesium Today (2005 – 2008)

Global Perspective: Light Metal Age (LMA) has been reporting on magnesium progress and addressing many of the issues and concerns just listed since its inception to the present time. In his April 2008 annual magnesium industry review, Robert E. "Bob" Brown, contributing editor for *LMA* and publisher of the *Magnesium Monthly Review* (Figure 1), summarized the unusual status of the worldwide magnesium industry today. [1,2] In line with his earlier prediction in February 2007 that "2007 may bring even more startling news for the magnesium industry," [3] 2007 turned out to be unusual indeed, with magnesium production setting new production records while the price was in his words "skyrocketing." Bob pointed out that prices have more than doubled in the 18 months before April 2008: "Prices now hover around $3 per pound for spot purchases after stalling at $1.20 per pound or less as recently as 2006."

As far as production is concerned, Bob reviewed the present worldwide situation thus: "In spite of the fact that there is no longer any magnesium being produced in Canada, Serbia, or the Ukraine, total world production of magnesium is estimated to be 757,500 mt in 2007, an increase of approximately 15% from the 707,500 mt produced in 2006. This is a record for world magnesium production." His summary chart of worldwide magnesium production in 2007 is shown in Table I, where it is seen that ~82% of the world magnesium was produced in some 80 plants in China, all by thermal reduction of dolomite with ferrosilicon (Pidgeon process).

Figure 1. Robert E. "Bob" Brown receiving a lifetime achievement award from the IMA at their 2007 annual meeting in Vancouver, B.C., Canada.[1]

Country of production	Total Magnesium Produced, metric tons	Total Thermal Mg Produced	Type of thermal process
United States(1)	43,000	0	
Canada	0	0	
Brazil (1)	(e)9,000	9,000	Bolzano (Ravelli)
PR of China(80)	627,500	627,500	Pidgeon
Serbia	0	0	
Russia (2)	(e)35,000	0	
Israel (1)	33,000	0	
Ukraine	0	0	
Kazakhstan (1)	10,000	0	
TOTALS	(e)757,500	636,500	84%

Table I. Worldwide magnesium production for 2007 (e = estimated).[2]

Regarding magnesium consumption in 2007, Bob gave an estimate of 593,500 mt, and broke out the major and minor market segments for the period 2001-2007 (Table II). He noted that, although wrought magnesium has long been a minor category of use, new developments are afoot to produce and use more magnesium sheet. For example, the Korean steel company Posco has opened a 3,000 mtpy magnesium sheet plant utilizing a FATA Hunter twin roll caster to continuously cast magnesium alloy coils.

The Canadian perspective on primary magnesium presented by George Simandl and coauthors was most instructive about the causes of the current supply/demand scenario, describing first the historic shift in magnesium production since 1915 and its influence on pricing, then analyzing the trend today.[4] Prices rose simultaneously in 2007 with the closing of Norsk Hydro's 45,000 mtpy Bécancour plant in Quebec (Figures 2 and 3), leaving Canada with no primary magnesium production for the first time since 1941. With primary magnesium in 2007 *at the crossroads*, the global outlook in Canada begs for stability of supply, with reactivation of Canadian projects held out as a possible but high risk future hope.

Automotive Magnesium Developments in China: The present status of magnesium in the Chinese automotive industry was extensively reported by Dr. Dajun Chen.[5,6] Reporting on the 2007 China Magnesium & Automotive Conference held in June in Chongqing, China, Dajun describes the

Market Segment	2001	2002	2003	2004	2005	2006	2007
Aluminum Alloying	142,810	145,610	137,000	162,000	165,500	172,000	180,000e
Die Casting	150,000	167,800	179,000	231,000	223,000	250,000	265,000e
Desulfurization	41,940	57,385	75,000	80,000	89,000	97,000	100,000e
Sub Totals	**334,750**	**370,795**	**391,000**	**473,000**	**477,500**	**519,000**	**545,000e**
Minor Markets							
Electrochemical	7,500	5,180	6,000	7,500	8,000	8,000	8,000e
Chemical Uses	6,000	4,790	5,000	5,000	6,000	6,000	6,000e
Metal Reduction	3,400	1,000	2,000	6,000	7,000	7,000	10,000e
Gravity Casting	(other)	1,860	2,000	2,500	2,100	3,000	3,000e
Wrought Products	3,200	3,100	8,000	7,500	7,000	7,000	8,000e
Nodular Iron	8,400	3,000	5,000	5,000	5,000	5,000	5,000e
Other uses	10,400	9,330	9,000	7,500	8,000	8,000	8,500e
Sub Totals	**38,900**	**28,260**	**37,000**	**41,000**	**43,100e**	**44,000**	**48,500e**
Totals	**373,650**	**399,055**	**428,000**	**514,000**	**520,600**	**563,000**	**593,500e**

Table II. World magnesium consumption in metric tons (e = estimated).[2]

evolution of China's magnesium product structure from a major primary producer to a high value-added producer. In 2006, he notes, there were about 90 magnesium alloy die casters, more than 30 magnesium sheet and profile producers, and 23 magnesium ingot casters in China. There were also 22 research institutes and universities offering research and technical support to the Chinese magnesium industry as a whole and contributing to the cooperative U.S.-Canada-China Magnesium Front End Research and Development (MFERD) project.

Indeed, as Dajun describes, China's automotive applications of magnesium are extensive. For example, the Shanghai Automotive Industry Corporation (SAIC) assembles VW and GM automobiles sold in China, while utilizing magnesium die castings for the gear box and cover in the VW Gol and Santana (Figure 4), an air pedal bracket in GM's Buick Regal (Figure 5), and the instrument panel for GM's Cadillac STS (Figure 6).

Figure 2. Norsk Hydro's Bécancour magnesium plant was shut down and sold in 2007.[2]

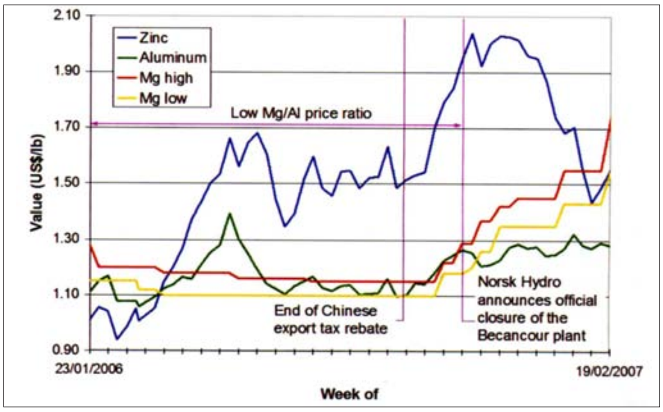

Figure 3. Comparison of price variations of magnesium, aluminum, and zinc (London Metal Exchange 2007).[4]

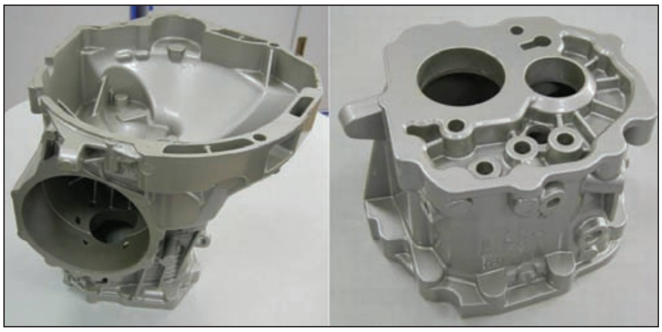

Figure 4. Magnesium gear box and cover for SAIC's Gol and Santana VW models.[6]

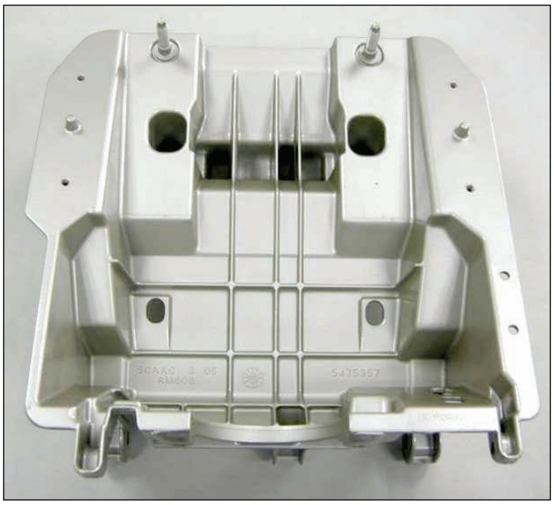

Figure 5. Magnesium air pedal bracket for SAIC's Buick Regal for GM.[6]

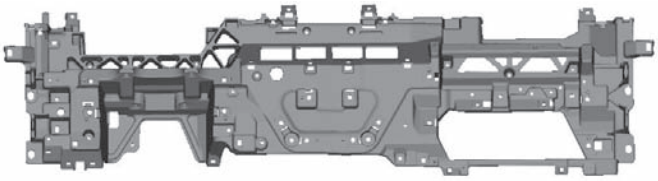

Figure 6. Magnesium instrument panel for SAIC's Cadillac STS for GM.[6]

The First Automotive Works (FAW) of China utilizes magnesium die casting in a variety of applications. Notably, FAW has recently used a Mg-Re alloy that has the same casting properties as AZ91 but much better creep resistance in the production of magnesium engine covers for a 1.3 l/55 kW diesel engine for its Tianjin-FAW passenger automobile (Figure 7).

