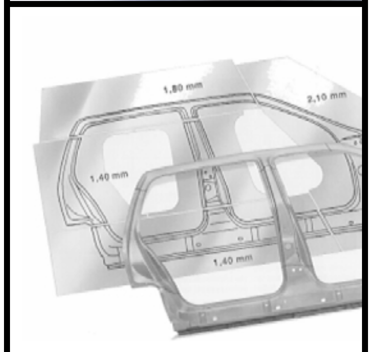
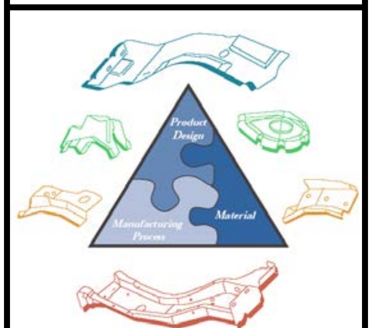
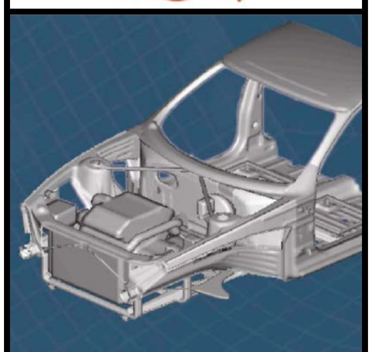






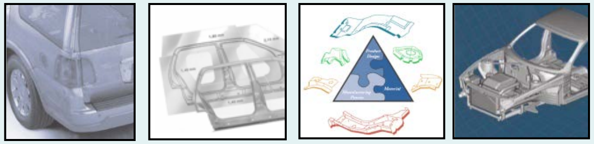
Lightweight Sealed Steel Fuel Tanks for Advanced Hybrid Electric Vehicles ASP-400

Philip A Yaccarino
General Motors

May 18, 2012

Project ID # LM066

Auto/Steel Partnership
www.a-sp.org



OVERVIEW

Timeline

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

Budget

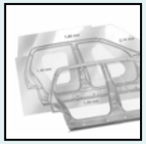
- Total project funding
  - DOE: $158K
  - Contractor: $158K
- DOE funding received
  - FY 2011: $99K
  - FY 2012: $56K

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.

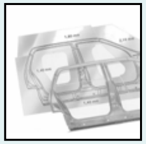



PROJECT OBJECTIVE

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.

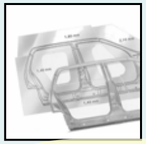
Target mass reduction 30-40%

PROJECT APPROACH

TWO BENCHMARK TANKS

	Step I	Step II	Step III	Step IV	Step V
	• **Procure Fuel Tanks** • **Generate CAD by scanning** • **Build FE Model**	• **Baseline Analysis** Strength Analysis under Pressure/Vacuum (+35/-16 kPa) condition Fatigue Analysis Stamping (one step)	• **Topology Optimization** Find optimum reinforcing area • **Topography Optimization** Find optimum bead pattern	• **Parametric Optimization** Material Selection HSS / AHSS Thickness selections	• **Verification Analysis for Finalized Result** Strength analysis under pressure/vacuum conditions Fatigue analysis Stamping analysis (one step)
Input	Physical Sealed Fuel Tank EDAG CAE Modeling Guidelines	EDAG CAE Stiffness Analysis Guidelines	EDAG CAE Optimization Analysis Guidelines	ASP Steel Material Database Terokal 5089 Adhesive Properties	Optimize candidates to finalize solution
Output	Systems and parts dimensions, weight CAD Data FE Model	Fuel tank stiffness baseline analysis results	Optimum reinforcing concept and locations Optimum Bead pattern	Optimum material and thickness combination for light weight	**LWSSFT Fuel Tank**
Tools Used	ANSA, Hyper Works, NASTRAN, Design Life, ABAQUS				

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

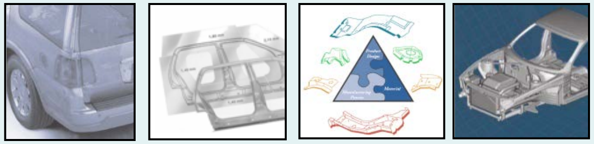
May 2011 – August 2011 — Completed

Optimize Shape

August 2011 – September 2011 — Completed

Phase 4: Report preparation and technology transfer

September 2011 — Completed

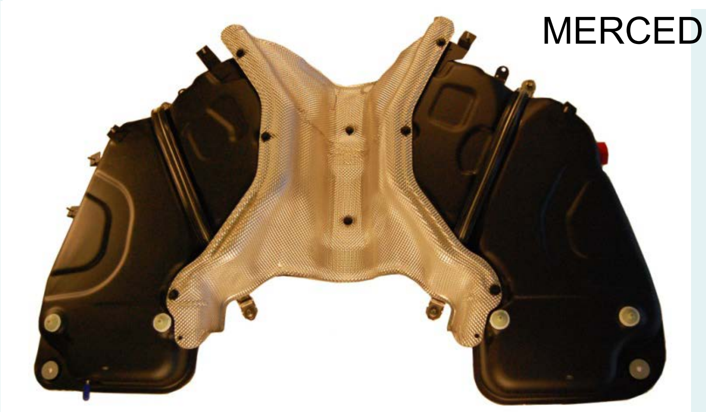


CHARACTERISTICS OF BENCHMARK TANKS

		Tank			Steel	
2010 Model	Vehicle Type	Capacity gal (liter)	Mass pound (kg)	Weld Method	Thickness inch (mm)	Type
LEXUS RX 450h	CUV	16 (60.6)	* 65.6 (29.83)	Electric Resistance Seam	0.079 (2.0)	Low Carbon
MERCEDES M 450H	SUV	24 (90.8)	** 67.5 (30.68)	Plasma	0.059 (1.5)	301 LN Stainless

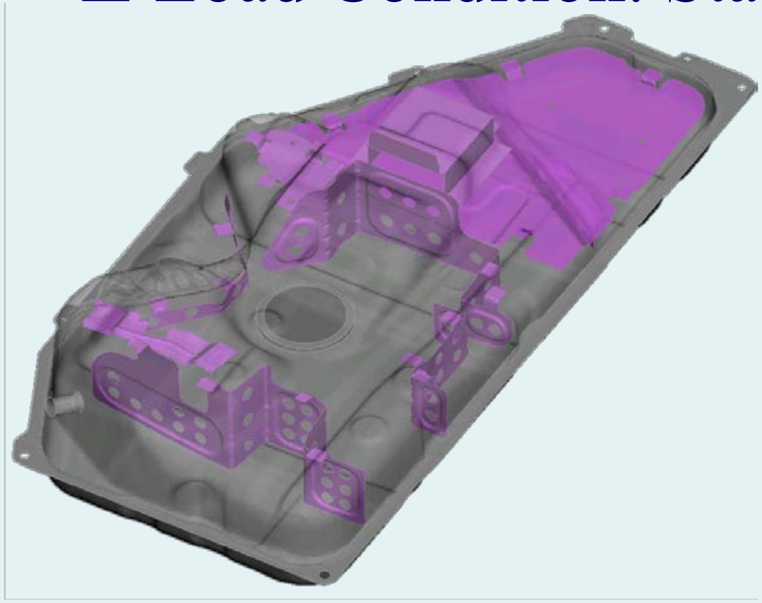
* Including post paint, ** with fuel tank accessories

LEXUS RX 450h



MERCEDES M 450H

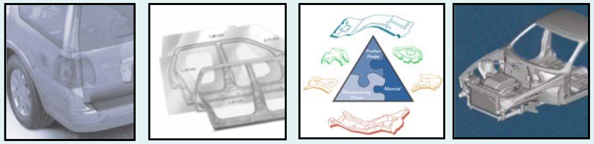
Load Condition: Static Pressure / Vacuum



- **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 :

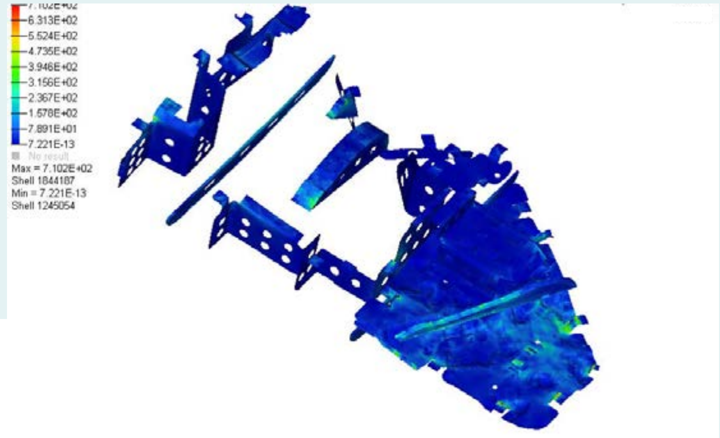
- **Pressure / Vacuum : 35kPa to -16 kPa**
- **Minimum Life 12,000 cycle x 1.5 SF = 18,000 cycles**

