Market Model Simulation: The Impact of Increased Automotive Interest in Magnesium

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Due to increasing energy and environmental concerns automakers have recently become more interested in lightweight alternatives to traditional component designs. Magnesium, the lightest standard engineering metal, has often been cited as showing potential in the automotive world, but has been resisted by automakers due to high prices and limited availability. Small production resources of magnesium limit the potential of magnesium in the automotive arena if growth in interest leads to material shortages and price volatility. To investigate the dynamics of the magnesium market, a system dynamics simulation model of the market was created. The model, which simulates supply, demand, and price interactions, was used to investigate market stability strategies that will benefit all market players.

INTRODUCTION

In the 1970s, when the Western world experienced oil shortages that greatly increased the price of petroleum products, the automobile became an easy target for regulators hoping to decrease the pain of the oil shock. In order to reduce energy consumption of gasoline, the U.S. Congress passed the Energy Policy and Conservation Act of 1975, which established nationwide standards for automotive fuel efficiency. This prompted automakers to address fuel economy, formerly a minor factor in automotive design, as a vital engineering requirement.

Although reducing vehicle mass improves fuel economy, low-density materials are typically more costly when compared to traditional automotive materials, such as steel.

Magnesium has the lowest density of the common engineering metals and has secured a growing role in select automotive applications despite its high cost and limited supply. Some applications where magnesium has gained a noticeable share of automotive designs include cross-car instrument panel beams, steering wheels, and valve covers. The market for automotive magnesium parts has grown rapidly, nearly 15% per year, during the 1990s and is expected to continue that trend as new applications are developed.[1]

Despite positive trends, the future of magnesium in automotive designs is uncertain, in part because it is higher priced than traditional materials such as steel and aluminum. Magnesium, costing $1.40–1.80/lb, is more than four times more expensive than steel on a mass basis. Another challenge to the development of magnesium automotive designs is the relative immaturity of the supply structure. More mature material industries, such as steel and aluminum, dwarf the output of the magnesium industry: steel produces nearly 1,400 times as much material on a yearly basis, and aluminum, 45 times more annually. Due to the small supply base, the price for magnesium is prone to swings as demand grows and absorbs available production.

Many new greenfield magnesium facilities have been proposed in order to sustain recent increases in automotive demand, but it is not certain whether these sources will be enough to stabilize the market. Price volatility has a negative impact on the use of magnesium in automotive applications. Recent swings in magnesium price have already been shown to cause automakers to switch magnesium components back to other competitive materials.[2]

A magnesium market simulation model was created based on market modeling techniques used in the Material Systems Laboratory at the Massachusetts Institute of Technology and incorporates aspects of econometrics, utility analysis, microeconomics, and system dynamics.

The model was used to examine the stability of the magnesium market

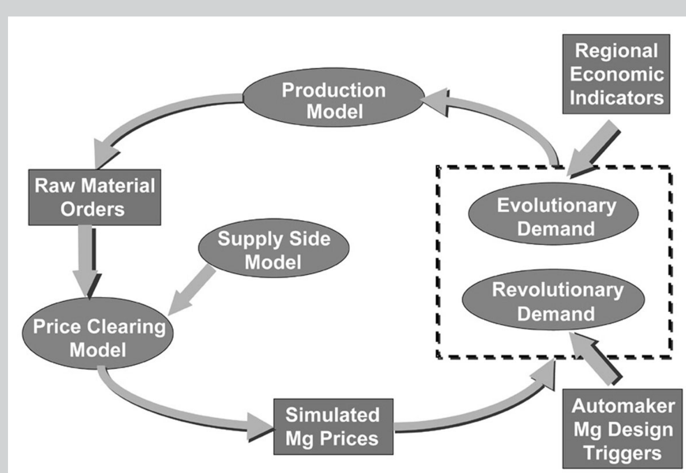

Figure 1. A simple magnesium market model schematic

and investigate the future impact of automotive demand on the supply-demand balance and prices. The insights gained from the model simulations suggest strategies on both supply and demand sides of the market to promote price stability.

MODEL DESCRIPTION

A system dynamics framework was used for the model structure. The approach proved useful for incorporating feedback relationships among the supply, demand, and pricing sectors. The model consists of five parts: the supply model, the demand models separated into evolutionary and revolutionary demand models (automotive), the production models, and the price-clearing model. The dynamic feedback loop and the interactions of the five model sectors is shown in Figure 1.

Supply Model

The supply model consists of a large data set of operating capacities and operating costs that correspond to each of the world's known magnesium producers. Data for the production capacities and operating costs were derived primarily from information in a Solomon Smith Barney report on Australian Magnesium, United States Geological Survey (USGS) Magnesium Mineral Yearbook entries, and discussions with magnesium producers.[3,4] The marginal cost of operating a facility does not include the cost of capital and other fixed costs.

Production capacity and operating cost data were used to approximate the short-term supply curve using standard microeconomic methods. Facilities were added stepwise to the curve in order of increasing operating cost. An example marginal cost estimate of the world magnesium supply curve is shown in Figure 2. This ordering was simplified by having five separate cost tiers with cost cutoffs. A facility's cost is compared to the cutoffs in order to assign the appropriate tier. The cutoffs were also helpful when performing a linear approximation of the supply curve during the price-clearing operation.

