21ST CENTURY TRUCK PARTNERSHIP

21CTP-0003
December 2006

Roadmap and Technical White Papers
Appendix of Supporting Information

...safely and cost-effectively move larger volumes of freight and greater numbers of passengers

...dramatically reducing dependency on foreign oil

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

21st CENTURY TRUCK PARTNERSHIP

This Appendix contains supporting information to the 21st Century Truck Partnership's Roadmap and Technical White Papers (21CTP-003). Information in this document chiefly supplements the Parasitic Loss section of the paper, as referenced in Sections 3.3 through 3.6.

This Appendix contains the following documents and links:

AERODYNAMICS
- 2006 DOE overview presentation by Rose McCallen, Lawrence Livermore National Laboratory
- 2006 Truck Manufacturers overview presentation by Robert Clarke, TMA
- 2006 Heavy Vehicle Systems Optimization Merit Review and Peer Evaluation (link)

AUXILIARY LOAD
- Summary of More Electric Truck
- DOE Fuel Cell Technical Plan
- Industry Fuel Cell APU Project #1
- Industry Fuel Cell APU Project #2
- Solid State Energy Alliance Overview (link)
- DOE FCVT Multiyear Program Plan, Waste Heat Recovery Section 3.3.4
- DOE 2006 Presentation on Thermoelectrics Program (link)
- Summary of Thermoelectrics Program

LIGHTWEIGHT MATERIALS
- A short summary of the structure of the DOE HSWR Materials Program and projects
- 2005 DOE Merit Review and Peer Evaluation Report for Heavy Vehicle Materials Program (link)
- FY2005 Progress Report for High Strength Weight Reduction Materials (link)

THERMAL MANAGEMENT, FRICTION AND WEAR
- 2006 Heavy Vehicle Systems Optimization Merit Review and Peer Evaluation (link)

21st CENTURY TRUCK
PARTNERSHIP

2006 DOE overview presentation by Rose McCallen, Lawrence Livermore National Laboratory (document)

DOE's Effort to Reduce Truck Aerodynamic Drag through Joint Experiments and Computations

Rose McCallen, Ph.D., et al

April 2006

Work sponsored by
U.S. Department of Energy
Energy Efficiency and Renewable Energy
FreedomCAR and Vehicle Technologies Program

*Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

DOE Consortium for Aerodynamic Drag of Heavy Vehicles

Rose McCallen, Kambiz Salari, Jason Ortega, Craig Eastwood, John Paschkewitz, Paul Castellucci	University of California Lawrence Livermore National Laboratory
David Pointer	ARGONNE NATIONAL LABORATORY
James Ross, Bruce Storms, J.T. Heineck, Steve Walker	National Aeronautics & Space Administration
Fred Browand, Tai Merzel, Charles Radovich, Dennis Plocher	USC UNIVERSITY OF SOUTHERN CALIFORNIA
Anthony Leonard, Mike Rubel	Caltech *California Institute of Technology*
Robert Englar	Georgia Tech Research Institute
Larry DeChant, Basil Hassan	Sandia National Laboratories
David Whitfield, Ramesh Pankajakshan Lafayette Taylor, Kidambi Sreenivas	UNIVERSITY OF TENNESSEE CHATTANOOGA
Chris Roy	AUBURN UNIVERSITY
Collaborator: **Kevin Cooper, Jason Leuschen**	National Research Council Canada

Class 8 tractor-trailers are responsible for 11 – 12% of the total US consumption of petroleum

2002 Statistics

2.2 million registered trucks

138.6 billion miles/year driving, 3-4% increase/yr

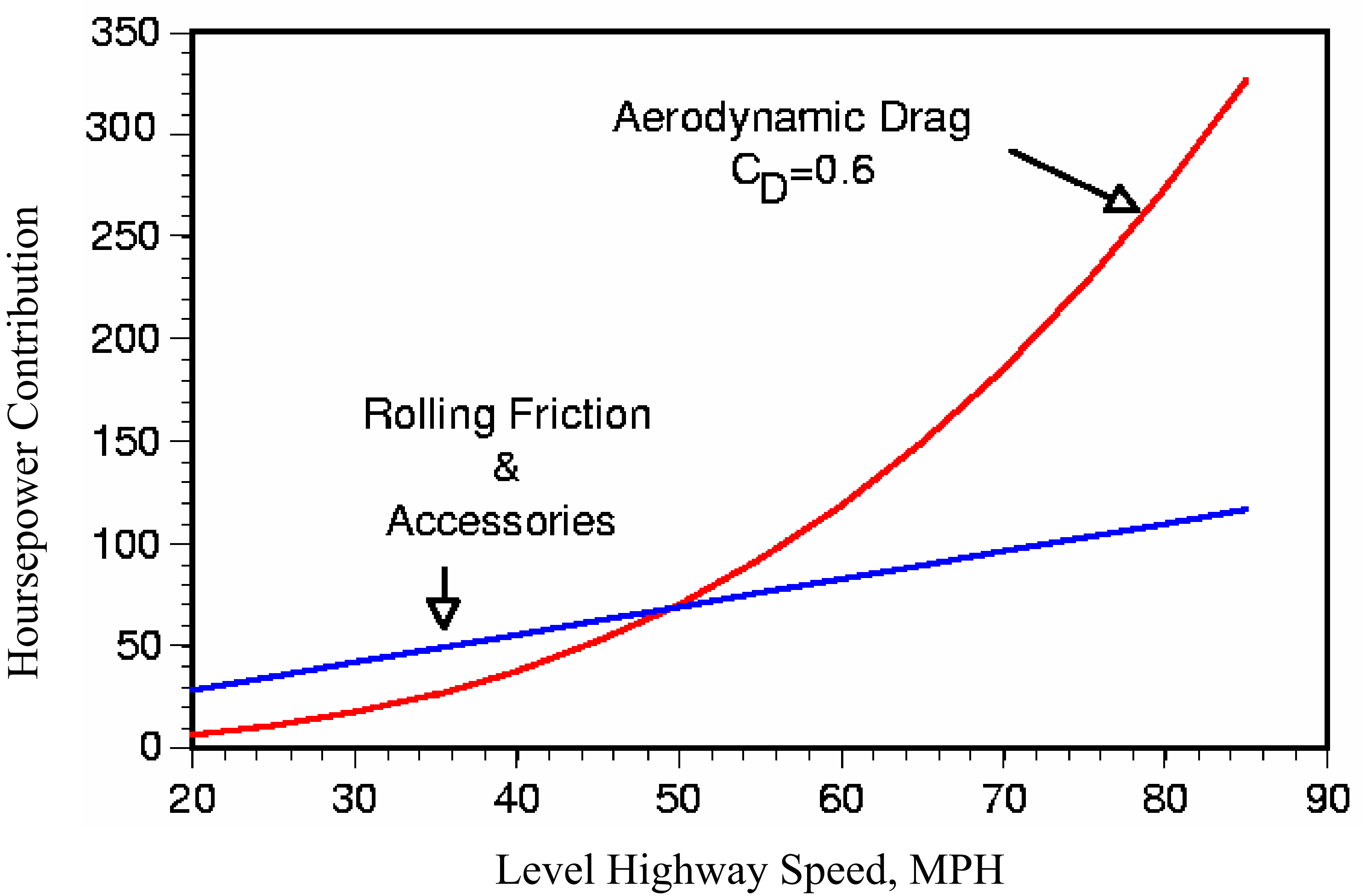
5.2 mpg

26 billion gallons of diesel fuel/year consumed, 4-5% increase/yr

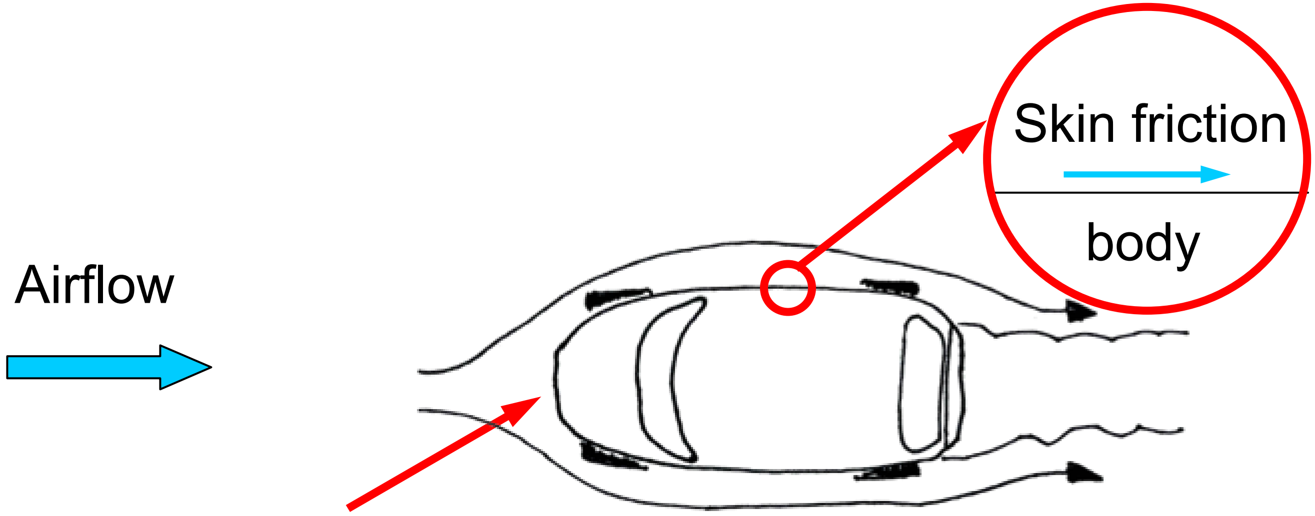
2.1 to 2.4 million barrels crude oil per day

19.7 million barrels crude oil per day total US consumption

Overcoming aero drag represents 65% of energy expenditure at highway speeds



Most of the drag results from pressure differences



Skin friction

body

Airflow

higher pressure

lower pressure

Net pressure force

$$D = C_D \times S \times (1/2)\rho U^2$$

drag coefficient,
dependent upon shape

cross-sectional
area

dynamic pressure

Reducing highway speeds is very effective

Relationship between changes in drag and changes in fuel consumption

property of the driving cycle η ≈ 0.5-0.7
for a car or truck at highway speeds

$$\frac{\Delta FuelConsumption}{FuelConsumption} = \eta \times \left(\frac{\Delta C_D}{C_D} + \frac{\Delta S}{S} + \frac{3\Delta U}{U} \right)$$

make changes in shape
to improve aerodynamics

make the car/truck
cross-section smaller

reduce highway
speeds— factor of 3 !

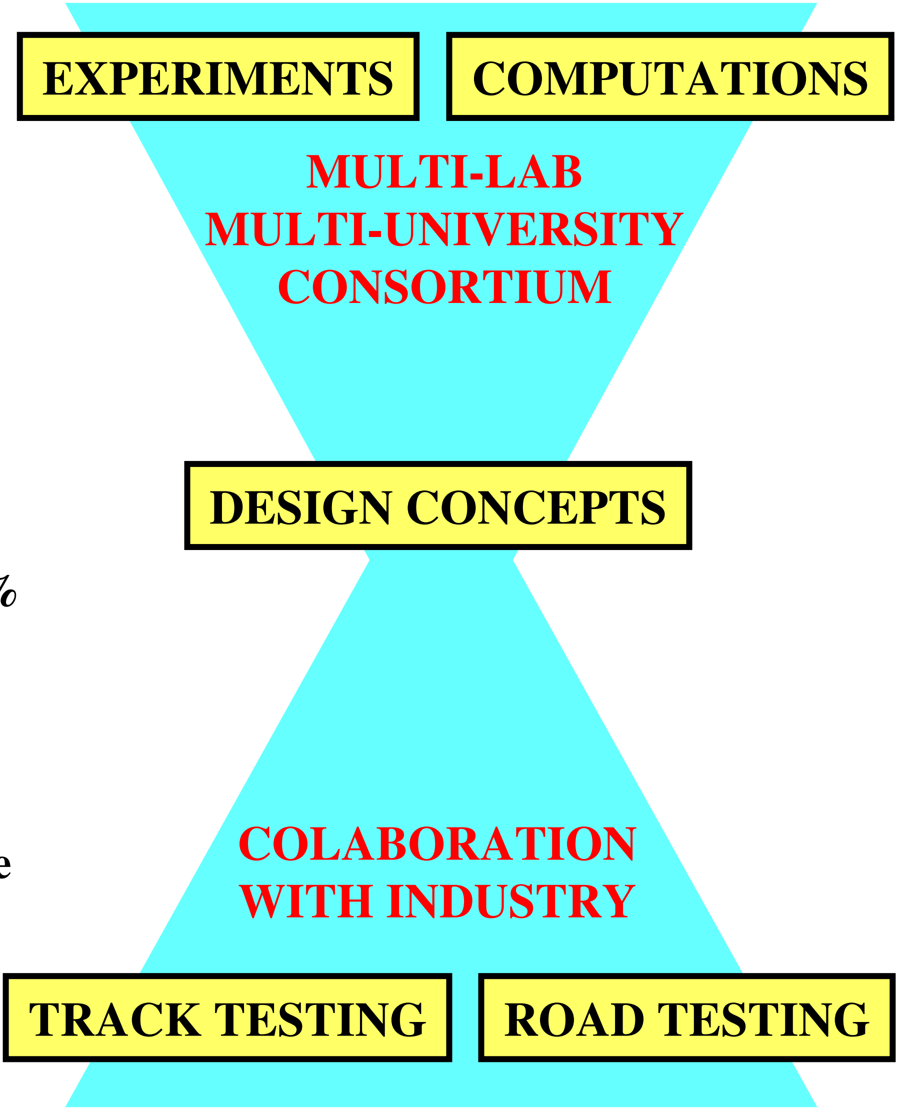
The goal is to reduce aerodynamic drag by 25% - 12% improved fuel economy or 4,200 million gal/year

Objectives

- In support of DOE's mission, provide guidance to industry in the reduction of aerodynamic drag
- To shorten and improve design process, establish a database of experimental, computational, and conceptual design information
- Demonstrate new drag-reduction techniques
- Get devices on the road

Accomplishments

- Concepts developed/tested that exceeded 25% drag reduction goal
- Insight and guidelines for drag reduction provided to industry through computations and experiments
- Joined with industry in getting devices on the road and providing design concepts through virtual modeling and testing
- International recognition achieved through open documentation and database



EXPERIMENTS

COMPUTATIONS

MULTI-LAB
MULTI-UNIVERSITY
CONSORTIUM

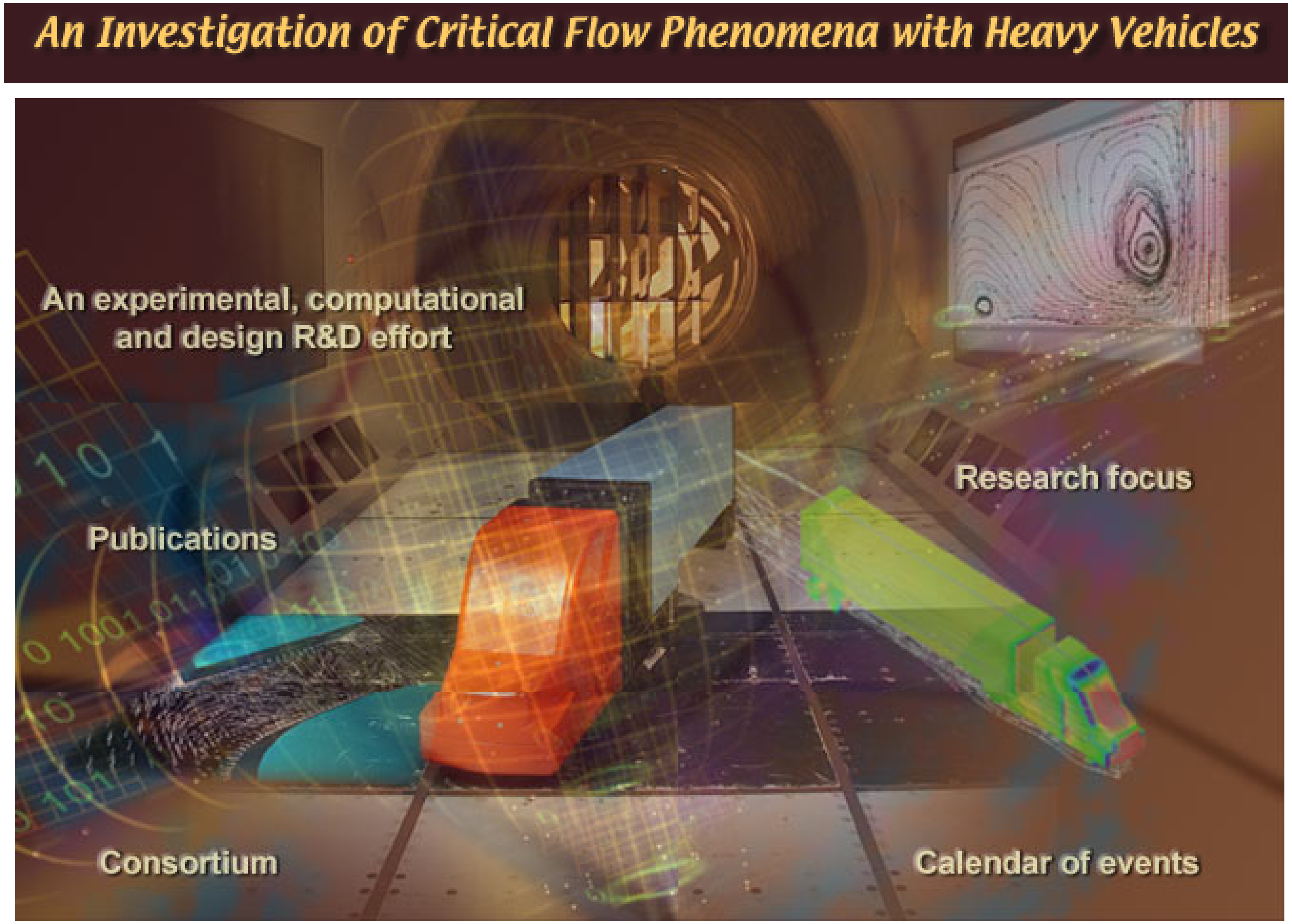
DESIGN CONCEPTS

COLABORATION
WITH INDUSTRY

TRACK TESTING

ROAD TESTING

Well attended, documented yearly meetings with industry and website have been very beneficial



An Investigation of Critical Flow Phenomena with Heavy Vehicles

An experimental, computational and design R&D effort

http://en-env.llnl.gov/aerodrag/

Effectively disseminate information to industry and have international recognition as the world leading R&D Team

Annual review meetings
One to two per year meetings with other R&D organizations and industry

Workshops
Phoenix, AZ; Livermore, CA; Detroit, MI

Magazine articles
Several in Design News

International UEF Conference, December 2002, Monterey, CA

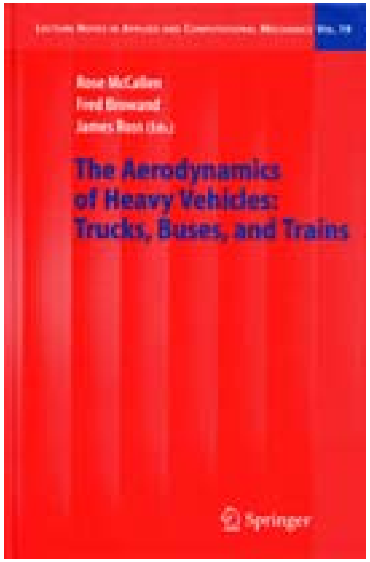
Papers, panel participants at SAE, AIAA, TMC meetings

Papers at Jul 2004 AIAA meeting, Portland Oregon

1. *DOE's Effort to Reduce Truck Aerodynamic Drag – Joint Experiments and Computations Lead to Smart Design*
2. *Evaluation of Commercial CFD Code Capabilities for Prediciton of Heavy Vehicle Drag Coefficients,* ANL
3. *A Study of Reynolds Number Effects and Drag-Reduction Concepts on Generic Tractor-Trailer,* NASA
4. *An Experimental Study of Drag Reduction Devices for a Trailer Underbody and Base*, LLNL
5. *Computational Prediction of Aerodynamic Forces for a Simplified Integrated Tractor-Trailer Geometry*, LLNL
6. *Characterization of the Flow Structure in the Gap Between Two Bluff-Bodies*, USC
7. *Unsteady Turbulent Flow Simulations of the Base of a Generic Tractor/Trailer*, Auburn and SNL
8. *2-D, Bluff Body Drag Estimation using a Green's Function/Gram-Charlier Series Approach*, SNL

Papers at Nov 2005 SAE meeting, Chicago, Il

1. *DOE's Effort to Reduce Truck Aerodynamic Drag through Joint Experiments and Computations,* McCallen, et al.
2. *Development of Guidelines for the Use of Commercial CFD in Tractor-Trailer Aerodynamic Design,* Pointer, Sofu, ANL
3. *Computational Fluid Dynamics Simulations of Heavy Vehicle Aerodynamic Drag Reduction Devices,* Ortega, LLNL
4. *Detailed Experimental Results of Drag-Reduction Concepts on a Generic Tractor-Trailer,* Storms, et al, NASA Ames
5. *Wind Tunnel Test of Cab Extender Incidence on Heavy Truck Aerodynamics,* Radovich, USC
6. *A comparison of Spray Dispersion Calculations in a Heavy Vehicle using Unsteady RANS and LES,* Paschkewitz, LLNL
7. *Entrainment and Ejection from Rolling Tires – Understanding Tire Splash,* Eastwood, Salari, LLNL, Browand, et al, USC
8. *Computational Simulation of Tractor-Trailer Gap Flow with Drag-Reducing Aerodynamic Devices,* Castellucci, Salari, LLNL
9. *Improved Pneumatic Aerodynamics for Drag Reduction, Fuel Economy, Safety and Stability Increases for Heavy Vehicles,* Englar, GTRI


The Aerodynamics of Heavy Vehicles: Trucks, Buses, and Trains

Springer

Fleets are profit driven and safety and driver comfort must be considered

Several trailers for every tractor

- Devices on trailer must be more economical

Maintenance, initial cost

- Devices add to cost & maintenance
- Related brake wear & performance issues

Safety

- Brake cooling
- Visibility – passing cars, brake lights, etc.
- Stopping distance

Driver preferences

- Style & chrome
- Access to underbody
- Turning radius (side extenders restrict)
- Devices are a nuisance, can be noisy, etc.

The trucking industry is multifaceted

Separate tractor & trailer manufacturers

Fleet owners/operators

- Customer that drives manufactured design

Docks and access

- Rear loading and at given height
- Road dips, bumps, sharp turns

Regulations

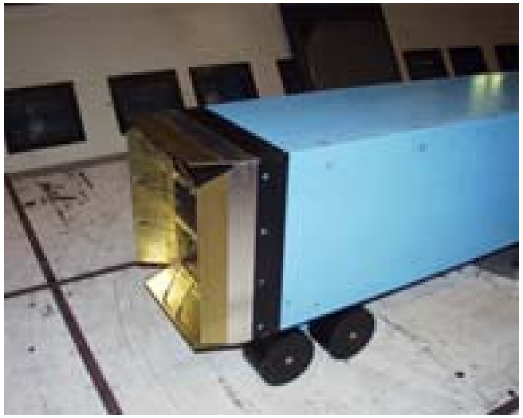
- Boattail can extend up to 5-ft from base of trailer – as of 4/02
- Control on trailer length NOT overall length

Conventional or Bullnose

Cabover Engine

Goal - *Reduce heavy vehicle drag by 25%*

Approach



Identify major contributors to drag

- Experiments
- Simulations

Design drag reducing add-on devices

- Utilize knowledge from experiments and simulations

Evaluate add-on devices using

- Wind tunnel experiments
- Simulation
- Track tests
- Road tests

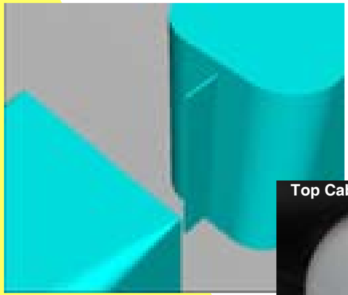
Get drag reducing add-on devices on the road

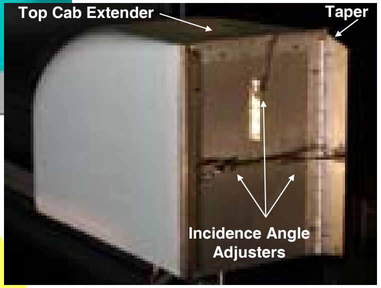
- Assist with operational and design concerns

NEAR-TERM BENEFIT

NORCAN ALUMINIUM

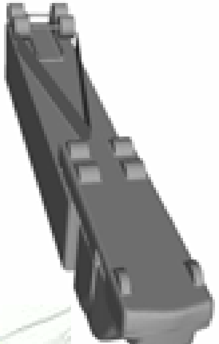
baseflaps

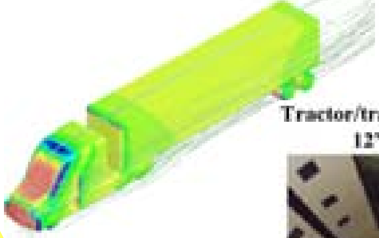




TRANSTEX COMPOSITE

aerovolution





Tractor/trailer model in 12' PWT

25% DRAG REDUCTION

U.S. XPRESS ENTERPRISES, INC.

FREIGHTLINER

PACCAR Inc

VOLVO

Mack

MICHELIN

A better way forward

INDUSTRY INVOLVEMENT

GOOD SCIENCE

Leveraged industry funding for track and road testing

Base-flaps

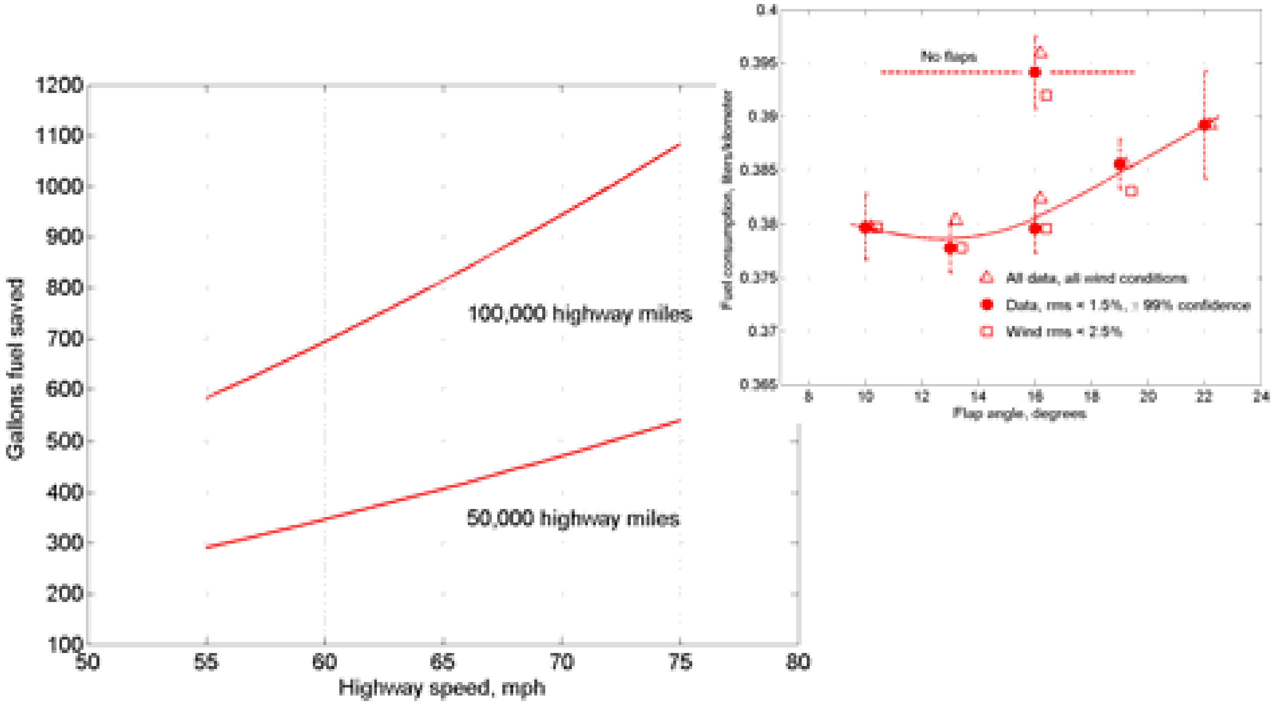
Track Test: NORCAN/Wabash/USC – 4.2% fuel savings

Road Test: NORCAN/DFS – 6% fuel savings

Clarkson University – 10% fuel savings

Pneumatic Device

Track Test: Volvo/Great Dane/GTRI



Add-on devices have big pay-off but have operational and maintenance issues

Increased Fuel Economy Possible

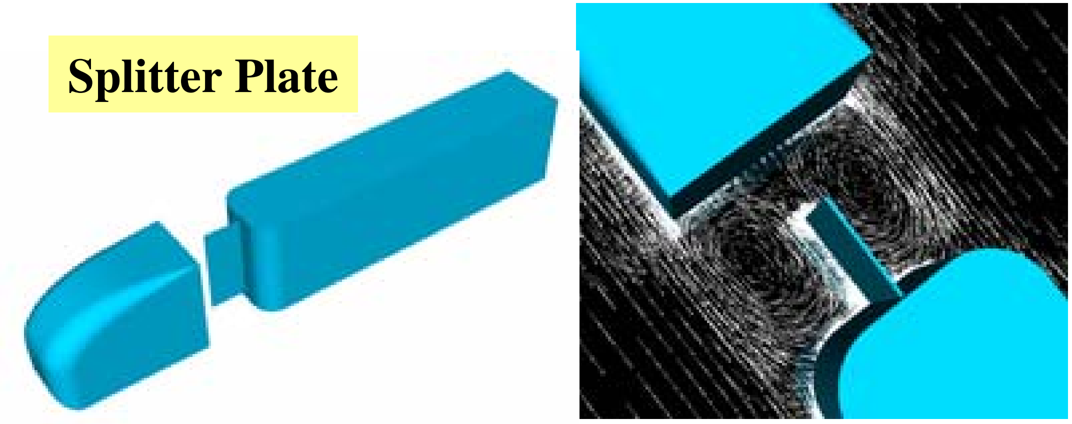
> 4% trailer base-flaps

> 6% trailer skirts

<u>> 2% gap splitter plate/side extenders</u>

> 12% Total – 130 midsize tanker ships !

Base flaps



Splitter Plate

Skirts

Addressing Issues

With our understanding of the key flow mechanisms, we are <u>developing less obtrusive and optimized innovative design concepts</u> using computational fluid dynamics and experiment

To get devices on road, <u>consequences</u> of aero improvements or use of devices need to be addressed

---

Operational and Maintenance Issues – previous slide

Tractor Aero - Underhood

Contouring hood reduces grill, reducing coolant flow

EPA 2007 regulation – more cooling needed

Devices effect Brakes

Reducing resistance

- Increases braking distance
- More braking down hills - overheating

Devices restrict critical air cooling

Device and Wheel Aero with Splash & Spray

Wheel aero - super singles vs duals, wheel guards/flaps, etc

Visibility: Base treatment/skirts appear to enhance upwash

Approach - Leveraging Efforts

Overlaps with device optimization

Industry/university support

Seeking joint funding – DOT/EPA/industry

Teaming/collaborations with industry and communications with ATA/TMC, TMA have been beneficial

Vehicle Aero

- Computations - PACCAR CRADA
- Full-scale wind tunnel testing – NRC Canada collaboration
- Full-scale/truncated wind tunnel design – Freightliner/NASA
- Road tests - seeking collaborations with Dana/ORNL

Devices

- Track/road tests – NORCAN/WABASH/USC, NORCAN/DFS
- Wind tunnel/track/road tests - Volvo/Great Dane/GTRI
- Wind tunnel tests/design concepts – Solus, NORCAN
- Computations – Aerovolution, NORCAN

Tractor Aero – Underhood

- Computations - CAT CRADA, new Cummins CRADA
- Experiments/Computations – NRC full-scale wind tunnel experiments

Safety – Braking distance/cooling, visibility

- Experiments - Michelin funding for splash and spray
- Computations - seeking joint DOT support for brake performance issues

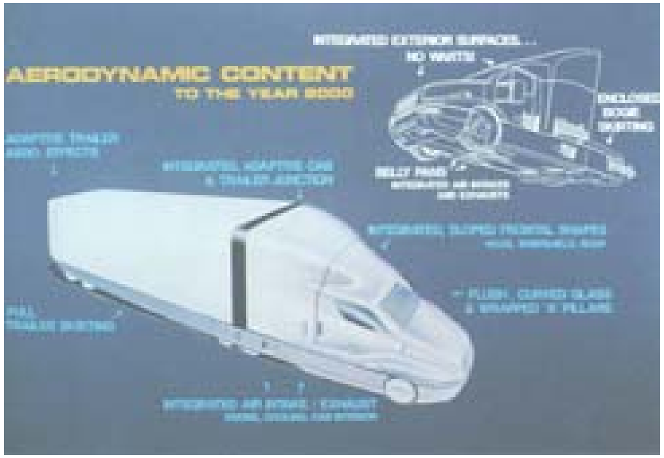
Accomplishments and Future Direction

Accomplishments

- Concepts developed/tested that exceeded 25% drag reduction goal
- Insight and guidelines for drag reduction provided to industry through computations and experiments
- Joined with industry in getting devices on the road and providing design concepts through virtual modeling and testing
- International recognition achieved through open documentation and database

Future

- Virtual testing capability to reduce design and testing process for less obtrusive/optimized devices
- Underhood/underbody investigations to improve aero & enhance thermal control
- Economic & duty-cycle with PSAT – Mechanistic data: Large drag contribution, variable with yaw, speed, geometry, environment, etc.
- Vision – integrated vehicle design



Courtesy of International Trucks

The DOE Consortium will Design the Next Generation Integrated Vehicle

- Design from scratch
- Science-based approach with validation
- Full-scale demonstration with industry

NEAR-TERM BENEFIT

Rocky Mountain Institute

FREIGHTLINER

PACCAR Inc

VOLVO

Mack

MICHELIN

U.S. XPRESS ENTERPRISES, INC.

Double Vehicle Efficiency

INDUSTRY INVOLVEMENT

GOOD SCIENCE

In Memory

Dr. Sid Diamond was our DOE Program Manager, supporter, and dear friend. This Consortium effort would not exist without Sid's vision, dedication, perseverance, and passion. His enthusiasm for this project, with his wonderful gusto for life, was contagious and pushed our effort forward. He will be dearly missed.