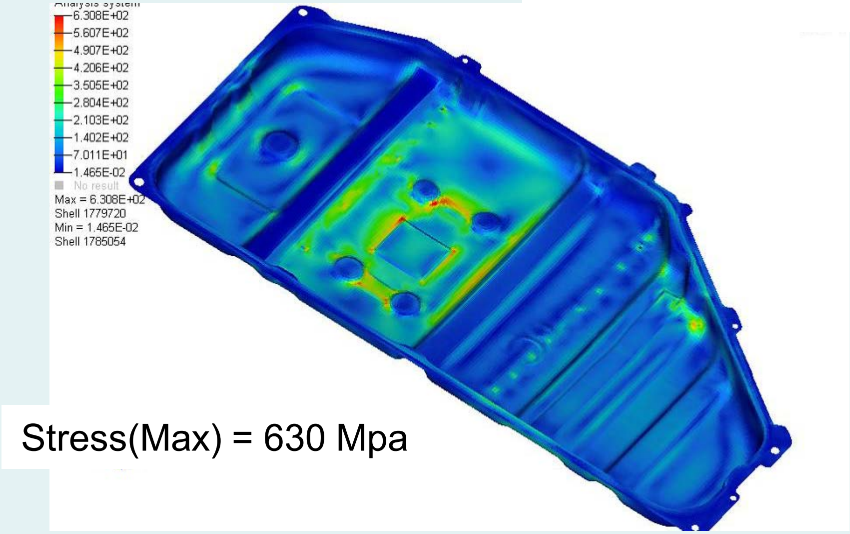


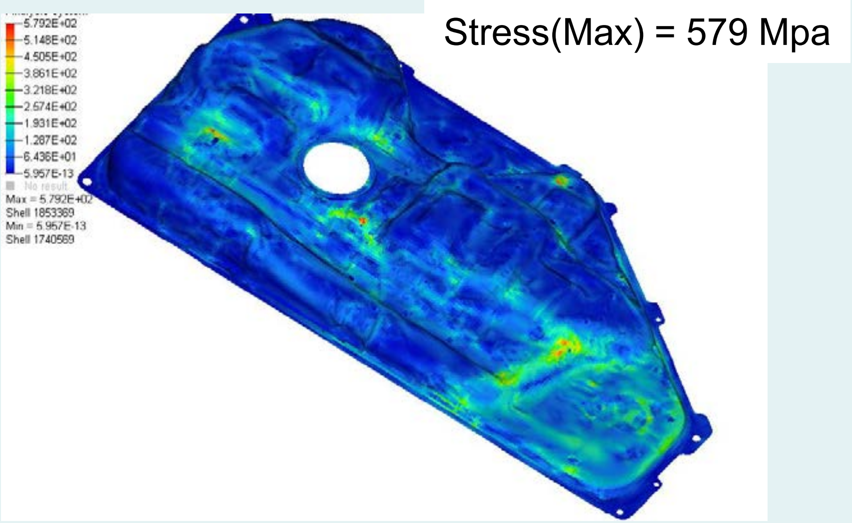
LEXUS - STRUCTURAL IMPROVEMENTS

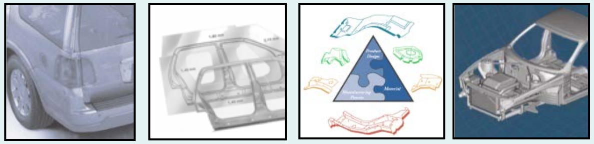
❑ Stress Analysis / Optimization Results

Additional Structural Baffles (1.0 mm Upper/Lower Shell thickness)



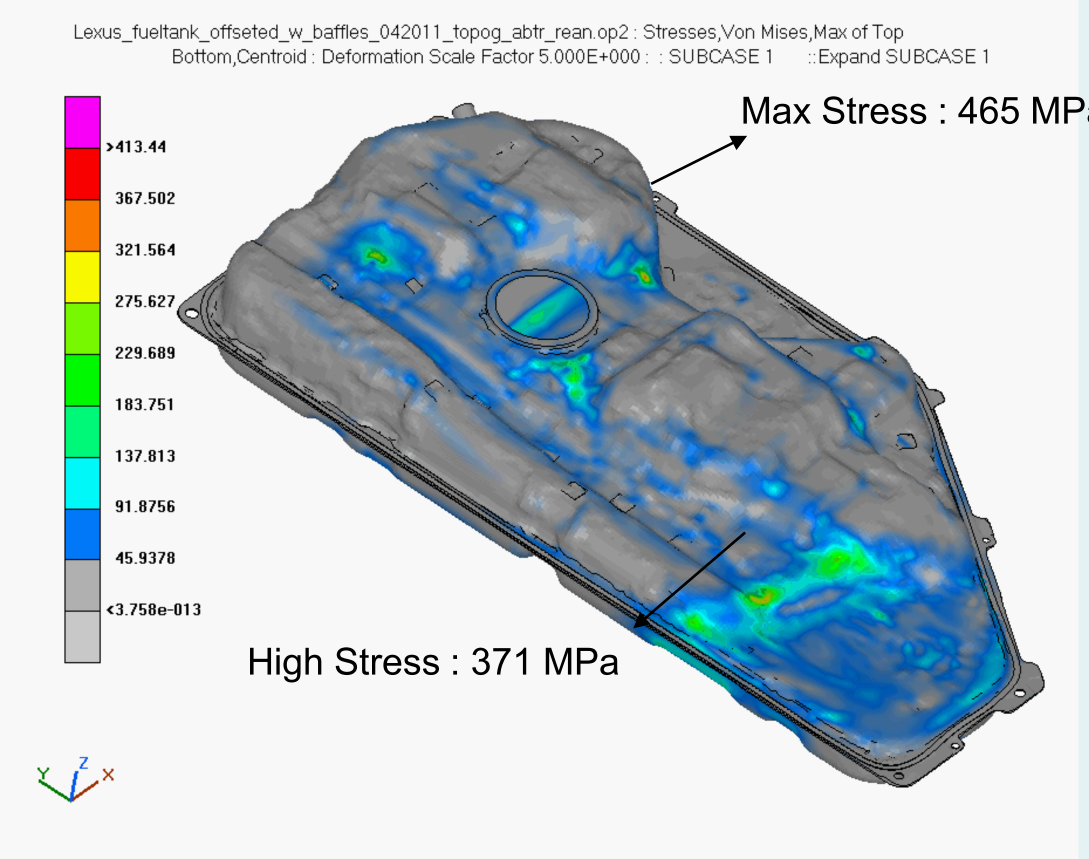


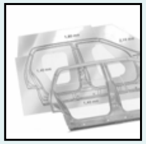




❑ Stress Analysis / Optimization Result based on Topography Optimization Result

❖ **Load Condition: 35 kPa Pressure**



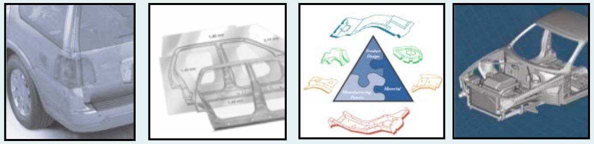
❑ Parametric Analysis Results Summary (with additional baffles)