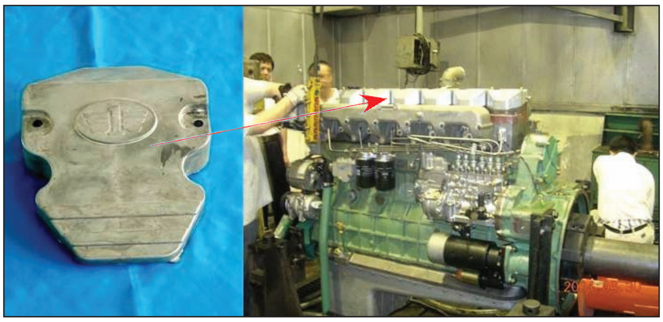

Figure 7. Mg-RE die cast engine cover for FAW's high performance diesel engine.[6]

With some 90 Chinese magnesium alloy die casters operating today, these are just a few of the many Chinese automotive magnesium components being produced for China's domestic market. As Dajun notes, "Generally speaking, as the largest magnesium producer and provider, largest magnesium market, and the largest automobile manufacturer in the world, China has unique advantages in developing automotive applications and will likely make important contributions to the world in automotive lightweighting."

Wrought magnesium applications are also being extensively pursued in China. In 2006, there were about 30 Chinese magnesium sheet and profile producers.[5] Wrought magnesium alloys in the form of sheet and extrusions will be used along with castings in the MFERD project, as described by Alan Luo of GM at the 18th Annual Magnesium in Automotive Seminar.[7] Also, at that seminar, Jim Brown described the developments at the WINCA Tech Group in Hebi, China, where WINCA has been producing AZ31 extrusions and sheet (Figure 8) from their DC cast billet and slab.[8]

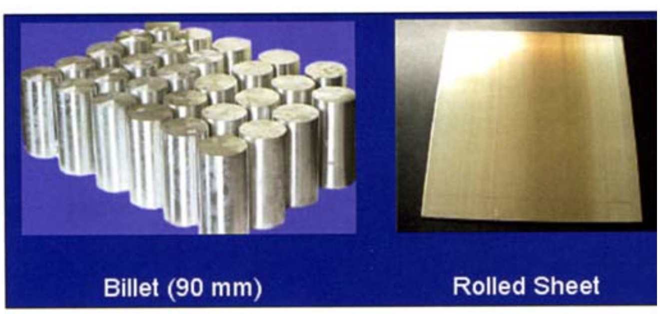

Figure 8. Samples of WINCA's AX31 extrusion billet and rolled sheet made from cast slab.[8]

Magnesium Research in Australia: Besides the Korean Posco venture, twin roll casting of magnesium alloys is also being developed in Australia (Figure 9) as was reported by Dr. John Grandfield, Grandfield Technology Pty. Ltd.[9] In his review of the present status of magnesium research in Australia, he notes, "Australian groups researching magnesium face considerable challenges with the demise of Australian smelter projects and production of only small tonnages of local magnesium parts."

In spite of the challenges, Grandfield points to significant achievements that have been made in Australia in metal production, alloy development, casting process technology, corrosion and coating technology, and joining technology. The collaborative research activities among Australian government agencies, industry, CSIRO

Figure 9. Twin-roll cast AZ31 coils of magnesium sheet (350 mm wide and 3 mm thick) being examined at CSIRO's pilot plant.[9]

(Australian national research agency), and universities are commendable, and many of their achievements have significant commercial potential and include:

- CSIRO has advanced the state of the art in twin roll casting of magnesium sheet
- CSIRO is using carbothermic reduction of magnesium at over 1,600°C to meet stringent environmental requirements
- CSIRO is a joint venture partner in the commercialization of the T-Mag™ low pressure permanent mold casting process for high integrity magnesium alloy castings (Figure 10)

Figure 10. T-Mag cast magnesium wheel at CSIRO.[9]

- The USCAR coalition of Chrysler, Ford, and General Motors and the U.S. Department of Energy have chosen AM-SC1™, a lean Mg-RE alloy developed by the Australian cooperative research center CAST, for engine block testing in the Magnesium Powertrain Cast Components project
- CAST has also developed a newly patented high speed extrusion alloy AM-EX1 that has an extrusion limit similar to AA6063
- CSIRO and CAST researchers have developed Air-CAST, a new direct chill hot top casting mold for pro-

ducing magnesium alloy extrusion billets with excellent surface quality

• Novel anti-corrosion coatings have been developed for magnesium wheels in a collaborative project led by CAST

• Considerable expertise has been achieved in the applications of self piercing rivets and laser welding of magnesium alloy components

Present Situation in Russia: In reporting on the 2nd Russian Magnesium – Broad Horizons meeting held in St. Petersburg in June 2007, Bob Brown reviewed the present production status at the main magnesium producers in Russia, Solikamsk Magnesium Works (SMK) and Avisma, where total magnesium shipments for 2007 were estimated at 28,000 mt, a decrease of ~10,000 mt over 2006.[10] Avisma uses magnesium metal to react with titanium tetrachloride to produce titanium metal. In July 2007, Boeing set up a joint venture (Ural Boeing Manufacturing) with the world's largest titanium producer, Russia's VSMPO-Avisma, to make titanium components for Boeing's new 787 passenger aircraft.

Bob also reported on the 1st Russian Magnesium – Broad Horizons meeting held in Moscow in November/December 2005.[11] At that conference, several papers were presented detailing, among others, production data from China presented by representatives of the China Magnesium Association, research and development of magnesium alloys in Korea, the recent progress made in creep resistant magnesium alloys by Dead Sea Magnesium (MRI series of magnesium alloys), twin roll casting/rolling of magnesium sheet up to 2,000 mm wide and 0.55 mm thick by ThyssenKrupp Stahl AG, twin roll casting/rolling of magnesium sheet by the FATA/Hunter process, the Keronite® plasma electrolytic oxidation process for protecting magnesium surfaces against corrosion and wear, improved routes for primary magnesium production, and magnesium alloys in aerospace applications. In the latter paper, magnesium usage in Tupolev aircraft was documented (Table III).

Year	Model No.	Type	Parts in Mag	Total Weight
1966	TY 134	Civil	1,325	780 kg
1974	TY 154	Civil	2,600	830 kg
	TY 144	Civil	900	380 kg
2000	TY 204	Civil	95	55 kg
	TY 334	Civil	45	50 kg
	TY 4 (B29 type)	Military		650 kg
	TY 22	Military		820 kg
	TY 95 MC	Military		1,550 kg

Table III. Magnesium usage in Tupolev civilian and military aircraft.[11]

Automotive Magnesium in North America: Recent automotive magnesium developments and applications in North America have been extensively covered in *LMA*.[7, 12-16]

In assessing the automotive lightweighting projects of the U. S. Council for Automotive Research (USCAR) and U. S. Automotive Materials Partnership (USAMP), *LMA* has documented the critical importance of magnesium to the overall FreedomCAR program that is sponsored in large part by the U.S. Department of Energy (DOE) and which grew out of the former Partnership for a New Generation of Vehicles (PNGV) program.[12-13] USAMP magnesium developments have already seen commercialization in General Motor's application of a magnesium engine cradle (replacing an aluminum engine cradle) for the 2006 Chevrolet Z06 Corvette (Figure 11).[14-15] The Z06 also contains high pressure die castings for the steering wheel, pedals, and master cylinder support as well as 14 Thixomolded® magnesium parts incorporated into its convertible roof top system.[14]

Figure 11. GM's Mike Meloeny and Lisabeth Riopelle (Hydro) showing the Corvette Z06 engine cradle that was high pressure die cast by Meridian Technologies from Hydro alloy AE44 at a 35% weight saving over the aluminum casting.[4]

Presently, magnesium represents a significant portion of the lightweight metals projects within the FreedomCAR program, whose goal is to achieve the high volume production of automotive vehicles that, compared with 2002 produced vehicles, have the following characteristics:

• Half the mass
• Are as affordable
• Have the same performance
• Are more recyclable
• Are equal or better in quality and durability

Due to the impact that magnesium can have in achieving these goals, several projects have been funded starting in 2000 through 2010 as part of the Automotive Magnesium 2020 plan, published in November 2006 as *Magnesium Vision 2020: a North American Automotive Strategic Vision for Magnesium* (available on the USCAR website: www.uscar.org), which targeted a growth of magnesium in North American automotive vehicles from 11-13 lb (5-6 kg) today to more than 330 lb (150 kg) per vehicle by 2020. Perhaps the three most prominent magnesium projects portfolio within the FreedomCAR program involve casting projects: the Magnesium Powertrain Cast Components (Figure 12), High Integrity Magnesium Automotive Castings, and Ultra-large Castings for Lightweight Vehicle Structures (Figure 13).