Program Review – DOE Consortium for Heavy Vehicle Aerodynamic Drag Reduction

Relevance to DOE Objectives

- Class 8 trucks account for 11-12% of total US petroleum consumption
- 65% of energy expenditure is in overcoming aerodynamic drag at highway speeds
- 12% increase in fuel economy is possible and could save up to 130 midsize tanker ships per year

Approach

- Good Science: Computations in conjunction with experiments for insight into flow phenomena
- Near-Term Deliverables: Design concepts and demonstration (wind tunnel, track, road testing)
- Information Exchange: collaboration with industry, dissemination of information (website, conferences, workshops)

Accomplishments

- DOE Consortium: MYPP with industry, leveraged ASCI funds, complimentary, LDRD/Tech Base, University, NASA funds
  - We understand flow mechanisms/restrictions, how to design, and model/test/evaluate
- Supporting DOE objective while addressing industries' most pressing issues
  - <u>Computational modeling</u>: choice of turbulence models/wall functions, grid/geometry refinement, commercial tools, validated methodology and tools for industry guidance and use
  - <u>Experiments</u>: advanced diagnostics at relevant highway speeds in pressure wind tunnel, realistic geometry with and without devices, validation database, experimental scaling - Determined if and when okay to test scaled models at reduced speeds, and road/track tests
  - <u>Design</u>: boattails, baseflaps, blowing, splitter plate, wedges/skirts – 8 Records of Invention and 3 Patents
- Increased fuel economy : >4% base treatment, >6% skirts/wedges, ~2% gap device, savings 4,200 millions of gal/yr
- Other transportation issues that benefit, e.g., reduce drag of empty coal cars by 20%, savings 1-2 millions of gal/yr
- Addressing consequences with aerodynamics and use of devices - Underhood, brakes, visibility, etc

Technology Transfer/Collaborations

- Multi-Lab (LLNL, ANL, SNL, NASA, GTRI), multi-university (USC, Caltech, UTC, Auburn) effort with NRC-Canada
- Industry
  - Vehicle Aero - PACCAR CRADA, design of Freightliner wind tunnel
  - Devices – track tests/WT experiments/computations with NORCAN/WABASH, Volvo/Great Dane, Solus, Aerovolution
  - Underhood - CAT CRADA complete, new Cummins CRADA, NRC-Canada full-scale wind tunnel testing
  - Safety - Michelin splash/spray funding, sought DOT support
  - Fleets – US Xpress, Dana, DFS, Payne

Future Directions – Integrated vehicle design

- Getting devices on road
  - Develop less obtrusive/optimized device concepts and transfer technology to industry
  - Demonstration wind tunnel, track, road tests - leverage work with Dana/ORNL, NRC-Canada, TMA
- Underhood - improved aerodynamics with enhanced thermal control
- Economic/duty cycle evaluation with PSAT
  - Provide mechanistic data, review road/track test plans, provide needed assistance in calibration/evaluation to Dana/ORNL

2006 Truck Manufacturers overview presentation by Robert Clarke, TMA (document)

Truck Manufacturers Program to Reduce Aerodynamic Drag

Robert M. Clarke
Truck Manufacturers Association
DOE Heavy Vehicle Systems Optimization Merit Review, April 2006 Truck Manufacturers Program to Reduce Aerodynamic Drag

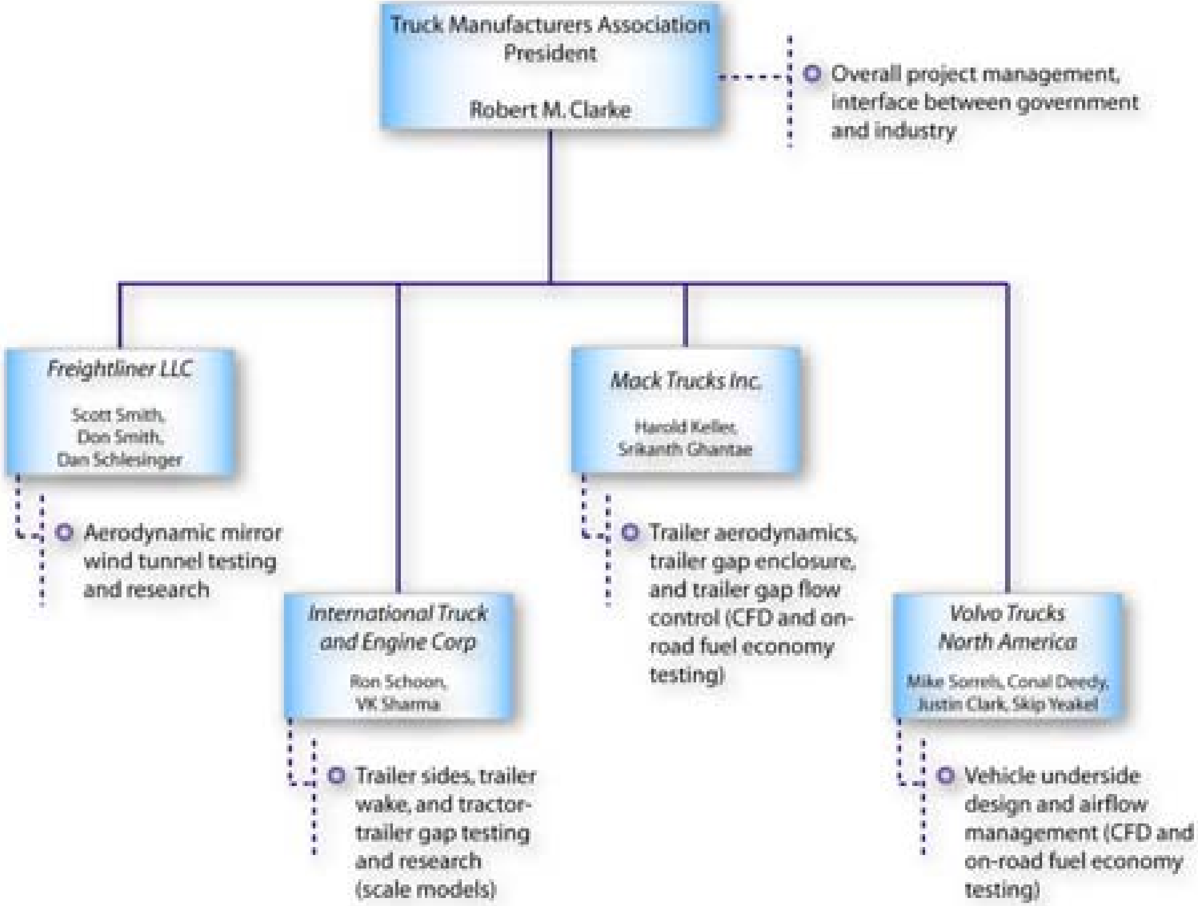
Project Overview

- Trucks dominate freight transportation, moving 64% of the value of all freight, 58% of the tonnage, and 32% of the ton-miles
- Aerodynamic drag is a major component of total horsepower needs and, therefore, fuel use of Class 8 trucks at highway speeds
- DOE goal: reduce aerodynamic drag of tractor-semitrailer systems by 20%, which translates to an approximate 10% reduction in fuel consumption
- Project goal is to develop practical aerodynamic solutions for near-term implementation and immediate fuel savings

Project Approach

- Four major U.S. truck manufacturers independently pursuing complementary research
  - Freightliner LLC, International Truck and Engine Corporation, Mack Trucks Inc., Volvo Trucks North America
- Focus on practical aerodynamic solutions for on-highway tractor-semitrailers
- Combination of wind tunnel testing, computational fluid dynamic modeling, and real-world vehicle testing to determine effects of devices and systems on aerodynamic drag and fuel economy
- Two-phase project
  - Phase I: Preliminary research and testing to determine most promising devices or vehicle modifications (CFD, wind tunnel)
  - Phase II: More in-depth testing of most promising devices or vehicle modifications (wind tunnel, on-road)

Project Structure



Truck Manufacturers Association
President

Robert M. Clarke

- Overall project management, interface between government and industry

Freightliner LLC

Scott Smith,
Don Smith,
Dan Schlesinger

- Aerodynamic mirror wind tunnel testing and research

International Truck and Engine Corp

Ron Schoon,
VK Sharma

- Trailer sides, trailer wake, and tractor-trailer gap testing and research (scale models)

Mack Trucks Inc.

Harold Keller,
Srikanth Ghantae

- Trailer aerodynamics, trailer gap enclosure, and trailer gap flow control (CFD and on-road fuel economy testing)

Volvo Trucks North America

Mike Sorrels, Conal Deedy,
Justin Clark, Skip Yeakel

- Vehicle underside design and airflow management (CFD and on-road fuel economy testing)

Project Accomplishments: General

- Researched tractor and semitrailer aerodynamic devices and their effects using CFD and wind tunnels
  - Aerodynamic mirror wind tunnel testing and research (Freightliner)
  - Trailer side, trailer wake, and trailer gap (International)
  - Trailer aerodynamics, trailer gap enclosure (Mack)
  - Vehicle underside design effects and airflow management (Volvo
- Quantified effects of changes to the tractor-semitrailer relative to baseline vehicles
- Determined best potential devices and vehicle modifications for Phase II work

Project Accomplishments Freightliner (1)

- Quantitatively assess fuel efficiency performance benefit that might be achieved with advanced mirror technology relative to current baseline technologies
- Combination of full-scale wind tunnel testing in Freightliner dedicated wind tunnel and computational fluid dynamics

Project Accomplishments Freightliner (2)

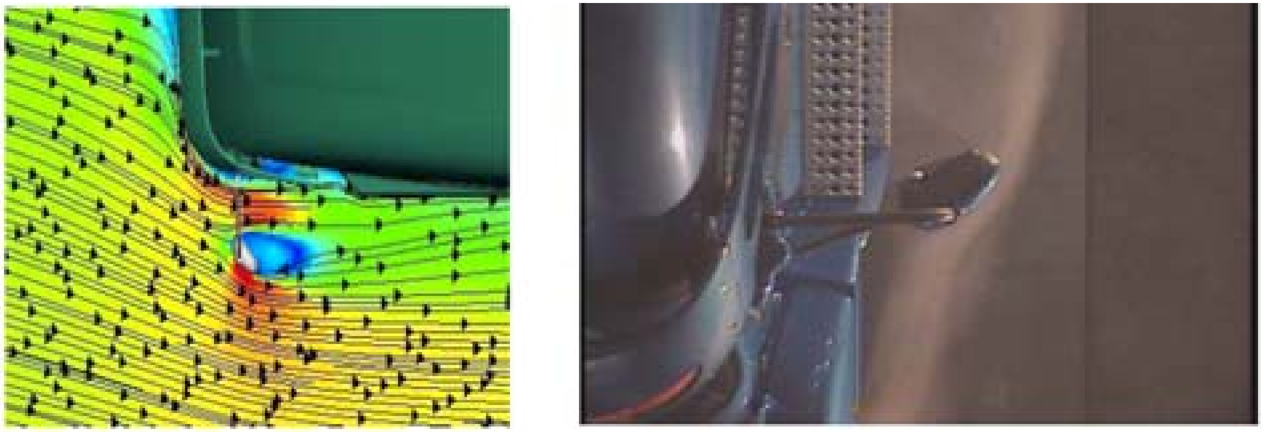
AERODYNAMIC DRAG DUE TO MIRRORS (% OF TOTAL VEHICLE DRAG)

	Yaw Angle		
	-6 degrees	0 degrees	+6 degrees
Wind Tunnel	3.2%	4.5%	2.4%
CFD	4.0%	5.8%	2.1%

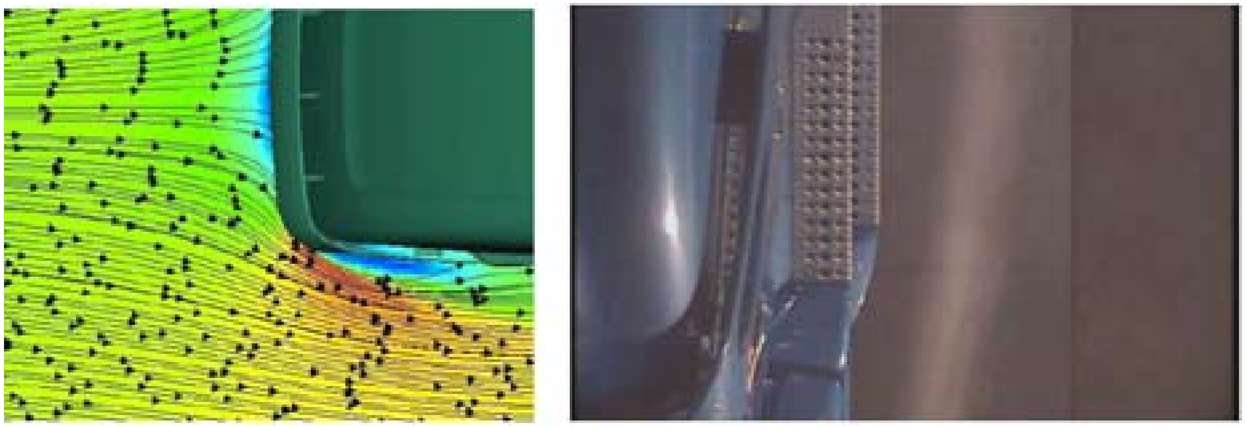
- Good agreement of CFD and wind tunnel results (CFD includes moving ground plane and spinning wheels)
- CFD and wind tunnel provide directionally similar results

Project Accomplishments Freightliner (3)

SAMPLE FLOW VISUALIZATION FROM CFD AND WIND TUNNEL



0 degree yaw
with mirrors
CFD (left)
Wind Tunnel (right)

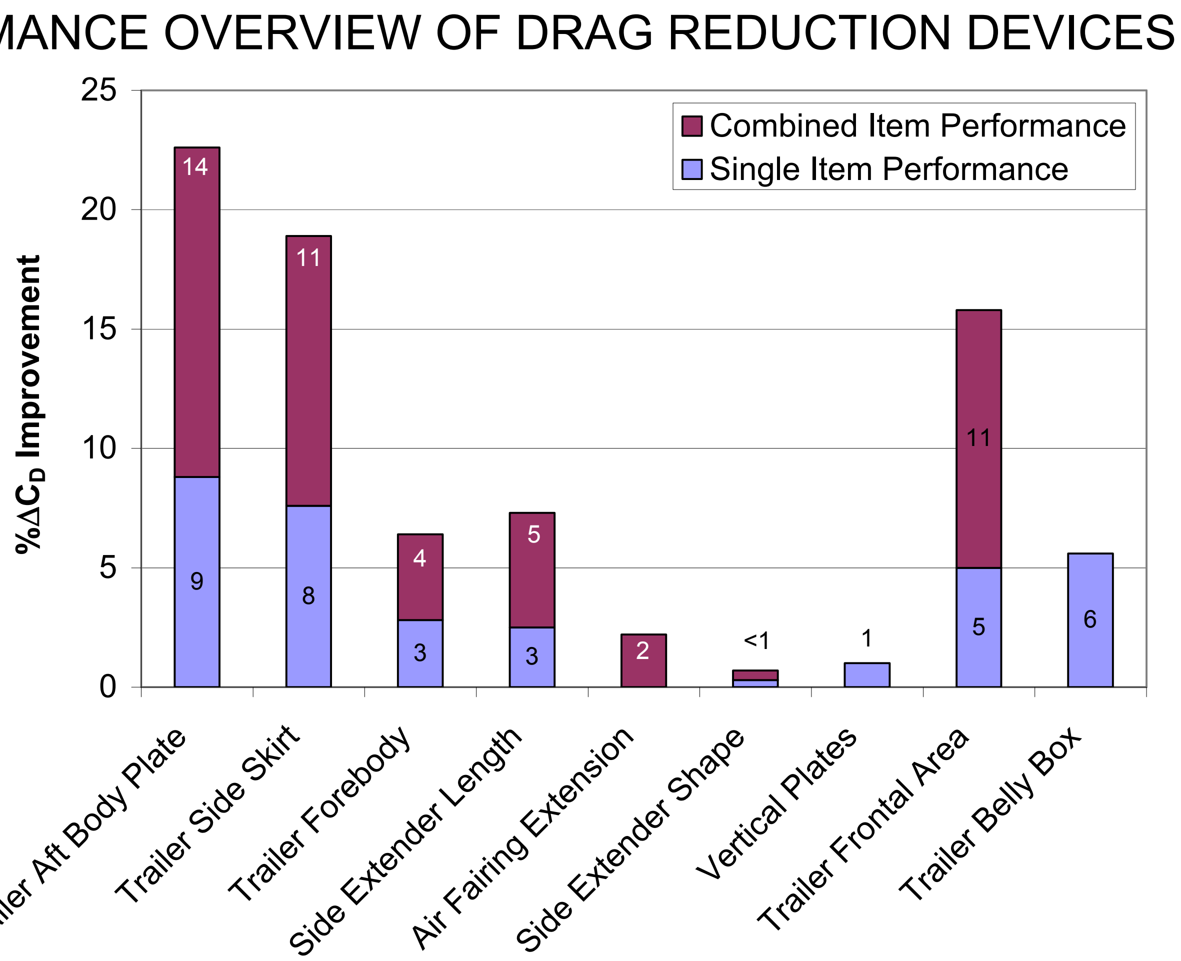


0 degree yaw
without mirrors
CFD (left)
Wind Tunnel (right)

Project Accomplishments International (1)

- Focus on practical devices to reduce aerodynamic drag
  - Tractor trailer gap closure
  - Trailer side
  - Trailer wake
- Scale model testing (1/8 scale models) at Texas A&M wind tunnel
- Incrementally evaluate about one dozen concepts

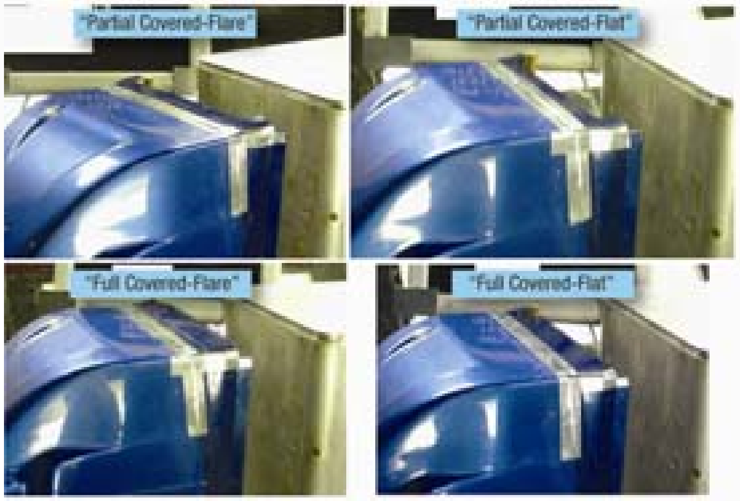
Project Accomplishments International (2)



Up to 23% improvement in drag coefficient with combination of devices (trailer aft body plates and trailer skirts)

Project Accomplishments International (3)

SAMPLE SCALE MODEL DEVICES



Project Accomplishments Mack (1)

- Test and evaluation of practical devices and systems to improve aerodynamic drag
  - Trailer gap enclosure (side extensions)
  - Trailer aerodynamics
- Combination of CFD modeling, discussion with experts in aerodynamics field, on-road testing

Project Accomplishments Mack (2)

TRAILER AERODYNAMIC AIDS

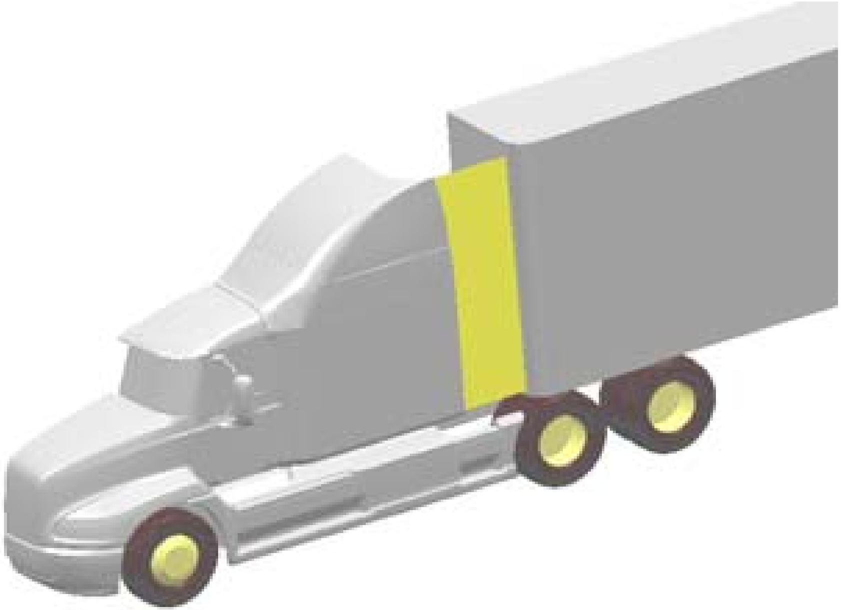
Vortex Traps from Solus

Boat tail (48 inch) from Clarkson University

Strakes from Solus

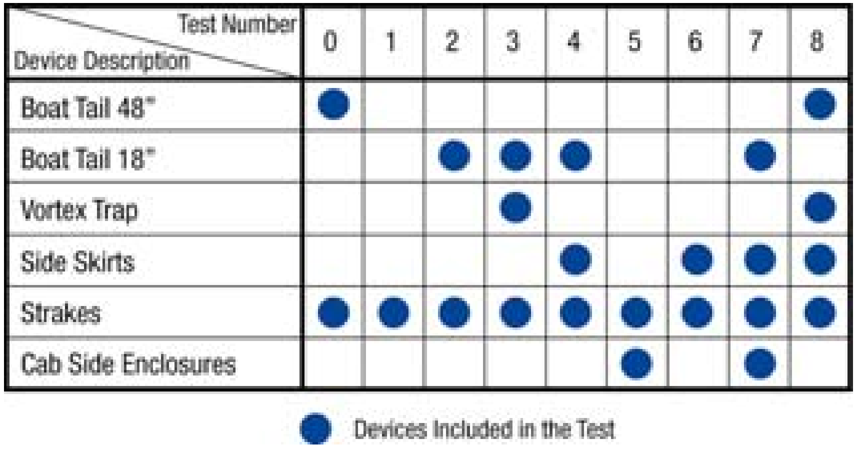
Trailer Side Skirts by Freight Wing Inc.

CAB SIDE EXTENDERS



Project Accomplishments Mack (3)

- Estimated drag force improvement for side extenders
  - 4% reduction at 0 degree yaw
- Through consultation with aerodynamics experts, determined most promising concepts and combinations for Phase II testing (see chart)



Test Number Device Description	0	1	2	3	4	5	6	7	8
Boat Tail 48"	●								●
Boat Tail 18"			●	●	●			●	
Vortex Trap				●					●
Side Skirts					●		●	●	●
Strakes	●	●	●	●	●	●	●	●	●
Cab Side Enclosures						●		●	

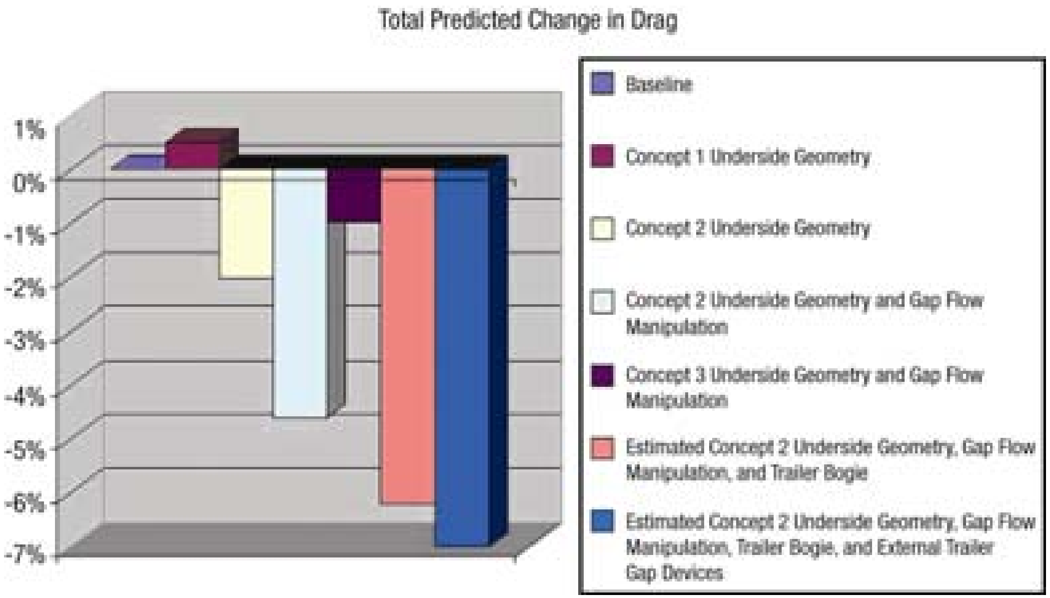
● Devices Included in the Test

Project Accomplishments Volvo (1)

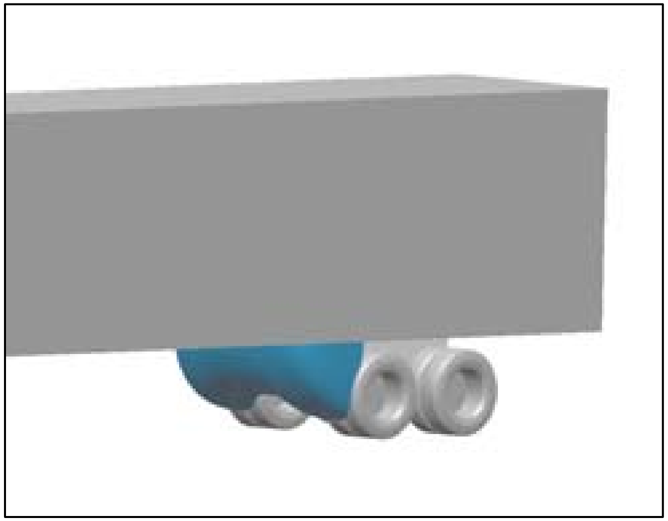
- Develop and demonstrate practical solutions to improve fuel economy by reducing aerodynamic drag in the focus areas
  - Focus areas = tractor and trailer underside and tractor-trailer gap
- Combination of CFD simulation, analysis of wind tunnel results, and on-road testing

Project Accomplishments Volvo (2)

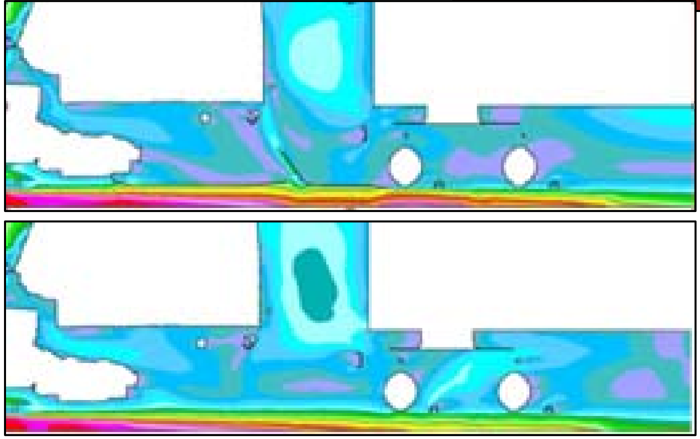
- Several combinations of underside geometry and trailer gap manipulation examined
- Trailer bogie deflector also examined
- Underside of tractor and trailer contribute about 35% to total vehicle drag
- Estimated effect of underside geometry modification, trailer gap manipulation, and trailer bogie deflector is 7% drag reduction



Project Accomplishments Volvo (3)



Trailer gap manipulation devices



Underside air flows

Collaborations

- Collaboration among four competitor OEMs to pursue complementary research and share results
- Work with existing DOE aerodynamic consortium
  - Presentation of project goals and objectives to consortium meeting (mid-2005)
  - Use of consortium members in Mack project to identify areas of potential interest for trailer aerodynamics

Future Plans

- Complete Phase II work for each manufacturer to achieve real aerodynamic benefits for Class 8 tractor-semitrailer combinations
  - Freightliner: Full-scale wind tunnel testing of different common mirror systems (West Coast style and aerodynamic) to determine aerodynamic drag effects
  - International: Full-scale prototype testing of concepts for tractor-trailer gap, trailer side, and trailer wake, for on-road impact on fuel economy
  - Mack: Full-scale prototype testing of combinations of boat tails, vortex traps, side strakes, side skirts, and cab enclosures for on-road impact on fuel economy
  - Volvo: Full-scale prototype testing of combinations of trailer bogie deflector, underside devices, and trailer gap devices for on-road impact on fuel economy
- Conduct end-of-project demonstration (location and date TBD, but probably in the fall of 2006) with sample test vehicles from all four manufacturers to illustrate results to government and industry representatives

Summary

- Relevance: Contribute toward DOE goal of reducing aerodynamic drag of Class 8 vehicles by 20%
- Approach: Examine aerodynamic devices and changes in vehicle configuration to understand drag effects through combination of CFD modeling, wind tunnel testing, and on-road vehicle testing in order to develop more aerodynamic tractor-semitrailer combinations
- Accomplishments: Calculated potential aerodynamic drag reductions of 4% to 23% for tractor-semitrailer systems
- Collaboration: Cooperation among four major truck manufacturers, work with existing aerodynamic consortia
- Future Research: Pursue combination of wind tunnel testing and on-road testing to demonstrate actual aerodynamic drag and fuel economy effects of changes to vehicle configuration

21st CENTURY TRUCK
PARTNERSHIP

2006 Heavy Vehicle Systems Optimization Merit Review and Peer Evaluation (link)

WEBLINK

The 2006 Heavy Vehicle Systems Optimization Merit Review and Peer Evaluation can be found at:

http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2006_hvso_merit_review.pdf

21st CENTURY TRUCK
PARTNERSHIP

Summary of More Electric Truck (document)

U.S. Department of Energy's "More Electric Truck" Hits the Road

The More Electric Truck Program is a government-industry collaboration

Initiated by:

The U.S. Department of Energy

Administered by:

Argonne National Laboratory

Industry Partners:

Caterpillar Inc.

Kenworth Truck Company

Emerson

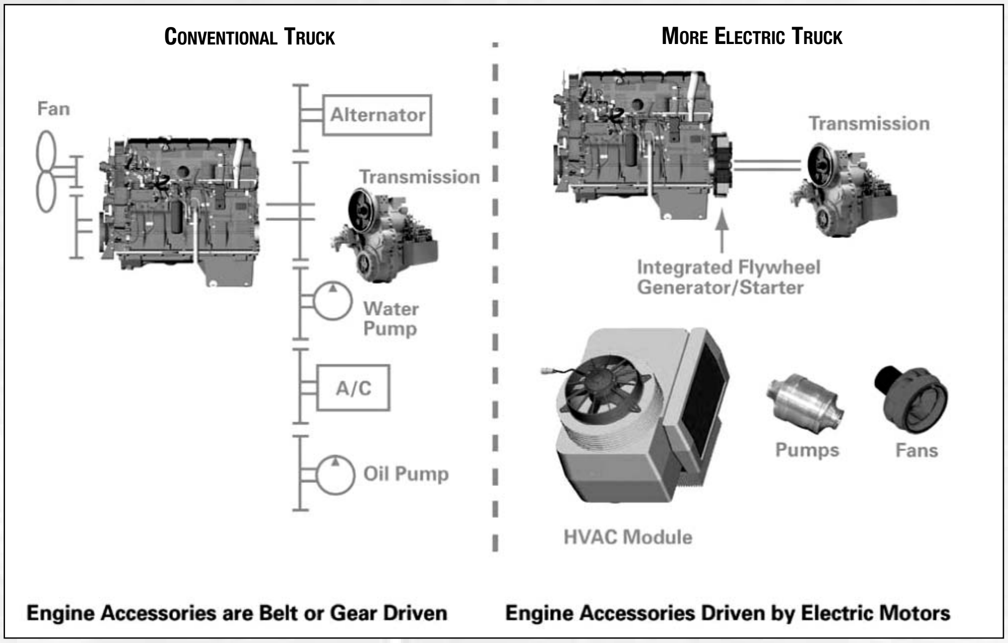
Engineered Machined Products

The engine compartment on today's trucks is a hot and crowded place. Pumps, alternators, compressors, and other engine accessories all give off heat as they compete for space and for the energy they need from the engine. These accessories have little effect individually on engine power, but together – via belts and pulleys – they can rob much of a diesel engine's fuel efficiency.

Now, thanks to a collaboration launched in 2000 between private industry and the U.S. Department of Energy (DOE), the life of a diesel engine in long-haul trucks is about to get easier, as in cooler and more efficient. A DOE project called the "More Electric Truck" is introducing new technology that takes a big load off the engine by using electrically powered accessories, instead of mechanically powered ones. Electrical power allows the accessories to operate independently of the engine, so they can perform at the precise speed, pressure, or flow rate required.

"The More Electric program is a collaborative government and industry effort initiated by the U.S. Department of Energy through Argonne National Laboratory, in partnership with Caterpillar, Kenworth, Emerson, and Engineered Machined Products," said Sid Diamond, the DOE's More Electric Truck Technology Development Manager. "Right now the prototype More Electric technology has been installed in a Kenworth T2000 truck for testing, and in 2004 we plan to build additional trucks incorporating key elements from the DOE truck demonstration. These vehicles will be out on the highways to prove the equipment's reliability and durability, and to demonstrate its improved fuel economy in fleet operations. The technology is expected to become commercially available to truck OEMs and fleets nationwide in late 2005."

The prototype vehicle has already been showcased in Washington, D.C., for members of Congress. It features an electrically driven heating, ventilating, and air-conditioning (HVAC) module, and a high-efficiency 30 kW generator. Other features include an integrated auxiliary power unit (APU) and a "shore-power" connection that permits the truck to plug in like a recreational vehicle at a campground. Shore power is being installed at a few initial truck stop demonstration sites and its availability is expected to grow quickly, so drivers won't have to idle their big diesels to stay comfortable and to keep their engines warm. The new More Electric accessories are not just add-on pieces of hardware, but are part of a highly integrated system specifically designed to meet the needs of the truck industry while minimizing weight and costs.



More Electric technology uses a generator to provide high-efficiency electrical power to drive several accessories on a flow/pressure/power-on-demand approach. The technology provides fuel savings, improved reliability, and several benefits such as better cold weather starting.

NEW CONCEPT IS GENERATING INTEREST

A More Electric Truck uses electrically driven accessories powered by a generator located inside the flywheel housing, which also serves as the starter motor. The accessories converted to electrical power on the research demonstration vehicle are the HVAC, brake air compressor, and oil and water pumps. These and future electrically driven devices, once commercially developed and validated, will start to appear on vehicles throughout the trucking industry.

TEST RESULTS ENCOURAGING

According to the program's technical leader, Caterpillar's Dr. Marcelo Algrain, "the test results showed that the fuel economy of the More Electric truck improved by 8 percent overall – 2 percent in over-the-road driving, and almost 6 percent from not idling the main engine overnight."

The reduction in engine idling alone could save over 600 million gallons of diesel fuel every year and annually reduce engine emissions equal to that produced by 15.5 million cars. Argonne National Laboratory researchers have shown that by eliminating overnight idling, more than $2,000 a year per truck could be saved in fuel and engine maintenance costs. Argonne's work also shows that trucks idling overnight put an estimated 7.6 million tons of carbon dioxide, 140,000 tons of nitrogen oxides, and 2,400 tons of carbon monoxide into our atmosphere.

MORE ELECTRIC IS MORE RELIABLE

Using electricity, instead of mechanical power, to operate engine accessories offers significant benefits for truck builders in their quest to manufacture "million mile accessories." Electrically driven accessories are typically more reliable than mechanical ones and also improve serviceability by permitting mechanics to easily swap out the modular units. Historically, when it comes to component reliability, the alternator and HVAC's air-compressor have been among the top five most problematic components on heavy-duty trucks. And it usually requires a specially trained refrigeration technician to service a truck's air-conditioning unit.

The More Electric APU is integrated with truck subsystems to produce a lower cost and weight package. This eliminates the need to idle the main diesel engine, which saves fuel, reduces emissions and lowers noise.

Conventional mechanical water pump (left) and equivalent More Electric electrically driven water pump.

The More Electric truck's new HVAC system combines everything into one preassembled, precharged, and pretested module that eliminates up to 65 parts. The new HVAC unit replaces the two separate heating and air-conditioning units used today on most trucks with sleeper cabs (one in the dashboard and one usually under the sleeper cab bunk). When used with the More Electric truck's integrated idling reduction features, an operator will have a more comfortable and quieter sleeping environment that enhances driver comfort and job satisfaction.

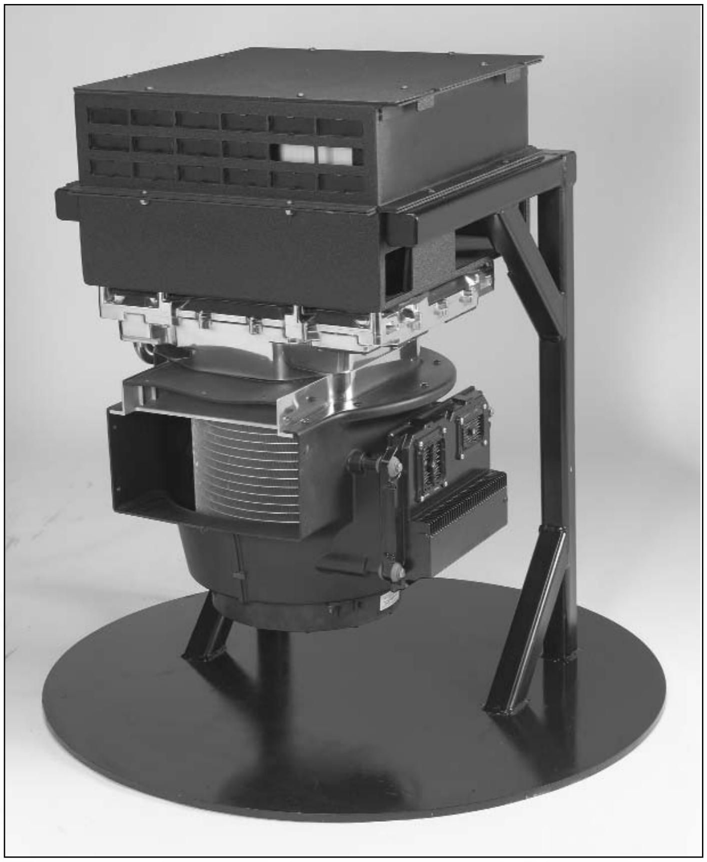
On a More Electric truck, the HVAC's electrically powered, hermetically sealed compressor and electric motor are located inside a sealed housing, which eliminates the refrigerant leaks from the shaft seal that are common with belt-driven automotive air conditioners. The resulting HVAC unit is five times more reliable and lasts up to three times longer than conventional air-conditioning systems. Electrically driven HVAC modules also permit truck OEMs to relocate the condenser coil from the engine compartment to other areas on the vehicle in order to increase space under the hood and take the air conditioner's thermal load off the radiator.

COLLABORATIVE GOVERNMENT-INDUSTRY TEAM EFFORT

Each partner brought core competencies to the $4.8 million, cost-shared More Electric Truck project, with Caterpillar providing engine technology, mechanical design, electronics, controls and overall systems integration; Kenworth supplying truck expertise, test vehicle and testing capabilities; Emerson offering its electric motor and power electronics knowledge; and EMP developing the new electrically driven water and oil pumps.

Making a more reliable and efficient truck is a primary reason why Kenworth is participating in the project. "People expect a very efficient truck when they buy a Kenworth, one that helps them lower their operating costs," said Dr. John Duffy, Senior Project Engineer in Kenworth's Advanced Concepts Group. "We believe that, in the future, electrically powered components will make our trucks even more durable and that the increased efficiency will offer a quick payback. This is what the industry wants to see before investing in new technology such as this."

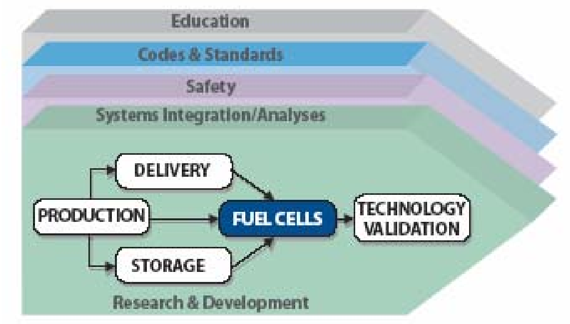
As more truck and component OEMs seek to offer longer product life, and as the need for cleaner, more fuel-efficient vehicles continues to increase, More Electric technology will be there to meet the needs of the truck industry. "It's definitely a win-win-win technology," says Randall Blanton, Director of Caterpillar's Advanced Electric Systems. "The production version of this technology is expected to have an estimated 18-month payback period. For the added investment in More Electric components, truck owners win by gaining an increase in fuel savings and from a significant improvement in the durability of two historically problem-prone accessories, the HVAC and the alternator. It's also a win for drivers, who will appreciate the dramatically improved cab environment during rest periods. And by reducing emissions and noise from idling trucks, More Electric technology is also a win for our environment."



The More Electric HVAC module has an electrically powered, hermetically sealed compressor.

DOE Fuel Cell Technical Plan (document)

3.4 Fuel Cells



Fuel cells have the potential to reduce our energy use and the nation's dependence on imported petroleum. The Fuel Cell subprogram emphasizes polymer electrolyte membrane (PEM) fuel cells as replacements for internal combustion engines in light-duty vehicles to support the goal of reducing oil use in the transportation sector. In addition to hydrogen fuel cells for vehicles, the program also supports fuel cells for stationary power, portable power and auxiliary power applications to a limited degree where earlier market entry would assist in the development of a fuel cell manufacturing base. The technical focus is on developing materials and components that enable fuel cells to achieve the fuel cell subprogram objectives, primarily related to system cost and durability.