Case#	Shell Thickness (mm)	Baffle Thickness (mm)	Mass (kg)	Mass Saving (%)	Von-Mises Max Stress (MPa)	Von-Mises High Stress @ Fatigue (MPa)
1	2.0	0.7	29.3	0.0	506.5	506.5
2	2.0	0.7	29.3	0.0	413	413
3	2.0	0.7	29.3	0.0	541	386
4	2.0	0.7	29.3	0.0	465	371
5	2.0	0.7	30.1	+2.7	465	250
6	2.0	0.7	30.1	+2.7	303	265
7	1.5	0.7	23.4	-20.3	447	388
8	1.0	0.7	16.6	-43.3	838	716
9	0.9	0.7	15.8	-46.0	994	834
10	1.5 Upper	0.7	19.4	-34.5	433	381
10	0.9 Lower				834	
11	2.0	0.7/1.0/1.4	30.4	+3.6	279	268
12	1.8	0.7/1.0/1.4	27.7	-5.6	312	302
13	1.6	0.7/1.0/1.4	25.0	-14.7	363	344
14	1.4	0.7/1.0/1.4	22.3	-23.9	464	415
15	1.2	0.7/1.0/1.4	19.6	-33.5	592	522
16	1.0	0.7/1.0/1.4	16.9	-42.3	744	678
17						
18	1.4 Upr	0.7/1.4	22.8	-22.3	341	550
18	1.4 Lwr				336	
19	1.3 Upr	0.7/1.4	20.1	-31.4	398	529
19	1.1 Lwr				529	
20	1.0 Upr	0.7/1.4	17.4	-40.6	579	631
20	1.0 Lwr				631	
21	1.0 Upr	0.7/1.4	18.7	-36.2	571	571
21	1.2 Lwr				450	
22	1.1 Upr	0.7/1.4	19.4	-33.8	500	531
22	1.2 Lwr				450	
23	0.9 Upr	0.7/1.4	17.4	-40.7	667	676
23	1.1 Lwr				529	

with Additional Baffle (cases 18–23)

Min. thickness range focused on stress range

Upper : 1.0 mm
Lower : 1.1 mm



LEXUS - VERIFICATION ANALYSIS

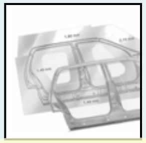
❑ Forming Analysis Results Summary

Case#	Model Description	Shell Thickness (mm)	Baffle Thickness (mm)	Mass (kg)	Mass Saving (%)	Von-Mises Max Stress (MPa)	Von-Mises High Stress @ Fatigue (MPa)	Steel Candidates
18	Model v8 07/17/11, Iter 1	**1.4 Upr**	0.7/1.4	22.8	**-22.3**	341	550	TRIP 350/600
18		**1.4 Lwr**				336		TRIP 350/600
19	Model v8 07/17/11, Iter 2	**1.3 Upr**	0.7/1.4	20.1	**-31.4**	398	529	TRIP 400/700 **OR** TRIP 450/800
19		**1.1 Lwr**				529		TRIP 450/800 **OR** 301LN-1/4 Hard
20	Model v8 07/17/11, Iter 3	**1.0 Upr**	0.7/1.4	17.4	**-40.6**	579	631	301LN-1/4 Hard
20		**1.0 Lwr**				631		301LN-1/4 Hard
21	Model v8 07/17/11, Iter 4	**1.0 Upr**	0.7/1.4	18.7	**-36.2**	571	571	301LN-1/4 Hard
21		**1.2 Lwr**				450		TRIP 450/800 **OR** 301LN-1/4 Hard
22	Model v8 07/17/11, Iter 5	**1.1 Upr**	0.7/1.4	19.4	**-33.8**	500	531	TRIP 450/800 **OR** 301LN-1/4 Hard
22		**1.2 Lwr**				450		TRIP 450/800 **OR** 301LN-1/4 Hard
23	Model v8 07/17/11, Iter 6	**0.9 Upr**	0.7/1.4	17.4	**-40.7**	667	676	301LN-1/4 Hard
23		**1.1 Lwr**				529		TRIP 450/800 **OR** 301LN-1/4 Hard

- **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)**

LEXUS - COST ANALYSIS

❑ 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 %

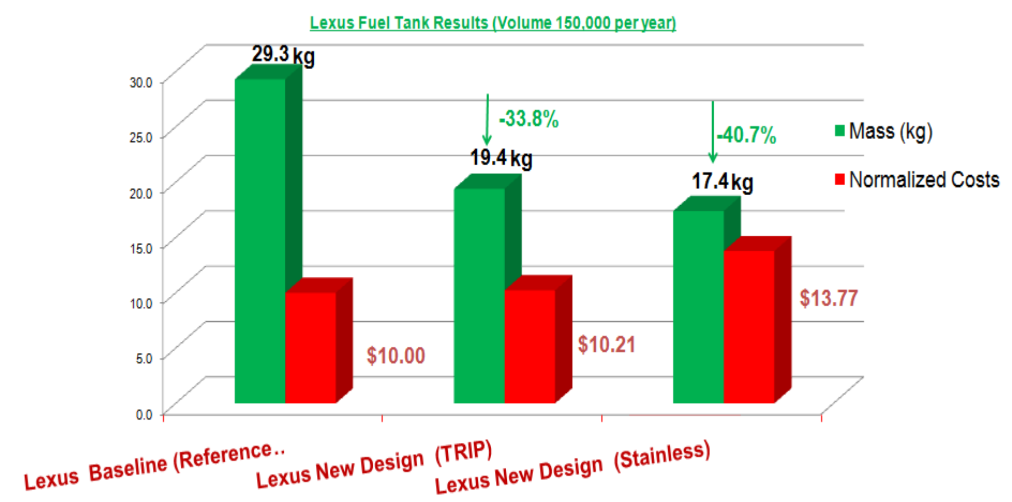
- Low product volume (50,000/yr)

  + 35.0 %

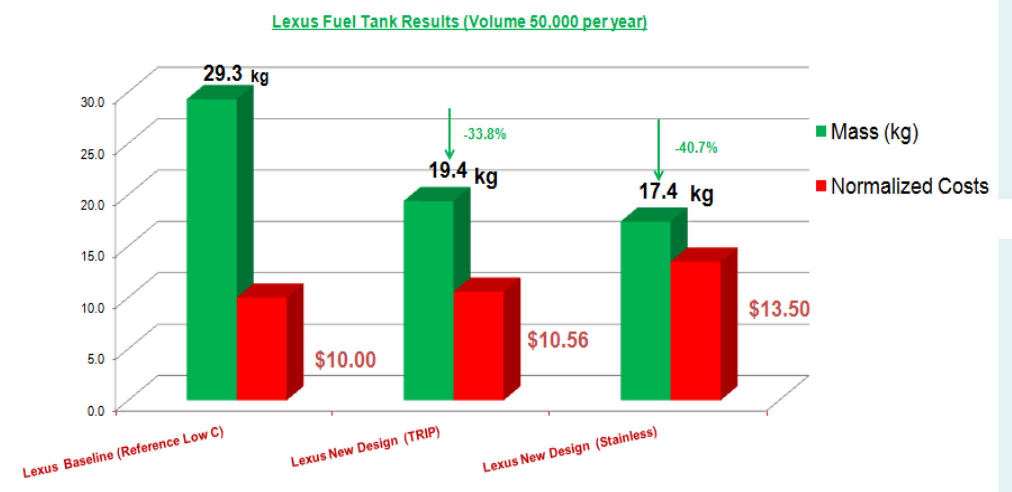
Cost per kilogram saved:
$2.10 (high volume)