The supply model is also dynamically adjustable. Import tariffs, brownfield expansion of current facilities, and new magnesium producers can be included in the supply curve for the investigation of specific scenarios.

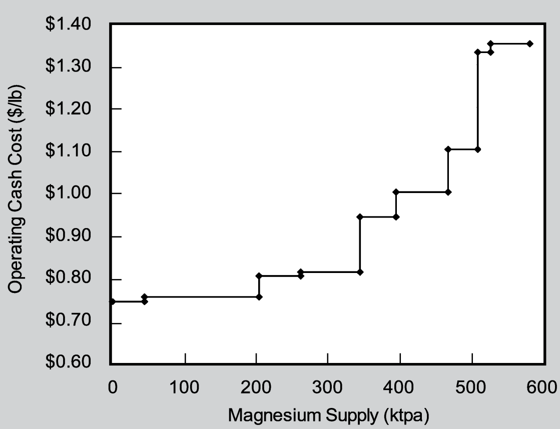

Figure 2. A marginal cost estimate of world magnesium supply curve.

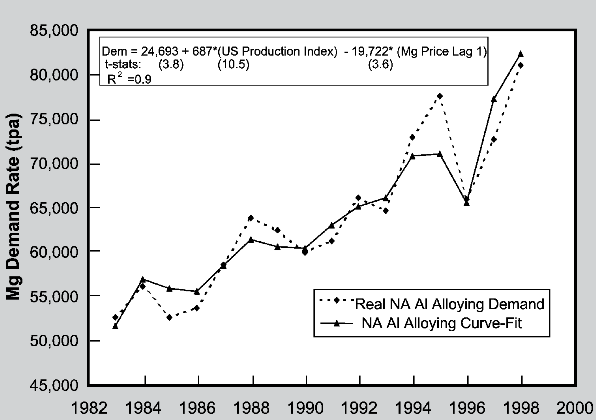

Figure 3. The North American aluminum-alloying magnesium demand and economic curve-fit.

Demand Models

Demand models were used to simulate world consumption of magnesium in the three major regions, Asia, Europe, and North America. Most applications of magnesium are expected to show demand patterns in the future that are similar to the past. These evolving demand sectors were modeled with econometric (statistical) techniques. The evolutionary demand sectors included aluminum alloying, steel desulfurization, nodular iron production, and chemical applications. In the rapidly expanding area of automotive die-casting, econometric techniques were not used because past trends are not an acceptable guide for future demand. For this reason, this sector was termed "revolutionary demand." The revolutionary demand models for automotive die-casting incorporate information about preferences for price-weight tradeoffs obtained from interviews with automotive design engineers.

Evolutionary Demand Models

Evolutionary demand models were used for five major categories of magnesium demand: aluminum alloying, die-casting (prior to 1999, after which the revolutionary demand model takes over), steel desulfurization, nodular iron production and "other" uses (including all remaining chemical and physical applications). These models were created by simulating historic demand using standard linear regression techniques. The model equations were of the form:

$$MD^{ij}_t = A^{ij} + B^{ij}\,(IA^{ij}_t) + C^{ij}\,(MP_{t-x})$$

where

MD^{ij}_t = Magnesium demand in industry i and region j during period t

A^{ij} = Linear additive constant

B^{ij} = Linear multiplicative constant for industrial activity

C^{ij} = Linear multiplicative constant for historic magnesium pricing

IA^{ij}_t = Industrial activity for industry i and region j in period t

MP_{t-x} = Historic magnesium pricing for a period t–x

Many of the industrial sectors (especially the largest sectors such as aluminum, steel, and die-casting) displayed very good fit to this model and the explanatory variables were all statistically significant at a 95% confidence level. An example of one such evolutionary curve-fit for North American aluminum alloying is shown in Figure 3.

Revolutionary Demand Models

To simulate automotive demand, auto design engineers were consulted about the impact of material price on implementation of magnesium designs. Materials engineers at Ford and General Motors were interviewed about a list of over 30 potential magnesium applications (brackets to engine blocks) aggregated along seven types of vehicles (small-, medium-, and large-sized cars and trucks, plus specialty cars). In each application, the engineers were asked to consider magnesium in relation to a competitive material (steel, aluminum, or polymer). The key information gained was the relative price at which magnesium would displace the current material in the component design (and vice versa) as well as the price residence period of stability before the substitutions would take place. These introduction and removal "trigger prices" were key to the simulation of future automotive magnesium demand.

Two general trends were revealed in the interviews. First, larger vehicles, either trucks or large, luxurious cars, had higher magnesium trigger prices. Smaller vehicles, targeted at cost-conscious consumers, would likely not pay a premium for magnesium. Second, magnesium components that presented special engineering challenges or advanced design efforts had lower trigger prices. Powertrain applications with creep issues or exterior applications with corrosion concerns had much lower trigger prices than simple brackets or instrument panels, where engineers have experience. Figure 4 shows an example of a "pseudo" revolutionary demand curve created from the data found during the interview process.

