FreedomCAR

DaimlerChrysler Ford General Motors

DEPARTMENT OF ENERGY

USCAR
UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH

FreedomCAR Technical Teams:

2002
Key Accomplishments

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Preamble

This report contains brief summaries of key accomplishments of the FreedomCAR program for 2002. The FreedomCAR Partnership is between the U.S. Department of Energy and the U.S. Council for Automotive Research (USCAR) member companies DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation, which maintain critical research and development resources in the United States to advance energy efficiency in the future U.S. vehicle fleet.

The current document highlights specific accomplishments that the FreedomCAR Partners recognize as significant milestones or breakthroughs achieved in 2002. In each case, they represent the culmination of many months or years of research.

2002 Significant Technical Achievements

- Lithium-ion battery lifetime
- Affordable HEV/fuel cell power inverter
- Injector design for reduced soot formation
- Engine turbulence simulation
- Imaging of water flow in fuel cell stacks

2002 Significant Progress

- Diesel aftertreatment
- Microchannel fuel processor
- Simulation of fuel processors
- Low Platinum electrodes for fuel cells
- Advanced membranes for fuel cells
- Carbon composite bipolar plates for fuel cells
- Structural composites focal project

2002 Critical Test Protocols & Nat'l Lab Facilities

- HEV battery accelerated life test
- Hydrogen Storage Test Laboratory
- Hardware-In-the-Loop Vehicle Emulation Test Facility

This report is also available on the USCAR Web site at www.uscar.org/freedomcar.

After-Treatment Subsystem Development Program
(CUMMINS/Argonne National Laboratory)

Diesel engines offer the potential for increased fuel economy if upcoming Tier 2 emission regulations can be met without offsetting fuel economy penalty. Emission control systems for NOx and particulates are the challenge.

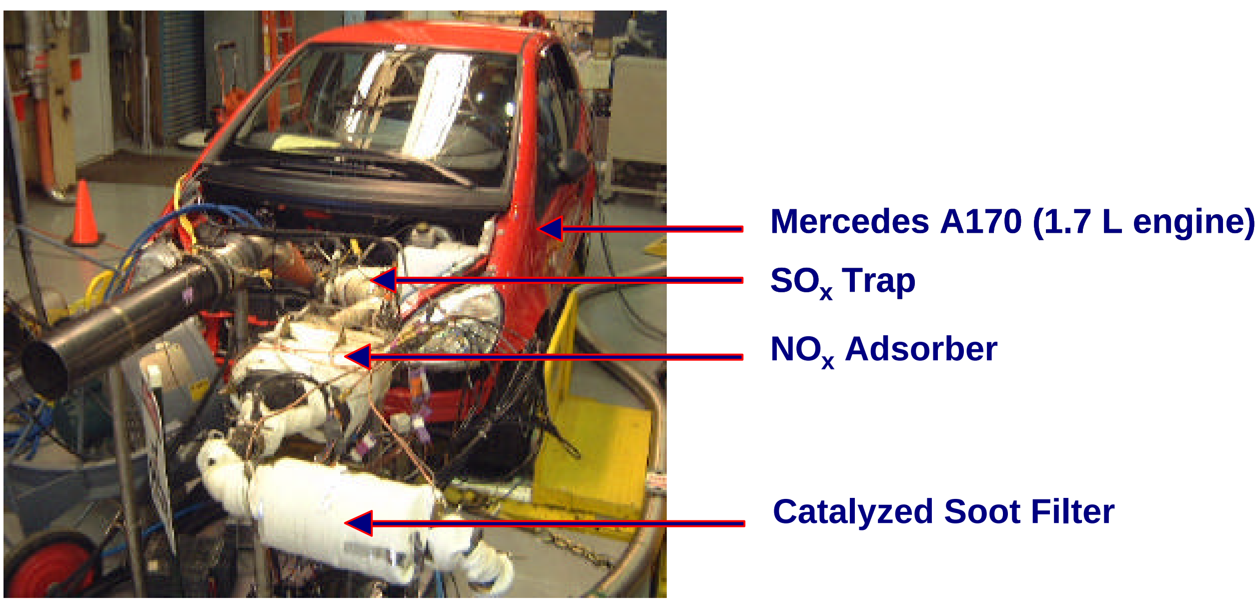
Cummins accomplished significant progress under contract to DOE to demonstrate a sulfur trap/NOx adsorber trap/particle filter system on a passenger vehicle with realistic engine emissions and drive schedules.

With a preconditioned pre-warmed catalyst, the system achieved the Tier 2 bin 5 emissions targets. This is a significant step forward.

The challenge is not complete, however. When the catalyst started from a cold condition, the emissions were higher. The system had unknown durability characteristics, and the fuel-economy penalty was higher than the target of 5 percent. Future R&D was defined to address low NOx catalyst efficiencies at low temperatures during startup, regeneration strategies for the NOx adsorber, and mitigation or prevention of sulfur poisoning.

<u>Significance</u>

The demonstration showed that NOx adsorber technology is progressing and remains a promising aftertreatment strategy. This knowledge will transfer to the study of an aftertreatment system for a larger displacement engine in a light-duty truck.



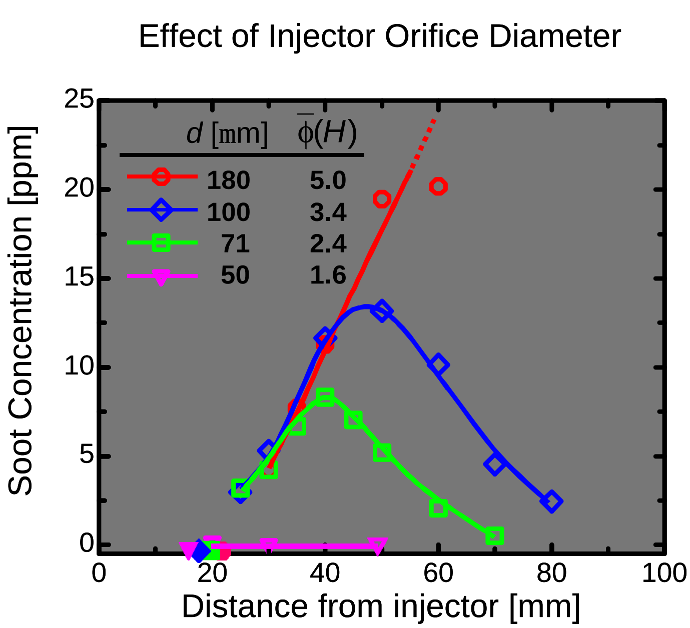
Soot Formation in Diesel Fuel Sprays
(Sandia National Laboratory)

Diesel engines offer the potential for increased fuel economy if upcoming Tier 2 emission regulations can be met without offsetting fuel economy penalty. Emission control systems for NOx and particulates are the challenge.