Lexus Tank Results

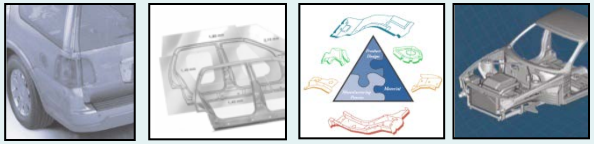
High Product Volume



Low Product Volume



A/S P

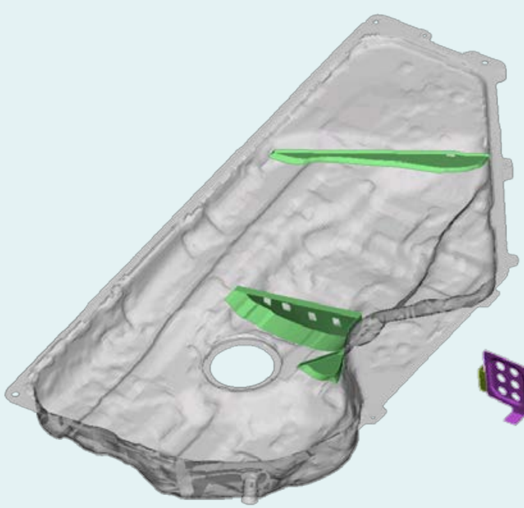


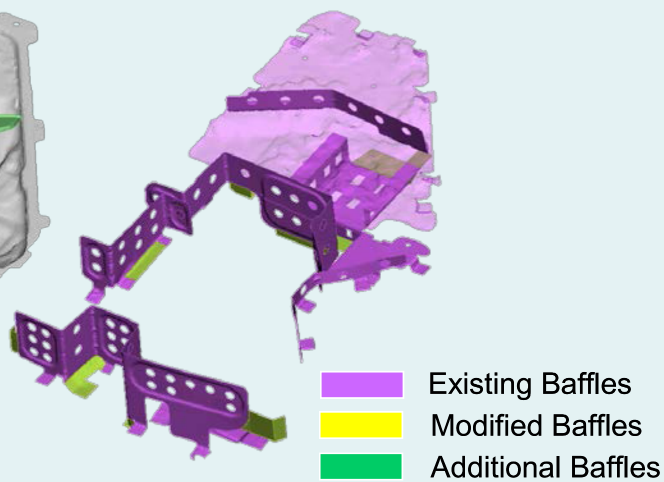
LEXUS - CONCLUSIONS

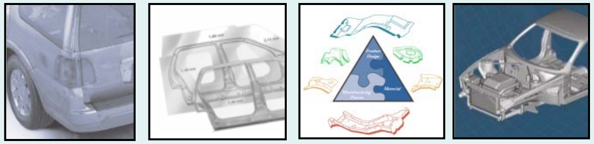
❑ Conclusions

- **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**

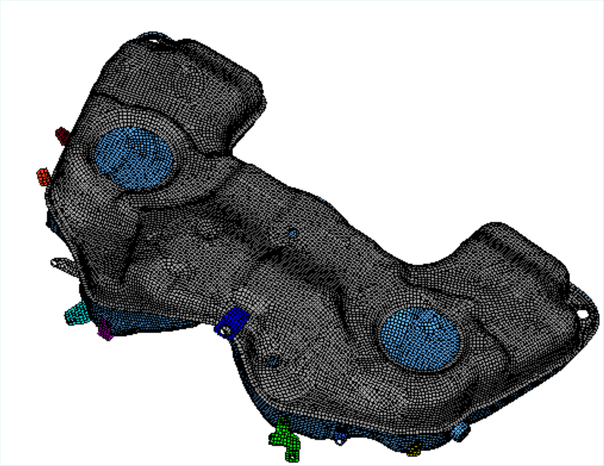
		Steel Grade	Initial Tank Mass (kg)	Reduced Tank Mass (kg)	Mass Saving (%)	Cost Changes High / Low Vol. (%)	Shell Thickness (mm)	
							Upper	Lower
Material Type	**AHSS**	**TRIP 450/800**	**29.3**	**19.4 (-9.9)**	**33.8**	**+2.7 / +6.8**	**1.1**	**1.2**
	Stainless Steel	**301LN - 1/4 Hard**		**17.4 (-11.9)**	**40.7**	**+37.7 / +35.0**	**0.9**	**1.1**



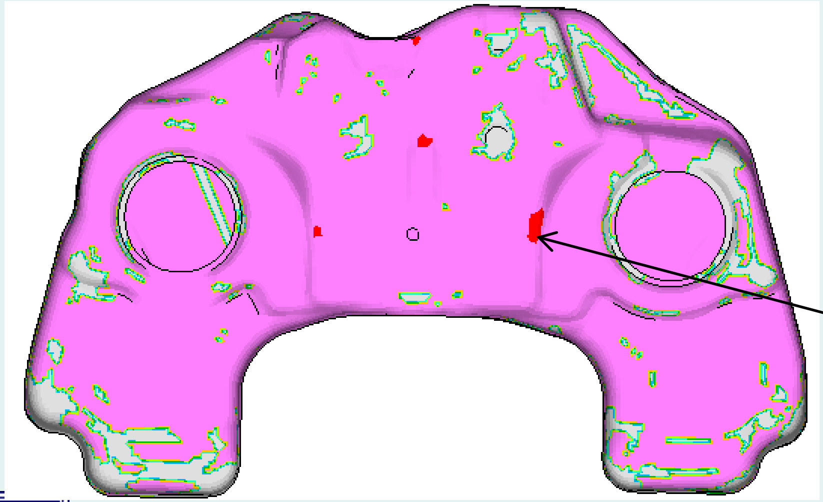




❑ Load Condition : Static Pressure / Vacuum

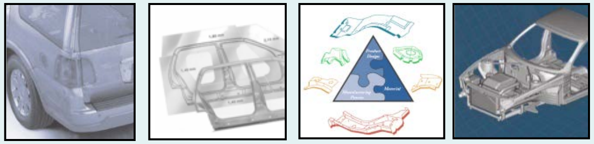


- ❑ **Set up Condition**
  - ❑ **Pressure Load : 35 kPa**
  - ❑ **Vacuum Load : -16 kPa**
- ❑ **Initial Tank Condition**
  - ❑ **Shell Thickness - Upper / Lower : 1.5 mm**
  - ❑ **Shell / Baffle Material : Stainless 301 LN**
  - ❑ **Total Mass : 24.2 kg**