The schematic shows how the mechanics of the revolutionary models work. Simulated magnesium prices enter the model and are compared to magnesium component triggers for the introduction or removal of magnesium designs. If the price is low enough for the specified residence period, a magnesium design decision will initiate. Likewise, if the material prices are too high, a magnesium replacement decision will occur. The decisions will only impact material demand, however, after an appropriate design period, assumed to be 3 years. After the decisions mature through the design cycle, the balance between magnesium and non-magnesium components shifts. A few magnesium parts may replace other designs, or current magnesium parts may revert to their original competing materials.

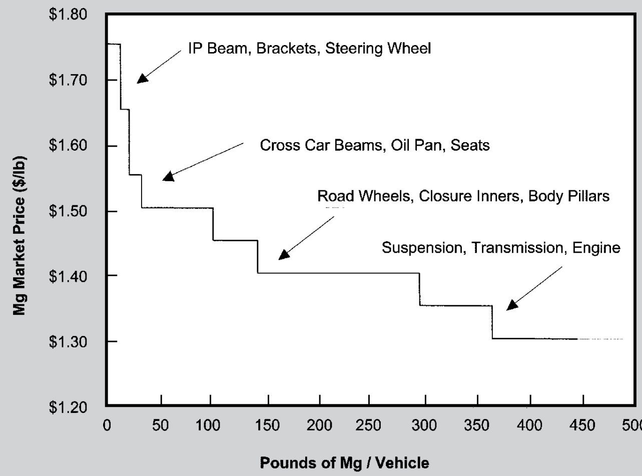

Figure 4. The magnesium automotive design deployment price sensitivity (e.g., North American large car).

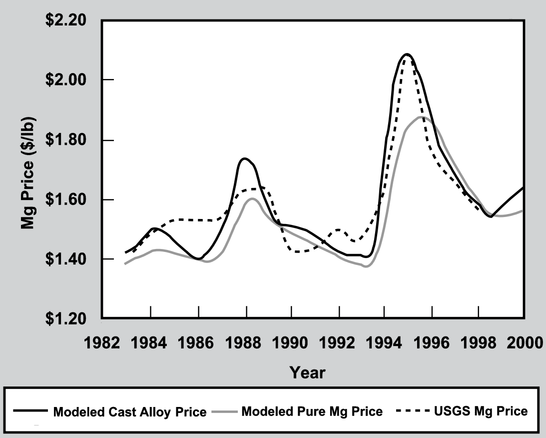

Figure 5. A market model simulation of historic magnesium pricing, 1983–2000.

During the simulation, the pool of magnesium components is monitored to determine the demand for raw material needed to produce the parts. The parts count is scaled by estimated part masses, expected platform penetration, production volume, and an assumed die-casting manufacturing scrap rate of 40%. Summing these figures over all vehicle types yields a projection of the revolutionary automotive magnesium demand.

Price-Clearing Model

The price-clearing model completes the market feedback loop by reconciling the raw material orders and with the supply curve.

The supply model, described in a previous section, reflects operating cast costs (primary variable costs). This curve, however, must be modified to reflect the long-term marginal costs of the industry. The pricing model approximates long-term costs by adding estimates of operating margins (e.g., capital charges, sales and administrative expenses, profit margin). Margin estimates were developed from discussions with representatives of magnesium producers and industry studies.

The operating margins and price volatility factors are similar, but slightly different, for pure magnesium alloy and die-cast grade materials. Die-cast pricing also utilizes a slightly more restrictive supply curve that eliminates lower-grade supplies (like thermally produced Chinese material) that is not applicable to the die-casting process.

Separate price-clearing models were employed to reflect these differences.

Solving for the intersection of the long-term supply curve and the orders for raw material, from the production models, yields the simulated prices for market clearing. These market prices feed the dynamic loop, creating new demand, production, raw material orders and, eventually, future market prices.

MODEL VALIDATION

The major verification criteria were the model's fit to the historic pricing data obtained from USGS reports and data for regional and sector demand for magnesium from International Magnesium Association sources. The simulation results of market pricing for the period 1983–2000 is shown in Figure 5. Due to equilibrium assumptions used to initialize system dynamics models, the first 4 years of the simulation show some deviation from the historic market performance. After this period, however, the model settles into good correlation with past behavior.

The consumption sector regression equations and the pricing models produced the volatility and cyclically similar to that observed in the market during the period of 1983–1998. Price spikes were also observed in the simulation in response to material order rates nearing material supply capacity and in response to anti-dumping tariffs (U.S. import duties against China and Russia in the late 1990s).

Casting-alloy prices also exhibited a damped and slightly delayed behavior (~1 year offset) similar to the general dynamic of pure alloy pricing. These behavioral differences between pure and alloy magnesium were characteristic of historic material price observations revealed during discussions with magnesium producers.

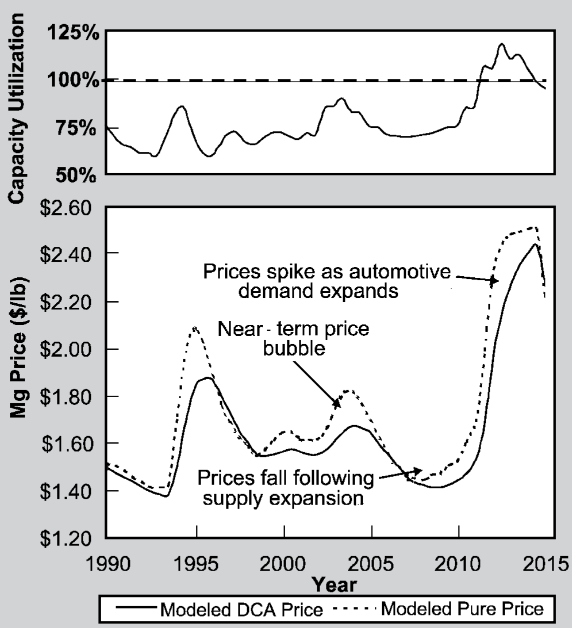

Figure 6. A near-term magnesium supply expansion scenario, projected material prices, and supply capacity utilization 1990–2015.