Sandia has designed and demonstrated injection fuel spray patterns for diesel engines that reduce particulate emissions.

Soot production in a chemically reacting fuel spray was measured in a combustion bomb. Soot formation decreased when in-cylinder temperatures and pressures decreased, when injector orifice diameters decreased or when fuel-injector pressures increased.

In these studies, the fuel-spray structure was studied for a wide range of injection pressure and ambient density, temperature, and composition. From the data, correlations and models for the spray structure were developed. These results suggest strategies to reduce soot formation during DI diesel combustion that were evaluated in subsequent engine tests. The establishment of the correlation of soot reduction to injector nozzle hole size and injection pressure will guide the development of diesel engine and fuel injection hardware and software. This work is applicable to all size diesel engines.



Swirl-Supported Diesel Combustion (Sandia National Laboratory)

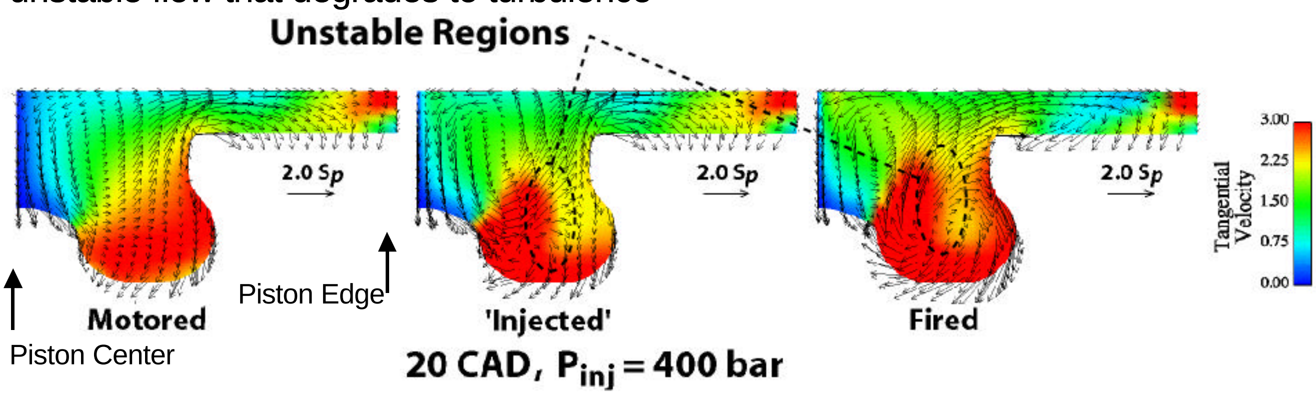
Significant advances in fuel economy and emissions from internal combustion engines can result from upcoming unprecedented controls for fuel and air injection, valve control and combustion modulation. Low-emission stratified and homogeneous-charge compression ignition engines, which include the next generation of clean diesel engines, will be designed with computer-based models that include the capability to simulate combustion chemistry and the turbulence generated during the injection and combustion processes.

The capability to simulate this critical turbulence has been achieved. Laser-velocity measurements were used to probe the interaction of fuel sprays with swirl in the piston bowl of a small-bore diesel engine to provide the experimental data to direct and validate the model development. Future engines can be designed to enhance and use this turbulence to achieve improved in-cylinder soot oxidation or alternative methods of combustion.

Just after fuel injection and during the combustion period, a region of high tangential velocity flow was found at the side of the piston bowl. This flow region is unstable and degrades to turbulence during the combustion period. The characteristics of this unstable flow depend on piston and injector geometry, injection pressure, and swirl ratio. Improved computer models now better predict this turbulence generation and its dependence on engine design parameters.

The generation of turbulence in the piston bowl during the expansion stroke could be a way to increase oxidation of fuel and particulates. Using insights from computer simulations, design details of the injector and combustion bowl might be changed to enhance this turbulence. Control of the turbulence produced during combustion could be a process to improve combustion.

High tangential velocity fluid is pushed toward the center of the piston creating an unstable flow that degrades to turbulence



Automotive Integrated Power Module Development
(Semikron)

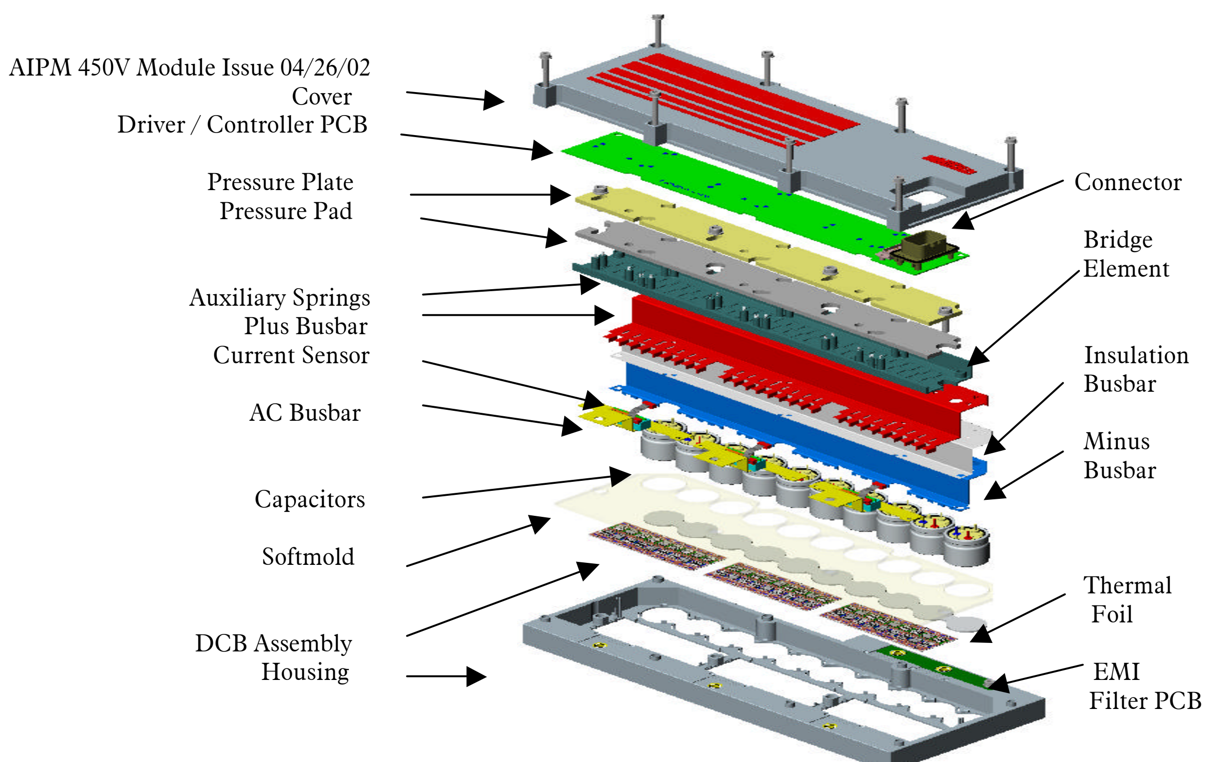
For electrical power to propel vehicles either with fully electric fuel cell powertrains or with hybrids, light, compact and low-cost power modules will be required for widespread, affordable vehicle use.