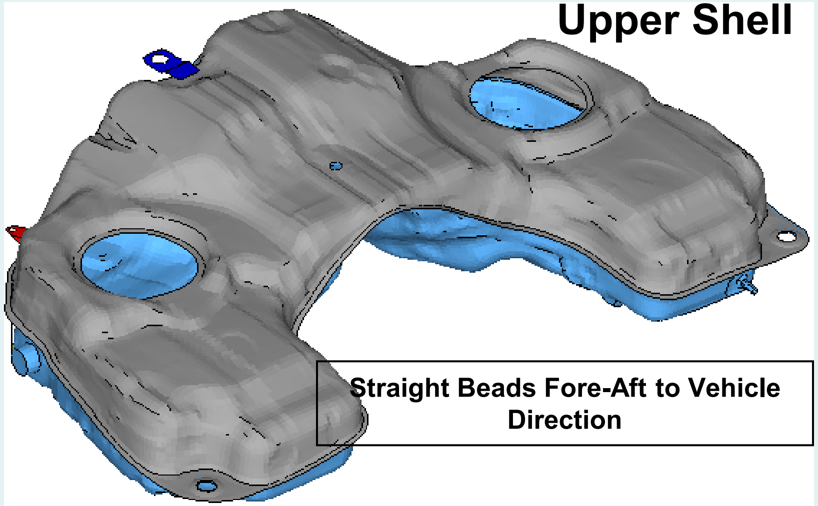


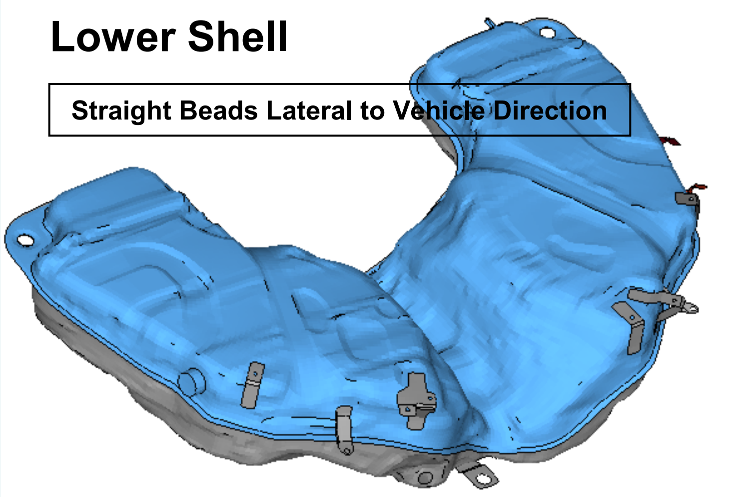
Fatigue Life of Baseline Mercedes Tank

- ❑ **29,000 cycles**

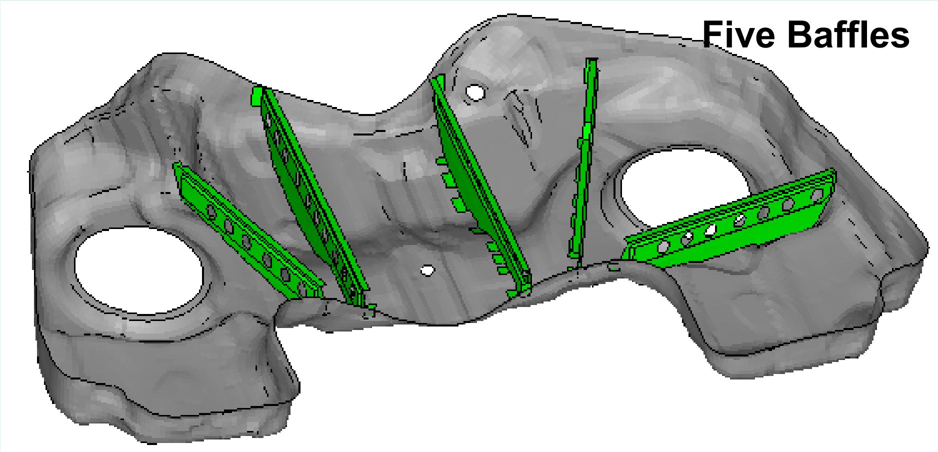


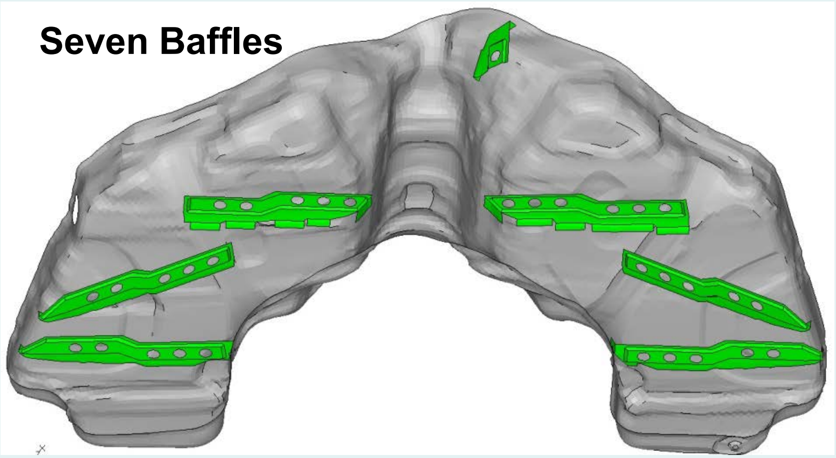
- Topography Optimization

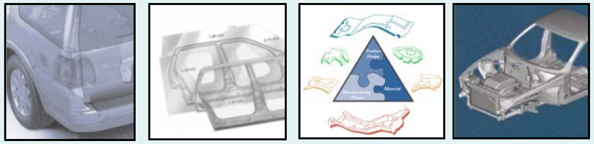




- Structural Improvements



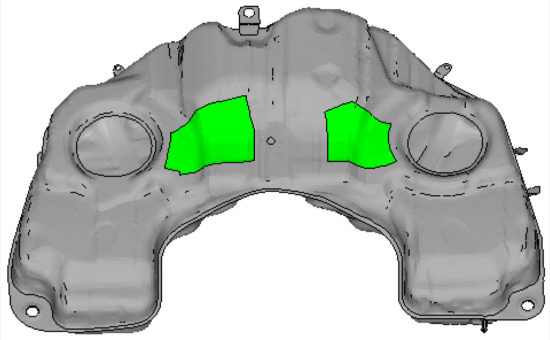


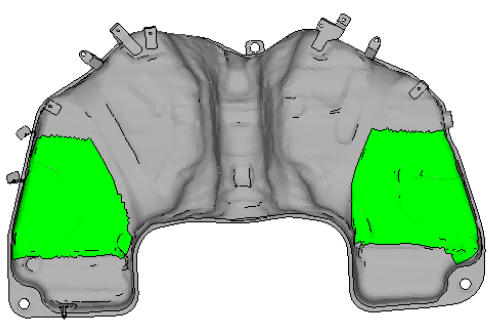


MERCEDES - STRUCTURAL IMPROVEMENTS AND RESULTS

❑ Model - Iteration WB2

1.1mm Upper and Lower Shell
0.3mm Steel Reinforcements with1.0 mm Terokal 5089 structural adhesive

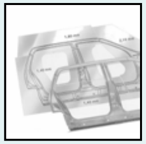




❑ MERCEDES - Mass Reductions

Iteration #	Description	Shell Thickness (mm)	Baffle/Reinf Thickness (mm)	Total Mass (kg)	Mass Change (kg)	Mass Change (%)	Von-Mises Max Stress (Mpa)
B	Baseline	1.5	---	24.2	---	---	282
O	Topography Optimized	1.5	---	24.2	---	---	252
B1	Baffles Added	0.8	0.7	14.9	-9.3	-38.4	262
WB1	Weld Bonded Reinf Added	0.8	0.3	15.1	- 9.1	-38.6	272
WB2	Weld Bonded Reinf Added	1.1	0.3	18.2	-6.0	-24.8	275

WB1 and WB2 iterations do not include baffles

MERCEDES - VERIFICATION ANALYSIS

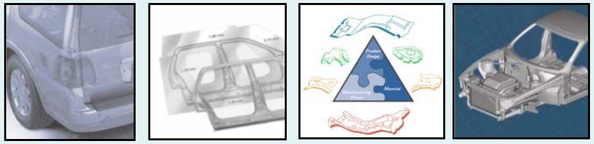
❑ Forming Analysis Results Summary – Upper Shell (Lower Shell Similar)

Material Type			Shell Thickness (mm)							
		1.6	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.8
Stainless HSS	201 LN								thinning	thinning
	301 1/4-hard	crack	crack	crack	crack	crack	crack	crack	crack	crack
	304 annealed								thinning	thinning
HSS	HSLA 350/450	crack	crack	crack	crack	crack	crack	crack	crack	crack
	TRIP 350/600	crack	crack	crack	crack	crack	crack	crack	crack	crack
	TRIP 400/700	crack	crack	crack	crack	crack	crack	crack	crack	crack

➢ Acceptable materials due to the forming geometry

❑ Fatigue Analysis Results Summary

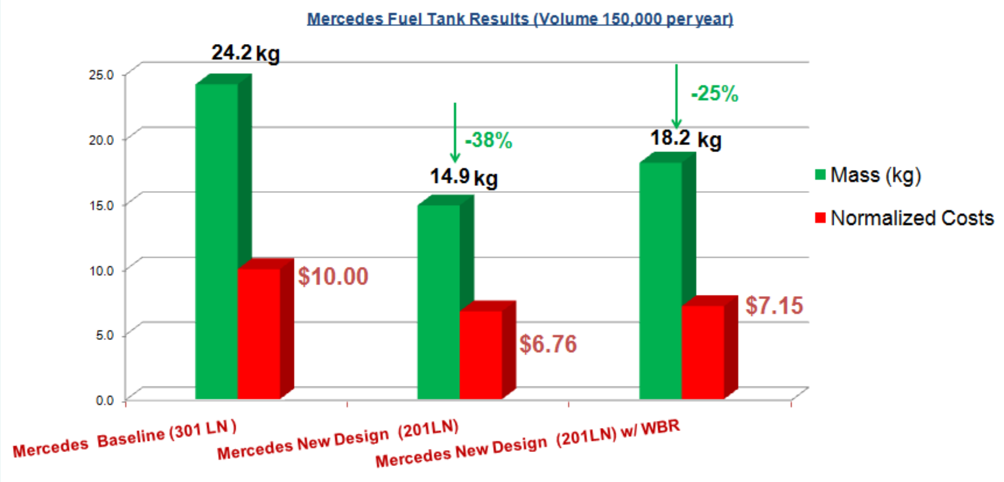
Iteration #	Description	Shell Thickness (mm)	Baffle/Reinf Thickness (mm)	Total Mass (kg)	Mass Change (kg)	Mass Change (%)	Von-Mises Max Stress (Mpa)	Fatigue Life (cycles)	Steel Type
B	Baseline	1.5	---	24.2	---	---	282	29,000	Stainless 301LN
O	Topography Optimized	1.5	---	24.2	---	---	252	---	---
B1	Baffles Added	0.8	0.7	14.9	9.3	-38%	262	40,000	Stainless 201LN
WB1	Weld Bonded Reinf Added	0.8	0.3	15.1	9.1	-38%	272	39,000	Stainless 201LN
WB2	Weld Bonded Reinf Added	1.1	0.3	18.2	4.4	-25%	275	39,000	Stainless 201LN