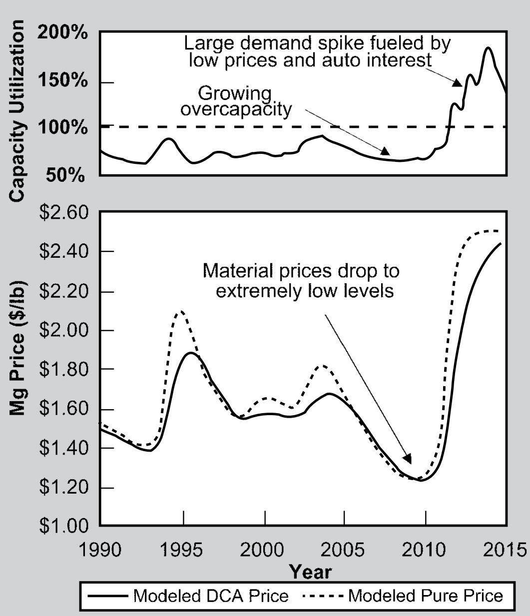

Figure 7. A medium-term magnesium supply expansion scenario, projected material prices, and supply capacity utilization 1990–2015.

MARKET MODEL SIMULATIONS

The market model was used to analyze three scenarios. First, the market consumption potential was assessed to determine the magnitude of growth the industry could expect in the next 15 years. Second, the published near- (present–2004) and medium-term (2004–2010) plans for capacity expansion were simulated in order to understand their impact on the stability of the magnesium market as the industry pursues growth. Third, stability strategies on both the supply and demand side of the market were examined as possible methods to achieve growth in demand without price volatility.

Supply Expansion: Impact of Near- and Medium-Term Magnesium Projects

The consumption scenarios showed the large potential demand for low-priced magnesium, especially in the automotive sector. Current magnesium producers and new entrants have initiated many magnesium supply expansion plans. These ventures hinge on the potential demand created by new facilities with lower operating costs. Magnesium smelters in various stages of planning are being proposed in areas like Australia, Congo, Netherlands, Iceland, and Jordan.

Examples of dynamic feedback systems and their volatile behavior, like those observed in the commodity markets, imply that large-scale expansion plans may not deliver an easy solution to expanding magnesium demand. Magnesium consumers are championing the new entrants to the supply base because of the expected negative pricing pressure. Although lower prices will lead to expanding growth, these effects are not always positive market developments. Low prices also have the potential to generate so much interest, especially in the automotive sector, that material supplies could be completely stripped. The magnesium pricing swings following the total absorption of supply would likely destroy prospects for growth.

Abandonment of materials with high price volatility is not uncommon in the auto industry and has been observed in the case of magnesium during mid-1990s when U.S. tariff policy caused large price swings in the magnesium market.[3] If the magnesium industry wishes to continue its growth trends in the automotive industry, suppliers and automakers alike will need to understand the impact of their own behavior on the stability of the magnesium market.

Several scenarios of supply expansion were performed to investigate the impact of new entrants. The first scenario focused on a small set of capacity expansions, which represent the near-term published plans of magnesium suppliers that are likely to start production over the next three years (up to 2004). The analysis was then expanded to include the vast array of other magnesium projects. These expansions are introduced after 2004. The final part of the expansion analysis examines a completely exogenous supply expansion scenario as a possible solution to the growth and stability problem of the world magnesium market.

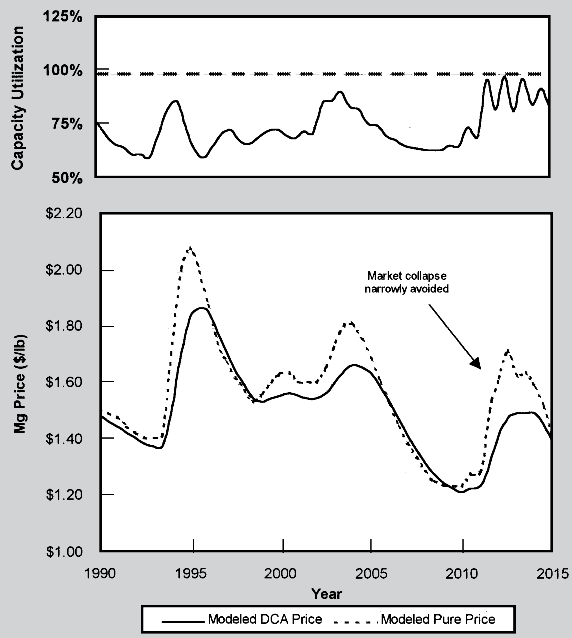

Figure 8. Forcing market stability, material prices, and supply capacity utilization 1990–2015.

