ESSENTIAL READINGS IN
MAGNESIUM TECHNOLOGY
ESSENTIAL READINGS IN MAGNESIUM TECHNOLOGY

Edited by

Suveen N. Mathaudhu, Alan A. Luo, Neale R. Neelameggham,
Eric A. Nyberg, Wim H. Sillekens
# TABLE OF CONTENTS

## Essential Readings in Magnesium Technology

Preface .................................................................................................................................................................. xiii

About the Editors .............................................................................................................................................. xvii

## Part 1: Magnesium Technology History and Overview

Magnesium Technology Growth in the 1990 Period .................................................................................. 3  
*R. Brown*

The Magnesium Industry Today…The Global Perspective ........................................................................ 13  
*G. Patzer*

Advances in Manufacturing Processes for Magnesium Alloys ................................................................. 19  
*H. Dieringa, J. Bohlen, N. Hort, D. Letzig, and K. Kainer*

Materials Comparison and Potential Applications of Magnesium in Automobiles .................................. 25  
*A. Luo*

Summary of Magnesium Vision 2020: A North American Automotive Strategic Vision for Magnesium .... 35  
*G. Cole*

Magnesium Front End Research and Development: A Canada-China-USA Collaboration ...................... 41  
*A. Luo, E. Nyberg, K. Sadayappan, and W. Shi*

Integrated Computational Materials Engineering for Magnesium in Automotive Body Applications .... 49  
*J. Allison, B. Liu, K. Boyle, L. Hector, and R. McCune*

A Lightweight Automobile Body Concept Featuring Ultra-Large, Thin-Wall Structural Magnesium Castings ... 55  
*S. Logan*

Magnesium Castings in Aeronautics Applications – Special Requirements ............................................. 65  
*A. Wendt, K. Weiss, A. Ben-Dov, M. Bambarger, and B. Bronfin*

Magnesium Alloys in U.S. Military Applications: Past, Current and Future Solutions ......................... 71  
*S. Mathaudhu and E. Nyberg*

High-Capacity Hydrogen-Based Green-Energy Storage Solutions for the Grid Balancing ...................... 77  
*F. D'Errico and A. Screnci*

## Part 2: Electrolytic and Thermal Primary Production

History of Primary Magnesium Since World War II ...................................................................................... 85  
*B. Clow*

Lloyd M. Pidgeon – Magnesium Pioneer ..................................................................................................... 89  
*R. Brown*

Magnesium Electrolysis – A Monopolar Viewpoint .................................................................................... 93  
*O. Wallevik, K. Amundsen, A. Faucher, and T. Mellerud*
**Part 4: Casting and Solidification**

Castability of Magnesium Alloys ..............................................................................................................................187  
A. Bowles, Q. Han, and J. Horton

Solidification of Cast Magnesium Alloys ..................................................................................................................193  
D. StJohn, A. Dahle, T. Abbott, M. Nave, and M. Qian

Solidification and Microstructure of Mg - Al - (Ca, Sr, Ce, La) Ternary Alloys ......................................................199  
N. Saddock, A. Suzuki, K. Wu, S. Wildy, Y. Chang, T. Pollock, and J. Jones

Hot Cracking Susceptibility of Binary Mg-Al Alloys ...............................................................................................205  
G. Cao, S. Kou, and Y. Chang

Phenomena of Formation of Gas Induced Shrinkage Porosity in Pressure Die-Cast Mg-Alloys ..............................211  
S. Lee and A. Gokhale

The Role of Microstructure and Porosity in Ductility of Die Cast AM50 and AM60 Magnesium Alloys ..........217  
G. Chadha, J. Allison, and J. Jones

Semisolid Processing and Its Application to Magnesium Alloys ..............................................................................223  
F. Czerwinski

Fatigue Behavior of Thixomolded® Magnesium AZ91D Using Ultrasonic Techniques ........................................227  
A. Moore, C. Torbet, A. Shyam, J. Jones, D. Walukas, and R. Decker

Development of Wrought Mg Alloys via Strip Casting ............................................................................................233  
S. Park, J. Lee, H. Lee, and N. Kim

Development of 1500MM Wide Wrought Magnesium Alloys by Twin Roll Casting Technique in Turkey .........239  
O. Duygulu, S. Ucuncuoglu, G. Oktay, D. Temur, O. Yucel, and A. Kaya

**Part 5: Alloy and Microstructural Design**

Grain Refinement of Magnesium ..............................................................................................................................247  
Y. Lee, A. Dahle, and D. StJohn

Preliminary Investigation on the Grain Refinement Behavior of ZrB₂ Particles in Mg-Al Alloys .......................255  
G. Klosch, B. McKay, and P. Schumacher

Solid Solution Effects on the Tensile Behaviour of Concentratred Mg-Zn Alloys .................................................263  
A. Blake and C. Caceres

Age Hardening Behavior of Mg-l.2Sn-l.7Zn Alloy Containing Al ........................................................................269  
T. Sasaki, T. Ohkubo, and K. Hono

The Relationship between Microstructure and Creep Behavior in AE42 Magnesium Die Casting Alloy ..........275  
B. Powell, V. Rezhets, M. Balogh, and R. Waldo

Development of Creep Resistant Mg-Al-Sr Alloys ...................................................................................................283  
M. Pekguleryuz and E. Baril

Phase Transformation and Creep of Mg-Al-Ca Based Die-Cast Alloys ............................................................291  
A. Suzuki, N. Saddock, J. Jones, and T. Pollock
Part 7: Modeling and Simulation

Design Magnesium Alloys: How Computational Thermodynamics Can Help .......................................................... 403
Z. Liu

A Thermodynamic Database for Magnesium Alloys .................................................................................................. 411
M. Piche, A. Pelton, and C. Brochu

Computational Thermodynamics and Experimental Investigation of Mg-Al-Ca Alloys ........................................... 415
K. Ozturk, Y. Zhong, and Z. Liu

Computational Thermodynamics and Experimental Investigation of the Mg-Al-Ca-Sr Alloys .................................. 421
Y. Zhong, K. Ozturk, Z. Liu, and A. Luo

New Phases in Mg-Al-Ca System .............................................................................................................................. 427
Y. Zhong, A. Luo, J. Nie, J. Sofo, and Z. Liu

Thermodynamic Database of Mg-Al-Ca-Sr: A Resource for Alloy Development and Improvement ...................... 433
H. Cao, J. Zhu, C. Zhang, and Y. Chang

The Mg-Al-Zn-Mn-Ca-Sr Alloy System: Backbone of Understanding Phase Formation in AXJ Alloys and
Modifications of AZ and AM Alloys with Ca or Sr .................................................................................................. 437
A. Janz, J. Groebner, and R. Schmid-Fetzer

Thermodynamics and Constitution of Mg-Zn-Ce Alloys .......................................................................................... 441
C. Chiu, A. Kozlov, J. Gröbner, and R. Schmid-Fetzer

Modelling of the Thermo-Physical and Physical Properties for Solidification of Mg-Alloys .................................... 445
N. Saunders, X. Li, A. Miodownik, and J. Schille

