Lightweight Sealed Steel Fuel Tanks for Advanced Hybrid Electric Vehicles
ASP-400

Philip A Yaccarino
General Motors
May 18, 2012

Project ID # LM066
www.a-sp.org
**OVERVIEW**

### Timeline
- Start: Jan. 2, 2011
- Finish: Sept 30, 2011
- Project complete
  - No further funding

### Budget
- Total project funding
  - DOE: $158K
  - Contractor: $158K
- DOE funding received
  - FY 2011: $99K
  - FY 2012: $56K

### Barriers
- High mass of current generation sealed steel tanks
- Forming, rigidity and fatigue of thin wall, low mass tanks
- Manufactured cost

### Partners
- Ford, GM
- ArcelorMittal
- Henkel Corporation
- No. American Stainless
- Nippon Steel, USA
- Soutec Ltd.
- Spectra Premium Inds. Inc.
- ThyssenKrupp Steel – USA
- US Steel Corp.
- EDAG Inc.
Enable and demonstrate the manufacturing feasibility of low-mass, sealed steel fuel tanks suitable for use in advanced hybrid electric vehicles (AHEV) while achieving equivalent performance and cost to the production tank.

Critical to allow a low mass metal option for fuel tanks for advanced hybrid electric vehicles which require pressurized fuel tank systems.

**Target mass reduction 30-40%**
# Project Approach

**Two Benchmark Tanks**

<table>
<thead>
<tr>
<th>Step I</th>
<th>Step II</th>
<th>Step III</th>
<th>Step IV</th>
<th>Step V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Procure Fuel Tanks</strong>&lt;br&gt;• Generate CAD by scanning&lt;br&gt;• Build FE Model</td>
<td><strong>Baseline Analysis</strong>&lt;br&gt;• Strength Analysis under Pressure/Vacuum (+35/-16 kPa) condition&lt;br&gt;• Fatigue Analysis Stamping (one step)</td>
<td><strong>Topology Optimization</strong>&lt;br&gt;• Find optimum reinforcing area</td>
<td><strong>Parametric Optimization</strong>&lt;br&gt;• Material Selection&lt;br&gt;• HSS / AHSS Thickness selections</td>
<td><strong>Verification Analysis for Finalized Result</strong>&lt;br&gt;• Strength analysis under pressure/vacuum conditions&lt;br&gt;• Fatigue analysis&lt;br&gt;• Stamping analysis (one step)</td>
</tr>
</tbody>
</table>

## Input
- Physical Sealed Fuel Tank
- EDAG CAE Modeling Guidelines

## Output
- Systems and parts dimensions, weight
- Fuel tank stiffness baseline analysis results
- Optimum reinforcing concept and locations
- Optimum material and thickness combination for light weight
- Optimum Bead pattern

## Tools Used
- ANSA, Hyper Works, NASTRAN, Design Life, ABAQUS

## Tools
- EDAG CAE
- ANSA, Hyper Works, NASTRAN, Design Life, ABAQUS
- ASP
- Steel Material Database
- Terokal 5089 Adhesive Properties
PROJECT MILESTONES

Phase 1: Establish methodology
   Establish project metrics
   January 2011 – February 2011 Completed

Phase 2: Optimize mass for flat fuel tank (Lexus)
   CAE/Forming Analysis
   February 2011 – March 2011 Completed
   Optimize Shape
   February 2011 – April 2011 Completed

Phase 3: Optimize mass for large, saddle, fuel tank (Mercedes)
   CAE/Forming Analysis
   May 2011 – August 2011 Completed
   Optimize Shape
   August 2011 – September 2011 Completed

Phase 4: Report preparation and technology transfer
   September 2011 Completed
<table>
<thead>
<tr>
<th>2010 Model</th>
<th>Vehicle Type</th>
<th>Capacity gal (liter)</th>
<th>Mass pound (kg)</th>
<th>Weld Method</th>
<th>Steel Thickness inch (mm)</th>
<th>Type</th>
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<tbody>
<tr>
<td>LEXUS RX 450h</td>
<td>CUV</td>
<td>16 (60.6)</td>
<td>* 65.6 (29.83)</td>
<td>Electric Resistance Seam</td>
<td>0.079 (2.0)</td>
<td>Low Carbon</td>
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<tr>
<td>MERCEDES M 450H</td>
<td>SUV</td>
<td>24 (90.8)</td>
<td>** 67.5 (30.68)</td>
<td>Plasma</td>
<td>0.059 (1.5)</td>
<td>301 LN Stainless</td>
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</table>

* Including post paint, ** with fuel tank accessories
Load Condition: Static Pressure / Vacuum

Set up Condition

- Pressure Load : 35 kPa
- Vacuum Load : -16 kPa

Initial Tank Condition

- Shell Thickness - Upper / Lower : 2.0 mm
- Shell / Baffle Material : Low Carbon Steel
- Baffle Shell Thickness : 0.7 mm
- Total Mass : 29.3 kg

Fatigue Loads & Requirements :

- Pressure / Vacuum : 35kPa to -16 kPa
- Minimum Life 12,000 cycle x 1.5 SF = 18,000 cycles
LEXUS - STRUCTURAL IMPROVEMENTS