Figure 12. Magnesium powertrain components for the Duratec 2.5 L/V6 engine developed for the USCAR FreedomCAR program displayed by Joy A. Hines of Ford and Bob Powell of GM.[13]

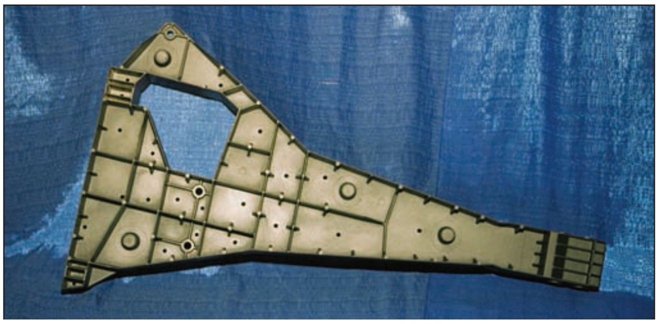

Figure 13. The “shotgun” structural AM60 magnesium member produced as a demonstration part by a modified thixocasting process connecting the A-pillar (firewall) to the radiator support on a Ford F-150 truck.[16]

How realistic is the 2020 magnesium goal? In responding to this question in October 2007, Gerry Cole, one of the authors of the Magnesium 2020 report, pointed out that presently there is too much risk aversion in Detroit with regard to major magnesium developments.[17] However, he proposes a possible solution, one that he proposed earlier at the 2007 China Magnesium and Automotive Conference: “If the Chinese decide to embark on a major demonstration of magnesium’s automotive relevance to their fuel problems, say by producing an ultralight, large, high-percentage magnesium vehicle for the 2010 Shanghai World’s Fair, the rest of the world will take notice…why not buy the automotive magnesium parts that they (China) will develop, produce and export, at lower prices than we could get them in North America.”

In Canada, the AUTO21 network of centers of excellence is a Canadian automotive R&D partnership, established in 2001, that supports academic and industrial cooperation on various automotive projects. The two magnesium projects supported by AUTO21 are: Wrought Magnesium for Automobiles (McMaster University) and Magnesium Casting Processes II (University of Western Ontario).[18] Canadian research labs, industrial partners, and their scientists and engineers participate with the U.S. and China in the MFERD program, however, as described previously by Bob Brown and George Simandl in their global perspective on the magnesium industry, the shutting down of the primary magnesium smelters in Canada puts the magnesium industry there *at the crossroads.*

Automotive Magnesium in Europe: In covering the 62nd Annual World Magnesium Conference held in Berlin, Germany in May 2005, Bob Brown noted that this particular conference was an outstanding success, with 450 delegates in attendance.[19] As Bob reported, “It was very fitting for the magnesium meeting to be held in Berlin, as Berlin was the main capital of Germany at the time that Germany developed the first commercial magnesium production process and greatly influenced the world development and use of magnesium.” To be sure, magnesium in Europe is driven by the lightweighting initiatives of the automotive industry in Germany. Among the featured automotive magnesium applications at that conference, was the BMW inline 6-cylinder composite Mg/Al crankcase (Figure 14) for their NG6 engine (Figure 15), which sets new standards in specific power, light weight, and reduced fuel consumption. This crankcase, made with an internal insert of AlSi17Cu4 aluminum alloys over which a creep resistant AJ52x Noranda Mg-Al-Sr alloy was high pressure die cast (Figure 16), saved 24% weight over the equivalent aluminum crankcase.

VW has been using Dead Sea Magnesium creep resistant alloys MRI 230D and MRI 153M in a variety of applications in their engine applications to replace aluminum alloy A380 (Figure 17). Weight savings credited to replacing

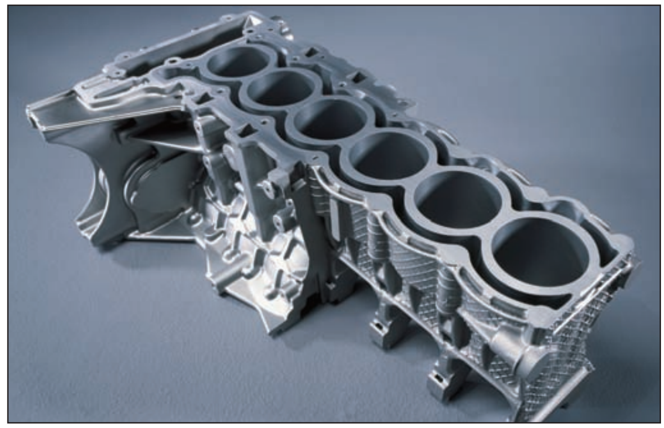

Figure 14. Composite Mg/Al crankcase for the BMW NG6 inline 6-cylinder engine.[15]

Figure 15. BMW NG6 engine (courtesy BMW AG).[20]

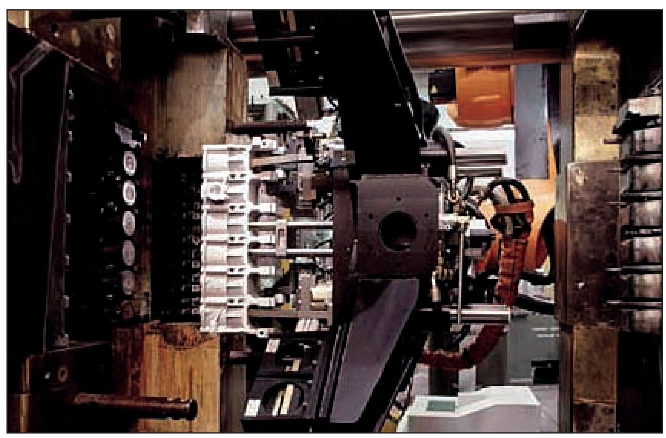

Figure 16. Robotic inlaying of the AlSi17Cu4 aluminum alloy insert into magnesium high pressure die casting die chamber.[19]

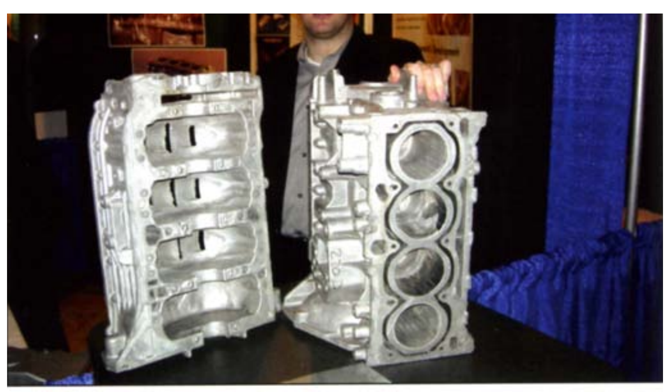

Figure 17. Dead Sea Magnesium displayed the VW 4-cylinder engine block cast from MRI 153M at the 18th Annual Magnesium in Automotive Seminar.[7]

A380 with these DSM alloys were 33-47% depending on application.[7]

New magnesium developments in Europe are being advanced under the umbrella of the InnoMagTec program funded by the German Research Foundation, which is a six year research program that began in April 2004. At the time of the 62nd Annual World Magnesium Conference, there were 25 active projects involving various companies, 15 universities and research centers in Germany, and one research center in Austria.[19]

Magnesium: Where Have We Been?

In order to obtain a good historical perspective on magnesium applications over the past 65 years, perhaps it is wise to work backwards in time from the perspective just presented, i.e., from *where we are now.* Thus, in assessing *where have we been*, the reportage in *LMA* will glance backwards through the years first from 2004 to 1995, then from 1994 to 1943. The material that follows will be presented as it was in the retrospective issues of *LMA* in reverse temporal order with no untoward comments made in hindsight, something that is relatively easily done when examining the past.

At the same time, in accessing all the magnesium articles published in the past issues of *LMA* back to May 1943, in the interest of brevity more than a few magnesium applications may have been missed, so apologies are due for any oversight.

Magnesium Yesterday (1995 – 2004)

A Magnesium Intensive Vehicle: Entrepreneurship has been active in magnesium automotive applications, as evidenced by Earle Canavan (Figure 18), who has been and still is intent on building the Kaiser Darrin all-magnesium car and other all-magnesium vehicles.[21] Aluminum intensive vehicles (AIVs) have done much to promote lightweight aluminum in automotive applications, and magnesium intensive vehicles (MIVs) may do the same. Earle developed his interest in automotive magnesium during a long racing career. Now Earle's company, Magnesium Automotive Group, like many private magnesium enterprises today, struggles with financing and support.

Figure 18. Earle Canavan holding a magnesium wheel preform above samples of other automotive magnesium parts made by the Magnesium Automotive Group.

Magnesium = The Racer's Edge: Magnesium wheels have been a major factor in auto racing due to the advantage offered by magnesium in reducing unsprung weight and greatly improving handling. As Bob Brown described earlier, the history of automotive magnesium wheels goes back as early as the 1920s, with major development of magnesium aircraft wheels during WWII, and magnesium racing wheels promoted after the war when racing began anew.[22] Microporosity is a problem with conventional casting of magnesium wheels, thereby necessitating expensive forging, spinning, or thixomolding. However, the Raffle direct injection die casting process, invented by Noel Raffle, has shown promise in the mass production of high integrity AM60B magnesium wheels from billet (Figure 19), that are 27% lighter than A356.2 aluminum alloy wheels.