For transportation applications, the Fuel Cell subprogram is focused on direct hydrogen fuel cells, in which the hydrogen fuel is stored on board and is supplied by a hydrogen production and fueling infrastructure. This hydrogen production and delivery infrastructure is being developed in parallel with fuel cell development efforts. For distributed stationary power generation applications, fuel cell systems will likely be fueled with reformate produced from natural gas, liquefied petroleum gas (LPG, consisting predominantly of propane) or renewable liquid fuels. Fuel cells for auxiliary power units in trucks will likely use either diesel or LPG, and recreational vehicles will be powered by LPG. In small consumer electronics, hydrogen or methanol will likely be the fuel of choice for fuel cell systems.

3.4.1 Technical Goal and Objectives

Goal

Develop and demonstrate fuel cell power system technologies for transportation, stationary and portable power applications.

Objectives

The primary focus is on fuel cells for transportation applications, with the following objective:

- By 2010, develop a 60% peak-efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of $45/kW; by 2015, a cost of $30/kW.

The secondary focus is on stationary power and other early market fuel cell applications to establish the manufacturing base, with the following objectives:

- By 2011, develop a distributed generation PEM fuel cell system operating on natural gas or LPG that achieves 40% electrical efficiency and 40,000 hours durability at $750/kW.[1]
- By 2010, develop a fuel cell system for consumer electronics (<50 W) with an energy density of 1,000 Wh/L.
- By 2010, develop a fuel cell system for auxiliary power units (3-30 kW) with a specific power of 100 W/kg and a power density of 100 W/L.

---

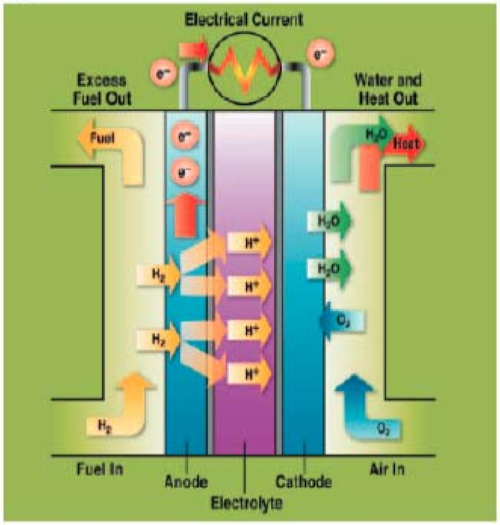
[1] Milestone delayed from 2010 to 2011 due to appropriations shortfall and Congressionally directed activities.

3.4.2 Technical Approach

Fuel cell research and development (R&D) will emphasize activities aimed at achieving high efficiency and durability and low material and manufacturing costs of the fuel cell stack. R&D to develop lower cost, better performing balance-of-plant components like air compressors, water and heat management systems and sensors is also being pursued. Each application – light-duty vehicle transportation, stationary power, auxiliary power units (APUs) for heavy-duty vehicles and portable power for consumer electronics—has specific requirements for technology development.

PEM fuel cells, shown in Figure 3.4.1, are the current focus for light-duty vehicles because they have fast- start capability and operate at comparatively low temperatures. High temperature fuel cells - solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC) - are the current focus for stationary power generation because of their fuel flexibility, high efficiency and the potential for combined heat and power generation. (DOE's Office of Fossil Energy supports R&D of SOFCs for distributed generation through its Solid State Energy Conversion Alliance program, http://www.netl.doe.gov/seca/.) If high-temperature (e.g., ~120°C) polymer membranes are successfully developed, PEM fuel cells could be considered for smaller scale combined heat and power applications. PEM technologies are being considered for back-up power or other applications that require faster start-up times. Because of their fuel flexibility and simpler reforming systems, SOFCs are more applicable as APUs on heavy-duty vehicles where systems may run for extended periods without frequent start and stop cycles. Direct methanol fuel cells (DMFCs) are well suited for portable power applications in consumer electronic devices where the power requirements are low and the cost targets and infrastructure requirements are not as stringent as for transportation applications.

Figure 3.4.1. Polymer Electrolyte Membrane Fuel Cell



To meet the efficiency, durability and cost requirements for fuel cells, R&D will focus on identifying new materials and novel design and fabrication methods for membranes, cathode catalysts and supports, cell hardware (including bipolar plates and seals) and balance-of-plant components (e.g., compressors, radiators, humidifiers, etc.). Developing low cost durable membranes and catalysts that tolerate a wide range of operating conditions is particularly challenging. Testing of new materials, designs and fabrication methods will be carried out by industry, national laboratories and universities. While progress is being made in developing fuel cell membranes, membranes that are capable of operating up to 120°C for automotive applications and above 120°C for stationary applications are needed for better thermal management. Continuing advancements are also needed to minimize precious metal loading, assess and improve component durability, develop thin catalyst coatings for membranes, and develop high-volume fabrication processes for highly conductive, gas-impermeable bipolar plates.

R&D efforts focus on materials, components and enabling technologies for low-cost fuel cell power systems operating on direct hydrogen for transportation, reformate for stationary and auxiliary power and methanol for consumer electronic applications. New R&D efforts will focus on advanced membrane materials including demonstration in membrane electrode assemblies (MEAs), water transport within the stack, advanced cathode catalysts and supports, cell hardware including bipolar plates and seals, innovative fuel cell concepts and the effects of impurities on fuel cell performance and durability. The Technology Validation subprogram (see section 3.5) will provide fuel cell vehicle and stationary power data under real-world conditions and, in turn, supply valuable results to help refine and direct future activities for fuel cell R&D.

3.4.3 Programmatic Status

Current Activities

Table 3.4.1 summarizes the current (FY 2006) activities in the Fuel Cells subprogram. Activities targeted towards polymer electrolytes include the identification and development of ionomers with increased conductivity, increased mechanical and chemical durability and reduced material costs. Failure mechanisms in fuel cells are being explored both experimentally and via modeling. Scaleable fabrication processes for production of membranes, electrodes, MEAs and bipolar plates are being designed. Catalysts and supports with reduced precious metal loading, increased activity and durability, and lower cost (including non-precious metal catalysts) are under development. Bipolar plates with lower weight and volume and with negligible corrosion are being investigated. To enable early-market entry of fuel cells, R&D on stationary and other applications such as portable power and auxiliary power units is pursued. To gauge the status of the technology, the cost and performance of fuel cell components are benchmarked and evaluated.

A new effort to develop high temperature, low relative humidity polymer electrolyte-type membrane materials suitable for use in a polymer electrolyte-type membrane fuel cell has begun. This effort will focus on alternative materials with performance up to 120°C and low relative humidity (pH2O 1.5 kPa or <10% relative humidity at 80°C) exceeding that of Nafion® (at 80°C and 100% relative humidity).

Table 3.4.1 Current Fuel Cell Activities

Challenge	Approach	Activities
Membranes		
Develop membranes that meet all targets	• Identify/develop ionomers/ membranes with reduced raw material cost • Identify/develop ionomers/membranes with improved conductivity and mechanical/chemical/thermal stability over the entire temperature and humidity range • Test and characterize membranes to improve durability • Design scaleable membrane fabrication processes for producing membranes with mechanical/chemical/thermal stability over the entire temperature and humidity range	• **DuPont:** Perfluorosulfonic acid membranes with extended lifetime • **Plug Power:** Polybenzimidazole-based, high temperature membranes • **Arkema Chemicals:** Polyvinylidenefluoride-based membranes • **3M:** Perfluorosulfonic acid membranes with extended lifetime • **Case Western Reserve University:** Nanocapillary network proton conducting membranes for high temperature fuel cells • **Case Western Reserve University:** Poly (p-phenylene sulfonic acid) with frozen-in free volume for high temperature fuel cells • **Arizona State University:** Protic salt polymer membranes • **Clemson University:** Fluoroalkylphosphonic-acid-based proton conductors • **Colorado School of Mines:** Hybrid heteropoly acid organic/inorganic composite materials • **FuelCell Energy, Inc.:** High temperature membrane with humidification-independent cluster structure • **GE Global Research:** High-performance polymer fuel cell membranes • **Giner Electrochemical Systems:** Dimensionally stable high temperature membranes • **Pennsylvania State University:** New proton-conducting composite materials • **Virginia Tech:** New multiblock co-polymers with proton-conducting fillers • **The University of Tennessee:** Poly(cyclohexadiene)-based polymer electrolyte membranes • **University of Central Florida:** Polymeric electrolyte phosphotungstic acid composite membranes • **Giner Incorporated (SBIR):** Dimensionally stable high performance membrane • **Oxford Performance Materials (I&I):** High temperature membrane and electrode device • **Argonne National Lab:** Dendronized

Table 3.4.1 Current Fuel Cell Activities

Challenge	Approach	Activities
		polymers, cross-linked dendrimers and organic/inorganic hybrid materials • **Lawrence Berkeley National Lab:** N-tethered imidazole polymers for high temperature membranes • **Los Alamos National Lab:** Non-Nafion® membranes • **National Renewable Energy Lab:** Heteropoly acid-based membranes • **Los Alamos National Lab:** Polymer-immobilized ionic liquids • **Sandia National Lab:** Hydrocarbon membranes using sulfonated Diels-Alder polymers
Electrodes		
Develop electrodes that meet all targets	• Develop electrocatalysts with reduced precious metal loading, increased activity, improved durability/stability and increased tolerance to air, fuel and system-derived impurities • Develop supports with reduced corrosion • Optimize electrode design and assembly, including design of scaleable, high-throughput fabrication processes and optimization of catalyst/support interactions and microstructure	• **Ballard:** Metal/chalcogen based cathode catalysts • **3M**: Innovative low cost technology to synthesize non-precious metal catalysts and their supports • **University of South Carolina:** Novel non-precious metal catalysts through molecular modeling and durability studies • **Cabot Superior MicroPowders:** New cathode catalysts and layer structures for high performance and low-platinum loading • **Jet Propulsion Laboratory:** Advanced cathode catalysts • **Farasis Energy (SBIR):** Low-cost cathode catalysts using novel combinatorial screening • **NuVant Systems (SBIR):** Low-cost cathode catalysts using high throughput, rapid screening methods • **Argonne National Lab:** Platinum stability and non-platinum catalysts • **Brookhaven National Lab:** Low-platinum loading catalysts • **Lawrence Berkeley National Lab:** Low-platinum loading electrocatalysts using materials-by-design approach • **Los Alamos National Lab:** Non-precious metal catalysts (chalcogenides and transition metal composites) • **Naval Research Laboratory:** Metal-oxide catalyst supports to reduce platinum loading

Table 3.4.1 Current Fuel Cell Activities

Challenge	Approach	Activities
Membrane electrode assemblies		
Develop MEAs that meet all targets	• Effectively integrate membrane and electrodes to optimize mechanical and chemical interactions of the catalyst, support, ionomer and membrane and to minimize interfacial resistances • Design scaleable, high-throughput fabrication processes for high-performance MEAs • Expand the operating range of MEAs (temperature, relative humidity, tolerance to air, fuel and system-derived impurities) and improve durability with cycling • Test, analyze and characterize MEAs before, during and after operation • Develop sustainable MEA designs that incorporate recycling/reclamation of catalysts and membranes and/or re-use of cell components	• **DeNora:** Integrated manufacturing for advanced MEAs • **3M:** Advanced MEAs for enhanced operating conditions, amenable to high volume manufacture • **UTC:** High temperature membranes and improved cathode catalysts for PEM fuel cells • **3M:** MEA and stack durability for PEM fuel cells • **Ion Power, Inc.:** Catalyst-coated fuel cell membrane component recycling and remanufacture/re-use • **Engelhard:** Recovery and recycling of precious metals • **Argonne National Lab:** Fuel cell start-up from cold and subfreezing conditions • **Argonne National Lab:** Impurity effects on electrodes and membranes • **Los Alamos National Lab:** Electrocatalyst supports and electrode structures • **Los Alamos National Lab:** Freeze-thaw effects on the performance and durability of MEAs • **Los Alamos National Lab:** Impurity effects on MEA performance • **Los Alamos National Lab:** Fuel cell durability (drive cycle, platinum particle growth, mass transport resistance) • **National Institutes of Standards and Technology:** Neutron imaging to characterize water transport in a working fuel cell • **Oak Ridge National Lab:** Microstructural characterization of PEM fuel cell MEAs • **Oak Ridge National Lab:** Fiber optic fuel cell characterization

Table 3.4.1 Current Fuel Cell Activities

Challenge	Approach	Activities
Gas diffusion layers (GDL)		
Develop low-cost, durable GDLs that improve fuel cell performance	• Increase performance and water management by optimizing GDL properties (conductivity and hydrophobicity) and pore structure and improving GDL coatings • Improve understanding of GDL corrosion and aging and develop mitigating strategies • Develop GDL testing and characterization protocols and techniques (including hydrophobicity and conductivity tests)	• **No current activity**
Bipolar plates		
Develop low-cost, durable bipolar plates that meet all targets	• Decrease weight and volume of bipolar plates • Design low-cost, scaleable fabrication processes • Improve understanding of bipolar plate degradation mechanisms and develop mitigating strategies	• **Porvair:** Scale-up of net-shape molded production of low cost carbon/carbon bipolar plates • **Nanosonic, Inc. (SBIR):** Economical, high performance thermoplastic composite bipolar plates • **National Renewable Energy Lab:** Corrosion protection of metallic bipolar plates • **Oak Ridge National Lab:** Cost-effective surface modification of metallic bipolar plates • **Pacific Northwest National Lab:** Low-cost, clad metal bipolar plates
Seals		
Develop reliable, durable, low-cost seals	• Develop seals that achieve very low leak rates • Develop seals that tolerate the entire fuel cell operating temperature and humidity range • Improve understanding of seal degradation mechanisms and develop mitigating strategies	• **No current activity**

Table 3.4.1 Current Fuel Cell Activities

Challenge	Approach	Activities
Balance-of-plant components		
Develop efficient, cost-effective air management technologies that meet all targets	• Develop new engineering approaches to compressor/expander technologies • Improve efficiency and performance of compressors/expanders • Reduce weight, cost and footprint of components	• **Honeywell:** Turbo compressor for PEMFC transportation systems • **Mechanology:** Toroidal intersecting vane compressor/expander module
Develop efficient, cost-effective thermal/water management systems	• Develop advanced cooling/heat exchange and humidification materials and concepts • Reduce weight, cost and footprint of components	• **Advanced Fluids (SBIR):** Improved coolant (water/glycol with nanoparticles) for use in automotive fuel cell systems • **Oak Ridge National Lab:** Carbon fibers for lightweight, compact thermal management system components (heat exchangers, radiators, evaporators) • **Honeywell:** Integrated thermal/water management system that efficiently uses the fuel cell waste heat and water
Develop effective, reliable physical and chemical sensors that meet all targets	• Develop accurate, reliable, durable, fast-responding sensors to measure physical properties and chemical species • Reduce cost and footprint of sensors	• **No current activity**
Stationary and other early market fuel cells		
Develop cost-effective, efficient, reliable and durable fuel cells for stationary applications that meet all targets	• Improve system durability • Improve performance of stack operating on reformate • Improve fuel processor performance • Increase system electrical efficiency and balance tradeoffs between performance and efficiency	• **Plug Power:** Fuel cells for back-up power/peak-shaving • **UTC Fuel Cells:** Fuel cell durability improvement and 150 kW power plant verification • **IdaTech:** Fuel cells with combined heat and power for building applications • **Nuvera:** Cost-effective, high-efficiency advanced reforming module
Develop cost-effective, reliable, durable fuel cells for portable power applications (e.g., cell phones, computers, etc.) that meet all targets	• Develop membranes that will reduce methanol crossover in portable power fuel cells • Design, build and test portable power systems	• **MTI Micro Fuel Cells:** Direct methanol fuel cell (DMFC) prototype for consumer electronics • **Polyfuel:** Membrane development for DMFCs for all-day wireless computing • **Tekion, Inc. (I&I):** Cell phones with fuel cells using renewable fuels

Table 3.4.1 Current Fuel Cell Activities

Challenge	Approach	Activities
Develop auxiliary power unit (APU) systems for heavy truck applications to reduce idling of the main engine that meet all targets	• Analyze and design fuel cell APU system • Build and test APUs	• **Delphi:** Full-scale laboratory demonstration of APU system with simulated load cycles • **Cummins Power Generation:** In-vehicle demonstration of diesel-fueled SOFC system
Develop system to allow PEM fuel cells to operate in off-road applications	• Evaluate air filtration technologies for off-road applications	• **IdaTech:** PEM fuel cell system for off-road applications
Analysis		
Conduct system and tradeoff analysis	• Evaluate rated power design versus performance and efficiency • Evaluate start-up energy and start-up time • Evaluate hydrogen quality versus durability and performance	• **Argonne National Lab:** System analysis, tradeoffs and optimization • **Lawrence Berkeley National Lab:** Failure mechanism model for polymer electrolyte fuel cells
Perform cost analysis	• Assess potential for cost reductions to reach customer-acceptable levels	• **Battelle:** Analysis of early markets for the hydrogen economy • **TIAX:** Automotive fuel cell system cost estimate • **Directed Technologies Inc.:** Automotive fuel cell system cost estimate
Annually update technology status	• Evaluate status of technology versus DOE targets	• **Argonne National Lab:** Technical analysis • **Los Alamos National Lab:** Technical analysis
Characterize and benchmark fuel cells		
Test and evaluate fuel cell components and systems	• Perform independent testing to characterize component and stack properties before, during and after operation • Experimentally determine stack failure mechanisms and system emissions • Obtain performance metrics of fuel cell components and systems	• **Argonne National Lab :** FCTES^{QA} -- analysis of fuel cell testing protocols as part of International Partnership for the Hydrogen Economy effort • **Los Alamos National Lab:** Fundamental understanding and technical underpinnings of fuel cell technology • **Los Alamos National Lab:** Component benchmarking • **Argonne National Lab:** Fuel cell testing to obtain status of technology

Table 3.4.1 Current Fuel Cell Activities

Challenge	Approach	Activities
Innovative concepts		
Develop innovative fuel cell designs that provide improved performance, durability and cost	• Develop novel, lower cost materials for fuel cells or balance-of-plant components • Develop alternative fuel cell system designs, materials or configurations that simplify, integrate or eliminate components or functions	• **No current activity**

3.4.4 Technical Challenges

Cost and durability are the major challenges to fuel cell commercialization. Size and weight are approaching targets but further reductions are needed to meet packaging requirements for commercial systems. The tolerance of fuel cell stacks to impurities has not been established. Tolerance to air, fuel and system derived impurities (including the storage system) needs to be established. Operation at low relative humidity (p_{H2O} 1.5 kPa or <10% relative humidity at 80°C) and start-up from sub-freezing temperatures has not been demonstrated. Cost, efficiency and packaging of fuel cell balance-of-plant components are also barriers to the commercialization of fuel cells. For transportation applications, fuel cell technologies face more stringent cost and durability requirements. In stationary power applications, raising the operating temperature of PEMs to increase fuel cell performance will also improve heat and power cogeneration and overall system efficiency. Fuel cell systems for consumer electronics need to have improved energy density to compete with batteries, and fuel cells for auxiliary power need to have a reduced size and weight to meet packaging requirements for heavy-duty trucks.

Transportation Systems

The cost of fuel cell power systems must be reduced before they can be competitive with gasoline internal combustion engines (ICEs). Automotive ICE power plants currently cost about $25-35/kW; a fuel cell system needs to cost less than $50/kW for the technology to be competitive. A significant fraction of the cost of a PEM fuel cell comes from precious metal catalysts that are currently used on the anode and cathode for the electrochemical reactions. Other key cost factors include the membrane, cell hardware and balance-of-plant components.

The durability of fuel cell systems operating under automotive conditions has not been established. Fuel cell power systems will be required to be as durable and reliable as current automotive engines, i.e., 5,000 hour lifespan (150,000 miles equivalent) and able to function over the full range of external environmental conditions (-40° to +40° C). Membranes are critical components of the fuel cell stack and must be able to perform over the full range of system operating temperatures with less than 5% loss of performance by the end of life and without external humidification. External humidification adds cost and complexity to the system. The durability of catalysts is also an issue and can be compromised by platinum sintering and dissolution, especially under conditions of load-cycling and high electrode potentials. Carbon support corrosion is another challenge at high electrode potentials and can worsen under load cycling and high temperature operation.

Fuel cell and stack hardware (bipolar plates, gas diffusion layers and seals) also need further development. Bipolar plates represent a significant fraction of stack cost and weight, which must be reduced. Seal materials must be durable over the lifetime of a fuel cell and achieve acceptable leak rates.

Air management for fuel cell systems is a challenge because today's compressor technologies are not suitable for automotive fuel cell applications. In addition, thermal and water management for fuel cells are issues. Fuel cell operation at lower temperatures creates a small differential between the operating and ambient temperatures necessitating large heat exchangers and humidifiers. These components increase the cost and complexity of the system and use some of the power that is produced, reducing overall system efficiency.

The size and weight of current fuel cell systems must be further reduced to meet the packaging requirements for automobiles. Size and weight reduction applies not only to the fuel cell stack (catalysts, membranes, gas diffusion media and bipolar plates), but also to the ancillary components (e.g., compressor/expander, heat exchangers, humidifiers and sensors) which make up the balance-of-plant. Finally, lightweight, compact on-board hydrogen storage systems and economically-viable hydrogen fuel also present challenges (see sections 3.3, 3.1 and 3.2).

Stationary/Distributed Generation and Other Fuel Cell Systems

Even though the specific performance requirements differ from transportation applications, some of the technical challenges for stationary and other fuel cell systems are the same. For example, the overall cost of these fuel cell power systems must also be competitive with conventional technologies or offer enhanced capabilities. However, stationary and other fuel cell systems have an acceptable price point considerably higher than transportation systems.

Performance of fuel cells for stationary applications for up to 20,000 hours has been demonstrated but market acceptance of stationary applications will likely necessitate more than 40,000 hours of reliable operation over the full range of external environmental conditions (-35°Cto 40°C).

The low operating temperature of PEM fuel cells limits the amount of waste heat that can be effectively used in combined heat and power (CHP) applications. Technologies need to be developed that will allow higher operating temperatures and/or more effective heat recovery systems. Improved system designs that will enable CHP efficiencies exceeding 80% are also needed. Technologies that allow the thermal energy rejected from stationary fuel cell systems to be utilized in heating and cooling systems also need to be evaluated. For example, the thermal energy can be utilized to regenerate desiccants in a desiccant cooling cycle. Start-up times need to be decreased in stationary fuel cell back-up power systems that operate on direct hydrogen.

Fuel cell systems for consumer electronics need to have improved energy density by more than a factor of three to compete with batteries. Fuel cells for auxiliary power applications need to have increased specific power and power density (by a factor of four) to meet packaging requirements for heavy-duty trucks.

3.4.4.1 Technical Targets

Tables 3.4.2 and 3.4.3 list the DOE technical targets specifically for integrated PEM fuel cell power systems and fuel cell stacks operating on direct hydrogen for transportation applications. These targets have been developed with input from the FreedomCAR and Fuel Partnership, which includes automotive and energy companies, specifically the fuel cell technical team. Tables 3.4.4 through 3.4.6 list the DOE technical targets for stationary applications. The targets have been developed with input from developers of stationary fuel cell power systems. These R&D targets do not go beyond 2011 because stationary applications are closer to market than transportation applications. The 2011 targets are those that would be necessary for technology readiness.

Tables 3.4.7 and 3.4.8 list the DOE technical targets for consumer electronics, and APUs and truck refrigeration. Tables 3.4.9 and 3.4.10 list DOE technical targets for automotive and stationary fuel cell system sensors and automotive compressor/expander units. Tables 3.4.11 through 3.4.14 list DOE technical targets for fuel cell components: membranes, electrodes/catalysts, membrane electrode assemblies and bipolar plates. Addition of these tables reflects a shift in program focus from development of fuel cell systems and stacks to component-level research. The tables will assist component developers in evaluating progress without testing full systems.

A draft specification of hydrogen quality required as input into the fuel cell system is provided in Appendix F.

All targets must be achieved simultaneously; however, status is not necessarily reported from a single system.

Table 3.4.2. Technical Targets for Automotive-Scale: 80-kW$_e$ (net) Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen[a]

Characteristic	Units	2003 Status	2005 Status	2010	2015
Energy efficiency[b] @ 25% of rated power	%	59	59	60	60
Energy efficiency @ rated power	%	50	50	50	50
Power density	W/L	440	500	650	650
Specific power	W/kg	420	470[c]	650	650
Cost[d]	$\$/kW_e$	200	110[e]	45	30
Transient response (time from 10% to 90% of rated power)	sec	3	1.5	1	1
Cold start-up time to 50% of rated power					
@–20°C ambient temp	sec	120	20	30	30
@+20°C ambient temp	sec	60	<10	5	5
Start up and shut down energy[f]					
from -20°C ambient temp	MJ	na	7.5	5	5
from +20°C ambient temp	MJ	na	na	1	1
Durability with cycling	hours	na	~1,000[g]	5,000[h]	5,000[h]
Unassisted start from[i]	°C	na	-20	-40	-40

[a] Targets exclude hydrogen storage, power electronics and electric drive.

[b] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Peak efficiency occurs at about 25% rated power.

[c] Based on corresponding data in Table 3.4.3 divided by 3 to account for ancillaries.

[d] Based on 2002 dollars and cost projected to high-volume production (500,000 systems per year).

[e] Status is from 2005 TIAX study and will be periodically updated.

[f] Includes electrical energy and the hydrogen used during the start up and shut down procedures.

[g] Durability with cycling is being evaluated through the Technology Validation activity. Steady state stack durability is 20,000 hours (See Table 3.4.4).

[h] Based on test protocol to be issued by DOE in 2007.

[i] 8-hour soak at stated temperature must not impact subsequent achievement of targets.

Table 3.4.3. Technical Targets: 80-kW$_e$ (net) Transportation Fuel Cell Stacks Operating on Direct Hydrogen[a]

Characteristic	Units	2003 Status	2005 Status	2010	2015
Stack power density[b]	W/L	1,330	1,500[c]	2,000	2,000
Stack specific power	W/kg	1,260	1,400[c]	2,000	2,000
Stack efficiency[d] @ 25% of rated power	%	65	65	65	65
Stack efficiency[d] @ rated power	%	55	55	55	55
Cost[e]	\$/kW$_e$	200	70[f]	25	15
Durability with cycling	hours	na	2,000[g]	5,000[h]	5,000[h]
Transient response (time for 10% to 90% of rated power)	sec	<3	1	1	1
Cold start-up time to 50% of rated power @ –20ºC ambient temperature @ +20ºC ambient temperature	 sec sec	 2 <1	 20 <10	 30 5	 30 5
Start up and shut down energy[i] from -20°C ambient temp from +20°C ambient temp	 MJ MJ	 na na	 7.5 na	 5 1	 5 1
Unassisted start from[j]	ºC	na	-20	-40	-40

[a] Excludes hydrogen storage, power electronics, electric drive and fuel cell ancillaries: thermal, water and air management systems.

[b] Power refers to net power (i.e., stack power minus auxiliary power). Volume is “box” volume, including dead space.

[c] Average of data from selected industry press releases issued in 2004 and 2005.

[d] Ratio of output DC energy to lower heating value of hydrogen fuel stream. Peak efficiency occurs at about 25% rated power. Assumes system efficiency is 92% of stack efficiency.

e Based on 2002 dollars and cost projected to high-volume production, (500,000 stacks per year).

[f] Status is from 2005 TIAX study and will be periodically updated.

[g] Durability is being evaluated through Technology Validation activity. Steady state stack durability is 20,000 hours (See Table 3.4.5).

[h] Based on the test protocol to be issued by DOE in 2007.

[i] Includes electrical energy and the hydrogen used during the start up and shut down procedures.

[j] 8-hour soak at stated temperature must not impact subsequent achievement of targets.

Table 3.4.4. Technical Targets[a]: Integrated Stationary PEM Fuel Cell Power Systems (5-250kW) Operating on Reformate

Characteristic	Units	2003 Status	2005 Status	2011
Electrical energy efficiency[b] @ rated power	%	30	32	40
CHP energy efficiency[c] @ rated power	%	70	75[d]	80
Cost[e]	$\$/\text{kW}_e$	2,500	2,500	750
Transient response time (from 10% to 90% power)	msec	<3	< 3	< 3
Cold start-up time (to rated power @ -20ºC ambient) Continuous use application	min	<20	<90	<30
Survivability (min and max ambient temperature)	ºC ºC	-25 +40	-25 +40	-35 +40
Durability @ <10% rated power degradation	hour	15,000	20,000	40,000
Noise	dB(A)	<65 @ 10 m	<60 @ 10 m	<55 @ 10 m
Emissions (combined NO$_X$, CO, SO$_X$, hydrocarbon, particulates)	g/1000 kWh	<8	<8	<1.5

[a] Includes fuel processor, stack and all ancillaries.

[b] Ratio of DC output energy to the LHV of the input fuel (natural gas or LPG) average value at rated power over life of power plant.

[c] Ratio of DC output energy plus recovered thermal energy to the LHV of the input fuel (natural gas or LPG) average value at rated power over life of power plant

[d] For LPG, efficiencies are 1.5 percentage points lower than natural gas because the reforming process is more complex.

[e] Includes projected cost advantage of high-volume production (2,000 units/year). Current cost does not include integrated auxiliaries, battery and power regulator necessary for unassisted start.

Table 3.4.5. Technical Targets: Stationary PEM Fuel Cell Stack Systems (5-250 kW) Operating on Reformate[a]

Characteristic	Units	2005 Status[b]	2011
Cost[c]	$\$/\text{kW}_e$	1,500	530
Durability	hours	20,000	40,000
Transient response time (for 10% to 90% of rated power)	sec	<3	1
Cold start-up time (to rated power @ ~20ºC)	min	<2	<0.5
Survivability (min & max ambient temperature)	ºC ºC	-25 +40	-35 +40
CO tolerance[d]			
steady state (with 2% max air bleed)	ppm	50	500
transient	ppm	100	1000

[a] Excludes feedstock processing/delivery system. Includes fuel cell ancillaries: thermal, water and air management systems.

[b] This is the first year for which status is available.

[c] Includes projected cost advantage of high-volume production (2,000 units/year). Current cost does not include integrated auxiliaries, battery and power regulator necessary for unassisted start.

[d] CO tolerance requirements assume capability of fuel processor to reduce CO. Targets for the stack CO tolerance are subject to trade-offs between reducing CO in the fuel processor and enhancing CO tolerance in the stack. It is assumed that H_2S is removed in the fuel processor.

Table 3.4.6. Technical Targets: Stationary Fuel Processors (Equivalent to 5-250 kW) to Generate Hydrogen-Containing Fuel Gas[a]

Characteristic	Units	2005 Status[b]	2011
Cost[c]	$/kW$_e$	1000	220
Cold start-up time to rated power @ -20ºC ambient	min	<90	<30
Transient response time (for 10% to 90% power)	min	<5	1
Durability[d]	hours	20,000	40,000
Survivability (min and max ambient temperature)	ºC ºC	-25 +40	-35 +40
CO content in product stream[e]			
Steady state	ppm	10	1
Transient	ppm	100	25
H_2S content in product stream	ppbv (dry)	<10	<4
NH_3 content in product stream	ppm	<1[f]	<0.1

[a] Excludes fuel storage; includes controls, shift reactors, CO cleanup and heat exchangers.

[b] This is the first year for which status is available.

[c] Includes projected cost advantage of high-volume production (2,000 units/year). Current cost does not include integrated auxiliaries, battery and power regulator necessary for unassisted start.

[d] Time between catalyst and major component replacement; performance targets must be achieved at the end of the durability period.

[e] Dependent on stack development (CO tolerance) progress.

[f] 0.1 ppm is detection limit for NH_3.

Table 3.4.7. Technical Targets: Consumer Electronics (sub-Watt to 50-Watt)

Characteristic	Units	2005 Status[a,b]	2006	2010
Specific power	W/kg	20	30	100
Power density	W/L	20	30	100
Energy density	Wh/L	300	500	1,000
Cost	$/W	40[c]	5	3
Lifetime	hours	>500	1,000	5,000

[a] This is the first year for which status is available.

[b] Unless otherwise noted, status is based on average of available data.

[c] Fuel Cell Seminar Abstracts, 2004, p. 290.

Table 3.4.8. Technical Targets: Auxiliary Power Units
(3–5 kW rated, 5–10 kW peak) and Truck Refrigeration Units (10–30kW rated)

Characteristic	Units	2003 Status (Stack)	2005 Status (System) [a]	2006	2010	2015
Specific power	W/kg	50[b]	25[b]	70	100	100
Power density	W/L	50[b]	25[b]	70	100	100
Efficiency @ rated power[c]	%LHV	20	15	25	35	40
Cost[d]	$/kW$_e$	>2,000	>2,000	<800	400	400
Cycle capability (from cold start) over operating lifetime	number of cycles	10	5	40	150	250
Durability	hours	100	100	2,000	20,000	35,000
Start-up time	min	2-3 hours	60-90	30-45	15-30	15-30

[a] Estimate of current capability based on cell and small stack laboratory developments.

[b] Without power conditioning. Source: *Proceedings of the Sixth Annual SECA Workshop*, Pacific, Grove, CA, April 2005.

[c] Electrical efficiency only—does not include any efficiency aspects of the heating or cooling likely being provided.

[d] Cost based on high-volume manufacturing quantities (100,000 units/year)

Table 3.4.9. Technical Targets: Sensors for Automotive and Stationary Fuel Cell Systems[a]

All sensors require industrial standard output, e.g., 4-20 mA, 1-5 V (DC), 0-5 V (DC), 0-10 V (DC)

Sensor	2010 Requirement
Carbon Monoxide	(a) Stored H_2 at 99.99% at transportation fueling station • 0.1 – 0.5 ppm • Operational temperature: <150°C • Response time: 0.1–1 sec • Gas environment: dry hydrogen at 1-700 atm total pressure • Accuracy: $\leq$2% full scale (b) Reformate from stationary fuel processor to PEM stack • 100–1000 ppm CO sensors • Operational temperature: 250°C • Response time: 0.1–1 sec • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure • Accuracy: $\leq$2% full scale
Hydrogen in fuel processor output	• Measurement range: 25%–100% • Operating temperature: 70°–150°C • Response time: 0.1–1 sec for 90% response to step change • Gas environment: 1–3 atm total pressure, 10–30 mol% water, 30%–75% total H_2, CO_2, N_2 • Accuracy: $\leq$2% full scale
Hydrogen in ambient air	• Measurement range: full confidence of the ability to detect half of the lower explosion limit • Temperature range: -30°C to 80°C • Response time: under 1 sec • Gas environment: ambient air, 10–98% relative humidity range • Lifetime: 10 years • Interference resistant
Sulfur compounds (H_2S, SO_2, organic sulfur)	• Operating temperature: -40°C to 300°C • Measurement range: 0.001–0.5 ppm • Response time: <1 min at 0.05 ppm • Gas environment: H_2, CO, CO_2, hydrocarbons, water vapor
Flow rate of fuel processor output	• Flow rate range: depending on fuel cell size, maximum flow rate ranges from 30-7,500 SLPM • Temperature: 0-100°C • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure
Ammonia	• Operating temperature: 70–150°C • Measurement range: 0.15 ppm • Selectivity: <0.1 ppm from gas mixtures • Lifetime: 5–10 years • Response time: <1 min at 0.1 ppm • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure
Temperature	• Operating range: –40°C to 150°C • Response time: in the –40°C to 100°C range <0.5 sec with 1.5% fullscale accuracy (including drift); in the 100–150°C range, a response time <1 sec • Lifetime: 10 years • Gas environment: high-humidity; air or: H_2 at 1-3 atm (see Appendix F for concentration) • Insensitive to flow velocity

Relative humidity for cathode and anode gas streams	• Operating temperature: 0-120°C • Response time: <0.5 sec • Relative humidity: 20–100% • Accuracy: 1% full scale (including drift) • Lifetime: 10 years • Gas environment: high-humidity air, reformate or H_2 at 1-3 atm (see Appendix F for concentration)
Oxygen at cathode exit	• Measurement range: 0–50% O_2 • Operating temperature: 30–120°C • Response time: <0.5 sec • Accuracy: 1% full scale (including drift) • Lifetime: 10 years • Gas environment: CO_2, N_2, H_2O at 1–3 atm
Differential pressure in fuel cell stack	• Range: 0–1 psi or (0–10 or 1–3 psi, depending on the design of the fuel cell system) • Temperature range: 30–120°C • Survivability: –40°C • Response time: <1 sec • Accuracy: 1% full scale (including drift) • Lifetime: 10 years • Other: Measure pressure in the presence of liquid and gas phases
Flow rate for direct H_2 system	• Flow rate maximum: 2,500 SLPM for wet H2 • Flow rate maximum: 1,000 SLPM for dry H2 • Gas environment: H2 dry (see Appendix F for concentration), 25-100% relative humidity plus N2 • Lifetime: 10 years • Accuracy: ±5% full scale (including drift)

[a] Sensors for transportation must enable conformation to size, weight and cost constraints. Sensors should also operate under the noise, vibration and hardness conditions typical to automotive environments. Many sensors are sensitive to shock and vibration and could send erroneous values.

Table 3.4.10. Technical Targets: Compressor/Expanders for 80-kW$_e$ Transportation Fuel Cell Systems Operating on Direct Hydrogen

Characteristic	Units	2005 Status[a]	2010	2015
Input power[b] at full load, 40°C ambient air (with expander/without expander)	kW$_e$	6.3/13.7[c]	5.4/12.8	5.4/12.8
Overall motor/motor controller conversion efficiency, DC input	%	85	85	85
Input power at full load, 20°C ambient air (with expander/without expander)	kW$_e$	5.2/12.4[c]	4.4/11.6	4.4/11.6
Compressor/expander efficiency at full flow (C/E only)[d]	%	75/80[e]	80/80	80/80
Compressor/expander efficiency at 20-25% of full flow (C/E only): Compressor at 1.3 PR expander at 1.2 PR	%	45/30[e]	60/50	60/50
System volume[f]	liters	22[c]	15	15
System weight[f]	kg	22[c]	15	15
System cost[g]	$	1,500	400	200
Turndown ratio		10:1	10:1	10:1
Noise at maximum flow (excluding air flow noise at air inlet and exhaust)	dB(A) at 1 meter	65	65	65
Transient time for 10-90% of maximum airflow	sec	1	1	1

[a] This is the first year for which status is available.

