# 5. LIGHTWEIGHT VEHICLE STRUCTURES

## A. Lightweight Trailer—Liburndas Project

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*Contract No.: WA-2003-054-ORO-786*

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### Objective

- Reduce the net weight of an aluminum tank semi-trailer by 20% using a cylindrical design, assimilating available composite technology for functional components and remain within current (DOT constraints).

### Approach

- Develop a new frameless vessel design incorporating a new cross-section, flangeless heads, and internal rings.
- Optimize design through finite element analysis (FEA) and field testing.
- Explore existing composite accessories.
- Conduct a focus group and a marketing study, including a campaign for the new design.
- Complete a manufacturing study, including a labor rate analysis.
- Manufacture and test prototype.
- Commercialization of the product.

## Accomplishments

- Cylindrical vessel design complete.
- FEA and analysis of vessel design complete.
- Samples sent to ORNL for Friction Stir Welding evaluation.
- Flangeless, dishless head design and test complete.
- Marketing has defined acceptable loading head envelope parameters
- based on real world operational requirements.
- Vessel Details complete.

## Future Direction

- Complete Prototype #1.
- Prototype #1 in-house testing results.
- Composite material study findings.
- Test track results (outside contract).
- Partner identification. Manufacturing cost study (includes tooling study).
- Complete Prototype #2.
- Prototype #2 field test results with partner.
- Complete Marketing campaign.
- Market Introduction.

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## Introduction

The Liburndas Project is Heil Trailer International's effort to design and build an aluminum semi-trailer for petroleum products that is lighter, stronger, and safer than any before it. By using a cylindrical cross section and assimilating composites into select trailer components, Heil's Program Engineering Group proposes to reduce the aluminum tank semi-trailer's net weight by 20 %. (See Figure 1).

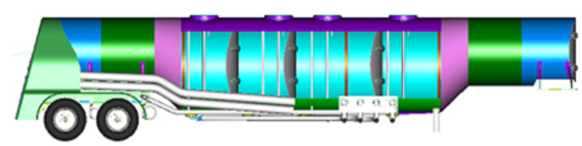

**Figure 1.** Liburndas trailer.

## Relevance to 21 CT Goals

Investigating a new aluminum alloy for the cylindrical vessel will ultimately help reduce the mass of the main structure. In areas of the barrel where components are added for functional purposes alone, Heil will utilize a new composite material to reduce parasitic energy loss. The successful results of this project will allow transportation resources to safely deliver 2000 – 2500 lbs. more payload per trip, ultimately reducing the daily average amount of miles required to deliver product by about 1%. On a national level (current population of petroleum tank trailers is approximately 50,000 units), this could equate to over 200,000 miles per year in fuel savings or 30,000 gallons of fuel per year.

Investigating a new aluminum alloy for weight reduction in areas not regulated by the U.S. Department of Transportation (DOT) is an objective of the project as well. Areas such as the frame rails for the suspension and fifth-wheel plate are valid candidates. Although some weight savings is possible, this is secondary to the contributions the new cylindrical design and composite accessories will make to Heil's overall weight reduction goals.

Accessories made from composites are critical to meeting weight reduction goals and will ultimately reduce the mass of the trailer, reduce the aero-dynamic signature and improve corrosion resistance. This project's purpose is not to create or test a new composite for these areas. Existing composites will be explored that have been proven successful in the market. Areas that are likely candidates for composites are fenders, cabinets, hose holders, ladders, and suspension support structures.

Although a successful vessel design and notable composite integration will result in reaching weight reduction goals, it is paramount to the project's success that the market accepts the new design. Because of the competitive nature of the market, data will be collected covertly, without divulging the new trailer's design or benefit. Therefore, the marketing study initially will determine acceptable envelopes for piping and discharge outlets, as well as conduct a preliminary commercial viability study based on the design's limits and/or restraints. A marketing campaign to bolster product acceptance will take place near the end of the project. The initial marketing study began during Phase 1 of the project and should be completed before the first prototype is built. The marketing campaign will take place during Phase 3 (after the successful field testing of the second prototype) and should result in orders for production models.

## Vessel Design

### Cross Section

An important part of Heil's new design concept for its petroleum trailer is the cross section of the vessel. In today's petroleum trailers, the most common cross section used is an elliptical shape, used to lower the overall height and center of gravity of the trailer. Since petroleum trailers are not unloaded or loaded with pressure, the elliptical shape works well.

When the structure of a petroleum trailer's vessel is studied, it is simply analyzed as a supported beam with reactions at the suspension and kingpin plate. This condition places the bottom of the trailer vessel in tension and the top in compression. The advantage of a round cross section under these loads is that the radius of the top is tighter or smaller and therefore more resistant to buckling under the compression loads. This allows the shell thickness of the vessel to be thinned, compared with an elliptical cross section, and thus saves weight and material.

Even though petroleum trailers are not pressurized, they do occasionally see some low vacuum or pressure differentials during loading and unloading. Today's trailers are equipped with vents to prevent damage to the vessel if this condition becomes excessive. In the event of a vent failure, a round vessel is more likely to survive a pressure or vacuum overload, whereas an elliptical vessel will tend to fail.

A round vessel is therefore stronger, lighter, safer, and more stable than an elliptical vessel for an equivalent cross sectional area. The only advantage of an elliptical trailer is its overall lower height and center of gravity. Designing a round vessel with a drop center can offset this advantage (see Figure 2).

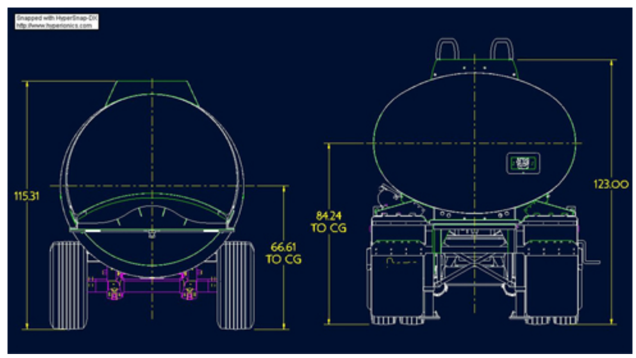


**Figure 2.** Height and center of gravity comparison.

### Drop Center Design

Dropping the center of the vessel in relation to the front and rear not only lowers the center of gravity but also causes the lateral center of mass to stay near the longitudinal center of the trailer.

Federal weight laws call for manufacturers to design trailers with equal loads on the tractor's drive axles and the trailer's suspension. By designing a lower front *and* rear end section of the vessel, we can engineer the trailer so that the mass is equally distributed over the rear of the trailer and the tractor's rear axles.

### Elimination of Surge Heads

Petroleum tank trailers are designed to DOT 406 specifications as found in the Code of Federal

Regulations Title 49. Section 178.345-7 of this code discusses circumferential reinforcements in trailers and mandates that the maximum unreinforced portion of the vessel's shell not exceed 60 in. Traditionally, this has been accomplished in petroleum trailers through the use of surge heads or baffles. These surge baffles are the same heads that separate the trailer's compartments, but they have holes formed in them to allow product to flow through them. These surge baffles help with the surge of the product during acceleration and deceleration and serve as the circumferential reinforcements.

Replacing these surge baffles with an adequately designed internal ring can achieve a considerable weight savings. However, rings will not help with product surge, and drivers will have to be trained to handle the "feel" of the tank in certain road conditions. The market's opinion (business owners and drivers) on internal rings and their advantages and disadvantages was one of the topics for the focus group and marketing study.

Liquid trailers without surge baffles are not uncommon in the chemical and food industry, where the cleanability of the inside of the trailer is important. Drivers in these industries have learned to drive safely without baffles; therefore, it is anticipated that the weight benefits will outweigh the surge issue. It should also be noted that there is no product surge when a trailer is completely full or empty.

## Flangeless, Dishless Heads

A new concept with regard to the vessel design is being applied to the Liburndas Project. This is a redesign of the compartment heads that separate different commodities in a petroleum trailer. These heads are typically dished and flanged bulkheads that are connected to the shell via a single fillet weld. The Liburndas vessel will use a flangeless, dishless head, which will be connected to the shell via two fillet welds. A Pro-E model of the head is depicted in Figure 3.

**Figure 3.** Flangeless head concept.

The Liburndas vessel is a perfect application for the flangeless head—it is lighter, the welds are stronger, the strength is comparable, and the manufacturability is more precise than for the current style head. The flangeless head is much easier to manufacture and should offset part of the cost of the composites. One of the goals of marketing is to ensure that the Program Engineering group's new design—lighter, stronger, and more stable—does not cost more than the market will bear for those benefits. This offset strategy should keep the price of the new design within acceptable limits for the market.

Heil has developed new forming techniques for this new head with the Alcoa Technical Center and has already conducted preliminary testing of a "simulated" prototype head at its Athens, Tennessee, R&D facility. Initial testing was promising, and advanced prototypes are planned for continued testing.

## Framing

The final design and FEA of the new frame has been successfully completed. It eliminated some framing requirements (and weight) for both the new and vessel mounting structure compared with current framing designs. The Liburndas new frame design can be seen in Figure 4 below.

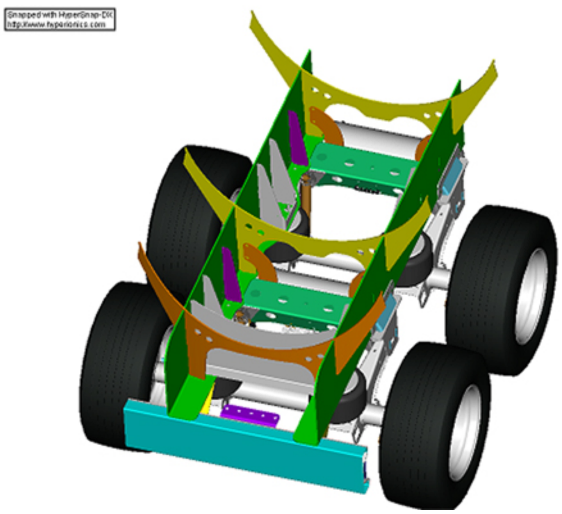

**Figure 4.** Liburndas Rungear frame.

The new Rungear frame is one of the most critical design areas for a petroleum trailer. The vessel experiences not only loads from the force of gravity acting on the payload but also loads due to articulation or twisting as it maneuvers over the road around corners. Consequently, a leak due to weld fatigue would most likely occur in this area. To simulate road conditions, FEA on the frame was completed for four load cases: (1) 2-G downward, vertical inertial; (2) 2-G forward, horizontal inertial; (3) 1-G lateral, horizontal inertial (10-ton axle load traveling around curves); and (4) 1-G lateral horizontal inertial load (turning on the spot).

The initial analysis indicated that the mild steel crossmember structure gave cause for concern with unacceptable stress levels under the load cases specified. However, the initial FEA model did not take into account the link of the top crossmember to the frame or the correct welding techniques. After further review and FEA remodeling, the new frame design actually experienced acceptable stress levels. To confirm our results, the new frame design was also tested by Hendrickson, the air ride suspension manufacturer. Hendrickson conducted similar FEA modeling and confirmed our final test results.

### Vessel Weight Reduction

To date, the total weight reduction goals are as follows: from the shell, 15%; from the heads, 20%; by eliminating the overturn/flashing rails, 20%. The remaining 45% will come from the framing and accessories design.

## Friction Stir Welding

During the project, Heil is also working closely with Oak Ridge National Laboratory to determine the feasibility of applying friction stir welding (FSW) to the manufacturing process for the Liburndas vessel. The most likely area will be the large, flat aluminum sheets that make up the barrel proper (currently done on a plasma table). FSW samples have been collected, along with both gas tungsten arc and gas metal arc samples, and bend and tensile testing will begin this phase.

## Conclusions

Progress has been made on the vessel and new Rungear design and FEA during this phase of the project. Design and FEA of the fifth-wheel plate are now on schedule and should be completed by the end of the year. All Phase 1 deliverables should be completed by the end of the year, according to the new project schedule.

Continued study and testing will take place on the flangless head design. Once a die is acquired and actual test heads are constructed, mock-up prototype testing will be completed. It is anticipated that the flangeless head design will be very successful, which will accelerate the project into Phase 3—field testing of a prototype.

The marketing research completed to date reflects initial acceptance of the new design, with the exception of the existing accessory locations. Redesign of the accessories will take place quickly over the next year. Market acceptance of the cylindrical design, flangeless heads, and internal rings will make the Liburndas trailer a viable alternative to and inevitable replacement for the elliptical trailer. Once it is in the market, the popularity of the trailer is expected to increase exponentially because of its improved fuel delivery capabilities and roll stability.

## B. Application of Superplastically Formed (SPF) Aluminum for Truck Body Panels

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*Contractor: International Truck and Engine Company*
*Contract No.: 400002669*

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### Objective

- Investigate applications of superplastic aluminum for low to moderate volume (up to 30000/year) body panels to provide a light weight and low tooling cost alternative to steel and Sheet Molding Compound (SMC).

### Approach

- Select a large exterior truck body panel having a complex shape and moderate production volumes.
- Develop part design, conduct forming simulation and Finite Element Analysis.
- Build prototype parts to demonstrate process capability and develop realistic part cost data.
- Evaluate the performance of the parts in the real vehicle environment.

### Accomplishments

The program was initiated in March 2005. To date following tasks have been completed.

- Appropriate exterior truck body part has been selected.
- Part design has been completed. The part support structure design concepts developed.
- Forming simulations have been completed to verify the manufacturability.
- Finite Element Analysis of part design and support structure is completed.
- Second iteration Finite Element Analysis of part support structure is underway to optimize the design.
- Superplastic Forming tooling is nearly complete.

### Future Direction

- Complete second iteration Finite Element Analysis of the support structure.
- Complete SPF and support structure tooling and produce prototype parts.
- Evaluate surface quality and material thickness variations of the formed parts.
- Develop realistic production tooling and part costs for comparison with alternate materials.
- Perform structural evaluation of the prototype parts under real vehicle environment.

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## Introduction

Traditionally, commercial truck (Class 5-8) cabs have been made from two materials – steel and aluminum. To stay profitable, the truck industry has been going through product rationalization. To reduce the tooling cost associated with two different cabs, there appears to be a trend to standardize to a single higher volume steel cab. This trend will make the class 7-8 vehicle cabs heavier and reduce the fuel efficiency.

This trend towards conversion from aluminum to steel in the heavy duty trucks can be reversed if formability of aluminum to produce future aerodynamic shapes is improved and tooling cost to produce aluminum cab panels can be significantly reduced. Deployment of superplastic forming (SPF) technology offers an opportunity to do so.