Figure 19. AM60B magnesium alloy wheel manufactured by Mg 12 Revolution Ltd. of South Africa utilizing the Raffle process and awarded the 2004 Annual Award of Excellence at the 2004 IMA meeting in New Orleans.[22]

In a major application of magnesium in automotive front end structures, DaimlerChrysler designed a fully integrated front-of-dash (FOD) for their 2003 Viper (Figure 20).[23] The FOD structure, made by Meridian Technologies, was a one piece magnesium alloy die casting assembled with three stamping subassemblies that replaced a multipiece steel assembly made of 51 stampings. The steel structure weighed 66 pounds against 21 pounds for the magnesium structure.

Strip Casting of Magnesium Sheet Reconsidered: Historical applications of magnesium alloy sheet produced by conventional rolling of ingot and the gaining attention

Figure 20. The DaimlerChrysler 2003 Viper used a fully integrated magnesium front dash structure made of a one-piece magnesium die casting.[23]

to twin roll casting and rolling of magnesium alloy sheet were reviewed by Bob Brown in February 2002.[24] Among the early historical applications of note in aircraft was the 500 kg (1100 lbs) of magnesium sheet used in the Focke Wulf Condor 200 civilian aircraft built in Germany in the 1930s. Subsequently, there were widespread applications of magnesium sheet in the 1950s, including Metro-Lite truck bodies (Metropolitan Body Company), consumer items such as luggage, lithographic printing sheet, and of course various aerospace applications. In the early 1980s, Hunter Engineering (now FATA Hunter) worked with Dow to develop strip casting of magnesium alloys. Most recently, the successful demonstrations of strip casting and rolling of magnesium alloy sheet in Australia, Japan, and Germany could encourage wider applications, especially in automotive markets.

EUCAR and USCAR Embrace Magnesium: The 58th Annual World Magnesium Conference of the IMA held in Brussels in May 2001 was noteworthy in stressing the importance of magnesium in automotive applications and the sensitivity of the European automobile industry to environmental and life cycle issues that magnesium can address.[25] At that meeting, the objectives of the projects under the umbrella of the European Council for Automotive R&D (EUCAR) were outlined:

- MAGCHASSIS – develop advanced manufacturing technology for automotive chassis components
- MAGJOIN – develop new joining techniques for Mg-Mg and Mg-Al components
- MAGEXTRUSCO – develop magnesium extrusions for structural components
- MAGENGINE – develop magnesium alloy(s) with improved high temperature properties and satisfactory corrosion resistance and castability for use in automotive engine and powertrain applications

These objectives with some differences are universal with respect to similar programs and projects in many other countries. In fact, at the Brussels meeting, EUCAR proposed the slogan that summarizes the role of magnesium in automobiles: **magnesium** = **m**ake **a**utomobiles **g**ree**n**er **e**fficient **s**afer w**i**th the **u**se of **m**agnesium.

The EUCAR efforts to use more magnesium to solve many of the problems associated with lightweighting vehicles are similar to those of vehicle programs worldwide, including those of the FreedomCAR program and the collaborative U.S.-Canada-China MFERD project. Indeed, results on automotive magnesium R&D projects in line with those of EUCAR were presented and showcased in April 2001 at the 12th Annual Magnesium in Automotive Seminar of the IMA in Troy, MI.[26] Earlier, at the Sinomag Magnesium Die Casting Seminar held in Beijing, China in October 2000,[27] and in September 2000 at the Magnesium Alloys and Their Applications meeting in Munich, Germany,[28] Gerry Cole (then with the Ford Motor Company Research Laboratory) described how USCAR in North America and EUCAR in Europe are internationalizing magnesium R&D activities and working together on a global pre-competitive knowledge base that can be used to promote wider applications of automotive magnesium components.

SAE 2001 World Congress Spreads the Message: In 2001, there were an estimated 50 million vehicles worldwide with an average usage of magnesium of only 2.27 kg (5 pounds) per vehicle. Optimism for the usage of automotive magnesium to rise at a rate of 15% annually was expressed repeatedly at the magnesium sessions of the 2001 World Congress of the Society of Automotive Engineers (SAE) held in Detroit, MI in March that year.[29] The magnesium sessions were held in large meeting rooms, which were packed with automotive engineers anxious to hear about the promise of automotive magnesium, exemplified by the successful die cast magnesium instrument panel (IP) cross car beams in use by automakers (Figure 21). These magnesium IPs were not considered part of the front end structure then; subsequent magnesium IPs were and are now designed to serve as structural members. Besides the nonstructural automotive magnesium applications, the stage was set at the 2001 SAE World Congress for more extensive use of magnesium in powertrain applications with data presented on various new creep resistant alloys, some of which were used in successful introductions in commercial automotive applications that were later to come.

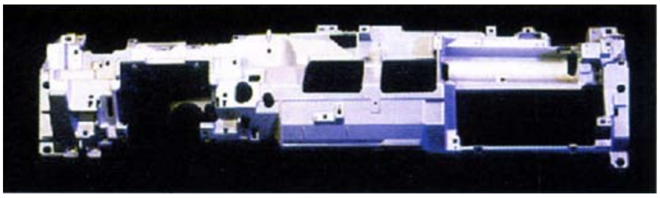

Figure 21. One-piece die cast magnesium automotive instrument panel that replaces many welded steel fabrications at a 50% weight reduction.[29]

Magnesium Smelter Projects Aim High in 1999 and 2000: In early 2000, with primary magnesium supply at about one half the present level, the optimistic automotive market growth projections were under consideration worldwide. Many new smelter projects were being considered and some already under construction as reported at Magcon 2000: the 2nd Australasian Magnesium Conference in Sydney, Australia and at the 57th Annual World Magnesium Conference of the IMA in Vancouver, British Columbia, Canada.[30-31] As Bob Brown summarized at Magcon 2000, total magnesium production was 476,000 metric tons in 1999, up from 470,000 metric tons in 1998, with about 50% of the production by the thermal reduction process, mostly in China where the growth was then the greatest and where Bob saw quality improving. Among the magnesium smelter projects enthusiastically discussed then were Noranda Magnola and several in Australia, all of these now abandoned. In reviewing the Australian magnesium projects in the beginning of 2000, Bob detailed the plans of nine different companies with, "Every state in Australia home to at least one project."[32] He concluded then that, with strapped financing and pilot plant problems, "…we will see little metal produced in 2000."

The push for magnesium smelter projects was also evident in 1999 at the First Australian Magnesium Conference, when session chairman Bob Brown noted 17 projects actively pursued worldwide, of which eight were in Australia. In providing a historical note, he mentioned that magnesium has experienced rapid expansion in the past and can do so again. For example, in the U.S. during WWII, primary magnesium capacity expanded from 2,500 tons per year to 250,000 tons per year in only five years. Primary magnesium production capacity in China went from 10,000 tons per year in 1990 to 200,000 tons in 1998. Again significant growth projections for automotive magnesium were made, necessitating perhaps a tenfold increase in total world production of magnesium by 2020.[33]

A critical review of worldwide primary magnesium production by Bob Brown and Rudolf Pawlek in June 1999 began, "Magnesium projects are springing up like popping corn."[34] They then pointed out many of the problems associated with process technology and decried the lack of conservative judgment on some of these projects, and they posed an interesting paradox, "To successfully market all of the magnesium production tonnage that is being discussed, the prices will have to be lowered. Lowered prices make the economics of a new magnesium plant much less favorable."

In a panel discussion held in February 2000 at the Second Israeli Conference on Magnesium Science and Technology, the rosy projections of magnesium demand prompted critical examination of the issues surrounding future magnesium smelter projects.[35] Barriers to magnesium growth were examined and it was concluded that there must be many plants built to accommodate the potential of 50 million cars worldwide and 100 kg per car. However, the panel realized that to build four million tons of new capacity at a low $8,000 per ton of capacity will cost billions of dollars. Then there must be component manufacturers to produce the products, requiring another $1,000 per ton of installed die casting capacity, adding four billion dollars. The total investment required would reach $40 billion. In his assessment of the magnesium panel considerations, Bob Brown felt, "That is a lot of money to pay back, and the financing charges will impact the market prices and it will not all be smooth sailing."

NADCA Gears Up for Die Cast Automotive Magnesium: Sponsored by the North American Die Casting Association (NADCA), the 20th International Die Casting Congress and Exposition, held in Cleveland, Ohio in November 1999, provided the venue for a separate magnesium session, chaired by Gerry Cole, who described how the automotive industry can achieve a 100 kg magnesium car within 20 years.[36] At the time, the magnesium content varied from 0.5 to 17 kg per vehicle and, considering that the magnesium industry is 1/50 the size of the aluminum industry, there loomed a great potential for die cast magnesium in automotive applications. As Gerry pointed out in the magnesium panel session, "Only in the past year (i.e., 1998) has the use of magnesium for die casting exceeded the use of magnesium for aluminum alloying." Another comment at that panel session was, "Magnesium is where aluminum was in the 1970s."