Constitution of Magnesium Alloys ............................................................................................................................ 451
R. Schmid-Fetzer, J. Groebner, D. Mirkovic, A. Janz, and A. Kozlov

Computer Modeling of DC Casting Magnesium Alloy WE43 Rolling Slabs ............................................................. 457

Magnesium for Crashworthy Components ........................................................................................................... 463
T. Abbott, M. Easton, and R. Schmidt

Numerical Modelling of Large Strain Deformation in Magnesium ........................................................................... 467
J. Lévesque, K. Inal, K. Neale, R. Mishra, and A. Luo

Atoms-to-Grains Corrosion Modeling for Magnesium Alloys .................................................................................. 473
H. Kwak, J. Xiao, and S. Chaudhuri

Effect of Substituted Aluminum in Magnesium Tension Twin .................................................................................. 479
K. Solanki, A. Moitra, and M. Bhatia

Part 8: Joining

Friction Stir Welding of Magnesium Alloys ................................................................................................................ 487
R. Johnson and P. Threadgill

Welding and Weldability of AZ31B by Gas Tungsten Arc and Laser Beam Welding Processes .............................. 493
S. Lathabai, K. Barton, D. Harris, P. Lloyd, D. Vlano, and A. McLean
Microstructural and Mechanical Aspects of Reinforcement Welds for Lightweight Components Produced by Friction Hydro Pillar Processing .................................................................499
  G. Pinheiro, J. dos Santos, N. Hort, and K. Kainer

Solid State Joining of Magnesium to Steel .............................................................................................................505
  S. Jana, Y. Hovanski, S. Pilli, D. Field, H. Yu, T. Pan, and M. Santella

Elevated Temperature and Varied Load Response of AS41 at Bolted Joint ...............................................................511
  O. Anopuo, G. Shen, S. Xu, N. Hort, and K. Kainer

Structure and Mechanical Properties of Friction Stir Weld Joints of Magnesium Alloy AZ31 ................................517
  T. Nagasawa, M. Otsuka, T. Yokota, and T. Ueki

Friction Stir Welding of Magnesium Die Castings ....................................................................................................523
  J. Skar, H. Gjestland, L. Oosterkamp, and D. Albright

The Effect of Process Parameters and Tool Geometry on Thermal Field Development and Weld Formation in Friction Stir Welding of the Alloys AZ31 and AZ61 .................................................529
  R. Zettler, A. Blanco, J. dos Santos, and S. Marya

Friction Stir Welding of Magnesium Oil Pan ............................................................................................................545
  F. Hunt, Q. Yang, H. Badarinarayan, K. Okamoto, and D. Platt

Fatigue Evaluation of Friction Stir Spot Welds in Magnesium Sheets ......................................................................551
  J. Jordon, M. Horstemeyer, J. Grantham, and H. Badarinarayan

An International Benchmark Test in the "Magnesium Front End Research and Development" Project ......................557

Part 9: Corrosion, Surface Treatment, and Coating

An Hydrogen Evolution Method for the Estimation of the Corrosion Rate of Magnesium Alloys...........................565
  G. Song, A. Atrens, and D. StJohn

A Novel Technique to Evaluate the Corrosion Behavior of Magnesium Alloys ..........................................................573
  B. Tiwari and J. Bommarito

Corrosion Phenomenon Evaluation of Mg Alloys Using Surface Potential Difference Measured by SKPFM .................581

Emerging Trends in Corrosion Protection of Magnesium Die-Castings .................................................................585
  J. Skar and D. Albright

Evaluation of Corrosion Protection Methods for Magnesium Alloys in Automotive Applications ..........................593
  P. Blanchard, D. Hill, G. Bretz, and R. McCune

Advanced Conversion Coatings for Magnesium Alloys ............................................................................................599
  S. Nibhanupudi and A. Manavbasi

Improved Corrosion Performance of AZ91D Magnesium Alloy Coated with the Keronite™ Process .....................603
  S. Shrestha, A. Sturgeon, P. Shashkov, and A. Shatrov

Adhesive Bonding and Corrosion Protection of a Die Cast Magnesium Automotive Door ........................................609
  G. Bretz, K. Lazarz, D. Hill, and P. Blanchard
PREFACE

“Magnesium will lighten the tasks of man in countless ways as yet undreamed of, except in the minds of far-seeing engineers […] who are already planning the future.”

— 1942 Dow Chemical Advertisement

Due to their extraordinarily low densities, magnesium (“Mg”) and its alloys have continued to be the focus of intensive research and development over the past century though widespread application has been restricted by property, cost, and performance limitations with respect to other metallic materials such as Al-alloys, Ti-alloys, and ferrous alloys. However, in light of Mg’s availability and global efforts to reduce weight in the transportation sector, there has been a tremendous resurgence in research, development, and applications of these remarkable alloys.

Along with this renaissance came renewed interest from government, academia, and industry, and in the year 2000, the first Magnesium Technology Symposium was held at The Minerals, Metals & Materials Society (TMS) Annual Meeting and Exhibition in Nashville, Tennessee. A proceedings volume with 56 manuscripts was published in parallel with the new symposium, and the tremendous interest that was generated enabled the symposium to be held annually with the Magnesium Technology proceedings becoming the de facto publication for the magnesium industry.

In your hands (or perhaps on your screen), you have some of the most influential and impactful papers of the 1024 manuscripts published in the proceedings between 2000 and 2012. This single reference chronicles and condenses the major global advances made over the last decade. To select the best papers, a team of editors was selected based on their extensive experience with various aspects of Mg technology, with all editors having served as organizers and editors on Magnesium Technology proceedings published during the selected timeframe (Mathaudhu, ’11–’12; Luo, ’04,’06,’07; Neelameggham, ’06–’12; Nyberg, ’08–’10; Sillekens, ’10–’12).

Manuscripts were comprehensively reviewed for prospective inclusion, and the final papers were selected based on the following three criteria:

1. **General Relevance.** Beginning in 2002, the symposium organizers and session chairs began selecting “best paper” awards for one student and one contributed manuscript. These papers, at the time, represented the latest scientific breakthroughs, and thus are included as “essential reading” (see Table 1 on page xv). Also included based on this criteria are a number of “review” type papers that summarize the state-of-the-art in Mg technology, and thus frame the true impact of recent advances.
2. Scientific Relevance. In the academic world, the largest indication of impact is based on citations. The Magnesium Technology proceedings are indexed by a number of databases, from which citation data were collected and analyzed and papers with a high number of citations were selected for inclusion.

3. Industrial Relevance. In 2007, a “best paper” award in application was added to the student and contributed awards. These manuscripts were selected for inclusion due to their representation of leap-forward advances and novel demonstrations of industrial applications.

