D. Magnesium Powertrain Cast Components

Project Manager: Bob R. Powell
GM Research & Development Center
MC 480-106-212
30500 Mound Road
Warren, MI 48090-9055
(586) 986-1293; fax: (586) 986-9204; e-mail: bob.r.powell@gm.com

Project Administrator: Peter P. Ried
Ried and Associates, LLC
6381 Village Green Circle, Suite 10
Portage, MI 49024-2680
(269) 327-3097; fax: (269) 321-0904; e-mail: pried_imagineer@netzero.net

Technology Area Development Manager: Joseph A. Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

---

Contractor: U.S. Automotive Materials Partnership
Contract No.: FC26-02OR22910

Objective

- Demonstrate and enhance the feasibility and benefits of using magnesium alloys in place of aluminum in structural powertrain components, thereby achieving at least 15% weight reduction of the cast components.

Approach

- Identify, benchmark, and develop a design database of the potentially cost-effective, high-temperature magnesium alloys and, using this cast-specimen database, select the alloys that are most suitable for the magnesium components. (Task 1)
- Design, using finite-element analysis (FEA), an ultra-low-weight engine containing potentially four magnesium components (cylinder block, bedplate, structural oil pan, and front engine cover) using the most suitable low-cost, recyclable, creep- and corrosion-resistant magnesium alloys. (Task 2)
- Create a cost model to evaluate alloy, manufacturing, and technology costs to predict the cost-effective performance of the engine. (Task 2)
- During the execution of Tasks 1 and 2, identify and prioritize the critical gaps in the fundamental science of magnesium alloys and their processing that are barriers either to the progress of the project or to the use of magnesium in future powertrain applications. Seed-fund the most critical research, and promote additional identified needs to support further development of the magnesium scientific infrastructure in North America, thereby enabling more advanced powertrain applications of magnesium. This will be one aspect of the technology transfer deliverables of the Magnesium Powertrain Cast Components (MPCC) Project. (Task 3)
- Refine the engine component designs as necessary (updating to match the properties of the alloy selected for each component), design and build tools and patterns, and cast the engine components. (Task 4)

- Excise specimens from the cast components and develop a full mechanical and corrosion design database for the alloys. Create an original equipment manufacturer (OEM)—common material specification for magnesium powertrain alloys. (Task 5)
- Assemble complete powertrains, dynamometer-test the components, and conduct end-of-test teardowns. Refine the cost model to support determining the cost-effective performance of the engine. (Task 6)
- Note that before addressing Tasks 4–6 and funding Task 3 research, an in-depth review of the engine design, including performance and durability predictions, alloy requirements and measured alloy properties, cost model, and predicted weight reduction will be conducted. Passing this gate review is necessary for entry into the second-half of the project, which has the goal of demonstrating/validating the engine design with respect to castability, manufacturability, performance, durability, and cost.

Accomplishments

- Conducted a successful gate review of the engine design.
- Completed the static and cyclic mechanical property testing of six high-pressure die casting (HPDC) alloys and three sand casting (SC) alloys.
- Rebuilt the architecture of the computer database to contain the above test results, populated the database with the test results, and distributed the compact disc (CD) containing the database to the Project Team.
- Created and used an analytical Pair-wise Analysis Comparison methodology to select the appropriate magnesium alloy for each engine component: the cylinder block, the structural oil pan, and the front engine cover.
- Revised the FEA designs for the structural oil pan and the front engine cover; assembled and issued purchase orders to the respective project teams to design and build the tools for HPDC these components. Design revisions also optimized each component for NVH and weight reduction. The design revisions of the cylinder block are ongoing.
- Defined an engine test matrix, which will be used to measure the performance and durability of the magnesium-intensive engine in dynamometer testing.
- Identified critical scientific needs for utilization of magnesium in powertrain applications and made this information public at a U.S. Council for Automotive Research (USCAR)-sponsored workshop and by presenting and publishing the findings at the 2004 TMS annual meeting. Received and reviewed 31 proposals and selected 5 for funding within the approved MPCC budget program.