Superplastic forming of certain aluminum alloys offers the ability to produce complex aerodynamic shapes for truck body applications using lower cost tooling. This technology allows production of light weight highly integrated, net-shape components that often consolidate many parts into one. This reduces the number of parts, fasteners, and assembly operations required for complex truck body parts and enables the use of aluminum in place of steel at competitive costs.

A typical superplastic forming process is illustrated in Figure 1. The process uses a single-sided die rather than a matched two sided die. The sheet blank is clamped in the die and blow formed. Complex shaped parts can be formed that are not otherwise possible.

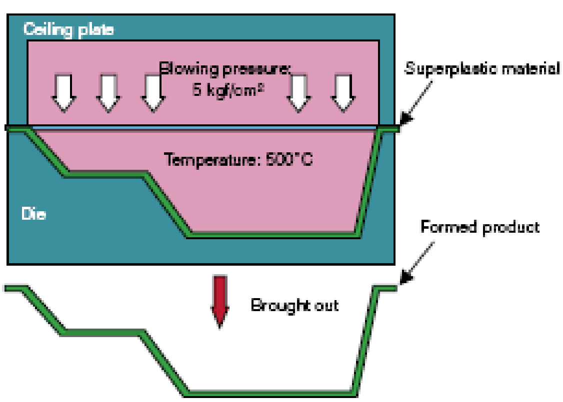


**Figure 1.** Illustration of typical superplastic forming process.

International Truck and Engine Company had studied the feasibility of using the SPF process for large truck panels in 1985. At that time the SPF aluminum process cycle times and superplastic aluminum material costs were high; also, "Class A" surface finish required for exterior body panels could not be achieved. Although the tooling costs were low, the part costs were very high. It was determined that SPF was economically viable only for very low Volumes (< 1000 pcs).

In recent years, significant new developments in the SPF materials and processes have been reported. It is reported that these developments have made higher production volumes, matching those of class 7-8 truck volumes, feasible through a combination of increased forming rates and lower material cost. It is also reported that for moderate levels of forming, the "Class A" surface condition required for exterior body panels is achievable.

These recent developments make SPF technology increasingly attractive for heavy vehicle applications. However, there is a strong need to validate the claims made about the forming cycle times, part costs, tooling costs, "class A" surface capability and fatigue properties as it applies to large cab panels and structural parts. The only way to convince the Heavy Truck Industry to deploy this relatively new technology is to demonstrate its feasibility for a large exterior body part.

## Project Goal

The project goal is to initially demonstrate the feasibility of SPF technology for a large exterior body panel as phase 1 of the project. If results look promising, in the second phase, application of SPF will be expanded to make more complex body sub-assemblies and/or the entire truck cab depending on the funding level provided.

## Project Plan

The phase 1 of the project involves design, analysis, prototyping and testing of the large exterior truck body part. The following task descriptions were proposed to address the key issues related to the application of SPF in heavy duty vehicle applications.

Part Design and Analysis: This task has helped to understand design and tooling considerations and limitations. It helped develop guidelines for future designs with SPF aluminum.

Build prototype parts: The production of prototype parts will help evaluate tooling issues, forming process cycle times, part wall thickness variations and capability of SPF aluminum to provide "class A" surface.

Perform Durability Tests: This will help evaluate assembly, stiffness and durability of SPF aluminum in the class 8 truck applications.

## Conclusions

The application of SPF for truck body panels is well underway. Significant SPF prototype parts will be produced before the end of the 2005 calendar year. Durability tests have been planned for these parts.

## Presentations/Publications/Patents

Nirmal Tolani, Heavy Vehicle Materials Program Review, Oak Ridge Tennessee, September 14, 2005.

# C. Advanced Composite Support Structures

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*Contractor: Oak Ridge National Laboratory*
*NCC/ORNL Contract No.: 4000039214*

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## Objective

- Lead the rapid implementation of lightweight composite materials in Class 7/Class 8 vehicles via the development of advanced composite support structures, specifically chassis lateral braces, which can number up to six per vehicle. Mass reductions are targeted for 50%.

## Approach

- Model composite support structures using finite element analysis (FEA).
  - Include part, subsystem, and system analyses and optimizations
- Determine guidance cost on production design.
- Fabricate sample plaques to determine affect of fatigue at different sequences of loads.
- Model failure mechanisms with progressive failure analysis (PFA).

## Accomplishments

### Modeling

- Obtained detailed loadcases from customer on system model.
- Analyzed current design system model and determined loadcases for subsystem model.
- Analyzed subsystem model and began composite model optimization.
- Further crack propagation VCCT (Virtual Crack Closure Technique) model.

## Future Direction

- Determine design and ROM (Rough Order of Magnitude) production costs for design scenarios.
- Insert final design into system model to ensure no change in load path.
- Deliver prototypes to customer MAY06 for track and field testing.
- Initiate second application of Value Analysis Value Engineering (VAVE).

## Introduction

The purpose of this effort is to lead the rapid implementation of lightweight composite materials in Class 7/Class 8 vehicles via the development of advanced composite support structures. This task specifically addresses lateral braces; primary beams are being targeted for future work. The mass reduction target is 50% with a minimum requirement of 30%. The benefits of mass reduction in commercial vehicle applications are well known. They include increased fuel economy and a larger payload, which translate into fewer total trips and thus fewer vehicles on the road. This leads to less traffic, which aids highway safety, and decreased emissions. Support structures offer an opportunity for significant weight savings. However, this area of the vehicle also represents a large hurdle in terms of composite applications and market acceptance.

The application of focus is a Class 8 tractor lateral brace. The estimated total annual usage of Class 8 lateral braces could exceed 1 million by 2007. Many are simple stamped parts which do not qualify for composite replacement on a per component basis. However, some are heavy duty and can benefit greatly from a composite redesign as is the present case. The application currently being studied has a production volume of about 50,000 per year. The total weight of the current design is 24 kg. A minimum weight savings of 30% is 7.2 kg per part. There are normally 2 of theses braces per vehicle totaling a minimum weight savings of 14.4 kg (31.7 lbs) per vehicle.

To facilitate this work and future endeavors advanced FEA and PFA software is being employed and developed. The FEA software contains a unique optimization algorithm that allows for the rapid optimization of such design variables as part thickness, fiber angle, fiber type, and even part shape while minimizing mass, strain, or even cost. PFA, although in development for composites, will provide the ability to model composite behavior in durability and fatigue situations.

## Modeling

In order to model the part effectively, the loadcases were reexamined with the customer. It was determined that there are 2 main loadcases that need to be applied in the design: racking and twisting. Racking occurs when one primary beam shifts ahead of the other one. This occurs during cornering, for example. Twisting occurs when one side of the chassis is lifted or lowered compared to the other side. Driving over debris or speed bumps or hitting potholes results in this loadcase.

The modeling is now being done on 2 hierarchical levels. The system and subsystem models are shown in Figures 1 and 2 respectively. The subsystem model was extracted from the system model as follows.

The system model of the current design was analyzed with the steel lateral brace for both loadcases. The customer provided the Rigid Bar Element (RBE) design to represent the bolts as shown in Figure 3. The customer also represented the chassis springs and tires with elastic elements at the bottom of each hanger, Figure 4. (Note that the hanger is a new addition to the model).

**Figure 1.** System FEA model.

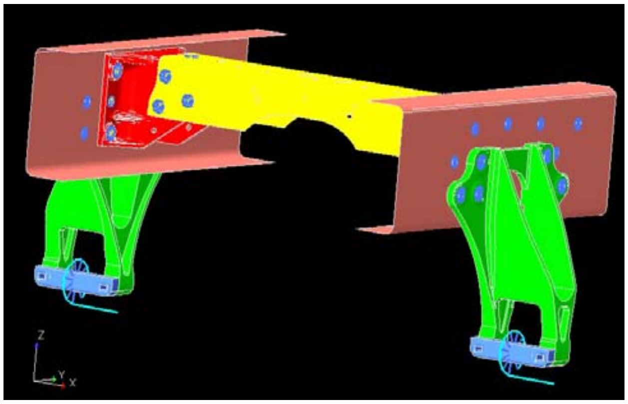


**Figure 2.** Subsystem FEA model.

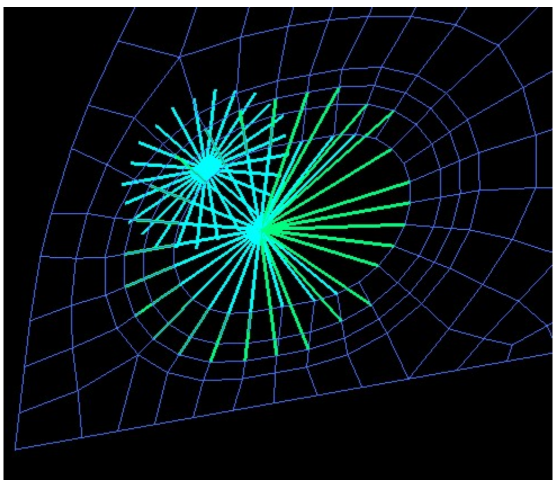


**Figure 3.** RBE assembly to represent bolts.

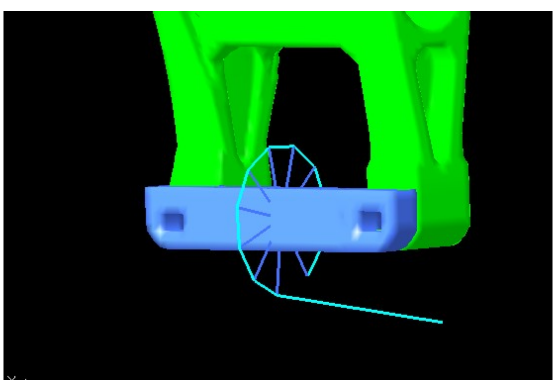


**Figure 4.** Representation of springs and tires via springs and bar elements.

To make the subsystem model, the primary beams were sliced on each side of the lateral brace. On the system model, the deflections at the edges of the primary beams and the deflections of the bottom of the hanger were determined from the analysis and used as the loads for the subsystem model. In other words, the loads for each loadcase are enforced displacements, and not applied loads.

The subsystem model was analyzed to determine the stresses throughout the parts. Figures 5 and 6 show the resulting von Mises stress contour for the steel center section for each loadcase. The stresses are maximum around the lower bolt holes. The racking loadcase tops out at 150 MPa (22 ksi) while the twisting loadcase is more severe at 250 MPa (36 ksi). Most of the part, however, only sees a stress of around 60 MPa (9 ksi).

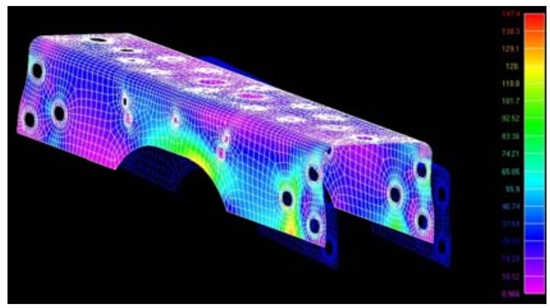


**Figure 5.** Racking stress contour for steel center brace

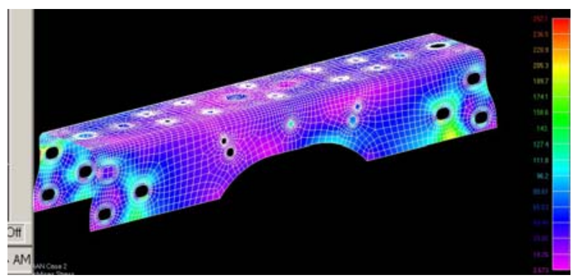


**Figure 6.** Twisting stress contour for steel center brace.

Similarly, the endbrackets, primary beam sections, and hangers were examined for maximum stress contours in Figures 7 – 12. In each case the twisting loadcase is more severe and the maximum stresses occur at the lower bolt holes. The results are finalized in Table 1. This information will be used for comparative purposes when optimizing the composite structures.

## Composite Design

A new postprocessor, Design Studio® from Vanderplaats Research and Development, Inc., has been developed which has the ability to examine the stresses and displacements at each layer in a PCOMP element. A PCOMP element is a shell