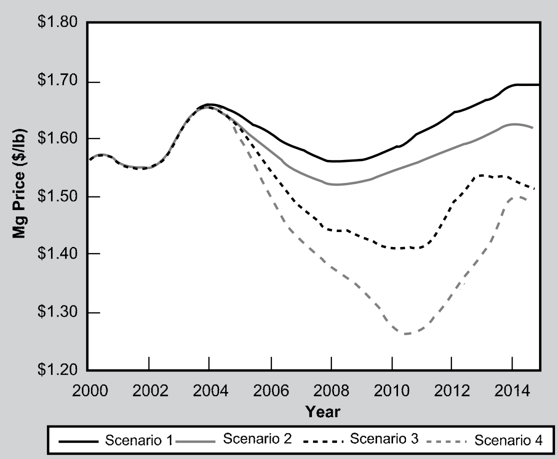

Figure 9. Automated supply expansion scenarios: die-cast alloy pricing projections.

Near-Term Magnesium Supply Expansion Plans

The near-term plans for magnesium supply involve a small set of magnesium projects, summarized in Table 1. These ventures have substantial consumer support, like QMC's backing from Ford Motor Company, or offer extremely low operating costs, like Mt. Grace's Australian project or the Congolese facility.

For simplicity, the facilities were assumed to come on in sets of roughly 60 kt/y with an operating cash cost of $0.75/lb. The results of this near-term expansion scenario are shown in Figure 6.

With the expansion of magnesium applications, the model suggests that consumption of primary magnesium in the near future may approach industry capacity, resulting in price increases (Figure 6) during the 2003–2005 timeframe. Because the near-term supply expansion facilities are only ramping up during this period, they have little immediate effect on this price bubble. The bubble, however, slows demand for material, especially in the automotive sector, in the following 5 years, just as the new facilities reach their full production levels. Slowing demand causes a glut in material capacity, which results in a steep drop in material prices, to nearly $1.40/lb, for the years 2006–2010.

The oversupply is not necessarily an adverse market development, however, as consumers (i.e., the automakers) finally get what they desire, inexpensive material. The emergence of cheap magnesium causes the automakers to expand the scope of their designs and pursue advanced magnesium applications. This eventually produces the market instability that the original supply expansions were attempting to prevent. When the automakers finally incorporate a large variety of advanced magnesium applications, 2–3 years after the material price bottoms out, the shear volumes of material they desire quickly outstrips the capacity of supply and prices spike. In the years following 2010 automotive consumption pushes material prices over $2/lb.

Medium-Term Magnesium Supply Expansion Plans

The near-term expansion simulation suggests that growth in auto demand could cause a magnesium shortage in the next decade. There are a large

Table I: Near-Term Greenfield Magnesium Projects[4]

Mg Project	Mg Source	Capacity	Current Status	Start-Up Date
Mt. Grace, NT, Australia	Magnesite	50 kt/y	Pilot testing	2003
Queensland Mg Corp., Australia	Magnesite	90 kt/y	Pilot testing	2004
Mg Alloy Corp., Congo	Carnalite	50 kt/y	Pre-feasibility	2004
Current Industry Capacity	Various sources	~550 kt/y	In operation	—

number of other magnesium projects that are also hoping to capitalize on expanding automotive magnesium demand. These projects, however, are less technically and financially certain.

Beyond those analyzed in the previous section, facilities proposed in Australia, Iceland, China, and Jordan, account for another possible 550 kt/y of supply. If these plans are realized, current worldwide magnesium capacity would be nearly doubled.

In the medium-term expansions simulations, new facilities were also assumed to enter the market in units of 60 kt/y and cash costs of roughly $0.75/lb. The published potential expansion plans would result in additions of nine of these generic plants beginning in 2005. By the end of 2013, all nine new facilities would be running, adding more than 0.50 Mt/y of capacity to the magnesium supply curve.

The medium-term supply expansion scenario creates a similar, but more dramatic, example of the boom-bust dynamic caused by low material prices, followed by an explosion in demand (Figure 7). By introducing more material supply in the years following the price bubble, the oversupply problem late in the decade is exacerbated. Prices fall to even lower levels, approaching $1.20/lb. The increasing overcapacity could be viewed as a preemptive move to get ahead of the automotive design boom, but it fails. The following demand spike locks in millions of tonnes of magnesium in automotive designs, which easily outpaces the reserve material capacity.

Medium-Term Supply Expansions Necessary for Market Stability

Maintaining price stability is a very difficult challenge for a nascent industry. An effort was made to discover if any expansion scheme could prevent the boom-bust cycle in the magnesium market simulation. Figure 8 shows the supply expansion, demand trends, and pricing projections for an exogenous introduction scheme that achieves a relatively stable market dynamic. The model anticipates the near-term expansions of three plants, and projects that, to meet demands, expansions of one plant per year will be needed from 2005 through 2009, ten in 2010, 11 in 2011, nine in 2012, three in 2013, and one in each 2014 and 2015.

The forced stability scenario shows that the expansions necessary to prevent a boom-bust cycle in the magnesium market are substantial if not ridiculous. The large price spikes seen in previous scenarios are avoided by the introduction of huge numbers of facilities at the turn of the decade (ten and 11 plants in 2010 and 2011, respectively). These additions account for 41 new facilities, which would lead to a nearly four-fold increase in the current magnesium supply base.

