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Life Cycle Assessment of a Transmission Case: Magnesium vs. Aluminum

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ABSTRACT

This paper describes a Life Cycle Assessment (LCA) done to evaluate the relative environmental performance of magnesium (Mg) and aluminum (Al) automatic transmission cases. Magnesium is considered a lighter weight substitute for aluminum in this application. Light weighting of vehicles increases fuel economy and is an important vehicle design metric.

The objective of this LCA is to quantify energy and other environmental trade-offs associated with each alternative for material production, manufacturing, use, and end-of-life management stages. Key features of the inventory modeling and the data collection and analysis methods are included in this paper along with life cycle inventory profiles of aluminum and magnesium alternatives. The life cycle inventory (LCI) was interpreted using a set of environmental metrics and areas needing further research were identified. A qualitative cost assessment was done in conjunction with this LCA to highlight potential cost drivers.

INTRODUCTION

Ford's Corporate Environmental Policy states that "consideration of potential health and environmental effects…is an early, integral part of the planning process" [1]. Additionally, there are efforts underway by automakers in Europe and North America to develop a new generation of highly fuel-efficient, and lighter weight cars. Several associated research projects have been undertaken by Ford, including a Life Cycle Design study of an engine intake manifold [2], the development of a Design for the Environment (DFE) course for engineers, and the development of recommendations for the design of lighter-weight vehicles (P2000) [3]. Past examples of magnesium being used in automotive applications include transmission cases, clutch housings, crankcases, intake manifold plenums, alternator brackets, instrument panel beams, steering column components, seat frames, and engine valve covers [4] [5].

In addition to the automotive light-weighting initiatives, there has been a recent trend of increased worldwide environmental regulations. Accordingly, there is a current need for better understanding of environmental burdens of automobiles. Evaluating environmental metrics such as energy consumption; global warming potential; acidification potential; and air, water and solid waste emissions helps to further this understanding. These metrics are quantified using LCA as a tool.

Several car manufacturers have conducted limited studies in the past in order to compare the environmental burdens of design options involving magnesium with those caused by traditional materials [6]. Typically, only energy burdens for the use and material production phases have been evaluated in these efforts, mostly due to the lack of available environmental data for other life cycle stages. The LCA presented in this study compares environmental metrics for substituting the lighter weight metal magnesium for the currently used aluminum in an automatic car transmission case. Currently, only one other confidential study in Germany has attempted to quantify this comparison [7].

METHODS

This LCA study was developed in accordance with the Society of Environmental Toxicology and Chemistry (SETAC) guidelines with the exception of the impact assessment [8]. Since impact assessment is a highly controversial part of LCA, a set of environmental metrics was tracked instead with the objective of highlighting specific trade-offs. Data from the Eco-balance DEAM™ database, published reports and direct contact with material suppliers were used to complete this study.

PRODUCT SYSTEM

The 1995 Ford Contour transmission case was chosen for this study. It should be noted that Ford is not planning to convert this transmission to magnesium. This component was chosen only as a model case study. One reason this component was selected is that the plant that manufactures it does not manufacture any co-products. Therefore, quantities such as materials used and wastes generated could be quantified by using totals shipped in and out of the plant, facilitating the comparison of environmental trade-offs between the aluminum and magnesium. Equivalent performance parameters also had to be evaluated for the materials. These parameters are described below.

The case is currently made of 100% secondary die-cast aluminum and weighs 9.435 kg. Experiences based on parts of other Ford vehicles as well as those from other Original Equipment Manufacturers (OEMs) [9] showed that a weight reduction of 30% for the magnesium substitution was reasonable to use for this study. Switching to magnesium initially raised concerns about mechanical stability due to the lower material strength of magnesium. The tensile strength of magnesium is 150 MPa versus that of aluminum which is 160 MPa. In response to this, a static stress assessment with a Finite Element (FE) model was conducted. It was found that in fact lower stresses were induced with the magnesium case due to better dampening capabilities of the material.

The change from aluminum to magnesium would require that the fasteners between the case and engine/converter housing and the drain plug to have different surface treatments. However, the excellent corrosion resistance of the considered magnesium alloy (AZ91 HP (HP=high purity)) rendered the application of any additional surface treatments for the case itself not necessary [9], as the two materials are equivalent in this respect. It was found that aluminum washers were required in the magnesium design to prevent corrosion between steel bolts and the magnesium metal. These washers were not modeled in this study.

SCOPE AND SYSTEM BOUDARIES

This assessment evaluates the following life cycle stages for the transmission case: raw material extraction, part manufacturing, car operation, and end-of-life management. Refer to Figures 1 and 2 for the overall life cycle of the aluminum and magnesium cases, respectively. For this study, it was assumed that differences in the two transmission cases do not cause any differences in vehicle assembly. Vehicle assembly was therefore not included in this study.