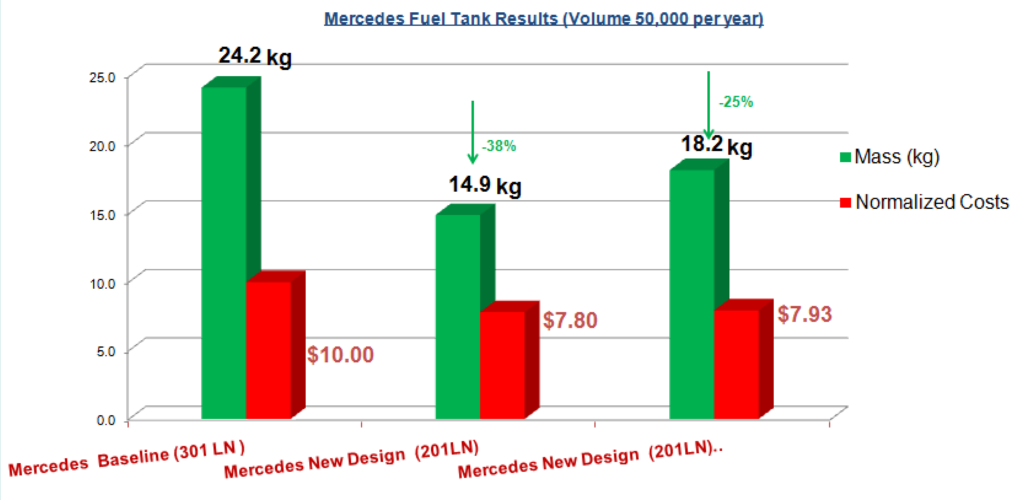
MERCEDES - COST ANALYSIS

Mercedes Result – Stainless Steels

High Product Volume



Low Product Volume



❑ Cost Comparison Facts

Baffle only

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

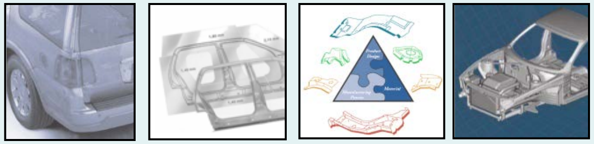
Savings per kg $4.69 (High Volume)

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**

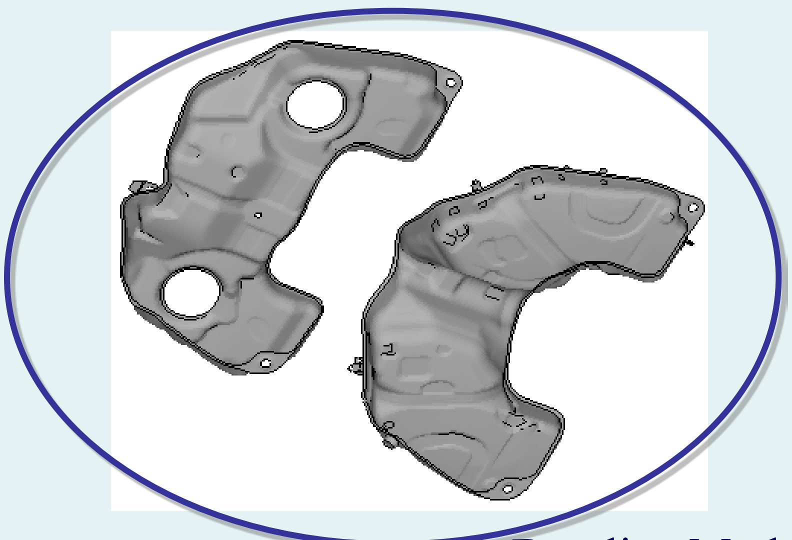


MERCEDES - CONCLUSIONS

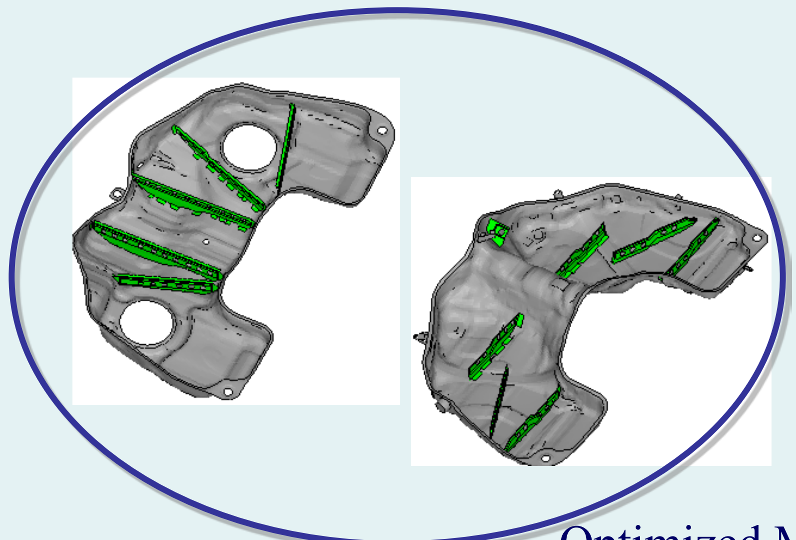
❑Conclusions

- 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

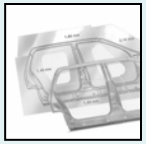
		Steel Grade	Initial Tank Mass (kg)	Reduced Tank Mass (kg)	Mass Saving (%)	Cost Changes High / Low Vol. (%)	Shell Thickness (mm)	
							Upper	Lower
Material Type	**Stainless Steel**	**201LN - Annealed**	**24.2**	**14.9 (-9.3)**	**38.5**	**-32.4 / -20.7**	**0.8**	**0.8**



Baseline Model



Optimized Model

OVERALL SUMMARY

- ❑ **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**

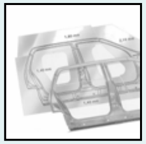
- ❑ **Vehicle level crashworthiness of designs not evaluated**

<u>Follow up Work Recommended:</u>

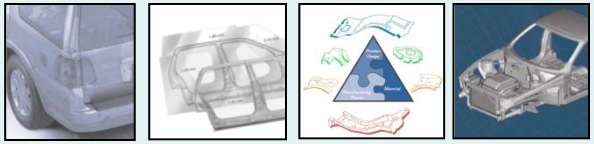
- ❑ **Evaluation of crashworthiness of proposed designs**

