Magnesium Replacement of Aluminum Cast Components in a Production V6 Engine to Effect Cost-Effective Mass Reduction

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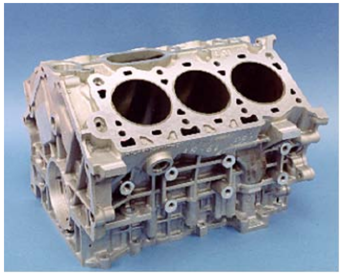
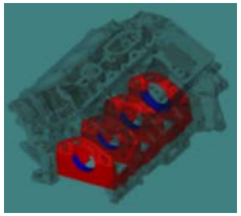
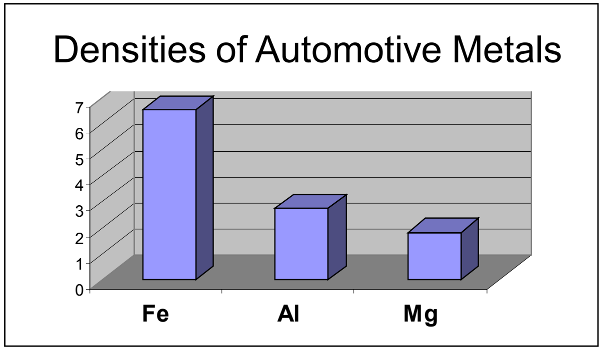
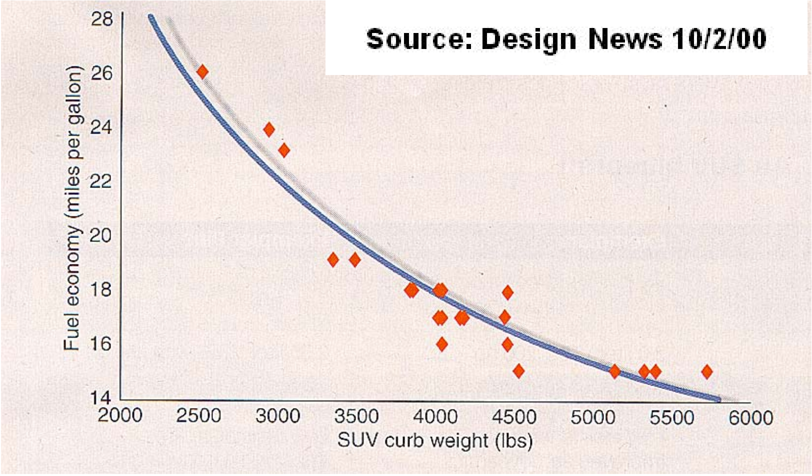




Questions about Magnesium

- **Why magnesium?**
  - Lightest structural metal
  - Can be cast thinner, faster, and machined easier than Al
  - High specific strength and high damping capacity
- **How much magnesium is used in cars and trucks?**
- **Why not more?**
- **What needs to be done?**

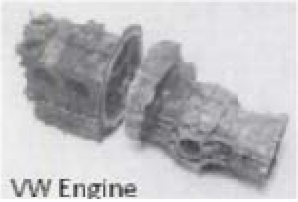




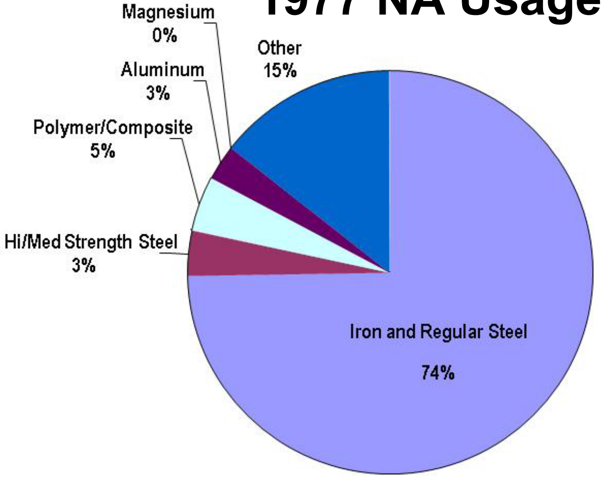
- **Vehicle weight reduction is an enabler for improved vehicle performance and fuel economy**

Magnesium Use After World War II

- **1950's**
  - Racing wheels and truck panels
  - VW Beatle
    - Engine and gear box (20 kg) - 42,000 mt Mg in 1971