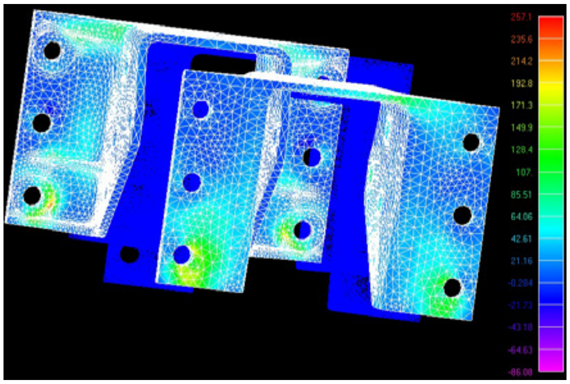


**Figure 7.** Racking stress contour for end brackets.

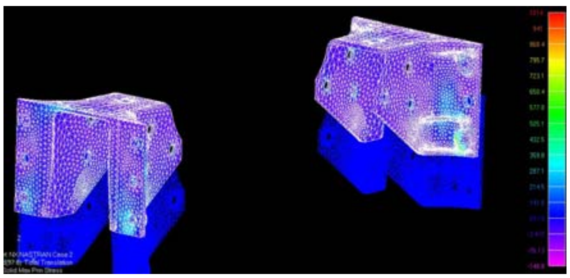


**Figure 8.** Twisting stress contour for end brackets.

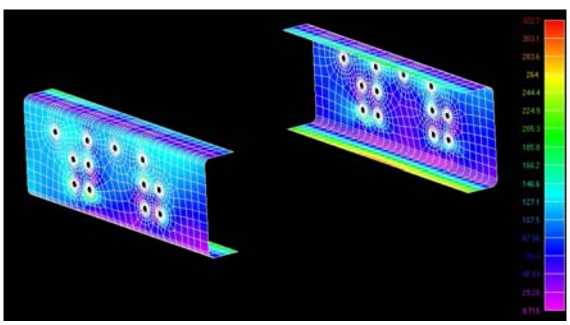


**Figure 9.** Racking stress contour for primary beam sections.

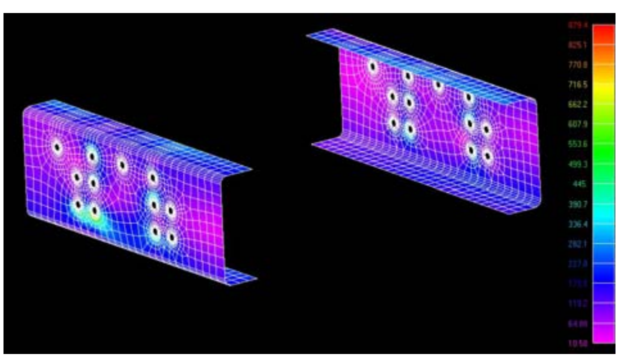


**Figure 10.** Twisting stress contour for primary beam sections.

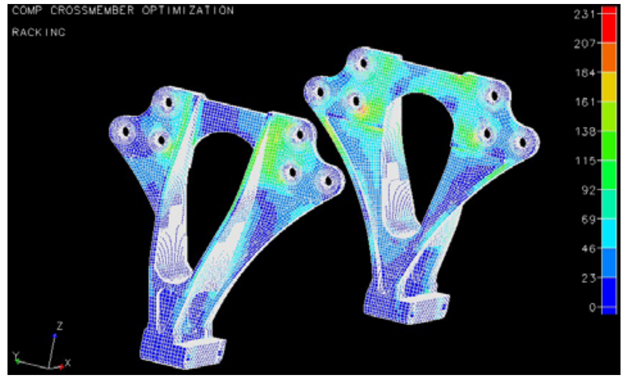



**Figure 11.** Racking stress contour for hangers.

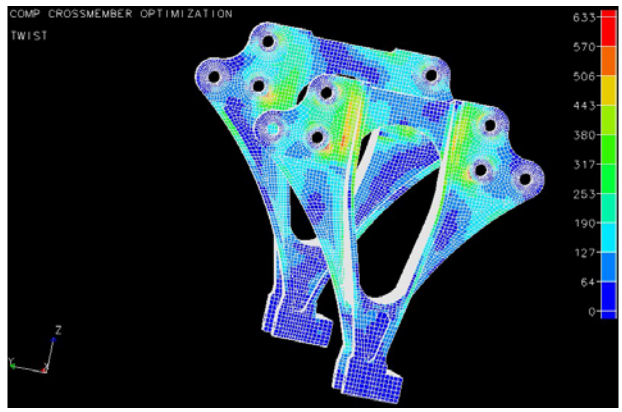



**Figure 12.** Twisting stress contour for hangers.

**Table 1.** Maximum stresses in MPa in current design.

| | Racking | Twisting | Farfield |
|---|---|---|---|
| center | 150 | 250 | 60 |
| end brackets | 260 | 1000 | 100 |
| primary beams | 325 | 875 | 200 |
| hangers | 230 | 630 | 50-150 |

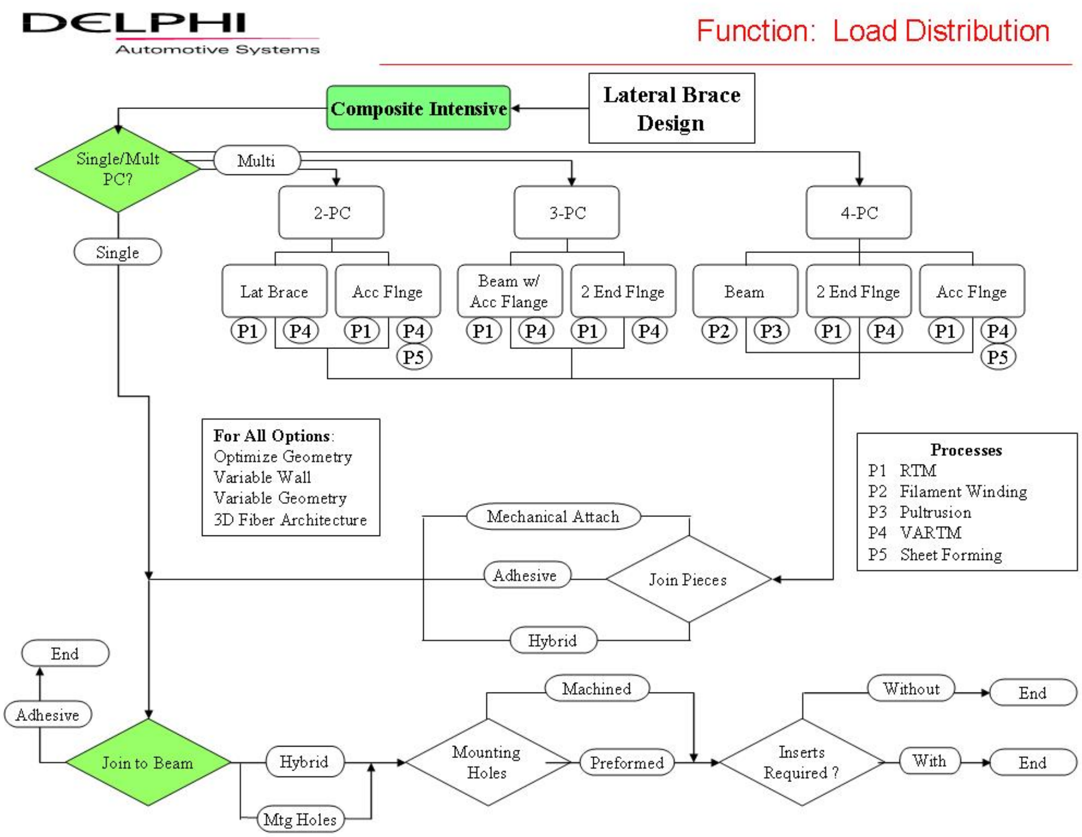
Likewise the resulting forces were compared due to the simulated twisting loadcase

element which consists of many layers. This is used to simulate the various composite plies which occur at different angles in this model. Design Studio® was used to model the composite lateral brace in the subsystem model.

## Scenarios

Recall that we were able to form a VAVE (Value Analysis Value Engineering) flowchart shown in chart 1 to determine the different scenarios for design and process development of this application.

**Chart 1.** VAVE flowchart for lateral brace.




The design was previously narrowed down to 3 scenarios:

1. Composite center piece only
2. Composite/Metal hybrid
3. One-piece composite with inserts

From the bolt modeling done by our partner (contract nos. DE-AC05-00OR22725 and DE-AC06-76RL01830) performed with ABAQUS, it was discovered that there is not enough material to pursue option number 3. Using inserts requires the removal of material resulting in very little composite left to handle the stresses.

Design scenario 1 has begun. First, the holes from the steel lateral brace had to be copied to the box beam composite mode as shown in Figure 13. Then, the entire composite was optimized as shown in Figure 14. There were 10 layers in the first optimization $[0/\pm12.5/\pm45]_s$. The design variables were the thickness of each layer and the angle of the 45 degree layers. The 12.5 degree layer angles were held constant because previous analysis showed that to be the optimum angle and it is the lowest processable angle from our suppliers. The results are in Table 2.

The resulting thickness is 26.9 mm. Additionally, this part weighs 15.2 kg which is *heavier* than the steel brace. The reason is seen by looking at the

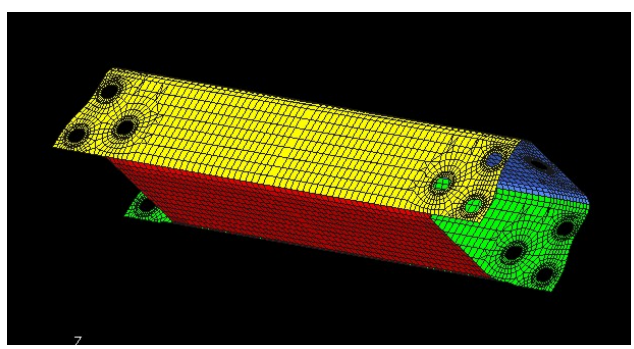


**Figure 13.** Incorporation of steel brace boltholes into composite box beam.

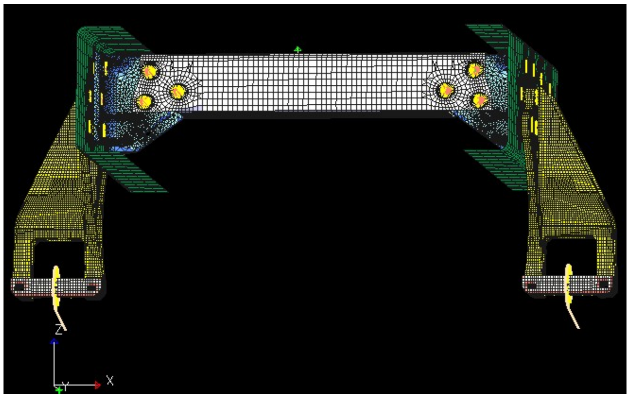


**Figure 14.** 1st optimization of composite center brace modeled composite as same lay-up everywhere.

**Table 2.** Results from 1st composite optimization.

| Design Cycle | 0 ply th, mm | 12.5 ply th, mm | 45 ply th, mm | 45 ply angle |
|---|---|---|---|---|
| 1 | 1.5 | 1.5 | 1.5 | 67.5 |
| 2 | 2.25 | 2.25 | 2.25 | 87.2 |
| 3 | 3.75 | 3.75 | 3.75 | 90.0 |
| 4 | 2.25 | 0.42 | 4.40 | 88.7 |
| 5 | 2.47 | 0.23 | 5.44 | 87.1 |
| 6 | 2.65 | 0.10 | 5.40 | 86.7 |

stress contour plot for layer 1 of the composite in Figure 15. The stresses around the holes reach above 230 MPa, but the rest of the part has near zero stress, which means it is much thicker than it has to be. This optimization was successful in designing the thickness around the joints, but not the rest of the part.

The second design scenario considered splitting the center piece into 2 sections: an end and a middle as shown in Figure 16. The end section utilizes the results from the first optimization since it is in the joining area. The lay-up here is [0/90/0] with thicknesses of 2.65, 21.6, and 2.65 mm. Optimization was performed on the middle section. There were 11 layers to start with $[0/\pm 22.5/\pm 67.5/90]_a$ with the design variables being the thickness of each layer and the angles of the 22.5 and 67.5 degree layers.

Table 3 displays the results. As expected, the thicknesses decreased greatly reducing the weight of this design to 6.6 kg.

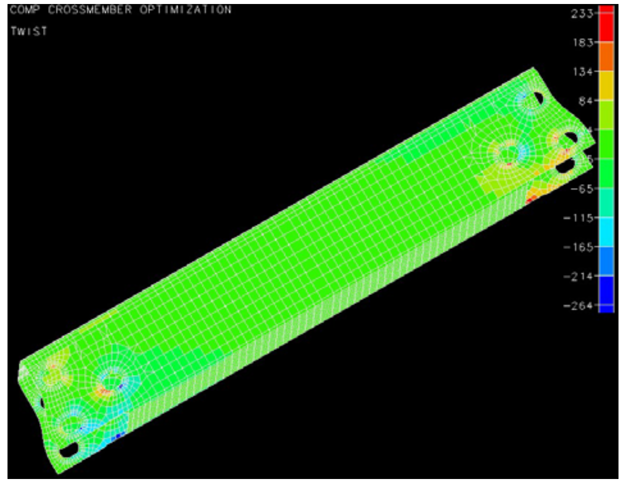



**Figure 15.** Stress contour of first design optimization.

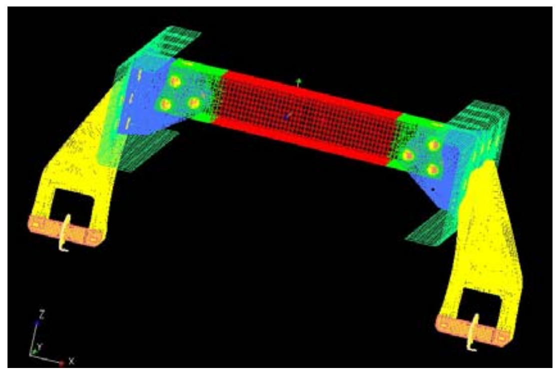


**Figure 16.** Separation of composite center brace into and end and middle for 2nd design optimization.

**Table 3.** Results from 2nd composite optimization (hard convergence on 6th cycle)

| Design Variable | Final Value |
|---|---|
| 0 ply th, mm | 0.18 |
| 22.5 ply th, mm | 0.13 |
| 67.5 ply th, mm | 0.80 |
| 90 ply th, mm | 0.57 |
| 22.5 ply angle | 11.8 |
| 67.5 ply angle | 90.0 |

Analysis of the resulting stress contours are shown in Figures 17 through 20. Figure 17 displays the composite section with both the middle and end parts. The contour here is for the first layer of the composite, which is the first 0 degree layer in both parts.