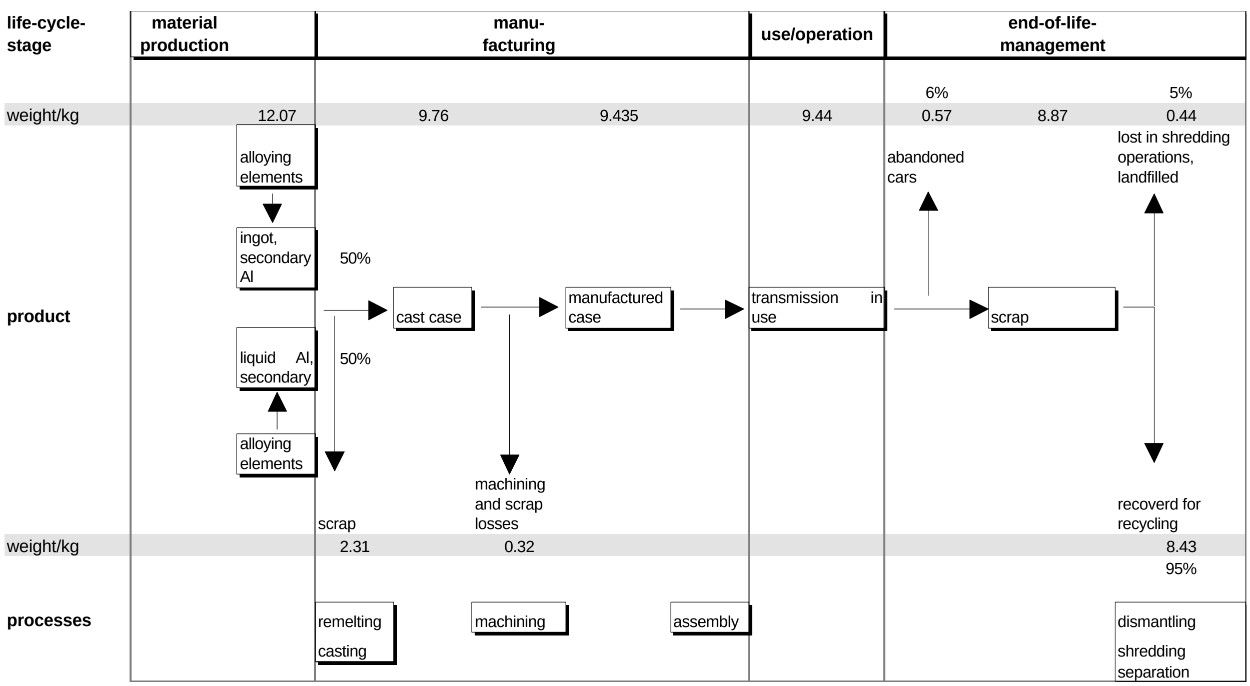

Figure 1. Life Cycle of the Aluminum Case

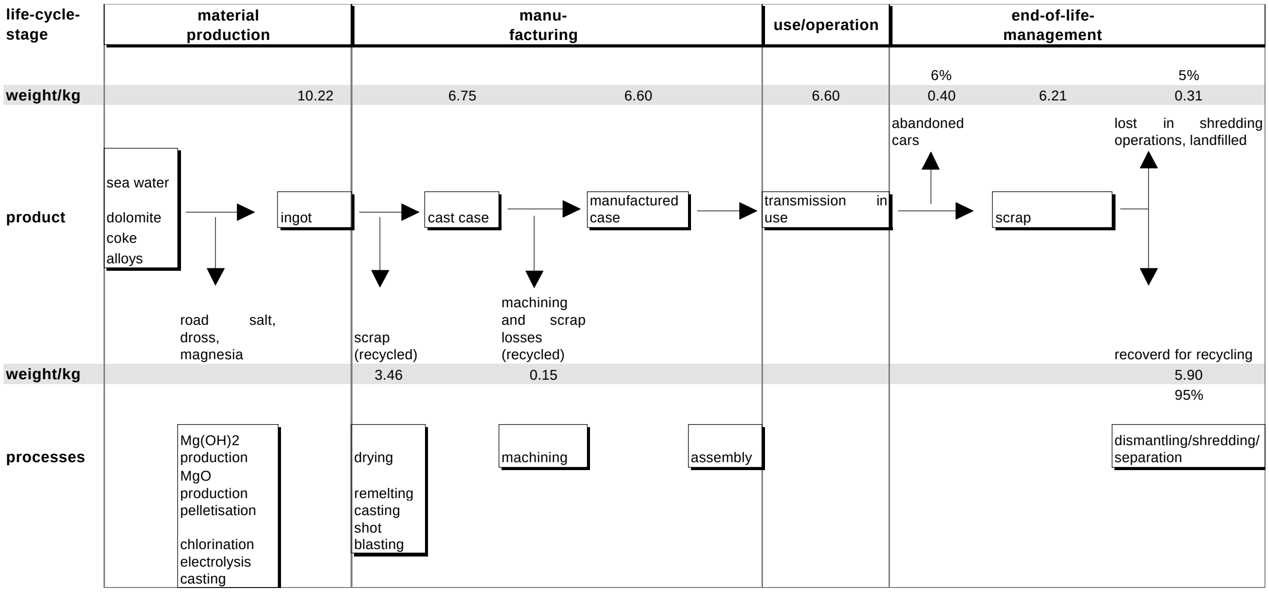

Figure 2. Life Cycle of the Magnesium Case

Pre-combustion and combustion burdens (energy consumption, emissions, and waste) for energy carriers in all life cycle stages are included in the scope. The energy consumption burdens associated with the generation of electricity are, for the most part, based on the average US grid as specified in DEAM™ (55% coal, 10.5% natural gas, 2% oil, 22.5% nuclear, 10% hydroelectric). Other energy source ratios were used for instances where a different grid was specified in collected data (e.g., magnesium production uses a higher percentage of hydroelectricity). Transportation activities of the product between the various life cycle steps were included.