- Stress Analysis / Optimization Results
  - Additional Structural Baffles (1.0 mm Upper/Lower Shell thickness)

Stress (Max) = 630 Mpa
Stress (Max) = 579 Mpa
Stress Analysis / Optimization Result based on Topography Optimization Result

- Load Condition: 35 kPa Pressure

Max Stress: 465 MPa
High Stress: 371 MPa
### Parametric Analysis Results Summary (with additional baffles)

<table>
<thead>
<tr>
<th>Case#</th>
<th>Shell Thickness (mm)</th>
<th>Baffle Thickness (mm)</th>
<th>Mass (kg)</th>
<th>Mass Saving (%)</th>
<th>Von-Mises Max Stress (MPa)</th>
<th>Von-Mises High Stress @ Fatigue (MPa)</th>
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<td>0.7/1.4</td>
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<td>631</td>
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<td>-33.8</td>
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<td>17.4</td>
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<td>0.7/1.4</td>
<td>17.4</td>
<td>-40.7</td>
<td>529</td>
<td></td>
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</tbody>
</table>

Min. thickness range focused on stress range

- Upper: 1.0 mm
- Lower: 1.1 mm
### Forming Analysis Results Summary

<table>
<thead>
<tr>
<th>Case#</th>
<th>Model Description</th>
<th>Shell Thickness (mm)</th>
<th>Baffle Thickness (mm)</th>
<th>Mass (kg)</th>
<th>Mass Saving (%)</th>
<th>Von-Mises Max Stress (MPa)</th>
<th>Von-Mises High Stress @ Fatigue (MPa)</th>
<th>Steel Candidates</th>
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<tbody>
<tr>
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<td>0.7/1.4</td>
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<td>550</td>
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<td>0.7/1.4</td>
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<td>-22.3</td>
<td>336</td>
<td>550</td>
<td>TRIP 350/600</td>
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<td>1.1 Lwr</td>
<td>0.7/1.4</td>
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<td>TRIP 450/800 OR 301LN-1/4 Hard</td>
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<td>631</td>
<td>301LN-1/4 Hard</td>
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<tr>
<td>20</td>
<td>Model v8 07/17/11, Iter 3</td>
<td>1.0 Lwr</td>
<td>0.7/1.4</td>
<td>17.4</td>
<td>-40.6</td>
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<td>631</td>
<td>301LN-1/4 Hard</td>
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<td>19.4</td>
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<td>TRIP 450/800 OR 301LN-1/4 Hard</td>
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<td>22</td>
<td>Model v8 07/17/11, Iter 5</td>
<td>1.2 Lwr</td>
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<td>TRIP 450/800 OR 301LN-1/4 Hard</td>
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<td>23</td>
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<td>0.9 Upr</td>
<td>0.7/1.4</td>
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<td>529</td>
<td>TRIP 450/800 OR 301LN-1/4 Hard</td>
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</tbody>
</table>

- **AHSS (TRIP450/800) → Case #22**
- **Stainless (301 LN-1/4 hard) → Case #20, 21, 22, 23**

### Fatigue Life Analysis Results – Case#21 (Iteration# 14)

- Analyzed fatigue life 72,420 Cycles (minimum) >> 18,000 Cycles (targeted)
Cost comparison

AHSS (TRIP) (with post paint)
- High product volume (150,000/yr) + 2.1%
- Low product volume (50,000/yr) + 5.6%

Cost per kilogram saved:
$0.14 (high volume)

Stainless (301 LN 1/4 hard) (without post paint)
- High product volume (150,000/yr) + 37.7%
- Low product volume (50,000/yr) + 35.0%

Cost per kilogram saved:
$2.10 (high volume)
## Conclusions

- Optimized results are shown in following table with baffles present and achieved 34%~41% mass reductions
- No significant tank volume change
- Structural baffles are built on existing sloshing baffles by extension and welding

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Steel Grade</th>
<th>Initial Tank Mass (kg)</th>
<th>Reduced Tank Mass (kg)</th>
<th>Mass Saving (%)</th>
<th>Cost Changes High / Low Vol. (%)</th>
<th>Shell Thickness (mm)</th>
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</thead>
<tbody>
<tr>
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<td>AHSS TRIP 450/800</td>
<td>29.3</td>
<td>19.4 (-9.9)</td>
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<td>+2.7 / +6.8</td>
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<td>+37.7 / +35.0</td>
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</table>
Load Condition: Static Pressure / Vacuum

- Set up Condition
  - Pressure Load: 35 kPa
  - Vacuum Load: -16 kPa

- Initial Tank Condition
  - Shell Thickness - Upper / Lower: 1.5 mm
  - Shell / Baffle Material: Stainless 301 LN
  - Total Mass: 24.2 kg

Fatigue Life of Baseline Mercedes Tank: 29,000 cycles
MERCEDES - OPTIMIZATION RESULTS

- Topography Optimization
  - Upper Shell
    - Straight Beads Fore-Aft to Vehicle Direction
  - Lower Shell
    - Straight Beads Lateral to Vehicle Direction