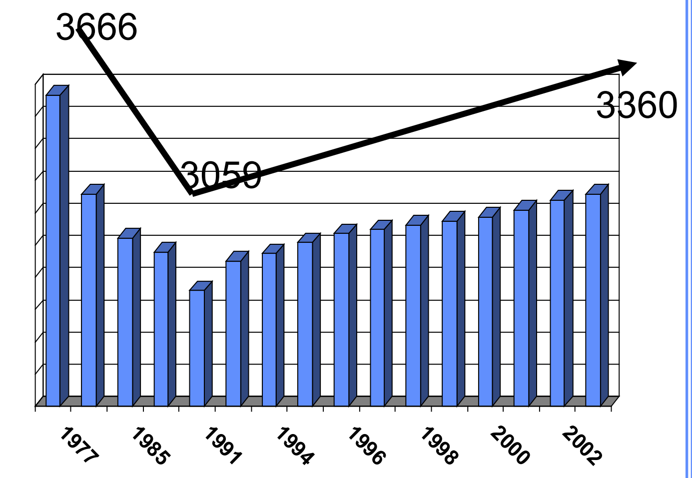
- **1970's**
  - Demand for greater power - AZ81 lacked creep resistance
  - AS41 and AS21 developed
  - AE42 developed – high cost alloy
- **1980's**
  - Water cooling replaced air cooling of engine
  - Mg corrosion resistance inadequate
  - Development of high purity alloys



American Metal Market

Magnesium Use in the 1990's

- **Increased focus on mass reduction**
  - Customer demand for features
- **Growing global Mg production**
  - Mg alloy cost competition
- **Instrument panels and cross-car beams**
  - GM and Audi
- **Corvette road wheels**
- **Steering wheels**
- **Transfer cases**

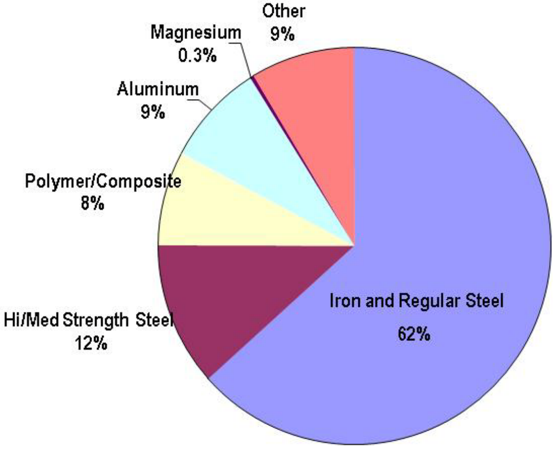


Average Passenger Vehicle Weight in Pounds

Magnesium Applications in the Powertrain

- **Perceived barriers to powertrain applications for magnesium**
  - High cost of creep-resistant alloys for > 125^{o}C
  - OEM reluctance to cast or machine Mg
  - Concerns about corrosion behavior
    - Coolant, galvanic, and atmospheric
  - Limited powertrain design experience
  - No long-term field validation or controlled-fleet testing data
  - Limited scientific understanding of Mg alloys, casting processes, and properties

2004 NA Usage



American Metal Market

Magnesium Powertrain Cast Components Project

- **GM, Ford, and Chrysler project supported by DOE and USCAR**
- **MPCC project team vision**
  - A magnesium-intensive powertrain that is cost-effective, durable, and has demonstrable performance benefits
- **Overall objectives**
  - **Phase 1 (2001 - 2003)**
    - Scientific, technical, and economic snap shot of Mg and determine its readiness for structural powertrain components
      - 15% mass reduction of cast components of V6 engine
      - Mg replacing Al – block, bedplate, oil pan, front engine cover
      - Cost effective - <$2 per lb mass reduced
  - **Phase II (2004 – 2009)**
    - Demonstrate Mg readiness and cost effectiveness by designing, casting, assembling, and testing a magnesium-intensive powertrain
    - Initiate fundamental research to address showstoppers and close critical scientific/technical gaps for future Mg applications

MPCC Project Timeline

Task 1

Alloy evaluation and selection for each engine component

1.1 Test matrix and test program
1.2 Castability trials
1.3 Electronic database
1.4 Alloy selection for prototype components – pair-wise analysis

Task 2

Engine component design and cost modeling – phases 1 & 2

2.1 Engine block, bore and journal strategies
2.2 Fasteners, gaskets, sealing
2.3 Coolant and corrosion – coolant selected April 2006
2.4 FEA design, integration and analysis
2.5 Component casting and casting analysis
2.6 Technical cost modeling

Task 3

Building Mg scientific infrastructure: 5 Research Projects

Task 4

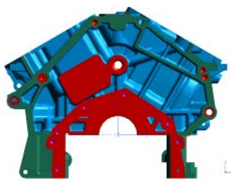
Casting operations – HPDC & LPPS

Task 5

Significant challenges

- Overcoming higher thermal expansion of Mg for engine
- Robust corrosion protection – coolant and galvanic
- Casting sound components: eliminate casting defects