Semikron working under DOE contract has designed and demonstrated an automotive integrated power module that meets weight, volume, efficiency and cost targets:

	Goal	Achievement
Cost	$7/kw	$6/kw
Weight	11.0 kg	5.0 kg
Volume	4.6l	4.7l
Efficiency	97%	97%
Useful life	15 years	15 years

Previously, hybrid and fuel cell vehicles have required three or four separate electronic modules to manage three key functions: (1) conversion from DC power (from batteries) to the AC power required to drive the electric motor; (2) control of the switching devices and (3) smoothing the current. Integration of the 3-4 devices into an Integrated Power Module was sought to reduce the overall cost, size and performance. And previously, the modules have been derived from expensive commercial modules for stationary power conversion that did not lend themselves to automotive applications.

This is the first time that a mass producible, compact module has been able to simultaneously meet the cost and performance goals of the FreedomCAR program.



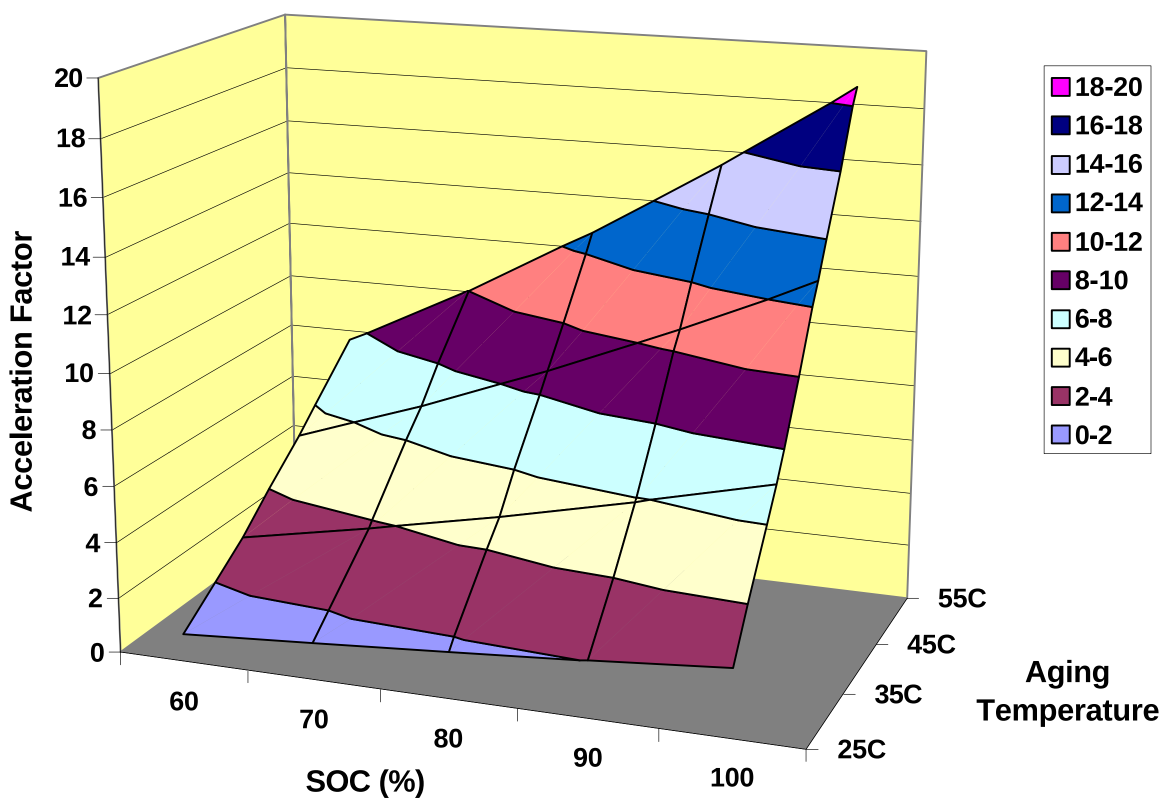
Accelerated Life Test Protocol
(Advanced Technology Development Program)

Expensive high power batteries required for hybrid electric vehicles (HEVs) must last the lifetime of the vehicle for the powertrains to be affordable. Therefore, it is critical that a reliable test of accelerated life be available to battery developers and automotive manufacturers to validate claims of 15-year useful battery life.

The DOE Advanced Technology Development (ATD) program at the national laboratories has developed an Accelerated Life Test that provides statistically robust methods that give estimates of cell life within confidence limits.

The proposed protocol consists of a series of experiments that will give cell life predictions at average storage conditions

A 15 year useful life for the batteries was a major program challenge. In the past it was very difficult to conduct independent testing of batteries to validate manufacturers' claims. This new protocol allows for more efficient and rapid screening of developmental cell chemistries and cell improvements.



Acceleration factor is proportional to battery lifetime (yrs) and depends on aging temperature and state-of-charge

Li-Ion Battery System
(SAFT)

Expensive high power batteries required for hybrid electric vehicles (HEVs) must last the 15-year lifetime of the vehicle for the powertrains to be affordable.

Saft working under DOE contract has developed a HEV power-assist lithium-ion battery that demonstrates a 150,000 mile useful life with less than 2% degradation in power, energy or efficiency. In addition the calendar life of the battery is projected to have improved to 10-15 years.