[b] Input power to the shaft to power a compressor/expander, or compressor only system, including a motor/motor controller with an overall efficiency of 85%. 80-kW$_e$ compressor/expander unit for hydrogen/air flow of 90 g/sec (dry) maximum flow for compressor, compressor outlet pressure is specified to be 2.5 atm. Expander (if used) inlet flow conditions are assumed to be 93 g/sec (at full flow), 80°C and 2.2 atm.

[c] Projected.

[d] The pressure ratio is allowed to float as a function of load. Inlet temperature and pressure used for efficiency calculations are 20-40ºC and 2.5 atm.

[e] Measured blade efficiency.

[f] Weight and volume include the motor and motor controller.

[g] Cost targets based on a manufacturing volume of 100,000 units per year; includes cost of motor and motor controller.

Table 3.4.11. Technical Targets: Membranes for Transportation Applications

Characteristic	Units	2005 Status[a]	2010	2015
Membrane conductivity at inlet water vapor partial pressure and:				
Operating temperature	S/cm	0.10	0.10	0.10
20°C	S/cm	0.07	0.07	0.07
-20°C	S/cm	0.01	0.01	0.01
Operating temperature	°C	≤80	≤120	≤120
Inlet water vapor partial pressure	kPa	50	≤1.5	≤1.5
Oxygen cross-over[b]	mA/cm^2	5	2	2
Hydrogen cross-over[b]	mA/cm^2	5	2	2
Area specific resistance	Ohm/cm^2	0.03	0.02	0.02
Cost[c]	$\$/m^2$	25[d]	20	20
Durability with cycling				
At operating temp of ≤80°C	hours	~2,000[e]	5,000[f]	5,000[f]
At operating temp of >80°C	hours	na[g]	2,000	5,000[f]
Unassisted start from	°C	-20	-40	-40
Thermal cyclability in presence of condensed water		Yes	Yes	Yes

[a] This is the first year for which status is available.

[b] Tested in MEA at 1 atm O_2 or H_2 at nominal stack operating temperature.

[c] Based on 2002 dollars and costs projected to high volume production (500,000 stacks per year).

[d] Based on 2005 TIAX study and will be periodically updated.

[e] Steady state durability is 25,000 hours.

[f] Includes typical driving cycles.

[g] High-temperature membranes are still in a development stage and durability data are not available.

Table 3.4.12. Technical Targets: Electrocatalysts for Transportation Applications

Characteristic	Units	2005 Status[a]		Stack Targets	
		Cell	Stack	2010	2015
Platinum group metal total content (both electrodes)	g/kW rated	0.6	1.1	0.3	0.2
Platinum group metal total loading[b]	mg PGM/cm^2 electrode area	0.45	0.8	0.3	0.2
Cost	$/kW	9	55[c]	5[d]	3[d]
Durability with cycling Operating temp ≤80°C Operating temp >80°C	 hours hours	 >2,000 na[g]	 ~2,000[e] na[g]	 5,000[f] 2,000	 5,000[f] 5,000[f]
Electrochemical area loss[h]	%	90	90	<40	<40
Electrocatalyst support loss[h]	mV after 100 hours @ 1.2V	>30[i]	na	<30	<30
Mass activity[j]	A/mgPt @900mV$_{iR\text{-}free}$	0.28	0.11	0.44	0.44
Specific activity[j]	μA/cm^2 @900mV$_{iR\text{-}free}$	550	180	720	720
Non-Pt catalyst activity per volume of supported catalyst	A/cm^3 @800mV$_{IR\text{-}free}$	8	na	>130	300

[a] This is the first year for which status is available.

[b] Derived from performance data at rated power targets specified in Table 3.4.14.

[c] Based on 2005 TIAX study and will be periodically updated.

[d] Based on 2002 dollars, platinum cost of $450/troy ounce = $15/g, loading < 0.2 g/$kW_e$ and costs projected to high volume production (500,000 stacks per year).

[e] Steady state single cell durability is 25,000 hours.

[f] Includes typical driving cycles.

[g] High-temperature catalysts are still in a development stage and durability data are not available.

[h] Tested per GM protocol (Mathias, M.F., *Electrochemical Society Interface*, Fall 2005, p. 24).

[i] After 25 hours.

[j] Test at 80˚C/120°C H_2/O_2 in MEA; fully humidified with total outlet pressure of 150 KPa; anode stoichiometry 2; cathode stoichiometry 9.5.

Table 3.4.13. Technical Targets: MEAs

Characteristic	Units	2005 Status[a]	2010	2015
Operating temperature	°C	≤80	≤120	≤120
Inlet water vapor partial pressure	kPa (absolute)	50	≤1.5	≤1.5
Cost[b]	$/kW	60[c]	10	5
Durability with cycling				
At operating temp of ≤80°C	hours	~2,000[d]	5,000[e]	5,000[e]
At operating temp of >80°C	hours	na[f]	2,000	5,000[e]
Unassisted start from	°C	-20	-40	-40
Performance @ ¼ power (0.8V)	mA/cm^2 mW/cm^2	200 160	300 250	300 250
Performance @ rated power	mW/cm^2	600	1,000	1,000
Extent of performance (power density) degradation over lifetime[g]	%	5[h]	10	5
Thermal cyclability in presence of condensed water		Yes	Yes	Yes

[a] This is the first year for which status is available.

[b] Based on 2002 dollars and costs projected to high volume production (500,000 stacks per year).

[c] Status is from 2005 TIAX study and will be periodically updated.

[d] Steady state single cell durability is 25,000 hours.

[e] Based on appropriate test protocol (to be issued in 2007).

[f] High-temperature MEAs are still in a development stage and durability data is not available.

[g] Degradation target includes factor for tolerance of the MEA to impurities in the fuel and air supply. To be evaluated as a percent decrease in cell voltage at all current densities (i.e., no more than 5%).

[h] Status is from 2 kW stack achieving 2,200 hours durability.

Table 3.4.14. Technical Targets: Bipolar Plates

Characteristic	**Units**	**2005 Status**[a]	**2010**	**2015**
Cost[b]	\$/kW	10[c]	5	3
Weight	kg/kW	0.36	<0.4	<0.4
H_2 permeation flux	$cm^3\ sec^{-1}\ cm^{-2}$ @ $80^{o}C$, 3 atm (equivalent to <0.1 mA/cm^2)	$<2 \times 10^{-6}$	$<2 \times 10^{-6}$	$<2 \times 10^{-6}$
Corrosion	$\mu A/cm^2$	<1[d]	<1[d]	<1[d]
Electrical conductivity	S/cm	>600	>100	>100
Resistivity[e]	Ohm-cm	<0.02	0.01	0.01
Flexural Strength[f]	MPa	>34	>25	>25
Flexibility	% deflection at mid-span	1.5 to 3.5	3 to 5	3 to 5

[a] This is the first year for which status is available. 2005 status is for carbon plates, except for corrosion status which is based on metal plates.

[b] Based on 2002 dollars and costs projected to high volume production (500,000 stacks per year).

[c] Status is from 2005 TIAX study and will be periodically updated.

[d] May have to be as low as 1 nA/cm^2 if all corrosion product ions remain in ionomer.

[e] Includes contact resistance.

[f] Developers have used ASTM C-651-91 Standard Test Method for Flexural Strength of Manufactured Carbon and Graphite Articles Using Four Point Loading at Room Temperature.

3.4.4.2 Barriers

Of the many barriers discussed here, cost and durability present two of the most significant challenges to achieving clean, reliable, cost-effective fuel cell systems. While addressing cost and durability, fuel cell performance must meet or exceed that of competing technologies. Ultimately, operation of components and subsystems will be validated within the Technology Validation subprogram (see section 3.5).

A. Durability. Durability of fuel cell stacks, which must include tolerance to impurities and mechanical integrity, has not been established. Tolerance to air, fuel and system derived impurities (including the storage system) needs to be established. Durability of fuel cell systems operating over automotive drive cycles has not been demonstrated. Operation at low relative humidity (p_{H2O} 1.5 kPa or <10% relative humidity at 80°C) and start-up from sub-freezing temperatures has not been demonstrated. Component degradation and failure mechanisms are not well understood, which makes development of effective mitigating strategies necessary.

Stationary fuel cells must achieve greater than 40,000 hours durability to compete against other distributed power generation systems. Sulfur-tolerant catalysts and membrane materials are required to achieve this durability target in both the fuel processor and the stack. Research is also needed to understand failure mechanisms and develop mitigation strategies. State-of-the-art systems need to be benchmarked.

B. Cost. Materials and manufacturing costs are too high for catalysts, membranes, bipolar plates and gas diffusion layers. Low-cost, high-performance membranes, catalysts enabling ultra-low precious metal loading, and lower cost, lighter, corrosion-resistant bipolar plates are required to make fuel cell stacks competitive. The use of non-precious metal catalysts will also reduce the cost of MEAs. Balance-of-plant components specifically designed for use in fuel cell systems need development in order to achieve cost targets. Low-cost, high-volume manufacturing processes are also necessary.

C. Performance. Fuel cell performance and efficiency must meet or exceed that of competing technologies in order to be commercially viable. Voltage losses at the cathode are too high to meet efficiency targets simultaneously with the other targets. Anode and cathode performance depend on precious metal loading, which is currently too high (at the cathode) to meet cost targets. Loss of electrochemical surface area can occur due to catalyst migration and agglomeration during processing and operation. Current activities are focused on cathode performance because the kinetics at the cathode are about 100 times slower than at the anode.

Power densities at the higher voltages required for high-efficiency operation are currently too low to meet cost and packaging targets. Membrane performance under the extremes of automotive drive cycles and the steady-state lifetime requirement has not been established. Conductivity under subfreezing and low humidity conditions needs to increase.

Cell/stack performance is affected by the chemical and electrical interface between the electrode and the membrane. Dissimilar electrolytes in the membrane and electrode may result in higher electronic resistance or chemical incompatibilities. Also, new electrolyte materials may require redesign of the electrode structure and interface to maintain performance.

D. Water Transport within the Stack. Effective management of the water produced in the fuel cell is needed to alleviate flooding and/or drying out of the membrane over the full operating temperature range. Ineffective water management leads to liquid-phase water blockage and mass-transport-limited performance or decreased proton conductivity due to dehumidification of the ionomer. Transportation and stationary fuel cells must be able to operate in environments where ambient temperatures fall below 0°C. R&D is needed to improve the designs of the gas diffusion layers, gas flow fields in bipolar plates, catalyst layers and membranes to enable effective water management and operation at subfreezing conditions.

E. System Thermal and Water Management. Thermal and water management processes include heat and water use, cooling and humidification. Improved heat utilization, cooling and humidification techniques are needed. The low operating temperature of PEM fuel cells results in a relatively small difference between the fuel cell stack operating temperature and ambient air temperature, which is not conducive to conventional heat rejection approaches and limits the use of heat generated by the fuel cell (approximately 50% of the energy supplied by the fuel). More efficient heat recovery systems, improved system designs, advanced heat exchangers and/or higher temperature operation of current systems are needed to utilize the low-grade heat and achieve the most efficient (electrical and thermal) systems, particularly for distributed power generation. Improved techniques to manage water during start-up and shutdown at subfreezing temperatures are also needed.

F. Air Management. Automotive-type compressors/expanders specifically designed for fuel cell applications that minimize parasitic power consumption and meet packaging and cost requirements are not available. Automotive-type compressors/expanders that meet the FreedomCAR and Fuel Partnership technical guidelines need to be engineered and integrated with the fuel cell stack so that the overall system meets packaging, cost and performance requirements.

G. Start-up and Shut-down Time and Energy/Transient Operation. Automotive fuel cell systems must start rapidly from any ambient condition with minimal fuel consumption. Strategies to address start-up and shut-down time and energy such as the use of hybrid systems and/or stored hydrogen are needed. Fuel cell power plants will also be required to follow load variations (e.g., drive cycles).

3.4.5 Technical Task Descriptions

Table 3.4.15 describes the technical tasks that are the focus of R&D within the fuel cell subprogram. There is a direct correlation between these technical tasks and the current fuel cell activities listed previously in Table 3.4.1. The barriers associated with each task are described in Section 3.4.4.2.

Table 3.4.15. Technical Task Descriptions

Task	Description	Barriers
1	**Develop membranes that meet all targets** Develop/Identify Ionomers • Reduce the cost of raw materials • Improve ionomer conductivity over the entire temperature and humidity range (e.g., operation at up to 120°C and water partial pressure (p_{H2O}) less than 1.5 kPa) • Increase the mechanical/chemical/thermal stability of the ionomer over the entire temperature and humidity range Fabricate Membranes From Ionomers • Design scaleable membrane fabrication processes • Increase the mechanical/chemical/thermal stability of the membrane over the entire temperature and humidity range (e.g., operation at up to 120°C and p_{H2O} less than 1.5 kPa)	A, B, C

Table 3.4.15. Technical Task Descriptions

Task	Description	Barriers
	Perform Membrane Testing and Characterization to Improve Durability • Address freeze/thaw issues (prove membrane survivability to -40^{o}C) • Evaluate the tolerance of the membrane to air, fuel and system-derived impurities • Prove the mechanical stability of the membrane with cycling • Identify chemical and mechanical degradation mechanisms • Develop strategies for mitigating degradation in performance and durability	
2	**Develop electrodes that meet all targets** Develop Improved Catalysts • Reduce precious metal loading of catalysts • Increase the specific and mass activities of catalysts • Increase the durability/stability of catalysts with cycling • Increase the tolerance of catalysts to air, fuel and system-derived impurities • Test and characterize catalysts Develop Improved Catalyst Supports • Reduce corrosion of catalyst supports • Lower cost of materials for catalyst supports Optimize Electrode Design and Assembly • Design scaleable, high-throughput processes for supported catalysts • Optimize catalyst/support interactions and microstructure	A, B, C
3	**Develop membrane electrode assemblies that meet all targets** Integrate Membrane and Electrodes • Optimize mechanical and chemical interactions of the catalyst, support, ionomer and membrane • Minimize interfacial resistances • Design scaleable, high-throughput processes for high-performance MEAs Expand MEA Operating Range • Address freeze/thaw issues • Expand temperature and humidity range • Improve MEA stability under voltage and humidity cycling • Develop techniques to mitigate effects of air, fuel and system-derived impurities Perform Testing, Analysis and Characterization of MEAs • Characterize MEAs before, during and after fabrication and operation • Test cells, MEAs and short stacks	A, B, C
4	**Develop gas diffusion layers** Improve GDL Performance • Optimize GDL pore structure, morphology and physical properties • Optimize GDL coatings to improve water management • Develop materials and structures with improved area-specific resistance	A, C, D

Table 3.4.15. Technical Task Descriptions

Task	Description	Barriers
	Improve GDL Durability • Stabilize coatings for the GDL • Understand corrosion and aging • Optimize internal water management, including freeze/thaw Develop Testing and Characterization Protocols and Techniques • Develop tests to determine hydrophobicity • Develop conductivity tests • Develop techniques for measuring morphology and pore structure	
5	**Develop bipolar plates** Improve Performance of Bipolar Plates • Decrease weight and volume • Develop techniques for measuring through-plane resistance Decrease Cost of Bipolar Plates • Design scaleable fabrication processes Improve Durability of Bipolar Plates • Understand degradation mechanisms • Develop strategies/technologies for mitigating degradation	A, B, C
6	**Develop seals** Improve Performance of Seals • Decrease leak rate • Increase temperature limits Improve Durability of Seals • Understand seal degradation mechanisms • Develop mitigation technologies	A
7	**Develop balance-of-plant components** Develop Sensors • Decrease costs • Improve durability and reliability of fuel cell sensors Develop Air Management Technologies (Compressors/Expanders) • Meet performance, packaging and cost requirements • Minimize parasitic power Develop Water and Thermal Management Technologies • Develop advanced heat exchange and humidification materials and concepts • Develop advanced coolants (e.g., nanofluids)	B, E, F
8	**Develop stationary and other early market fuel cells** Develop Stationary Fuel Cell Systems • Improve system durability • Improve stack performance with reformate • Improve fuel processing performance • Increase system electrical efficiency Develop Auxiliary Power Units	A, B, C, G

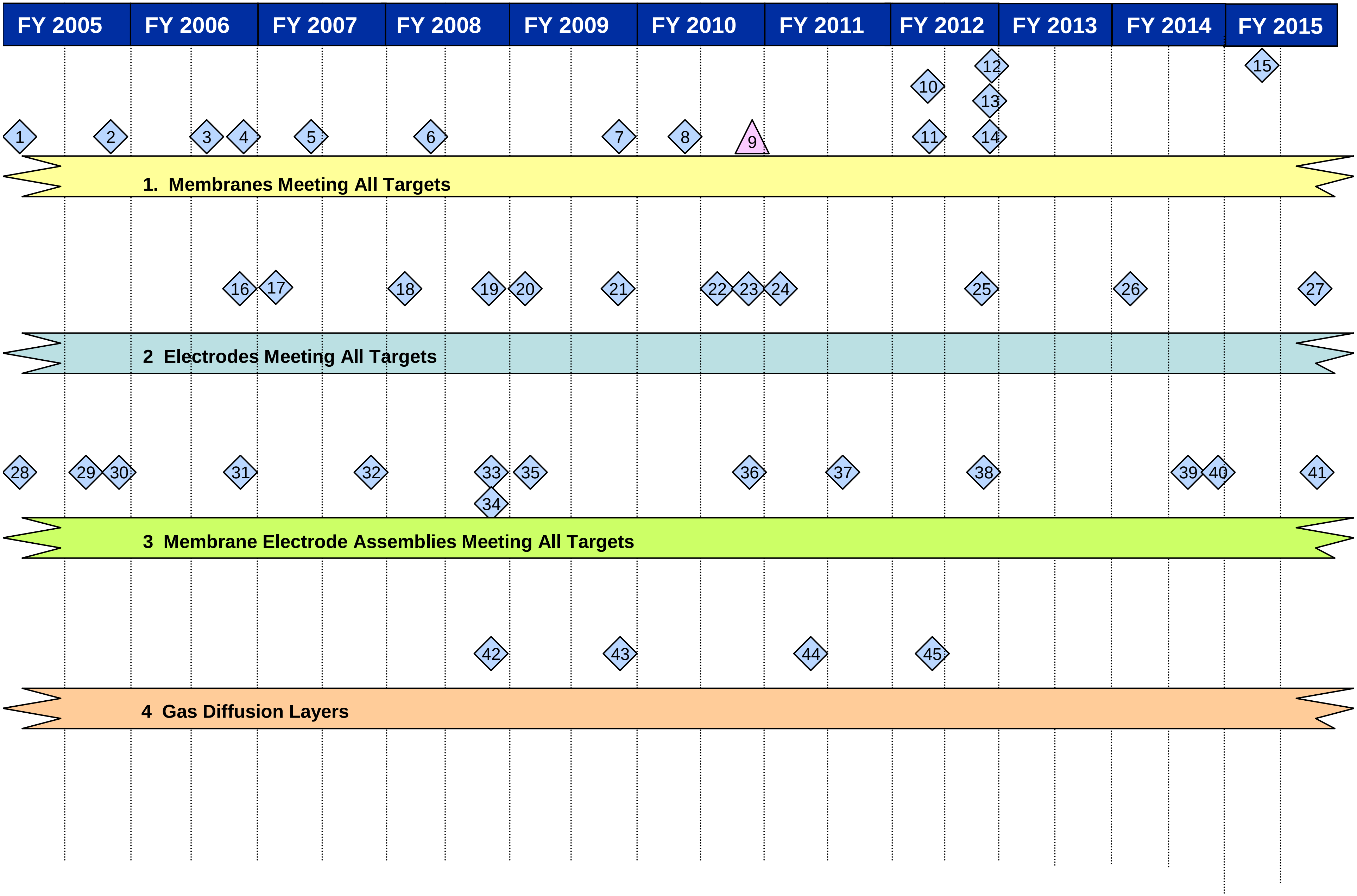
Table 3.4.15. Technical Task Descriptions

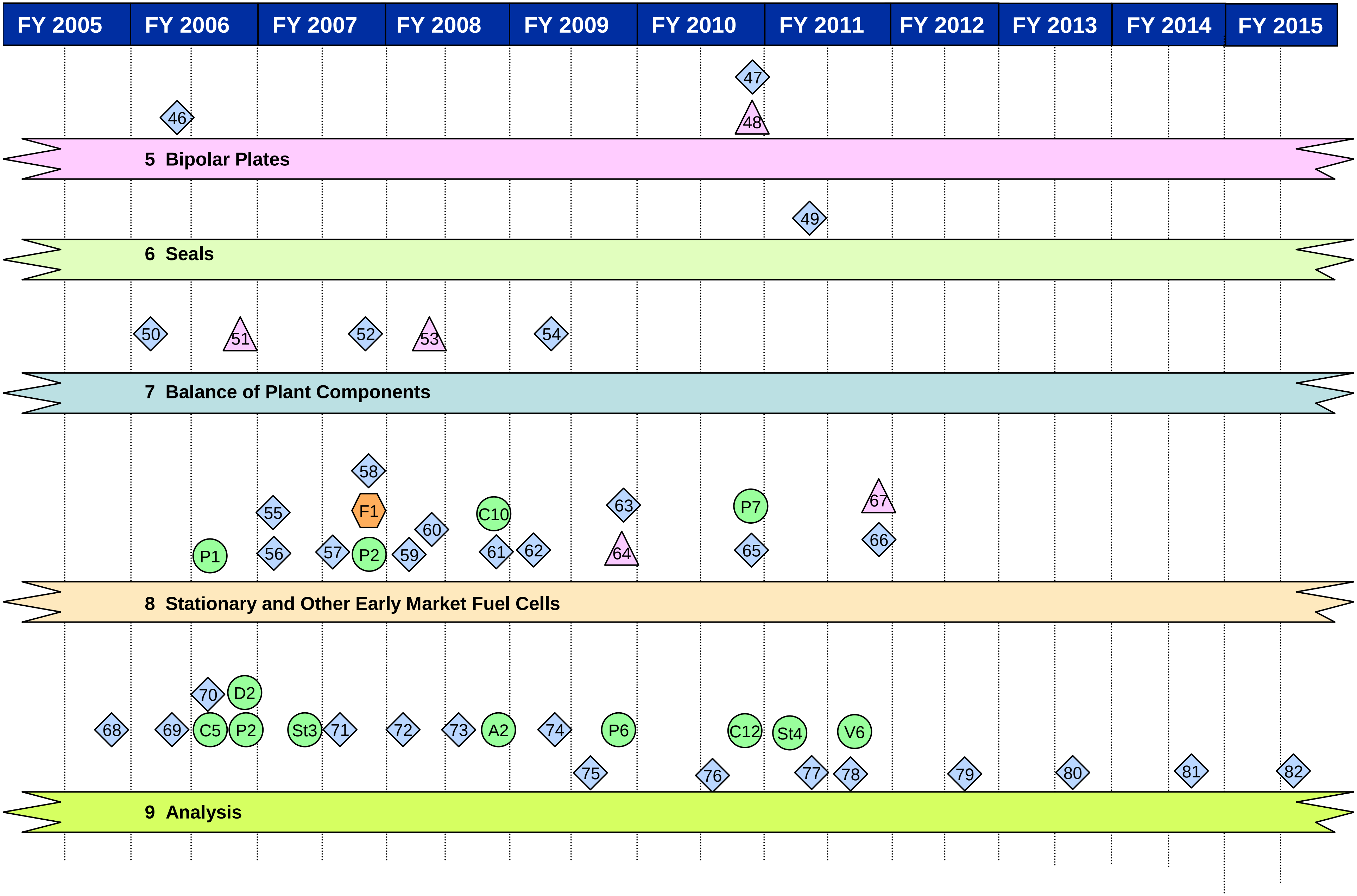
Task	Description	Barriers
	• Develop diesel fuel processor • Develop fuel cell that operates on reformate • Design, build and test APUs under real-world conditions Develop Portable Power Technologies • Develop membranes that will reduce methanol crossover • Design, build and test portable power systems under real-world conditions Develop Fuel Cells for Off-Road Applications • Evaluate air filtration technologies	
9	**Conduct analysis** Perform Cost Analysis Annually Update Technology Status Conduct Tradeoff Analysis • Rated power design points vs performance and efficiency • Start-up energy and start-up time • Hydrogen quality level vs durability and performance Improve Technical Understanding/Characterization • Develop, validate and utilize models to address impurity effects • Develop, validate and utilize models to address durability/degradation • Develop, validate and utilize models of freeze/thaw effects on fuel cell operation and performance • Develop and validate component performance models using most recent data	A, B, C, D, E, F, G
10	**Characterize and benchmark fuel cells** Develop Protocols for Testing Experimentally Determine Long-Term Stack Failure Mechanisms Experimentally Determine System Emissions Perform Independent Testing to Characterize Component and Stack Properties Before, During and After Operation	A, C, D, G
11	**Develop innovative concepts for fuel cell systems** Improve Balance-of-Plant Designs, Materials or Configurations • Simplify, integrate or eliminate components or functions • Develop novel materials Improve Fuel Cell Performance and Durability While Lowering Cost via Alternative Designs, Materials or Configurations • Simplify, integrate or eliminate components or functions • Develop novel materials	A, B, C, D, E, F, G

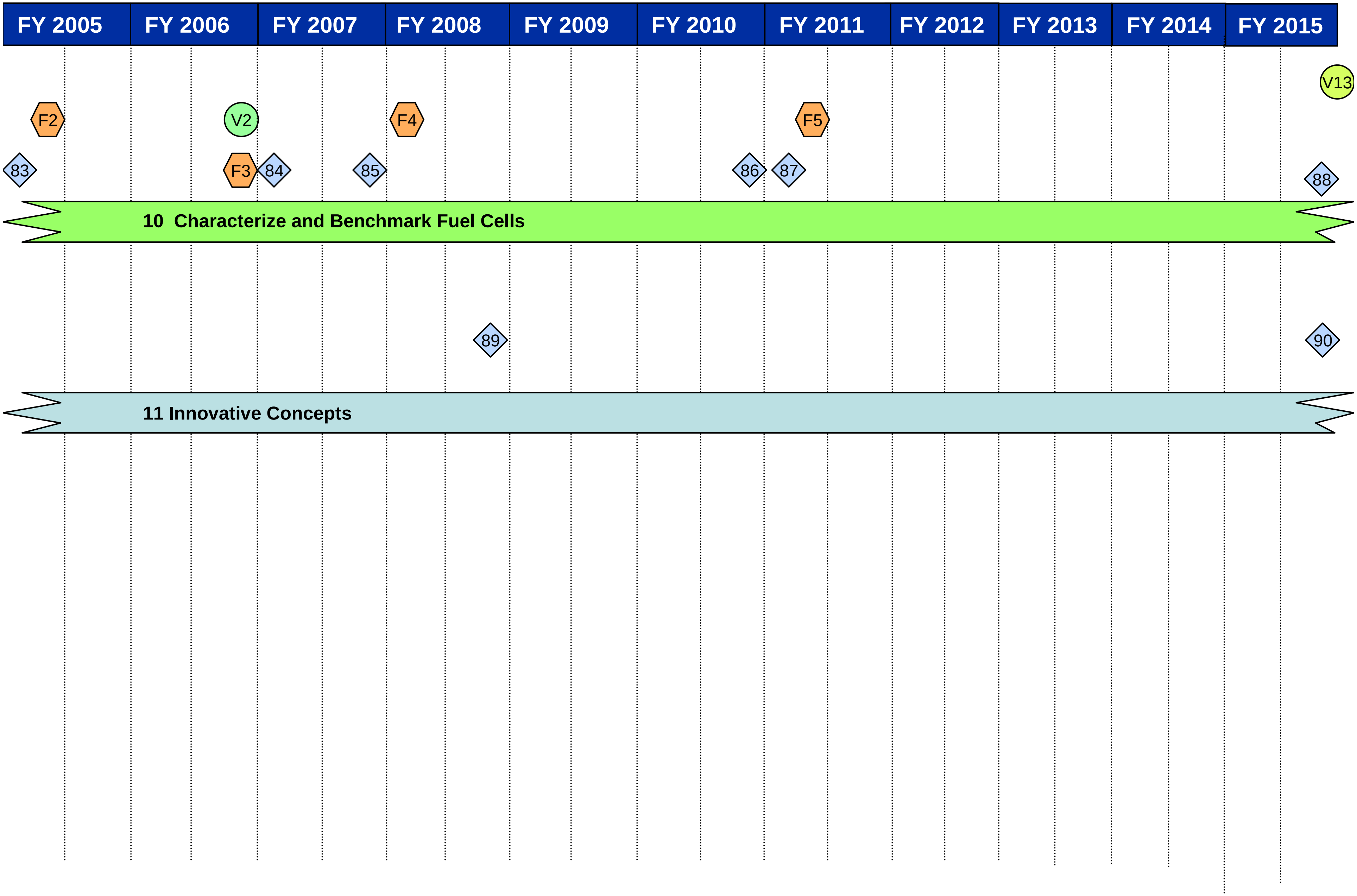
3.4.6 Milestones

The following figure shows the interrelationship of milestones, tasks, supporting inputs and technology program outputs for the Fuel Cell subprogram from FY 2005 through FY 2015. This information is also summarized in Appendix B.

Fuel Cell R&D Milestone Chart




FY 2005
FY 2006
FY 2007
FY 2008
FY 2009
FY 2010
FY 2011
FY 2012
FY 2013
FY 2014
FY 2015
47
46
48
5 Bipolar Plates
49
6 Seals
50
51
52
53
54
7 Balance of Plant Components
58
55
F1
60
C10
63
P7
67
66
P1
56
57
P2
59
61
62
64
65
8 Stationary and Other Early Market Fuel Cells
70
D2
68
69
C5
P2
St3
71
72
73
A2
74
P6
C12
St4
V6
75
76
77
78
79
80
81
82
9 Analysis


FY 2005
FY 2006
FY 2007
FY 2008
FY 2009
FY 2010
FY 2011
FY 2012
FY 2013
FY 2014
FY 2015
V13
F2
V2
F4
F5
83
F3
84
85
86
87
88
10 Characterize and Benchmark Fuel Cells
89
90
11 Innovative Concepts

1. Membranes Meeting All Targets

Milestone 1 (1Q05) - Evaluate >80°C membrane in MEA/single cell and compare to MEA targets

Milestone 2 (4Q05) - Develop procedures for accelerated testing of membrane mechanical stability

Milestone 3 (3Q06) - Evaluate ionomer conductivity at >80°C and < 25% RH and compare to membrane targets

Milestone 4 (4Q06) - Identify major chemical and mechanical degradation mechanism for PFSA type membranes operating at 80°C

Milestone 5 (2Q07) - Evaluate first generation >120°C membrane in MEA/single cell and compare to MEA targets

Milestone 6 (2Q08) - Evaluate < 80°C membrane against 2010 targets

Milestone 7 (4Q09) - Evaluate chemical and thermal stability and conductivity of ionomer materials and compare to membrane targets

Milestone 8 (2Q10) - Evaluate membrane technologies for >2,000 hour durability operating at >80°C

Milestone 9 (4Q10) - Go/No-Go Decision: Assess ability of high temperature membranes to achieve 2015 technical targets simultaneously. If go, continue high temperature membrane R&D. If no-go, focus on lower temperature membrane materials.

Milestone 10 (2Q12) - Evaluate chemical and thermal stability and conductivity of ionomer materials and compare to membrane targets

Milestone 11 (2Q12) - Identify degradation mechanisms for advanced, low cost membranes operating at > 80°C

Milestone 12 (4Q12) - Develop strategy to increase lifetime of advanced low cost membranes at > 80°C to > 5,000 hours

Milestone 13 (4Q12) - Demonstrate multiple freeze/thaw cycles

Milestone 14 (4Q12) - Evaluate membrane tolerance to impurities (fuel, air, and system derived) and compare to membrane targets

Milestone 15 (2Q15) - Evaluate membrane technologies for >5,000 hour durability operating at >80°C

2 Electrodes Meeting All Targets

Milestone 16 (4Q06) - Determine the effect of potential, potential cycling and temperature on dissolution of Pt and Pt alloy catalysts

Milestone 17 (1Q07) - Characterize electrochemical performance of non-precious metal catalyst and assess against 2010 targets

Milestone 18 (1Q08) - Use accelerated testing protocol to evaluate catalyst supports against target

Milestone 19 (4Q08) - Identify and quantify impurities (fuel, air and system-derived) that affect catalysts

Milestone 20 (1Q09) - Develop *in situ* characterization techniques

Milestone 21 (4Q09) - Evaluate the performance of platinum group metal (PGM) and non-PGM catalysts and assess against 2010 targets

Milestone 22 (3Q10) - Evaluate most promising electrode designs in MEAs against 2010 and 2015 MEA targets

Milestone 23 (4Q10) - Evaluate progress towards developing catalysts tolerant to fuel, air and system derived impurities

Milestone 24 (1Q11) - Use accelerated testing protocol to evaluate catalyst supports against target

Milestone 25 (4Q12) - Evaluate the performance of PGM and non-PGM catalysts and assess against 2015 targets

Milestone 26 (1Q14) - Characterize catalysts that have undergone durability testing using the DOE durability protocol

Milestone 27 (4Q15) - Evaluate the performance of advanced PGM and non-PGM catalysts and assess against 2015 targets

3 Membrane Electrode Assemblies Meeting All Targets

Milestone 28 (1Q05)- Evaluate reproducibility of MEAs in high-rate manufacturing processes

Milestone 29 (3Q05) - Evaluate >80°C MEA in <10kW stack and compare to MEA targets

Milestone 30 (4Q05) - Demonstrate MEA in single cell meeting 2005 platinum loading targets

Milestone 31 (4Q06) - Initiate testing of 20-cell stack with durable MEA and GDL

Milestone 32 (4Q07) - Evaluate progress toward extending durability to >5000 hours with simplified cycling

Milestone 33 (4Q08) - Evaluate progress toward 2010 targets

Milestone 34 (4Q08) - Evaluate technology for PGM recycling

Milestone 35 (1Q09) - Identify methods to mitigate effects of fuel, air and system-derived impurities

Milestone 36 (4Q10)- Evaluate progress towards extending durability to >40,000 hours for stationary applications

Milestone 37 (3Q11) - Evaluate methods to mitigate effects of fuel, air and system-derived impurities

Milestone 38 (4Q12) - Evaluate progress toward 2015 targets

Milestone 39 (3Q14) - Evaluate methods to mitigate effects of fuel, air and system-derived impurities

Milestone 40 (4Q14) - Evaluate automotive short stack with improved MEAs against 2015 targets

Milestone 41 (4Q15) - Evaluate progress toward extending durability to > 5000 hours with automotive cycling

4 Gas Diffusion Layers

Milestone 42 (4Q08) - Develop models that advance the understanding of water transport in the GDL

Milestone 43 (4Q09) - Develop test protocols for GDLs

Milestone 44 (2Q11) - Downselect GDL technologies

Milestone 45 (2Q12) - Develop improved diffusion materials to enable time stable operation at high power density

5 Bipolar Plates

Milestone 46 (2Q06) - Complete demonstration of bipolar plate manufacturing process that includes net-shape molding, low-cost bonding, optimized plate materials, and robust sealing methods to produce high quality, uniform plates with target properties. Develop bipolar plate cost estimate to illustrate the cost reduction due to these process improvements and compare to the 2010 target of $6/kW

Milestone 47 (4Q10) - Evaluate progress of full scale bipolar plates in short stack and compare to 2010 targets

Milestone 48 (4Q10) - Go/No-Go Decision: Determine whether to continue bipolar plate R&D based on progress towards meeting technical targets

6 Seals

Milestone 49 (2Q11) - Downselect seal technologies

7 Balance of Plant Components

Milestone 50 (1Q06) - Complete development and testing of low-cost, high-sensitivity sensors

Milestone 51 (4Q06) - Go/No-Go Decision: Assess the status of sensor and control technologies and compare with technical and cost targets. On the basis of this assessment, the technologies will be released for use, more development will be indicated, or the effort will be terminated.