Alloy selection for components



Excised specimen evaluation

Engine Testing **NVH**

Task 6

Phase 1 Review Decision Gate

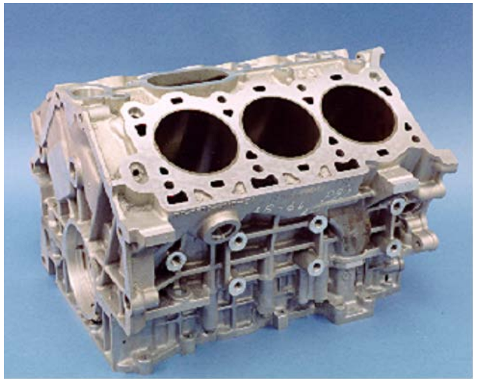
Patent application and award

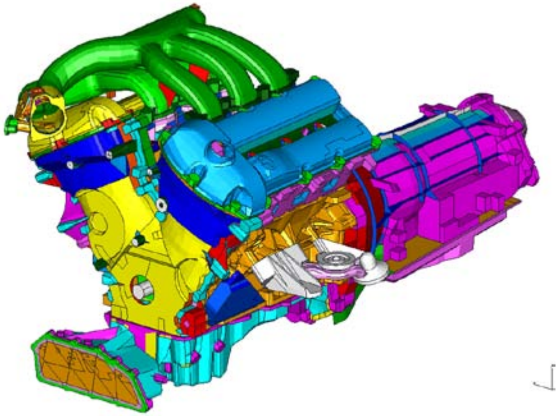
Final Report

2001	2002	2003	2004	2005	2006	2007	2008	2009

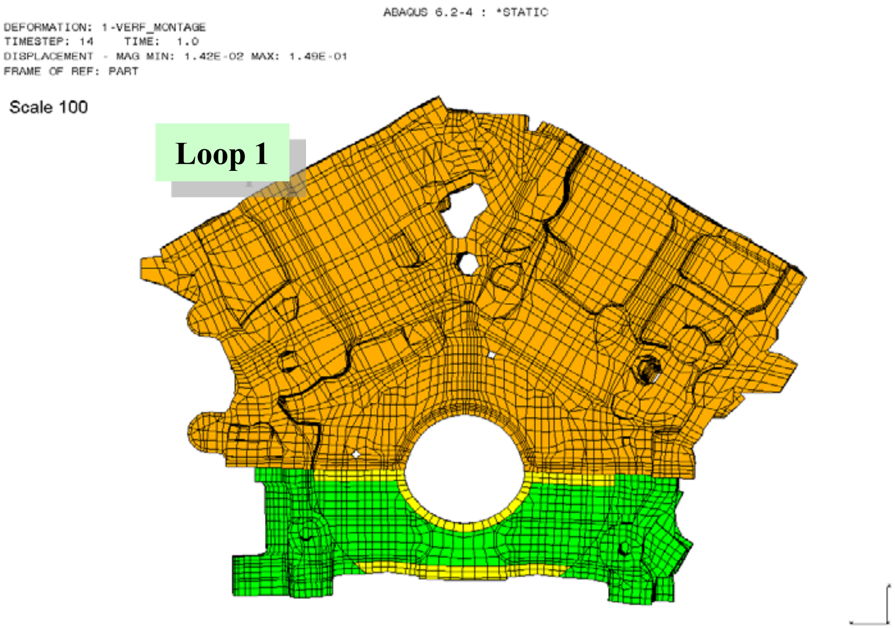
MPCC Engine Design

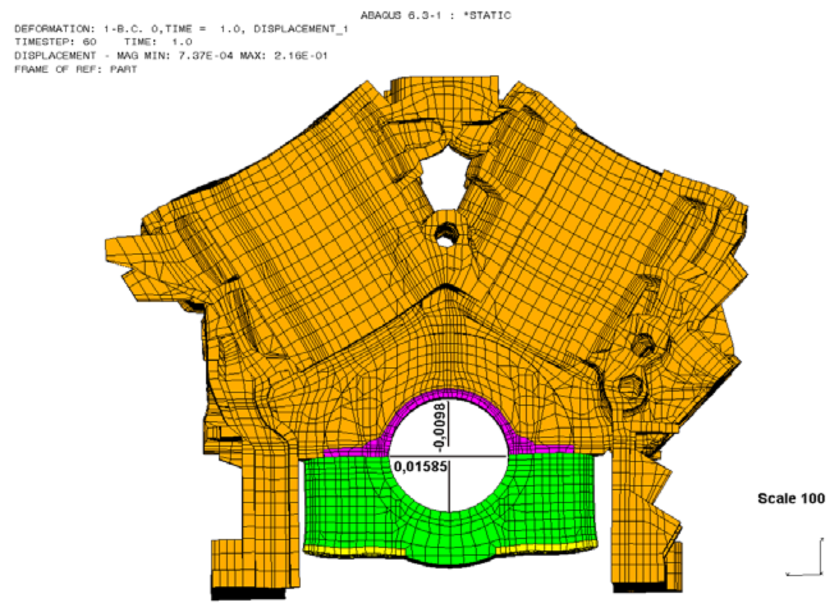
- **Design decisions**
  - Production Ford Duratec 2.5 L V6 head and moving parts
    - Mg cylinder block, oil pan, and front engine cover
    - Use 3.0 water jacket to increase bore wall stiffness
  - Replace iron liners with thermal-sprayed, wear-resistant coating
  - Ethylene glycol:water coolant with magnesium protective additives
  - Steel head bolts and aluminum bolts for front cover and oil pan
  - New head gasket design for Al head and Mg block
  - Thin wall oil pan and front engine cover strategy for NVH
  - Iron inserts in bulkheads to maintain crank bore size and cylindricity