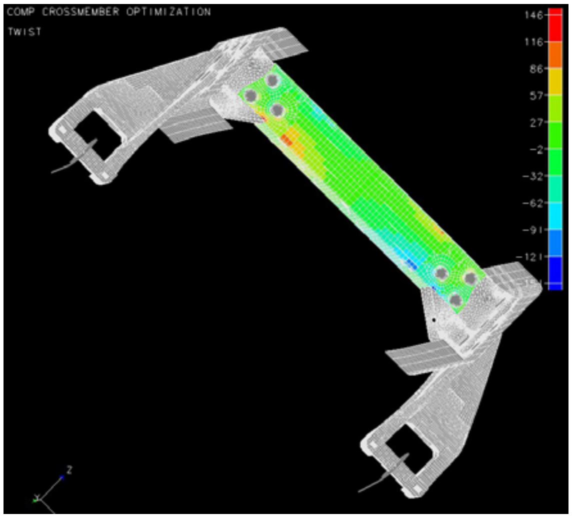



**Figure 17.** Twisting stress contour for 2 zoned composite center section after 2nd design optimization.

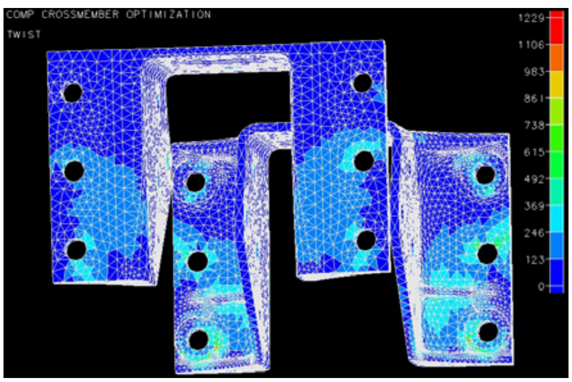



**Figure 18.** Twisting stress contour result for end brackets after 2nd composite optimization.

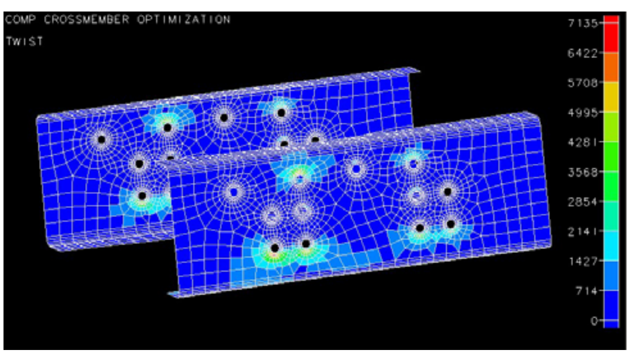



**Figure 19.** Twisting stress contour for primary beam sections after 2nd composite design optimization.

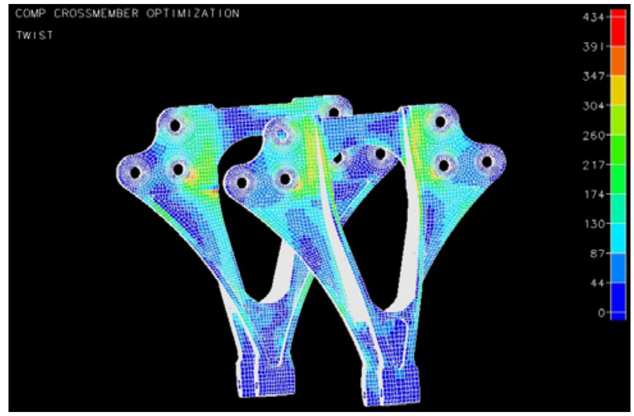



**Figure 20.** Twisting stress contour for hangers after 2nd composite design optimization.

Notice the stresses at the bolt holes are incredibly large especially in the primary beam sections. The truth is these are contact stresses, and for the value of these stresses to be known quantitatively a nonlinear and contact processor must be run. The processor for this optimization is linear and static and does not take into account contact stresses. Therefore, although we know these areas are stress risers, we don't know the actual values and the values shown are not real. However, the farfield stress contour is legitimate. Table 4 lists these stresses and compares them to the results in Table 1. They are actually pretty comparable since we expect the longitudinal failure stress for composites to be around 1000 + MPa to have a durable design. Our concern now really is to decrease the stresses in the end brackets and primary beam sections while reducing even more weight. It is possible this can be done by *decreasing* the stiffness of the composite center section.

**Table 4.** Maximum stresses in MPa in steel vs. 2nd design iteration for Twisting loadcase

| | Composite | Steel | % Diff |
|---|---|---|---|
| center | +150 | 250 | 149 |
| end brackets | 1230 | 1000 | 23 |
| primary beams | 7000 | 875 | 700 |
| hangers | 450 | 630 | 29 |

**Table 5.** Farfield stresses in MPa in steel vs. 2nd design iteration for Twisting loadcase

| | Composite | Steel | % Diff |
|---|---|---|---|
| center | -20 | 60 | 67 |
| end brackets | 300 | 100 | 200 |
| primary beams | ~300 | 200 | 50 |
| hangers | 130 | 150 | 13 |

After the composite is optimized, the nonlinear contact processor will be used to design the joints, which will enable us to minimize the mass in these areas while ensuring durability.

## PFA

Progressive failure analysis has progressed to include a VCCT (Virtual Crack Closure Technique) as shown in Figure 21. This model will help to assist in the designs of the joints. It relies on a predefined crack path and fracture toughness data to work effectively. The advantages are that it can detect the failure mechanisms at both the macro and micro levels.

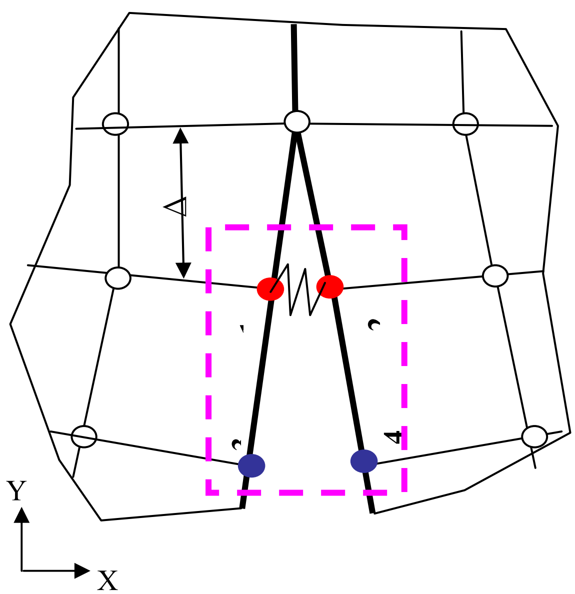



**Figure 21.** VCCT model.

## Conclusions

Accomplishments in second half of FY 2005 include the following:

- Successfully obtained working loadcases from the customer
- Extracted a subsystem model with the new loadcases from the system model
- Analyzed the current design in the system and subsystem model
- Transferred the loadcase environment to a composite subsystem model
- Initiated composite design and optimization.
- Narrowed design scenarios down to 2.
- Added VCCT modeling for PFA

## Future Direction

### Modeling

The composite optimization will be completed by the end of Nov. 05. We will then work with our joining team to model the joints. This should be completed by Jan. 06.

### Process Development

We are working with our customer to assemble a supplier list. We currently have 4 suppliers whom we are going to visit beginning Nov. 05. In Jan. 06 and Feb. 06 we will obtain ROM (Rough Order of Magnitude) guidance costs for our 2 design scenarios. In Mar. 06 we will select the design and supplier and obtain quotes for production. We will then initiate the cutting of the tools. We expect to have first prototypes by May 06.

# D. New-Generation Frame for Pickup/Sport Utility Vehicle Application

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*Contractor: Pacific Northwest National Laboratory*
*Contract No. DE-AC06-76RLO 1830*

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## Objective

- Evaluate the design of an optimized hybrid materials frame that represents a new generation of pickup/sport utility vehicle (PU/SUV) frame applications and vehicle architecture.

## Approach

- Apply high-risk manufacturing and design methods to the PU/SUV frame to reduce mass while meeting cost goals consistent with a high-production vehicle.

## Accomplishments

- Established performance, packaging, and weight targets for the second iteration of the new-generation frame “the next-generation frame” (NGF).
- Created a design for the NGF that projects a greater weight reduction and a decrease in the number of parts compared with the current steel baseline frame.
- Created a computer-aided engineering (CAE) model of the NGF and evaluated impact; noise, vibration, and harshness (NVH); and durability of the NGF.
- Completed CAE and design iterations to meet DCX 5-Star crash worthiness rating.
- Created complete bill of materials for the prototype and initiated procurement.
- The prototype frame has been constructed and delivered to DCX for torsion and stiffness testing after which the frame will be assembled into a full size vehicle and road tested at the DCX Proving Grounds.

## Future Direction

- The frame will be evaluated by DCX for torsion and stiffness testing after which the frame will be assembled into a full size vehicle and road tested at the DCX Proving Grounds.

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## Introduction

Increased consumer demand for PUs/SUVs has resulted in increased fleet fuel consumption. The fuel demand for this class of vehicle has exceeded that of passenger automobiles and now consumes approximately 27% of the United States oil.[1] The objective of this project is to explore manufacturing methods and materials to reduce the mass of the SUV/PU frame, thereby reducing fuel consumption for this class of vehicle.

During the second quarter of FY 2003, DaimlerChrysler completed vehicle testing at the DCX Proving Grounds using an SUV/PU platform equipped with a hybrid frame. Results of the accelerated testing have proved that (1) the hybrid frame design had sufficient strength and durability to meet the vehicle performance requirements, and (2) the frame was probably somewhat overbuilt and heavier than required even with a substantial weight savings from the current baseline steel frame.

The next phase of the project will evaluate the use of a lighter frame, called the Next Generation Frame (NGF). The NGF uses a CAE approach and higher-risk manufacturing technologies. The projected weight for the NGF is lighter than the previously tested new-generation frame and requires 35% fewer components.

## Approach

A CAE model of the NGF will be created and design iterations performed to meet the NVH, impact and durability requirements for a DCX 5-Star rating. A prototype of the frame will be fabricated and evaluated by frame flexure and road tests.

## Progress

CAE analyses of the frame are complete and satisfy all of DCX requirements for 5-Star crash worthiness, NVH and durability. The frame has been completed and delivered to DCX and Magna for full scale automotive testing. Figure 1 shows the frame being fabricated in the assembly fixture.

**Figure 1.** Next Generation frame components and assembly fixture prior to final assembly.

## Future Direction

The frame components have been assembled into the NGF and submitted to DCX for full frame testing. Tests will include full frame torsion and stiffness tests. After static stiffness tests, the frame will be attached to a full vehicle and road tested on the DCX Proving Grounds test track.

## References

*Light Duty Vehicle Trends: 1975 through 2004,* United States Environmental Protection Agency, *EPA 420-R-04-00, April 2005.*

# E. Advanced Superplastic Forming Development for Heavy Vehicle Structures

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*Contractor: Pacific Northwest National Laboratory*
*Contract No. DE-AC06-76RLO 1830*

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## Objective

- Evaluate the use of superplastic forming for heavy vehicles.

## Approach

- The project will focus on demonstrating the technology using mutually agreed on truck components, with the goal of developing the superplastic forming (SPF) design and material property knowledge base to the point where the individual companies have the ability to design and implement it for their new vehicle designs.

## Accomplishments

- Room temperature tensile properties of 5083 sheet superplastically formed to a biaxial strain of 0.45 were performed.
- Superplastic tensile tests were performed on the baseline 5083 aluminum alloy.
- A die was designed to evaluate the elimination of secondary operations.
- Performed initial tests on the 6013 alloy to determine if a heat treatable alloy may be used in a low cost superplastic forming process. Results indicate that a post SPF aging treatment will be required.

## Future Direction

- Additional trays will be formed and an S-N fatigue curve will be developed.
- Tests will be performed with the new die.
- A process for a low cost high strength SPF alloy will be developed.

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## Introduction

Replacement of low strength glass fiber-reinforced plastics with aluminum in heavy vehicle hoods and other cab components can significantly reduce the weight of Class 6-8 truck components. Although the use of aluminum has been viewed as a desirable weight savings approach for some time, the complex shape of aerodynamic hoods, bumpers and fairings, the limited room temperature formability of aluminum, and the high cost of forming tools have restricted its use. SPF, in the context of this proposal, is an elevated temperature gas pressure forming technology that has been widely used in aerospace applications, and more recently introduced by General Motors (in a modified form) for selected aluminum automotive components. Advantages of SPF include inexpensive tooling, the ability to form complex aerodynamic shapes, simplified die design compared to traditional stamping and the opportunity for significant part count consolidation. Although SPF is traditionally viewed as a slow forming process, recent advances in aluminum alloys and forming process procedures have reduced typical forming times to the point where SPF appears well-suited for typical heavy truck production volumes. However, a number of technical barriers remain; including the ability to form Class A surfaces, the availability of suitable SPF sheet materials for large components, and the performance of SPF components and structures in heavy-duty truck applications.

## Approach

The objectives of this project are to evaluate current production SPF capabilities and limitations through parallel Truck OEM demonstration components, develop cost and design allowable tools that allow the OEMs to select proper applications for SPF, and to advance SPF materials and processing capabilities for heavy vehicle applications. The project team involves collaboration between two major truck manufacturers, International Truck and PACCAR Technical Center (PTC) (parent company of Kenworth and Peterbilt). Because of the competitive nature of the truck manufacturers, the project will focus on demonstrating the technology using mutually agreed on truck components, but will have the goal of developing the SPF design and material property knowledge base to the point where the individual companies have the ability to design and implement it for their new vehicle designs.

## Progress

International and PTC have identified candidate components for prototype SPF components. International has initiated manufacturing of the components and PTC is completing a stress analysis of the selected component.

To facilitate design of the components, the Pacific Northwest National Laboratory(PNNL) superplastically formed samples of the 5083 aluminum alloy sheet to be used and measured tensile properties normal and parallel to the rolling direction after a biaxial strain of 0.45 at 850$^o$F and 1.3x$10^{-3}$ $s^{-1}$ strain rate. Room temperature tensile samples were removed from the long dimension of the formed tray, shown by Figure 1, and tested per ATSM E8. Additional samples were subjected to the

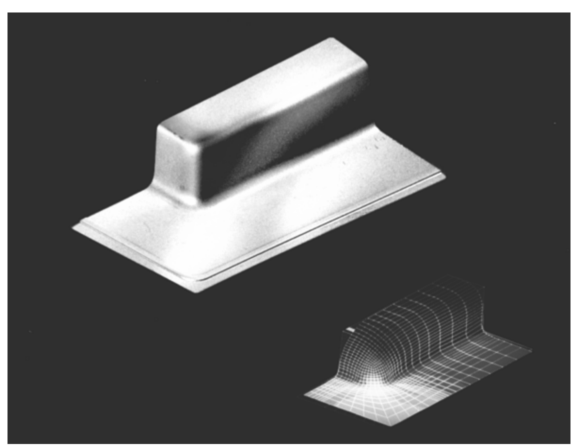

**Figure 1.** Sample SPF part used to characterize tensile properties from 0.047 inch 5083 aluminum sheet.

850°F thermal cycle only and compared to the tensile tests from formed trays.

The results of the tensile tests, when tested in the rolling direction, indicate that after forming to 0.45, at $1x10^{-3}$ $s^{-1}$, at 850°F the sheet properties were very similar to the as-annealed properties where yield strength, ultimate strength and elongation were 23,000 psi, 44,000 psi and 32% and 22,000 psi, 43,000 psi and 31% for the annealed and formed materials, respectively.

The results of the tensile tests, when tested transverse to the rolling direction, indicate that after forming to 0.45, at $1x10^{-3}$ $s^{-1}$, at 850°F the sheet properties were very similar to the as-annealed properties where yield strength, ultimate strength and elongation were 23,000 psi, 42,000 psi and 30% and 21,000 psi, 41,000 psi and 29% for the annealed and formed materials, respectively. The results of the tensile tests are summarized on Table 1.