Introductions to each part further frame the importance and significance of the selected manuscripts. The papers selected for inclusion were divided along nine topical thematic areas, with the papers arranged by subject area rather than chronologically to support the cohesiveness of subtopics within each theme. The nine themes are as follows:

1. Magnesium Technology History and Overview
2. Electrolytic and Thermal Primary Production
3. Melting, Refining, Recycling, and Life-Cycle Analysis
4. Casting and Solidification
5. Alloy and Microstructural Design
6. Wrought Processing
7. Modeling and Simulation
8. Joining
9. Corrosion, Surface Treatment, and Coating

A significant amount of time and resources have gone into this volume, and many thanks are owed to those who have donated their energy to its success. Primary thanks goes to the many authors whose work is presented in this volume, the many symposium organizers and participants who have continually maintained a high level of scholarship and ensured the continual growth of this discipline. The production team at TMS and Wiley, primarily Matt Baker, are acknowledged for their continual support and motivation to see this project to completion. It is our hope that this volume will provide a key resource for those “far-seeing engineers” who have, and will, dedicate their livelihoods to the advancement of this amazing metal.

Suveen N. Mathaudhu, U.S. Army Research Office
Alan A. Luo, The Ohio State University
Neale R. Neelameggham, IND LLC
Eric A. Nyberg, Pacific Northwest National Laboratory
Wim H. Sillekens, European Space Agency
### Table 1: Magnesium Technology Best Paper Award Winners

<table>
<thead>
<tr>
<th>PART</th>
<th>AWARD</th>
<th>AUTHOR(S)</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part 1: Magnesium Technology History and Overview</td>
<td>2013 Best Application Paper</td>
<td>D’Errico F., Scerri A.</td>
<td>High-capacity hydrogen-based green-energy storage solutions for the grid balancing</td>
<td>77</td>
</tr>
<tr>
<td>Part 2: Electrolytic and Thermal Primary Production</td>
<td>2010 Best Student Paper</td>
<td>McLean K., Pettingill J., Davis B.</td>
<td>Cathode wetting studies in magnesium electrolysis</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>2007 Best Student Paper</td>
<td>Lee S.G., Gokhale A.M.</td>
<td>Phenomena of formation of gas induced shrinkage porosity in pressure die-cast Mg-alloys</td>
<td>211</td>
</tr>
<tr>
<td></td>
<td>2010 Best Application Paper</td>
<td>Duygulu O., Ucuncuoglu S., Oktay G., Temur D.S., Yucel O., Kaya A.A.</td>
<td>Development of 1500mm wide wrought magnesium alloys by twin roll casting technique in Turkey</td>
<td>239</td>
</tr>
<tr>
<td></td>
<td>2006 Best Student Paper</td>
<td>Blake A.H., Cáceres C.H.</td>
<td>Solid solution effects on the tensile behaviour of concentrated Mg-Zn alloys</td>
<td>263</td>
</tr>
<tr>
<td></td>
<td>2013 Best Fundamental Paper</td>
<td>Sasaki T.T., Ohkubo T., Hono K.</td>
<td>Age hardening behavior of Mg-1.2Sn-1.7Zn alloy containing Al</td>
<td>269</td>
</tr>
<tr>
<td></td>
<td>2006 Best Contributed Paper</td>
<td>Suzuki A., Sadiock N.D., Jones J.W., Pollock T.M.</td>
<td>Phase transformation and creep of Mg-Al-Ca based die-cast alloys</td>
<td>291</td>
</tr>
<tr>
<td></td>
<td>2011 Best Student Paper</td>
<td>Lee J.-K., Kim S.K.</td>
<td>Fire-proof evaluation of CaO added Mg-3Al, Mg-6Al, and Mg-9Al Mg cast products</td>
<td>305</td>
</tr>
<tr>
<td></td>
<td>2012 Best Application Paper</td>
<td>Takahashi N., Wang Q., Gao Y., Yin D., Chen C.</td>
<td>Applicability of Mg-Zn-(Y,Gd) alloys for engine pistons</td>
<td>325</td>
</tr>
<tr>
<td></td>
<td>2011 Best Fundamental Paper</td>
<td>Chun Y.B., Davies C.H.J.</td>
<td>The evolution of in-grain misorientation axes (IGMA) during deformation of wrought magnesium alloy AZ31</td>
<td>345</td>
</tr>
<tr>
<td></td>
<td>2012 Best Student Paper</td>
<td>Stutz L., Bohlen J., Letzg D., Kainer K.U.</td>
<td>Formability of magnesium sheet ZE10 and AZ31 with respect to initial texture</td>
<td>357</td>
</tr>
<tr>
<td></td>
<td>2005 Best Contributed Paper</td>
<td>Kurz G.</td>
<td>Heated hydro-mechanical deep drawing of magnesium sheet metal</td>
<td>389</td>
</tr>
<tr>
<td></td>
<td>2013 Best Student Paper</td>
<td>Sagaparam D., Efe M., Moscoso W., Chandrasekar S., Trumble K.P.</td>
<td>Non-basal textures in magnesium alloy strips produced by extrusion-machining</td>
<td>395</td>
</tr>
<tr>
<td></td>
<td>2012 Best Fundamental Paper</td>
<td>Solanki K.N., Moitra A., Bhatia M.</td>
<td>Effect of substituted aluminum in magnesium tension twin</td>
<td>479</td>
</tr>
<tr>
<td></td>
<td>2003 Best Contributed Poster</td>
<td>Tiwari B.L., Bommarito J.J.</td>
<td>A novel technique to evaluate the corrosion behavior of magnesium alloys</td>
<td>573</td>
</tr>
<tr>
<td></td>
<td>2004 Best Student Paper</td>
<td>Mandagie M., Brandt M., Durandet Y., Jahedi M.</td>
<td>Parametric study of laser cladding of AS 21 magnesium alloy with aluminium silicon/tungsten carbide powder</td>
<td>617</td>
</tr>
</tbody>
</table>
Suveen N. Mathaudhu

Suveen Mathaudhu serves as the Program Manager for Synthesis and Processing of Materials with the U.S. Army Research Office (ARO), Materials Science Division. He received his B.S.E. in Mechanical Engineering from Walla Walla University in 1998, and Ph.D. in Mechanical Engineering from Texas A&M University in 2006. In his current position, he manages programs that focus on the use of innovative approaches for processing high performance structural materials reliably and at lower costs. He also concurrently serves as an Adjunct Assistant Professor in the Department of Materials Science and Engineering at North Carolina State University, where his research interests include ultrafine-grained and nanostructured materials by severe plastic deformation, consolidation of metastable particulate materials and processing-microstructure-property relationships of refractory metals and lightweight metals, and thermally stable nanocrystalline materials. He has co-authored more than 60 technical publications in these areas. He is an active member of ASM, TMS, and MRS, and has served as the Chair of the TMS Magnesium Committee, and as organizer of the 2012 Magnesium Technology symposium.