Volkswagen Partners with Dead Sea Magnesium: With Volkswagen (VW) as partner (35% interest), Dead Sea Magnesium Works began production in April 1997. At the First Israeli International Conference on Magnesium Science and Technology, held at Dead Sea, Israel in November 1997, H. Friedrich and S. Schumann of VW presented an impressive display of their potential applications of magnesium for lightweighting their automobiles (Figures 22).[37] The magnesium VW B80 manual gearbox housing for the Audi A4/A6 and Passat (Figure 23) is a prime example, having saved 4.5 kg (26%) weight compared with aluminum. The 1997 Passat in total utilized 14 kg of magnesium (1% of the vehicle weight), and VW projections at the time indicated that for comparable vehicles this could double or even triple by 2005. Subsequent VW presentations on magnesium usage were also made at other conferences.[38-39]

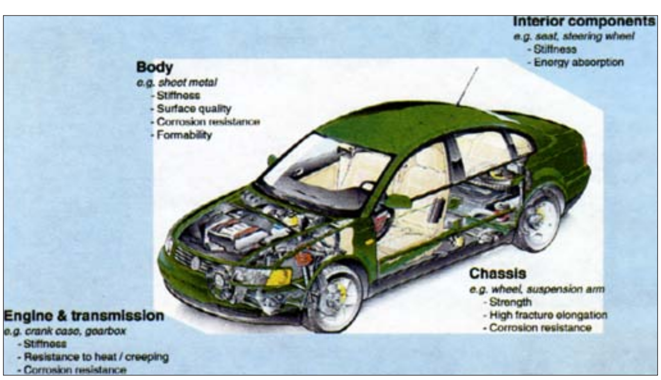

Figure 22. Potential magnesium components in an automobile and characteristics needed in these parts as of 1997 (courtesy Volkswagen AG). [37]

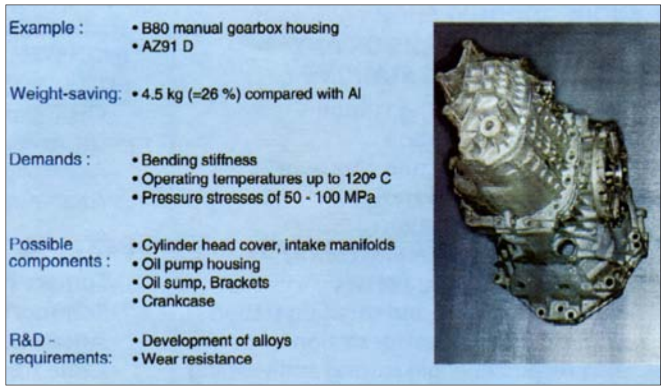

Figure 23. Volkswagen B80 manual gearbox housing for the Audi A4 and A6 and Passat 1997 models (courtesy Volkswagen AG).[37]

It was duly noted at these conferences that the German automobile industry began using magnesium (AS41 alloy) in the air cooled engine of the 1934 VW Beetle, with the high point of magnesium use in the Beetle reaching approximately 42,000 mt in 1971. In 1995, VW rediscovered magnesium and made a major investment in the Dead Sea Magnesium project.

IMA Annual Meetings and Automotive Seminars Show the Way: With its birds-eye view of the magnesium business and organizing ability, the IMA has been a beacon in the storm by attempting to read the future and guide its members, no mean feat in any field. The trend toward increased use of magnesium die castings for nonstructural and structural applications in automotive and other markets, so apparent after the fact, has been repeatedly forecast at several early IMA annual conferences and automotive seminars. Looking back to 1997, at the 54th IMA Annual World Conference,[40] magnesium use in alloying aluminum was still the largest application, although usage was leveling off (138,200 mt in 1996 against 157,000 mt in 1995 and 142,000 mt in 1994). At the same time, the growth trend in die casting, especially in automotive applications was steadily rising (72,300 mt in 1996 against 62,500 mt in 1995 and 51,000 mt in 1994). Desulfurization applications of magnesium, which typically rank third among magnesium applications, stood at 39,600 mt in 1996.

The global trend toward increased magnesium applications in automotive structures was growing at a rate of 15% at the time of the 53rd IMA Annual World Conference held in June 1996 in Ube City, Japan, while uses for magnesium in aluminum alloying and desulfurization were forecast to grow at a slower rate.[41] Indeed, featured magnesium castings on display at that meeting were mostly automotive components (Figure 24). Also, the IMA Awards presented at the IMA-53 banquet were automotive magnesium die castings (Figure 25).

The golden opportunity for magnesium in the North

Figure 24. Automotive magnesium castings on display at IMA-53 in Ube City, Japan.[41]

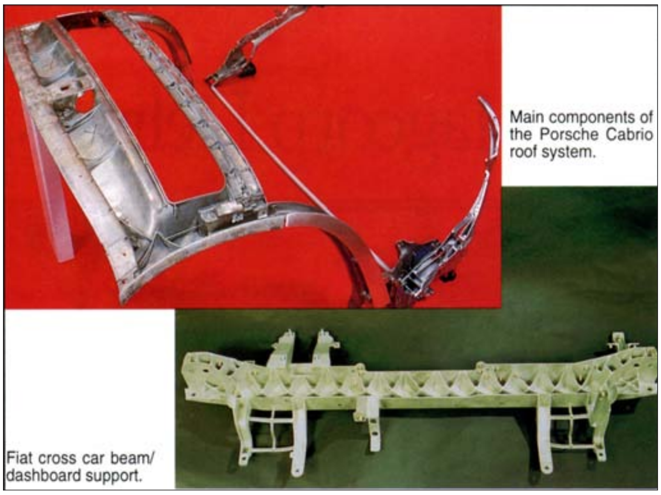

Figure 25. Design Award winner at IMA-53 for the six-piece Porsche Cabrio roof system die cast in AM50 alloy and the Application Award winner at IMA-53 for the cross beam/dashboard support die cast in AM60B alloy.[41]

American automotive market was especially inviting as was apparent at the 52nd IMA Annual World Conference held in San Francisco, CA in 1995.[42] Demand for magnesium as die castings at the "Big Three" North American automotive companies was projected to grow at about 20% through 1998 (Table IV). Extrapolations of this table made it reasonable to predict that the North American automobile industry would be using 60,000 metric tons of magnesium die castings in the projected 12 million vehicles to be built in 2000.

Metric Tons

	1995	1996	1997	1998
General Motors	3,400	7,800	9,600	15,800
Chrysler	3,900	5,400	5,900	5,800
Ford	12,100	15,200	15,800	17,800
Total Produced	19,400	28,400	31,300	39,400
Mass of magnesium per vehicle*,(kg)	1.6	2.4	2.6	3.3

Memo: Growth rate over 5 year period 1994-1998 = 20%

* Volume assumed constant at 1994's rate of 12 M vehicles per year

Table IV. Projections made in 1995 at IMA-52 for use of magnesium die castings in vehicles produced in North America through 1998.[42]

Nineteen ninety-five was also the time when the PNGV projects for lightweighting automobiles were concentrating on aluminum, with magnesium looking like a contender in the materials competition. Most of the aluminum alloys being considered for automotive applications then and still do now all contain magnesium, on a weight percentage basis from fractional amounts (6xxx, 2xxx, and 3xx aluminum alloys) to as much as 3.0-4.5% (5xxx aluminum alloys). To be sure, the market growth opportunity for magnesium stemming from the growth of aluminum alloys in automotive applications was projected to reach 36,000 tons by 2004.

Semisolid Magnesium Forming: As reviewed by Ed Nussbaum, semisolid forming of aluminum and magnesium by various processes was establishing itself during the 1990s, especially in the automotive industry.[43] Thixomolding of magnesium is a one step process that combines elements of die casting and plastic injection molding by feeding solid magnesium alloy particles through a heated barrel that partially melts the charge to achieve a 30-50% volume fraction of solids and injecting the semisolid slurry into a clamped die. In 1990, magnesium thixomolding was commercialized by Thixomat, Inc., Ann Arbor, MI. Thixomat, Inc., which has maintained its headquarters in Ann Arbor all these years, has often invited attendees at IMA's Annual Magnesium in Automotive Seminar (as was the case this year at this 19th IMA event) to see a demonstration of the process. At the time, HPM Corporation built the first "Thixomolder" (Figure 26) for thixomolding magnesium and had it installed at the Lindberg Corporation plant in Racine, WI.

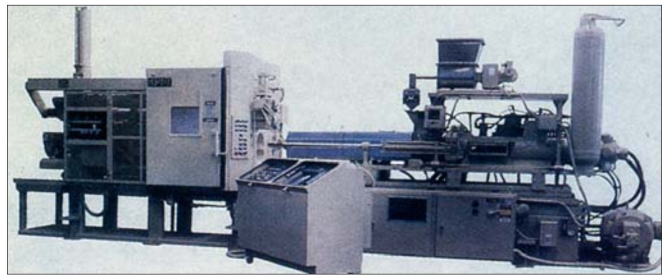
Figure 26. The 400-ton "Thixomolder" built by HPM Corporation.[43]

Magnesium Yesterday (1943-1994)

In reviewing past magnesium applications beyond two decades, especially in such a changing environment in which the global magnesium industry finds itself presently, it is perhaps prudent to make it short. Actually, many of the articles reviewed and referenced here contain much historical perspective extending far into the past. Overall, since its first issue, *LMA* has published hundreds of articles on the extractive metallurgy, alloying, processing, and applications of magnesium. Thus, as we review the existing and proposed magnesium applications for the period 1943-1994, for the sake of brevity, only the high points are considered here. And, unlike the previous section (Magnesium Today 2005-2008) featuring contemporary magnesium applications and developments looking back in time, it is instructive and enlightening to start at the beginning (May 1943 issue of *LMA*) and look forward from that time to better understand the evolution of magnesium into the metal we have today.