- ❑ **Evaluation of manufacturing feasibility**

A/S P

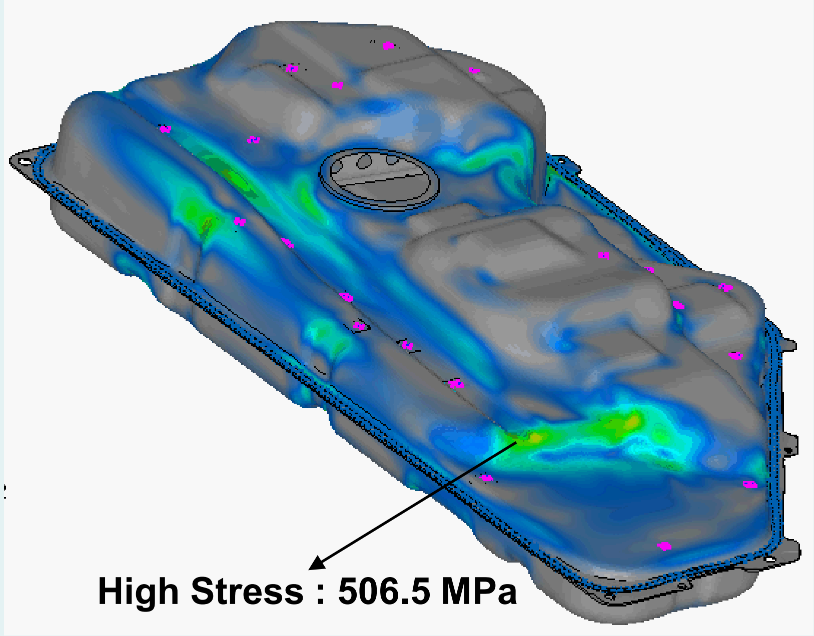
TECHNICAL BACK-UP SLIDES



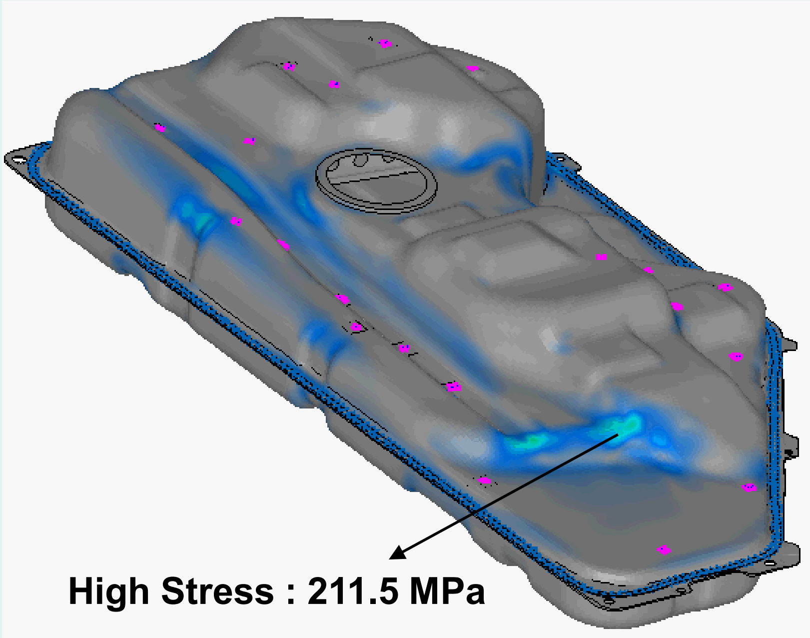
STRESS ANALYSIS - BASELINE RESULTS

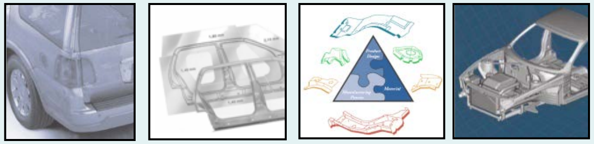
❑ Stress Analysis Results - LEXUS

❖ Static Pressure



❖ Static Vacuum

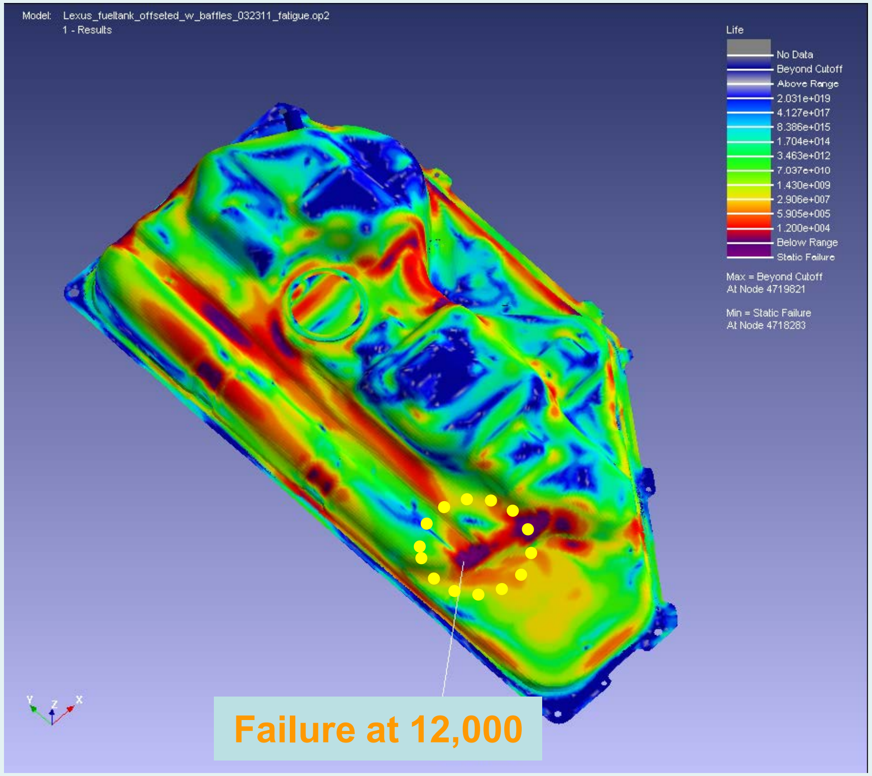




FATIGUE ANALYSIS - BASELINE RESULTS

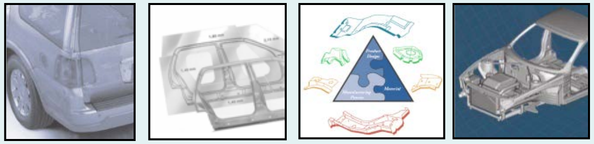
LEXUS TANK

- ❑ Fatigue Analysis Results



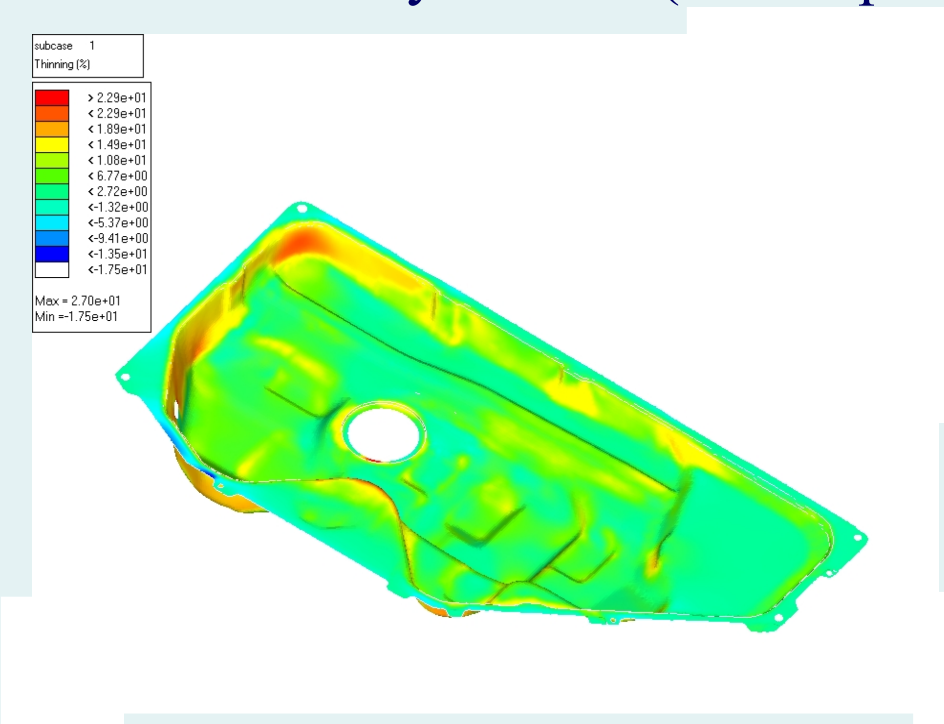
<u>Fatigue Life of Lexus Tank</u>

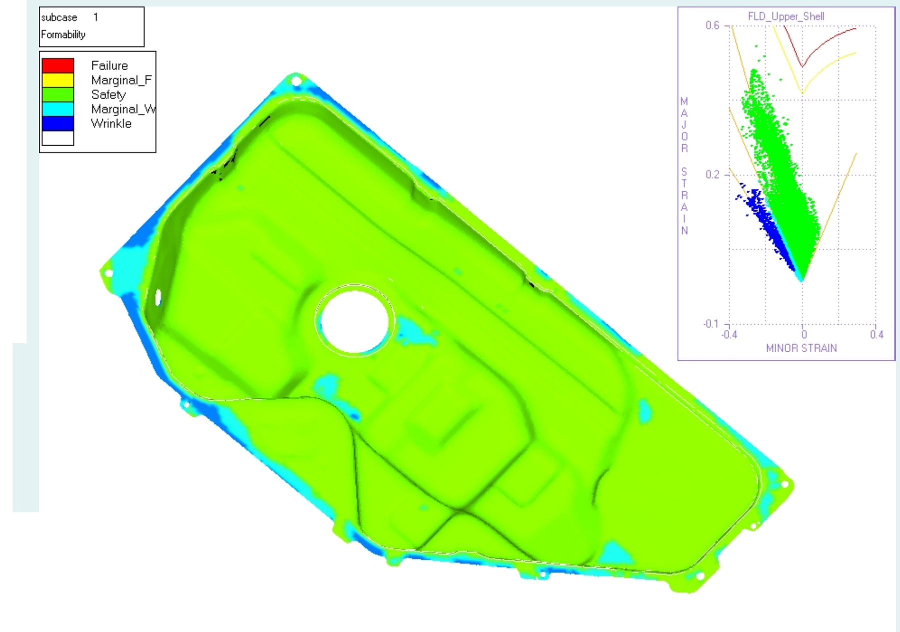
Test Result by GM



FORMING ANALYSIS - BASELINE RESULTS

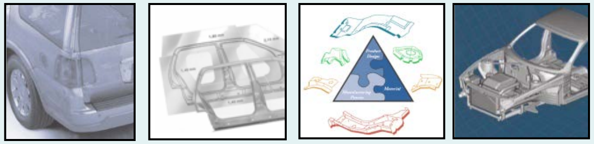
❑ Formability Results (one step forming) - Upper Shell - LEXUS