Alan A. Luo

Alan Luo is a Professor of Materials Science and Engineering and Professor of Integrated Systems Engineering (Manufacturing Group) at The Ohio State University (OSU) in Columbus, Ohio, USA. Prior to joining OSU in July 2013, Dr. Luo was a GM Technical Fellow at General Motors Global Research and Development Center (Warren, Michigan, USA) with 20 years of industrial experience. Dr. Luo won two John M. Campbell Awards for his fundamental research, and three Charles L. McCuen Awards for research applications at GM. He has 16 patents and more than 170 technical publications in advanced materials, manufacturing, and applications. Dr. Luo is an elected Fellow of ASM (American Society of Metals) International. He received the TMS (The Minerals, Metals & Materials Society) Brimacombe Medalist Award and SAE (Society for Automotive Engineers) International Forest R. McFarland Award in 2013, and USCAR (United States Council for Automotive Research) Special Recognition Award in 2009, and ASM Materials Science Research Silver Medal in 2008. Dr. Luo’s research is also recognized by several Best Paper awards from TMS, SAE, and AFS (American Foundry Society). He is the Vice Chair of TMS Light Metals Division and SAE Materials Division and the Chair of SAE Non-Ferrous Metals Committee.
Eric A. Nyberg

Eric A. Nyberg is a Chief Engineer at the Pacific Northwest National Laboratory (PNNL) in Washington state. Nyberg has conducted materials processing and characterization research of lightweight metals such as aluminum, magnesium, and titanium for more than 20 years. His research in magnesium has included producing rapidly solidified and extruded magnesium alloys, developing superplastically formed sheet panels, and developing high strain rate deformation models of magnesium for automotive applications. He has been recognized as an invited speaker at multiple international conferences for his work on lightweight automotive applications. He holds three U.S. Patents, an R&D 100 Award, and a Federal Laboratory Consortium Award for titanium injection molding. Both his B.S. and M.S. degrees are in Materials Science and Engineering from Washington State University. He has been actively involved with the TMS Magnesium Committee and TMS Magnesium Technology symposium since their inception in 2000.

Neale R. Neelameggham

Neale R. Neelameggham is “Guru” at IND LLC, involved in technology marketing and consulting in the field of light metals and associated chemicals, [boron, magnesium, titanium, lithium and alkali metals], rare earth elements, battery and energy technologies, etc. He has more than 38 years of expertise in magnesium production technology from the Great Salt Lake brine in Utah. He was involved in the Process Development of its startup company, NL Magnesium, through the presently known US Magnesium LLC, and was its Technical Development Scientist from where he retired. Dr. Neelameggham’s expertise includes all aspects of the magnesium process, from solar ponds through the cast house including solvent extraction, spray drying, molten salt chlorination, electrolytic cell and furnace designs, lithium ion battery chemicals and byproduct chemical processing. In addition, he has an in-depth and detailed knowledge of alloy development as well as all competing technologies of magnesium production, both electrolytic and thermal processes worldwide. Dr. Neelameggham holds 13 patents and a pending patent on boron production, and has several technical papers to his credit. As a member of TMS, AIChe, and a former member of the American Ceramics Society, he is well-versed in energy engineering, bio-fuels, rare-earth minerals and metal processing, and related processes. Dr. Neelameggham has served in the TMS Magnesium Committee since its inception in 2000, chaired it in 2005, and has been a co-organizer of the Magnesium Technology Symposium since 2004. In 2007 he was made a permanent co-organizer for the Magnesium Technology Symposium. He has been a member of the Reactive Metals Committee and Recycling Committee, and a Programming Committee representative of the TMS Light Metals Division. In 2008, the TMS Energy Committee was created following the symposium on CO₂ Reduction Metallurgy initiated by him, and he was selected as the inaugural Chair for the committee. He received the Light Metals Division Distinguished Service Award in 2010 and has been a co-editor of the Energy Technology symposium proceedings volume. Dr. Neelameggham holds a doctorate in extractive metallurgy from the University of Utah.
Wim H. Sillekens

Wim H. Sillekens is a project manager in the New Materials & Energy Unit at the research and technology center of the European Space Agency (ESA–ESTEC), where he is currently acting as the coordinator of the European Community research project ExoMet. He obtained his Ph.D. from Eindhoven University of Technology, Netherlands, on a subject relating to metal-forming technology. He has been engaged in aluminum and magnesium research, among others on (hydromechanical) forming, recycling/refining, (hydrostatic) extrusion, forging, magnesium-based biodegradable implants, and as of late on light-metal matrix nanocomposites. His professional career includes positions as a post-doc researcher at his alma mater and as a research scientist / project leader at the Netherlands Organization for Applied Scientific Research (TNO). International working experience covers a placement as a research fellow at MEL (now AIST) in Tsukuba, Japan, and – more recently – shorter stays as a visiting scientist at GKSS (now HZG) in Geesthacht, Germany, and at PNNL in Richland, Washington, USA. He has authored or coauthored book chapters, journal papers, patents, conference papers, oral presentations (keynote/invited/contributed), and so on (about 135 entries to date). Other professional activities include an involvement in association activities (among others, as the lead organizer of the TMS Magnesium Technology Symposium in 2011), international conference committees, and as a peer reviewer of manuscripts for scientific journals and conference proceedings as well as of research proposals. Research interests are in physical and mechanical metallurgy in general and in light-metals technology in particular.
PART 1: MAGNESIUM TECHNOLOGY
HISTORY AND OVERVIEW

Alan A. Luo

Magnesium, an alkaline earth metal, is the ninth most abundant element in the universe by mass, the eighth most abundant element in the earth crust, and the third most abundant element dissolved in seawater. According to the U.S. Geological Survey, the leading use (41%) of primary magnesium is as an alloying element in aluminum-based alloys for packaging, transportation, and other applications. Structural uses of magnesium (castings and wrought products) accounted for about 32% of primary metal consumption in 2010. Desulfurization of iron and steel accounted for 13% of U.S. consumption of primary metal, and other uses were 14%.

Brown provided an excellent review on the historical development of magnesium production projects around the world in the 1990s. Many of these projects failed due to technical and commercial reasons, providing good lessons for future development of magnesium industry. Fast forward to 2010, Patzer reviewed the global magnesium production in the new century, with China becoming the major producer, and forecasted increasing use of magnesium in die casting and wrought alloys for automotive and 3C (computer, communication, and consumer products) industries. Dieringa and colleagues summarized the latest developments in manufacturing processes of cast and wrought alloys in Europe, especially Germany.

Luo compared the mechanical properties, structural performance, and mass saving potential of magnesium alloys with several major structural materials, and provided an overview of magnesium applications in automotive subsystems. Cole summarized a Magnesium Vision 2020 study sponsored by the United States Automotive Materials Partnership (USAMP), outlining the strategy and roadmap for increased use of magnesium components in the automotive industry. The next two papers by Luo and colleagues and Allison and colleagues described a first-of-its-kind Canada-China-USA collaboration on magnesium automotive applications focusing on a front end body structure and test bed and related Integrated Computational Materials Engineering (ICMÉ) development, which is followed by a paper by Logan describing a lightweight automobile body concept utilizing a hybrid materials approach with emphasis on a magnesium and aluminum structure to support a high fuel-efficiency vehicle project.