Magnesium from the Perspective of 1943-1944: Magnesium took a prominent position during WWII as a strategic resource, with a production capacity in 1943 being 60 times greater than in 1939, i.e., peak production during WWII was approximately 232,000 mt, mostly from the 15 plants built in the U.S. By comparison, production capacity of aluminum in 1943 was five times greater than in 1939. Due to the war, these light metals were restricted to military applications, however, significant plans for postwar magnesium, and aluminum as well, were already being laid in May 1943.[44-47]

As noted in the Introduction, mining engineer and publisher Roy Fellom named the first issue of his magazine (a title that has been retained ever since) after the new age of metals–THE LIGHT METAL AGE. This view was shared by Zay Jeffries, one of the noted metallurgists of that time, who in that same issue predicted: "The future of aluminum and magnesium will not be limited by ore supply…it will be what man can make it.…For the longer term, therefore, it can be predicted with reasonable certainty that the light metals will take their place second to only iron and steel, in both tonnage and value. The time schedule cannot be predicted with such certainty. It will depend on many unknown factors, including the nature of the peace which will follow the present World War and the rate of growth of industry generally throughout the world."[44]

In his review of the magnesium production processes in existence in 1943, Roy cited the Dow process, which accounted for the bulk of production.[45] However, he noted that, since 1940, there was a tremendous increase in magnesium production from magnesite and dolomite utilizing one of four methods in treating these ores: the electrolytic process (magnesite ore), carbide process (magnesite ore), carbothermic process (calcined dolomite ore), and ferrosilicon process (calcined dolomite ore, known as the Pidgeon process).

An aeronautical engineer's viewpoint of light metals as of May 1943 was both optimistic and pessimistic about the future, pointing out that the mammoth industrial plants that were producing aluminum and magnesium for the war effort, mainly for aircraft construction and components (Figure 27), would face difficult times after the war.[46] It was duly noted then that, in spite of optimistic hopes, the aircraft industry would not be able to absorb the high rate of production of the light alloys in the early years of peacetime. As predicted, "A situation will arise which will require all of commercial shrewdness and technical skill of both, the light alloy industry as well as the manufacturing industries contemplating the use of light alloys in their products."

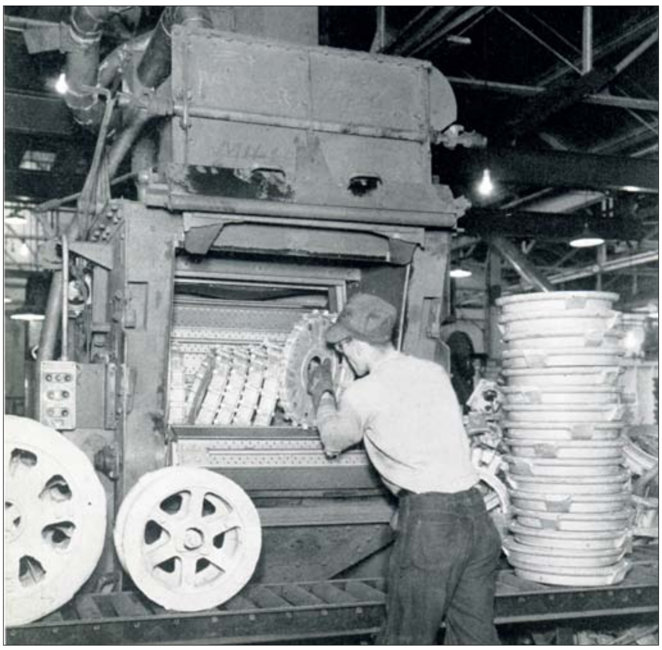

Figure 27. Cast magnesium bomber wheels being 'Wheelabrator' cleaned at American Foundry.[46]

In 1943, one of the leading automotive and aircraft designers of Detroit, George W. Walker, proposed widespread postwar applications of magnesium and aluminum in automobiles and aircraft.[47] In citing one particular influence on postwar automotive design, he considered the contribution magnesium (and also aluminum) could make to reducing engine weight. He stated that, "The automotive industry, the most conscious and the toughest competitor on the industrial front, should show the way in the use of newer metals just as fast as this competition makes their use practical."

As for aircraft, Walker cited the influence of magnesium on postwar design, as exemplified by the "Flying Wing" type of plane (Figure 28). Henry Kaiser proposed such an aircraft, designed for speed and maneuverability, made largely out of magnesium; it was later built by Northrop Aircraft Co. and flown as a jet propelled prototype.

In 1943, in quick succession after the inaugural issue, the July and September issues of *LMA* covered magnesium sand casting for aircraft applications,[48] machining characteristics of magnesium,[49] variations in elastic modulus measurements of magnesium,[50] corrosion characteristics of magnesium alloys,[51] magnesium fire prevention,[52] and laboratory testing procedures for magnesium and its alloys,[53] along with many short news releases about U.S. government orders, newly discovered magnesium ore deposits, magnesium ingot pricing, opening of new magnesium foundries, etc.

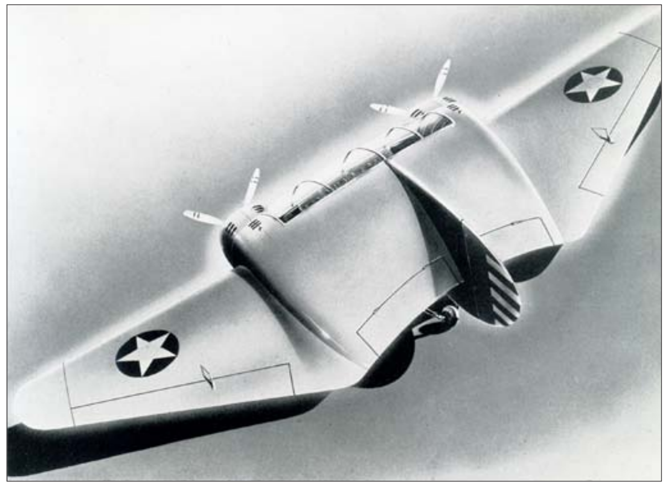

Figure 28. The magnesium intensive "Flying Wing" aircraft proposed during WWII.[47]

In 1944, *LMA* magnesium articles covered a wide variety of topics: production and consumption statistics, powder fabrication, heat treatment of magnesium alloys, safety practices, new ore deposits, pricing and business news, aluminum alloys with magnesium, coating magnesium alloys, applications in aircraft, applications in consumer goods, microshrinkage in castings, impregnation of castings, safe hot metal transport of magnesium, metallography of magnesium alloys, microstructure and properties, smelting, usage statistics, foundry practices, casting design principles, sand casting, die casting, processing of castings for special applications, x-ray inspection of castings, foundry cost accounting, magnesium alloy nomenclature, forgings, sheet forming, organic finishes, cathodic protection, magnesium dry batteries, and vulcanizing rubber with magnesium.[54]

1st Magnesium Association Annual Meeting: Coverage of the 1st Magnesium Association Annual Meeting, held in New York on October 3-4, 1944, attended by over 250 attendees, was extensive (Figure 29).[55] At that meeting, Dr. Willard Dow gave a speech on "Magnesium–Today and Tomorrow" in which he strongly promoted the role of magnesium in the postwar era. He felt that this would require a growing private industry unhampered by government regulations.

Magnesium Applications 1944-1945: In this year, the military needs for magnesium, especially in aircraft, exceeded the production capacity of the industry. For WWII aircraft, enormous quantities of magnesium were required for liquid and air cooled engines, wheels, oil tanks, frame structures, instrument housings, gyro frames, and many others, often requiring many thousands of tons of magnesium alloys in each plane. All-magnesium wings were tested successfully in service. Army and navy were then investigating the use of magnesium in mobile equipment. Requirements for magnesium-containing aluminum alloys in sheet and extrusion form were critical as well during that time.

Many lightweight magnesium applications were developed and being considered at the time that looked beyond WWII, such as:[54,56]

- Postwar aircraft structures and components
- Shipping containers
- Fan and propeller blades
- Bicycle frames

Figure 29. Magnesium Association luncheon at the 1st Annual Meeting in New York on October 3-4, 1944.

• Motorcycle frames
• Scooters
• Pneumatic tool housings
• Baby carriages
• Canoes
• Wheelbarrows
• Foundry patterns for sand casting ferrous and non-ferrous metals
• Textile machinery components
• Artificial limbs for the war wounded veterans
• Braces for infantile paralysis cases
• Furniture
• Hardware items
• Camera and motion picture equipment components
• Typewriters
• Trailers
• Conveyor components
• Tire molds
• Fire extinguishers
• Ladders and scaffolds
• Automobiles, buses, and trucks
• Loading ramps

In one estimate of post-WWII consumption, total annual consumption was slated to be 228 million pounds, with 100 million pounds used in aircraft, another 100 million pounds used by industry, 13 million pounds used for alloying aluminum and other metals, and 15 million pounds in melting and other losses.[57]

Magnesium Postwar:[58] In spite of the efforts put forth to maintain the magnesium market in peacetime, projections for postwar magnesium applications were overly optimistic and, by 1946, demand worldwide fell back to pre-war levels, world production capacity fell to 10,000 mt, and supply and consumption did not start to build up until 1980. After WWII, the U.S. government prepared to divest itself of magnesium plants and facilities, although it considered many factors to maintaining a healthy magnesium industry against future emergencies. The disposition of leases and options on magnesium metal plants and fabrication facilities was facilitated throughout 1946 by the U.S. Surplus Property Administration.