For a successful automotive application a useful life of 15 years is a basic requirement. As recently as 2 years ago this was not thought possible for a Lithium-Ion battery. Based on the results of this project the participants have now consensed that such a useful life is achievable.

	Goal	SAFT System
Mass	40 kg	44 kg
Volume	32 liters	41 liters
Voltage	440 volts	260 volts
Total Energy	0.3 kWh	2 kWh
Power	25 kW	31 kW

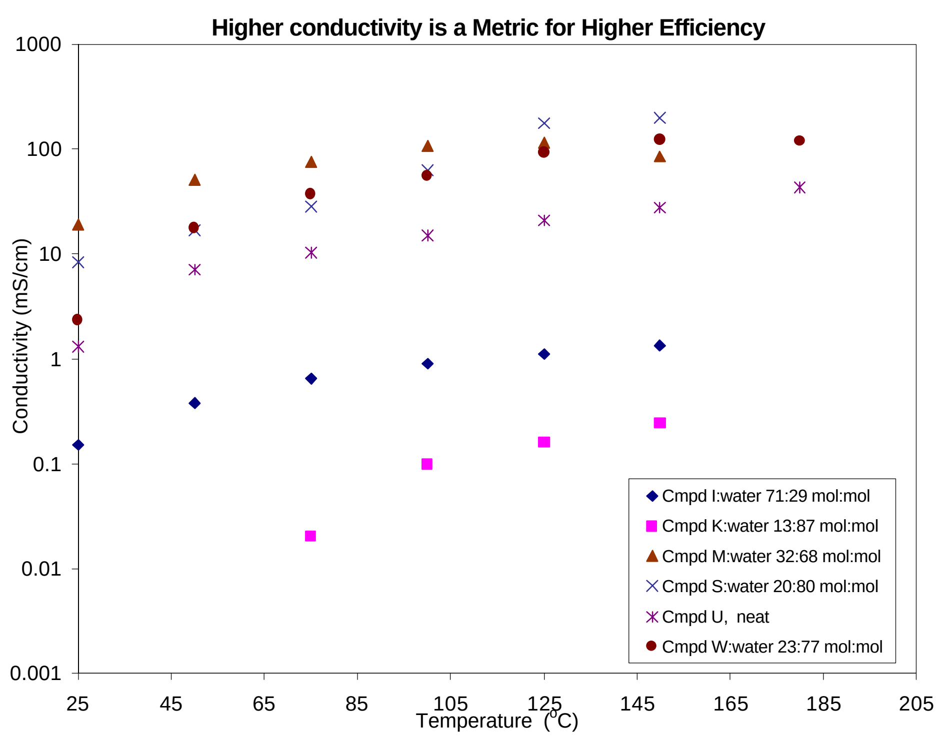
Advanced Membrane-Electrode Assemblies (DeNora and DuPont)

The goal of this DOE-sponsored work is to discover and develop proton exchange membranes (PEM) that can operate at higher temperatures of 120-150°C while maintaining low-temperature performance adequate for start-up and avoiding leaching of any components. A second goal is to create cathode structures and catalysts for PEM fuel cells that allow a significant reduction of precious metal without loss in performance.

The following tasks were completed:

- Measured conductivity vs. humidity at elevated temperatures for a number of novel liquid precursors to membranes and identified a compound with appreciable conductivity in the absence of water.
- Evaluated different catalyst preparation methods, of which an organic method was shown to have the best potential for controlling catalyst structure.
- Use of a novel organic-chemistry method for catalyst preparation led to about a 60% reduction in platinum due to more efficient catalyst utilization.

For the high temperature membrane needed for PEM fuel cells, achieving high conductivity at low relative humidity is one of the most challenging requirements. This project made important progress by obtaining high-conductivity liquid electrolytes as precursors to membranes. Further development of the structure-function approach to catalyst design should result in greatly enhanced cathode structures.



Carbon Composite Bipolar Plates
(Porvair and Oak Ridge National Laboratory)

Develop scalable carbon composite bipolar plate technology and representative test procedures. Evaluate carbon composite bipolar plates in fuel cell stack testing. Develop scalable manufacturing techniques.

The following tasks were completed:

- Produced uniform 50x50x2.5 millimeter carbon composite bipolar plates.
- Plates exhibited excellent materials properties using low-cost ingredients.
- Testing indicates acceptable torsion resistance.
- Demonstrated significantly improved wetting of bipolar plate surface.
- Built research production line that will be scaled up to a pilot unit.

The availability of high-quality, low-cost bipolar plates is a key enabler for commercialization of automotive fuel cells. Carbon composites have the potential to provide an attractive alternative to existing bipolar plate materials, which present numerous manufacturability challenges. This project showed that carbon composite bipolar plates with excellent properties can be produced from low-cost materials. The project also passed a first key milestone toward high volume manufacture by installing a successful research production facility capable of being scaled up to a pilot production line in the next phase of the project.

Carbon composite vacuum forming equipment

Chemical vapor infiltration furnace

Approach

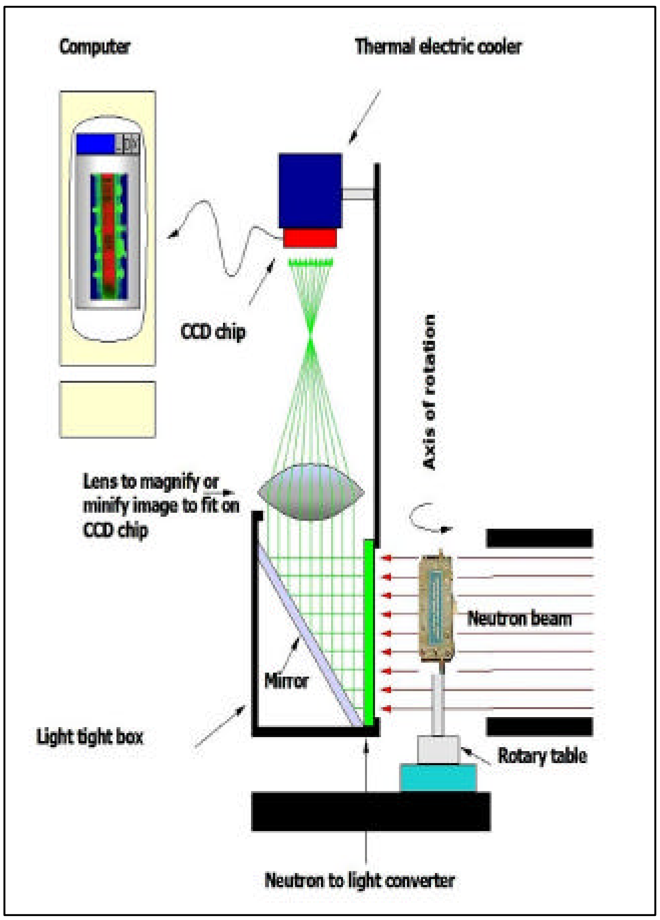
- Slurry molded carbon fiber material w/ carbon chemical vapor infiltrated sealed surface as bipolar plate
- Design and installation of material forming and processing equipment
- Construction of 300 plate/hr pilot production line
  - Demonstrate high-volume low-cost manufacturing
- Testing of embossed bipolar plates in fuel cell stack
  - In-situ evaluation of bipolar plates at UTCFC