- Structural Improvements
  - Five Baffles
  - Seven Baffles
Model - Iteration WB2
1.1mm Upper and Lower Shell
0.3mm Steel Reinforcements with 1.0 mm Terokal 5089 structural adhesive

MERCEDES - Mass Reductions

<table>
<thead>
<tr>
<th>Iteration #</th>
<th>Description</th>
<th>Shell Thickness (mm)</th>
<th>Baffle/Reinf Thickness (mm)</th>
<th>Total Mass (kg)</th>
<th>Mass Change (kg)</th>
<th>Mass Change (%)</th>
<th>Von-Mises Max Stress (Mpa)</th>
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<tbody>
<tr>
<td>B</td>
<td>Baseline</td>
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<td>24.2</td>
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<td>---</td>
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<td>O</td>
<td>Topography Optimized</td>
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WB1 and WB2 iterations do not include baffles
### Forming Analysis Results Summary – Upper Shell (Lower Shell Similar)

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- Acceptable materials due to the forming geometry

### Fatigue Analysis Results Summary

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<thead>
<tr>
<th>Iteration #</th>
<th>Description</th>
<th>Shell Thickness (mm)</th>
<th>Baffle/Reinf Thickness (mm)</th>
<th>Total Mass (kg)</th>
<th>Mass Change (kg)</th>
<th>Mass Change (%)</th>
<th>Von-Mises Max Stress (Mpa)</th>
<th>Fatigue Life (cycles)</th>
<th>Steel Type</th>
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<tbody>
<tr>
<td>B</td>
<td>Baseline</td>
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<td>24.2</td>
<td>---</td>
<td>---</td>
<td>282</td>
<td>29,000</td>
<td>Stainless 301LN</td>
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<td>O</td>
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<td>1.5</td>
<td>---</td>
<td>24.2</td>
<td>---</td>
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<tr>
<td>B1</td>
<td>Baffles Added</td>
<td>0.8</td>
<td>0.7</td>
<td>14.9</td>
<td>9.3</td>
<td>-38%</td>
<td>262</td>
<td>40,000</td>
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<td>WB1</td>
<td>Weld Bonded Reinf Added</td>
<td>0.8</td>
<td>0.3</td>
<td>15.1</td>
<td>9.1</td>
<td>-38%</td>
<td>272</td>
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<td>0.3</td>
<td>18.2</td>
<td>4.4</td>
<td>-25%</td>
<td>275</td>
<td>39,000</td>
<td>Stainless 201LN</td>
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</tbody>
</table>
Cost Comparison Facts

**Baffle only**
- High product volume (150,000/yr) -32.4 %
- Low product volume (50,000/yr) -22.0 %

Savings per kg $4.69 (High Volume)

**Weld Bonded Reinforcement (WBR)**
- High product volume (150,000/yr) -28.5 %
- Low product volume (50,000/yr) -20.7 %

Savings per kg $6.37 (High Volume)

*Seam welding assumed as joining method for all cost calculations and without post paint*
Conclusions

- Significant mass reduction achieved by using stainless steel

- Achieved mass reduction: 38.5% (24.2 kg → 14.9 kg)

- Optimized stainless steel tanks exceed fatigue & rigidity requirements and are lower cost

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Stainless Steel</th>
<th>Steel Grade</th>
<th>Initial Tank Mass (kg)</th>
<th>Reduced Tank Mass (kg)</th>
<th>Mass Saving (%)</th>
<th>Cost Changes High / Low Vol. (%)</th>
<th>Shell Thickness (mm)</th>
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<tbody>
<tr>
<td></td>
<td>201LN - Annealed</td>
<td>24.2</td>
<td>14.9 (-9.3)</td>
<td>38.5</td>
<td></td>
<td>-32.4 / -20.7</td>
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</tbody>
</table>

Baseline Model

Optimized Model
Target mass reductions of 30-40% achieved

Enablers:

Structural supports:
- Stiffening ribs
- Structural baffles
- Weld-bonded adhesive patches

Thinner steels for tank walls:
- Carbon AHSS (TRIP) steel
- Stainless steel

Fatigue and structural rigidity requirements met

Low cost/kg of mass savings

Vehicle level crashworthiness of designs not evaluated

Follow up Work Recommended:

- Evaluation of crashworthiness of proposed designs
- Evaluation of manufacturing feasibility
Stress Analysis Results - LEXUS

- Static Pressure
  - High Stress: 506.5 MPa

- Static Vacuum
  - High Stress: 211.5 MPa
FATIGUE ANALYSIS - BASELINE RESULTS

LEXUS TANK

Fatigue Analysis Results

Fatigue Life of Lexus Tank

Test Result by GM

Failure at 12,000

Fatigue Life of Lexus Tank
Formability Results (one step forming) - Upper Shell - LEXUS

Max. Thinning 27%
The physical tank thicknesses have been measured and correlate with the forming simulation

Formability Results
No Failures
Parametric Analysis Results Summary
Fatigue Life Analysis Results – Case#22 (Iteration# 15)

- Analyzed fatigue life 27,380 Cycles (minimum) >> 18,000 Cycles (targeted)