Major ancillary materials and gasoline were also evaluated. The relevant data are taken from the Eco-balance DEAM™ database. A brief description of the these materials follows:

- Major materials for primary magnesium production (coke, dolomite, alloying metals zinc and aluminum)
- Major constituents of the required machining fluid (petroleum distillate)
- Polypropylene and cardboard used for transportation of transmissions to the vehicle assembly plant

Potential secondary light-weighting effects on other vehicle components, as a result of the case weight reduction, were neglected. If total vehicle light weighting becomes dramatic enough to change structural, braking, and/or other relevant vehicle design parameters, this aspect should be considered in future studies.

LIFE CYCLE STAGE BOUNDARIES

MATERIAL PRODUCTION

Aluminum – Since the aluminum case is made of 100% secondary material, no raw material extraction and primary material production burdens were considered. The production of the secondary material, and the burdens associated with recovered material delivery to the material suppliers and shipping of aluminum to the part casting operations were included. Due to limited data availability, the data for secondary aluminum production was based on the mid-1990's market in Europe.

According to the part caster, about one third of the secondary aluminum is delivered in molten form. The balance is shipped as ingot and requires re-melting (part of the next life cycle stage).

Magnesium – The ratio of primary vs. secondary magnesium available from material suppliers can fluctuate between 0 and 100% [10]. Magnesium suppliers have recommended assuming that 60% of the magnesium needed for this part is primary and 40% is secondary [11].

For primary magnesium, the material production model starts with raw material extraction and ends with magnesium ingots leaving the site of production. These data were obtained from Hydro Magnesium [12, 13] and are based on the 1994 production process in Porsgrunn, Norway.

Scrapped cast parts/chips and trim (e.g., runners, gates) from the automotive industry are the major source for secondary magnesium [10]. The major recycling use for this material is as a desulphurizer in the steel-making processes. The source for data on the environmentally relevant flows in secondary magnesium production is a Japanese study on personal computer housings [14].

No burdens due to the by-products of the production of magnesium (e.g., MgO), were allocated in this model because quantities of such were not available.

CASTING – This stage includes the following steps: re-melting of ingots, blending with delivered molten material (aluminum), blending with additional alloying metals, die-casting of the transmission case, and shot-blasting of the case (magnesium, tension relief). For this stage, 1996 data were used.

It is assumed that the same die would be used for the aluminum and magnesium castings. Accordingly, the casting efficiencies for aluminum and magnesium are assumed to be equivalent. This would imply that the volume losses would also be equivalent. The mass of the magnesium lost is calculated based on the known volume of aluminum lost and the densities of aluminum and magnesium.

Using the weight of the aluminum case as a basis, a 30% weight reduction of the finished part is assumed for magnesium. Slightly less magnesium material is required for the rough casting because of lower machining losses of magnesium relative to aluminum. It is assumed that for magnesium, 30% less volume would be lost in the succeeding machining processes. This contributes 0.035 kg to the 0.115 kg already saved due to the lower weight of the machining scrap (e.g., chips and off-spec parts). Therefore the mass of the magnesium cast part was calculated to be 6.75 kg.

Aluminum – The source of aluminum information for the casting step was the current supplier of the Contour transmission case. The mass of this aluminum cast part is 9.76 kg.

Magnesium – A supplier of a magnesium part for another Ford vehicle contributed the data for magnesium casting. The data have been scaled to the transmission case on a per-kg-of-output basis. No information was available on water or air emissions from the actual magnesium casting process.

A major supplier of magnesium reported that 0.00064 kg SF_6 are consumed per kg cast primary magnesium. This species is a major contributor to global warming potential. Even though other casters reported significantly different figures, the 0.00064 kg SF_6/kg cast primary magnesium was assumed for this study. Volkswagen, for example, reports only 0.0001 kg SF_6/kg cast magnesium [15].

For secondary magnesium however, data from a Japanese study were used [14]. It was noted in this study that approximately 122 g of flux are consumed per case. However, due to the lack of composition data for this material, environmental burdens of its production are not included in the model.

To prevent fires, the magnesium casting operation requires heat-drying of ingots before they are fed into a furnace. The added energy consumed for this has been accounted for in the model.

PART FABRICATION – This stage includes the following processes, shot-blasting, de-burring, machining, parts cleaning, assembly of transmissions, and testing.