**Table 1**. Summary of room temperature tensile tests performed on samples machined from superplastically formed trays made from 0.047 inch 5083 aluminum sheet; all trays were formed at an average strain rate of $1.3x10^{-3}$ $s^{-1}$ and 850°F with a total cycle time (heat up to cool down) of 12 minutes.

| | | Yield strength (0.2% offset) | Ultimate strength | Elongation |
|---|---|---|---|---|
| **Sheet Condition** | **Orientation** | **1000 psi** | **1000 psi** | **%** |
| As-Received sheet | Rolling Direction | 57 | 65 | 10 |
| | Transverse | 57 | 67 | 9 |
| Annealed 850°F for 12 minutes | Rolling Direction | 23 | 44 | 32 |
| | Transverse | 23 | 42 | 30 |
| Formed tray | Rolling Direction | 23 | 42 | 30 |
| | Transverse | 21 | 41 | 29 |

The 5083 alloy used for superplastic forming generally has a very fine grain structure developed by high levels of cold work that results in a low flow stress under the controlled temperature and strain rate conditions. The material supplied to PNNL was tested in tension at room temperature and was found to have a 57,000 psi yield and 66,000 psi ultimate strengths and an elongation of 10%. The high strength sheet material can be beneficial prior to SPF because of high scratch and dent resistance forming. However, it can result in higher material costs if the sheet cannot be coiled, particularly in thick gage.

The sheet material was tested for superplasticity at 850 and 950°F and exhibited tensile ductility and strain-rate sensitivity, m-value, expected from fine grain superplasticity in the 5083 alloy[1]. The samples were tested using constant strain rate as approximated by an exponentially increasing crosshead velocity[2] at $5x10^{-4}$, $1x10^{-3}$ and $5x10^{-3}$ $s^{-1}$. At a strain of 0.15, the crosshead velocity was increased by 20% and the stress increase was used to determine the strain-rate sensitivity, m-value, using the relationship:

$$m = \log(\sigma_2 / \sigma_1) / \log(\dot{\varepsilon}_2 / \dot{\varepsilon}_1)$$

A typical stress strain curve derived for an SPF tensile test has been included here for illustrative purposes as Figure 2. The superplastic tensile test results are summarized on Table 2.

**Figure 2**. Typical superplastic tensile test curve performed at constant strain rate with a 20% velocity bump at 0.15 strain to determine strain rate sensitivity, m. The results shown by Figure 2 were from tensile tests performed at 850°F from 0.047 inch 5083 aluminum sheet.

**Table 2**. Superplastic tensile properties measured for the 0.047 inch 5083 aluminum sheet.

| Temperature | Strain rate | | | Initial Flow stress | Elongation |
|---|---|---|---|---|---|
| **°F** | **$s^{-1}$** | **Orientation** | **m-value** | **psi** | **%** |
| 850 | $5x10^{-4}$ | Rolling | 0.54 | 1200 | 300 |
| | | Transverse | 0.50 | 1200 | 300 |
| | $1x10^{-3}$ | Rolling | 0.49 | 1800 | 240 |
| | | Transverse | 0.45 | 1800 | 240 |
| | $5x10^{-3}$ | Rolling | 0.34 | 3300 | 190 |
| | | Transverse | 0.33 | 3500 | 180 |
| 950 | $5x10^{-4}$ | Rolling | 0.55 | 500 | 260 |
| | | Transverse | 0.51 | 540 | 250 |
| | $1x10^{-3}$ | Rolling | 0.50 | 1000 | 250 |
| | | Transverse | 0.43 | 1000 | 230 |
| | $5x10^{-3}$ | Rolling | 0.35 | 2000 | 260 |
| | | Transverse | 0.37 | 2100 | 230 |

The m-values ranged from a low of 0.33 at $850^{o}$F at $5x10^{-3}\ s^{-1}$ to high of 0.55 at $950^{o}$F $5x10^{-4}\ s^{-1}$. The elongation was relatively insensitive to testing conditions and was 230 to 300% except for the $850^{o}$F $5x10^{-3}\ s^{-1}$ test condition where elongation values dropped to below 200%. Consistent with high strain rate sensitivity of superplastic materials the initial flow stress of the sheets was dependent upon test conditions and ranged from a low of 500 psi at $5x10^{-4}\ s^{-1}$ and $950^{o}$F to a high of 3500 psi at $5x10^{-3}\ s^{-1}$ $850^{o}$F.

Recent developments in the automation of superplastic forming have significantly reduced the cycle time to load, form and unload an SPF part. The newly reduced cycle time and transfer presses may enable the use of a higher strength alloy that has a heat treat response analogous to "paint baking" in steels. Therefore, a brief study was initiated to determine if a higher strength and less stress corrosion cracking susceptible alloy 6103 could be used. The study used hardness data to determine if a solution heat treated sheet subjected to a rapid heat up to 850 and $950^{o}$F could exhibit an aging response and if a sheet formed at 850 to $950^{o}$F removed rapidly from a die could have a post SPF age response without a water quench.

Initial results showed that the hardness of a sheet heated and held at $850^{o}$F and $950^{o}$F even for only 1 minute were less than 10 HRB indicative of a fully annealed sheet. Thereby, suggesting that it is unlikely that the rapid heat up and short cycle time associated with an automated SPF process could result in a "paint bake" for a solution heat treated 6013 sheet. However, 6013 sheets heated to 850 and $950^{o}$F, removed quickly from a furnace and air cooled, exhibited an age response when held at $350^{o}$F. The hardness achieved in the air cooled sample was less than that of a sample that was water quenched. However, it did indicate that a post SPF aging treatment could result in a higher hardness without a water quench. Figure 3 is given here to show the aging curves.

## Future Direction

The development of data for the use in SPF component design will continue. Fatigue data from

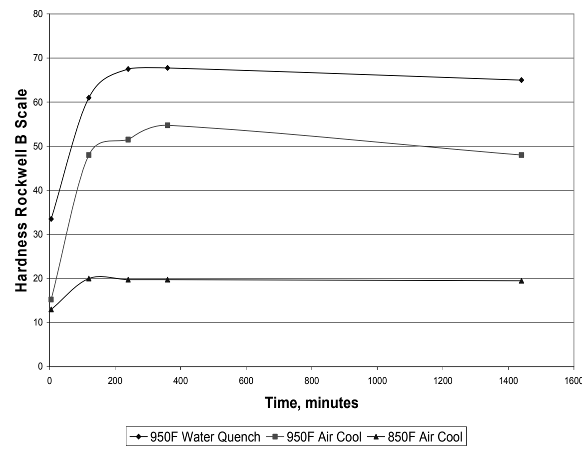


**Figure 3.** The age hardening response, measured in Rockwell B scale, of the aluminum alloy 6013 at $350^{o}$F after being subjected to air cooling and water quenching at temperatures typical of SPF.

A survey of the existing literature regarding 6XXX was performed. The data [3,4] indicate that by controlled thermomechanical processing, the 6013/6111 alloy could be made superplastic. The processes used required extended aging times that would be prohibitively costly for heavy vehicle sheet products. A variant will be developed at PNNL.

superplastically formed 5083 aluminum sheets will be determined.

The evaluation of a low-cost high strength alloy process for high rate SPF will continue with the development of a low-cost thermomechanical process.

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# F. Development of Magnesium for Heavy Vehicle Powertrain Components

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*Contractor: Pacific Northwest National Laboratory*
*Contract No.: DE-AC06-76RL01830*

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## Objective

Develop magnesium (Mg) composite casting technology and associated low-cost tooling for manufacturing of ultra-lightweight low-cost heavy-vehicle powertrain components. The project is focused on three development tasks, which include 1) development of compositing technologies to produce low cost MMC materials; 2) advanced shape casting manufacturing processes; and 3) innovative designs for new powertrain components.

## Approach

Development of advanced Mg alloys and processing technologies is a major technical hurdle to widespread application of Mg in the heavy vehicle manufacturing industry. As such, the approach taken for this project includes active participation by a truck OEM, as well as suppliers where appropriate. The philosophy of this teaming approach is to insure meaningful technology transfer of enabling and new technical developments. Below is a project outline and general approach. The underlying focus is on process development and economical manufacturing methods for Mg and its composites. The approach and cost analysis will consider product design, material-specific characteristics and component performance.

- Address technical challenges for use of Mg
  - Development of high strength low-cost Mg MMC – Pacific Northwest National Laboratory PNNL/Supplier
    - Current Mg alloys will have limited application for heavy vehicles
    - High strength Mg-MMC that can improve strength while minimizing cost
    - Increase durability: fatigue life more demanding than automobiles and operating temperatures/creep resistance needed
  - Develop economical manufacturing/casting/compositing method
    - Stir-cast Mg process development
    - Hybrid lost-foam/pressure infiltration casting to be demonstrated
- Application of Mg to heavy vehicles
  - How and where best to use Mg – PNNL/OEM
    - Design guidelines and property database needed
  - Manufactured part cost – OEM/Supplier/PNNL
    - Issues with integration of Mg into vehicle manufacturing process

### Accomplishments

- Down selection of Mg powertrain component for project application focus: transmission case w/ potential for 50% weight reduction over Al case.
- Experimental trials for stir-cast Mg-MMC production performed.

### Future Direction

- Develop compositing ability to in-situ cast and mix a Mg composite casting.
- Evaluation of a modified lost-foam casting process that combines casting and compositing into one process step.

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## Introduction

Ultra-lightweight high-performance Mg MMCs can improve fuel utilization, while increasing component durability for heavy-vehicles. As a rule of thumb, light-weighting can contribute to roughly 6-7% mpg increase for every 10% reduction in mass an estimated 3000 lbs of mass can be targeted for reduction in heavy vehicle suspension, driveline, and transmission applications. There is roughly 200-500 lbs. of potential weight savings by redesign and replacing cast iron components with Mg-MMC. Down-sizing of ancillary fixtures can result in additional mass and fuel savings. Increased component durability in applications where wear is a factor can also lead to improved vehicle operating costs, which is an incentive for fleet owners and independent truckers to embrace the new technology.

Although Mg alloys can be easily machined into various parts, Mg really stands out when die cast. Mg can be formed into complex shapes and as a single piece, often reducing cost by eliminating several steel stampings and the associated assembly cost. One great advantage of Mg is its ability to be cast with very thin walls, optimizing design and decreasing the component's weight. The microstructure also gives the alloys good sound and vibration dampening qualities. In fact, many higher performance engines use Mg alloys for valve covers and other under-the-hood covers, to keep engine bay noise to a minimum.

Like aluminum, die cast Mg is attractive because it can design to specific yield strength, fatigue, and to a fair extent creep criteria. Even though there is little creep in Mg alloys at room temperature, at elevated temperatures (as low as 150ºC) component design needs to accommodate for significant creep factors.

Creep-resistant alloys are being developed; however, they may contain expensive alloying elements such as strontium, calcium or rare earths for stable performance at elevated temperatures. These additions have a tendency to sacrifice castability for the increased creep performance.

The objective of this project is to enhance the properties of Mg alloys by creating a Mg-ceramic composite. This class of material is usually referred to as a metal matrix composite (MMC), in which fine ceramic particles or very short fibers are added to the metal matrix to form a composite structure. The resulting composite has very high specific strength and stiffness, and significantly improved wear resistance. Thin cast sections are still possible, and in the case of Mg, NVH and load carrying capacity are increased beyond the basic alloy. This is especially beneficial for vocational trucks, where load capacity and noise are two of the more common design problems facing engineers.

## Approach

This project was initiated in February of 2005, and is a collaborative effort with Mack Trucks. The project goal is to develop Mg composite casting technology and associated low-cost tooling for manufacturing of ultra-lightweight heavy-vehicle powertrain components. The project scope is broken down into three tasks: 1) Assess the potential to use Mg for vocational and long-haul trucks through technology development, evaluation of full-scale prototype components, and economic analysis; 2) Develop advance Mg materials and processing capabilities for heavy vehicle applications; and 3) Develop a low-cost shape-forming process that combines casting and in-situ compositing for metal matrix composite (MMC) components.

The specific technical approach and developments to pursue are outlined as follows:

- Address technical challenges for use of Mg
  - Development of high strength low-cost Mg MMC – PNNL/Supplier
    - High strength Mg-MMC that can improve strength while minimizing cost
    - Increase durability: fatigue life more demanding than automobiles and cost-effective alternates to elevated temperature creep resistance needed
  - Develop economical manufacturing, casting, compositing methods
    - Stir-cast Mg process development
    - Hybrid lost-foam/pressure infiltration casting to be demonstrated
- Application of Mg to heavy vehicles
  - How and where best to use Mg – PNNL/OEM
    - Design guidelines and property database needed
  - Manufactured part cost – EM/Supplier/PNNL
    - Issues with integration of Mg into vehicle manufacturing process

## Metal Compositing Method

Stir-casting techniques are currently the most common commercial method to produce aluminum MMC materials. This approach utilizes mechanical mixing of the reinforcement particulate into a molten metal bath. A simplified compositing apparatus is shown in Figure 1, and typically is comprised of a heated crucible containing molten aluminum metal, with a motor located above the crucible that drives a paddle, or mixing impeller that is submerged into the melt. The reinforcement is poured into the crucible above or below the melt surface and at a controlled rate, in order to insure a smooth and continuous feed. As the impeller rotates at moderate speeds, a vortex is generated in the aluminum melt that draws the reinforcement particles into the melt from the surface. The impeller is designed to create a high level of shear in the aluminum melt, which helps strip adsorbed gases

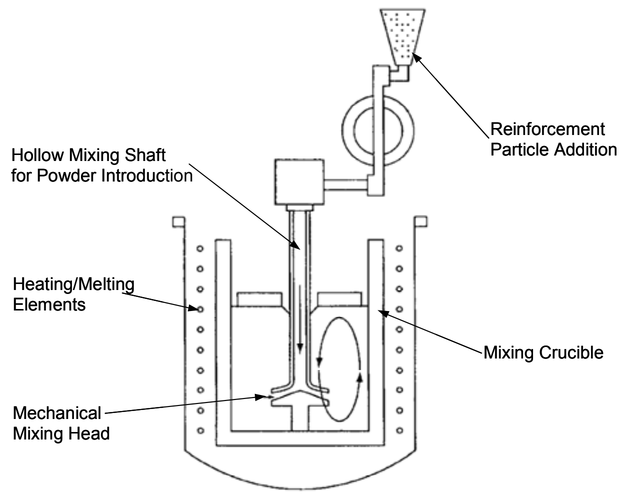


**Figure 1.** Schematic of MC-21 rapid mixing concept and compositing chamber setup.

from the surface of the particles and engulfs the particles in molten aluminum, which promotes proper aluminum-reinforcement wetting. In addition, proper mixing techniques and impeller design must be employed, in order to produce adequate melt circulation and homogeneous distribution of the reinforcement throughout the matrix material.