Once privatized, the magnesium industry continued to make significant improvements in coatings, metalworking processes, casting methods, and alloying. Many of the postwar applications planned were developed as prototypes or commercialized products. Again many postwar magnesium developments were in aircraft, including a jet propelled flying wing[59] originally proposed by Henry Kaiser[47] and the B-36 bomber (Figure 30).[60] The B-36 bomber used a total of 20,000 pounds of magnesium in castings, forgings, and sheet. However, at

Figure 29. Magnesium Association luncheon at the 1st Annual Meeting in New York on October 3-4, 1944.

the same time, ground vehicles benefited as well from the lightweighting that was made possible by magnesium (Figure 31).

Magnesium in the 1950s:[62] In spite of a sparse postwar market, significant magnesium developments were made in the 1950s, including many new coatings to protect the magnesium alloys from corrosion and improve wear characteristics. Anodic, electroless-Ni, and Cr-plating of magnesium were used in high production applications. Viable ceramic/porcelain coatings for magnesium were developed. Processes for cladding of magnesium sheet and plate alloys with other magnesium alloys and aluminum were developed. So were new magnesium powder metallurgy processes. Various welding, brazing, adhesive bonding, and mechanical fastening techniques for joining magnesium were perfected. Magnesium usage in the reduction of titanium and zirconium grew. Mg-RE, Mg-Th, and Mg-Th-Zr high temperature alloys for use at temperatures of 400-700°F were made available, however, their cost limited their applications to supersonic aircraft and missile components.

Magnesium die casting techniques became refined and widely used to make engine-driven tools (chain saws, post hole diggers, etc.). Dow Chemical Co. developed the hot chamber die casting process for magnesium. Casters, forgers, extruders, and fabricators of magnesium made significant strides during this period. R&D at magnesium companies provided many answers to questions about phase equilibria, alloying effects, and the relationship of structure and properties. New ASTM magnesium alloy nomenclature and temper designations were adopted by The Magnesium Association.

Almost 64% of magnesium used in the U.S. at the beginning of the 1950s was in structural applications, half of which went into aircraft and ground transportation. Product applications for magnesium expanded in the commercial sector in the 1950s. Samsonite introduced a line of lightweight luggage made with vinyl coated magnesium. Magnesium die castings were used in automotive applications such as steering column shrouds, brackets, instrument covers, and other semi-structural parts. They also found wide application in business machines, portable tools, cameras, binoculars, and projectors.

A new semi-racing class automobile was made in Britain by Essex Aero Ltd. with a 132 pound magnesium one piece body welded from sheet. Magnesium also met many of the military needs at the time, e.g., lightweight magnesium frame shelters for military vehicles, thin magnesium strip for special military battery applications, guided missile applications, mobile radar installations, and tooling plate for aircraft fabrication. However, in

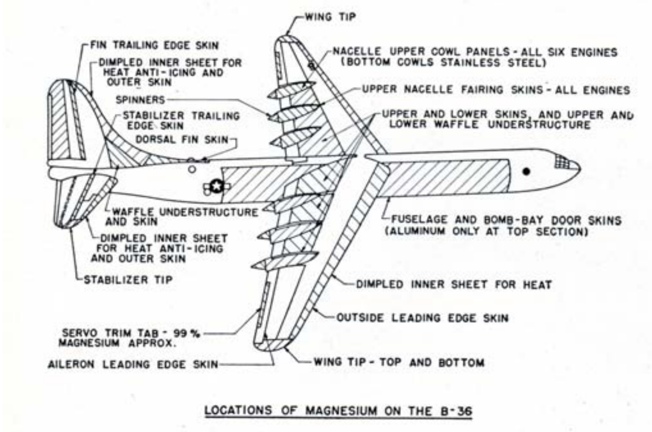

Figure 30. The 8000 pounds of magnesium distributed in the airframe of the B-36 bomber, saving 1900 pounds of dead weight in the empty craft.[60]

Figure 31. American Stores panel truck bodies of magnesium (supplied by Revere Copper and Brass Inc.) weighing 2100 pounds against 3600 pounds in steel.[61]

1955, use of primary magnesium only amounted to about 55,000 mt.

To highlight the robustness of magnesium in highly challenging applications during the 1950s, consider the magnesium "Mechanical Mule" (Figure 32) developed at the Detroit Arsenal for use by the Army and Marine Corps and officially known as Carrier, Light Weapons, Infantry, ½-ton, 4x4, XM274.[63] The "Mule" served the military needs for lighter, more compact equipment that could be airborne and mobile.

Figure 32. The U.S. Army "Mechanical Mule" magnesium vehicle negotiating rough terrain.[63]

Magnesium in the 1960s:[64] For magnesium, the 1960s were the doldrums, especially in the U.S. By the 1960s, many magnesium applications were developed and shown to be practical in use. For example, at the 17th Annual Magnesium Association meeting in 1961, there was an exhibit of "150 Commercial Uses of Magnesium." So much variety and quantity of commercial applications surprised many of the attendees. Yet, with U.S. primary production a feeble 41,000 mt, the year 1961 was dubbed "the year of standing still" exemplifying another year of consolidation of previously developed applications. Consumption of magnesium in North America in 1961 was stagnant but not so in Europe due to 20,000-25,000 tons being used in one application in Germany—the Volkswagen Beetle.

At the same time, this was the period of the Cold War, and military applications of magnesium were prominent, for example, the 2,250 pounds of magnesium sheet, plate, and extrusions used in the lightweight Minuteman intercontinental ballistic missile shipping container/transporter built under subcontract for Boeing Aircraft Company (Figure 33).[65] A machined Mg-Li chassis helped to trim 65 pounds relative to a conventional aluminum alloy chassis from the computer used to guide the huge Saturn V rockets that would launch the three-man Apollo lunar vehicles. High temperature magnesium alloys in sheet and extrusion form constituted 85% of the adapter module, a large conical structure attached to the re-entry crew compartment, in the Gemini spacecraft. In this aerospace market, commercial airliners averaged 360 pounds of magnesium in each power plant installation, saving 180 pounds per engine or 720 pounds in aircraft weight overall.

Figure 33. Magnesium was specified for doors and panels of the Minuteman missile shipping container in order to keep the shipment within highway load limits.[65]

In his address at the 23rd Annual Magnesium Association meeting in 1966, president Roger Wheeler said that the magnesium industry had failed in the past 15 years to take its place as a basic industrial commodity metal in the U.S. Per capita consumption of magnesium in 1965 at 65,000 mt was below that in 1951; this was 1/10th of what was estimated a decade earlier. Wheeler pointed out that future growth depended on structural markets over chemical and metallurgical markets, and that the automotive market was the most lucrative. He noted, "If American automobile manufacturers used magnesium in their vehicles in the same ratio as Germany in the Volkswagen, the domestic market would increase more than ten times." Besides price, to compete with steel and aluminum in this market, apparently automotive engineers needed to lose their apprehension about magnesium.

Meanwhile, progress on automotive engine development was taking place in Germany. Magnesium consumption in West Germany in 1965 stood at 38,000 mt, thanks in large part to the requirements for die casting at Volkswagen, which was then the largest consumer of magnesium in the world. The weight of all the magnesium cast parts for the Beetle and the Station Wagon averaged about 44 pounds and 50 pounds for the 1600 Sedan. Besides the smaller engines die cast at Volkswagen, Porsche had the crankcase for their six-cylinder 911 series (Figure 34) die cast in 1967.[66] This 36.6 pound magnesium crankcase—the largest and most complex magnesium die casting ever made at the time—shaved 22 pounds off the previous aluminum crankcase. The Porsche Carrera 6 with a similar magnesium crankcase ran at 187 mph on the Le Mans straightaway and came in 1st, 2nd, and 3rd at Daytona Beach and 1st and 2nd at Sebring. Other magnesium parts on the 911 series brought the total magnesium weight to 48.86 pounds.

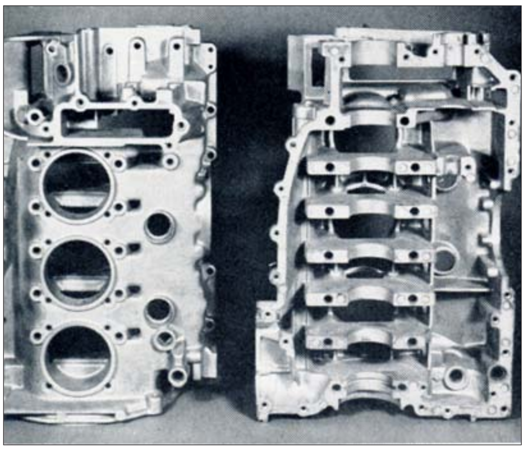

Figure 34. The six-cylinder die cast magnesium crankcase in production for the 1968 Porsche 911 series.[66]

By 1967, in the U.S., magnesium production stood at about 97,000 mt and consumption at 99,000 mt. That year, the growth of the aluminum market in general and especially can sheet absorbed 37% of magnesium shipments, while die castings used in various consumer products requiring lightness absorbed 27%. Military and aerospace needs accounted for about 15,000 mt in 1967. The balance represented smaller markets, i.e., racing car components, luggage, tooling plate, lightweight materials handling equipment, etc.