Aluminum – For the evaluation of environmentally relevant material and energy flows, actual 1996 data from the plant that manufactures the case were used. This includes all of the manufacturing processes (machining and cleaning of parts, and assembling of the entire transmission) and the non-production/overhead at the plant.

Magnesium – Due to the lack of actual data for magnesium machining/assembling operations, the aluminum model was modified to reflect those changes that would be likely to occur for a magnesium case. Despite the much easier machinebility of magnesium (machining power ratio Mg:Al = 1:1.8), no effects on the energy consumption would be visible since the actual energy to remove the material in the machining process comprises only a very small fraction of the energy consumption of the machining unit. All other plant-wide energy consumption figures were assumed to be the same as aluminum for magnesium.

Since contradicting information about changes in replacement intervals for cutting fluid was received, the model assumes that the same amount of cutting fluids would be consumed per year for the magnesium as for the aluminum. This is also based on the common practice of various magnesium-machining corporations that machine both types of metals on the same line. Additionally, practices of a major European car manufacturer, and a major U.S. coolant supplier indicate that no change in the type of cutting fluid would be necessary. Accordingly, it is assumed that the same cutting fluid is used for both metals.

Near-net-shape-castability and obsoleteness of some thread manufacturing steps are taken into account in the model. Reduced manufacturing losses found in a Ford proprietary report were assumed in the study. Due to this, and to the lower weight of the magnesium chips and scrap parts, the mass of recycled material plant output is lower for the magnesium model vs. the aluminum (3.15% vs. 3.29%, respectively).

USE PHASE – The use-phase part of this LCA model encompasses only the emissions due to gasoline production, gasoline consumption during vehicle operation, and the differences in fuel consumption based on the variation of the part weight. It is assumed that maintenance requirements would be comparable for both systems and therefore it was not included in this study.

It is also assumed that the changes in weight from aluminum to magnesium are linearly proportional to fuel consumption and that the vehicle travels 200,000 km in its lifetime. The following correlation for the Ford 1995 Contour was used to calculate the contribution of the transmission case weight to the use phase energy consumption [2]:

$$F_{(l)} = M_{IM} \times L \times \frac{FE_{(l)}}{M_v} \times \frac{\Delta f}{\Delta M}$$

where,

$F_{(l)}$ = fuel used over the life of the transmission case (liters)

L = lifetime driving distance (200,000 km)

M_{IM} = mass of the transmission case (kg)

$FE_{(l)}$ = fuel economy: 0.0746 liter/km, based on the 1995 Ford Contour: 7.46 liter/100km (31.5 miles per gallon)

M_v = test weight (mass) of vehicle: 1,471 kg

$\frac{\Delta f}{\Delta M}$ = correlation of fuel consumption with mass: 0.4 (10% weight reduction equals 4% reduction in fuel consumption)

The emissions data for carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) were obtained from EPA tests (EPA Test #94-28-48) [16]. These calculations account for the emissions from a properly functioning car, and are based on chassis dynamometer tests with various speeds and loads. In order to represent real world emissions data, three additional categories for emissions are included: off-cycle, malfunction and evaporative [17]. "Off-cycle" emissions account for driving styles with occasional command enrichment. “Malfunction” emissions represent tailpipe emissions from vehicles whose emissions control systems have failed or are malfunctioning, and those caused by “poor engine performance.” “Evaporative” emissions include fugitive emissions that escape from the fuel tank during refueling, and vapor migration allowed by the evaporative control system.

END-OF-LIFE-MANAGEMENT – This last life-cycle stage includes the dismantling, shredding, and materials separation processes. The environmental burdens associated with the collection and recycling of the recovered materials after the separation was determined as outside of the system boundaries. Those burdens would be picked up by the product system that uses these recycled materials. Currently 94% of retired cars in the U.S. are returned for recycling [18]. Both aluminum and magnesium are considered to have a 95% recovery rate. In addition, even though approximately 50% of the cars retired into the recycling infrastructure have their transmissions dismantled and refurbished [19], it is assumed that 100% of them are shredded since the sale of a refurbished transmission would result in a broken transmission entering the recycling stream.

Due to lack of other specific process data, only the environmental burdens associated with the energy consumption and the transportation (next section) between end-of-life process steps was included in this model.

TRANSPORTATION – This stage addresses the energy consumption from transporting the case in its various forms between all the life cycle stages, as well as the consumption of packaging materials associated with those activities (plastic fasteners and cardboard). Excluded from this section is the transportation of the case during the operation of the car, which was covered in the use-phase section previously.

The specific steps included are the transportation from the:

1. material production facilities to the part casting operations
2. part casting operations to the manufacturing site
3. parts manufacturing plant (as part of an assembled transmission) to the car assembly plants (USA, Mexico, Belgium)
4. car assembly plants to the dealerships (only within USA, and normalized to the AAMA percentages of new cars shipped to each state in 1995) [20]
5. point of retirement of the car (dealership) to a disassembly/shredding plant, and from there continuing to the separation operations

The only packaging material that is not recycled is comprised of small plastic screws and nuts needed for securing the transmissions on their way to the car assembly plants.