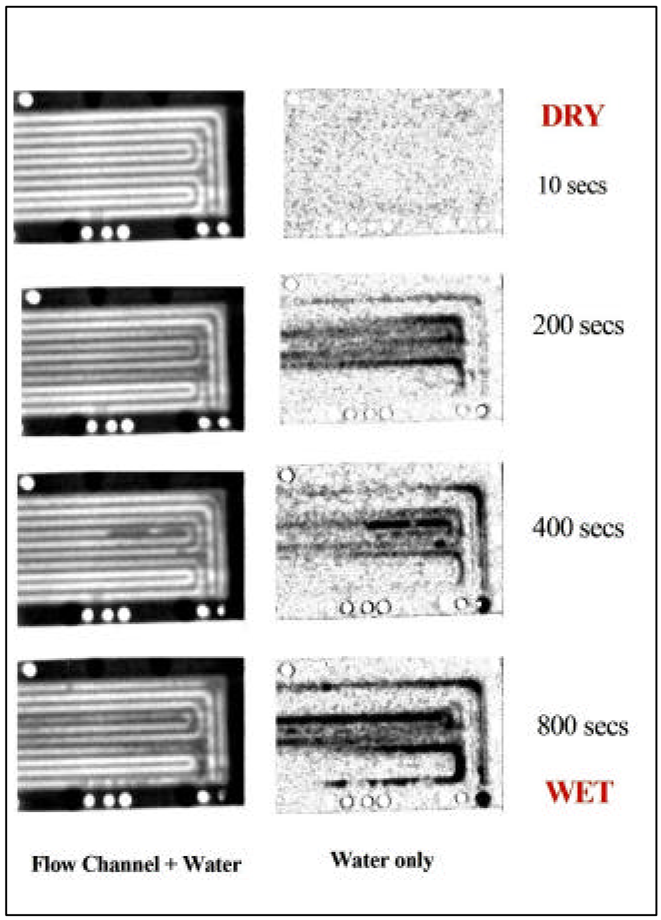
Fuel Cell Neutron Imaging
(National Institute for Standards and Technology)

Effective water management is critical to the optimal functioning of fuel cells, both for high energy efficiency and start-up after freezing. Design modifications require precise and accurate diagnosis of water transport issues. Previously direct evidence of water transport in the interior of a fuel cell was not available.

Neutron imaging provides that evidence with real time, non-destructive evaluation of water transport mechanisms inside operating PEM fuel cells. Specifically, the technique has been developed as an in-situ technique to evaluate: 1) water distribution in flow channels and the membrane assembly; 2) catalyst utilization of hydrogen; and 3) hydration status of the membrane.

The non-destructive techniques developed by this project can be useful in modeling water transport mechanisms of fuel cells during actual operation. This in turn can be a helpful tool in the understanding of catalyst behavior and hydration state and in the design of optimized flow channels. This project was co-sponsored by NIST and the Department of Energy.





Low Platinum-Loading Electrode
(3M)

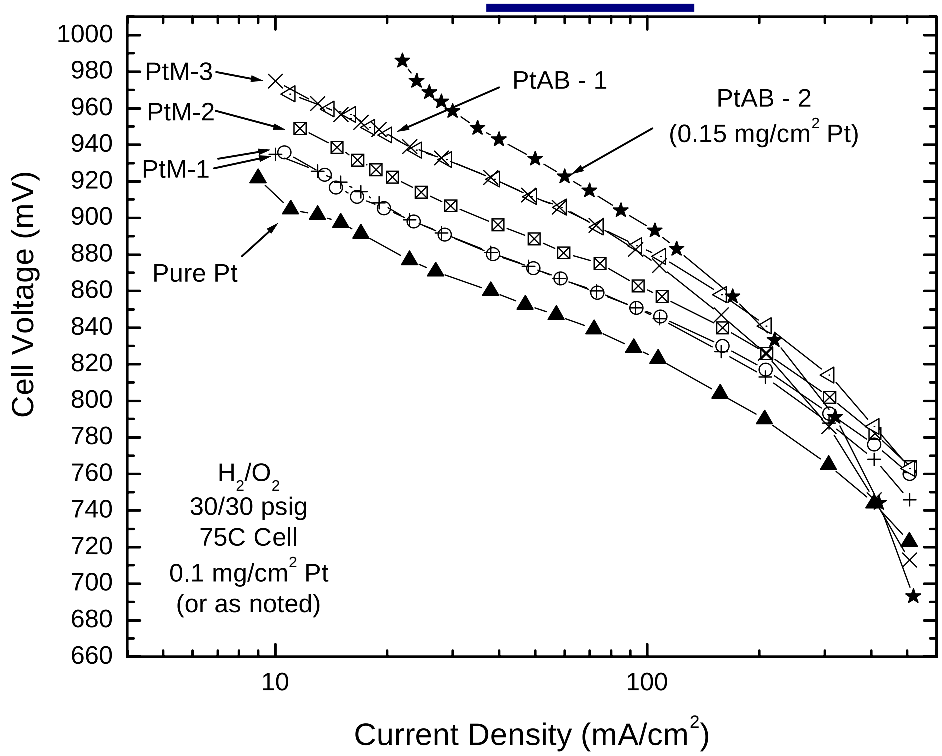
Fuel cell stacks use the expensive precious metal platinum as a catalyst in the stack electrodes. Reducing the platinum loading is a key requirement for affordable fuel cell power systems.