Future Direction

- Complete necessary component design revision; freeze the design, and build tooling for SC of the cylinder block. Because of a fire in early 2004 at Eck Industries, that foundry will not be available to the Project as previously planned. Instead, the Project Team has been working with the Structural Cast Magnesium Development Project Team to cast the cylinder blocks at Denison Industries.
- Complete and implement cylinder bore treatment for the cast cylinder blocks.
- Document machining observations for each of the magnesium components to comprehend any potential differences between the chosen magnesium alloys and aluminum.
- Excise specimens from cast magnesium engine components and test to create an excised-specimen property database of the three selected magnesium alloys, which will complement the cast-specimen database completed during Phase I.
- Complete dynamometer testing, teardown, and analysis of the magnesium-intensive engines.
- Input data from all stages of the manufacture of the die cast oil pan and front engine cover and the sand-cast cylinder block into the cost model to determine the cost-effective performance of the magnesium-intensive engine.

- Initiate each of the five basic research projects, and complete each with one midpoint review.
- Deliver final reports for the project by June 30, 2006.

Introduction

In October 2003, the Magnesium Powertrain Cast Components (MPCC) project team successfully completed a review of the Phase I accomplishments and was given the go-ahead for Phase II, the completion of the project. The major accomplishments and ongoing activities in FY 2004 thus comprised: (1) completing and distributing the cast specimen mechanical and thermo-physical database for the alloys tested in Phase I, (2) selecting from those alloys the most appropriate alloy for each magnesium engine component, (3) completing the engine component design revisions based on the properties of the alloys selected for the respective components, (4) contracting the teams for tool design and build and casting of the engine components, (5) defining the test matrix for the component and engine dynamometer tests, and (6) selecting the Task 3 research projects for initiation in 2004.

Excellent progress was made in each area. However, a mishap at the foundry where the magnesium cylinder block was to be cast removed that capability. Accordingly, much activity by the MPCC and the Structural Cast Magnesium Development (SCMD) project teams has involved developing an alternative low-pressure casting site. This activity is continuing.

Mechanical Property Testing and Database Development

The property testing planned for Phase I of the project was completed, as was the architecture for the expanded computer database. The resulting information is the cornerstone of the alloy selection process, in particular because it was obtained from specimens that were separately cast and tested using identical protocols. The database was developed at Westmoreland Mechanical Testing & Research. The amount of data to be contained in the database required a substantial upgrade to the architecture. This and beta testing of the software was completed. Distribution of the compact discs (CDs) containing the complete database to the MPCC project team was begun. The property test matrix has been described in previous progress reports. Briefly, it was developed by consensus of the General Motors (GM), Ford, and DaimlerChrysler powertrain members of the MPCC Project. It represented, in their judgment, the most relevant tests and test conditions for the evaluation of materials to be used in the engine components: the cylinder block, the bedplate, the oil pan, and the front engine cover.

The alloy properties contained in the database include chemical compositions, Brinell hardness, corrosion behavior, compressive and tensile strengths, compressive and tensile creep behavior, density, modulus, and in some cases fatigue and fracture analysis. Also included in the database are the thermo-physical data for several of the alloys, including those which were selected for the engine components. This information (solidus and liquidus temperatures, fraction solid evolution through the mushy zone, molten metal viscosity, specific heat capacity, latent heat, thermal diffusivity and conductivity, density, and linear thermal expansion) is essential for fill and solidification modeling of the engine components, which in turn is essential for tool design and build.

Examples of the compressive yield strengths for the sand and die casting alloys are shown in Figures 1 and 2. For each value shown in the figures, the user will find in the database the following information: the specimen geometry and test procedure; the specimen casting and test history, and both the individual specimen test values and the statistical summary. Exportable stress-strain curves for each test are also contained in the database.