POTENTIAL COST DRIVERS

The following items were identified as potential cost drivers, varying between aluminum and magnesium:

- Fluctuating metal market prices
- Fire protection/prevention equipment for part fabrication
- Worker training requirements
- Waste disposal costs
- Changes in tooling intervals in casting and machining operations
- Varying revenues for recovered scrap material
- Elimination of some machining operations for magnesium, such as drilling and tapping
- Fuel economy of vehicles
- Recovery value of discarded transmission cases

RESULTS AND DISCUSSION

ENVIRONMENTAL ASSESSMENT – In order to account for the differing environmental impacts of the various material and energy inflows and outflows, several impact assessment methodologies have been developed worldwide. The following list represents some of the most well known ones:

- EPS method (IVL, Sweden) [21]
- Ecopoint method (BUWAL, Switzerland) [22]
- Equivalency Assessment (CML, Netherlands) [22]
- Eco-Indicator method (Novem, Netherlands) [22]
- Critical Dilution Volume (BUWAL, Switzerland) [22]

- Threshold Inventory Interpretation Method (Owens, USA) [22, 23, 24]
- Mackay Unit World Model (Mackay, Canada) [25]

None of these methods are without controversy and it is currently being debated which method is optimal. Since no uniformly accepted method is available, for this study a set of environmental metrics will be used to help interpret and evaluate the inventory. Before any serious material substitutions are considered, these metrics should be reexamined to ensure their validity. The metrics are as follows:

- Global warming potential (GWP)
- Acidification potential
- Categorized air emissions
- Categorized water emissions
- Solid waste emissions
- Fossil fuel and energy consumption
- Water consumption

GLOBAL WARMING POTENTIAL – Global warming potential (GWP) is associated with the release of warming gases into the atmosphere. It is calculated in kg equivalents of CO_2 [26, 27]. Contributors to GWP include CO_2 and SF_6. The global warming potential (GWP) over the life cycle of a transmission case made of magnesium is about twice as that for a case made from aluminum (Figure 3). This is primarily due to SF_6 emissions from the magnesium casting process. SF_6 is currently used to cover the surface of the molten magnesium to prevent it from oxidizing. Its global warming potential is 24,900 times that of carbon dioxide [28]. Even with the prospect of 100% usage of secondary magnesium this issue would still have to be resolved. Worldwide efforts to find an SF_6 replacement are ongoing.

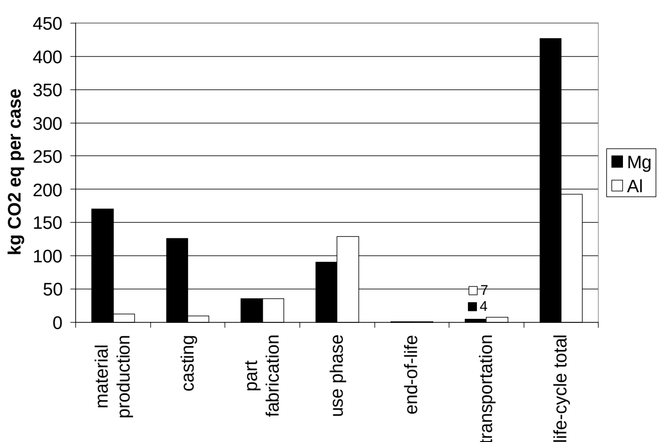

Figure 3. Global Warming Potential

ACIDIFICATION POTENTIAL – Acidification potential measures the emissions which contribute to acid rain. It is measured in kg equivalents of sulfuric acid [26, 27]. Out of the six different contributors to the acidification potential two specific releases result in the more than 3-fold higher value for magnesium (Figure 4). The halides released in the production of secondary magnesium are assumed to be fluorides. These halides are the largest contributors to the acidification potential. A follow-up study will have to determine if this classification is justified, and secondly, if the applied numbers from the Japanese study [14] are applicable to North America. If both conditions are true, an increase in the percentage of secondary magnesium would amplify this number. The second largest contributor is sulfur dioxide mainly released during the primary magnesium production process.