Crank Bore Distortion –
Mg Block with vs. without Bedplate



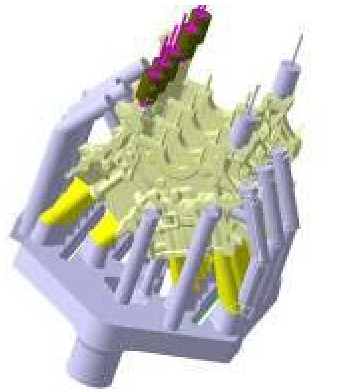


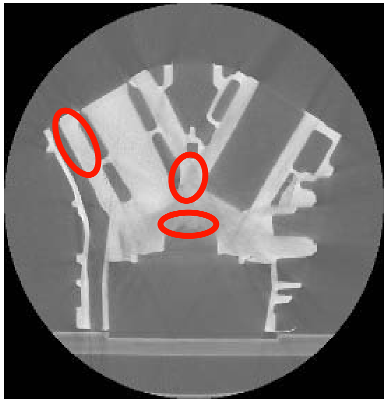
US Patent 7,288,528 issued to USAMP

Analysis by Magna Powertrain

Engine Block Casting

- Part cast by Fonderie Messier, Arudy, France
- AMT SC-1 alloy
- Low pressure sand cast
- Cast in pan-rail up position
- Chilled bores to meet porosity specification for thermal spray coating





Oil Pan, Front Cover, and Rear Seal Carrier Castings

- Cast at Intermet
- HPDC process
- MRI 230D alloy
- 2.5 mm nominal wall thickness

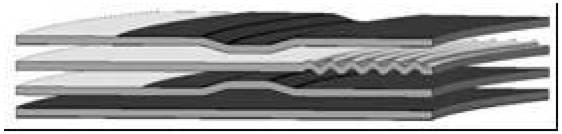
- Cast at Spartan LMP
- HPDC process
- MRI153M ally
- 3.0 mm nominal wall thickness
- Deeper pockets for transmission mounting flange

- Cast at Thixomat
- Thixomolding
- MRI153M alloy

Sub-Assembly Testing

- **Passed pulsator testing of head gasket**
    - Validated cylinder head life and design for sealing Al head on Mg block

Schematic of Dana/Victor Reinz design for MPCC gasket

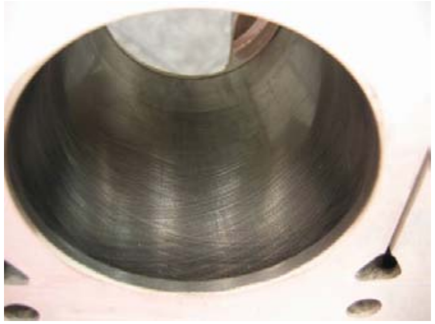


- **Passed cyclic and static thermal aging of block**
    - Head and main bolt load retention
    - Cylinder and crank bore distortion
        - and growth acceptable
    - **Head gasket sealing surfaces stable**

Engine Testing – Scuff and Durability

- **Passed hot and cold scuff tests**
  - Low lubrication conditions
  - Normal piston wear
  - Piston/ring packs compatible with bore
  - Wear resistance of sprayed bore coating
  - Adhesion of coating
  - **Iron liners not required**