The paper by Wendt and colleagues reviewed the past and current applications of magnesium castings in aircrafts and described an international research project (IDEA) to develop new magnesium alloys for special use aerospace industry. Mathaudhu and Nyberg provided an excellent review of historical, current, and potential future magnesium applications with a focus on scientific, engineering, and social barriers relevant to integration of magnesium alloys. The final paper, by D’Errico and Screnci, explored new applications in high-capacity hydrogen-based green-energy storage solutions for the grid balancing.
Abstract

Electrolytic magnesium production has been the mainstay of the world's magnesium industry since magnesium was first discovered by Davy in 1808. Many of the early workers developed small advances until the electrolysis of anhydrous magnesium chloride became the standard method of production. From the very first days, the importance of anhydrous magnesium chloride has been recognized. It remains the major problem area of economic and efficient electrolytic magnesium production.

There has been a dramatically increased usage of magnesium in the past ten years by the automotive industry. This usage is projected to continue a large growth as automakers continue to strive for better fuel economy with reduced emission. The use in die casting alone has been projected to increase at 10-15% per year for the next 10 years.

Cost of magnesium and its alloys is constantly compared to aluminum and its alloys by the automakers on all continents. Magnesium usually loses this battle, in spite of the different densities. Aluminum is 50% heavier than magnesium, hence for the same casting shape a pound of magnesium would make three castings while a pound of aluminum would make only two. Automakers feel that to be fully competitive, magnesium should be priced at 1.5 times the price of aluminum. This only takes into account the densities and not the other advantages offered by magnesium such as damping capacity and strength and rigidity.

In recent years, the interest in magnesium has grown dramatically and there is a great deal of basic research and pilot plant work going on to identify better and more economic ways to produce electrolytic magnesium metal. There is more technical brainpower being applied to magnesium than ever before at anytime in history. The work has no boundries or restrictions and can be found on all the major continents (except maybe Antarctica).
ELECTROLYTIC MAGNESIUM HISTORY

Magnesium as an element was discovered by Sir Humphrey Davy in 1808. There is no record showing that Davy ever isolated magnesium as a metal. The first actual production of pure magnesium metal in the metallic form has been credited to the French scientist Bussy, who fused anhydrous magnesium chloride with metallic potassium. The German scientists Liebig and Bunsen and the French scientists St. Claire Deville and Caron all worked on methods of producing magnesium from anhydrous magnesium chloride. Michael Faraday is credited with producing the first magnesium by electrolysis of molten magnesium chloride salt. A major step toward the mass production of magnesium was made by Robert Bunsen, the German scientist, who made a small laboratory cell for the electrolysis of fused magnesium chloride in 1852. Graetzel and Fischer, also German scientists, started investigating the use of carnallite from Stassfurt as the raw material for electrolytic production of magnesium.

The original electrolytic cells that were developed by Chemische Fabrik Griesheim-Elektron used a cell feed of molten carnallite (MgCl$_2$KCl·6H$_2$O). The dehydration of carnallite is much easier than the dehydration of pure magnesium chloride solution (MgCl$_2$·6H$_2$O). Most of the electrolytic magnesium production cells operating today are derivatives of the original Chemische Fabrik which became part of I. G. Farben in 1927.

Up until 1915, Germany was the only magnesium producer. When WWI started in 1914, there was a shortage of magnesium for pyrotechnics in military ordinance. Magnesium had long been used for flares and for tracer bullets. The price of magnesium was $5.00 to $6.00 per pound. Eight companies in North America went into the production of magnesium metal. As soon as the war ended, the number of companies dropped off to two, Dow in Midland, Michigan and American Magnesium Corporation (Alcoa) at Niagara Falls, NY.

Dow Chemical had gotten into the production of magnesium from underground brines at the Midland, Michigan plant. Dow could not solve the anhydrous problem and developed a special process that fed "wet" feed (MgCl$_2$·1.5H$_2$O) to the Dow-designed electrolytic cell. American Magnesium Corporation used the oxide fluoride process developed by Harvey. This process was similar to the aluminum production process in that it was electrolysis of magnesium oxide in fluoride melts. However, the slight solubility of magnesium in the fluoride created many problems, including high operating temperatures, and high specific gravity of the eutectic mixtures (largely barium chloride) which caused the liberated magnesium to immediately rise to the top of the bath and oxidize.

The Dow process was cheaper and gave more pure magnesium, so American Magnesium Corporation ceased production in 1927. AMC costs of production were 43 cents per pound in 1927 while Dow's were 22.5 cents per pound. AMC negotiated a purchase agreement with Dow to purchase all their magnesium requirements from Dow and ceased production. It was an 18 month contract and a new five year contract was signed in 1928. The prices paid by AMC were below the market and decreased even more as the Dow total sales increased.

For most of the 1930 period, Dow Chemical in the US and MEL in England and two companies in France continued to produce and market magnesium metal in small quantities.

It took the start of hostilities in Europe for the US to become aware of the need for strategic materials. To assist in a build up, the US created the Defense Plant Corporation. This group had the job of building plants for production and fabrication of strategic materials. Magnesium was a strategic material. The US increased their magnesium production rapidly by building new electrolytic plants and 7 silicothermic plants.

Most of these plants were shut down after the war and eventually Dow found itself in the US as the sole producer. The electrolytic plant in Michigan was closed and all of the magnesium metal production concentrated in Texas.

Magnesium production appears to be quite simple. This is merely a deceptive appearance that has trapped many of the world's foremost metals companies and several junior companies. A normal question would be, "If it is simple why aren't more people doing it?" For some reason that idea has not seemed to cause second thoughts among too many experts, who usually feel that they can solve the problem of profitable magnesium production that few people have ever been able to solve.

It is the "profitable" part that has given the most problems. There have been many plants and many processes that have produced magnesium, but not very many that have produced profits.

Since 1950, there have been many projects attempted as is shown in Table 1. See Appendix attached.

NEW MAGNESIUM PROJECTS BEING DISCUSSED

There are 18 new magnesium projects under consideration somewhere in the world. They range from new smelters to expansions to feasibility studies. Surprisingly, in the USA, there are no new magnesium projects being discussed. The largest and oldest US producer, Dow Chemical, shutdown their total magnesium operations in 1998, removing 65,000 tons per year of magnesium production from the market. This metal supply has been picked up by many of the other magnesium production sources.

NORTH AMERICA

The leading new project is the Magnolia project of Noranda Magnesium being constructed at Asbestos, Quebec (see LMA Feb 1998). The C$733 million project includes a total facility to produce anhydrous magnesium chloride cell feed from asbestos tailings (serpentine) using a proprietary process. Alcan electrolytic cells (24) will be used to convert the magnesium chloride to 63,000 metric tons per year of magnesium metal. Design and engineering is approximately 98% complete with construction about 70% complete. The plant is presently on schedule to start producing magnesium metal by mid-2000 with commercial production by March 2001. Hatch Engineers did the process work on the project and plant design and engineering and construction is by SNC-
Lavalin of Montreal.

Norsk Hydro Canada Inc has plans to expand its primary magnesium plant at Becancour, Quebec. Plans are to take the 45,000 metric ton per year plant to 85,000 metric tons per year in two phases. The decision to start construction has on the first phase has been postponed because of economic problems at the parent company. It had been expected to produce metal by 2001. The plant uses imported magnesite from the Pacific Rim for its feed and converts it to anhydrous magnesium chloride by a proprietary process. Norsk Hydro also has a proprietary electrolytic cell design which operates at over 400 kA.