Not only would quadrupling the current supply base be unlikely, the solution suggested by the forced stability scenario is also fragile. The removal of a single plant, especially in the years 2008 and beyond, causes the simulation to return to a boom-bust dynamic.

Stability-Enhancing Market Feedback Mechanisms

Two feedback strategies were investigated for improving the market dynamic discovered in the exogenous expansion scenarios. First, a mechanism was added to the model that linked future automotive demand directly to new capacity. This method was used to add new supply intelligently rather than forcing expansions exogenously. Second, a demand-side feedback mechanism was employed to address the difficulties encountered with material oversupply and shortages. This strategy investigated reserving low-priced magnesium in periods of oversupply for use during future periods of booming demand.

Supply-Side Feedback: Capacity Expansions Linked to Auto Demand

To coordinate supply expansion plans, an automated mechanism was introduced into the market model. The mechanism tracks automotive designs, anticipates magnesium demand, and initiates supply expansions when warranted.

A tracking sector catalogs new magnesium parts in the design phase and creates an automotive magnesium demand predictor 3 years before their introduction, then automatically adjusts the supply curve by adding new facilities like those described in the exogenous expansion section.

Several scenarios were run to examine

Table II. Automated Supply Expansion Scenarios

Scenario No.	Exogenous Expansions	Notes
1	None	All future plans are triggered solely based on increased automotive demand
2	Single plant in 2003	Exogenous addition could represent Mt. Grace facility
3	Single plants in 2003 and 2004	Additions represent Mt. Grace and QMC
4	Single plant in 2003 and two plants in 2004	All near-term planned plants are added (Mt. Grace, QMC, Congo)

the impact of coordinated supply expansions. In the first scenario, all expansions, from the year 2000 onward, were created automatically. The remaining three scenarios forced exogenous additions to the supply curve outside the automated mechanism. These runs signify the three near-term expansion plants in Australia and the Congo (Table II).

Table III summarizes the results of the four scenarios. Scenarios 1 and 2 added few additional plants and raised supply and demand to relatively low levels. Adding more near-term facilities, as in scenarios 3 and 4, generated a sizable automotive interest that needed to be satisfied by larger supply expansions. The larger expansions are necessary due to the negative price pressure created by the exogenous near-term expansions. Figure 9 shows the price projections of die-casting alloy for the four scenarios.

Table III. Automated Supply Expansion Scenario Results Summary

Scenario No.	Mg Plant Exp. by 2015	Ind. Capacity 2015	Min. Mg Price	Av. Auto Mg Content 2015
1	1	0.85 Mt/y	$1.56	7.7 kg / veh (Eur) 10 kg / veh (NA)
2	2	0.96 Mt/y	$1.52	8.1 kg / veh (Eur) 12.2 kg / veh (NA)
3	10.5	1.54 Mt/y	$1.41	16.8 kg / veh (Eur) 25.9 kg / veh (NA)
4	36	3.00 Mt/y	$1.25	~34 kg / veh (Eur) ~68 kg / veh (NA)

Scenarios 1 and 2 display relatively stable prices at levels close to those observed today. Magnesium accounts for nearly 9–14 kg per vehicle by 2015 (up from 4 kg today). Scenario 3 represents medium growth, with prices slightly lower than today and slightly higher growth in demand, supply, and automotive consumption. This scenario is fairly consistent with the current expansion plans for the magnesium industry. The addition of roughly 11 new facilities, as suggested in scenario 3, should be possible given the industry's current expansion plans.

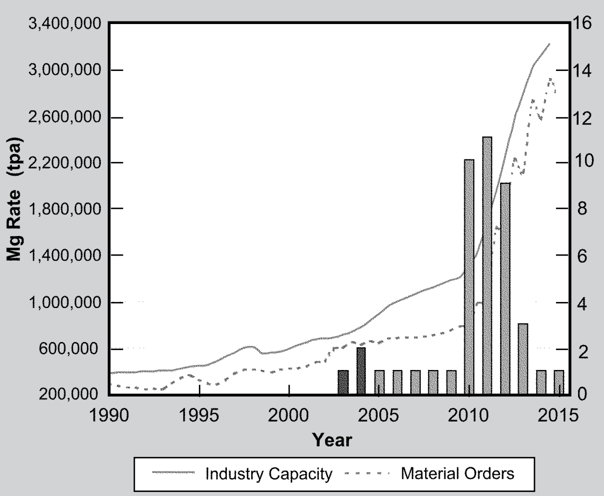

Figure 10. Demand feedback—aggressive supply expansion: supply and demand.

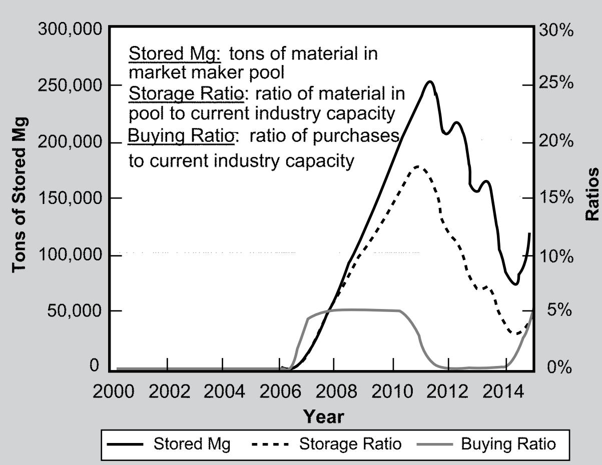

Figure 11. Demand feedback—aggressive supply expansions: material storage profile.