Milestone 52 (4Q07) - Complete development and testing of low-cost, high-efficiency, lubrication-free compressors, expanders, blowers, motors and motor controllers

Milestone 53 (2Q08) - Go/No-Go Decision: Based on input from Tech Validation, decide whether to initiate further development of compressor/expander technology

Milestone 54 (2Q09) - Demonstrate heat rejection technologies -- compact humidifiers, heat exchangers and radiators

8 Stationary and Other Early Market Fuel Cells

Output F1 (4Q07) - Output to Production: Research results of advanced reformer development

Input P1 (3Q06)- Input from Production: Hydrogen production technology for distributed systems using natural gas with projected cost of $3.00/gge hydrogen at the pump, untaxed, assuming 500s of units of production per year

Input C10 (4Q08)- Input from Codes and Standards: Final draft standard (balloting) for portable fuel cells

Input P7 (4Q10)- Input from Production: Hydrogen production technologies for distributed systems using natural gas with projected cost of $2.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 500s of units of production per year

Milestone 55 (1Q07) - Demonstrate prototype back up power system

Milestone 56 (1Q07) - Complete evaluation of fuel cell system designs for APUs

Milestone 57 (3Q07) - Complete 15,000-hour stationary fuel cell system test

Milestone 58 (4Q07) - Complete testing on 50kW stationary module system

Milestone 59 (1Q08) - Evaluate fuel processing subsystem performance for distributed generation against system targets for 2011

Milestone 60 (2Q08) - Evaluate portable power systems performance against 2010 targets

Milestone 61 (4Q08)- Evaluate system performance for distributed generation towards meeting 2008 efficiency targets

Milestone 62 (1Q09) - Demonstrate the effective utilization of fuel cell thermal energy for heating to meet combined heat and power (CHP) efficiency targets

Milestone 63 (4Q09)- Evaluate system performance for distributed generation towards meeting 2009 efficiency targets

Milestone 64 (4Q09) - Go/No-Go Decision: Determine whether to continue auxiliary power, portable power and off-road R&D based on the progress towards meeting 2010 targets

Milestone 65 (4Q10)- Evaluate system performance for distributed generation towards meeting 2010 efficiency targets

Milestone 66 (4Q11)- Evaluate system performance for distributed generation towards meeting 2011 efficiency targets

Milestone 67 (4Q11) - Go/No-Go Decision: Determine whether to continue stationary fuel cell system R&D based on progress towards meeting targets

9 Analysis

Input St3 (2Q07) - Input from Storage: Report on metal hydride system and evaluation against 2007 targets

Input St4 (1Q11) - Input from Storage: Report on full-cycle chemical hydride system and evaluation against 2010 targets

Input V6 (3Q11) - Input from Technology Validation: Validate cold start-up capability (in a vehicle with an 8-hour soak) meeting 2010 requirements (time and start up and shut down energy)

Input C5 (3Q06)- Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification

Input P2 (4Q06)- Input from Production: Assessment of fuel contaminant composition

Input A2(4Q08) - Input from Systems Analysis: Initial recommendation on hydrogen quality at each point in the system

Input P6 (4Q09)- Input from Production: Assessment of fuel contaminant composition

Input C12 (4Q10)- Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard
Input D2 (4Q06) – Input from Delivery: Hydrogen contaminant composition and issues (see Appendix F)

Milestone 68 (4Q05)- Develop a current fuel cell technology cost estimate and compare it to the FY 2005 target of $125/kW for a hydrogen-fueled 50kW fuel cell power system

Milestone 69 (2Q06) - Develop models/tools to characterize degradation in single cells

Milestone 70 (3Q06) - Update fuel cell technology cost estimate and compare it to the FY 2006 target of $110/kW for a hydrogen-fueled 80kW fuel cell power system

Milestone 71 (3Q07) - Update fuel cell technology cost estimate and compare it to the FY 2007 target of $90/kW for a hydrogen-fueled 80kW fuel cell power system

Milestone 72 (1Q08) - Generate transportation fuel cell system cost projections based on achievement of 2010 and 2015 technical targets

Milestone 73 (3Q08) - Update fuel cell technology cost estimate and compare it to the FY 2008 target of $70/kW for a hydrogen-fueled 80kW fuel cell power system

Milestone 74 (2Q09) - Develop models to characterize degradation in stacks

Milestone 75 (3Q09) - Update fuel cell technology cost estimate and compare it to the FY 2009 target of $60/kW for a hydrogen-fueled 80kW fuel cell power system

Milestone 76 (3Q10) - Update fuel cell technology cost estimate and compare it to the FY 2010 target of $45/kW for a hydrogen-fueled 80kW fuel cell power system

Milestone 77 (2Q11) - Develop system-level models to characterize degradation

Milestone 78 (3Q11)- Update fuel cell technology cost estimate and compare it to the FY 2011 target of $42/kW for a hydrogen-fueled 80kW fuel cell power system

Milestone 79 (3Q12) - Update fuel cell technology cost estimate and compare it to the FY 2015 target of $30/kW for a hydrogen-fueled 80kW fuel cell power system

Milestone 80 (3Q13) - Update fuel cell technology cost estimate and compare it to the FY 2015 target of $30/kW for a hydrogen-fueled 80kW fuel cell power system

Milestone 81 (3Q14) - Update fuel cell technology cost estimate and compare it to the FY 2015 target of $30/kW for a hydrogen-fueled 80kW fuel cell power system

Milestone 82 (3Q15) - Update fuel cell technology cost estimate and compare it to the FY 2015 target of $30/kW for a hydrogen-fueled 80kW fuel cell power system

10 Characterize and Benchmark Fuel Cells

Output F2 (2Q05) - Output to Systems Analysis and Systems Integration: Develop preliminary hydrogen quality requirements

Output F3 (4Q06) - Output to Technology Validation: Provide automotive stack test data from documented sources indicating durability status

Output F4 (1Q08) - Output to Technology Validation: Verify short stack cold start (-20°C) to 50% of rated power in 60 seconds

Output F5 (2Q11) - Output to Technology Validation: Provide automotive stack test data from documented sources indicating durability status

Input V1 (4Q06) - Input from Technology Validation: Validate maximum automotive fuel cell system efficiency

Input V14 (2Q16) - Input from Technology Validation: Report on the status of validation of 5000 hour durability target and cold start capability

Milestone 83 (1Q05) - Complete initial evaluation of 25-50-kW advanced integration, atmospheric gasoline reformed system

Milestone 84 (1Q07)- Test 5kW stationary fuel cell system efficiency and durability towards 2011 targets

Milestone 85 (4Q07) - Complete full-scale MEA evaluation in short stack

Milestone 86 (4Q10)- Evaluate short stack against 2011 targets for operation over the full operating temperature range

Milestone 87 (1Q11) - Test and evaluate fuel cell systems and components such as MEAs, short stacks, bipolar plates, catalysts, membranes, etc. and compare to targets

Milestone 88 (4Q15)- Test and evaluate fuel cell systems and components such as MEAs, short stacks, bipolar plates, catalysts, membranes, etc. and compare to targets

11 Innovative Concepts

Milestone 89 (4Q08) - Evaluate advanced fuel cell system against 2010 targets

Milestone 90 (4Q15) - Evaluate advanced fuel cell system against 2015 targets

21st CENTURY TRUCK
PARTNERSHIP

Industry Fuel Cell APU Project #1 (document)

VII.K.6 Solid Oxide Fuel Cell Development for Auxiliary Power in Heavy-Duty Vehicle Applications

George Simopoulos
Delphi Automotive Systems
2705 South Goyer Road
Kokomo, IN 46904
Phone: (765) 451-3755; Fax: (765) 451-3780; E-mail: george.n.simopoulos@delphi.com

DOE Technology Development Manager: John Garbak
Phone: (202) 586-1723; Fax: (202) 586-9811; E-mail: John.Garbak@ee.doe.gov

DOE Project Officer: David Peterson
Phone: (303) 275-4956; Fax: (303) 275-4753; E-mail: David.Peterson@go.doe.gov

Contract Number: DE-FC36-04GO14319

Subcontractors:
Electricore, Inc. Valencia, CA
Volvo Trucks North America
Mack Powertrain
PACCAR, Inc.

Start Date: September 1, 2004
Projected End Date: October 31, 2008

Objectives

To demonstrate a solid oxide fuel cell (SOFC) auxiliary power unit (APU) capable of operating on low sulfur diesel fuel, in a laboratory environment, for the commercial trucking industry.

- Develop APU system requirements and concepts with major truck original equipment manufacturers (OEMs) input
- Design, test and develop the needed SOFC APU subsystems for the selected concept
- Build and bench demonstrate the diesel fueled APU system to the DOE and OEM partners

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- B. Cost
- F. Fuel Cell Power System Integration.

Technical Targets

Table 1. Auxiliary Power Units (3-5 kW rated, 5-10 kW peak)

Characteristic	Units	2006 DOE Target[1]	2005 Delphi SOFC APU Target	Delphi SOFC APU Status
Specific Power	W/kg	70	40	18.8
Power Density	W/L	70	44	23
Efficiency @ Rated Power	%LHV	25	21	12
Cost	$/kW	<800	800	1,490
Cycle Capability (from cold start) over operating lifetime	Number of cycles	40	6	3
Durability	Hours	2,000	1,500	60
Start-up Time	Min	30-45	45	75

[1] From Table 3.4.9 (page 3-82) of the DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program – Multi Year Research, Development and Demonstration Plan

Approach

- Develop Application Requirements with OEM Input
- Develop APU System Mechanization Concepts
- Develop APU System Requirements, Concept Evaluation, and Selection
- Design and Layout APU System
- Develop Subsystem Requirements and Development Plan
- Design and Build SOFC Hardware
- Build Subsystem Test Fixture Hardware
- Complete Subsystem Testing and Development Iterations
- Develop and Test System Module
- Develop and Test Full APU System
- Laboratory Demonstration of APU System with Simulated Load Cycles
- Prepare Final Report and Presentation

Accomplishments

- Task 1.1 – Completion of Project Plan with input from OEM partners PACCAR and Volvo Trucks North America (VTNA).
- Task 1.2 – Completion of the following subtask with collaboration from OEM partners PACCAR and VTNA:
  - Quantifying APU power requirements for heavy duty truck applications
  - Vehicle load profile
  - On-road operating conditions and durability requirements
  - Operator interfaces
  - Safety parameters
  - Volume, mass and mounting requirements for various truck models

- Task 1.3 – Completion of Milestone –1 (Requirements Review) Meeting with DOE and OEM partners was held on April 14th, 2005.
- Task 2.1 – Completion of APU mechanization concepts. Reviews with OEM partners have been scheduled.
- Task 2.2 – Teamwork with OEM partners PACCAR and VTNA are underway to finalize application requirements for the SOFC APU system.
- Presentation of project status and accomplishments at "21st Century Truck Idling Reduction Technology Review" March 16, 2005, Washington, D.C.
- Presentation of the SOFC APU project at "Hydrogen Program Review" May 24th, 2005, Washington D.C.

Future Directions

- Remainder of FY 2005
  - Development of Vehicle System and APU System Mechanization Concepts
  - APU System Requirements
  - Milestone #2 Review
- FY 2006
  - APU Design and Layout
  - Subsystem Requirements Document
  - SOFC APU Subsystem Hardware Design and Build

Introduction

Delphi Automotive Systems, LLC (Delphi) has teamed with heavy-duty truck OEMs PACCAR and VTNA to define system level requirements and develop an SOFC-based APU. The Delphi team has enlisted Electricore, Inc. to serve as administrative manager for the project.

Project work conducted thus far has focused on APU system requirements as applied to heavy-duty trucks, development of APU system mechanization concepts, and pull-ahead SOFC APU hardware design and build. Product engineering work focused on the completion of the truck application and requirements information being developed in conjunction with Delphi's truck OEM partners, VTNA and PACCAR. A requirements review meeting was held in April 2005 (Milestone #1), thereby ending Phase I of the project. Phase II of the project has begun and completion of APU mechanizations concepts and reviews with OEM partners have been scheduled.

Approach

Program technical approach involves extracting hydrogen and CO from diesel fuel in a catalytic operation through a reformer. The output gas from the reformer will be sent to the fuel cell stack and converted to electrical energy (storage of pure hydrogen is not required).

The project will first define system level requirements, and subsequently design and implement an optimized system architecture using an SOFC APU to demonstrate and validate that the APU will meet system level goals. The primary focus will be on APUs in the range of 3-5 kW for truck idling reduction. Fuels utilized will be derived from low-sulfur diesel fuel.

Results

Detailed information for the following task is OEM (PACCAR & VTNA) confidential and is not available for public distribution.

Task 1.2 Define Application Requirements with OEM

Delphi conducted meetings with OEM development partners VTNA and PACCAR to produce detailed application requirements for the on-board APU. The following items have been finalized:

- Application requirements and metrics
- On-road operating conditions for the APU
- Electrical load duty cycles
- Vehicle-level diagrams showing how the APU could be integrated into the vehicle subsystems
- Vehicle operating cycles from OEM for system testing
- Fuel requirements for the SOFC APU

On-road operating conditions for the APU

The following on-road environmental operating conditions for a common typical Class 8 commercial truck SOFC APU have been defined:

- Temperature
- Thermal cycling (for environmental exposure testing schedule)
- Thermal shock by splash
- Vehicle vibration loads/schedule
- Drop and shock handling loads
- Humidity
- Automotive fluids exposure
- Salt spray exposure
- Direct water spray
- Gravel bombardment

Electrical load duty cycles

The following typical Class 8 commercial truck electrical load requirements have been defined:

- Maximum/peak power output and duration
- Continuous power output
- Continuous low hotel load
- Minimum power output
- Power output range
- Voltage output range

Vehicle-level diagrams showing how the APU could be integrated into the vehicle subsystems

Figure 1 shows the primary vehicle-level electrical system diagram identifying how the APU could be integrated into the vehicle subsystems. Specific integration architecture of the APU will depend on the manufacturer's preference.

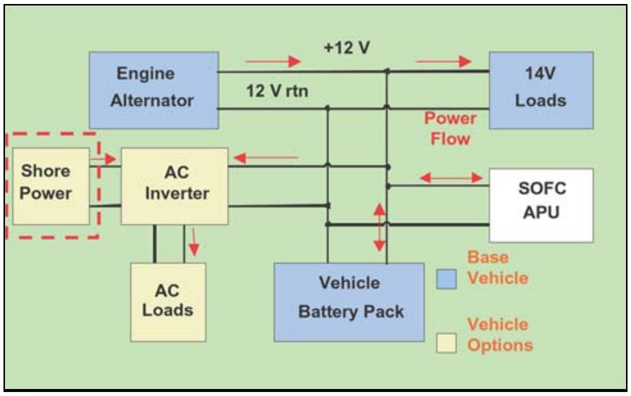


Figure 1. Vehicle Electrical System Diagram

Vehicle operating cycles from OEM for system testing

Vehicle operating cycle requirements have been established based upon the input from OEM partners PACCAR and VTNA. The targeted fundamental power, durability, electromagnetic compatibility (EMC), and electro-static discharge (ESD) testing that have to meet in a heavy-duty truck application have been established. In addition, the following requirements have been defined:

- Maximum intermittent power
- Maximum continuous power
- Minimum power
- Voltage
- Target life
- EMC
- ESD

Establish fuel requirements for the SOFC APU in study

Fuel requirements for the SOFC APU have been established. The diesel fuel shall be per ASTM D975, ultra-low sulfur diesel (ULSD), and Grade No.2-D S15. The fuel will likely contain additional additives such as kerosene (up to 20%), biodiesel (currently up to 5% possibly up to 20% in the future), flow enhancers, fuel system lubricants, and others.

The sulfur in fuels is expected to decrease due to the legislative action of governments in the U.S. and Europe. In the U.S., the sulfur levels are expected to decrease to 80 ppmw (maximum) with 30 ppmw (average) for gasoline and 15 ppmw (average) in diesel by 2006. In Europe, the levels are expected to decrease to less than 50 ppmw by 2005

Task 2.1 Develop APU System Mechanization Concepts

The progress to date has been a series of mechanizations and vehicle schematics by vehicle systems engineering that are being reviewed for validity and benefit to the truck operator and for system viability. System efficiency is a parameter that is under scrutiny to better understand the trade-offs involved in electrical and thermal energy generation, especially at low electrical power conditions that may not have adequate thermal power for the coolant system.

Potential APU system mechanizations based on VTNA input were submitted to VTNA for review. A web meeting was conducted with VTNA on April 29, 2005, to review the proposed system mechanizations.

Potential APU system mechanizations and 24-hour APU usage profiles were submitted to PACCAR for review. PACCAR provided Delphi with documentation on potential vehicle hotel loads and current vehicle engine idling practices.

Task 2.2 Develop the APU System Requirements Document

The APU system requirements document is ongoing and will be concluded following the completion of the truck OEM's input. Each OEM will provide an APU requirements document that will be the basis and record of their input to the project.

A comprehensive SOFC APU requirements document will be generated from the OEM's vehicle level requirements, which will also accommodate other markets and strategies that are key elements of Delphi's SOFC APU business and product plans.

Task 2.6 SOFC APU Hardware Design and Build

The SOFC APU system hardware is divided into three major modules:

- Hot Zone Module (HZM): SOFC stack module system, system heat exchanger and component manifold, system tailgas combustor (Figure 2)
- Plant Support Module (PSM): Balance of plant, power conditioner, APU system controller, anode recycle system
- Application Interface Module (AIM) and Product Enclosure: Product enclosure (serves as module frame and application cover), air filtration, fuel desufurization

Note: The AIM is closely integrated with the PSM, but remains customized for power needs and style.

Currently, SOFC hardware design work is focused on the vaporization techniques of the diesel fuel at startup. To accomplish this, a fuel delivery system was designed, consisting of a fuel-metering pump coupled to a heat exchanger, which was then coupled to an electric heating device. The concept being investigated functions as follows:

- The controller receives a command for reformate. The controller then powers-up an electric heater to predetermined temperature set point.
- Fuel is then pumped through a cold heat exchanger at desired mass flow rate, which then flows into the electric heater.
- The electric heater assembly is closed-loop controlled to set temperature.

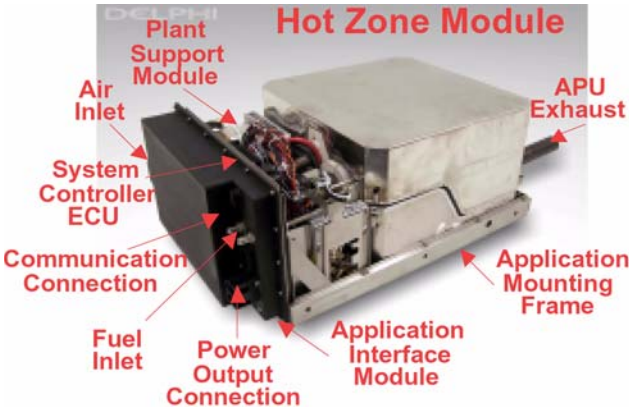


Figure 2. SOFC APU Hardware – Generation 3 APU System

- Combustion pre-heat of the reformer is accomplished with the electrically heated fuel vapor.
- As the heat exchanger comes up to a certain temperature, power to the electric heater is reduced, and then turned off when no longer needed.
- The electric heater can be used to adjust the heat input as required.
- Reformate generation is proportional to fuel mass flow.

A block diagram of this process flow is shown in Figure 3.

The benefits provided by this concept over air heating and fuel pressurization are: reduced startup time, lower steady-state parasitic energy losses, smaller overall reformer size, and lower system costs. This system requires electric power only during a short startup cycle of about 60-100 sec. During this period the fuel will be heated both electrically and by waste heat. The reformer size is reduced and efficiency improved by introducing smaller fuel particles to the incoming air. This allows for faster and better mixing of the air/fuel. This reduces wall wetting, and shortens the mixing distance ahead of the reforming catalyst.

The work performed lays the groundwork for testing and development of the fuel system. A combustion bench complete with controls has been fabricated. The bench requires some refinement but is functional enough to begin addressing many of the critical issues related to building components for a prototype reformer. It is also providing understanding into some of the reliability challenges related to heating the fuel. Key starting points for electric vaporization such as actual power requirements and heat transfer efficiency are being correlated to calculated values. Operation parameters for ignition, combustion, and reforming sequences are being developed. Initial testing to determine the time to generate reformate has begun. Early results show quality reformate could be obtained in 90 sec from startup using only electric heating. The heat exchanger hardware is now available for testing. The efficiency, flow capacity, and backpressure at temperature are currently being studied for comparison to calculated values.

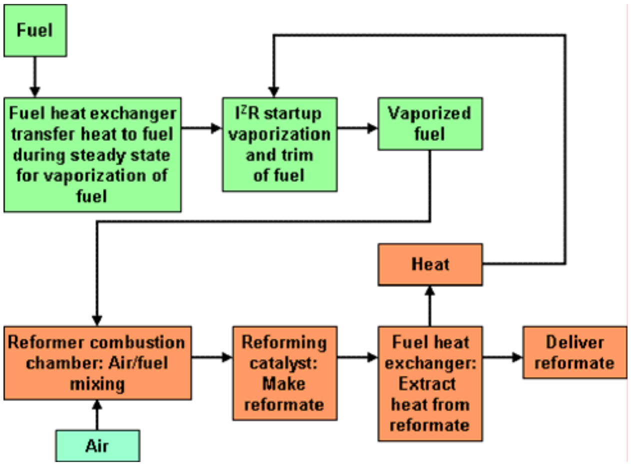


Figure 3. Fuel Delivery System Process Flow Block Diagram

Conclusions

A significant amount of work has been done to meet DOE's objectives to have SOFCs on-board heavy-duty trucks for powering the accessory loads. The APU system requirements as applied to heavy-duty trucks, system mechanization concepts for the interface of the SOFC with the rest of the truck electrical system, and the planning for the design of the hardware have been completed. The focus of the next phase of the project will be on design of the hardware, parts procurement, building the bench demonstration unit and test, and the final report preparation.

This project has provided a significant insight to the opportunities available for improving the efficiency and reducing the emissions in heavy-duty trucks and how the SOFC APU could be a part of this next generation technology.

References

1. "Hydrogen, Fuel Cells and Infrastructure Technologies Multi-Year Research, Development and Demonstration Plan", United States Department of Energy, March 2005

FY 2005 Publications/Presentations

1. Presentation of Program status and accomplishments at "21st Century Truck Idling Reduction Technology Review" March 16, 2005, Washington, D.C.
2. Presentation of the SOFC APU Program at the "Hydrogen Program Review" May 24th, 2005, Washington D.C.

Industry Fuel Cell APU Project #2 (document)

VII.K.10 Diesel Fueled SOFC for Class 7/Class 8 On-Highway Truck Auxiliary Power

Daniel Norrick (Primary Contact), Jim Butcher
Cummins Power Generation
1400 73rd Avenue N.E.
Fridley, MN 55432
Phone: (763) 574-5301; Fax: (763) 528-7229; E-mail: daniel.a.norrick@cummins.com
Phone: (763) 574-5310; Fax: (763) 528-7229; E-mail: jim.i.butcher@cummins.com

DOE Technology Development Manager: John Garbak
Phone: (202) 586-1723; Fax: (202) 586-9811; E-mail: John.Garbak@ee.doe.gov

DOE Project Officer: David Peterson
Phone: (303) 275-4956; Fax: (303) 275-4753; E-mail: David.Peterson@go.doe.gov

Technical Advisor: John Kopasz
Phone: (630) 252-7531; Fax: (630) 972-4405; E-mail: kopasz@cmt.anl.gov

Contract Number: DE-FC36-04GO14318

Subcontractors:
International Truck & Engine Corp, Fort Wayne, IN
SOFCo-EFS Holdings LLC, Alliance, OH

Start Date: September 1, 2004
Projected End Date: August 31, 2007

Objectives

Overall:

- On-vehicle demonstration and evaluation of a solid oxide fuel cell (SOFC) auxiliary power unit (APU) with integrated on-board reforming of low sulfur diesel fuel

Sub-tasks:

- Define, analyze and design the balance of plant for a functioning SOFC APU
- Perform sub-system testing and development on SOFC stacks, diesel reformer system, power electronics and controls, isolation system etc.
- Perform laboratory evaluation of complete system
- Perform in vehicle evaluation of complete system

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- A. Durability
- D. Thermal, Air and Water Management
- F. Fuel Cell Power System Integration
- G. Power Electronics

Technical Targets

Table 1. Progress Against Technical Targets

CPG Progress Toward Meeting DOE Auxiliary Power Unit Targets						
Characteristic	**Units**	**DOE 2006 Target**	**Diesel [(1)] APU Market Benchmark**	**Market [(1)] Entry Targets**	**CPG [(1)] Proposal 2006 Prototype**	**Current Status (estimate)**
Specific Power	W/Kg	70	25	16	17	17 [(2)]
Power Density	W/L	70	21	11	8	8 [(3)]
Efficiency @ rated power	%/LHV[(4)]	25	20	25	25	25
Cost	$/kWe	<800	400	600	1500	1500 [(5)]
Cycle capability (from cold start) over operating lifetime	No cycles	40	>1000	500	10	10
Durability	hours	2,000	10,000	5,000	1500	1500
Start up time	min	30 - 45	<10 sec	2 hours	1 hour	4 hours

[1] As included in CPG Proposal, DE-PS36-03GO9300
[2] Based on 2.5 KWe gross fuel cell and 136 Kg package
[3] Based on 2.5 KWe gross fuel cell and 337 liter package
[4] Lower heating value
[5] Based on 2.5 KWe gross fuel cell, excludes DC to AC Inverter

Approach

- Develop System Technical Profile to define SOFC APU output requirements and operating environment
- Analyze truck electrical and thermal load profile
- Utilize SOFC technology developed in parallel Solid State Energy Conversion Alliance (SECA) project
- Conduct bench testing to evaluate suitable diesel reformer catalysts
- Identify and evaluate potential solutions for internal water management concepts
- Obtain and analyze real world truck vibration data to support suitable analysis and design of SOFC APU isolation system
- Design and evaluate separate subsystems
- Integrate and evaluate overall system in laboratory and on truck

Accomplishments

- Technical Profile developed
- Analysis of truck electrical and thermal load profile requirements has shown that the thermal load can equal or exceed the electrical load
- Alternate approaches to providing thermal load have been examined
- A simulink-based system level model has been created to evaluate and optimize trade-offs between fuel cell (e.g. size, transient response) and the batteries (capacity, losses)
- Micro reactor testing is underway to support reformer catalyst evaluations
- Alternative internal water management concepts have been evaluated and an approach has been selected (this addresses the DOE technical barrier on water management)

- Preliminary design work has started on the SOFC hot box assembly
- Suitable truck vibration signatures have been identified to aid in SOFC isolation and design and test. (this work is to help address the DOE technical barrier for durability of a mobile system)

Future Directions

- Complete truck load profile analysis against time vs fuel cell output to optimize SOFC stack size vs battery capacity (efficiency/component sizing/cost tradeoffs) using the system model
- Complete reformer catalyst evaluation
- Design the controls and power electronics incorporating SECA project experience
- Continue with vibration analysis and design and the determination of vibration tolerance of fuel cell stacks
- Commence sub-system design

Introduction

The over the road Class 7/Class 8 truck is one of the mainstays of the U.S. economy. It is estimated that over 500,000 of these trucks travel more than 500 miles from their home base on their daily trips. These distances require the truck to overnight at truck stops. To provide heating and cooling and auxiliary power for lights and hotel loads for the sleeper cab, typically a part of these long distance trucks, the truck operator currently runs the main vehicle engine overnight. In doing so the truck typically consumes 1 gallon of diesel fuel per hour as well as contributing in a negative manner to the air quality in the neighborhood of the truck stop.

The SOFC APU is being designed and developed to provide the heating and electric power currently being provided by the main vehicle engine but at a lower fuel consumption and at a much lower emission level. By using an on-board diesel fuel reformer to provide hydrogen and carbon monoxide as the fuel for a SOFC, the SOFC APU will help support the hydrogen economy, significantly reducing/eliminating the current idling emission levels, and it will also support the DOE 21st Century Truck Initiative by reducing overall diesel fuel consumption. If all overnight trucks were equipped with SOFC APUs, it is estimated that over 600 million gallons of diesel fuel could be saved annually.

Approach

Cummins Power Generation is a SECA team member and is working on a project to develop a functioning SOFC suitable for mobile power. For the SOFC APU project the approach is to take the knowledge gained from the SECA project and build on this for the smaller stack required for the truck APU. To be successful, the SOFC APU has to provide a rapid payback, (18 to 24 months), for the truck owner/operator. Two of the key factors in this equation are initial cost and fuel consumption. As the size of the fuel cell stack is one of the key cost drivers, the fuel cell stack should not be any larger than that required to complete the mission. As the transient response of the fuel cell is not capable of responding to instantaneous load increases, the SOFC APU system will need to include a DC storage device to provide load “ride through” as the fuel cell output ramps up.

To obtain the correct size balance between the SOFC stack and the DC storage batteries, it will be necessary to accurately understand the expected truck loads and duty cycles. To aid in optimizing the correct fuel cell size and DC battery capacity, the APU system will be modeled and expected truck load duty cycles will be examined for their impact on fuel cell size and the minimum state of charge for the DC storage batteries.

Results

In developing the SOFC technical profile and working through the expected truck loads it was determined that the maximum thermal load during the heating months, i.e. the thermal output required to heat the main vehicle engine and provide heat for the sleeper cab is greater than the maximum electrical loads. This shows that for the SOFC APU to adequately satisfy the truck performance requirements the SOFC APU must be capable of providing both electrical and thermal output. As one characteristic of the SOFC is a high temperature exhaust stream, this exhaust stream will be used to heat the coolant loop which the truck manufacturer plans to use as the heat transfer medium for heating both the main engine and the sleeper cab. This approach will help maximize fuel efficiency during the heating months, an important factor in achieving the overall target efficiency level of 25% LHV.

Table 2. APU Thermal vs Electrical Loads

Peak electrical load during summer	4.4 Kwe
Average electrical load during summer	1.5 Kwe
Peak electrical load during winter	3.4 Kwe
Avg electrical load during winter	0.5Kwe
Peak thermal load requirement during winter	4.4Kwe
ie. During winter, the thermal load is *greater than* the electrical load	

Research [1] into the current emission levels of idling truck engines and diesel powered APUs has confirmed the significant fuel saving and emission benefits of the proposed SOFC APU (Figure 1).

To control reformer catalyst temperatures and to prevent soot formation, it is important that the reformer be supplied with appropriate quantities of water, the so called "water management" issue. Various methods were considered for this such as providing a separate water supply on the truck, but as this would entail the monitoring and supply of another fluid which was considered undesirable. Two internal water management approaches were considered and evaluated. The first was to recycle a portion of the anode gas, which contains moisture, and the second was to use a water separation membrane to extract the water from the anode gas.

Aspen modeling showed that the anode gas recycle approach has the potential to increase the fuel cell efficiency and reduce the reformer temperatures. The humidification membrane approach would permit smaller components than those required for the anode gas recycle approach. Testing of the recycle approach using a micro reactor showed no negative impact on reformer performance. However, testing of the humidification membrane resulted in less than target water recovery and also showed evidence of sensitivity to contaminants.

Based on these results the decision has been made to pursue anode gas recycling as the approach for providing internal water management (Figure 2).

To achieve the durability goals expected by the trucking industry, any fuel cell APU will need to be extremely rugged. Unlike APUs powered by reciprocating engines, where the isolation goal is to isolate the truck from APU induced vibrations, the challenge for fuel cells is to isolate the APU from the truck shocks and vibration induced by road hazards. To aid in the isolation system design, vibration data collected from appropriate over-the-road truck testing has been analyzed and a model has been created to replicate the truck frame response. This vibration response can be used as the input to a

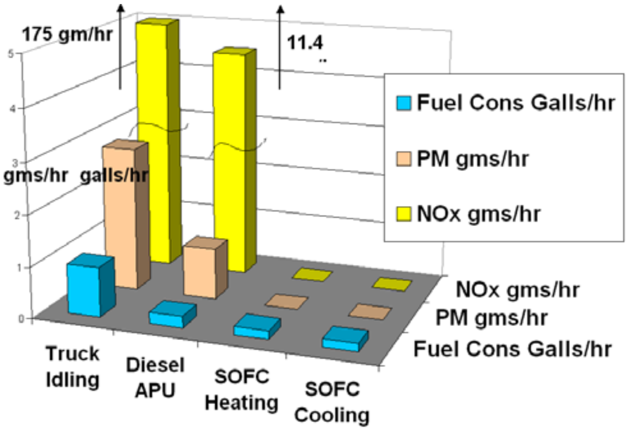


Figure 1. SOFC APU Fuel Consumption and Emission Benefits

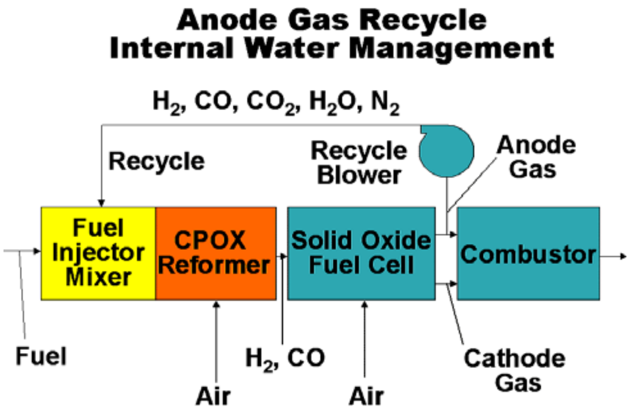
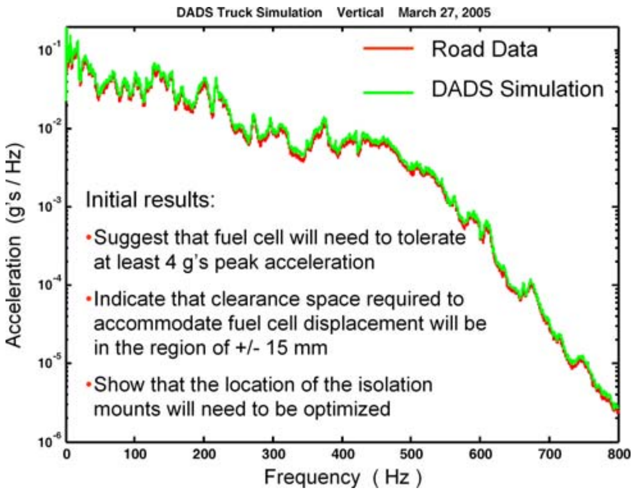


Figure 2. Diesel Fueled SOFC APU with Anode Exhaust Gas Recycle

model of the SOFC APU and its isolation system to predict the expected response of the SOFC APU. Based on preliminary modeling work, the results indicate that the fuel cell stack will be subjected to peak acceleration levels in excess of 4g (Figure 3). As the ability of the fuel cell stack to withstand vibration is not well understood, testing is planed to better understand the vibration limits of the fuel cells components themselves.



Initial results:

- Suggest that fuel cell will need to tolerate at least 4 g's peak acceleration
- Indicate that clearance space required to accommodate fuel cell displacement will be in the region of +/- 15 mm
- Show that the location of the isolation mounts will need to be optimized

Figure 3. Vibration Isolation of SOFC APU

Conclusions

The thermal load requirement for cab and engine temperature control for over-the-road sleeper trucks can equal or exceed the electrical load requirement

SOFC exhaust energy can be used as an efficient way to provide this thermal load

Internal water management can be achieved by means of recycling a percentage of the anode exhaust gas, eliminating the need for a separate water supply

An effective SOFC APU isolation system is going to be required to ensure adequate SOFC APU durability

FY 2005 Publications/Presentations

1. Presentation given at the 21st Century Truck Merit Review, March 16, 2005, Washington DC.
2. Poster presentation given at the DOE 2005 Hydrogen Program Review, May 24, 2005, Washington DC.

References

1. SAE Paper 2003-01-0289, "Particulate Matter and Aldehyde Emissions from Idling Heavy-Duty Diesel Trucks", Storey et al.

21st CENTURY TRUCK
PARTNERSHIP

Solid State Energy Alliance Overview (link)

WEBLINK

The Solid State Energy Alliance Overview can be found at:

http://www.fuelcellseminar.com/pdf/2006/Tuesday/1A/Surdoval_Wayne_0310_1A_71(rv4).pdf

21st CENTURY TRUCK PARTNERSHIP

DOE FCVT Multiyear Program Plan, Waste Heat Recovery Section (document)

3.3 Advanced Combustion Engine R&D and Fuels Technology

The Advanced Combustion Engine R&D and Fuels Technology subprograms support the mission of FCVT to develop more energy-efficient and environmentally friendly highway transportation technologies that enable the United States to use less petroleum. They will contribute to the FCVT Program goals by dramatically improving the efficiency of internal combustion engines (ICEs) and by identifying fuel properties that improve the system efficiency or can displace petroleum based fuels. Improved efficiency and petroleum displacement fuels both can directly reduce petroleum consumption.

The Advanced Combustion Engine R&D subprogram is focused on removing critical technical barriers to the commercialization of higher-efficiency, advanced combustion engines in light-duty vehicles (passenger cars and light trucks) and commercial medium- and heavy-duty vehicles. R&D focus is on improving engine efficiency while meeting future federal and state emissions regulations through a combination of combustion and fuels technologies that increase efficiency and minimize in-cylinder formation of emissions, and aftertreatment technologies that further reduce exhaust emissions. Activities under the Advanced Combustion Engine R&D subprogram include Combustion and Emission Control R&D, Heavy Truck Engine R&D, Waste Heat Recovery, and Health Impacts.

The Fuels Technology subprogram supports R&D to provide vehicle users with fuel options that enable high fuel economy, deliver lower emissions, contribute to petroleum displacement, and are cost competitive. This subprogram's Fuels for Advanced Combustion Engines activity is closely coordinated with the Combustion and Emission Control R&D activities since different fuel characteristics and reduced property variability may be needed to meet the efficiency and emissions goals. Without the suitable fuels, high-efficiency advanced combustion engines may not be introduced into the market and oil savings will not be realized.

The Advanced Combustion Engine and Fuels Technology R&D activities are undertaken in collaboration with industry, national laboratories, and universities and in conjunction with the FreedomCAR and Fuel Partnership and the 21st Century Truck Partnership (21st CTP).

The following activities are discussed in this section:

- Combustion and Emission Control R&D;
- Heavy Truck Engine R&D;
- Fuels for Advanced Combustion Engines;
- Waste Heat Recovery; and

- Health Impacts.

3.3.1 Combustion and Emission Control R&D

The Combustion and Emission Control R&D activity focuses on enabling energy-efficient, clean vehicles, powered by advanced combustion engines that use clean, petroleum- and non-petroleum-based fuels, and hydrogen**.** This research activity focuses on developing technologies for light-, medium-, and heavy-duty engines operating in advanced combustion regimes, including homogeneous charge compression ignition (HCCI) and other modes of low-temperature combustion, which will increase efficiency beyond current advanced diesel engines and reduce engine-out emissions of Nitrogen Oxides (NO_x) and particulate matter (PM) to near-zero levels.

Advanced combustion engines are a key element in the pathway to achieving the goals of the FreedomCAR and Fuel Partnership. Advanced engine technologies being researched and developed will allow the use of hydrogen as a fuel in ICEs and will provide an energy-efficient interim hydrogen-based powertrain technology during the transition to hydrogen/fuel-cell-powered transportation vehicles.

3.3.1.1 External Assessment and Market Overview

Although the achievement of EPA Tier 2 emissions performance has been demonstrated by advanced light-duty diesel engine technology, the rate of market penetration will still be limited by the energy consumption, cost, and durability of the emission control system. The National Academy of Sciences' Committee on the Effectiveness and Impact of Corporate Average Fuel Economy Standards "believes that the Tier 2 NO_x and PM standards will inhibit, or possibly preclude, the introduction of diesels into vehicles under 8500 lb." [a] Research in this activity has transitioned to the development of technologies that will enable advanced engines to operate in low temperature combustion (LTC) regimes with diesel-like efficiency and near-zero emissions. The lower engine-out emissions are expected to enable the use of lower-cost emission control systems with little or no energy consumption and greater durability, making these more efficient combustion engines cost-competitive with current gasoline engines and gaining greater market penetration in passenger vehicles.