Experimental investigation of stir-cast Mg-MMC production method was initiated in FY2005. This process will be developed, along with a hybrid compositing/casting method for the production of Mg-MMC components. The hybrid system will consist of combining evaporative pattern (lost-foam) casting techniques and low-pressure infiltration to create the metal-ceramic composite during the shape forming (casting) operation. This second process, though a higher technical risk for success, would significantly reduce component manufacturing cost. It is also expected to allow for easy selective reinforcement of cast components, where the reinforcement particles are placed only where there will have the greatest benefit to part performance.

## Mg MMC Development

In order to develop proper Mg-MMC materials for powertrain components, it is necessary to investigate alloy-reinforcement combinations that will work best to achieve the mechanical performance and the environmental performance goals as well. To accomplish this task, a stir-cast metal composite mixer has been designed by MC-21 Inc., Carson

City, Nevada, that will be constructed and installed at PNNL in the first quarter of FY2006. With this capability, multiple combinations of alloy-reinforcement chemistry can be produced and evaluated.

The micromixer is to be designed based on MC-21's experience in aluminum MMC mixing units and proprietary mixing technology. This technology is unique in the fact that it is a highly efficient means of mixing together (compositing) ceramic and molten metal, resulting in a metal composite material.

The mixing unit will be constructed such that it can melt and mix Mg alloy, with the following capabilities:

- Utilize MC-21's rapid mixing technology and stir-head design for incorporation of ceramic particulate of various chemistries and sizes in the 5-50 micron range.
- A special mixing head will be employed for use with Mg composite mixing.
- Mixing container capable of tilt pouring all of the liquid in the crucible.
- Able to melt and stir 10 kg of Mg or aluminum metal in a single batch.
- Use of an electric resistance melter and temperature control capable of 1500°F maximum.
- Specially designed crucible for casting and mixing reactive metals such as Mg.
- Crucible and heating system will be designed for an inert-gas atmosphere or addition of a vacuum chamber for mixing in an atmosphere or down to 0.1 torr pressure.
- Perform mixing action in either liquid (fully molten) or semi-solid (partially molten) state.
- Stirring mechanism will be hydraulically driven, with variable speed control up to 2000 rpm.

## Future Work

For FY2006, the project scope will focus on completing the economic analysis of commercial Mg MMC micromixer design, install the new stir-casting unit being constructed, and initiate compositing trials of new Mg alloy and ceramic particulate combinations. These composites will then be evaluated for mechanical and physical properties, and down-selected to the combination(s) that will meet design and component performance needs.

In-situ casting/compositing experiments will be pursued to demonstrate the ability to in-situ cast and mix a Mg composite casting. The project team will also generate a performance and design allowable matrix for selected prototype truck components.

## Publications and Presentations

None to report.

## Summary

Mg Metal Matrix Composites (MMC) have outstanding specific strength and stiffness properties, as well as NVH dampening characteristics greater than Mg alloys alone. They also have enhanced wear and creep resistance over unreinforced alloys. One drawback to Mg and its MMC is that the supply base has all but disappeared in North America, requiring OEMs and specialty/prototype casters to assume production roles. The focus of this project is to develop manufacturing technologies that allow for the production of low-cost Mg MMC components. It is intended that the low cost process can be applied by either an OEM, or the technology easily transferred to a supplier. The development of Mg composite casting technology will include low-cost tooling approaches for manufacturing of ultra-lightweight heavy-vehicle powertrain components, as well as the development of low-cost shape-forming process that combines casting and in-situ compositing for MMC components.

# G. Lightweight Stainless Steel Bus Frame—Phase III

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*Contractor: Autokinetics Inc.*
*Contract No.: 4000010114*

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## Objectives

- Investigate and demonstrate the mass saving potential of ultra-high-strength stainless steel as applied to the structure and chassis of a full-size urban transit bus.
- Finalize design and analysis and build a full-scale prototype of the body structure and chassis.
- Investigate all of the fundamental feasibility issues related to the structure and chassis:
  1. Fabricate and test large lightweight stainless steel sandwich panels
  2. Fabricate roll-formed, high-strength stainless steel sections
  3. Test feasibility of lightweight stainless steel cantilever seats
  4. Design and fabricate lightweight stainless steel independent suspension
  5. Integrate the traction motors into the suspension design

## Approach

- Execute the basic body structure, including the floor/roof sandwich panels, pillar assemblies, longitudinal rails, and suspension subframes.
- Choose prototyping techniques that emulate the intended production process as closely as possible to aid in developing robust but cost-effective manufacturing techniques essential to meeting the objectives of the project.
- As computer-based design and analysis details of the bus develop, conduct hands-on physical experimentation in parallel to support the concepts and methods.

## Accomplishments

- Received delivery of gear reduction units.
- Finalized detail drawings and preparations to cast rear suspension components.
- Progress on braking system.
- Progress on glass.
- Refinement of side impact analysis.
- Provided support for independent cost analysis.
- Received delivery of cooling system for motors and inverters.

- Fabricated driver controls.

### Future Direction

- Complete the fabrication and installation of suspension, steering, and spring components.
- Assemble propulsion components.
- Assemble close-out panels.
- Complete fabrication and install glass.
- Prototype two seats.
- Testing of structure.

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## Introduction

Advanced technology transit bus concepts have made significant advancements in terms of light weight and fuel economy. However, these gains have come at the expense of higher manufacturing costs. In spite of attempts to use life-cycle costs to justify their purchase, initial cost remains a major obstacle to the introduction of fuel-efficient buses.

Autokinetics was approached by the Office of FreedomCAR and Vehicle Technologies (OFCVT) of the U.S. Department of Energy to attempt to solve this problem. Specifically, the OFCVT asked Autokinetics to develop concepts for a lightweight urban transit bus based on the use of high-strength stainless steel. In the passenger car field, Autokinetics had developed structural and manufacturing techniques for the cost-effective use of stainless steel in spaceframes and suspensions. The OFCVT wanted to determine whether this approach could be applied to transit buses as well.

The program was structured in three phases:

- Phase I – Initial Concept Development
- Phase II – Concept Verification and Initial Design
- Phase III – Final Design and Prototyping of Body and Chassis

Phase I and Phase II have been successfully completed. Phase III will result in a full-size body structure and suspension that will be tested statically and dynamically. The development of an optimized hybrid powertrain and other vehicle systems will be addressed in a separate project.

This project was unusual in that no formal mass or cost targets were given. The object was to save as much mass and cost as possible.

## Current State of Progress

As stated in the previous progress report, the overall body structure is nearing completion. Much of the focus during this reporting period has been shifted to the final design of suspension components, and initiating their fabrication. Considerable effort was also spent on specification and acquisition of propulsion hardware such as traction motors, controllers, and reduction gears.

## Rear Suspension Components

As reported previously, a change in the traction motor selection required adjustments in the rear suspension design to accommodate the different physical characteristics of the new motor. During this reporting period, much of this refinement work was completed and detailed designs for the rear suspension componentry were prepared.

Other open issues were resolved such as procuring physical hardware for the gear reduction unit and brake drums. At this point, we are now ready to begin releasing suspension components for fabrication.

## Braking System

An extensive search was conducted to identify any readily available brake systems that would be compatible with this unusual suspension/drive system combination (i.e., hub-mounted motors in an independent suspension). Both drum and disc type brakes were explored. It was found that the selection of designs for 19.5 inch wheels is quite limited. Unfortunately, no brake systems were found that could meet the capacity requirements and be packaged in the available space.

Some common issues found among drum brake systems were; shoe position too far inboard interferes with the hub-mounted motors, "S" cam and hydraulic actuators further complicate this interference, shallower drums are too large in diameter to allow adequate cooling air space between drum and wheel, and shoe design interferes with wheel bearings.

Even among disc brake systems, significant issues were found which include; caliper position interferes with the wheel-motor at the rear axle and the steering arms at the front axle, and the low profile wheels necessitate a disc mounting configuration which would complicate maintenance and add mass.

As a result, a hydraulic drum brake system, unique to this application, was designed. It is based on the dual shoe principal (common practice) but omits the self-energizing, leading shoe geometry. This approach results in reduced sensitivity to fade, water, and oil. The design is proportioned to fit the wheel-motor and independent suspension arrangement. With this design, all major components are common among all four corners with the exception of wheel cylinders. The front cylinders are larger than the rear cylinders in order to achieve hydraulic proportioning of the brakes from front to rear. The wheel cylinders will consist of specially fabricated housings. However, commercially available pistons, seals and boots will be used. The brake shoe anchorage points and wheel cylinder mountings have been integrated into the knuckle casting design, eliminating the traditional large, heavy anchor plate. Webb Wheel Products (Cullman, Alabama) has supplied prototype brake drums by modifying an existing design. Autokinetics will fabricate the brake shoes and assemble the system.

It is expected this effort will yield a simple and effective brake system for this vehicle, and possibly find future applications in similarly configured suspensions.

## Body Glass

Laminated glass was chosen for all glazing positions because it provides a number of benefits over tempered glass. Since it is stronger than tempered glass, thinner and therefore lighter panes may be used. Laminated glass offers much better damping characteristics, resulting in improved NVH performance. This is especially important with the relatively large, nearly flat windows. Laminated glass also provides greater safety in the event of breakage or vehicular crash. Furthermore, it was found the laminating layer could contain special materials for solar rejection and thermal absorption as well as tint. The lighter weight and thermal properties will contribute directly to energy efficiency of the overall vehicle.

Fox Fire Glass (Pontiac, Michigan) was selected to fabricate the prototype glass for all side windows and the two-part windshield. All tooling for the prototype glass was completed during this reporting period.

For the side glass, which requires only a simple, cylindrical curvature, stainless steel draping forms were designed and fabricated by Autokinetics using techniques similar to the floor and roof sandwich panels. All side window pieces can be formed on these common tools and trimmed to the required length per individual piece requirements.

The windshield, however, requires compound curvature and must be made on more complex ceramic tooling. To simplify fabrication and installation, one, two, and three piece windshield configurations were studied. It was determined the two-piece configuration would provide a good combination of piece size and economical tooling. Final surface data for the windshield halves was generated and sent to Fox Fire to create the tooling. A number of laminated glass samples with various color and solar rejection material combinations were created to evaluate through-visibility and general appearance. The combination of light blue-gray tint with Solutia's Vanceva™ "honeycomb" solar rejection product, in the side and rear glass only, was chosen.

As of the end of this reporting period, all side glass has been fabricated. Glass for the windshield has also been formed and is in the final steps of processing. It is expected that all glass will be delivered and installed onto the body structure very soon.

## Side Impact Analysis

As reported previously, initial side impact analysis indicated the necessity to reinforce the lower portion of the side pillars (in the impact zone). A variety of concepts were generated and evaluated to solve this problem. The most promising approach appears to be reconfiguring the pillar section profile as a "hat" section roll formed with the flanges and the open portion of the "hat" oriented toward the outside of the vehicle. This open portion would be bridged, by attaching (spot-welding) a strip from flange to flange, along the length of the pillar, to create a closed box section.

This arrangement is much more accessible for spot-welding, allowing more welds and locating the welds such that stresses on the individual welds are within allowable limits.

This configuration also potentially offers additional benefits such as; a simple one-piece joint for attachment of the pillars to the sandwich panels, more streamlined assembly, the ability to tailor material thickness along the length of the pillar, and to provide a continuous attachment flange around the entire periphery of the window openings.

This enhancement is proposed as a design change for future versions of the body structure only, and will not be incorporated into the current prototype build.

A nonlinear finite element analysis of this design modification was performed by Srdjan Siminovic and Gustavo Aramayo of the Oak Ridge National Laboratory (ORNL). The results of this analysis indicate a high likelihood of meeting side impact requirements in the production version of the bus.

## Independent Cost Analysis

The Department of Energy commissioned IBIS Associates (Waltham, MA) to conduct an independent cost analysis of the stainless steel bus structure concept in comparison to current practices. (A separate description of the study can be found in Report 5.I in this same publication. A production forty-foot, low floor metropolitan transit bus was used as a basis for comparison. Separate *Technical Cost Models* were developed for a conventional bus body structure and the stainless steel concept with their respective processing techniques. Data collected from major North American transit bus and coach manufacturers were compiled for the conventional model, and Autokinetics provided data for the stainless steel concept.

Initial results were presented during this reporting period. The conclusions drawn indicate a compelling economic case for the stainless steel concept. The study found the weight saving design and associated processing techniques produced savings that more than compensated for the greater cost per pound of the stainless steel. IBIS also points out that further gains result as additional items are accounted for such as roof, flooring, and skins which are not considered part of a conventional structure but are integral to the stainless steel concept.

The actual manufacturing cost savings are projected to be on the order of 30%. This is a rather unusual result in that a new concept which improves performance and reduces weight can be manufactured at a lower cost.

## Cooling System

A cooling system is needed to remove waste heat generated by the traction motors and controllers, and keep the temperature of critical electronics within acceptable limits. The two traction motors and controllers are liquid cooled, so a conventional automotive type radiator could be used. Brushless DC motors were specified for the pump and fans to increase efficiency and reduce maintenance. A complete cooling system was designed, and components of appropriate capacity were acquired and assembled.

## Dissemination and Commercialization

10/18/04 – Emmons presented a project review at ORNL. Attended by Dr. Sidney Diamond, Dr. Joseph Carpenter (DOE), Dr. Phil Sklad, Srdan Simunovic, et.al. (ORNL), and Tony Mascarin (IBIS Assoc.).

11/02/04 – Meeting with Michigan State University (MSU). Attended by Al Bierut (MSU).

11/17/04 – Meeting with Electric Power Research Institute (EPRI). Attended by Kurt Yeager (EPRI) and entrepreneur John Friedl (TerraDyne).

11/23/04 – Meeting with NextEnergy. Attended by Rachel Kuntzsch (NextEnergy) and Vince Nystrom (Michigan Economic Development Corp - MEDC).

12/06/04 – Meeting with MSU. Attended by Gerry Skellenger (MSU).

12/17/04 – Emmons presented a project overview at MSU ARES lab. Attended by Dr. Harold Schock, Al Bierut, et al., (MSU) and Mr. James Croce (NextEnergy).

1/12/05 – Commercialization discussion with John Friedl (TerraDyne).

1/27/05 – Emmons attended Global Insight seminar “Future Heavy-Duty Powertrain Technologies”.

2/22/05 – Meeting with MSU-HEV team. Attended by Dr. Harold Schock, Al Bierut, Gerry Skellenger, Dr. Elias Strangas, Dr. Peng (MSU), Rachel Kuntzsch (NextEnergy), and Vince Nystrom (MEDC).