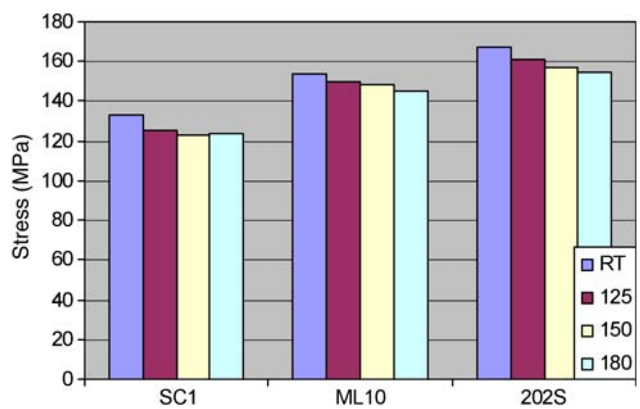

Figure 1. Compressive yield strengths of the SC alloys.

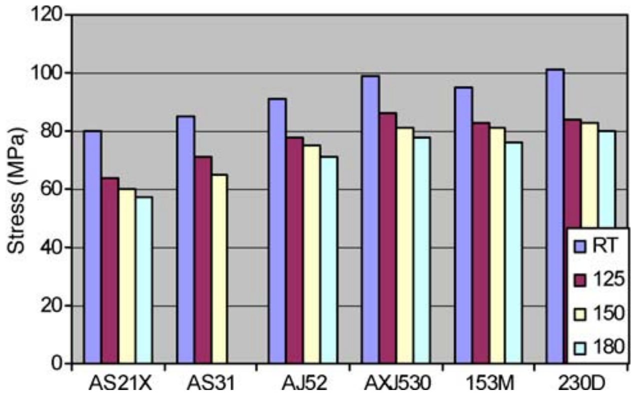

Figure 2. Compressive yield strengths of the HPDC alloys.

This database will be expanded in Phase II of the Project to include specimens excised from the cast components.

Alloy Selection—Pair-wise Analysis

Three major components of the Duratec engine were converted from aluminum to magnesium. One alloy was selected for each component. Having begun the project with seven high-pressure die casting (HPDC) alloys and three sand casting (SC) alloys, selection of the appropriate alloy for each component was a critical task of the project. To ensure objectivity of this process as much as possible, the project team used Pair-wise Analysis. This methodology involved identifying the most important criteria and categories for qualitatively and quantitatively rating the candidate alloys. The categories considered were mechanical properties, thermo-physical properties, corrosion behavior, and material and process cost. Within each category, specific criteria with component design-driven minimum or target values were identified against which to rate the alloys. For example, criteria deemed to be the most important among the block mechanical properties were the ultimate tensile strength, the high-cycle fatigue strength, the yield strength (stiffness) and the creep behavior. The criteria chosen for the other block categories were coefficient of thermal expansion and thermal conductivity (thermo-physical properties), salt-spray corrosion, heat-rejection surface corrosion in the coolant and galvanic corrosion in the coolant (corrosion behavior), and alloy cost and casting behavior (material and process cost).

Once the above categories and criteria were identified, a table was constructed to allow the relative importance of the each category to be compared and determined. Then, for each category a similar table was also created for determining the relative importance of the respective criteria within that category. Weighting was then calculated for each category and criterion, providing a relative, yet quantitative, level of importance for each. Having thus created the tables, rating of each alloy for each criterion was accomplished by comparing the measured property with the predetermined minimum or target property values previously specified. If a minimum property value was not achieved by a given alloy, then the alloy was eliminated from further consideration. Nevertheless, the category and criteria tables were completed for every alloy so that the alloy suppliers would have a complete picture of the relative performance of their respective alloys. Resultant scores for each criterion within each category were calculated and then summed to generate overall scores for each alloy, as is shown in Figure 3. Threshold tests were also performed on the resultant overall scores to determine whether the calculated scoring differences were significant. The process was repeated for each component: the sand-cast block, the die-cast oil pan, and the die-cast front engine cover.