Scenario 4 was not as stable as the other three runs. The near-term expansions were excessive following the price bubble in 2003–2004 and drove magnesium prices below $1.30/lb. Substantial automated medium-term supply expansions are required early in the next decade and add roughly 2 Mt/y of capacity. Each year between 2010 and 2012, six or more plant openings are required to maintain market stability. The source of demand growth is centered in the automotive industry, which pursues advanced magnesium designs. The automotive industry's rapid expansion of applications results in an average magnesium content of nearly 68 kg and 34 kg per vehicle in North America and Europe respectively. Many of these gains will likely be lost, however, as larger prices swings early in the new decade would likely result in substitution back to other materials.

Demand-Side Feedback: Market-Making Mechanisms and Storing Material

To investigate potential demand-side price stability strategies, a new sector of the market model was created as a "market-maker." The idea is to purchase low-priced magnesium in times of overcapacity and sell material when prices rise. This would require an organization with enough capital to hold onto material in times of low demand in order to turn a profit when demand heats up. This could be a large financial organization akin to the London Metals Exchange, which deals in other metals, or even an automaker holding onto low-priced material in anticipation of future magnesium designs.

The purchasing and release rules were

Table IV. Base Case Market-Maker Rules

Rule	Restriction/Cap	Notes
Buying rate	Below $1.40/lb buy up to 5% of industry capacity	Restricts max. buying rate, relaxed in some scenarios to accommodate larger stockpiles
Supply/demand gap	Below $1.40/lb buy up to 35% of gap between supply and demand	Coupled with above rule, restricts max. rate of flow into market-maker pool
Release rate	Above $1.50/lb release material at rate equal to size of pool	First-order exponential release rate of material from market-maker into market
Pool size	Initially no cap on size (tonnage) of market-maker pool	Cap on pool size is used to assess minimum required storage that prevents wild fluctuations

selected in order to obtain stable prices that fall on the cusp of rapidly expanding magnesium demand. From the previous supply expansion scenarios, it was shown that material prices falling near $1.40/lb tended to encourage rapid expansions in demand. The market-maker was instituted with logic that would initiate magnesium purchases at $1.40/lb. Releasing material from the stockpile was initiated in periods when material prices exceeded $1.50/lb (Table III).

Additional restrictions were used to cap the purchasing of material based on a maximum percentage of annual production and maximum levels of material in storage. These caps were used as common-sense limitations on the operation of the market-maker. Most runs had a maximum purchase rate limited to 35% of the overcapacity gap in the supply-demand interaction up to 5% of the total yearly production of primary magnesium. This assumption was only relaxed in cases where large, but unrealistic, stockpiles were needed to prevent market instability (Table IV).

The scenarios used to test the market-making mechanism were centered on market stability following the expected near-term expansions in 2003–2004 and aggressive medium-term expansions (single yearly plant additions following 2004). The results of the run are shown in Figures 10 and 11.

The scenario shows that that the market-maker, in conjunction with supply expansions, is capable of keeping prices in the range of $1.40–1.50/lb. When material prices are below this range, the mechanism accelerates to maximum buy ratio of 5% of industry production and, as prices rise above this range, material is released to satisfy some demand.

The expansion plans and the size of the material store, however, present some concerns about the viability of the demand-side feedback solution. Similar to the plans termed technically "unrealistic" in the automated supply expansion scenarios, more than seven plant openings are required in peak demand years to prevent market volatility.

Another troubling result is the material storage pool. Figure 11 shows that the size of the store peaks at 250 kt, roughly 17% of the industry's capacity. Assuming material purchases are being performed at prices around $1.40/lb, an investment of over $700 million would be necessary.

Additional scenarios were used to investigate demand-side solutions to aggressive expansion with more reasonable plans and/or smaller "market-makers". These scenarios were further restricted by capping the maximum level of material in the store. A minimum of 140 kt was required in the base case to prevent wild market swings. This would reduce the investment in the store to $400 million, but does not address the problem of building more than seven magnesium plants each year.

To address the problem of unrealistic yearly expansions, the restrictions on material purchases were loosened while capping the maximum yearly expansions. Larger market-maker pools would reduce the requirement for additional future capacity.

The results in Figure 12 show that any reduction in the allowed yearly expansions will result in larger required stores of material to maintain market stability. Limiting yearly expansions to six plants per year requires storage of 220 kt (investment ~$675 million). More reasonable plans, four facilities per year (or maybe two to three larger ones) inflate required storage over 320 kt (investment ~$ 1 billion).

Further demand-side scenarios were also run with more moderate expansion plans and the market maker showed some more reasonable success. By limiting supply expansions following 2004 to every other year, a stabilized market simulation could be created with prices in the range desired—$1.40/lb to 1.50/lb, yearly maximum plant expansions limited to four per year, and a material store on the order of 100–140 kt ($300–450 million investment).