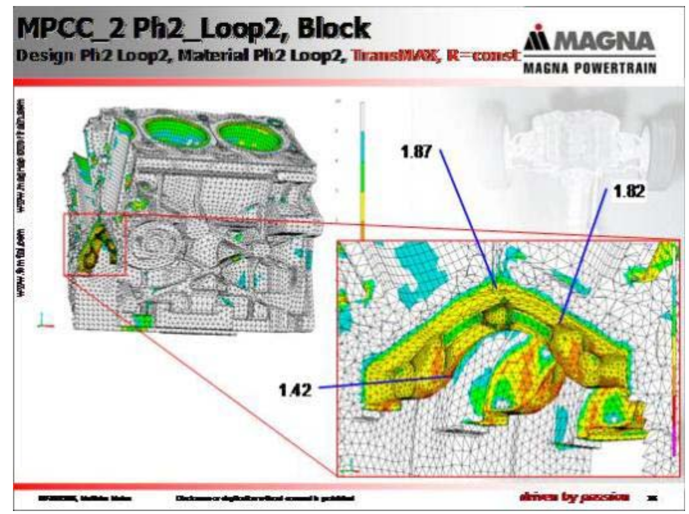
Normal piston wear



- **Passed 675 hr high speed durability test**
  - Mg oil pan and Mg front cover on Al block
  - No failure of Mg parts
  - No loosening of Al bolts
  - No corrosion
  - **No abnormal noise and vibration – this result led to extensive NVH testing**

Engine Testing – Deep Thermal Shock

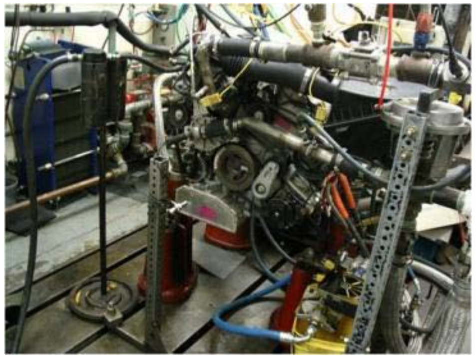
- ❑ **Deep Thermal Shock Test – bulkhead failure during break-in**

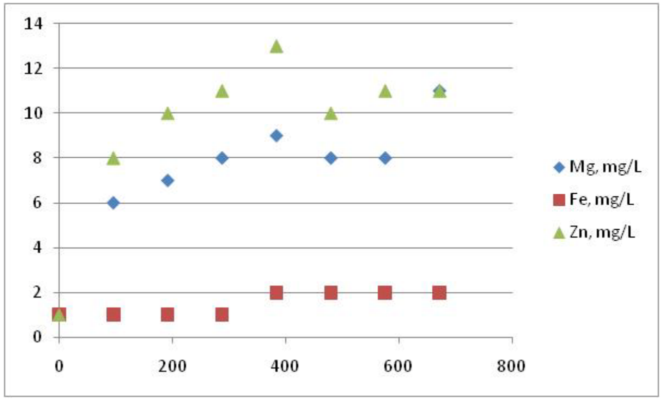


- ❑ **Completed root cause analysis**
  - Failure at Fe insert/Mg bulkhead interface
  - Original FEA did not predict failure
  - Revised New FEA does
  - Offer sdesign alternatives to prevent failure in future
    - **Bulkhead inserts not a show stopper**

Engine Testing – Coolant Corrosion

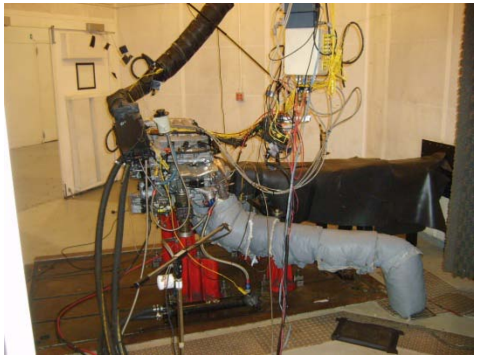
- **Passed 672 hr test of engine with Mg block**
- **Ford BL 102-02 variant)**
  - Simulate on-road engine cycle for small Ford vehicle - determine coolant corrosion
  - Engine runs 16 hours and soaks 8 hours - 42 days
  - Coolant samples every 96 hours
  - Tear down inspection
    - Water passages free of corrosion product
    - Minimal corrosion product of metal surface
    - Coolant clear
    - Coolant chemistry excellent
    - **Coolant corrosion not a show stopper**





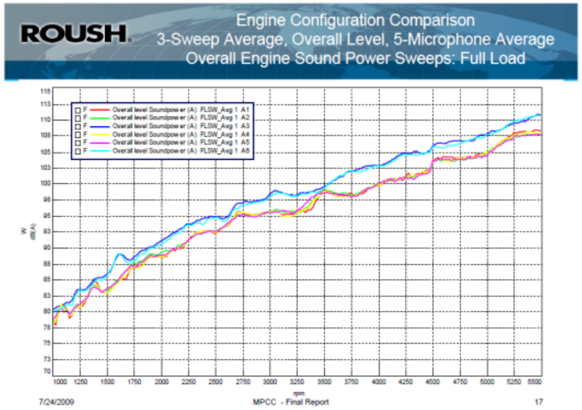
Engine Testing – NVH

- **Determine effect of Mg vs. Al on NVH**
  - Jaguar 2.5L V6 with transmission as baseline
  - Roush NV Facility in Livonia, MI
  - Task leader – Clyde Bulloch – GM
  - Standard automotive testing protocol