The plant expansion will make use of much of the infrastructure already in place. The existing dehydration units will be modified to accommodate the first phase. The project includes new electrolytic capacity and technological improvements leading to higher productivity per cell. Other changes, recently identified will lead to reduced energy consumption and increased throughput in various units in the plant.

Gossan Resources continues to work on their high purity dolomite property at Inwood, Manitoba, 50 miles north of the city of Winnipeg. Metallurgical testing was carried out by Hazen Research of Golden, Colorado in mid 1997. Hatch and Associates of Montreal were engaged to carry out a prefeasibility study on the Inwood magnesium project. The report indicated that a 50,000 metric ton per year magnesium metal production plant using off-the-shelf technology of a silicothermic plant would be about US$0.89 per pound and US$1.13 per pound after financing. Gossan is working on a market study for magnesium metal that would be produced from this project.

Minroc Mines Inc. has started shipment of high-grade chrysotile product from the Cassiar operation in British Columbia, Canada, utilizing the company’s own proprietary wet process technology. Minroc has recently announced that it will proceed with investigations and work on a project at the Cassiar Mine for the production of magnesium metal from the existing tailings source at the mine. The high purity of the chrysotile at Cassiar, with its low iron content, they feel is a prime requirement for economic and competitive production. The Cassiar chrysotile feed is 23% magnesium and 5.5% iron. This compares with the Noranda Chrysotile project in Quebec which is announced at 21%-23% magnesium and 4%-8% iron. The Minroc Cassiar Magnesium project is being evaluated at production rates of 30,000 and 60,000 mtpy. The project has been assured of competitive rates for power, which is the key factor in costs and economics of any magnesium project.

Minroc also signed a memorandum of understanding with a division of the Korean automaker, Hyundai. The latest plans say that the magnesium plant will produce 90,000 mtpy of magnesium and the Aluminum Company of Korea (a Hyundai company) will be entitled to as much of the product as it may require with the remainder to be made available for sale to the international markets. Aluminum of Korea may acquire a 35% interest in the project in conjunction with an initial $25 million financing under the agreements, and could acquire a 65% interest in the project by providing additional project funding.

A preliminary assessment report by Kilborn/SNC Lavalin suggests that the mine’s reclamation pile contains enough magnesite for 100 years of production. SNC Lavalin is assisting the company in securing financing. Detailed tests for producing magnesium metal will take place simultaneously with the reclamation activities.

A great new future for Newfoundland-Labrador was discussed at the 11th Annual Mining Conference in Baie Verte, Newfoundland. The Minister of Mines, Chuck Furey said, “A new industry is being investigated for the old asbestos mine site. Geotech Survey Ltd was given permission by the government a few months ago to determine if it’s feasible to produce magnesium from the old asbestos ore tailings.

The Northwest Alloys (Alcoa) plant continues to operate the modified Magnetherm process at Addy, Washington. The plant is rated at 41,000 mtpy. Production is of high purity magnesium used for alloying in Alcoa aluminum plants. In recent years, there has been an interest in the production of diecasting alloy at this plant. The plant has been upgraded over its entire life and further work to improve the process has been announced. NWA will work with Mintek of South Africa at developing a modified reduction reactor at Addy. The original plant had nine furnaces rated at 4,000 mtpy each. In later years, the plant has increased its rated capacity while reducing the number of furnaces in service.

Magnesium Corporation of America at Rowley, Utah is investing $46 million to evaluate new electrolytic magnesium cell technology and to install a new magnesium DC caster. The new cells when installed will have the potential to provide manufacturing efficiencies and reduce costs of magnesium production. With improved efficiencies, the production of the plant at Rowley could increase its capacity from the present announced rating of 41,000 mtpy. The new caster enables MagCorp to produce various sizes, shapes and weights of magnesium ingots and billets at lower cost. It can also produce T-Bar ingot which is used for aluminum alloying and offers a void-free, large shape.

AUSTRALIA

Australia has a number of magnesium projects being actively discussed and studies for magnesium metal plants are being conducted in all of the 6 major states. Tasmania and Western Australia have two each. The first large magnesium metal production project and the one that is furthest along is the project in Queensland which was originally developed by Queensland Metals as one of the end uses of its large high-purity magnesite deposit at Kunwarara, north of Rockhampton. It has been incorporated as Australian Magnesium Corporation (AMC).

Australian Magnesium Corporation is a company that is owned by Queensland Metals (50%) and Normandy Mining (50%) subject to financial support and a 5% interest held by Fluor Daniel for engineering services. Normandy also holds a 36.85% interest in QMC. AMC is the most advanced of the potential new producers in Australia and has a partner (Normandy) which is financially sound. Ford invested $40 million to assist the project into a pilot plant stage. Ford has also signed a long term off-take agreement for one-half of the planned production of 90,000 metric tons per year. AMC is operating a 1500 tpy demonstration plant to prove the process and gather operational data to complete the feasibility study. The construction of the commercial plant slated for completion by mid 2002 with commissioning and commercial operations by the end of 2002. The plant uses a process patented by CSIRO, an Australian Government Research arm, for production of...
anhydrous magnesium chloride from magnesite. Alcan electrolytic cells will be used in the commercial plant. The plant is expected to cost A$780 million including working capital.

The demonstration plant consisting of the CSIRO feed process and one full-scale Alcan Multipolar cell has been run since August 1999. The cash cost of producing magnesium is estimated to be A$0.65.

The electrical contract was signed at 20 mills which is somewhat less than the original number that was used in their feasibility calculations. The new plant site at Stanwell is near the power station, near a major gas pipeline and only a short distance from a major ocean port.

Crest Magnesium was one of the leading projects, but recently seems to be struggling to keep all of the partners working to get a plant built. Located on a very good deposit of magnesite in NW Tasmania, the project seemed to be going quite well until late in 1999. Discussions with a potential JV partner, Xstrata of Switzerland, were broken off.

The project as originally planned had Crest with the exclusive rights for Australia and New Zealand to use technology developed by the Ukrainian National Research and Design Titanium Institute and VAMI JSC over 20 years. There was talk of doubling the plant capacity in three stages over an 11 year period - taking production to 190,000 mtpy. The large Australian engineering and construction firm, Multiplex and Hatch Associates Limited of Canada were reviewing the technology in conjunction with Hatch or other approved consultants, and would provide a performance guarantee as to the nameplate operation of the plant (95,000 metric tons per year). The Tasmanian government will act as an intermediary for the supply of all energy; gas, electricity and commercial steam at a price that meets the indicative price already supplied by Duke Energy. Electrical costs are estimated to be 40% of the total cash production costs and Crest estimates an electrical cost of US$0.28 to produce each pound of magnesium.

Crest and Multiplex agreed to dissolve their JV partnership in October 1999.