7/ 18-7/20/05 – Emmons attended a Transportation Familiarization Tour in Chattanooga, TN. Sponsored by ATTI and the Chattanooga Chamber of Commerce.

9/14/05 – Emmons presented a summary of the lightweight bus project at a special project peer review at ORNL.

## Conclusions

Autokinetics remains confident that high-strength stainless steel has the potential to achieve substantial mass reductions of bus structures. The bus body structure is now nearly complete; most of the identified technical risk issues have been resolved; and structural and chassis mass estimates remain nearly unchanged compared with early predictions. Ongoing fabrication of the physical prototype has provided concrete mass numbers and it is now expected the actual mass reduction of the complete battery electric vehicle will be close to 50%.

It is also hoped that practical commercialization can be achieved in the not too distant future. Low capital investment and ample knowledge base are key enablers for this. Much has been learned thus far about processing and assembling of the body structure and many useful techniques have been developed. Given the relative ease of constructing this prototype within our own facility, it is quite apparent that capital requirements for commercializing this technology will be relatively small.

The independent cost analysis commissioned by the Department of Energy supports this as well as the predicted mass and unit cost savings.

# H. Side Impact Analysis of a Lightweight Stainless Steel Bus Structure

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*Contractor: Oak Ridge National Laboratory*
*Contract No.: DE-AC05-00OR2272*

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## Objective

- The objective of the research was to model and evaluate the structural performance of a Lightweight Stainless Steel Bus Structure (LSSBS) to a side impact by a Sport Utility Vehicle (SUV). The evaluation of the initial design led to design modifications that were shown to significantly improve the side impact performance.

## Approach

- The impact analysis simulation is conducted using the Finite Element Method (FEM) computer program LS-DYNA. A detailed model of central five-column long section of the LSSBS has been developed to model the deformable area of collision. The front and end sections of the bus were modeled with less detail. Their role was to better simulate overall vehicle kinematics as compared to initial simulations reported in 2004. The FEM model of the SUV was developed at the Oak Ridge National Laboratory (ORNL) under a project sponsored by the Department of Transportation. The two models are combined into a side impact collision scenario. The simulations were performed on the ORNL Center for Computational Sciences supercomputers.

## Accomplishments

- A detailed side-impact model of the LSSBS and has been developed. The simulations lead to several design modifications that resulted in a safer design without compromising on vehicle weight, production cost and energy efficiency.

## Future Direction

- This report concludes the research on side impact structural safety of the LSSBS. The developed model can also be extended for other structural performance investigations that are outside the scope of current research, such as structural vibrations, dynamic response, and static loading problems.

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## Introduction

The ultra light stainless steel urban bus concept (LSSBS) was developed by Autokinetics, Inc. [1] with an objective to demonstrate feasibility of stainless steel [2] structural design for weight reduction in mass-transit vehicles. The resulting bus employs high strength stainless steels and monocoque design in order to simultaneously achieve the weight reduction and to maintain or surpass the performance of the conventional bus designs. Bus body structure is shown in Figure 1.

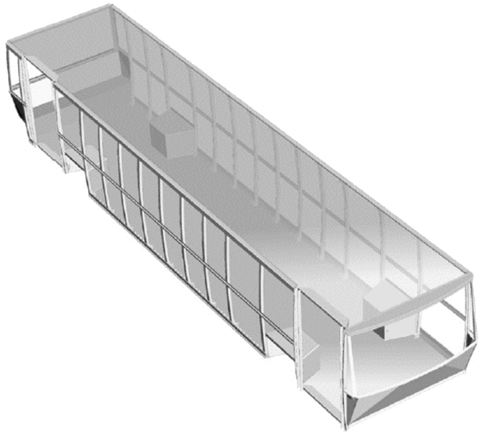

**Figure 1.** Ultralight Stainless Steel Bus Structure.

Bus performances with respect to torsional and flexural rigidities and axial impact have been investigated using computational models. The side impact response was the subject of this research. A collision model scenario that is considered to be a good measure of the side impact performance of the bus is a simulation of an impact of a mid-size SUV-class vehicle [3] into the half span of the bus. One of the distinctive performance advantages of the LSSBS is its low floor, but because such design makes the point of impact of the SUV above the bus floor, the impact load and energy management must be efficiently transferred to the floor and roof structures while maintaining a safe zone for the passengers. The other essential structural LSSBS component that comes directly into contact with the impacting vehicle is the lower reinforcement rail. This rail is supposed to distribute the impact force between the neighboring pillars. The bus floor and the roof are the final destinations of the SUV impact load. In order to achieve a controlled load transfer into the floor and roof it is necessary to maintain a reasonable stability of the pillars and the reinforcement rail. Joints connecting pillars into the floor/roof must distribute the load very quickly without creating local instabilities or joint failure. Figure 2 shows the initial design of the pillar and roof joint.

Impact simulations with the initial design showed that the open geometry of the pillar cross-section does not provide desired structural strength. The cross-section of the pillar has been changed to a closed top-hat section. The new pillar cross-section, together with the connection to the roof is shown in Figure 3.

Design changes in one component may affect the overall management of the impact load, so that this change lead to review and modifications of pillar connections with other components, primarily of the floor and roof brackets in order to optimize the structural response. Location, geometry and bonding of the joint brackets are important for local load transfer and therefore, it is necessary to model them in sufficient detail to determine the local stability of the connection. Detailed computational FEM models have been developed to adequately address the above issues, and to provide a framework for evaluation of the LSSBS in the side impact.

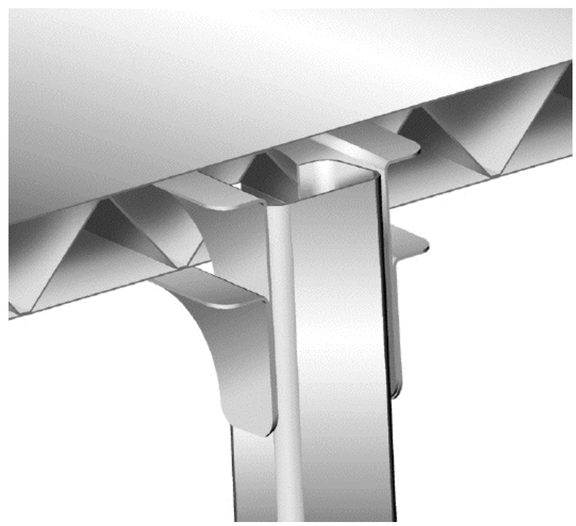

**Figure 2.** Pillar joint detail.

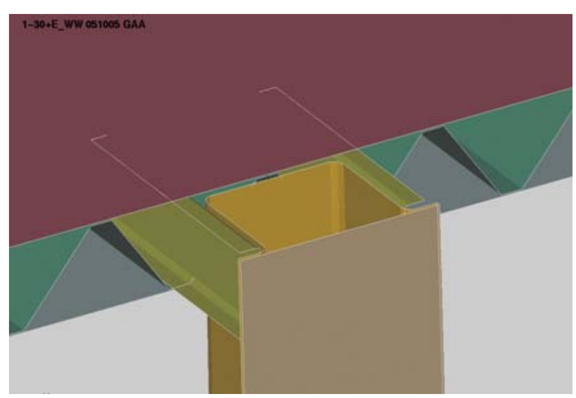

**Figure 3.** Modified pillar joint detail.

## Development of the FEM Model

The development of the FEM model of the bus structure involved several steps. The basic geometry data was used to generate surfaces for the FEM mesh generation. The data was provided for a single typical section ('segment') of the structure, Figure 4. Repeated reflections and translations are used for the generation of the model used in the analysis.

The integrity of the body structure is provided almost exclusively by spot welds. Therefore, in order to create a realistic model for side impact it was essential to include them in the model. A graphical representation of the spot weld locations is shown in Figure 5.

The FEM model was developed using the spot weld locations as key locations for the mesh generation so that the location of the spot welds exactly matches the location specified in the solid model geometry. The developed FEM model for the ten base segments is shown in Figure 6.

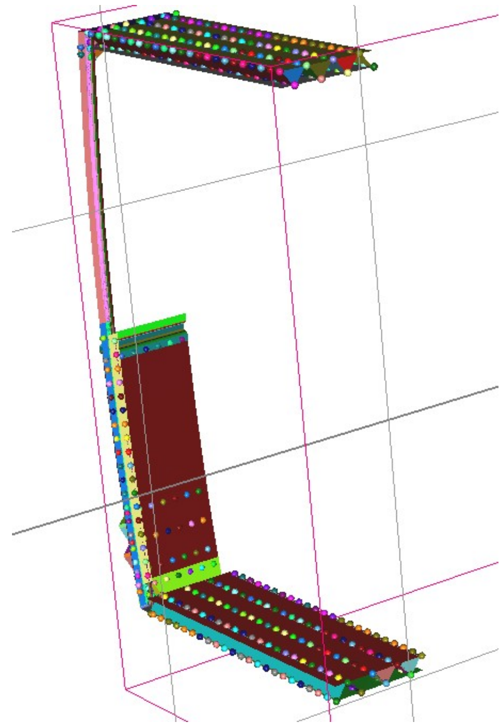

**Figure 5.** Spot Welds in Bus 'segment'.

## FEM Simulations of Side Impact

The FE model has been developed as a combination of two components: a plastically deformable central section that includes the detailed model of the structural components and non—deformable

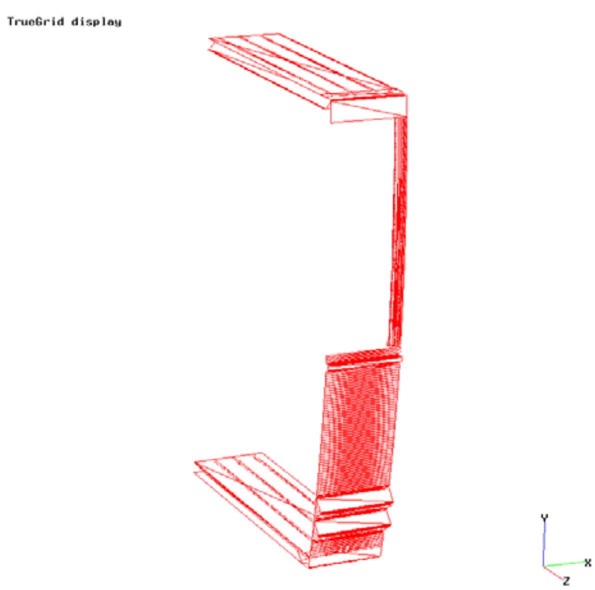


**Figure 4.** ViewPoint surfaces of bus 'segment' model.

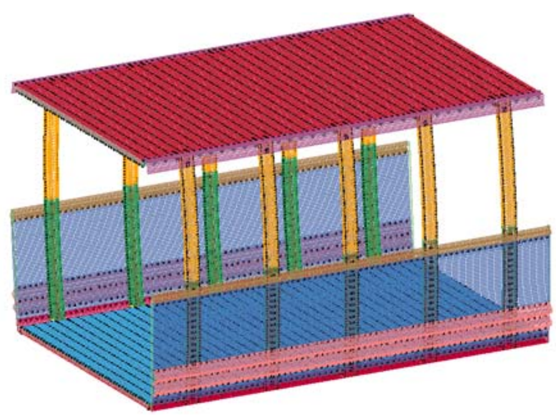

**Figure 6.** FEM Model of the central bus section.

idealization of the front and rear sections of the bus. The objective of the non-deformable components is to provide a good estimate for the overall kinematics and weight distribution. The non-deformable component and the final bus model are shown in Figures 7 and 8, respectively.

The final step in the development of a side impact simulation was the addition of the SUV model [3]. SUV's velocity is 25 mph. Figure 9 shows the assembled impact scenario.

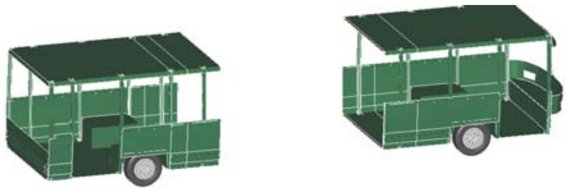

**Figure 7.** Non-deformable components of the FEM model.

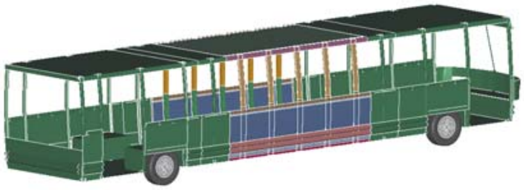

**Figure 8.** Final FEM model of the LSSBS bus.

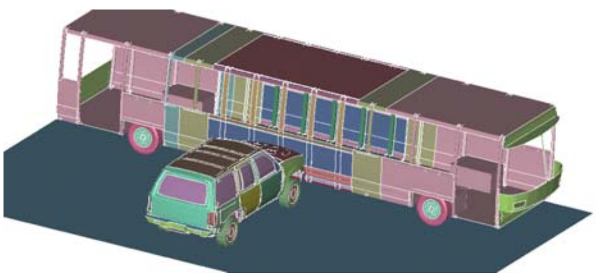

**Figure 9.** FE Model of Ford Explorer-BUS used in analysis

The combined Ford Explorer-BUS FE model has a total of 709723 nodes, 691258 shell elements, 3178 solid elements, 449 beam elements, 10396 spot-welds, 11 contact entities.

FEM analyses were performed for numerous bus designs under considerations. Figure 10 shows the cross section of the final model at the time of maximum intrusion in a plane that includes the pillar at the point of contact and normal to the axis of the bus. The intrusions were measured at a point in the pillars of side panels that is 528.32 mm (20.80 inches) above the top plate of the floor panels which corresponds to the seat locations.

Figure 11 shows the cross section of the model when deformation is completed and vehicles move as rigid bodies.

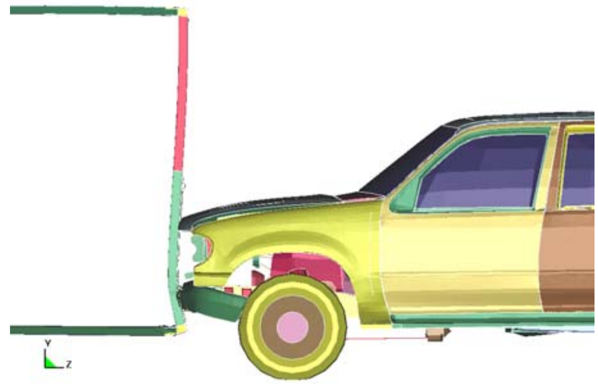

**Figure 10.** Cross-section of the bus at time of maximum intrusion.

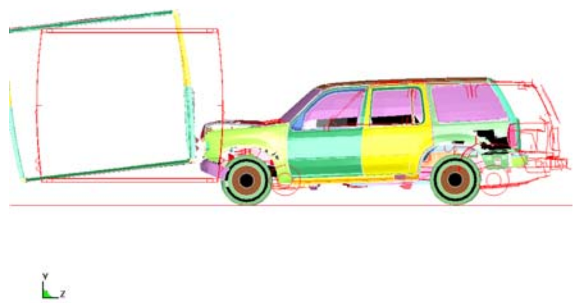

**Figure 11.** Cross-section of SUV-BUS at time 0.3 sec. The permanent intrusion at the pillar location at the 20.80 inch elevation is equal to 2.4 inches.