3M, working under DOE contract, has developed platinum alloys that lower the requirements for platinum in PEM fuel cell electrodes, while maintaining or improving performance.

The following tasks were completed:

- Developed a new platinum ternary alloy catalyst that has the same active surface area with half the amount of platinum as the standard pure platinum catalyst.
- The new ternary catalyst shows nearly a 100 mV improvement in performance at low current densities, which is equivalent to a 32-fold increase in catalytic activity.

Due to the high cost of precious metals, reducing the amounts required for successful fuel cell operation is a key enabler for commercializing the technology. This project developed a new catalyst material for fuel cell electrodes which reduced the requirement for platinum by half, while delivering improved performance.



Microchannel Fuel Processor Development
(Pacific Northwest National Laboratory)

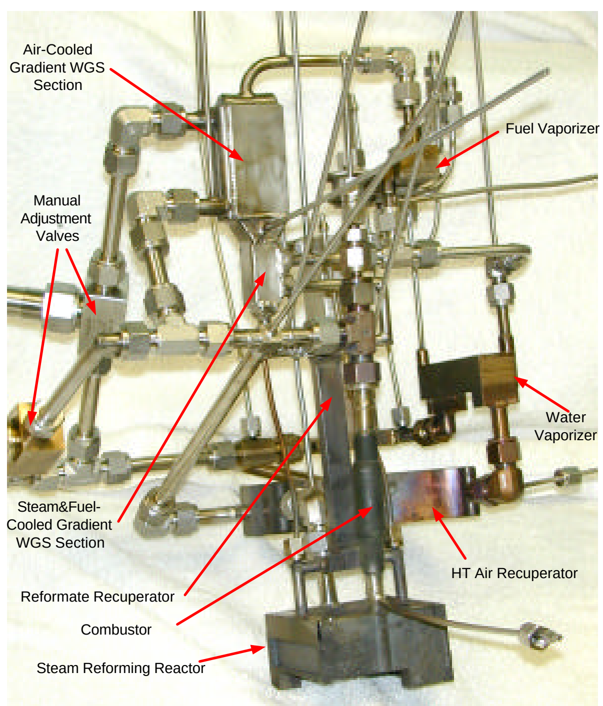
One path to bringing fuel cell power systems into use before the availability of hydrogen fuel would be through use of a compact, steam reformation-based fuel processing system for the mobile reformation of hydrocarbon fuels. Progress was made in the development of such a fuel processing system toward FreedomCAR performance targets for energy density, efficiency, residual CO content, durability, rapid start-up, and transient response.

The following tasks were completed:

- Built a small-scale (<1 kWe) microchannel fuel processing system which is fuel-flexible for long-term durability testing.
- Projected properties of a 50 kWe system from the behavior of individual small-scale reactors.
- Tested performance of steam reformer section on various fuels, including benchmark gasoline with 10 ppm sulfur.
- Demonstrated that counter-flow design can reduce the size of the shift reactor.
- Demonstrated the components of a compact PrOx (CO-cleanup) unit.

This project assessed the extent to which the improved heat transfer obtainable from novel reactive heat exchangers could reduce the volume, mass, and transient times of fuel processors. Component experiments demonstrated a potential pathway to meeting DOE volume targets. Improvement of catalyst productivity and the use of lightweight alloys for low temperature components are needed to meet stringent mass and start-up energy requirements.

Small Scale Microchannel Fuel Processing System



Quick Starting of Fuel Processors
(Argonne National Laboratory)

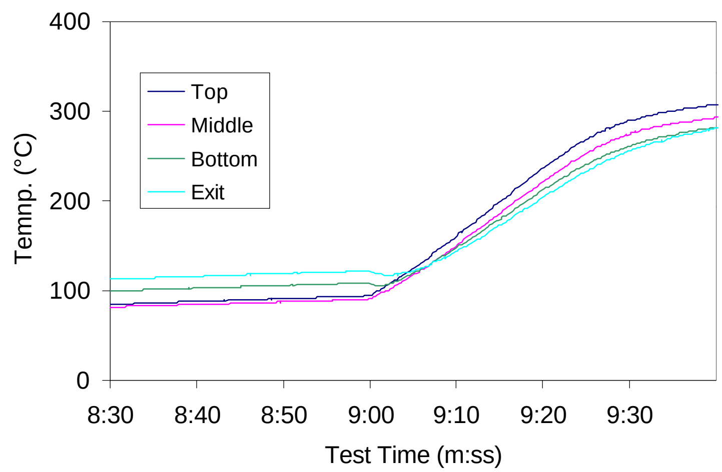
One path to bringing fuel cell power systems into use before the availability of hydrogen fuel would be through use of a compact gasoline processing system for onboard hydrogen production.

Progress was made in the development of such a fuel processing system toward FreedomCAR performance targets for energy density, efficiency, residual CO content, durability, rapid start-up, and transient response. Several strategies were developed for future test and evaluation.

The following tasks were completed:

- Evaluated burner feeds and heat load required to warm up a 50 kWe fuel processor to 75 percent of rated power in 30 seconds.
- Developed a computational fluid dynamic (CFD) model to simulate heat-up of individual reactor zones and concluded that an autothermal reformer can be rapidly heated, but airflow availability may limit the heating rate.
- Fabricated a generic test reactor to validate the CFD model.

Currently, fuel cell systems using on-board reforming of gasoline to produce hydrogen require unacceptably long warm-up times. A pathway toward start-up time of less than 1 minute was identified for at least some of the components of the fuel processor. Argonne National Laboratory is calculating, and will later measure, the energy needed for fuel processor startup. The National Renewable Energy Laboratory will calculate the relative impact of this startup energy on total vehicular energy consumption over representative drive cycles.