Testing to be Conducted					Hardware Configuration			
Proposal Line No.	Overall Sound Power	Component Sound Power	Cold Start	Block Vibration	Block	Front Cover	Oil Pan	Comments Mechanical changes
A.2.	Yes	None	No	No	Al	Mg	Mg	**Aluminum Block** with **Magnesium Components**
A.5.	Yes	Mg Frt Cvr	No	No	Al	Mg	Al	Remove Mg Oil Pan install **Al oilpan**
A.4.	Yes	Mg Oil Pan	No	No	Al	Al	Mg	Remove Mg Front Cover & Al Oilpan - install **Al Front Cover** & Mg Oilpan
A.1.	Yes	Al Block, Frt Cvr, Oil Pan	Yes	No	Al	Al	Al	Remove Mg Oil pan install Al oilpan
A.3.	Yes	Magnesium Block	Yes	No	Mg	Mg	Mg	Install **Mg Block with Mg Oil Pan and Front Cover** System
A.6.	Yes	None	No	Yes	Mg	Al	Al	Remove Mg Oil Pan and Front Cover - Install Al oilpan and Front Cover

Engine Testing Results– NVH



❑ Component Sound Power – Mg vs. Al

- Mg front cover and oil pan
  - Small/acceptable increase vs. Al baseline
- All Mg engine <2 dBA

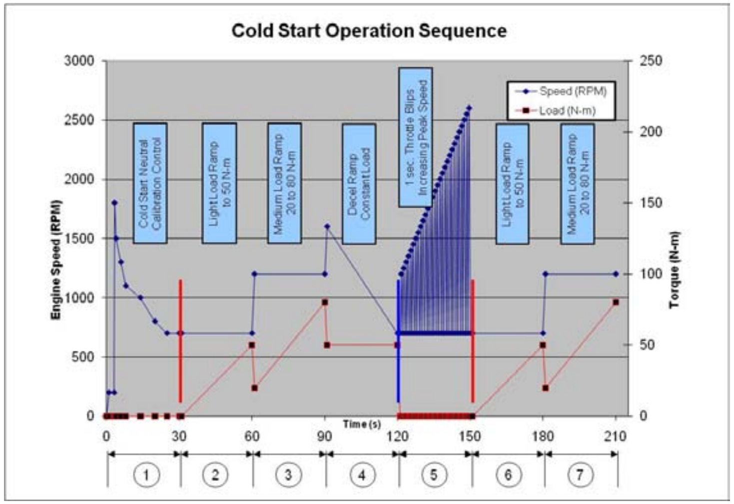
RPM	Load	FEC Al/Al	FEC Mg/Al	SOP Al/Al	SOP Mg/Al	All Al	All Mg
Idle	None	81.5	82.8	76.6	76.6	73.6	74.6
2500	(81Nm)	96.0	96.4	90.6	91.8	89.3	92.7

❑ Overall Sound Power – Mg block

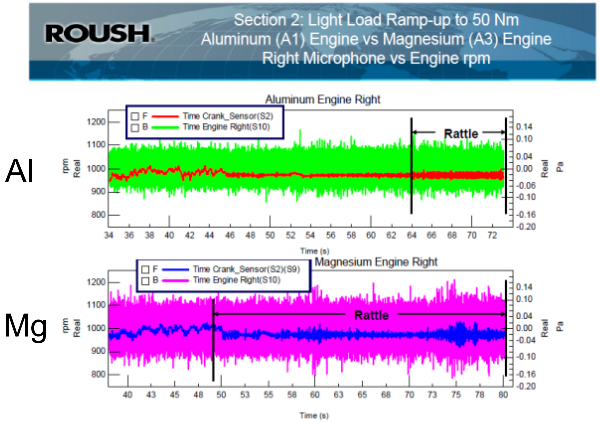
- Significant increase at high speed/load –
  - 5-6 dBA in 1250-1600 Hz at 2500 RPM, 81 Nm
  - 3-5 dBA in 250-2500 Hz at 4000 RPM, 230 Nm
- Major factor (~75%) – weaker bottom end
  - Deep skirt with unsupported crankcase walls
  - **NVH is not a showstopper**