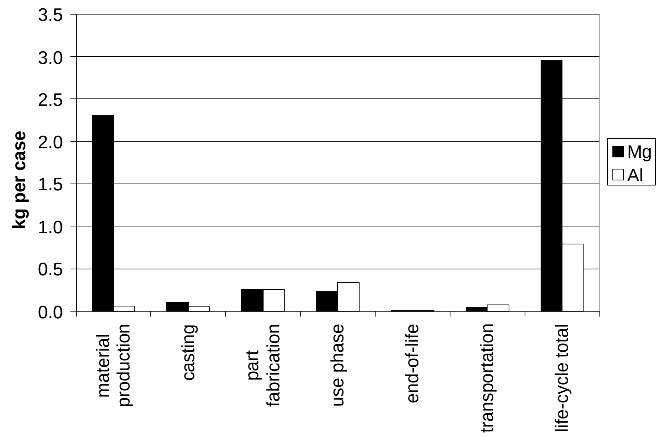

Figure 4. Acidification Potential

FOSSIL FUEL AND ENERGY CONSUMPTION – The current scenario of approximately 40% secondary magnesium vs. 100% secondary aluminum results in a more then 7-fold higher fossil fuel consumption during the material production phase of magnesium. Even with energy savings in the use and part transportation phases, magnesium results in a 8.5% higher energy consumption. Figure 5 shows 2,902 MJ were consumed for magnesium while 2,673 MJ were consumed for aluminum. If the recycled content in die-cast magnesium parts reaches 100%, as is the case with aluminum already, energy consumption would be 20% lower for magnesium. Fossil fuel consumption is dependent on the amount of hydropower used to generate electricity. For this study, even though primary energy is higher for magnesium, the fossil fuel consumption is actually 9% lower. This is due to the assumption that the US average fuel mix is used in secondary aluminum production. Also, the energy requirements for magnesium production are specific to the supplier referenced in this study and they utilize a large percentage of hydroelectric power.

WATER CONSUMPTION – The study results for water consumption show an approximately 50% lower value for the magnesium case (Figure 6). There are two important caveats with this result. First, the consumption of seawater is not included in this study because it is not a scarce material, but it would have changed the magnesium number to be 10 times higher than that for aluminum. Second, there is no other water consumption reported in the primary magnesium source used [29], which does not necessarily mean that there was no water consumed during the primary material production process.

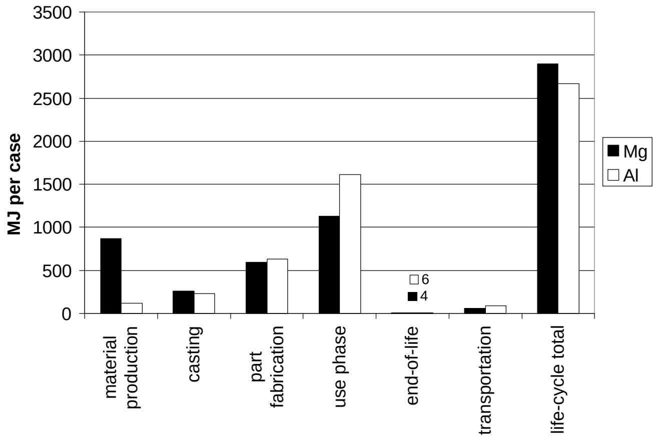

Figure 5. Life Cycle Energy

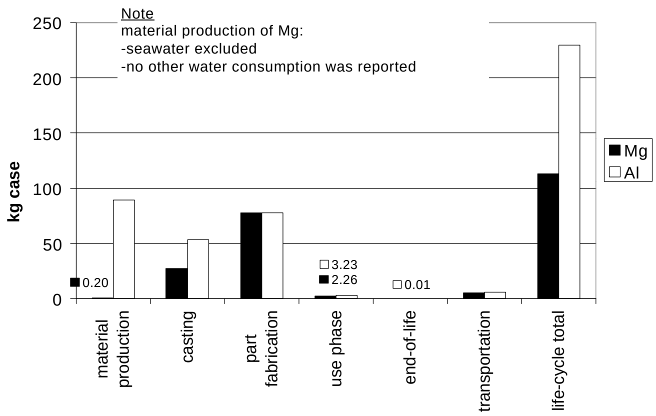

Figure 6. Water Consumption

AIR AND WATER EMISSIONS – In order to adequately evaluate air and water emissions, temporal and regional data must be included in the analysis. Since this study was completed to help establish a life cycle benchmark for magnesium parts, it is presented in a generalized format. If a more detailed assessment of these emissions is desired in future studies, site specific data would need to be collected and evaluated.

For this study, air and water emissions were classified into several categories. Categorization facilitates the interpretation of large amounts of data providing a balance between aggregation and speciation. Categorization can help to provide an overall picture of air and water emissions and enable determination of areas which might need further investigation.

Air Emissions – Air emissions were grouped into categories as follows:

- Heavy metals
- Hydrocarbons
- Carbon Dioxide
- Criteria Air Pollutants (ozone, carbon monoxide, nitrogen oxides, sulfur oxides, particulate matter and lead)
- Total Air Emissions

The air emissions inventory is presented in Figure 7. It should be noted that in the casting step only air emissions due to energy consumption have been included. Part fabrication is responsible for almost two-thirds of the heavy metal air emissions. Hydrocarbons and CO_2 emissions are emitted mainly during the use phase but criteria air pollutants are more evenly contributed during both part fabrication and the use phases. Also, the criteria pollutant emissions are dominated by carbon monoxide emissions from gasoline combustion in the use phase (Figure 7).