The alloys thus selected were Australian Magnesium Corporation's SC1 for the cylinder block, Dead Sea Magnesium's MRI153M for the structural oil pan, and Dead Sea Magnesium's 230D for the

Criteria	Weights	Specification	Test Data	Alloy Rating	Score
Mechanical	33.333				41.80
UTS	0	235 MPa			
YS	8.889	120 MPa	123 MPa	3	26.40
Creep T	4.444	0.02%	5% at 100 hr	0	0.00
Creep C	2.222		Poor	0	0.00
Fatigue	10	75 MPa	tbd		
Modulus	7.778	45.7 Gpa	38.5 Gpa	2	15.40
Thermophysical	8.333				
CTE	4.167				
TC	4.167				
Corrosion	29.167				53.47
Salt	7.292	4 mils per yr	13.08	1	7.29
Galvanic	2.431	30 mg etc	35	3	7.29
Heat Rejection	19.444	1 mm etc.	5.87	2	38.89
Cost (29)	29.167				74.38
Alloy cost	2.917	AZ91D	5%	3	8.75
Solidification	8.750	1.75	1.9	4	35.00
Affinity/melt T	8.750	1.6 AZ	1.4	3	26.25
Hot tears	7.292	???			0.00
Recycling	1.458	AZ91D		3	4.38
Total	100.000				169.65

Figure 3. Pair-wise analysis of a candidate alloy.

front engine cover. Whereas the alloy selection criteria for the SC block and the structural oil pan were specific to those components, the criteria for the front engine cover were based on the requirements for a HPDC cylinder block, thus allowing a preliminary component-level evaluation of a third alloy.

The selected alloys will be used to cast the components, which will be tested in assembled engines. While each of these alloys was determined to have the best overall combination of available properties required for their respective component application, differences between alloys were often small. Consequently, the alloys selected for the magnesium-intensive V-6 engine represent the best collective engineering judgment of the Project Team. Because no single alloy was considered ideal, however, the Project Team expects that world-wide alloy development will continue until market forces determine a few standard powertrain alloys. The fact that several promising alloys are now available demonstrates the significant progress that has been made in magnesium.

Engine Component Design Revisions

The magnesium-intensive V-6 design, which was based upon the aluminum 2.5/3.0L Ford Duratec, exceeded the weight reduction target that was set by the Project Team at the start of the project. In postgate review activities, the Project Team further evaluated the engine design and design criteria using thermal, computational fluid dynamics, structural, durability, and noise, vibration, and harshness (NVH) performance criteria. The Phase I design of the engine was based on literature data. Having completed the property measurements and the selection of the alloys for the specific magnesium components, the focus of efforts in 2004 has been design revisions of the components for their respective alloys. In these activities, the goal was to optimize the designs for the aforementioned criteria and to take full advantage of the castability and other advantages of magnesium, relative to aluminum, to maximize weight reduction and the other performance criteria.

The design revisions for the structural oil pan and the front engine cover were completed. These were addressed first because of the lead time that will be necessary for die design and build. The cylinder block, which will be sand cast, is currently undergoing design revisions.

Optimized NVH performance was a major goal of the design revision effort for the oil pan and the front engine cover. Because of its lower modulus, and because the relationship between stiffness and NVH, it is generally thought that the weight reduction potential of magnesium is substantially nullified by the lower stiffness. In the design effort, two strategies were considered, a "soft" design which did not try to compensate for the less stiff magnesium, and a "stiff" design which did. Surface noise predictions were made for both design approaches over the full range of engine revolutions per minute and at several important regions in the acoustic spectrum. Figure 4 shows one set of results. In the