Engine Testing Results – Cold Start NVH

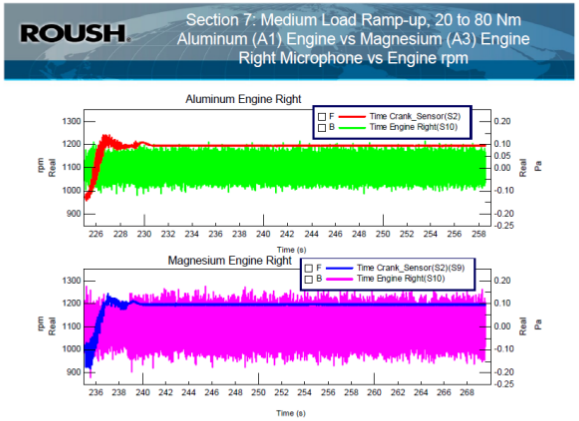
- **Cold Start Testing**
  - Mg subjectively louder
  - Different sound quality
    - More impulsive sound pressure instances
  - Piston slap
    - Occasional for Mg



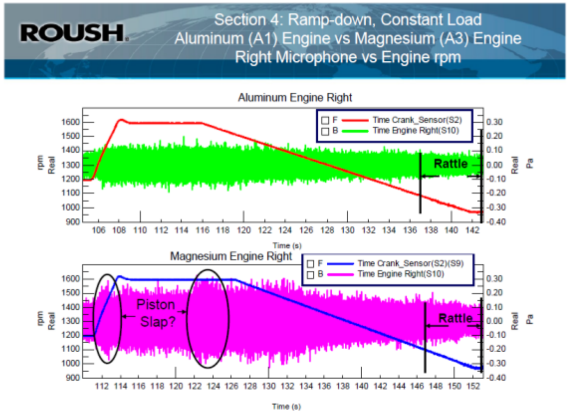
Light Load, Ramp Up



Medium Load, Ramp Up



Constant Load, Ramp Down



Engine Mass Reduction Realized

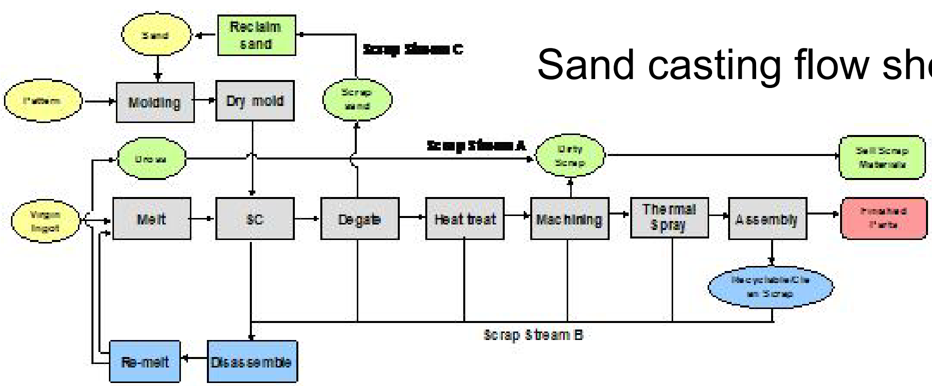
Component	Production Al Duratec kg	MPCC Mg-intensive kg	Mass Reduction kg (percent)
Block assembly	32.2	24.0	8.2 (25%)
Oil Pan	4.4	3.2	1.2 (27%)
Front Cover	5.6	2.6	3.0 (53%)
Total for 3 Cast Components	42.2	29.8	12.3 (29%)
Complete Engine (with exhaust and flexplate)	176.8	163.0	13.8 (8%) 29 pounds

Donor Engine Weight (with exhaust and flexplate) = 176.8 kg (389 lbs)

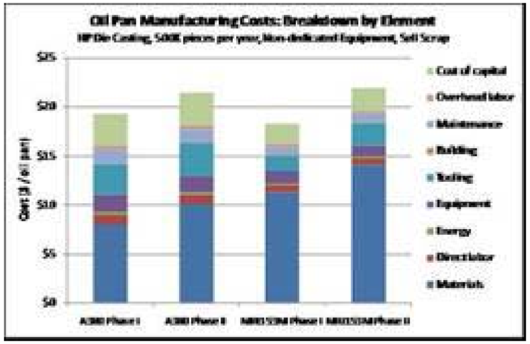
Mg Engine Weight (with exhaust and flexplate) = 163.0 kg (360 lbs)

Cost of Mass Reduction

- ❑ **Goal was cost-effective mass reduction, <$2/lb**
- ❑ **Cost models for sand casting and die casting**
  - Based on compete production flow sheets
- ❑ **Data acquired from tooling build and casting of Mg components**
- ❑ **Models predict component cost and show cost contributors**
- ❑ **Cost of 29% mass reduction of Mg components was $4/lb**
  - ~ the cost of a gallon of gas when model was run
  - Mg ingot primary cost factor (increased >50% from 2003 to 2008)