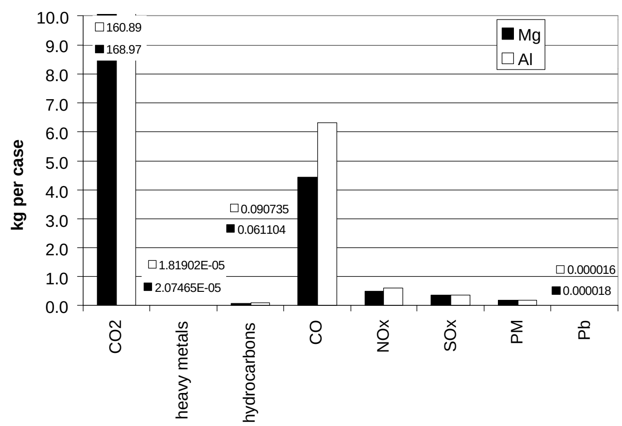

Figure 7. Air Emissions

Water Emissions – Water emissions were grouped into categories as follows:

- Heavy metals
- Hydrocarbons
- BOD
- COD
- Dissolved solids
- Suspended solids
- Total water emissions

These emissions are listed in Figure 8. It should be noted that in the casting step only water emissions due to energy consumption have been included. Heavy metals are emitted mainly in the material production and manufacturing stages. COD, dissolved solids, and suspended solids were mostly contributed by the use phase. The majority of the BOD results from magnesium casting operations.

SOLID WASTES – A very conservative approach was taken in this analysis. First, a comparison between total waste numbers was completed (Figure 9). This reveals for example that in the case of primary magnesium production, waste is reported as “mostly … inorganic salts and minerals” [29] while mostly “slag and sludge” [14] result from secondary magnesium production. The overwhelming majority of the waste associated with the manufacturing phase on the other hand stems from the electricity generation process. The life-cycle waste generation is about 50% higher in the magnesium scenario.

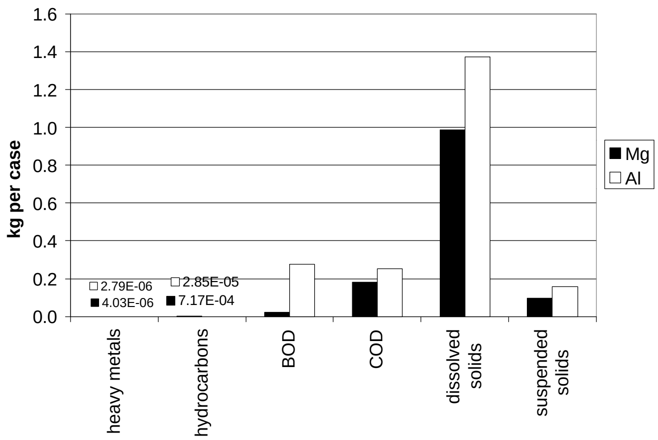

Figure 8. Water Emissions

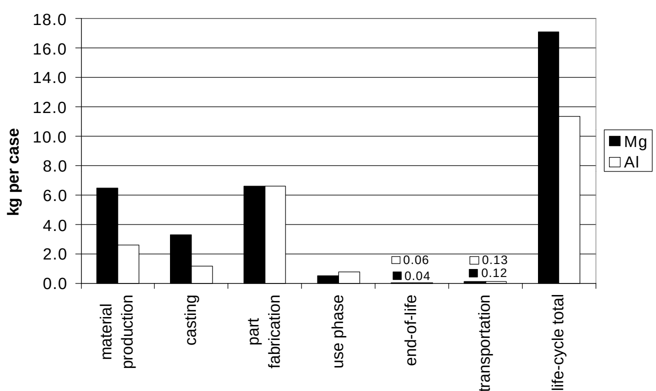

Figure 9. Solid Waste

CONCLUSION

These conclusions are valid for only the assumptions presented in this paper. Assessments on other magnesium components need to use component-specific assumptions and address the data gaps identified in this paper.

When comparing the material options of aluminum vs. magnesium. for a transmission case in terms of the presented environmental criteria, many trade-offs become apparent. For example, energy saved in the use phase can be overwhelmed by the material production phase for a magnesium case. This is highly dependent on the amount of secondary magnesium available for vehicle components. However, even though energy consumption is higher for magnesium, fossil fuel consumption is lower given the use of hydropower. Additionally, SF_6 from the magnesium smelting process is a major contributor to the significantly higher global warming potential of the magnesium scenario.

Existing data gaps were identified through completion of this study. The current and potential future mix of secondary magnesium needs to be better understood. Actual design changes required for a magnesium component also need further quantification to establish a more accurate weight change between magnesium and other materials. Similarly, exact data from a magnesium casting facility needs to be collected.

The entire list of findings builds a solid foundation for prioritizing areas for environmental improvement, and indicates topics for further research. These areas can now be targeted more effectively.