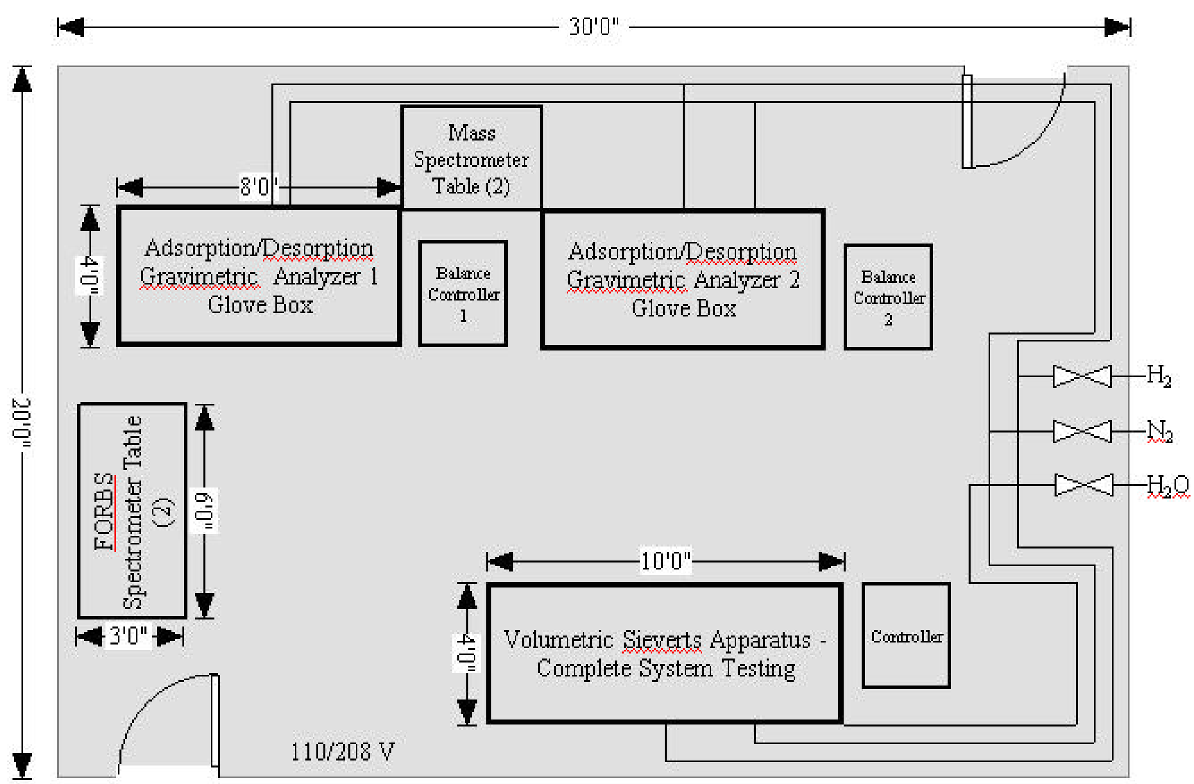
Experimental heatup of a cylindrical zone using electrically heated air, flowing at a gas hourly space velocity of 60,000/h

Standardized Testing Program for Emergent Chemical Hydride and Carbon Storage Technologies (Southwest Research Institute)

The foremost technical challenge to the advent of a hydrogen economy is the development of a compact, energy-efficient, light and affordable storage system for hydrogen. Irregularities in the quality of claims of hydrogen storage performance have been an obstacle in developing priorities for research. Consequently, the unambiguous measurement of hydrogen storage is critical in sorting priorities for further development.

With funding from the Department of Energy, a facility has been designed for measurement of hydrogen storage by materials developed under the FreedomCAR program. Individuals who will operate the facility have received training in state-of-the-art procedures and industry requirements.

Emergent H_2 Storage, Laboratory Configuration



Commodity-Grade PAN Precursors for Low-Cost Carbon Fiber (Hexcel Corporation subcontract from ORNL)

Polymeric materials reinforced by carbon fibers, primarily to increase stiffness, offer substantial weight-savings over their steel equivalents in body structures or in high pressure hydrogen storage tanks. However, carbon fibers are expensive to manufacture, about half the cost being in the precursor materials used.

This project shows that textile-grade polyacrylonitrile (PAN) may be an acceptable alternative precursor material to those currently used, though less than half as expensive. Thus, the use of commodity-grade PAN precursors has the potential to reduce the cost of carbon fibers by at least 25%.

Accomplishments:

- Lab-scale evaluations eliminated many alternative precursor materials because of cost and/or technical feasibility
- Developed carbonization and graphitization schedules to provide the fiber properties needed
- Used a continuous in-line chemical pretreatment process to reduce stabilization times by 50%
- Developed two-stage sulfonation process to speed oxidation of Linear Low Density Polyethylene (LLDPE) and Polypropylene (PP) fibers

Textile precursor and carbon fiber

High-Strength Steel Stamping
(Auto/Steel Partnership)

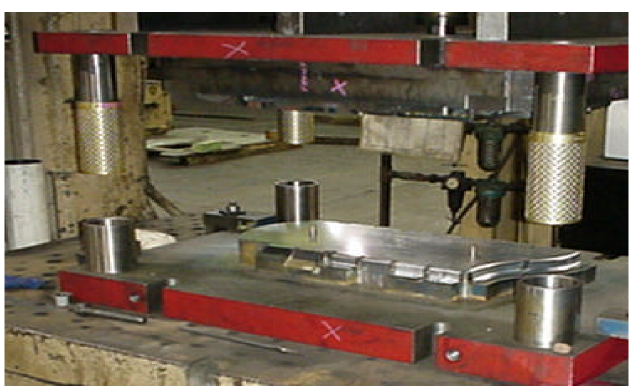
Although there are now new materials that have the potential for significant weight-savings in vehicles when used as replacements for traditional steels, there are often offsetting disadvantages. High-strength steels (HSS), for example, tend to exhibit greater springback. The design of stamping dies must therefore allow for this to ensure accurate part production.

A computer-based model capable of predicting springback accurately in high-strength steel (HSS) has been developed and used to identify designs and manufacturing processes that can minimize springback and other distortions. This work was supported as a joint effort of the members of the Auto/Steel Partnership and the U.S. Department of Energy.

These new computer simulations greatly enhance predictive capabilities and will allow both better compensation for springback and part designs that can minimize it.