Golden Triangle Resources NL which was originally investigating the possibility of another magnesium project based on another section of the Main Creek Magnesite Deposit (adjacent to the Crest/Multiplex section), six to seven kilometers south of the Savage River Iron Ore Mine. The projects lie southwest of Burnie in northwest Tasmania. Golden Triangle exercised an option to acquire this portion of the Main Creek Magnesite Resource (47 million tonnes) from Savage Resources Limited in September 1998. First stage bench scale hydrometallurgical test work by Oretest Pty Ltd in Perth has now been augmented by Lakefield Research Limited of Canada who have begun work on the second phase of laboratory test work that will lead to a pilot plant program. This project has been deferred in favor of the Woodsreef project.

Bass Resources, a Tasmanian mining company has announced that it has identified the site for a new magnesium production plant at Bell Bay. Bass Resources is planning to develop an arrangement with Pasminco which will provide access to a mineral resource based on the Main Creek magnesite deposit. If that proceeds, Bass Resources would be in a position to obtain access to Golden Triangle Resources' exploration results and process technology.

Golden Triangle now intends to make the development of the magnesium project, the "Woodsreef" project in New South Wales, its main focus. Drill testing of the 24 million tonne Woodsreef asbestos tailings dump, located in Northern New South Wales has been completed. This is similar to the resource being developed in Canada by Noranda Magnesium.

In January 1999 Golden Triangle announced that it had awarded a contract to carry out "Comparative Magnesium Production Scoping Study" between the Tasmanian and New South Wales magnesium projects to South African engineering group, Bateman Brown and Root. The Bateman Group has some recent magnesium experience, having worked with the Israeli Chemical Industries in the development of the Dead Sea Magnesium Project. Golden Triangle has engaged the services of Mintek, South Africa's national minerals-research organization, which is separately involved with the development of Plasma magnesium processing technology.

Pima Mining N.L. is a mineral exploration company. In September of 1998, Pima's 80% owned subsidiary, South Australian Magnesium Corporation (SAMAG) acquired a 100% interest in a number of magnesite deposits in the Leigh Creek area of Australia, and plans to establish a magnesium metal production plant at Port Augusta, South Australia. Magnesite has been mined intermittently in South Australia's Flinders Ranges since 1919. Currently, SAMAG is proceeding towards the development of a proposed magnesite mine in the Willouran Ranges, North West of Leigh Creek. Their estimated mineral resources total 205 million tonnes of magnesite, with 16 million tonnes being in the "measured" category.

SAMAG has recently announced that they purchased Dow magnesium process and plant design. Plus they purchased the research records from Dow and hired several top Dow technical employees from Texas Division. The key component is electrical energy at a competitive price. This power situation has become a problem and recent statements from South Australian power officials indicate that project power costs of about 2 cents per Kwh may not be obtained.

Hatch Associates have completed a pre-feasibility study of the Port Augusta magnesium metal project, based on Dow electrolytic cell technology. SAMAG indicates that the study confirms that there is significant potential to produce magnesium metal at a cash operating cost of less than the US$0.61 per pound originally stated. Pima recently stated that, "The SAMAG project should produce 52,500 tpa of magnesium or magnesium alloys." A detailed study on this project by Hatch has confirmed the low projected costs of production. First commercial production is scheduled for the first half of 2003.

In the Northern Territory, Mt. Grace Gold Mining N.L. acquired a 100% interest in the Batchelor Magnesite Deposit in late 1998. The Company has reported extensive occurrences of magnesite in their tenement near Batchelor, some 85 kilometers south of Darwin. The Company has now initiated a metallurgical testing program to demonstrate that Batchelor magnesite is amenable to beneficiation by flotation and is suitable for the production of magnesium metal. The stated aim is to construct a 50,000 tpa magnesium metal smelter with commissioning by July 2002. Energy may be available from a proposed development of Timor Sea natural gas together with the existing natural gas...
pipeline infrastructure crossing Mt. Grace's reserve.

Mt. Grace had retained DevMin Consultants to do a pre-feasibility study which will lead to a six to 12 month bankable feasibility study to prove the project's viability.

Mt. Grace has signed an agreement with Magnesium Developments International to use their magnesium production plant. The Heggie process is a thermal process.

Pilbara Magnesium Metal Associates (PMMA) is a joint venture based on Onslow Salt deposits in Western Australia. It was reported that HCC Pty Ltd and Multiplex Construction were part of this project. The plant would use bitterns from existing salt operations for the source of magnesium credits. This would require technology somewhat similar to that used in Israel or at the Great Salt Lake. It has been reported that Uni Ben Noon, the former CEO of Dead Sea Magnesium, is a consultant to this project. An Israeli engineering company is providing a preliminary feasibility study. It is also reported that test work is being conducted in Russia and Israel. The venture proposes a 50,000 metric ton per year magnesium plant.

CRA in conjunction with Fluor Daniel Australia and St. Joe Minerals conducted testing and pre-feasibility work in this same area in 1985-86 with the intention of using by-product magnesium-rich liquor from the CRA gypsum operations. At that time, the anhydrous magnesium chloride feed production process investigated was the NaIco process. There was an earlier 1970's feasibility study for a magnesium metal production plant done by CRA and Ubc Industries Ltd of Japan.

Electrolytic magnesium production plants produce more pounds of chlorine than they do magnesium. Shell and Dow are considering an integrated chemical plant in the same region and could possibly use the chlorine by-product stream for chemical production. With good sound basic technology for magnesium chloride production and an efficient electrolytic cell, the metal cost could be competitive with the other Australian projects.

It has been rumored that PMMA is in discussions with the Solikamsk magnesium production facility in Russia to obtain the latest electrolytic magnesium production technology.

Hazelwood Power is again investigating the possibility of recovering magnesium metal from fly ash. Hazelwood Power is a 1600 MW brown coal fired electricity generator located in the LaTrobe Valley of Victoria. The Victoria state power commission looked at recovering magnesium from fly ash in 1970's. The private company (Hazelwood) is working with HRL Technology Ltd to conduct pre-feasibility studies into the possibility of using a magnesium chloride feed liquor produced from flyash for magnesium metal production. It has been reported that there is sufficient fly ash available to supply a 30,000 metric ton per year smelter for 30/40 years. The big advantage would be transmission-free energy contracts, excellent water resources, and waste disposal potential. The study was based on the Alcan process for the production of anhydrous magnesium chloride and Alcan electrolytic cells.

Anaconda Nickel has announced an A$1 billion magnesium smelter will be built near a magnesite deposit they discovered when looking for nickel. The project development plans have not been clearly established at the present time. Shortly after the announcement of the magnesium project, Anglo American bought 23% of Anaconda Nickel and are said to be very interested in magnesium.

A summary of some of the planned magnesium projects was presented by Chris Laughton of Golden Triangle at a magnesium meeting in Sydney, Australia in June 1999. See Table 2.

**REPUBLIC OF CONGO (Brazzaville)**

Magnesium Alloy Corporation (MAC) commissioned SNC-Lavalin in Montreal to perform a feasibility study for the Kouilou hydroelectric site conditional upon certain financing arrangements by SNC-Lavalin. Upon completion of the study MAC-Lavalin may assist MAC in the financing and/or construction of the Kouilou hydroelectric site in Congo. SNC-Lavalin with its engineering expertise in hydroelectric facilities as well as its extensive construction experience in Africa, makes an important addition to MAC's technical team. MAC has an option to develop the Kouilou hydroelectric site as a potential low-cost energy source for this extraction plant. The Kouilou River site lies 50 km north of Pointe Noire.