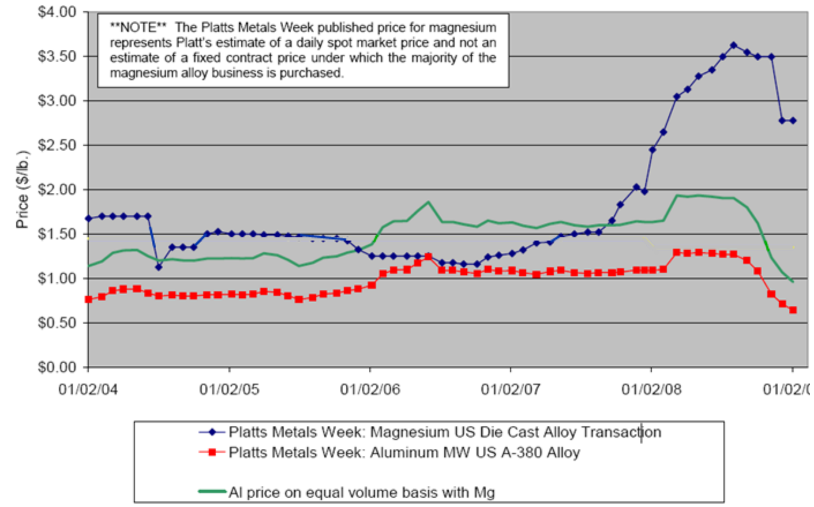
Sand casting flow sheet



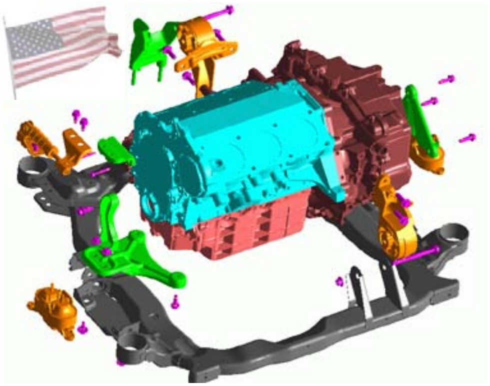
MPCC Project Accomplishments

1. 29% mass reduction - cost of $4 / lb ($1.79 / kg)
2. Tested Mg components and assembled engines
3. Passed four engine tests; failed bulkheads during break-in on DTS test
4. Root cause analysis identified design alternatives to avoid bulkhead failure
5. CTE mismatch between Mg and Fe is a significant, but addressable challenge: US Patent 7,288,528 issued to USAMP
6. Neither corrosion nor creep proved to be show stoppers
7. NVH performance of Mg excellent; not a show stopper
8. Seed-funded fundamental Mg research has become project legacy
    - Penn State - Computational Thermodynamics of Mg Systems
    - NRC – CANMET – Hot Tearing Behavior of Mg Alloys
    - Michigan at Ann Arbor – Creep and Bolt Load Retention of Mg Alloys
    - Michigan at Dearborn – Corrosion Evaluation Methods and Mechanisms
    - Recycling – Case Western Reserve University

Magnesium for the future – Remaining Concerns



- ❑ **Alloy Cost**
  - High cost and price volatility
- ❑ **Corrosion Protection**
  - Galvanic Couples and Coolants
  - Low cost, reliable protection
    - Avoid use of coatings
  - Design guide for corrosion avoidance
  - Corrosion resistance in multi-component systems
- ❑ **Creep Resistant Alloys**
  - Design Guide for Bolt Load Retention
  - Gasket Design Guide
- ❑ **Fastening and Joining of Dissimilar Metals**
  - Design Guide
- ❑ **NVH**
  - Design Guide for Mg as noise sources and/or transmitters



MPCC Project Team

Leadership Team:	Chrysler, Ford, GM
Product Design:	Ford, GM, Chrysler, Magna Powertrain
Alloy Suppliers:	AMC, Dead Sea Magnesium, GM, Noranda, Norsk-Hydro, Solikamsk, VSMPO-Avisma
Casters:	Eck, Gibbs, Intermet, Lunt, Meridian, Nemak, Spartan, Thixomat
Bore Treatment:	Gehring, Flame Spray
Tooling:	Becker, Delaware, EXCO, HE Vannatter
Coolants:	Ashland/Valvoline, ChevronTexaco, Honeywell/Prestone, INTAC
Fasteners:	RIBE
Gaskets:	Dana/Victor Reinz
Testing and R&D Labs:	Amalgatech, CANMET, Stork, Westmoreland, Quasar
Casting Modeling:	EKK, Flow Science, MAGMAsoft, Technalysis
Professional Organizations:	IMA, NADCA
Project Administration:	Ried and Associates

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