Tasks accomplished include:

- Experiments were conducted on structural rails made from eight different HSS steels
- Finite Element Analysis (FEA) showed fair agreement between baseline simulation studies and the experimental data
- Flange springback has been measured in 15 typical flange configurations and the results evaluated by regression analysis
- Work has been initiated on designs that will minimize springback



Complete die used to produce experimental parts

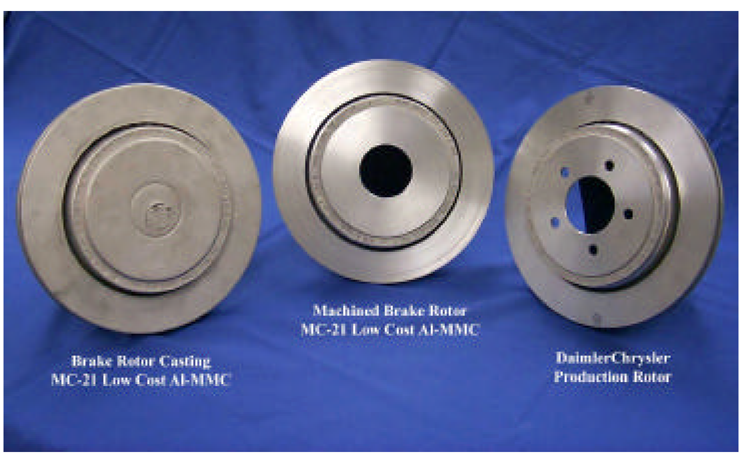
Low-Cost Cast Aluminum Metal Matrix Composite (Pacific Northwest National Laboratory)

The demand for better fuel economy is a major reason to reduce vehicle mass. In principle, substitution of metal matrix composite material for the steel provides a significant opportunity to reduce vehicle mass in for braking systems and powertrain applications.

Aluminum metal matrix composite materials possess both lightweight and high wear-resistance characteristics, making them ideal for light weight brake rotors. A metal matrix composite (MMC) manufacturing process was developed that allows significant weight reduction, good performance and achievement of cost targets with aluminum MCC componentry.

The following tasks were accomplished:

- The MC-21 rapid mixing process has been used to incorporate up to 45% by volume of low-cost SiC reinforcement in an aluminum MCC material.
- The cost target of $1/lb. for aluminum MCC with 20% volume reinforcement has been met.
- Prototype brake rotors, using a revolutionary geometry from Visteon Corporation, have been manufactured by a process that is tailored to the MCC properties.
- Preliminary cost estimates, based on the new low-cost material and innovative shape-casting methods, indicate that the target cost of $15 per brake rotor is achievable.



Brake Rotor Application

Magnesium Powertrain Cast Components
(USAMP: Automotive Metals Division)

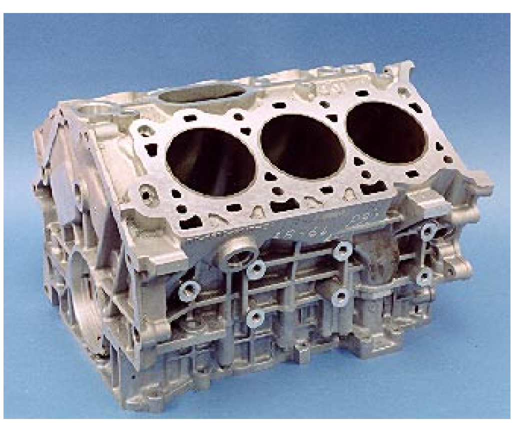
The demand for better fuel economy is a major reason to reduce vehicle mass. In principle, substitution of magnesium for the cast iron traditionally used for engine blocks and heads can reduce the mass substantially. The density of magnesium is one-third less than that of aluminum and only a quarter of that of iron, making it a potential lightweight alternative in automotive applications. However, magnesium alloys suitable for powertrain use are expensive (partly because of high-cost constituents needed to give requisite high-temperature creep resistance), knowledge of their properties is limited, and there is little design experience.

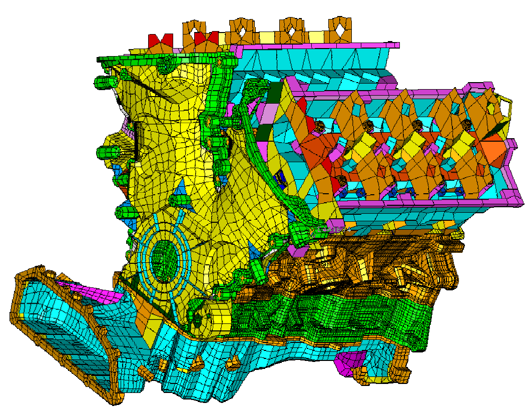
The present work, performed under a cooperative agreement between the USCAR partners and the U.S. Department of Energy, has identified several potentially low-cost, creep-resistant alloys for evaluation. In addition, considerable progress has been made in expanding technical knowledge about these materials, including coolant corrosion behavior as well as mechanical properties.

The following tasks were completed:

- Cast 4000 specimens to develop database of materials properties and evaluate alloy castability
    - Die-cast seven and sand-cast three high-temperature, creep-resistant alloys
    - Die-cast 1500 transfer cases for the castability study
- Conducted computational fluid dynamics (CFD) and heat transfer analysis of Ford Duratec V-6 engine. Four aluminum components from the engine are being designed for magnesium
- Initiated structural analysis and cost modeling

This project will ultimately demonstrate the feasibility of high-volume production of magnesium-intensive engines that are cost-effective, durable and satisfy performance requirements.





Ford Duratec V-6 Engine

Structural Composites Focal Project
(Automotive Composites Consortium)

The demand for better fuel economy is a major reason to reduce vehicle mass. In principle, substitution of composite material for the steels traditionally used for the structural load-bearing auto body (body-in-white (BIW)) can reduce the body mass by a factor of two or so while retaining structural strength. The challenges are to provide the required functional performance at a competitive cost.

The present work, jointly supported by the Automotive Composites Consortium and the U.S. Department of Energy, shows that a 60% mass reduction is feasible, based on the appropriate design and use of carbon-fiber-reinforced composites, together with improved manufacturing and joining processes. Work has been initiated on molding parts for the body side.

The following tasks were completed:

- Design analysis shows 60% mass reduction is achievable
- Process trials on reinforcement fiber production and molding for B-pillar
- Preliminary cost estimate of body side parts, based on programmable powder preform process (P4) and structural reaction injection molding (SRIM)

Mold with molded fiberglass inner and outer B-pillars lying in the cavity

Hardware-In-the-Loop Vehicle Emulation Test Facility
(Argonne National Laboratory)

The new facility provides DOE with a new capability to evaluate its deliverables from FreedomCAR contracts. It provides a real time vehicle environment and a hardware-in-the-loop test bed to emulate system and subsystem performance. This allows the hardware to be evaluated as if it were in an actual vehicle without the timing or cost of building a new vehicle.

The following task was accomplished:

- Setting up and commissioning of 4WD Super Ultra-Low Emissions Vehicle (SULEV) facility:
  - Temperature control of ± 1°F
  - Humidity control of ± 2%
  - Hydrocarbon emission measurement threshold capability of 1 ppm