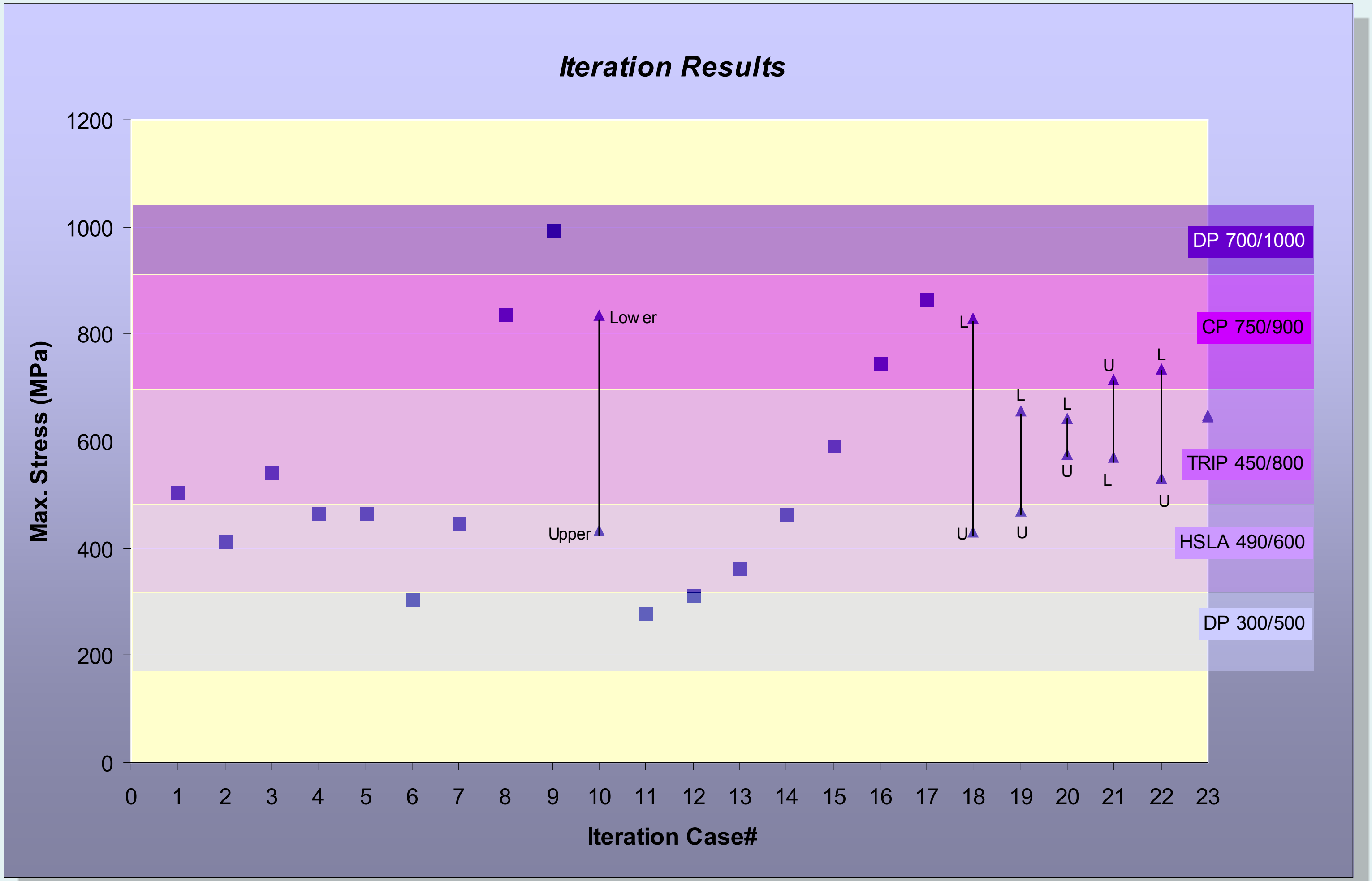


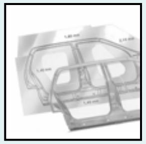
<u>Max. Thinning 27%</u>
The physical tank thicknesses have been measured and correlate with the forming simulation

<u>Formability Results</u>
No Failures



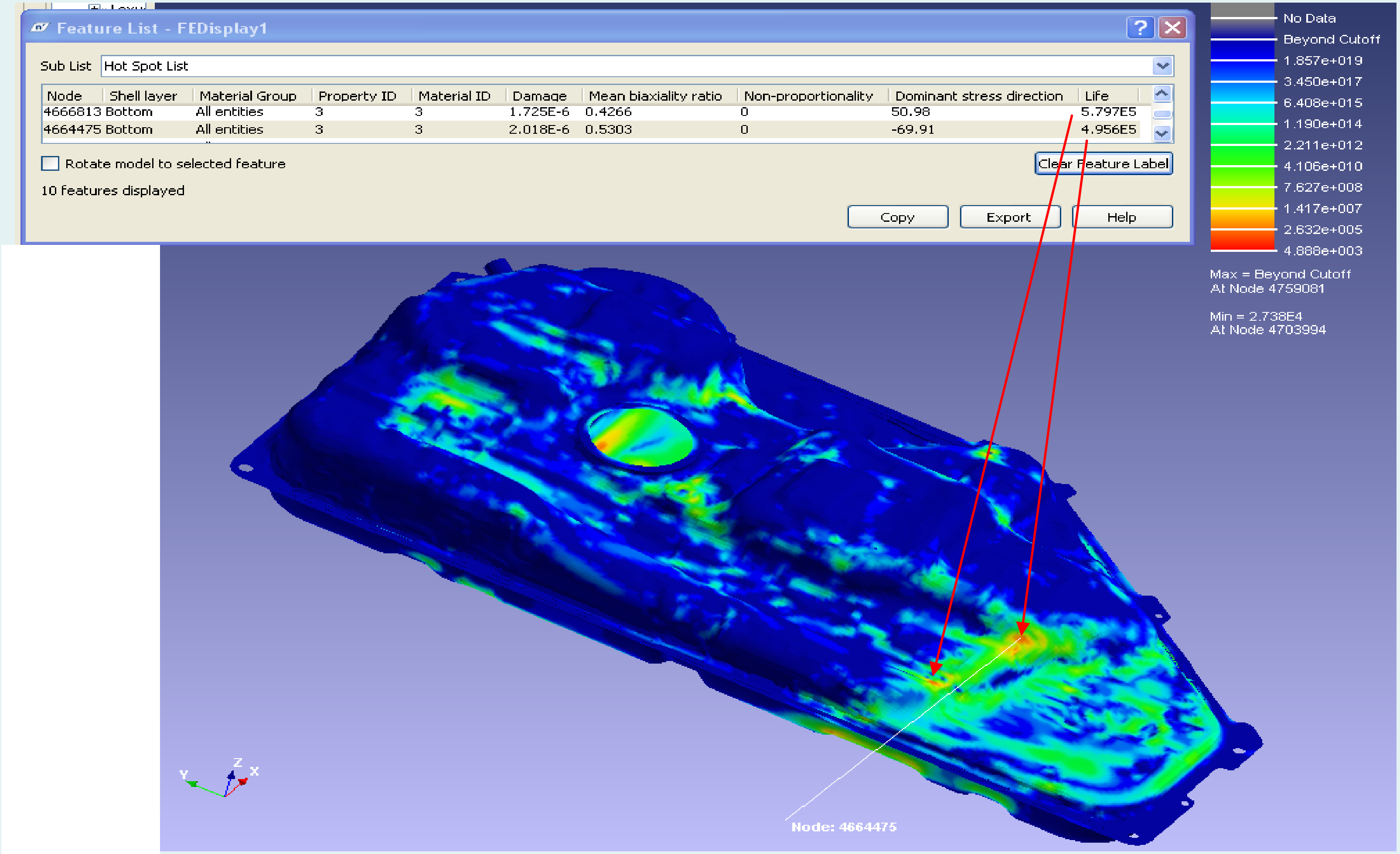
❑ Parametric Analysis Results Summary



LEXUS - VERIFICATION ANALYSIS

❑ Fatigue Life Analysis Results – Case#22 (Iteration# 15)



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