3.3.1.2 Internal Assessment and Activity History

The compression ignition direct injection (CIDI) engine, an advanced version of commonly known diesel engines, is the most promising technology for achieving dramatic energy-efficiency improvements in light-duty vehicle applications, where it is suited to both conventional and hybrid-electric powertrain configurations. High efficiency and durability are the attributes that made the diesel the primary engine for commercial heavy-duty applications. Although it is more efficient than conventional gasoline engines, if the CIDI engine is to become widely used in light-duty passenger

---

[a] National Research Council, Effectiveness and Impact of Corporate Average Fuel Economy (CAFÉ) Standards, 2002, p. 35

vehicle applications, advancements will be required in the mid-term to further improve efficiency while meeting more stringent future emissions standards. The CIDI engine offers a propulsion platform with the potential for further significant efficiency improvements beyond its current capabilities. Advancements will be required in clean combustion, emission control technology, and clean diesel fuels. The Combustion and Emission Control R&D activity initially focused on technologies that enabled the CIDI engine for all applications, from light- to heavy-duty vehicles. Work has since transitioned into engines operating in advanced LTC regimes that offer substantial improvements in efficiency and near-zero emissions.

Advanced fuel formulations and fuel quality are also crucial to achieving higher energy efficiencies and meeting emissions targets. The EPA rule mandating that the sulfur content of highway diesel fuel be reduced to less than 15 ppm starting in 2006 will greatly benefit the effectiveness, durability, and life of emission control devices. There is close coordination with the Fuels for Advanced Combustion Engines activity because operation in combustion regimes such as HCCI and LTC is enabled by, and heavily dependent on, especially tailored fuel properties. In addition, the subprogram is in the process of securing unanimous concurrence from current participants in the Sandia Advanced Combustion Engine Memorandum of Understanding (MOU) to add FreedomCAR and Fuel Partnership energy companies as full participants.

Work is also undertaken in hydrogen-fueled ICE research that will provide an interim hydrogen-based powertrain technology that promotes the longer-range FreedomCAR and Fuel Partnership goal of transitioning to a hydrogen-fueled transportation system. This goal is shared by FCVT and HFCIT. Hydrogen engine technologies being pursued have the potential to provide diesel-like engine efficiencies with near-zero emissions.

3.3.1.3 Federal Role

Bringing together expertise from both the public and private sectors through collaborative efforts to expand the knowledge base in high-risk, pre-competitive technology areas is a proper Federal Government role. The experimental research and modeling tasks conducted by participating DOE national laboratories will allow a more effective evaluation of potential advanced combustion engine technologies and validation of technology selection. Working at the forefront of these new technologies enhances the knowledge base that can be used by industry partners and suppliers (e.g., original equipment manufacturers, engine manufacturers, emission control device manufacturers, catalyst suppliers) to develop energy-efficient, cost-effective advanced engine and emission control systems. Cooperative research conducted with universities and industry partners accelerates the introduction of these high-risk, mid-term technologies into the marketplace.

3.3.1.4 Approach

The Combustion and Emission Control activity will address in-cylinder combustion and emission control, exhaust aftertreatment technologies, and fuel formulation strategies simultaneously for the most cost-effective approach for optimizing advanced combustion engine efficiency, emissions, and performance. Experimental data and validated computer simulation models will be developed to provide a more definitive understanding of the in-cylinder fuel injection, combustion, and emissions formation processes, as well as the evolution of emissions in the aftertreatment systems. The models to be developed will enable rapid and effective optimization of the fuel injection and combustion systems and the aftertreatment devices for maximum overall system efficiency, compliance with emissions standards, and cost-effectiveness.

3.3.1.5 Performance Goals

The following goals are intended to enable FCVT to meet energy-efficiency improvement targets for advanced combustion engines suitable for passenger cars and light trucks, as well as to address technology barriers and R&D needs that are common between light- and heavy-duty vehicle applications of advanced combustion engines:

- By 2007, achieve engine efficiency of at least 42 percent and, combined with some emission control devices, meet EPA Tier 2, Bin 5 in a light-duty vehicle using diesel fuel (specified by the Fuels Technology subprogram) with a fuel efficiency penalty of not more than 2 percent.
- By 2010, develop the understanding of novel low-temperature engine combustion regimes needed to simultaneously enable engine efficiency of 45 percent with a fuel efficiency penalty of less than 1 percent.

Presented in the following table are the technical targets (consistent with the goals) for the Combustion and Emission Control activity. The FreedomCAR and Fuel Partnership goals for both hydrocarbon- and hydrogen-fueled ICEs are also shown. These apply to light-duty vehicles (passenger cars and light trucks).

3.3.1.6 Strategic Goals

The Combustion and Emission Control R&D activity supports DOE's Energy Security Strategic goal to "improve energy security by … exploring advanced technologies that make a fundamental improvement in our mix of energy options, and improving energy efficiency."

3.3.1.7 Market Challenges and Barriers

The primary market challenge is as follows:

A. ***Cost.*** Engines that use LTC are more expensive than conventional, port fuel-injected, spark-ignited engines; the engine structures must be stronger to accommodate the inherently higher combustion pressures. Also, the high-pressure fuel injection systems must be correspondingly more robust, and an air boosting system is required to increase power density. The emission control devices required by engines to meet emission targets add to the cost of the system.

Table 3.3-1. *Technical Targets for the Combustion and Emission Control Activity*

Characteristics	Units	FY 2007	FY 2009	FY 2010
FreedomCAR and Fuel Partnership Goals				
ICE Powertrain				
Peak brake thermal eff. (CIDI/H_2–ICE) (H_2–ICE)	%			45/45 45 (2015)
Cost (CIDI/H_2–ICE) (H_2–ICE)	\$/kW			30/45 30 (2015)
Reference peak brake thermal efficiency[a]	%	32	34	35
Target peak brake thermal efficiency/part-load brake thermal efficiency (2 bar BMEP[b] @1500 rpm)	%	42/29	44/30	45/31
Powertrain cost[c,d]	\$/kW	35	30	30
Emissions[e]	(g/mile)	Tier 2, Bin 5	Tier 2, Bin 5	Tier 2, Bin 5
Durability[e]	Hrs.	5000	5000	5000
Thermal efficiency penalty due to emission control devices[f]	(%)	<3	<1	<1

[a] Current production, EPA-compliant engine.

[b] Brake mean effective pressure.

[c] High-volume production: 500,000 units per year.

[d] Constant out-year cost targets reflect the objective of maintaining powertrain (engine, transmission, and emission control system) system cost while increasing complexity.

[e] Projected full-useful-life emissions for a passenger car/light truck using advanced petroleum-based fuels as measured over the Federal Test Procedure as used for certification in those years.

[f] Energy used in the form of reductants derived from the fuel, electricity for heating and operation of the devices, and other factors such as increased exhaust back-pressure, reduce engine efficiency. A cycle average thermal efficiency loss of 1 to 2% is equivalent to a 3 to 5% fuel economy loss over the combined Federal Test Procedure drive cycle.

Better use of advanced LTC modes to reduce the formation of emissions in-cylinder will reduce aftertreatment system requirements and associated costs.

3.3.1.8 Technical Challenges and Barriers

The technical challenges and barriers to achieving the technical targets are as follows:

B. ***Fundamental knowledge of engine combustion.*** Engine efficiency improvement, engine-out emissions reduction, and minimization of engine technology development risk are inhibited by an inadequate understanding of the fundamentals of fuel injection, fuel-air mixing, thermodynamic combustion losses, and in-cylinder combustion/emission formation processes over a range of combustion temperature regimes of interest, as well as by an inadequate capability to accurately simulate these processes. An insufficient knowledge base will inhibit the development of advanced LTC or mixed-mode combustion systems that operate effectively over the full load range of an engine. These advanced combustion systems offer significant potential for providing engines that operate with CIDI-like engine efficiencies over the full load range while meeting EPA Tier 2 emissions standards with greatly reduced aftertreatment system requirements.

C. ***Emission control.*** Meeting EPA requirements for oxides of nitrogen and particulate matter emissions standards with little or no fuel economy penalty will be a key factor for market entry of advanced combustion engines. NO_x adsorbers appear to be the most viable NO_x reduction devices for light-duty vehicles, but they are very sulfur-sensitive, resulting in an increasingly greater energy penalty over time to compensate for loss of activity. Other technologies under consideration have their own technical barriers as well. Particulate trap technology is costly, and certain regeneration technologies are energy-intensive. The most effective particulate trap technologies cause reductions in engine efficiency through increases in backpressure. While there is more experience with PM emission control devices than with NO_x control devices, PM control technology will likely be pushed to its limits in favor of controlling NO_x emissions, which currently is the more intractable of the two problems.

D. ***Engine controls.*** Effective sensing and control of various parameters will be required to optimize operation of engines in advanced LTC regimes over a full load-speed map similar to that of the CIDI engine. Parameters and operations that need improved controls include 1) ignition timing across the load-speed map, 2) the rate of heat release, and 3) transients and cold starts.

E. ***Durability.*** The emission control system has to perform effectively for 120,000-miles of light-duty vehicle (cars and light trucks) operation.

3.3.1.9 Strategies for Overcoming Barriers/Challenges

Fundamental combustion R&D will focus on developing greater understanding of the combustion and emissions processes and their dependence on fuel spray characteristics, in-cylinder air motion, and fuel selection so that pathways to higher engine efficiencies and lower NO_x and PM from the engine can be identified. R&D tasks will include:

- Identification of advanced combustion system concepts that enable high efficiencies and fuel injection strategies for the implementation of advanced combustion systems;
- Research on combustion systems for advanced fuels;
- Investigation of mechanisms and strategies to reduce thermodynamic combustion losses;
- Investigation of NO_x and PM formation mechanisms in the engine; and
- Identification of potential fuel-derived reductants.

Numerical and chemical kinetics models will be developed to guide the experimental combustion research.

Advanced combustion engine technologies that will be pursued are those that operate in LTC regimes that can provide high, diesel-like efficiencies and have ultra-low engine-out NO_x and particulate levels. Engines to be investigated include engines operating purely on LTC modes such as HCCI; and engines that use conventional

CIDI or spark-ignited (SI) combustion modes for starting and at higher loads, and use LTC modes at moderate to light loads, referred to as mixed-mode operation. In the case of mixed-mode operation with CIDI at high loads, the high-efficiency, high-load capabilities of CIDI are coupled with the high-efficiency, low-emission capabilities of the LTC modes, overcoming the deficiencies in CIDI aftertreatment systems at light loads and the limited high-load capabilities of LTC modes. In the case of mixed-mode operation with SI at high loads, CIDI-like engine efficiencies can be achieved by using LTC at moderate to light loads to eliminate part-load throttling losses and to control emissions, while maintaining the high-load capabilities of conventional port-fuel-injected engines.

Research will also be undertaken to develop a fundamental knowledge base on very lean, low-temperature hydrogen combustion under high-pressure in-cylinder conditions. This will support both the development of advanced hydrogen-fueled engines and the simulation tools used to aid the development of the knowledge base and the optimization of engines. This will require improved understanding of hydrogen injection and fuel-air mixing processes; combustion stability, combustion duration and pre-ignition phenomena; emissions formation; and the effects of engine speed and load, combustion chamber geometry, and in-cylinder air motion (e.g., swirl) on hydrogen combustion and emissions processes.

Fuel systems R&D focuses on injector controls and fuel spray development. The fuel injection system pressure and fuel spray development influence the spray penetration and fuel-air mixing processes and thus combustion and emissions formation within the combustion chamber. These phenomena are being researched using X-ray and optical diagnostics with the experimental results used to develop spray models. In-cylinder emissions reduction can also be achieved with very careful control of injection timing, duration, and rate shape. Recent developments have shown that the application of multiple injections in a cycle can result in much lower engine-out emissions.

Engine control systems R&D will focus on developing engine controls that are precise and flexible for enabling improved efficiency and emission reduction in advanced combustion engines. These control system technologies will facilitate adjustments to parameters such as intake air temperature, fuel injection timing, injection rate, variable valve timing, and exhaust gas recirculation (EGR) to allow advanced combustion engines to operate over a wider range of engine speed/load conditions. In addition, control strategies will be developed to enable the effective transition from low-temperature, low-emission modes of combustion used at lighter loads to conventional CIDI or SI combustion at higher loads (e.g., control strategies for mixed-mode operation).

Complex, precise engine and emission controls will require sophisticated feedback systems employing new types of sensors. NO_x and PM sensors are in the early stages of development and will require additional advances to be cost-effective and reliable.

However, these technologies are essential to control systems for these advanced engine/aftertreatment systems.

Development of technologies enabling LTC will be undertaken to achieve the best combination that enables meeting maximum fuel economy and performance requirements. These include variable compression ratio (VCR), variable valve timing, variable boost, advanced sensors, and exhaust emission control devices (to control hydrocarbon emissions at idle-type conditions) in an integrated system. Variable valve control, independent valve control, and VCR offer the potential for operating with the highest efficiency and for providing ignition timing control through control of in-cylinder temperature or internal EGR. These technologies can reduce engine-out NO_x emissions and thus reduce the need for ancillary systems such as external EGR.

Emission control system R&D tasks will focus on reducing the energy penalty of emission control systems through development of more-effective emission control devices for reducing NO_x and PM in exhaust systems.

Research on improving the effectiveness of NO_x adsorbers for diesel engine exhaust aftertreatment will focus on 1) defining the optimum regeneration schedule with a lean-burn engine, 2) improving NO_x reduction at the lower exhaust temperatures of the duty cycle for light vehicles, and 3) determining long-term degradation mechanisms and susceptibility to sulfur poisoning. As lower engine-out emissions are achieved, continuous lean-NO_x catalysis again becomes a viable alternative. High-throughput combinatorial chemistry will be employed to develop lean-NO_x catalyst materials with higher conversion rates and greater durability. Several common issues—such as sulfur tolerance, reductant optimization, and long-term degradation mechanisms—crosscut among all the NO_x-reducing technologies and will be investigated.

PM-reduction devices face challenges in the areas of long-term degradation and the ability to effectively regenerate despite the relatively cool exhaust temperatures typical of light-duty engines. The focus will be on the refinement of existing technologies and development of novel and innovative PM control technologies. Three different PM-reducing technologies—the catalyzed diesel particulate filter, the continuously regenerating diesel particulate filter, and the microwave-regenerable filter—will continue to be pursued. Research will focus on evaluations of their potential to meet the PM emissions targets, especially in conjunction with NO_x-reducing technologies. To help improve the understanding of PM formation and in-cylinder control, especially during engine transients, new high-energy, laser-based diagnostics with real-time capabilities for measuring and characterizing PM emissions at low concentrations will be used. Other enabling technologies that will be investigated include sulfur traps, sulfur-tolerant catalysts, and low temperature oxidation catalysts for control of HC and CO.

3.3.1.10 Tasks

A description of each task, along with the estimated duration and the associated barriers, is provided in the following table. These tasks support the mid-term goals of the FreedomCAR and Fuels Partnership. They were initiated in January 2002 with the inception of the Partnership and will continue through 2015.

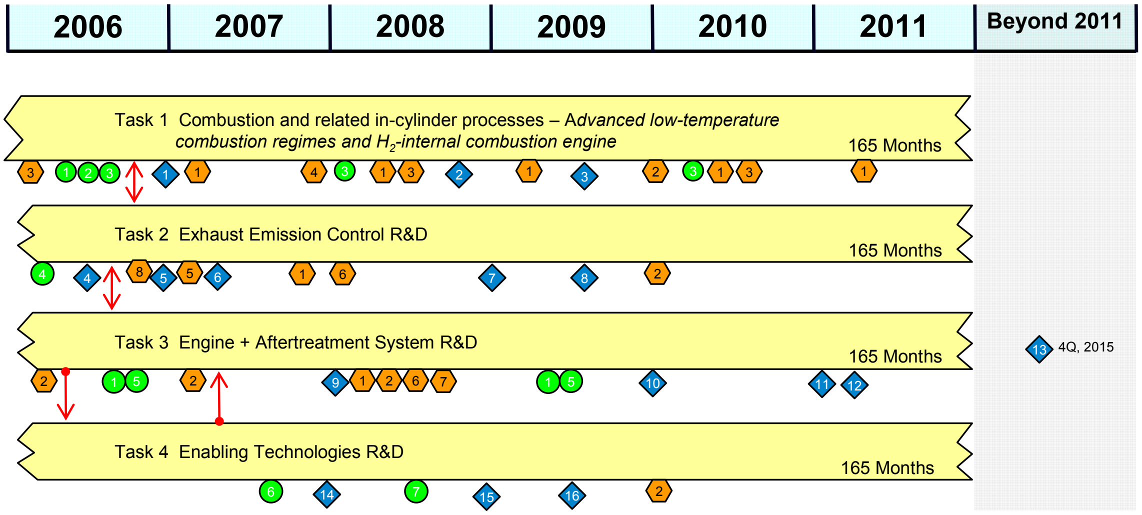
***Table 3.3-2.** Tasks for Combustion and Emission Control R&D*

Task	Title	Duration & Barriers
1	***Combustion and related in-cylinder processes - Advanced low-temperature, low emission combustion regimes and H_2-ICE*** • Develop fundamental understanding of low-temperature combustion regimes and their control over a range of engine loads and speeds through experimental and modeling/simulation approaches • Exploit emissions characteristics of LTC regimes and methods of coupling to aftertreatment systems to achieve maximum efficiency • Establish relationships between new combustion regimes and potential efficiency gains and develop paths to efficiency targets • Develop understanding and methods for mixed-mode approaches that must alternate between conventional and new combustion regimes • Develop fundamental understanding of H_2-ICE combustion processes	165 months Barriers A, B, C, E
2	***Exhaust Emission Control R&D*** • Improve the scientific foundation of NO_x adsorber–catalyst performance and degradation mechanisms to mitigate the trend of greater efficiency loss as catalyst ages • Develop strategies for mitigating sulfur effects on aftertreatment, including catalyst tolerance, regeneration methods, and further reduction of sulfur sources (lubricants) • Improve the catalyst materials and systems for lean NO_x catalysis with urea and alternative reductants for performance over wider temperature range. • Improve the simulation capability for exhaust aftertreatment devices to accelerate the design of the most efficient and effective emission control systems • Improve the technologies and strategies for PM filters to achieve reliable regeneration at low exhaust temperatures	165 months Barriers A, C, E
3	***Engine + Aftertreatment System R&D*** • Develop and demonstrate integrated controls and strategies for engine and aftertreatment systems with maximum fuel economy at the necessary emissions levels	165 months Barriers A, B, C, D, E
4	***Enabling Technologies R&D*** • Develop and validate NO_x and PM sensors for engine and aftertreatment control and diagnostics • Develop advanced engine control methods and strategies for operation over a range of loads and speeds	165 months Barriers A, C, D, E

3.3.1.11 Milestones and Decision Points

Combustion and Emission Control R&D activity milestones and decision points are provided in the following chart:

Combustion and Emission Control R&D Network Chart



Legend

◆ **Milestone**

1. Complete assessment of two-stage ignition fuels for extending to high-load LTC
2. Complete characterization of engine-out HC, CO, PM, and NOx emissions from LTC engine
3. Complete development and construction of 30kW prototype hydrogen free-piston engine
4. Complete evaluation of catalyst materials using combinatorial chemistry
5. Validate NO_x and PM control device efficiencies (sufficient to limit NO_x to 0.07 g/mile and PM to 0.01 g/mile, respectively) using 15-ppm sulfur-content fuel with durability to projected full-useful-life requirements
6. Complete microwave regeneration of PM filter
7. Complete protocols for emission control simulation tools
8. Complete demonstration of emission control strategy compatible with LTC
9. Validate 42% thermal efficiency with <2% fuel efficiency penalty for meeting standards with emission control devices using a fuel formulation recommended by the Fuels Technology sub-program

◆ **Milestone**

10. Validate 44% thermal efficiency with <1% fuel efficiency penalty for meeting standards with emission control devices using a fuel formulation recommended by the Fuels Technology sub-program
11. Validate 45% peak thermal efficiency H2-IC engine
12. Validate 45% thermal efficiency with <1% fuel efficiency penalty for meeting standards with emission control devices using a fuel formulation recommended by the Fuels Technology sub-program
13. Validate 45% peak thermal efficiency H2-IC engine at $30/kW
14. Evaluate sensors to control HCCI combustion
15. Validate efficiency improvement with variable valve timing
16. Validate at least 5% fuel economy improvement with variable compression ratio

⬢ **Technology Program Output**

1. Transfer of technical data/information to industry
2. Technical results to Heavy Truck Engine R&D
3. Fuel Property requirements for HCCI, to Fuels Technology R&D
4. Technical results on H_2-ICE to Hydrogen, Fuel Cells, and Infrastructure Technologies Program
5. Rapid aging protocol for NO_x adsorber system, to Fuels Technology R&D
6. Technical results and feedback to Fuels Technology
7. Technical results to Vehicle Systems R&D
8. Engine/emission control system model that predicts fuel effects on the system (to Fuels for Advanced Combustion Engines)

● **Supporting Input**

1. Fuel formulation that enables emission control system to meet useful life requirements, from Fuels Technologies R&D
2. Input from Hydrogen, Fuel Cells, and Infrastructure Technologies Program
3. Fuels composition that meets requirements of HCCI, from Fuels Technology R&D
4. Technical data on sulfur trap, from Fuels Technology
5. Fuel-derived reductant for emission control use, from Fuels Technology
6. Validated small orifice fuel injector from Heavy Vehicle Propulsion Materials
7. Validated emission control devices (sensors, PM filter), from Automotive Propulsion Materials

Figure 3.3-1. Network Chart for Combustion and Emission Control R&D

3.3.2 Heavy Truck Engine R&D

Heavy Truck Engine R&D is focused on increasing heavy-duty diesel engine efficiency significantly above current levels, as well as addressing efficiency penalties resulting from technologies required to meet increasingly stringent emissions standards. The engine efficiency losses would result in higher operating costs to truck owners and operators and, ultimately, higher costs to consumers. On a national scale, increased heavy truck fuel efficiency would result in reduced petroleum demand.

3.3.2.1 External Assessment and Market Overview

The truck industry and government partners in the 21st CTP have developed a common vision–"that our Nation's trucks and buses will safely and cost-effectively move larger volumes of freight and greater numbers of passengers while emitting little or no pollution and dramatically reducing the dependency on foreign oil."[b] Ultimately, the partnership seeks safe, secure, and environmentally friendly trucks and buses that use sustainable and self-sufficient energy sources, thereby helping enhance America's global competitiveness. Primarily due to the requirements of long-haul commercial vehicles for long driving range and cargo carrying capacity, the heavy-duty diesel engine is seen as the only viable option to power trucks of the 21st Century. R&D is needed to continue to improve the heavy-duty diesel engine system efficiency while meeting applicable EPA emissions standards.

3.3.2.2 Internal Assessment and Activity History

The Heavy Truck Engine activity supports the development of technologies needed to significantly improve the efficiency of heavy-duty diesel engines beyond present levels while meeting the 2007/2010 heavy-duty engine emissions standards. This activity was initiated in FY 1999 to address the energy efficiency impact of the anticipated more stringent 2007 and 2010 EPA heavy-duty diesel engine emissions standards. An efficiency penalty of as much as 10 percent in heavy-duty diesel engines was anticipated with the use of emission control technologies available at that time. Also, the high sulfur content of available diesel fuel has deleterious effects on the performance of emission control devices.

In December 2000, EPA enacted the 2007 Heavy-Duty Diesel Engine Emissions Standards. EPA also issued a rule in January 2001 requiring that 80 percent of all on-road diesel fuel have less than 15 ppm sulfur, starting in 2006. This rule is in conjunction with the phase-in of emissions standards in the 2007–2010 timeframe. The rule on sulfur content of diesel fuel is expected to greatly benefit the performance and durability of emission control technologies under development.

3.3.2.3 Federal Role

Freight transport provided by heavy trucks has continued to increase with the expansion in economic activity and has resulted in a significant contribution to the increase in U.S. highway transportation energy use. Heavy truck engine technologies

---

[b] Secretary Spencer Abraham, Unveiling of the 21st Century Truck Partnership, Dearborn, Michigan, November 12, 2002.

R&D undertaken to meet this growing energy demand more efficiently while meeting future emissions standards is an appropriate Federal role because heavy trucks are critical to economic growth due to their extensive use in trade and commerce and in providing essential services. Targeted investment in technology research and development in strategic partnerships with commercial heavy-duty engine and vehicle manufacturers and national laboratories will produce leveraged benefits for the American taxpayer.

3.3.2.4 Approach

An integrated systems approach involving advancements in engine design, fuels, and aftertreatment technologies is required to simultaneously address fuel efficiency and emissions. R&D in combustion, materials, fuels, and aftertreatment devices provides the foundation for technology advancement, including simulations (virtual labs) in concert with controls development and experimentation.

3.3.2.5 Performance Goals

The long-term (2013) goal of this activity is to develop the technologies that will increase the thermal efficiency of heavy-duty diesel engines to at least 55 percent while reducing emissions to near-zero levels. More specifically,

- By 2006, increase the thermal efficiency of heavy-duty engines to 50 percent while meeting EPA 2010 emission standards.
- By 2013, increase the thermal efficiency of heavy truck engines to 55 percent while meeting prevailing EPA emissions standards.

The technical targets for Heavy Truck Engine R&D are provided below:

Table 3.3-3. *Technical Targets for Heavy Truck Diesel Engine R&D*

Characteristics	Year			
	2002 status	2006	2009	2013
Engine thermal efficiency, %	>40	50	51	55
NO_x emissions,[a] g/bhp-h	<2.0	<0.20	<0.20	<0.20
PM emissions,[a] g/bhp-h	<0.1	<0.01	<0.01	<0.01
Stage of development	Commercial	Prototype	Prototype	Prototype

[a] Using 15-ppm sulfur diesel fuel

3.3.2.6 Strategic Goals

The Heavy Truck Engine R&D activity supports the Department's Energy Security Strategic goal to "improve energy security by … exploring advanced technologies that make a fundamental improvement in our mix of energy options, and improving energy efficiency" – and also the 21st Century Truck Partnership goal to develop and validate a commercially viable, 50 percent efficient, emissions-compliant engine system for Class 7 and 8 highway trucks by 2010.

3.3.2.7 Market Challenges and Barriers

The market challenge is as follows:

A. ***Cost.*** The emission control devices required by engines to meet emission targets add costs to the heavy truck engine system. Increased cost is a critical consideration to truck operators who need to be fully competitive in the prevailing markets.

3.3.2.8 Technical Challenges and Barriers

The technical challenges and barriers to achieving dramatically improved efficiency and near-zero emissions in heavy truck engines are as follows:

B. ***Efficiency.*** There are several barriers to improving engine efficiency. In-cylinder NO_x reduction methods in conventional diesels, using traditional combustion modes, limits efficiency by limiting peak in-cylinder temperatures and the time spent at peak temperatures. Aftertreatment systems have energy penalties that reduce the overall engine/aftertreatment system efficiency. Current commercially viable materials and lubricants limit engine efficiency by limiting peak cylinder temperatures and pressures at which critical engine components can operate.

C. ***Emissions.*** The key barriers to achieving the emissions reduction targets for heavy truck diesel engines include (1) maintaining efficiency and low NO_x while keeping PM down; (2) incomplete development of aftertreatment technology, especially for NO_x; and (3) immature simulation and control systems integration capabilities, as well as a lack of static and dynamic optimization of multiple emission reduction systems. Common to each barrier is a lack of adequate simulation capabilities and 'ready to implement' sensing and process control systems. Improved simulation capabilities are needed to optimize both the combustion and aftertreatment systems so as to transform a "statically" integrated system into an optimized overall engine/aftertreatment package that results in maximum efficiency and performance and minimum emissions. In turn, a mature and robust sensing and control system will monitor and navigate these multiple systems over the complex "dynamics" of normal over-the-road vehicle operation, while yielding the best vehicle fuel economy, performance, and emissions.

D. Durability. The barrier to achieving 435,000-mile durability for heavy-duty engines and their emission control systems is the premature degradation of the emission control devices due to operation under high-temperature and high-flow-rate conditions.

3.3.2.9 Strategies for Overcoming Barriers/Challenges

Improving Engine Efficiency. R&D to improve the understanding of energy losses in engine operation such as the combustion process, mechanical friction, heat transfer, air handling, and exhaust losses. All are important in improving engine efficiency. Major elements of the technical approach include the following:

- Define baseline engine designs in sufficient detail to delineate the areas of required technology advancement. This will be a guide for enabling technology tasks. Conduct, on a continuing basis, analysis and supporting validation tests to assess progress toward goals.

- Optimize the mechanical design and combustion system for increased expansion ratio and thermodynamic efficiency.
- Develop and integrate cost-effective exhaust-heat-recovery technologies into the engine system.
- Improve the fundamental understanding of diesel combustion and emissions formation processes and exhaust aftertreatment systems, and the predictive simulation capabilities for these processes and systems needed to more effectively optimize performance.
- Develop and exploit advanced fuel injection and engine control strategies and new LTC regimes for their potential efficiency gains. Use modeling and simulation as an integral component of the system design strategy.
- Improve turbocharger and/or air handling systems and controls, and trade-offs between turbocharger efficiency and transient response. Develop new low-inertia materials and response-enhancing technologies.
- Continue the refinement of piston/cylinder designs, valve trains, and other mechanical components for reduced friction losses.
- Develop accurate, robust sensors for control systems.

Close coordination between the Heavy Truck Engine R&D and the Heavy Vehicle Propulsion Materials R&D, discussed in the Materials Technology, Section 3.4, ensures that materials issues important to engines are addressed.

Reducing Emissions. Simultaneous attainment of thermal efficiency targets and future emission standards requires unprecedented attention to the effective integration of multiple, new system technologies. At the historical and most fundamental level, systems optimization and component performance has been and continues to be accelerated through the application of computer simulations. The emphasis is on high-order "off-line" calculations that are crucial to understanding and defining the basic engine configuration and its performance and emission signature. Simulation and control techniques are active companions in the diesel engine development and operational process. A high-priority need is the advancement of computational simulation capabilities for all systems, especially for aftertreatment systems, which are currently in an immature state of development. Major elements of the technical approach to meet emissions targets also include:

- Further develop flexible fuel-injection systems and engine control strategies and new combustion regimes for their emissions reduction potential, integrating modeling and simulation with engine controls development.
- Optimize cooled exhaust gas recirculation (EGR) for maximum NO_x reduction and minimum PM emission, mitigating durability concerns with EGR through materials engineering and operational controls.
- Improve the fundamental understanding of diesel combustion/emissions formation processes and exhaust aftertreatment systems, and the predictive

simulation capabilities for these processes and systems needed to minimize emissions.

- Develop strategies for mitigating the effects of sulfur on aftertreatment, including catalyst tolerance, regeneration, and further reduction of sulfur sources (lubricants).
- Improve the scientific foundation of NO_x adsorber-catalyst performance and degradation mechanisms. Improve the catalyst materials and systems for lean NO_x catalysis using reductants, so that performance can be maintained over a wider temperature range.
- Improve methods for generating and introducing NO_x reductants to catalysts.
- Develop and apply sensors in controls and diagnostics of engine and emission control processes.
- In the development of emission control devices, include features necessary to make the devices suitable for retrofit on existing trucks.

Fuel properties, particularly sulfur content, are pivotal to the success of NO_x adsorber catalyst technology. Work involving fuels is coordinated with the Fuels for Advanced Combustion Engines activity as discussed in Section 3.3.3.

3.3.2.10 Tasks

A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in the following table. Tasks 2, 3, and 4 began with the reinstitution of 21st CTP in November 2002 and will continue through 2013.

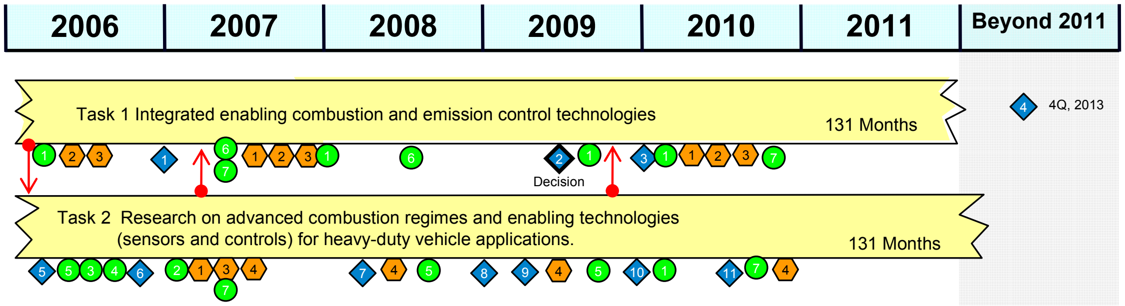
Table 3.3-4. *Tasks for Heavy Truck Engine R&D*

Task	Title	Duration & Barriers
1	***Integrated enabling combustion and emission control technologies***	131 months Barriers B, C, D
2	***Research on advanced combustion regimes and enabling technologies (sensors and controls) to increase efficiency for heavy-duty vehicle application:*** • Exhaust heat utilization • Mitigating thermodynamic combustion losses • Reduced parasitic losses • Reduced air handling losses • Improved thermal management sensors • Sulfur traps • Catalyst and filter fundamentals	120 months Barriers B, C, D

3.3.2.11 Milestones and Decision Points

The Heavy Truck Engine R&D activity milestones and decision points are provided in the following chart:

Heavy Truck Engine R&D Network Chart



Legend

◆ **Milestone**

1. Validate at least 50% peak thermal efficiency diesel engines while meeting 2007 Federal emissions levels
2. **Decision.** Decision on 55% peak thermal efficiency for heavy-duty engines while meeting beyond 2010 emissions standards
3. Validate at least 51% peak thermal efficiency for heavy-duty engines while meeting prevailing emissions standards
4. Validate at least 55% peak thermal efficiency for heavy-duty engines while meeting prevailing emissions standards
5. Complete evaluation of fuel injection systems for mixed-mode operation and determine best path forward
6. Complete evaluation of catalyst material for high temperature operation

◆ **Milestone**

7. Complete evaluation of low temperature combustion approaches and select best approach
8. Complete testing to assess durability and reliability of ultra-high pressure injector
9. Complete evaluation of path(s) to 55% efficiency and determine feasibility of achieving goal while meeting prevailing Federal emissions standards.
10. Complete testing to validate precision of feedback control NOx/PM sensors
11. Complete evaluation of durability and reliability of feedback control system

⬢ **Technology Program Output**

1. Technical data to industry
2. Materials requirements to Heavy Vehicle Propulsion Materials
3. Technical data to Vehicle Systems R&D
4. Feedback on specifically designed fuel(s) for HCCI engines to Fuels Technology
5. Input information (to Waste Heat Recovery R&D)
6. Engine exhaust emissions sample (to Health Impacts R&D)

● **Supporting Input**

1. Technical data from Combustion and Emission Control R&D
2. Technical data on surface modification technology to reduce friction, from Materials Technology
3. Result of "Material-by-Design" effort for HCCI engine components, from Materials Technology
4. Advanced material NOx sensor developed for low temperature regime application, from Materials Technology
5. Specifically designed fuel for HCCI application, from Fuels Technology
6. Technical data (from Waste Heat Recovery R&D)
7. Technical data (from Health Impacts R&D)

Figure 3.3-2. Network Chart for Heavy Truck Engine R&D

3.3.3 Fuels for Advanced Combustion Engines

The Fuels for Advanced Combustion Engines activity is undertaken 1) to enable current and emerging advanced combustion engines and emission control systems to be as efficient as possible while meeting future emission standards and 2) to reduce reliance on petroleum-based fuels. This activity will enable advanced combustion regime engine technology as well as identify practical, economic fuels and fuel-blending components with the potential to directly displace significant amounts of petroleum. These fuels and fuel-components are anticipated to be derived from non-fossil renewable resources such as biomass, vegetable oils, and waste animal fats, as well as from fossil sources other than light, sweet crude oil (e.g., natural gas, heavy crude, oil sands, oil shale, and coal). The production of diesel fuel from these sources is technically feasible, yet none is in significant use in the United States because of lack of adequate data on fuel properties, their quality, and/or cost. The Fuels Technology subprogram activities focus on the properties and quality of the finished fuels derived from these sources, not primarily on their production. Fuel production and processing issues are considered in coordination with the appropriate DOE entities through the Fuels Crosscut Team.

3.3.3.1 External Assessment and Market Overview

World crude oil is becoming heavier (lower API gravity) and more sour (including greater amounts of sulfur) over time. This trend is well-established and not expected to change. Moreover, much domestic crude is heavy (e.g., California crude from the San Joaquin Valley) and many potential future sources of energy are heavier still (e.g., bituminous coal, oil sands). In addition to presenting different refining issues than light crude, the fuels produced from such feedstocks may differ from those for which the U.S. domestic refining industry is optimized.

Venezuelan and domestic heavy crude use in U.S. refineries is well-established. Refining of synthetic crude derived from oil sands is growing in use in Canada, and expansion into U.S. petroleum pools is beginning. Fischer-Tropsch diesel fuels, synthesized from natural gas or coal, have been studied in numerous engine tests to determine their impact on emissions and have been used as a blending material in California diesel fuels since 1993. Use of similar fuels derived from biomass – Biomass-to-Liquid (BTL) fuels – may increase in the future. Biodiesel (fatty acid methyl esters), produced from vegetable oils and waste fats, has been used extensively as a blending component in Europe and its use in the United States is increasing. The Fuels Technology subprogram will track and exploit some of these developments for applicability to the United States as a significant potential source of displacement of foreign petroleum.

Desirable attributes for advanced combustion engine fuels include compatibility with all aspects of the existing fueling infrastructure, and thus the capability to be used as replacements for current fuels and a general lack of undesirable components, such as sulfur and aromatics. Fuels with these characteristics are intended to enable the implementation of advanced-combustion-regime technologies. In addition, these fuels will enable more-effective, more-durable, yet less-expensive emission control systems that require less energy for operation and therefore reduce the negative impact of those devices on vehicle efficiency.

3.3.3.2 Internal Assessment and Activity History

Advanced fuels are critical for enabling diesel engines – currently the highest-efficiency engines available – to meet future emission standards. Future diesel-powered vehicles will be dependent on exhaust emission control devices to control NO_x and particulate emissions. Even the most attractive NO_x emission control devices are deactivated by sulfur in currently-available fuels. An important objective of the Fuels Technology subprogram has been the determination of the diesel fuel sulfur level that can be tolerated by effective and durable NO_x emission control devices.