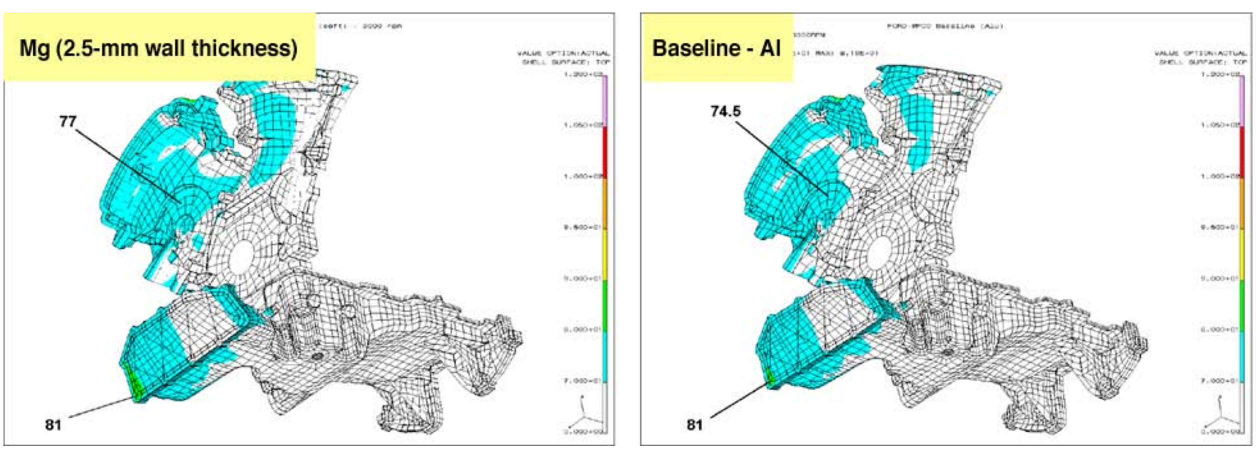

Figure 4. NVH analysis of the structural oil pan and front engine cover for octave band 250 Hz at 3000 rpm comparing the soft magnesium design with the aluminum baseline.

figure, the magnesium soft design version is compared with the aluminum components. The peak values for surface noise are labeled in each image. It is surprising that both versions show essentially the same NVH performance. As a result of these predictions, the Project Team elected to use the "soft" version, which would further lower the mass of the components. Predictions such as this challenge the prevailing notions about magnesium and designing with magnesium. These predictions will be thoroughly evaluated by the engine dynamometer testing planned for this engine.

Having completed the design revisions for the structural oil pan and the front engine cover, the computer-aided design (CAD) files were "handed off" to the die build team (see below), and work focused on completing the cylinder block design. It is expected to be completed in the first quarter of FY 2005.

Component Die Design and Build

Through competitive bidding, project teams for both the structural oil pan tool and the front engine cover tools were selected and contracts issued to them. The structural oil pan team comprises Technalysis, H. E. Vannatter, and Spartan Light Metal Products. These companies will design, manufacture, and use the tool, respectively. Sufficient oil pans will be HPDC to allow component and engine dynamometer testing and excising specimens for the mechanical property database. Exco Engineering and Intermet comprised the team to design, build, and use the front engine cover tool. Both sets of die casting tooling will use premium quality H-13 inserts. The MPCC Core Team chose H-13 over the less robust P-20 tool steel that is commonly used for prototype tools, so that tools could be made available to other alloy suppliers for casting trials and possibly for excised specimen testing once the engine test requirements have been met.

Once the cylinder block design is completed, a contract will be issued for tool build and low-pressure SC of the blocks. It was noted in the introduction, however, that the site where casting was to have taken place is no longer available to the Project. It was established during the castability trials of the SC alloys that low-pressure casting would be required to meet the melt quality requirements for the cylinder block. This is primarily due to the behavior of the grain refiners that these alloys require and, secondarily, to the recognized benefit of low-pressure casting for controlling metal fill of empty cavity molds. The MPCC project team is working with the SCMD project team to develop the capabilities of the Denison Industries for casting both the MPCC cylinder blocks and the SCMD engine cradles, both of which require high-temperature, creep-resistant alloys.