CONCLUSIONS

From the analyses and scenarios that were run with the magnesium market model, it is easier to understand the challenges that surround the future of the industry. Capacity expansions are being pursued to harness potential demand for low-cost material in the auto industry. The entrance of new producers, however, could jeopardize market stability by rapidly increasing the automakers' interest in the limited supply

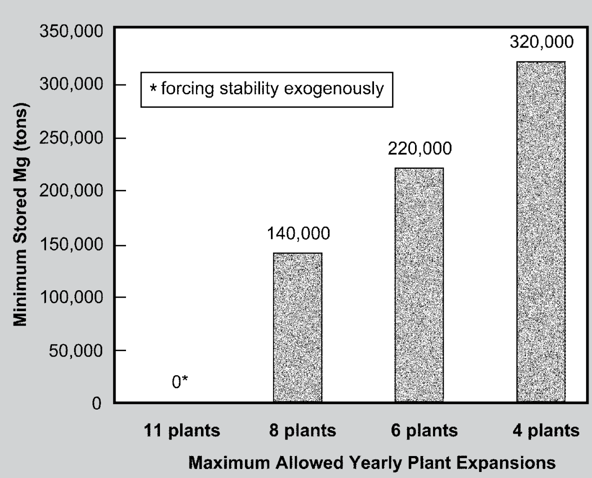

Figure 12. Demand feedback—aggressive supply expansions: minimum required material storage after limiting yearly supply expansions.

of magnesium. The amount of material that the automakers demand could potentially surpass industry capacity, cause wild price swings, and force abandonment of the material. Because of the negative impact of this dynamic, two distinct methodologies on the supply-and-demand side were investigated to prevent market instability.

The supply-side strategies linked capacity expansion plans directly to the expected increases in auto demand for magnesium components. This yielded an improved market dynamic and eliminated the most violent swings in material price. Despite its successes, however, the automated supply-side feedback scenarios create a few questions about the efforts necessary for its successful implementation.

The amount of coordination between automakers and amongst magnesium suppliers in the automated expansion scenarios would need to be substantial. Automakers would need to make their material choice decisions transparent in order to be certain of material availability. Due to competitive pressures in the automotive industry, a completely open material selection process is unlikely. Despite supply-demand coordination difficulties, the seeds of some coordination are already apparent in increased automaker involvement magnesium supply ventures (Volkswagen-Dead Sea Magnesium, Ford-QMC).

Coordination between magnesium suppliers could prove even more difficult. Each additional forced exogenous expansion into the automated supply-side scenarios subjected the model to an increasingly volatile pricing and demand reaction. The last run of the supply-side scenarios, which included the introduction of three near-term facilities by 2004, displayed a weakness in the coordinated expansion strategy to independent entrants. This scenario showed that aggressive supply expansion, especially as demand is softening, floods the market with inexpensive material. Low material prices lead to large capacity requirements as auto demand expands. Industry coordination to limit capacity expansion during periods of slowing demand or initiate large expansions in times of strong demand (virtual collusion) would be nearly impossible given the fractured supply base and diverse interests.

The second method of demand-side coordination was investigated as a possible solution to the aggressive supply expansion problem discovered in the supply-side scenarios. The concept was to store low-price material in a market-making device during times of low prices and weak demand for release when prices and demand rise.

In terms of improved market dynamics, the mechanism was successful in controlling the most aggressive expansion plans. Prices were stabilized in the \$1.40–1.50/lb range and demand was kept within the limits of the industry capacity. From a financial and industry planning point-of-view, however, the solution seemed unlikely.

The demand-side solution to aggressive expansion had two weaknesses: either the size of the magnesium store became too large of an investment or the scope of the supply expansions necessary to maintain market stability were too large. When the size of the magnesium store was restricted to reasonable levels, on the order of 100 kt (\$400 million), heroic expansion plans were necessary to keep up with expanding demand. Conversely, if expansion plans were capped to an optimistic, but more technically reasonable, four plants per year, magnesium stores of over 300 kt (nearly 25% of industry capacity, costing nearly \$1 billion) were necessary. More moderate expansion plans were stabilized by the combination of smaller market-maker stores and reasonable expansion plans, offering the hope that the demand-side method could offer a small degree of insurance in some market scenarios.

If a rapid of influx of low-priced material is inevitable due to a fractured supply base, it could be wise to store some material for future use. It may be wise to have ~100 kt of material in reserve as an insurance policy against rapid increases in automaker demand. A store of this size is no guarantee of market stability when faced with the most violent demand spikes, but could offer stability in some borderline cases.

Due to the negative price effects and spikes in automotive demand, however, market coordination and investment in reserve material could prove ineffective when supply expansions are initiated haphazardly. This leads directly the final conclusion: more reserved expansion plans result in more stable market dynamics. Pushing magnesium market prices below \$1.40/lb often resulted in wild spikes in automotive demand followed by material shortages and higher prices. This netted no gains in the long term as automakers abandoned magnesium designs. Expanding the supply base slowly and maintaining market prices slightly above \$1.40/lb, however, led to more stable demand and supply growth. By the end of these less aggressive scenarios, respectable gains for magnesium in auto design, ranging from 9 kg to 36 kg per vehicle in 2015 (from ~5 kg today) were shown as likely results.

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