Testing and analysis conducted by the Fuels Technology subprogram in collaboration with EPA, the engine manufacturers, emission control device manufacturers, and fuel producers conclusively demonstrated that fuel sulfur content had immediate adverse effects on the effectiveness of fresh emission control devices. This information was used by EPA in issuing a final rule on January 18, 2001 that established a single comprehensive national control program to regulate both heavy-duty vehicle emissions and diesel fuel. The diesel sulfur rule limits the amount of sulfur in on-highway diesel fuel to 15 ppm, beginning in 2006. This is in preparation for the implementation of the EPA 2007-2010 heavy-duty diesel engine emissions standards. These emission standards are the first for heavy-duty diesel engines that are expected to require exhaust emission control devices.

In 2001, the Clean Diesel Independent Review Panel was created to conduct a review of the 2007 heavy-duty diesel engine emissions standards and the diesel fuel sulfur content standard and provide "advice to the EPA on technology issues associated with the introduction of technology to reduce engine exhaust emissions and technology to lower the sulfur level of highway diesel fuel in accordance with the dates incorporated in the highway diesel program promulgated in 2001." The panel was composed of leading experts from the public health community, petroleum refiners, fuel distributors and marketers, engine manufacturers, emission control systems manufacturers, and state governments. The specific objectives of the panel's charter were to: 1) assess the progress of manufacturers of diesel engines and emission control systems in developing technology to reduce engine exhaust pollutants; and 2) assess the progress of the fuels industry in developing and demonstrating technologies to cost-effectively lower the sulfur level of highway diesel fuel. In its final report, the panel found that NO_x adsorbers and catalyzed particulate filter systems are the two leading emission control technologies for diesel engines. The panel also identified improving the durability of the NO_x adsorber, especially as it relates to desulfation (removing accumulated sulfur), as the most significant fundamental challenge that is being addressed currently.

The panel's findings directly support the research priorities of the Fuels activity. Although EPA has set a sulfur limit of 15 ppm, it is still unclear whether this is an adequately low sulfur level for advanced diesel engines with advanced emission control systems. The durability of these systems at this level of fuel sulfur has not been established. Also, with these emission control devices, the optimum fuel formulation for advanced diesel engines has yet to be defined. The current base of knowledge suggests that NO_x-adsorbers may not be sufficiently durable and/or energy efficient when exposed to fuel containing 15 ppm sulfur allowed under the 2006 standard. The Fuels activity is funding work to expand technological, non-regulatory approaches to solving any remaining sulfur and fuel-contaminant problems. Blends of petroleum-based fuels and non-petroleum fuels can be effective in reducing sulfur content and, in some cases, improving performance. In previous work, Fischer-Tropsch distillate has shown potential for synergistic emission reductions when paired with existing emission control devices. There is some evidence that biodiesel may also exhibit synergistic effects.

3.3.3.3 Federal Role

At present, little detailed information is available on the chemistry of fuels. While such investigations are inherently complex, DOE's national laboratories have the expertise and facilities to begin an investigation into what physical and chemical properties are of most significance to advanced combustion regime engines. Such investigations are typically beyond the scope of business interest of the energy industry. Even if such information is sought by the energy industry, in most cases the companies do not have the specialized capabilities equivalent to those available at the national laboratories. Also, information obtained by private industry is generally not available to the public. Activities of the Fuels Technology subprogram, therefore, play an important role in the pre-competitive arena addressing these issues in partnership with the energy, engine and automotive industries.

3.3.3.4 Approach

A major focus of the Fuels Technology activities is to determine the impacts of fuel properties on the efficiency, performance, and emissions of advanced combustion engines. In the near term, these are expected for the most part to be direct-injection diesel engines and their associated emission control systems. There exists little understanding of the compatibility of the engine-emission control system with renewable fuels such as biodiesel or BTL. Additional information is also required on performance and durability with fuels derived from heavy-crude, oil sands, oil shale, and coal.

For the long term, focus is on fuels optimized for advanced combustion regimes, which include a variety of technologies that have the potential to provide diesel-like (or greater) efficiency with extremely low engine-out emissions. HCCI and LTC are examples of such combustion regimes. Work is not expected to remain confined to the parameter space of pure HCCI or, indeed, even to the general area of low-temperature combustion in investigating the limits of advanced combustion engine efficiency. Consideration will be given to the potential of fuel-related factors for fostering or hindering the expansion of operating conditions of HCCI and related technologies. Work will be constrained to pre-competitive areas with potential for commercial viability.

While anecdotal evidence points to variations in performance and emissions in near-term (e.g., prototype model year 2007) engines related to fuel-property variations, it is almost certain that future, advanced combustion engine technologies will show a greater sensitivity to such variations. As such, co-development of fuels and engines will be essential to ensure availability of fuels optimized for operation in advanced combustion regime engines in the post-2010 timeframe; this necessitates a much-improved state of fundamental knowledge about fuel properties and composition and their impact on combustion phenomena. If fuel specifications need tighter definition for engine operation in advanced combustion regimes, close coordination between the Advanced Combustion Engine R&D and Fuels Technology subprograms will be essential.

The expertise of the national laboratories is used for in-house research and development efforts, in "working group"–level interactions in government-industry consortia, and in technical management. In the near term, fuel issues associated with 2007–2010 engines and emission control systems are of immediate concern. Included in this near-term focus are tasks that support removing sulfur from the fuel at fueling stations or on-board the vehicle prior to combustion in order to provide a near-zero sulfur level, if necessary. An additional focus is on assessing the impact of renewable and non-petroleum blending components such as biodiesel and BTL, along with an examination of the impacts of use of fuels derived from heavy-crude. For the long term, the challenge is development of a fuel specification optimized for operation of advanced combustion regime engines up to full load and during transients. Other challenges include assessing the implications of the properties of newly developed fuels on engine performance and emissions, and identifying compatible lubricants for use with newly developed fuels.

3.3.3.5 Performance Goals

The primary goal of the Fuels Technology subprogram is to identify fuel formulations with increasingly significant use of non-petroleum fuel components that will enable emerging advanced ICEs to be more energy-efficient while meeting future emissions standards. More specific goals are as follows:

- By 2007, identify fuel formulations optimized for use in 2007-2010 technology diesel engines that incorporate use of non-petroleum-based blending components with the potential to achieve at least a 5 percent replacement of petroleum fuels by 2015.
- By 2010, identify fuel formulations optimized for use in 2010-2020 advanced combustion regime engines providing high efficiency and very low emissions, which incorporate use of non-petroleum-based blending components with the potential to achieve at least a 10 percent replacement of petroleum fuels by 2025.

Fuels, engines, and emission control devices are being addressed, in collaboration with the Advanced Combustion Engine R&D subprogram, in the context of complete, integrated engine power systems. The following table lists the fuels-specific technical targets that support crosscut targets with the Advanced Combustion Engine R&D subprogram (shown in italics), as well as direct petroleum fuel replacement targets.

Table 3.3-5. *Technical Targets for Advanced Combustion Engine Fuels*

Characteristic	Unit	2007 Targets	2010 Targets
Crosscut Targets with Advanced Combustion Engine R&D			
Engine efficiency	*%*	*>50 (heavy-duty engine)*	*30–45 (light-duty engine)*
NO_x emissions	*g/bhp-h*	*<0.20 (50% phase-in)*	*<0.20*
PM emissions	*g/bhp-hr*	*<0.01*	*<0.01*
Durability	*Miles (equivalent)*	*120,000 light duty) 435,000 (heavy duty)*	*120,000 (light duty) 435,000 (heavy duty)*
Fuels Targets			
Fuel sulfur level (available fuel)	Ppm	15	15
Fuel sulfur level (w/on-board or fuel-station based removal)	Ppm	<5	<3
Emission control penalty reduction	%	50	>50
Fuel price differential	% of retail diesel	<5	<5
Potential for replacement of petroleum	%	At least 5	>5
Compatibility with infrastructure	NA	Validated	Validated
Health effects Unregulated toxics and ultra-fine PM Health and safety of fuel	(by analysis)	No significant increase in composite risk compared with conventional fuels	No significant increase in composite risk compared with conventional fuels
Life-cycle greenhouse and criteria emissions	(by analysis)	No increase	

3.3.3.6 Strategic Goals

The Fuels Technology subprogram supports DOE's Energy Security Strategic goal to "improve energy security by … exploring advanced technologies that make a fundamental improvement in our mix of energy options, and improving energy efficiency" – and also the goal of 21st CTP to develop and validate a commercially viable, 50 percent efficient, emissions-compliant engine system for Class 7 and 8 highway trucks by 2010.

3.3.3.7 Market Challenges and Barriers

The market challenges and barriers are as follows:

A. ***Infrastructure.*** The lack of a fuel quality specifications, as well as distribution and fueling infrastructure, is a major barrier for any non-petroleum-based liquid fuel component that is not compatible with all current systems. This barrier must be addressed to have a significant impact on reducing the transportation sector's dependence on petroleum-based fuels.

B. ***Cost.*** There are insufficient public data on refinery economics and processing strategies to enable comparison of options for advanced combustion engine fuels. Also inadequate are the databases on the health, safety, and regulatory issues associated with most non-petroleum fuel components that might be used to replace petroleum-based fuels, as well as the knowledge base on the technical and economic impacts of non-petroleum fuel components on the distribution, storage, and fueling infrastructure.

3.3.3.8 Technical Challenges and Barriers

In order to fully exploit the full potential of high-efficiency, clean advanced combustion regime engines, co-development of the engines and fuels is a necessity. Nearer term, the understanding of the compatibility of non-petroleum based fuels with 2007-2010 engines is critical to increasing use of these fuels. The technical barriers to achieving this are as follows:

C. ***Inadequate data and predictive tools for fuel property effects on combustion and engine optimization.*** Existing data and models for engine efficiency, emissions, and performance based on fuel properties and fuel-enabled engine designs or operating strategies are inadequate. They are limited in scope, have unexplained differences among various engine types, and do not adequately account for the effects that the physical properties and molecular structures of fuels have on the dynamic operation of the fuel injection system and on the ability to operate in low-emission, low-temperature combustion regimes. Also, the variability of refinery stream (blendstock) composition on the efficiency, performance, and emissions of engines appears to be significant but is poorly understood.

D. ***Inadequate data and predictive tools for fuel effects on emissions and emission control system impacts.*** The database on the extent to which petroleum fuel and non-petroleum fuel components contribute to toxic emissions is inadequate and must be improved in order to optimize engine and aftertreatment systems from a fuel economy standpoint. The relationship between fuel properties and the formation of ultra-fine particles (i.e., particles of <0.1 nm in diameter) is not well established. Also inadequate are data on the effects of fuel properties (other than sulfur) on exhaust emission control systems, and widely-accepted test procedures to measure these effects do not exist. Furthermore, suitable test equipment and universally-recognized test procedures to generate this knowledge base are not available.

E. ***Long-term impact of fuel and lubricants on engines and emission control systems.*** The knowledge base is inadequate on the effect of fuel properties on the deterioration rates and durability of engine fuel system and emission control system devices and components. The effects of lubricating oil on engine emissions and emission control devices are not clearly understood, nor are the effects of non-petroleum based fuels on lubricating oil performance. Improved understanding is needed in developing approaches that mitigate any deleterious effects caused by fuel and lube oil components. Furthermore, new fuel formulations could require corresponding new lube oil formulations.

3.3.3.9 Strategies for Overcoming Barriers/Challenges

Activities of the Fuels Technology subprogram will test and evaluate a wide variety of fuels to develop a better understanding of the relationships between fuel properties, engine efficiency, system durability, and emissions. Exhaust emission control devices are expected to be necessary to meet future emissions standards for diesel-powered vehicles. Fuels-compatibility testing will include such devices as they become available (through close collaboration with the Advanced Combustion Engine R&D subprogram).

Key deliverables from these activities will be test data and test-data–based analyses of the sensitivity of the performance and emissions of engines and emission control devices to fuel and lubricant properties. As data accumulate in the database, it will become increasingly feasible to predict fuel formulations with favorable properties to reduce emissions of NO_x and PM. In addition, some emission control strategies rely on reductants derived from the fuel to operate effectively, a fact that will be taken into account as required reductant properties are identified by the Advanced Combustion Engine R&D subprogram.

Guidance on the fuels to be tested and other tasks will be provided by representatives from the automotive, energy, and engine companies; renewable and non-petroleum based fuel manufacturers; industry associations; and national laboratories. Government/industry technical and supporting groups will make specific recommendations for tasks, data analyses, and overall direction.

Through the use of roundtable discussions, government-industry workshops, peer reviews, participation in the Coordinating Research Council (CRC), and through other forums, this activity has obtained what is believed to be a good understanding of the inadequacies of predictive tools and fuel property data necessary to identify fuel property requirements for fuels for advanced combustion engines.

3.3.3.10 Tasks

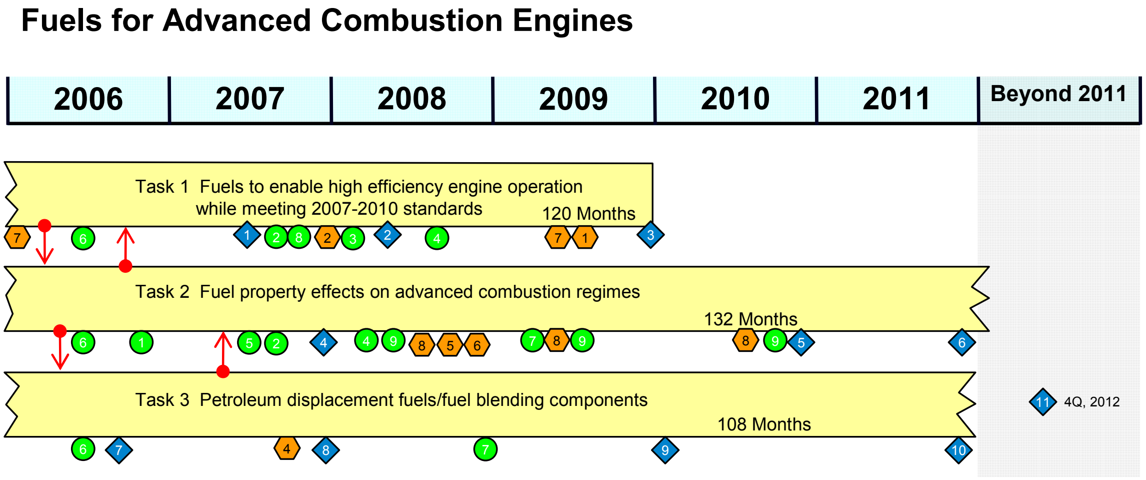
The technical task descriptions are provided in the following table:

Table 3.3-6. *R&D Tasks for Fuels for Advanced Combustion Engines*

Task	Title	Duration / Barriers
1	***Fuels and Lubricants to Enable High Efficiency Engine Operation while Meeting 2007–2010 Standards*** • Evaluate long-term degradation and loss of effectiveness of light- and heavy-duty engines equipped with 2007–2010 technology emission control devices and using 15-ppm-sulfur diesel fuel and renewable blending components such as biodiesel • Improve fundamental understanding of the effect of fuel and lubricant composition on aftertreatment systems by applying experimental and modeling approaches • Investigate options for optimizing engine and emission control systems for both emissions and performance when switching between conventional fuel and non-petroleum based fuels • Identify fuel properties other than sulfur that are critical to improving the efficiency, performance, and emissions of diesel engine and aftertreatment systems • Develop measurement techniques and characterize unregulated emissions from 2007–2010 engines and aftertreatment systems • Study fuels-based in-cylinder strategies to achieve high-efficiency, low-emissions operation at high power density and to improve understanding of hydrocarbon molecular structure effects on the sooting tendency of diesel fuel constituents	120 months Barriers A, B, C, D, E
2	***Fuel Properties Effects on Advanced Combustion Regimes*** • Develop fundamental understanding of fuel effects on in-cylinder combustion and emissions formation processes in advanced combustion regimes through experimental and modeling approaches • Develop predictive tools that relate molecular structure to ignition behavior and heat release for fuels used in advanced combustion engines • Evaluate new fuels and fuel blends for efficiency, emissions, and operating stability with advanced combustion regimes • Evaluate the potential of reforming small amounts of fuel to generate additives that can be used to achieve fast control in low-temperature combustion modes • Evaluate the performance of traditional lubricant formulations in engines using advanced combustion regimes and identify any performance deficiencies	132 months Barriers B, C, D, E
3	***Petroleum Displacement Fuels/Fuel Blending Components*** • Study combustion and emissions-formation processes of non-petroleum based fuels and blending components using experimental and modeling approaches • Identify renewable and synthetic fuel blending components that provide enhanced efficiency, performance, and emissions characteristics • Quantify the potential for improving engine and/or vehicle fuel economy through the use of renewable biolubricants • Enhance the use of petroleum displacement fuels and non-petroleum based fuels infrastructure development through technical forums and by providing specialized technical support to early adopters of these advanced non-petroleum based fuels • Perform R&D to support appropriate codes and standards to increase the availability of petroleum displacement fuels	108 months Barriers A, C, D, E

3.3.3.11 Milestones and Decision Points

The milestones and decision points for Fuels for Advanced Combustion Engines are provided in the following chart:



Legend

◆ Milestone

1. Complete determination of maximum tolerable level of sulfur and other contaminants in fuels and lubricants for emission control systems to meet full useful life with reduced emission control fuel penalty
2. Complete identification of fuel formulation that provides >50% reduction in energy penalty due to meeting 2007 –2010 emission requirements (using 7% penalty as baseline)
3. Validate that fuel formulation use in advanced combustion regime engine results in reducing emissions energy penalty by 50% and meets useful life requirement.
4. Complete identification of fuel and lubricant characteristics that are critical to engine operation in advanced combustion regimes
5. Complete identification of fuel and lubricant formulation for advanced combustion regime engines needed to achieve >50% efficiency, emissions compliance, and power density >20 bar bmep
6. Validate that advanced fuel formulation can enable > 50% engine efficiency with full in-cylinder emissions reduction and eliminates the need for exhaust gas aftertreatment
7. Complete evaluation of adequacy of existing codes and standards to fuels with non-petroleum and synthetic blending components
8. Complete optimization of fuel formulation for 2007 – 2010 engines to incorporate use of non-petroleum based blending components with the potential to achieve at least 5% replacement of petroleum fuels by 2015

◆ Milestone

9. Complete R&D to eliminate technical barriers to achieving a 5% petroleum displacement in 2007 – 2010 engines
10. Complete identification of fuel formulations optimized for use in advanced combustion engines (2010-2020) that provide high efficiency and very low emissions
11. Validate that at least 10% replacement of petroleum fuels can be achieved by 2025

⬢ Technology Program Output

1. Fuel formulation that allows emission control system to meet useful life requirements, to Combustion and Emission Control R&D
2. Fuel formulation for materials compatibility evaluation, to Materials Technologies/Heavy Vehicle Propulsion Materials
3. Fuel-derived reductant for emission control use, to Combustion and Emission Control R&D
4. Fuels composition that meets requirements of HCCI, to Combustion and Emission Control R&D
5. Fuel formulation for full scale vehicle system testing, to Vehicle Systems R&D
6. Fuels formulation for health impacts testing to Health Impacts Research
7. Technical data on sulfur trap, to Combustion and Emissions Control R&D
8. Specifically designed fuel for HCCI application, to Heavy Truck Engine R&D

● Supporting Input

1. Engine/emission control system model that predicts fuel effects on the system, from Combustion and Emission Control
2. Fuel formulation constraints for APUs, from Vehicle Systems R&D
3. Rapid aging protocol from Combustion and Emission Control R&D
4. Technical data on materials compatibility of fuel formulations, from Materials Technologies/ Heavy Vehicle Propulsion Materials
5. Fuel physical property requirements for HCCI, from Combustion and Emission Control R&D
6. Technical data and information from industry
7. Technical data and information from Health Impacts Research activity
8. Technical results and feedback, from Combustion and Emissions Control R&D
9. Feedback on specifically designed fuel(s) for HCCI engines, from Heavy Truck Engine R&D

Figure 3.3-3. Network Chart for Fuels for Advanced Combustion Engines

3.3.4 Waste Heat Recovery

The Waste Heat Recovery activity develops technologies for converting waste heat from engines into useful energy (e.g., electrical energy) to improve overall thermal efficiency and reduce emissions.

3.3.4.1 External Assessment and Market Overview

Effective use of waste heat from ICEs would significantly increase vehicle fuel economy. Only about 30-35 percent of the fuel's energy currently is used for vehicle propulsion. Approximately 35-40 percent is lost in the exhaust gases and another 30-35 percent is lost to the coolant. Recovery of energy from engine exhaust and/or engine cooling system represents a potential for 10 percent or more improvement in overall engine efficiency. Technologies for engine waste heat recovery include direct thermal-to-electric conversion and turbocharging/turbocompounding.

The temperature differences between the ambient air and the radiator, lubricating oil sump, exhaust gas, exhaust gas recirculation loop, turbocharger compressed air discharge (engine intake air), and brakes present opportunities for direct conversion of heat to electricity known as the Seebeck effect (an electric current is generated when a temperature differential is applied across a thermoelectric material).

Thermoelectrics were used as thermocouples and thought of as an "academic curiosity" through a major part of the 19th century and the first half of the 20th century. In the later half of the 20th century, bulk semiconductors appeared that provided 5 to 6 percent conversion efficiency when operating between 50°C and 250°C. They were labor-intensive to make due to small volumes and typical applications were for niche markets. Thermoelectrics, mated with radioisotope power sources, have worked continuously in space for over 30 years with less than 10 percent degradation.

The same devices used to convert heat to electricity can be used to heat or cool, depending on the polarity of the direct current passed through the thermoelectric device. This is known as the Peltier effect. The largest use of thermoelectrics for this application is the climate control of car seats; it takes 40 watts to cool a person while air conditioning uses over 1,000 watts to cool the front passengers' seat space. GM, Ford, and Toyota purchased one million of these units in 2004.

In the early 1990s, a new theory based on advances in nanostructured devices[c] made by Mildred Dresselhaus and her research group at Massachusetts Institute of Technology, envisioned thermoelectric materials of 20 percent and higher efficiencies. Since then, several organizations have experimentally validated, at the laboratory bench level, that nanostructured thermoelectrics can achieve efficiencies that are 3 times those obtained with the bulk semiconductor thermoelectrics.

---

[c] Hicks, L.D., Harman, T.C., Dresselhaus, M.S., "Use of Quantum-Well Superlattices to Obtain a High Figure of Merit from Nonconventional Thermoelectric-Materials," Applied Physics Letters, 63, 3230-3232, 1993.

Recovery of engine exhaust energy is also possible with turbocharging or turbocompounding. Current turbocharger efficiencies are around 50 to 58 percent; these could be increased to 72 to 76 percent with enhancements such as variable geometry. An electrically driven turbocharger with increased transient response would be another approach. Integrating an electro-turbocompound unit with the engine control system has the potential to enable production of about 3 to 5 kW from light-duty engine waste heat for passenger vehicles, and up to 20 kW from heavy-duty engine waste heat for commercial vehicles.

3.3.4.2 Internal Assessment and Activity History

The FCVT Program initiated a project with Hi-Z Technology in the mid-1990s to determine if thermoelectric generators were viable for heavy truck applications. Hi-Z developed a 1 kW(e) thermoelectric generator that was integrated with the muffler but restricted to a tap on the radiator cooling water for the cold side. This device installed in a Class 8 heavy truck which was run fully loaded by PACCAR Incorporated on their test track for the equivalent of 550,000 miles. The only failure was in the cooling water line which was easily repaired. Hi-Z also supplied a 350 watt unit to Clarkson University for installation in a GM lift truck for a joint program with the New York State Energy Research and Development Agency (NYSERDA). A similar device was provided to Ohio State for test on a Ford vehicle. These test provided satisfactory results.

Bulk semiconductor thermoelectric devices are currently 6 percent efficient. Recent developments in quantum well thermoelectrics suggest a potential improvement to over 20 percent is possible. These can provide a 10 percent efficiency improvement to a diesel or gasoline vehicle propulsion engine efficiency. But the technology must be advanced from the laboratory to commercially viable production and installed as a thermoelectric generator using the engine’s waste heat to be competitive.

Focusing the thermoelectric generator market on transportation vehicles provides the most probable major improvement in fuel economy in the next 15 years, which would be accompanied by the bonus of CO_2 reduction. The potential volume of thermoelectric devices in the transportation sector could provide the base for low cost, low grade energy recovery thermoelectrics with opportunities for application in industrial processes, geothermal energy recovery, ocean thermal energy recovery, and energy storage battery temperature control.

The FCVT Program initiated collaborative work with industry in FY 2001 on the development of electrically driven turbochargers for recovering light-duty engine waste heat to improve passenger car fuel economy. Work was also initiated on electric turbocompounding combined with starter motor-alternator and damper technology to eliminate turbo-lag and improve heavy-duty engine overall thermal efficiency by up to 10 percent.

3.3.4.3 Federal Role

Bringing unique expertise and capabilities of the national laboratories, to assist industry and conducting collaborative research that bridges the gap between science and the marketplace, is an appropriate role for DOE. Stimulating the development and adoption of high efficiency thermoelectric technologies for vehicle applications is high-risk and would not be undertaken by industry on its own.

3.3.4.4 Approach

A competitive solicitation was conducted for waste heat recovery R&D and awards were made to eight teams (four teams for thermoelectrics and four for turbocompounding) for five-year cooperative agreements to develop the technologies for automobile and commercial diesel engines.

The selected teams for thermoelectrics include: a) manufacturers of thermoelectric devices who could develop high efficiency thermoelectric modules that can convert engine waste heat to power levels suitable for vehicle applications; and b) vehicle and engine manufacturers who could undertake integration of commercially viable engine waste heat recovery devices into their products; and c) national laboratories or R&D laboratories with expertise in applied thermoelectrics R&D. Work is done through cost-shared cooperative agreements. Two of the teams are focusing on Class 7 and 8 heavy-duty truck diesel engines and the other two are developing thermoelectric generators for light trucks (pickups, vans, and sport utility vehicles) and for automobiles.

Success with the single thermoelectric project would lead to a follow on project wherein 5 thermoelectric generators would be used to maximize engine waste heat recovery to achieve a 55 percent efficient heavy duty diesel engine or a nominally 45 percent efficient light truck/auto diesel engine with potential for even higher efficiencies. Achieving these efficiencies would require the thermoelectric generated electricity to go into power conditioning and then be integrated with the "beltless engine" or "more electric engine" concept where all the engine accessories are electric motor driven (e.g., the 2005 BMW 5 series car has an electric water pump).

Thermoelectric generators could also be used with the integrated motor/alternator/starter which could absorb the electrical energy and reduce engine drag. It is estimated that on a per vehicle basis, compared with an equivalent 2005 gasoline engine, there could be as much as a 50 percent fuel economy gain and a 42 percent reduction in CO_2 (greenhouse gas) emissions.

3.3.4.5 Performance Goals

The longer-term goal of this activity is to develop the technologies for recovering engine waste heat and converting it to useful energy that will improve overall diesel engine thermal efficiency to 55 percent for Class 7 and 8 trucks, and 45 percent for passenger vehicles while reducing emissions to near-zero levels. More specifically,

- By 2012, enable commercially viable turbocompound units that can produce up to 40 kW of additional power from heavy-duty engine waste heat recovery.
- By 2012, achieve at least 25 percent efficiency in quantum well thermoelectric devices for waste heat recovery.

This activity also supports the overall engine efficiency goals of the FreedomCAR and Fuel Partnership and 21st CTP.

The technical targets for Waste Heat Recovery are shown in following table:

Table 3.3-7. *Technical Targets for Waste Heat Recovery*

Characteristics	**Units**	**Year**		
		2003 Status	**2008**	**2010**
Thermoelectric Devices				
Efficiency				
• bulk semiconductor	%	5–7	--	--
• quantum well			>15	>20
Projected cost/output (250,000 production volume)	$/kW	--	500	180
Turbocompound System				
Class 7–8 trucks				
Fuel economy improvement	%	<1	>5	>10
Power	kW	<10	>20	>40
Projected component life	hours	<10	>5,000	>10,000

3.3.4.6 Strategic Goals

The Waste Heat Recovery R&D activity supports DOE's Energy Security Strategic goal to "improve energy security by … exploring advanced technologies that make a fundamental improvement in our mix of energy options, and improving energy efficiency."

3.3.4.7 Market Challenges and Barriers

A. ***Cost.*** The electro-compound system capital cost to the owner and operator should be repaid in 24 months or less. This payback period will depend on the cost of the fuel or a tax incentive. For nano-thermoelectrics, achieving the large-scale production goal of devices for direct conversion of heat to electricity would require large-scale sputtering equipment that could cost-effectively deposit the layers in an automated high throughput manner. There are two very large companies that are interested in the production of thermoelectric modules who are participating in this activity at no cost to the Government.

3.3.4.8 Technical Challenges and Barriers

B. ***Scale-up to a practical thermoelectric device.*** High efficiency thermoelectrics are a turn-of-the-century technological development. Several types of high efficiency thermoelectrics are emerging. They are based on increasing electrical conductivity while reducing thermal conductivity. This only works in the nano-scale. The primary thermoelectrics being evaluated are the two-dimensional quantum well, quantum dots, segmented, and skutterudites. As an example, the two-dimensional system is essentially a nanostructure consisting of alternate N and P layers about 100 Angstroms thick deposited on an extremely thin low thermal conductivity substrate. The challenge is to develop coating techniques that can deposit a sufficient number of layers to achieve the efficiency goal. This entails dramatically increasing the size of the laboratory developed specimens and doing so cost effectively. In addition, new technologies for heat transfer in these nanostructure films need to be explored and techniques for measuring key parameters in these nano-films need to be further developed.

C. ***Turbocompound device/system packaging.*** The electro-turbocompound system, including its power electronics and overall system controller, must fit under the vehicle hood with adequate space for cooling. All of the power must be absorbed by the integrated motor/starter/generator or by accessories converted from belt-driven to electric-motor-driven. The turbocharger that has the motor/alternator attached between the turbine and compressor operates at a nominal 55,000 rpm for Class 7 and 8 heavy trucks and 120,000 rpm for light trucks. This is pushing the state of the art for the light truck application. This system will increase exhaust gas backpressure and adversely affect fuel economy, The turbocompound system must not cause drivability or noise, vibration and harshness (NVH) problems.

D. ***Component/system durability.*** Specific durability requirements must be met by the waste heat recovery systems. The electric turbocompound system must perform for 250,000 miles and 500,000 miles in light and heavy truck applications, respectively. High efficiency thermoelectric devices will have to survive vibrations encountered in vehicle applications. Although lessons learned with the thermoelectric generator developed with bulk semiconductors will be useful, quantum well thermoelectric devices present a more difficult challenge due to their more complex fabrication.

3.3.4.9 Strategies for Overcoming Barriers/Challenges

The technical approach to developing commercially competitive thermoelectric devices[d] for transportation applications is first to validate the bulk semiconductor-based 2-kW thermoelectric generator. The emphasis will be to develop thermoelectrics (or “nano-thermoelectrics”) that can perform power generation (using the Seebeck effect) or heating/cooling (using the Peltier effect) for vehicular applications within the cost criteria for commercial production. A measurement

---

[d] A detailed discussion of past efforts in thermoelectrics, the current state of the art for quantum well thermoelectrics, available approaches for improved thermoelectric device performance, present and past R&D tasks by DOE and other entities, as well as detailed steps of the technical approach appears in the document *R&D Approaches to Exploit Recent Major Breakthroughs in Thermoelectrics, for FY 2003–2007*, Office of FreedomCAR and Vehicle Technologies, U.S. Department of Energy, 1000 Independence Avenue, SW, Washington DC 20585, September 2003 draft.

technique for these ultra-thin devices will be developed. Multilayer devices will be made by sputtering with alternate N and P layers (on the order of 1000 layers). Multilayer systems that will initially be investigated include Si/Si0.8Ge0.2 and B4C/B9C deposited on 0.5-mm-thick kapton or other low thermal conductivity substrates. Coating parameters will be optimized, and heat transfer issues will be addressed.

Iterative test and redesign efforts will be conducted for electric turbocompound systems to validate the electric power produced and the resulting overall engine efficiency gains. In addition, turbochargers can improve the low-speed torque which can result in reduced engine size for the same performance. Validation will be undertaken by motoring the turbocharger during acceleration to reduce turbo-lag and improve emissions. Testing will also be conducted in the Heavy Truck Engine activity with EGR-equipped engines to validate NO_x reduction achieved due to increased exhaust back pressure.

3.3.4.10 Tasks

A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in following table:

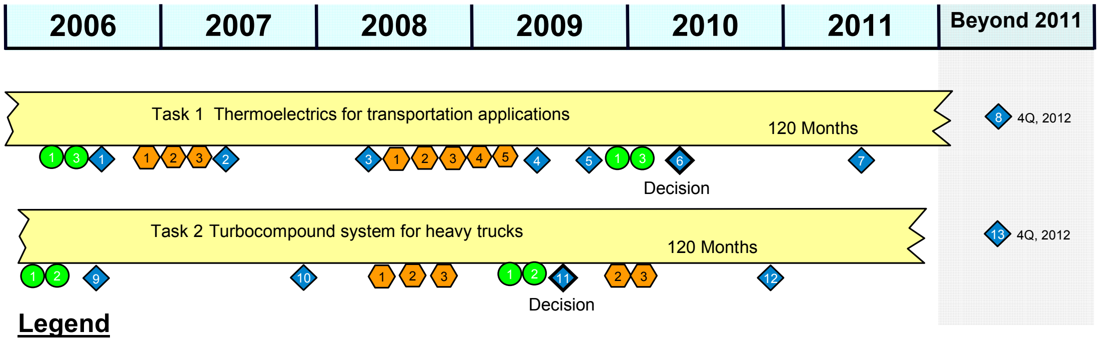
Table 3.3-8. *Tasks for Waste Heat Recovery R&D*

Task	Title	Duration & Barriers
1	***Thermoelectrics for Transportation Application*** • Produce a 10% fuel economy improvement from both heavy truck (Class 7 and 8) and autos and light trucks with a thermoelectric generator • Fabricate high efficiency thermoelectric device with at least 21% efficiency • Based on a successful 10% thermoelectric generator, extend to 6 thermoelectric generators on radiator, lube oil sump, exhaust, EGR loop, turbocharger discharge air, and brakes, which when integrated with the beltless engine would produce a nominal 55% efficient diesel engine. • Develop vehicular air conditioning system based on the high efficiency thermoelectrics developed for the generator which would provide a 20% improvement in efficiency while eliminating the R-134a refrigerant	120 months Barriers A, B, D
2	***Turbocompound System for Heavy Trucks*** • Develop a system to provide an additional 40 kW of electric power • Integrate an electric turbocompound system with heavy truck engine controls and validate through laboratory tests that 40 kW can be produced for over 10,000 h for a 10% fuel economy improvement • Redesign the system using laboratory test results, install the modified electric turbocompound system in a Class 7/8 heavy-duty truck engine, and validate a 10% fuel economy improvement over 10,000 h	120 months Barriers A, C, D

3.3.4.11 Milestones and Decision Points

The Waste Heat Recovery R&D activity milestones and decision points are provided in the following chart:

Waste Heat Recovery



Legend

◆ **Milestone**

1. Complete scale up of high efficiency thermoelectrics from laboratory to commercially viable devices
2. Complete fabrication of heat exchanger with integrated high efficiency thermolectric devices
3. Complete integration of thermoelectric generator electric power with vehicle electric power system
4. Complete installation of thermoelectric generator on engine and testing to validate at least a 10% fuel economy improvement without degrading emission controls
5. Complete cost analysis of thermoelectric generator for commercial vehicle application
6. **Decision.** Review to scale up to 5 thermoelectric generators integrated with the beltless engine (electric motor driven accessories) and/or integrated motor/alternator/starter to improve overall diesel engine efficiency to 55%
7. Complete design and fabrication of a vehicle air conditioning system using high efficiency thermoelectrics that will further improve fuel economy while eliminating currently used R-134a refrigerant
8. Validate potential for >25% efficient thermoelectrics with 500ºC temperature differential

◆ **Milestone**

9. Complete design and installation of motor alternator on a diesel engine turbocharger shaft that is powered during acceleration to achieve air-fuel management and develop electrical power at steady speed
10. Complete integration of electric turbocompound unit with engine control system and validate that up to 20 kW can be produced from Class 7 and 8 heavy-duty truck engine waste heat
11. **Decision.** Review to continue development to 30 kW electric (at maximum power) turbocompound unit
12. Validate 30 kW electric turbocompound unit for heavy-duty engine waste heat recovery
13. Validate potential for 40 kW electric turbocompound unit for heavy-duty engine waste heat recovery

⬢ **Technology Program Output**

1. Technical data to Vehicle Systems R&D
2. Technical data to industry
3. Technical data to Heavy Truck Engine R&D
4. Technical data to DOE/EERE/OIP Process Heat Recovery
5. Coordination with DoD Programs

● **Supporting Input**

1. Input from Heavy Truck Engine R&D
2. Input on turbocharger materials, from Heavy Vehicle Propulsion Materials
3. Input from DARPA/ONR Multiple University Research Initiative High Efficiency Thermoelectrics Laboratory Investigations

Figure 3.3-4. Network Chart for Waste Heat Recovery

3.3.5 Health Impacts

The FCVT Program and its industry partners are on the leading edge in the development of future light- and heavy-duty vehicle technologies to improve fuel economy and enable the use of non-petroleum based fuels. The Health Impacts research activity performs the critical role of elevating potential health issues related to these future vehicle technologies to the attention of industry partners and DOE/FCVT management. By proactively evaluating the potential air quality and human health impacts of changes in fuel, engine, lubricant, and aftertreatment technologies before they are widely implemented in transportation vehicles, this activity ensures that development of new vehicle technologies considers the possibility of causing negative health impacts, rather than just complying with existing standards.

3.3.5.1 External Assessment and Market Overview

At times in the past it has been assumed that new fuels and vehicle technologies would have no negative health related side effects. One such instance occurred with the installation of the automotive catalytic converter in 1975, which has led to the assumption that emissions from gasoline engines have been rendered totally benign. While catalytic aftertreatment of automobile exhaust has been extremely successful, degradation of catalyst effectiveness over time often due to lack of proper vehicle maintenance has led to “high emitters’ which are now becoming recognized as the source of the bulk of toxic emissions from motor vehicles. In addition, ultra-clean, new gasoline vehicles might still emit ultra-fine particles, the health impacts of which have never been documented. Studies have only recently been initiated to look into the potential health impacts of fine particle emissions emanating from these new vehicles.