Engine Dynamometer Test Program

Just as the MPCC project team sought OEM consensus on the mechanical property test matrix, OEM consensus was used to develop the engine dynamometer test matrix. This matrix of tests will evaluate both the performance and durability aspects of the magnesium-intensive V-6 engine. The production Duratec (aluminum) will serve as the baseline for these tests. Testing will include block assembly and thermal distortion, thermal aging, hydraulic and thermal fatigue, hot scuff and cold scuff of the cylinder bores, NVH, and durability. Having defined the test matrix, the project will solicit bids for testing in 2005.

Critical Scientific Needs for Powertrain Magnesium Alloys

Phase I of the MPCC Project sought to determine the feasibility and practicality of producing a magnesium-intensive engine. Through the finite-element analysis (FEA) design activities, cost modeling, and extensive alloy casting and testing, the project team sought to quantify the technical and economic requirements of the V6 engine and which of the newly developed, high-temperature magnesium alloys best met those requirements. The additional objective of the project was to identify the fundamental scientific challenges of using magnesium alloys and casting processes in powertrain components both within the ongoing project and for more advanced powertrain components. This was accomplished by recognizing and documenting the critical scientific needs of the project as the Project Phase I was executed. The areas of critical scientific need are shown in Table 1.

During the reporting period these needs were compiled and rolled out to the North American scientific community in two ways. The first was a

Table 1. Areas of critical scientific need and MPCC project to address those needs

Area of need	Project	Principal investigator
Phase equilibrium and computational thermodynamics	Computational Thermodynamics and Alloy Development of Magnesium Alloys	Z. K. Liu Pennsylvania State University
Casting, solidification behavior, and microstructure	Hot Tearing Behavior of Magnesium Alloys	D. Emadi National Research Center of Canada
Alloy development and structure-property relationships	(No proposal selected)	
Creep and bolt-load retention	Creep, Bolt Load Retention, and Microstructural Analysis of High-Temperature Magnesium Alloys	W. Jones University of Michigan—Ann Arbor
Corrosion behavior and protection	Evaluation of Magnesium Corrosion by Various Methodologies and Surface Composition of Magnesium Alloys by Rutherford Backscattering Spectroscopy	P. Mallick University of Michigan—Dearborn
Alloy recycling	Fluxless Recycling Methods and Process Control for Creep-Resistant Magnesium Alloys	D. Schwam Case Western Reserve University

workshop held at the USCAR offices in Southfield, Michigan, to which representatives from universities and government laboratories were invited. The second was by presenting and publishing these needs at the Magnesium Technology 2004 Symposium, which was held at the TMS Annual Meeting in Charlotte, North Carolina, in March 2004.

Subsequent to the USCAR workshop, requests for proposals were solicited. Thirty-one proposals were received and evaluated by the project team. Using project funds allocated for this purpose in the original project budget, five of the proposals will be funded and initiated in 2005. These have been selected and the specifics of the work statements and funding are being finalized. A report was delivered to DOE, which contained all of the proposals with critiques by the MPCC Project Team. It is hoped that some of these additional proposals will be funded by other organizations. The projects to be executed within the MPCC activity are also shown in Table 1.

The newly developed, creep-resistant magnesium alloys are promising candidates for automotive powertrain applications. However, the limited amount of research and lack of understanding regarding these alloys remains a considerable obstacle to the full implementation of magnesium powertrain components. Conducting research in the areas shown in Table 1 will benefit both the short-term, immediate needs of the project in Phase II and will provide a long term legacy of the project by promoting new and strengthening existing research programs and thereby strengthening the scientific infrastructure for magnesium in North America.

Conclusions

The MPCC Project has made excellent progress since its inception in 2001. Project accomplishments include the science and engineering property database for the high-temperature, creep-resistant magnesium alloys; the selection of the alloys for the magnesium-intensive engine and the methodology used to make the selection; the engine design and cost model to predict cost-effective performance of the magnesium-intensive engine; and the selection and initiation of the basic science research projects. In fiscal year 2005, the project team expects to complete the technical work of the project. Completing of the research projects and documentation for the entire Magnesium Powertrain Cast Components Project will occur in 2006.