The lead contractor for the feasibility study is Salzgitter Anlagenbau GmbH (SAB), an engineering and general contracting division of Preussag AG of Germany. Kavernen Bau-und Betriebs (KBB), another member of the Preussag Group, has extensive experience in all phases of solution mining including modeling of reserves, solution mining simulation, drilling production wells together with brine extraction and transport.

VAMI, SAB and KBB, the principal contractors along with several sub-contractors have done detailed studies. VAMI and Ukrainian State Titanium Institute have been performing evaluation of advanced and improved modifications to proven magnesium extraction technologies. VAMI and the Titanium Institute took part in the design and implementation of the magnesium extraction technology for the Dead Sea Works Magnesium facility. They also took part in the technical design for the proposed magnesium facility in Iceland in conjunction with Salzgitter. VAMI developed the technology and took part in the design and construction of all the magnesium plants in the former Soviet Union (Berezniki, Solikamsk, Kalush, Zaporozhe, Ust-Kamenogorsk).

Preliminary reviews of the MAC project, subject to low energy costs as currently indicated, indicate very low cost magnesium production. MAC anticipates a first phase annual production rate of 58,000 metric tons with a second phase of 16,000 tons. Production decision due in 1999 with production possible by 2001.

**NETHERLANDS**

The Dutch development of the magnesium project for the Northern Netherlands is proceeding at this time. The project is part of the Antwerp public-private project organization charged with developing the metal business climate in Northern Netherlands. The Magnesium Development Project Delfzijl (MDPD) project team is led by Reinder Rentema as chairman. A plan for a magnesium metal production plant of 40-60,000 metric tons per year has been presented to interested magnesium producers and magnesium users and the investment community.
It has an estimated installed cost of US$400 million. A study run by Hatch Associates of Quebec, Canada recently evaluated and compared the “Antheon” option with existing magnesium-producing technologies. That study shows that thanks to the high purity brine and other favorable production factors, the planned region can offer a proposition that will feature one of the lowest cost structures of all existing and planned magnesium producing plants worldwide.

The exact technology to be used has not been chosen, but the planned project location has operating magnesium chloride solution mines that are presently being mined at a rate of 200,000 tons of magnesium chloride per year. Hydro Terra of Canada is working on a feasibility study for this project. Ample electrical energy is available and power deregulation in Europe in 2002 will help keep costs competitive. The brine is reported to be very pure. Long term plans call for a combined plant that will use the chlorine by-product of the magnesium operations to combine with ethylene to make ethylene dichloride. One of the partners is Nedmag, a former Billiton Company.

**NORWAY**

The original Norsk Hydro magnesium production plant in Norway was built at Porsgrunn during World War II using I.G. Farben technology. This plant has been upgraded and modified to reach the present capacity of 40,000 mtpy. Presently, this plant uses seawater and dolomite to produce its anhydrous magnesium chloride cell feed. The plant has been upgraded to take care of environmental concerns and additional 10,000 tons of recycling capacity has been added in recent years. Further details will be available from a more detailed presentation by Norsk Hydro.

**FORMER SOVIET UNION (FSU)**

Now the oldest magnesium production operation in the world is the Solikamsk facility in Russia. It has been in operation since 1934. Solikamsk has installed a magnesium powder production plant and has a contract with GM for magnesium alloy. Solikamsk produces about 10,000 tpy of primary metal and 10,000 tons of alloy. The new magnesium granule plant is rated at 2,000 tpy with potential to expand to 8,000 tpy. Solikamsk also produces recycled magnesium. There have been plans and discussions to double the size of the primary magnesium plant. It was reported in 1998 that Solikamsk would participate in a project to use asbestos tailings from Uralbest. The plans were to double the Solikamsk production of primary metal and alloy. Estimated project costs were reported at US$300-500 million.

Avima which is the magnesium plant at Berezniki produces an estimated 15,000 mtpy and no immediate plans were known about expansion.

In Kazakhstan, the magnesium plant at Ust-Kamenogorsk produced an estimated 10,000 tons in 1998 with no announced plans of expansion.

In the Ukraine, there are two magnesium plants: Zaporozhe which did not operate in 1998 and Kalush produced an estimated 10,000 tons of primary magnesium in 1998. No plans for expansion have been seen although there have been several announcements made about start-up plans.

**ICELAND**

The Iceland Magnesium Project has been around in various forms since 1971. Promoted by the Sudenes Heatir Corporation, a producer of heat and electricity from geothermal steam, the project has had new life. A consortium of Salzgitter Magniy (VAMI and UTI), and Amalgamet did a feasibility study for a 50,000 metric ton primary magnesium metal production plant. The proposed plant used an electrolyte process with cell feed produced using VAMI technology. This study confirmed the technical viability of such a project. Both seawater and imported magnesite were reviewed. Again, the potential supply of low cost electricity made the production costs attractive.

In 1998, Australian Magnesium Investments purchased a 40% share in the Icelandic Magnesium Project. No decision has been made at this time as to when the design and construction will start. AMI is part of the Australian Magnesium Corporation and the acquisition presumably gives them the access to the Russian-Ukrainian technology or they could possibly use the technology that is being developed in Queensland. No immediate decision to proceed is expected until AMC gets the final results of the feasibility study based on demonstration plant operation.

**ISRAEL**

Dead Sea Magnesium has struggled to get into full production. In 1998, they produced 25,000 mt. Israeli Chemical Limited, the parent of DSM, will put up $50 million more for debottlenecking work. It was stated that this money will be used to improve equipment serving the DSM electrolytic reduction plant. It was said that the present auxiliary equipment can only process 27,000 tpy, but DSM hopes to develop a capacity of 35,000 tons. The latest $50 million is in addition to the $460 million already spent.

The board of directors of Israel Chemicals (ICL) and its subsidiary Dead Sea Works Ltd have authorized the deal (on October 18, 1999) in which the magnesium unit which was a subsidiary of Dead Sea Works will be transferred to Israel Chemicals,” ICL Joseph Rosen reported recently. Dead Sea Works hold a 65% stake in the unit, while Volkswagen AG holds 35% of the joint venture. After the deal, ICL will hold 65% of the Magnesium unit.

ICL, a chemical holding company, will inject $65 million into the magnesium unit to promote growth and sales. Officials from Volkswagen and ICL have agreed on a joint business plan to invest $100 million into the magnesium unit to promote growth and profitability. According to the plan, Volkswagen will invest $35 million into the unit.

**JORDAN**

The Jordan Magnesia Company has built a US$70 million magnesium oxide plant. The project has a planned production of 50,000 metric tons per year of high quality magnesium oxide and 10,000 tons of specialty products from Dead Sea brine. The plant will be near the potash project. The Jordan Magnesia Company is owned by Arab Potash and JDICA.