Magnesium in the 1970s:[67] Important magnesium articles published in *LMA* in the 1970s reported on new magnesium production facilities, use of magnesium in alloying aluminum, special magnesium applications for NASA, magnesium composite materials, new high temperature magnesium alloys, new magnesium-containing additions for desulphurizing steel and nodularizing cast iron, magnesium in zirconium production, coverage of Russian magnesium R&D, repeated mention of "potential" uses of magnesium in the automotive industry, melt handling in die casting shops, new fluxing methods, hot chamber die casting, squeeze casting, recycling of magnesium, new anodizing processes for magnesium, and magnesium production and consumption statistics and forecasts.

In 1974, world demand for magnesium was about 280,000 mt or only 2% of the aluminum demand that year. Aluminum alloying commanded the major share (40%) of the global magnesium market that year; in Japan, magnesium in aluminum alloying represented ~70% of the total magnesium consumption in that country. In Germany, Volkswagen alone consumed 15% for die castings mainly, and the rest was used as value-added products in the form of castings, extrusions, sheet and plate, forgings, powder, anodes, etc.

Complex economic uncertainties dominated the magnesium trading forecasts for 1975 and beyond, with high magnesium prices, an oil crisis, and the rapid decrease in sales of the Beetle causing Volkswagen and other automakers to sharply curtail magnesium consumption starting in 1975. The market was held in balance in the early 1970s by sales from the U.S. General Services Administration and exports from the U.S.S.R. However, the U.S. government magnesium stocks were essentially depleted by 1974. Thus, expanded production facilities were being considered by several firms in spite of the uncertain economic climate that was experienced worldwide. By 1976, the price of magnesium had doubled relative to the early 1970s, while aluminum pricing remained steady, making aluminum more competitive.

The International Magnesium Association (IMA) was formed in 1974 from the Magnesium Association, reflecting the global nature of the industry and the fact that 50% of the membership in 1973 was outside of the U.S. The venue for that watershed 1974 IMA Annual Meeting was Paris, France. Subsequent IMA meetings in 1975-1979 looked for market growth in aluminum alloying and steel desulphurization, while decrying the lack of magnesium parts in automotive applications. At the 36th Annual IMA Conference held in 1979 in Oslo, Norway, all the speakers were European, emphasizing the international character of the organization. There was great optimism then for expanded automotive magnesium due to cut fuel costs; however, desulphurization and deoxidation of steel was considered the most favorable growth market.

Magnesium in the 1980s:[68] The year 1980 began with worldwide magnesium capacity at 256,000 mt (174,000 mt in North America, 69,000 mt in Western Europe, and 13,000 mt in Asia/Oceania) and the worldwide consumption for the year estimated at 234,000 mt, which was flat relative to 1979 due to recession in the U.S. Besides the recession affecting the U.S. automobile and building and construction industries at that time, government restrictions were imposed on leaded gasoline use for which magnesium was used as a catalyst for Grignard lead reactions. Projections made for 1985 worldwide consumption were up by 100,000 mt relative to 1980. Aluminum alloying consumed almost half of magnesium production in 1980 and was expected to grow at about 5% per year, while some other markets such as desulfurization and die casting were expected to grow more rapidly (Table V).[69]

Estimated 1977	Estimated 1978	Estimated 1979	Use	Projected 1980	Projected 1985
93	100	109	Alum Alloying	113	145
19	20	22	Nodular Iron	20	26
4	5	7	Desulfurization	9	25
29	31	32	Chemical/Reduction	32	40
36	34	35	Die Casting	38	63
15	13	16	Structural	15	20
1	7	8	Other	7	15
197	210	229	Total	234	334

TABLE 4

PRIMARY MAGNESIUM CONSUMPTION PATTERN
WESTERN WORLD, 1979 - Thousand Metric Tons

Use: / Area:	North America	Latin America	Western Europe	Africa Mid East	Asia Oceania	Total	Percent
Alum Alloying	63	1	26	2	17	109	47
Nodular Iron	11	1	8	–	2	22	10
Desulfurization	5	–	2	–	–	7	3
Chemical/Reduction	20	–	8	–	4	32	14
Die Casting	5	13	16	–	1	35	15
Structural	12	–	4	–	–	16	7
Other	1	3	3	–	1	8	4
Total	117	18	67	2	25	229	100

TABLE 5

Table V. Primary magnesium consumption in the Western world by region and markets (1000 mt).[69]

The use of magnesium by Volkswagen was reviewed extensively by Volkswagen engineers in the August 1980 issue of *LMA*.[70] Magnesium orders at Volkswagen peaked at 42,000 mt in 1971, when magnesium air cooled rear engines were used in the production of more than two million Volkswagen cars that year alone. Magnesium orders at Volkswagen bottomed out at 10,000+ mt in 1975, then increased to nearly 25,000 mt by 1980. During that time, Volkswagen was working out the production technology required for die casting, machining, and recycling magnesium while also working out the manufacturing technology for casting and processing magnesium engine components from magnesium alloys with high creep strength at engine operating temperatures. Looking beyond 1980, although Volkswagen had a positive view of the lightweighting opportunities that magnesium could bring to the vehicles, they hedged their bets by planning equipment purchases that would be applicable to both aluminum and magnesium in case the Mg:Al price ratio went beyond 1.6:1, which was considered sustainable at the time.

Not ignoring the potential of magnesium use in alloying aluminum, the magnesium industry was feeling the pinch from the push for aluminum recycling and began examining options for expanded applications in transportation. This was exemplified by the Volvo LCP 2000 experimental car (Figure 35) exhibited at the 1985 SAE Congress in Detroit; the vehicle weighed 700 kg or 1544 pounds and contained 50 kg or 120.3 pounds of magnesium castings.[71]

Figure 35. The experimental Volvo LCP 2000 at the 1985 SAE Congress had 7% of its body weight as magnesium castings that included a three-cylinder direct injected diesel engine block.[71]

The push to use more magnesium in lightweighting automobiles and trucks was starting to bear fruit in North America by 1988, having increased from 8.9 million pounds in 1985 to 13.3 million pounds in 1988.[72] Research efforts to meet the challenges of some high performance automotive applications included advanced rapidly solidified magnesium alloys and magnesium alloy composites. Echoing some of the goals of the automotive industry today, research in the early 1980s even included magnesium hydride storage of hydrogen for futuristic hydrogen powered vehicles—either all electric or hybrid![73]

Magnesium 1990-1994:[74] The 48th Annual IMA Annual World Magnesium Conference held in Quebec City, Canada in 1991 again set new records for attendance and include a tour of the new Norsk Hydro electrolytic primary magnesium plant at Bécancour as well as a tour of the newly opened Institute of Magnesium Technology (IMT) at Sainte-Foy, Quebec. The IMT, funded by the Quebec and Canadian governments, had 25 members at the start and was 90% devoted to magnesium castings in automotive applications. As reported at that meeting, magnesium shipments in 1990 were 252,000 mt and magnesium production was 260,800 mt. Usage in aluminum alloying was about level, but magnesium die casting usage grew by 27% in 1990, making die casting the second largest end use for magnesium.[75]

Coming off the 1972-1982 period when there was practically no growth in magnesium die castings in North America, the 1982-1993 period witnessed a compounded annual growth rate of 18+% in this market sector, with 25,000 mt of magnesium die casting consumption in North America reported for 1993. In the April 1994 issue of *LMA* , Darryl Albright and Tom Lunt, at the time with Hydro Magnesium, detailed the 60 different magnesium die cast components in production at GM, Ford, and Chrysler in 1994, while mentioning, "Each of these applications has come to the marketplace because it has survived the intense scrutiny of the automotive engineering teams throughout a multi-year development process." [76]

Magnesium–Where Are We Going?

Having reviewed where we are now and where we have been since 1943 in magnesium, the easy part is over. The reading and reviewing of many of the 400+ magnesium articles published in *LMA* since its first issue in May 1943 (now available on a specially issued CD at www.lightmetalage.com) was a pleasant task and most informative, helping to put the future of magnesium in some perspective. To answer the question of where are we going, we obviously must not forget the past but, at the same time, we must take account of the many factors mentioned previously in Where are We Now? and learn something from Where Have We Been? before assessing the future of magnesium. Looking over some of the past *LMA* articles that projected the future of magnesium, in most cases the view from within and often from without was overly optimistic.

Although I hope for the best for this lightweight material champion, I concede that I do not know nor can I predict the future of magnesium, much less the future price of any other commodity. However, in reviewing the rich history of this important light metal, I am fascinated how it has survived ups-and-downs in applications over the years and feel a sense of *déjà vu*. Thus, I take to heart the words of T. S. Eliot:

We shall not cease from exploration
And the end of our exploring
Will be to arrive at where we started
And know that place for the first time

T. S. Eliot (1888-1965), *Little Gidding*

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