Acknowledgements

The success of this project is due to the dedicated efforts of a large number of team members, in particular the author's colleagues at Ford, DaimlerChrysler, and General Motors. The many other companies and organizations making up the project team were listed in the FY 2003 Progress Report. However, the author would like to acknowledge the MPCC core team for their work: John Allison, Joy Hines, and Robert McCune from Ford; Randy Beals and Lawrence Kopka from DaimlerChrysler; Larry Ouimet, James Quinn, and Grant Tappen from General Motors; and Peter Ried from Ried and Associates. The continuing support of our respective companies and the U.S. DOE is gratefully acknowledged.

Presentations and Publications

1. "Magnesium Powertrain Cast Components Project," B. R. Powell, presented at the AMD Board Casting Off-Site, September 29, 2004, Southfield, Michigan.
2. "Overcoming the Technical Barriers to a Magnesium-Intensive Engine," B. R. Powell, L. J. Ouimet, J. E. Allison, J. A. Hines, R. S. Beals, L. Kopka, and P. P. Ried, presented at the 10th Metal Casting Congress, sponsored by the American Foundry Society and the North American Die Casting Association, Rosemont, Illinois, June 12, 2004 (invited).
3. "USCAR Update on High Temperature Alloys for Magnesium Powertrain Cast Components Project," J. A. Hines, J. E. Allison, R. McCune, B. R. Powell, L. J. Ouimet, R. S. Beals, L. Kopka, and P. P. Ried, 14th Magnesium in Automotive Seminar, sponsored by the International Magnesium Association, Troy, Michigan, April 20, 2004 (invited).
4. "The Magnesium Powertrain Cast Components Project: Part II—Properties of Several New Creep-Resistant Magnesium Alloys," J. A. Hines, R. C. McCune, J. E. Allison, B. R. Powell, L. J. Ouimet, R. S. Beals, L. Kopka, and P. P. Ried, presented at the Magnesium Technology 2004 Symposium of the TMS Annual Meeting, Charlotte, North Carolina, March 15, 2004.
5. "The Magnesium Powertrain Cast Components Project: Part I—Accomplishments of Phase I and the Objectives and Plans for Testing the Magnesium Engine in Phase II," B. R. Powell, L. J. Ouimet, J. A. Hines, J. E. Allison, R. S. Beals, L. Kopka, and P. P. Ried, presented at the Magnesium Technology 2004 Symposium of the TMS Annual Meeting, Charlotte, North Carolina, March 15, 2004; also published in the symposium proceedings, pp 3-10 (2004).
6. "The Magnesium Powertrain Cast Components Project: Part III—Fundamental Scientific Needs for Magnesium Utilization in the Powertrain Environment," R. S. Beals, L. Kopka, J. A. Hines, R. C. McCune, J. E. Allison, A. A. Luo, B. R. Powell, L. J. Ouimet, and P. P. Ried, presented at the Magnesium Technology 2004 Symposium of the TMS Annual Meeting, Charlotte, North Carolina, March 15, 2004; also published in the symposium proceedings, pp. 11–18 (2004).
7. "Progress Toward a Magnesium-Intensive Engine: The USAMP Magnesium Powertrain Cast Components Project," B. R. Powell, L. J. Ouimet, J. E. Allison, J. A. Hines, R. S. Beals, L. Kopka, and P. P. Ried, presented at the Magnesium Technologies session of the 2004 Society of Automotive Engineers World Congress, Detroit, Michigan, March 9, 2004; also published as SAE Technical Paper No. 2004-01-0654 and to be published in *SAE Transactions* (2004).
8. "The USAMP Magnesium Powertrain Cast Components Project," B. R. Powell, published in *JOM*, **55**(11), 28–9 (2003).
9. "The Magnesium Powertrain Cast Components Project" B. R. Powell and P. P. Ried, Jr., presented at Advanced Technologies session at the 2003 North American Die Casting Association International Congress, Indianapolis, Indiana, September 15, 2003; also published as paper no. T03-28 in the NADCA Transactions (2003).