## Conclusions

The results of the analysis, for the impact scenarios considered, show that the permanent intrusion at the pillar section and at the mid span between the pillars is under the recommended 3 inches. The models used in the determination of intrusion have several changes that include change of thickness in the pillar hat section, pillar outer plate, top and bottom floor plates. The analysis also indicated a need for increased spot weld capacity between the pillar hat and pillar plate, and between the pillar hat and web of the supporting channel brackets. Additional possible modifications in the welding topology may further reduce the calculated intrusions.

The analyses show that the requirement for low intrusion values is based on the ability to maintain integrity at the web-channel/pillar-hat interfaces in the roof and floor of the frame cross-section. The capability of the spot welds at these interfaces is a function of the shear capacity of these spot welds at the bracket-pillar interface that balances the moment associated with the impact force and the distance from the point of application of this force and the resultant shear force on the spot welds. It is likely that by re-arrangement of the spot weld pattern the stiffness of the bracket-pillar interface can be further optimized.

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# I. Stainless Steel Bus Structure—Manufacturing Cost Analysis

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*Contract No.: 4000030946*

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## Objectives

- Provide the bus development program with manufacturing cost analysis and economic understanding to plan a technology and application development strategy.
- Assess the cost of conventional and proposed stainless steel bus structure fabrication.
- Explore the impact of key design and process assumptions.
- Characterize the potential commercial value of the concept.
- Extend previous baseline structure comparison to include floor, skins, and roof for conventional bus, and pillar reinforcements for stainless steel design.

## Approach

- Collect design and assembly data from manufacturers, materials and pricing from suppliers.
- Characterize SS pillar reinforcements and assembly requirements.
- Update baseline analyses and comparisons.

## Accomplishments

- Collected data on conventional floor, skin and side assembly from production facilities.
- Update cost model and scenario designs.
- Presented side-by-side cost comparison of stainless steel concept to incumbent practice.
- Analyzed sensitivities to annual production volume, throughput, assembly time, etc.

## Future Direction

- Assess the impact of powertrain and interior systems.
- Analyze life-cycle and usage costs in terms of fuel, operation, and maintenance costs.

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## Introduction

DOE, in conjunction with Autokinetics, is pursuing a design and process technology development program for alternative metropolitan bus structure manufacturing. Central to the effort is the stainless steel roll-formed design concepts developed by Autokinetics. Key to the success of this program is a demonstration of commercial viability: reduced piece cost, lower capital investment, or improved lifecycle economics relative to incumbent practices. Based on process and design scenario information provided to IBIS from the DOE/ Autokinetics team, IBIS has evaluated the alternative design concepts for these structures and provided an analysis of manufacturing economics. This analysis seeks to quantify the commercial production economics of the design and production techniques developed by Autokinetics relative to incumbent practices for conventional bus manufacturing.

## Bus Structure Scenarios

The basis for comparison of the conventional bus structure to the stainless steel concept is a 40-foot, low-floor metropolitan transit bus.

Conventional bus structure manufacturing involves labor-intensive arc welding of tube stock. Sides, floors, roofs, and front and rear end units are made separately in subassembly cells on semi-dedicated fixtures (which can be modified for bus length). After final structure assembly, the frame is subjected to grit blasting and a zinc phosphate coating. The resulting structure is a 6215-lb. weldement.

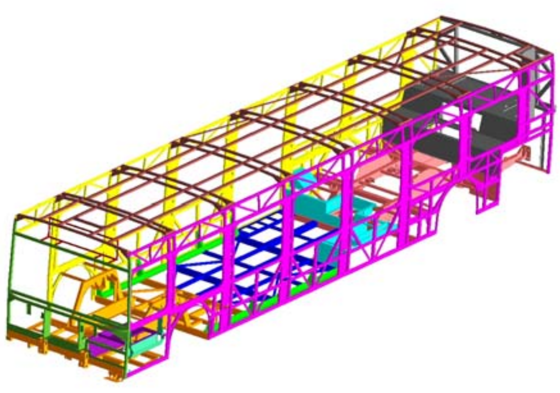

**Figure 1.** Conventional Bus Structure.

In summary, the stainless steel concept involves a floor and roof composed of three-layer panels made from welded outer skins and a corrugated, roll-formed core. Roll-formed pillars, rails, and sills complete the skeletal structure. Wheel wells and front and rear cap assemblies are welded from brake or press formings. The structure is assembled using spot welding.

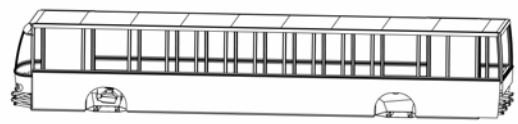

**Figure 2.** Roll-Formed SS Bus Structure.

The initial analysis as previously reported was strictly a structure-to-structure comparison. However, given that the stainless steel design incorporates functional floor, roof, and skins integral to the structure, the analysis was extended to include the secondary assembly of these elements in conventional scenario in order to present a more functionally equivalent comparison. Furthermore the side impact analysis suggested a need for additional reinforcement of the pillar structures for the SS design. These elements were added to the analysis and the resulting cost comparisons are presented.

## Model Development

The model structures developed during the previous reporting period were used for the current analysis, using newly collected process data and updated structure designs. The conventional bus assembly cost model required the addition of an operation module to address the floor, roof, and skin assembly. The stainless steel bus model only required the addition of the additional reinforcement components and labor time for the welds required.

## Data Collection

Data used in the technical cost models were collected through interviews and site visits with many sources, principally existing transit bus and motor coach manufacturers, as well as metropolitan transit authorities. Autokinetics provided design information for the stainless steel concept.
Conventional bus floors are 0.75-inch marine grad plywood. Assembly requires three laborers for ten hours to cut, place, and fasten the floor. Skins are

2.0-2.5mm Aluminum sheets that require a three-person crew fifteen hours to assemble. The roof is a two piece fiberglass (35% glass) molding. Modification to the SS design included the additional of 24 reinforcing plates requiring 110 spot welds each and improved pillar bracket designs.

## Analyses

For comparison and simulation manageability, operations for each scenario were grouped as shown in Figures 3 and 4. The resulting cost breakdown by operation and sensitivities to annual production volume are shown in Figures 5 through 8. Figures 9 and 10 show the comparison of the direct manufacturing cost between the conventional and stainless steel scenarios.

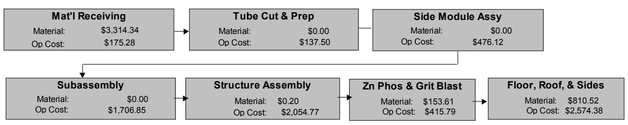


**Figure 3.** Conventional Process Flow.

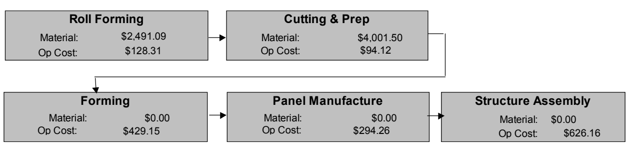


**Figure 4.** SS Structure Process Flow.

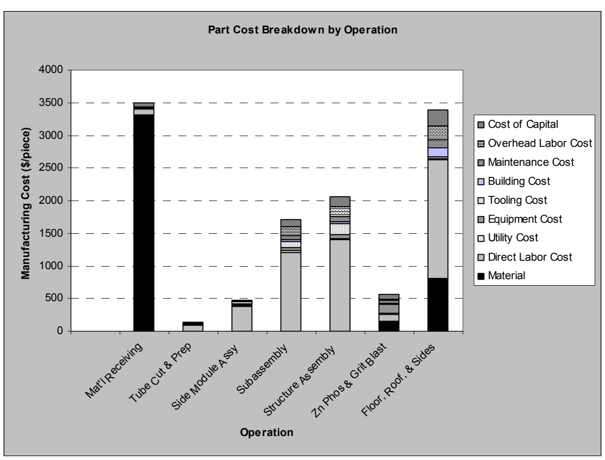


**Figure 5.** Conventional Manufacturing.

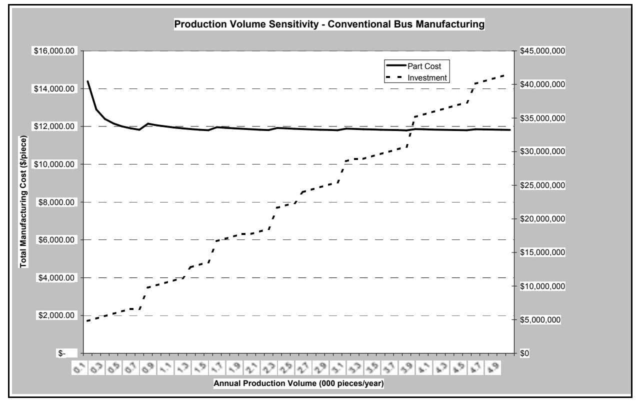


**Figure 6.** Production Volume Sensitivity.

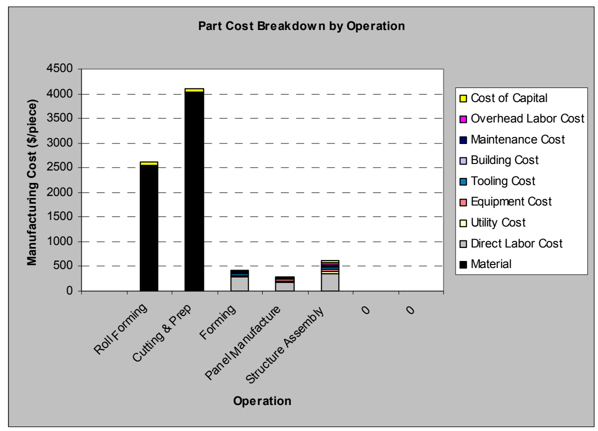


**Figure 7.** SS Structure Manufacturing.

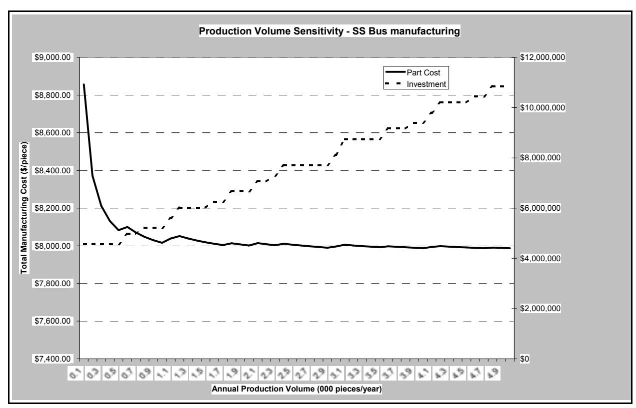


**Figure 8.** Production Volume Sensitivity.

| COST SUMMARY BY OPERATION | $/part Conventional | $/part Stainless | |
|---|---|---|---|
| Total Material | $3,468.15 | $6,492.59 | Total Material |
| Roof, Floor, & Side Material | $810.52 | | |
| Mat'l Receiving | $175.28 | $128.31 | Roll Forming |
| Tube Cut & Prep | $137.50 | $94.12 | Cutting & Prep |
| Side Module Assy | $476.12 | $429.15 | Forming |
| Subassembly | $1,706.85 | $294.26 | Panel Manufacture |
| Structure Assembly | $2,054.77 | $626.16 | Structure Assembly |
| Zn Phos & Grit Blast | $415.79 | | |
| Floor, Roof, & Sides | $2,574.38 | | |
| TOTAL MFG COST | $11,819.37 | $8,064.59 | |

**Figure 9.** Cost Comparison Table.

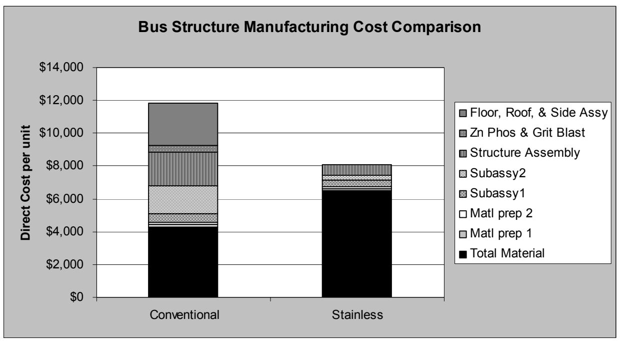


**Figure 10.** Cost Comparison Chart.

The production volume sensitivities in Figures 6 and 8 show how both per-unit manufacturing costs and facility investment totals change as a function of annual production volume. The baseline assumption for the analysis was 720 units per year based on typical model production volumes. The sensitivity analysis explored the range of 100 to 5000 units per year. In each chart, the left hand axis reflects unit manufacturing cost for the solid line, while the right hand axis displays fixed investment for equipment, tooling, and building space, relating to the dotted line.

## Conclusions

In addition to the weight savings gained from the stainless steel design [current numbers show approximately 1000 lb. (based on the 6215 lb. conventional steel tube structure vs. the 5300 lb. roll formed stainless steel structure), plus an additional 850 lbs. accounting for the mass of flooring, skins, and roof already integral to the structure], the manufacturing economics of the stainless steel design are compelling, even more so in this updated analysis than the earlier baseline. The combination of the novel design approach, using roll forming and high-rate spot welding (instead of arc welding), allows for a reduction in assembly labor and fixturing to offset the much greater material price of stainless steel relative to the steel tube stock.

In the updated phase of the analysis, the cost and mass of the stainless design was increased by the addition of the reinforcement elements to the structure pillars. However, this increase (217 lbs.) was more than offset when the comparison is made to the conventional bus including floor, roof, and skins (850 lbs.).

As the program moves into the next phase of demonstrating a working powertrain, the extended benefits of the lightweight structure on reduced power requirements and secondary mass savings can be explored. The economic analysis can also be employed to demonstrate to potential manufacturers the specific capital requirements needed for commercializing the proposed concept.