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REFERENCES

1. Ford Environmental Policy Letter No. 17, August 28, 1996
2. Kar, Krish. and Gregory A. Keoleian, "Application of Life Cycle Design to an Intake Manifold," SAE Technical Paper Series. 960410, (Warrendale, PA:SAE International, 1996)
3. “Ford P2000 is more fuel efficient. Today's briefing.” *Detroit News*, 28 Oct 1997, p 3B
4. Davis, J., “Magnesium in Drive Train Components”, SAE-paper 850419.
5. Polmear, I.J., “Light alloys: metallurgy of the light metals”, 3rd ed., Arnold, London, UK, 1996, p.241.
6. Winter, Drew. “Curbing curb weight. US automakers quietly admitting weight problem. Materials. Environment.” *Ward's Auto World*, Sep 1997, v 33 n 9 p 52-53.
7. Ebinger, Axel, “Ökobilanzierung von Gehäusewerkstoffen am Beispiel Pkw-Automatikgetriebe”, 1997, (Company Firma ZF Friedrichshafen, Germany).
8. Fava, James A. (editor) et. al. “Workshop Report Society of Environmental Toxicology and Chemistry: A Technical Framework for Life-Cycle Assessments.” SETAC, Pensacola, 1991.
9. Barnreiter, K., Eichberg, O., “Leichtbaumaßnahmen am manuellen Schaltgetriebe Audi B80”, in ATZ/MTZ, Sonderausgabe Der neue Audi A6, Friedr. Viewg & Sohn Verlagsgesellschaft mbH, Wiesbaden, 1997, p.74.
10. Dugeld Reid, Hydro Magnesium, purchasing, personal communication, 7/28/97
11. Darryl Albright, Director of Market Development, Hydro Magnesium, personal communication
12. Magnesium in Automotive, An Environmentally Sound Solution, Hydro Magnesium, 08/1995
13. Albright, D.L., Haagensen, J.O., "Life Cycle Inventory of Magnesium", Hydro Magensium, 1997

14. Higuchi, K., Nakajima, K., "Closed Loop Recycling of Magnesium PC Housing" Proc. 1996 IEEE International Symposium on Electronics and the Environment, May 6-8 1996, pp 102-108
15. Haldenwanger, H.-G., Rösch, R., Leichtbau mit Magnesium-eine Renaissance in der Automobiltechnik, AUDI AG, Ingolstadt, Germany, (1997).
16. US EPA. 1995 Model Year Certificates of Conformity with the Clean Air Act of 1990. US Environmental Protection Agency National Vehicle and Fuel Emissions Laboratory, Ann Arbor, MI, 1994
17. Ross, M., Goodwin, R., Watkins, R., Wang, M., Wenzel, T., "Real-World Emissions from Model Year 1993, 2000 and 2010 Passenger Cars", American Council for an Energy-Efficient Economy.
18. Sullivan, J.L. and J.Hu. Life Cycle Energy Analysis for Automobiles, SAE papaer 951829, 1995.
19. Bernd Gottselig, Ford Motor, personal communication.
20. Motor Vehicle Facts & Figures 1995, American Automobile Manufacturers Association, Detroit, MI, 1995
21. Beyer, H.-M., "Life-Cycle-Assessment-Combined Efforts of the European Automotive Industry", SAE-paper 971172.
22. Owens, J. W. “Life Cycle Assessment-Constraints on Moving from Inventory to Impact Assessment.” *J. Industrial Ecology.* 1 (37), 1997.
23. De Smet, B.; White, P. R.; Owens, J. W. “Integrating Life Cycle Assessment Within an Overall Framework For Environmental Management.” Chapter 16 in *Environmental Life-Cycle Assessment*, Editor: M. A. Curran, McGraw-Hill, N.Y., 1996.
24. Pither, R. T.; Beal, R.; Hunt, R. G. “Threshold Inventory Interpretation Methodology: A Case Study of Three Juice Container Systems.” *International Journal of LCA.* Vol. 1, No. 3 pp. 121-180, 1996.
25. French, C. (Project Officer). “Life Cycle Impact Assessment, A Conceptual Framework, Key Issues, and Summary of Existing Methods.” EPA-452/R-95-002.
26. Heijungs, R. (Editor). “Environmental Life Cycle Assessment of Products, Guide.” NOH (The National Reuse of Waste Research), Report Number 9266, 1992.
27. Heijungs, R. (Editor). “Environmental Life Cycle Assessment of Products, Backgrounds.” Leiden, NOH (The National Reuse of Waste Research), Report Number 9267, 1992.
28. Haagensen, J., Opheim, B., Westengen, H. “Life Cycle Inventory of Magnesium - Results, Reliability and How To Use Them in the Automotive Industry.” VDI Berichte NR. 1307, Düsseldorf, Germany, 1996., p. 181
29. Magnesium in Automotive, An Environmentally Sound Solution, Hydro Magnesium, 08/1995.

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ADDITIONAL SOURCES

1. Grebetz, J., Albright, D., “Recycled Magnesium Alloys for High Ductility Automotive Applications”, SAE-paper 960413.
2. Renaud, J., Watanabe, K., “Design Considerations for Magnesium Components”, SAE-paper 930416.
3. Proceedings IMA 54, Congress June 8-10 1997, International Magnesium Association, 1997.
4. Spicer, A., et al., “Machining Magnesium With Water Base Coolants”, SAE-paper 910415.
5. Davis, J., “The Potential for Vehicle Weight Reduction Using Magnesium”, SAE-paper 910551.
6. Sauer, B., Franklin, W., “How to Perform a Life Cycle Inventory”, SAE-paper 971208.
7. Schuckert, M., et al., “Life Cycle Analysis of Cars-Experiences and Results”, SAE-paper 951836.
8. Saur, K., et al., “LCA as Decision Making Support in the Automotive R&D”, SAE-paper 971185.