In another instance, use of methyl tert-butyl ether (MTBE) as a gasoline additive was mandated by EPA to reduce carbon monoxide emissions and to clean urban air, but since then it has been found to result in serious groundwater contamination[1]. Even more recently, high levels of toxic compounds such as formaldehyde and 1,3-butadiene have been measured in natural gas vehicle emissions[2].

As the U.S. continues to address the energy security issue due to the growing dependence of transportation on imported oil, there are major health concerns that cannot be overlooked in the rush to commercialize alternatives.

---

[1] Health and Environmental Assessment of MTBE, Report to the Governor and Legislature of the State of California, prepared by U.C. Toxic Substances Research and Teaching Program, November 12, 1998.

[2] Ahlvik, P. and A. Brandberg, "Relative Impact on Environment and Health from the Introduction of Low Emission City Buses in Sweden," SAE Technical Paper 2000-01-1882, presented at the International Spring Fuels and Lubricants Meeting and Exposition, Paris, France, June 19-22, 2000.

3.3.5.2 Internal Assessment and Activity History

One technology that offers the potential to achieve significant reduction in transportation petroleum use is the diesel engine. Diesel engines have a fuel efficiency advantage over gasoline engines and hence, will require less fuel and produce lower emissions of the greenhouse gas carbon dioxide. However, despite this advantage, use of the diesel engine to improve transportation fuel economy has been slow to gain favor in the U.S. because of the highly visible emissions experienced with the old generation diesel engines. Although diesel engine emissions have been reduced considerably in recent years, the negative image continues to persist.

When FCVT adopted a "dieselization" strategy for reducing transportation fuel use, in addition to carrying out research to eliminate noxious emissions from diesel engines, it also initiated a comprehensive Health Impacts effort to develop a better understanding of the health issues related to the cleaner new diesel engines and aftertreatment technologies. Results from the Health Impacts research, which have been widely disseminated in technical meetings, workshops, other conferences, and peer-reviewed journals, have shown greatly lessened emissions levels from the new clean diesel technologies and disproportionately large contributions to air pollution made by high emitting vehicles (both gasoline and diesel).

3.3.5.3 Federal Role

It is incumbent upon FCVT and in the public interest that no new technologies are deployed that could unintentionally cause adverse human health impacts. The FCVT research on advanced vehicle and fuel technologies is in the exploratory and developmental stages and therefore is not yet sufficiently commercial for EPA regulatory oversight. In addition, this research investigates the health impacts of complex mixtures (e.g., engine exhaust) where toxic synergisms are enhanced and develops information that puts the health impacts of advanced technologies in context with respect to the relative risk from alternative means of providing transportation. R&D into these technologies would necessarily have to include approaches to mitigate any impacts.

3.3.5.4 Approach

Assessment of the health impacts of specific vehicle technologies is accomplished through the development of more accurate measurements of deleterious emissions components and validated models that can differentiate the contribution of these new technologies relative to current technologies. Although PM and NO_x are known to present health hazards at high concentrations, much less is known about the hazards presented by other emission components, or the relative importance of other components to PM and NO_x. Emissions from advanced technologies will be screened for toxicity and in selected cases where possible, components responsible for toxicity will be determined to ascertain if engineering solutions can reduce the toxic components. Of special interest to FCVT are emissions from advanced combustion engines using fuels optimized for new combustion regimes such as HCCI.

FCVT is not primarily a health research program, but it does direct some resources toward a limited scope of well-focused, technology-specific health impacts research activities to ensure that there are no unintended consequences from emerging technologies. Other agencies addressing health issues related to exposure to emissions from the current technologies in the vehicle population will have interest in future technologies as they begin entering the commercial market. To leverage resources, FCVT Health Impacts research is done in collaboration and communication with others (EPA, California Air Resources Board [CARB], Sacramento California Air Quality Management District [SCAQMD], industry, Combustion Research Council [CRC], Health Effects Institute [HEI], etc.) who have found the FCVT results to be unique and important in guiding the development of more accurate models and standards.

3.3.5.5 Goals

The goals of FCVT Health Impacts activity are as follows:

- To provide a sound scientific basis underlying any unanticipated potential health hazards associated with the use of new power train technologies, fuels and lubricants in transportation vehicles.
- To ensure that vehicle technologies being developed by FCVT for commercialization by industry will not have adverse impacts on human health through exposure to toxic particles, gases, and other compounds generated by these new technologies.

3.3.5.6 Strategic Goals

The Health Impacts Research activity supports the Department's Energy Strategic Goal: To protect our national and economic security by reducing imports and promoting a diverse supply of reliable, affordable, and *environmentally sound* energy.

3.3.5.7 Market Challenges and Barriers

A. ***Market Perception.*** There is increasing public awareness of adverse health impacts related to vehicle emissions. As a result market acceptance is contingent upon improved understanding and knowledge that these new technologies have considered mitigation of known health impacts and will have no unknown potential health impacts.

3.3.5.8 Technical Challenges and Barriers

The technical challenges to be addressed are:

B. ***Lack of actual emissions data on pre-commercial and future combustion engines.*** The health impacts of future technologies (e.g., 2007/2010 compliant production engines) have to be evaluated well in advance of their market introduction and, therefore, lack actual real-world emissions data, not to mention the difficulty of measuring very low level emissions that are expected from them.

C. ***Lack of analytical tools (rapid assay techniques) relevant to human toxicity.*** This includes lack of standardized "baseline case" inhalation exposure atmospheres and collected samples with which to compare *in vivo* and *in vitro* responses; the need for confirmation that *in vitro* toxicity test systems accurately mirror relative response of lungs to different exposures, and the poor ability to separate different components from “whole” emissions; or to selectively eliminate components for inhalation exposures.

D. ***Lack of credible validated models for emissions source apportionment.*** There are no universally recognized molecular markers to distinguish between gasoline and diesel exhaust, as well as other fuel types, and little data from various source types to adequately apportion air toxics to their respective sources (cars vs. trucks). There is an inadequate understanding regarding engine operating conditions (and ambient conditions) that influence emissions from mobile sources and a lack of standardized “baseline” collected real-world emissions samples with which to compare the health response.

3.3.5.9 Strategies for Overcoming Barriers/Challenges

The most accurate measurement methods and tools will be applied to characterize the physical and chemical properties of vehicle emissions and possibly to differentiate emissions from various mobile sources (e.g., gasoline-, diesel-, natural gas-fueled and other alternative fuel vehicles). The contribution of emissions from these sources to the total emissions inventory will be established. Emissions from new and in-use technologies and non-petroleum-based fuels will be evaluated. Impacts of diesel and gasoline PM emissions in air quality will be investigated, compared, and contrasted. The atmospheric reactivity of exhaust emissions from alternative-fuel engines will be evaluated to assess the impact on urban air quality relative to conventional fuels. Work will also contrast primary and secondary particulates associated with the use of different fuel formulations. More specifically, it is necessary to achieve the following:

- Characterize the chemical and physical properties of diesel exhaust at the low emissions 2007/2010 certification standards required by EPA to evaluate if there are potential adverse health impacts.
- Evaluate the impact of unregulated emissions and toxic compound components from the 2007/2010 compliant engines on human health at some exposure levels.
- Measure, characterize the chemical and physical properties of, and possibly differentiate, emissions from various mobile sources (e.g., gasoline-, diesel-, natural gas-fueled vehicles) highway vehicles (and/or farm and construction equipment and locomotives, as needed) as a function of fuel composition, lubrication technology, and duty cycle.
- Establish the proper apportionment of emissions among the various mobile sources, e.g., cars vs. heavy trucks, and conventional fuel (gasoline and/or diesel fuel) versus alternative fuels (e.g., non-petroleum based fuels).
- Establish a scientific basis for determining the impacts of emissions on human health.

3.3.5.10 Tasks

A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in the following table:

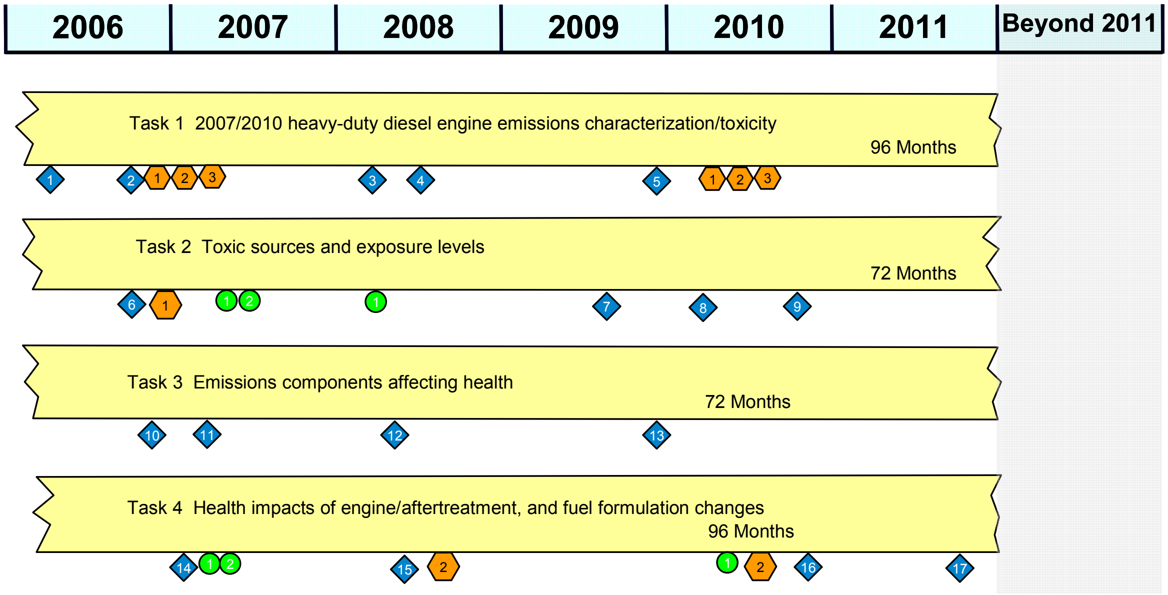
Table 3.3-9. *Tasks for Health Impacts Research*

Task	Title	Duration & Barriers
1	***Characterization of 2007/2010 emissions-compliant heavy-duty diesel engines and evaluation for toxicity and health impacts*** • Collection and chemical characterization of emissions samples from at least 4 representative 2007 emission compliant heavy duty diesel engines; selection of representative emissions profile • Exposure over specified time periods, of animals (rats, mice), bacteria (Ames test) and cultured mammalian lung cells to emissions from representative engine • Identification and statistical interpretation of observed biological responses to specified exposure levels • Replicate protocol for 2010 compliant heavy duty diesel engines	96 months Barriers B, C, D
2	***Characterization of toxic emissions from mobile sources and evaluation of the relative contribution to exposure levels; establish relative health hazards of diesel, gasoline, and natural gas engine system(s) emissions*** • Identify molecular markers that differentiate emissions from various sources • Establish apportionment of emissions among various among various sources	48 months Barriers B, C, D
3	***Emissions components affecting health*** • Identify components of complex "whole" emissions responsible for health hazard • Establish protocol for determining toxicity of various emissions components and corresponding health hazard	72 months Barriers B, C, D
4	***Health impacts of engine/aftertreatment and fuel formulation changes*** • Testing and evaluation of non-petroleum-based fuels for toxic emissions	96 months Barriers B, C, D

3.3.5.11 Milestones and Decision Points

Health Impacts Research activity milestones and decision points are provided in the following chart:

Health Impacts



Legend

◆ **Milestone**

1. Complete evaluation of production-intent prototype 2007 EPA-compliant heavy-duty diesel engines; one representative engine/aftertreatment system selected for exhaust emissions characterization and toxicity assessment.
2. Complete collection of emissions sample from representative 2007 compliant diesel engines for toxicity studies.
3. Complete evaluation of production-intent prototype 2010 EPA-compliant heavy-duty diesel engine; one representative engine/aftertreatment system selected for emissions characterization and toxicity assessment.
4. Complete installation of representative engine for emissions generation at health facility.
5. Complete chronic inhalation bioassay on two rodent species (2010 EPA-compliant diesel engines).
6. Complete characterization of oil-derived and conventional diesel nanoparticles.
7. Complete collaborative government/ industry evaluation of effects of lubricating oil composition on gasoline and diesel vehicle exhaust.
8. Complete evaluation of evaluation of sources of in-cabin vehicle pollutant exposure during on-road driving conditions

◆ **Milestone**

9. Complete apportionment study of contributors to ambient ozone levels in the Los Angeles basin.
10. Complete validation comparison of *in vitro* and *in vivo* responses to diesel and gasoline emissions.
11. Complete evaluation of chemical determinants of toxicity of natural gas engine emissions.
12. Complete multivariate analysis of toxic agents in conventional diesel, gasoline, and natural gas vehicle emissions from roadside samples.
13. Complete comparison of toxicity emissions from gas-to-liquids, kerogen-derived, heavy-oil derived, and biodiesel in conventional diesel engine.
14. Complete initial sample collection for subsequent toxicity testing of metallic compounds in engine emissions originating from fuels and lubricants.
15. Complete evaluation of effect of lube oil composition and usage on toxicity of diesel emissions.
16. Complete initial evaluation of potential health hazards from HCCI engines and fuels.
17. Complete evaluation of potential health hazards from hybrid-electric duty cycles and fuels.

⬢ **Technology Program Output**

1. Technical data/information to refereed journals for wide public dissemination.
2. Technical data/information to Fuels Technology.
3. Technical data/information to Heavy Truck Engine R&D

● **Supporting Input**

1. Input from industry.
2. Fuel specifications from Fuels Technology.
3. Engine exhaust emissions sample from Heavy Truck Engine R&D.

Figure 3.3-5. Network Chart for Health Impacts

DOE 2006 Presentation on Thermoelectrics Program (link)

WEBLINK

The DOE 2006 Presentation on the Thermoelectrics Program can be found at:

http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2006/session6/2006_deer_fairbanks.pdf

21st CENTURY TRUCK
PARTNERSHIP

Summary of Thermoelectrics Program (document)

21 CTP - Parasitic Energy Loss Reduction White Paper
Waste Heat Recovery & Utilization (WHR&U) Project
Submitted by Terry Hendricks, PNNL

Background

Efficient energy management has become a paramount concern nationwide in many light-duty (i.e. passenger cars, vans, and sport-utility vehicles) and heavy-duty vehicle applications because of the rising cost of energy in all forms (i.e. natural gas, petroleum-based energy products). A large amount of waste energy is generally available to be captured and converted (i.e., 10's of kilowatts of available thermal energy) into useful energy forms in vehicle exhaust and coolant streams within a variety of transportation sector applications. Advanced vehicle energy recovery systems to capture this energy are not currently available and are critically needed to improve energy management in vehicles. Nationwide current estimates indicate there is ~4-5 Quads of thermal energy dissipated annually in exhaust streams of light-duty passenger cars, SUVs and vans and another ~1.5 Quads dissipated annually in exhaust streams of Class 3-8 heavy-duty vehicles. Exhaust temperatures are 350 – 570^{o}C in heavy-duty vehicle exhausts, slightly lower than the 400 – 700^{o}C in light-duty vehicle exhausts. However, the exhaust thermal energy available per vehicle is much higher in heavy-duty vehicles compared to the relatively low thermal energy per vehicle (lower engine energy levels and resulting exhaust flow rates) in light-duty vehicles. Recovering and using this energy on-board a vehicle to improve vehicle fuel efficiency (i.e. fuel economy) is critically important in helping reduce the nation's dependence on oil and fossil fuel resources. Not only is this a nationwide energy issue, but this has become a growing issue of national and economic security. OFCVT developed and implemented in FY 2005 an on-going program in Waste Heat Recovery & Utilization to exploit exhaust gas energy recovery opportunities in heavy- and light-duty vehicles. The goal of this program is to increase fuel economy by 10% through exhaust gas energy recovery using advanced thermoelectric (TE) power generation systems.

Project Approach & Structure

OFCVT has funded four contractor teams through Cooperative Agreements, as part of the WHR&U project, to research and develop waste heat recovery systems in light-duty and heavy-duty vehicles. Two project teams are researching and developing light-duty exhaust energy recovery systems, while two project teams are developing heavy-duty exhaust energy recovery systems (See industry partners/teams below).

Industry Partners/Teams:

Light-Duty Vehicle Systems
- General Motors Team
  - General Electric, University of Michigan, University of So. Florida, RTI, ORNL
- BSST Team
  - Visteon, BMW-North America, Marlow Industries, Purdue University, UC-Santa Cruz, JPL, NREL

Heavy-Duty Vehicle Systems
- Michigan State University Team
  - NASA-Jet Propulsion Laboratory, Tellurex, Cummins
- United Technologies Team
  - Pratt & Whitney, Caterpillar, Hi-Z Technology, PNNL

The project is targeting advanced thermoelectric systems using advanced TE materials being developed at Michigan State University (LAST compounds), NASA-JPL (skutterudites), and Massachusetts Institute of Technology (Quantum Well materials). It ultimately intends to research, develop and demonstrate advanced prototype systems to recover waste energy in vehicle exhaust streams to show the potential vehicle-level benefit, help surmount system integration challenges, and develop systems-level experience and lessons-learned to propel this technology into next-generation vehicle commercialization. The project is cooperating and sharing information with on-going DOD programs

(Office of Naval Research, in particular) in advanced TE materials and systems to leverage their results toward accomplishing the WHR&U goals. Collaborative technical workshops were held with EPRI and the Office of Naval Research in FY 2004, FY 2005, and FY 2006. Technical papers from this work were presented at the International Conference on Thermoelectrics in 2005 and 2006 and the 2006 European Thermoelectrics Conference.

Accomplishments

The cooperative agreement projects have now progressed through their Phase I and Phase II work plans at the funding levels available in FY 2005 and FY 2006. Certain original work plans and milestones were postponed due to constrained available funding levels. System designs & system-level evaluations were performed per Milestone 8 in the Parasitic Energy Load Reduction Schedule of Activities and Milestones. Table 1 shows a summary of the resulting anticipated performance levels, targeted applications, and expected advanced TE materials for project team system designs developed in Phases I and II.

Table 1 – System-Level Evaluation Results & Designs

WHR&U Team	Application / Platform	Projected Power (W)	Projected System Efficiency	TE Materials	Comments
BSST	BMW 5 Series	750	~8 %	Skutterudites, Bi_2Te_3, TAGS, PbTe	Segmented Design, TE Material Development Proceeding, Plans for Laboratory to Production Transition
GM	Light-Duty Passenger Car, SUV, Vans	355 (Minimum)	5.5%	MischMetal, Skutterudites, 2-D Superlattice Materials, TAGS, PbTe, Clathrates, Bi_2Te_3	Segmented Designs
MSU	Cummins Engine & Associated Heavy Vehicle	12000	9.1 %	LAST(T) Compounds, PbAgSbTe Alloys	TE Material Development Proceeding, Moving Toward Production Volumes
UTRC	Caterpillar Engine & Class 8 Long-Haul	12000	18 %	Si/SiGe Thin-Film Quantum Well Materials	Serious Material Technical Concerns, Reproducibility & Contacts

Funding Profile

The original project solicitation in FY 2004 anticipated a total project funding level of approximately $17 million. Table 2 shows the originally proposed cost plans and the actual funding in FY 2005 and FY 2006, as well the revised cost plan through FY 2010. Budget constraints and earmarks in FY 2005 and FY 2006 budgets limited the FY 2005 and FY 2006 expenditures to less than 50% of the original funding plans. This has severely limited the progress and accomplishments noted in Table 1.

Table 2 – Project Funding Profile

WHR&U Teams	FY 2005		FY 2006		FY 2007	FY 2008	FY 2009	FY 2010
	Original Plan	Actual Cost	Original Plan	Actual Cost	Revised Plan	Revised Plan	Revised Plan	Revised Plan
BSST, GM, MSU, UTRC	$5.0 M	$1.27 M	$6.5 M	$3.2 M	$7.5 M	$5.1 M	$3.25 M	$3.6 M

Future Work & Remaining Technical Barriers

Future work will concentrate on achieving Milestone 9 in the Parasitic Energy Load Reduction Schedule of Activities and Milestones. This involves evaluating and demonstrating advanced TE devices / systems on heavy- and light-duty vehicles under typical operating conditions and environments. The technical barriers to overcome in achieving this are shown below.

Technical Barriers

- Transition new advanced TE materials into production-volume manufacturing processes
- Integrating new advanced TE materials into operational devices & systems
- Verifying performance of key thermal interfaces
- Verifying material and component thermal expansion & thermal diffusion characteristics under actual operating conditions
- Integrating/Load Matching advanced TE systems with vehicle electrical networks
- Verifying device & system performance under operating conditions
- Demonstrating adequate device / system lifetimes in light- and heavy- duty vehicle environments
- Low system-level costs in-line with industry & market requirements

Overview of Thermoelectric Applications for Vehicles	John W. Fairbanks	U.S. Department of Energy	(PDF 7.1 MB)
High-Efficiency Waste Heat Recovery System for Vehicle Applications	John W. LaGrandeur	BSST LLC	(PDF 565 KB)
Develop Thermoelectric Technology for Automotive Waste Heat Recovery	Jihui Yang	General Motors	(PDF 892 KB)
Cost-Effective Fabrication Routes for the Production of Quantum Well Structures and Recovery of Waste Heat from Heavy-Duty Trucks	Rhonda Willigan	United Technologies Research Center	(PDF 2.4 MB)
Progress in Thermoelectric Energy Recovery from a Light-Duty Truck Exhaust	Eric Thacher	Clarkson University	(PDF 781 KB)
Potential of Thermoelectrics for Fuel Efficiency Gains and Occupant Comfort in Vehicle Applications	Lon E. Bell	BSST LLC	(PDF 1.2 MB)
A Quantum Leap for Heavy-Duty Truck Engine Efficiency — Hybrid Power System of Diesel and	Gerhard Regner	AVL Powertrain Engineering Inc.	(PDF 339 KB)

WHR-ORC Engines			
Electric Turbo-Compounding — A Technology Whose Time has Come	Carl T. Vuk	John Deere	(PDF 1.5 MB)
In-Vehicle Exhaust Energy Recovery for Thermal Efficiency Improvement	Christopher R. Nelson	Cummins Inc.	(PDF 616 KB)
NAFTA Heavy-Duty Engine and Aftertreatment Technology: Status and Outlook	Glenn Lysinger	Chief Compliance Officer, NAFTA Powertrain, Detroit Diesel Corporation	

LIGHTWEIGHT MATERIALS

21st CENTURY TRUCK
PARTNERSHIP

Summary of DOE HSWR Materials Program (document)

Lightweight Materials

High Strength Weight Reduction Materials Program – Program Structure

This outline describes the key technology areas addressed by the Department of Energy's High Strength Weight Reduction Materials Program. The activities are divided into several projects which are closely linked to the FreedomCAR and Vehicle Technologies Program R&D Plan.

Project 18540 Processing Techniques

The objective of this project is to develop robust, flexible, and reliable manufacturing processes for components in heavy vehicle applications to optimize for part consolidation, net shape forming, lower assembly costs, and low-cost tooling. Specific technology development includes development of processing techniques for magnesium sheet and titanium springs made form powder, superplastic forming of aluminum for heavy vehicle applications, lost foam casting of magnesium, and technologies for processing and implementing magnesium metal matrix composites.

Project 18541 Enabling Technologies

In addition to materials and process development, implementation of lightweight materials requires development of design databases, joining technologies, and computational modeling. The objective of this project is to provide supporting R&D that will enable increased acceptance of new materials by the heavy vehicle industry and more rapid implementation. Specific tasks focus on developing advanced joining technologies, microstructural modeling, developing databases for design properties (corrosion, friction, wear, etc.), and developing attachment techniques for carbon fiber composites in heavy vehicle applications.

Project 18538 Lightweight Vehicle Structures

The purpose of this project is to cost-effectively apply lightweighting materials to heavy vehicle structures and demonstrate improved performance without sacrificing functionality, durability, reliability, or safety. Activities focus on development of a lightweight tanker trailer as well as a lightweight bus/step van.

Project 18537 Application of Innovative Materials

The purpose of this project is to perform research and development on innovative materials which can be strategically applied to key heavy vehicle applications to take advantage of their special properties. Specific activities include application of carbon fiber composites to large structural components, carbon fiber SMC applications, and advanced support structures made from carbon fiber composites. It is also recognized that improved materials may enable implementation of other technologies that can further improve the fuel efficiency of heavy vehicles.

Project 18539 Materials Development

The objective of this project is to develop lighter weight materials to replace conventional materials for body, chassis, and suspension applications while still meeting the demanding performance requirements of heavy vehicles. Specific activities will focus on lightweight functional materials and advanced materials for friction brakes.

Accomplishments

Vehicle Weight Reduction:

Vehicle weight reduction was the primary focus of the HSWR Materials Program, which is not funded following completion of FY2006 activities. Selected accomplishments for the HSWR Materials Program during the program period from FY2003 through the end of FY2006 are listed below.

Hybrid Composites for Weight Critical Structures

Current materials and manufacturing technologies used for heavy vehicle door systems are often dictated by the high cost of tooling and the relatively low production volumes for Class 8 trucks. Automotive-style stamped door designs, whether of steel or aluminum, require multistage stamping dies that are generally cost-prohibitive at lower production volumes (<50,000 units per year). Alternate materials, such as glass-reinforced sheet molding compound (SMC), require less expensive tooling and can provide a Class A finish, but the relatively poor specific properties of SMC tend to compromise design and result in a heavier door system. For many production truck cabs, a simple aluminum extrusion frame is used with a flat aluminum sheet riveted to the frame. Although this approach does not require expensive tooling, the use of constant cross-section extrusions in the frame is less than optimum, and it requires more assembly labor than other approaches. PACCAR, a world leader in Class 8 truck design and manufacturing, teamed with PNNL to explore alternate "hybrid" door system designs that minimize tooling cost and per/part door cost, while providing a lightweight, structurally stiff, automotive-style door.

Following completion of the design selection phase of the project, full-scale hardware components were developed and shipped to PACCAR Technical Center for assembly and testing. In addition to the static deflection tests, a complete door was assembled and mounted in a Class 8 truck cab for fit and functional tests (Figure 1). Subsequently, the door was placed into a door durability cab test which is currently being run to completion.

The team and its selected subcontractors completed the prototype development of hybrid door components for an advanced heavy truck door. The team has completed prototype assembly, including inspection and assembly fitting, as well as adhesive bonding development. The team assembled three prototype doors for cab testing and evaluation during calendar year 2005. Static testing and cab functional test and evaluation have been completed. A prototype door is currently undergoing cab durability testing. The hybrid door design that will be prototype-tested reduces door weight by 37%. If the hybrid design were to move into production, the use of a stamped aluminum outer panel (cost-prohibitive during the prototype stage) would improve structural performance, reduce cost to project goals, and increase weight savings to 55%.

Figure 1. Prototype door assembled in Class 8 cab for functional testing

Application of Carbon Fiber Composites for Large Structural Components

Current Class 8 trucks use up to 1000 lbs. of fiberglass-reinforced polymers in the fabrication of hoods, fairings, and sleeper modules, and in many cases in the manufacture of cab doors. These fiberglass composites have relatively low structural strength and impact properties, and suffer from molding and manufacturing defects that severely limit their useable strength and stiffness. This project investigated alternate toughened resin systems, hybrid combinations of glass, carbon fiber and polymer core materials, and alternate manufacturing methods centered around vacuum-assisted resin transfer molding.

Interest in the attractive properties arising from the combination of polyester and urethane resin chemistries prompted investigation into efficient manufacturing methods using a blended polyester/urethane system. By mating this material to a glass/carbon hybrid fiber preform, an optimization of properties from all of the constituents was achieved at a relatively low cost. A challenge for heavy duty trucks is that the composite hoods and fairings have are very large components with substantial material area and long resin flow paths when applying resin transfer molding approaches. Using combinations of these materials, test panels were manufactured at different lengths to provide specimens and validate the feasibility of molding large (>5ft) and thin (<3mm) components. Close monitoring of developing manufacturing procedures provided valuable data concerning the behavior of both the resin and fiber hybrids in vacuum assisted resin transfer molding (VARTM) and closed molding operations.

Two approaches were taken for tooling on a hood design. The first was a multiple insert tool approach that allowed for offline surface prep and demold from the press which helped keep cycle times low and through put high. The second approach was the vacuum assisted resin transfer molding using lighter and lower costs tooling to accomplish the same end result. Figure 2 illustrates the large hood that was planned for testing, which when fabricated from a hybrid carbon fiber/glass composite perform and the urethane-modified resin system would have resulted in an overall weight savings exceeding 30% when compared to the comparable Sheet Molding Compound or open-molded glass reinforced hood. The project had started building the hood tool with a supplier to the partner and they ended up being bought out by a competitor, and the resulting delays and prototype cost growth resulted in the industry partner (Freightliner LLC) to drop the development effort. However, the toughened urethane-modified resin system developed around this application has been commercialized by the participating material supplier.


Figure 2. Prototype truck hood for hybrid composite molding.

The flow trials gave us valuable insight as to how fast the large panels will fill. The rheology studies indicate time sensitivity when the two resin components are mixed and have the largest influence on the viscosity. The viscosity data became very useful with the modeling which illustrated the fill time and pressure gradients with in the part. These models and the correlation data gave us the information needed to be able to model large structures prior to building the tool that will help reduce the risk of the unknown with any large complicated and expensive tool.

Experimental correlation will be evaluated on the large molded parts. A large tool was used to compare cost estimates for two different tool designs. The parts that have been chosen are to demonstrate the most challenging aspects of the process capability, namely highly structural, Class A surfaces in direct line-of-sight, with some complex process details required for success. Tooling quotes have been received and cost compared with the VARTM tooling being the lowest cost by 9 fold. Supply chain issues have been and problem and may limit the program from moving forward on the large hood tooling. A patent application has been written for the process.

Next Generation Frame for Pick-Up/Sport Utility Vehicle Applications

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. 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. Under the goals of the HSWR Materials Program, the materials and manufacturing technologies that were demonstrated for the DaimlerChrysler Next Generation Frame can be readily transferred and applied to commercial vehicles in the Class 3-5 range.

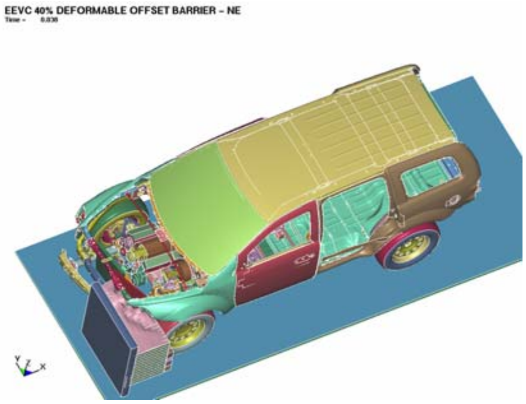


Figure 3. Crash modeling simulation of Next Generation Frame

During the previous frame development effort, in the second quarter of 2003 DaimlerChrysler (DCX) completed vehicle testing at the DCX Proving Grounds of a SUV/PU platform equipped with a hybrid steel/aluminum 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 overbuilt and heavier than required even with a substantial weight savings from the current baseline steel frame.

The next phase of the project evaluated the use of a lighter frame, the Next Generation Frame (NGF). The NGF uses a Computer Aided Engineering (CAE), extensive use of aluminum extrusions, castings, and stampings, higher-risk manufacturing technologies. The projected weight for the NGF is significantly lighter (>40% weight reduction) than the previously tested hybrid frame and requires 35% fewer components. CAE analyses of the frame were completed, and the frame design satisfied all of DCX requirements for 5-Star crash worthiness, NVH, and durability. Modeling results for the offset frontal impact test of the vehicle with the Next Generation Frame is shown in Figure 3. The frame fabrication and assembly has been completed and delivered to DCX and Magna for full-scale automotive 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.

Superplastic Forming of Heavy Vehicle Components

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. Superplastic forming (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.

A major challenge in applying SPF to heavy vehicle cab structures and components is the requirement for higher strength, dent-resistant aluminum sheet components. 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 offer the potential to use of higher strength alloys that has a heat treat response analogous to “paint baking” in steels. A significant accomplishment of this project has been to develop thermomechanical processing techniques and SPF forming schedules that allow the development of higher as-formed strengths through the use of a 6000-series aluminum alloy. The project is currently completing the forming of 10 large cab structural components using SPF of both 5000- and 6000-series aluminum, and the components will be assembled into a production cab for cab “shaker” testing. The SPF aluminum component will replace a large open-molded fiberglass part, which will reduce the weight of the part by over 35%, while providing higher cab performance. Studies being conducted by PACCAR indicate that SPF aluminum could be applied to a larger pportion of their cab structures with weight savings between 15 and 30%. This project is scheduled to be completed in mid-2007.

Friction Stir Welding/Friction Stir Processing

A critical problem that has emerged in the development of these hybrid structures is that for many material combinations, traditional joining technologies (like fusion welding or mechanical fastening) are not appropriate. For some highly specialized materials, like aluminum MMCs, titanium, and high-strength steels, a better joining technology can have significant impact on whether these materials have a role in future vehicle structures. In the past 15 years, a new joining technology, FSJ, has emerged that has the potential to join many lightweight materials. This process, invented by TWI, Ltd., is a solid-state process that employs severe plastic deformation to create joints between a wide variety of different materials. The weld is created by clamping the materials to be joined and plunging a spinning tool into the surface. The spinning tool is then translated down the joint line, leaving behind a weld zone characterized by a fine-grained, dynamically recrystallized microstructure. Typically, the tool is spun at 400 rpm to 2000 rpm and translated down the joint line at a rate of 4 to 300 in./min depending on tool design, base material, and thickness. As the tool rotates and translates, complex flow patterns develop in the base materials that create an intimate mixing of materials from both sides of the weld. Heat input during plastic deformation generally creates a temperature in the weld between 0.6 and 0.8 of the absolute melting temperature, so no liquid phase is generated.

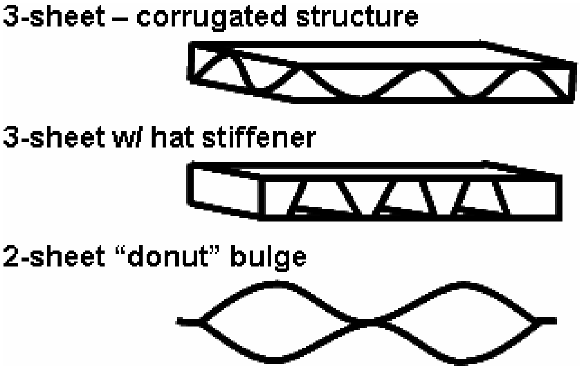


Figure 4. Geometries of test panels fabricated for this program

The objectives of this project in the 2005 to 2006 time period was to investigate how FSJ can be applied to advanced materials including AL-MMCs, titanium, steels, cast iron, superplastic materials, and materials that display graded structures with unique surface properties. The primary task in 2006 was the application of FSJ to superplastic forming environments. Numerous opportunities exist to use this manufacturing technology to reduce weight on heavy vehicles. One barrier to SPF manufacturing is that hang-on truck components are complex and often very large, larger than the standard coil widths. If sheets are joined together to make a large part by fusion welding, the weld region does not deform superplastically. However, when FSJ is used under the proper welding conditions, the weld can behave in a superplastic manner, allowing large integrated components of greater weight savings to be formed. A second application of FSJ for superplastically-formed truck components is the joining and forming of complex multi-sheet aluminum panels. Geometries for several panels developed by this project are shown in Figure 4. The second task investigated was continued development of a numerical modeling process using an approach called Smooth Particle Hydrodynamics (SPH). This modeling approach has not been previously applied to FSJ/P, but our preliminary work suggests that it may be able to provide significant insight into the fundamental nature of the heat generation and material flow that occurs during the FSJ/P process.

Composite Door Structural Surround (Delphi/ORNL contract)

The objective of this project is to develop a long-fiber reinforced polymer door surround for a class 8 tractor cab, such that the door surround mass is at least 30% less than that of the incumbent design. The project team designed, manufactured, and tested an advanced composite door surround for a class 8 tractor. The door surround is the structural frame into which the cab door fits and seals against the cab structure. The current design is liquid compression molded vinyl ester reinforced with non-oriented 35-40% glass mat preform, with local steel backing.

Figure 5. Molded composite cab door surround structure.

The project commenced in June 2001. It met all technical and cost milestones, but was delayed in 2004 due to supply chain issues and OEM resourcing challenges. Activities in FY 2006 will include process validation, and possibly the production tooling release. The project successfully demonstrated the application of long fiber reinforced composites for cab structural components, which, when implemented will reduce cab weight when compared to conventional glass-fiber reinforced composites. The purpose of this project is to cost-effectively apply lightweighting materials to heavy vehicle structures and demonstrate improved performance without sacrificing functionality, durability, reliability, or safety. Activities focus on development of a lightweight tanker trailer as well as a lightweight bus/step van.

Advanced Composite Structural Chassis Components

The objective of this project is to develop long-fiber reinforced polymer structural chassis components for class 8 trucks, such that the component mass is 40% - 60% less than that of the incumbent design. The components include the main supports, trailing arms, and lateral links.

The project team will design, manufacture, test, and commercialize advanced composite structural chassis components for class 8 trucks. Conventional structural chassis components are constructed from forged or fabricated steel. The next logical step for additional mass reduction is the development of advanced, continuous fiber reinforced composite components. This project has a targeted mass reduction of 60%, with cost parity to today's metal components. It is anticipated that technology developed here can later be systematically applied to chassis and suspension modules to reduce vehicle mass by over 1,000 pounds.

A lateral link has been successfully developed for passively steerable auxiliary axles. 6,000 production units, in four configurations, have been shipped to two customers. Front steer lateral links were found to be too expensive at current carbon fiber prices. Early trailing arm designs showed that substantial mass could be removed using aluminum, with reduced cost as well. The aluminum trailing arms are 66% lighter than the steel versions and are now in validation testing. The development of composite trailing arms was terminated. A proof-of-concept, metal-composite hybrid main support that is ~ 50 lb. lighter than the incumbent product has been designed and tested. Further technical work on the main support was deferred pending resolution of commercialization plans.

Figure 6. Composite suspension component commercialized for heavy vehicle steer axles.

Carbon Fiber SMC Hood Systems for Heavy Vehicle Applications

The objective of this project is to develop an economical carbon fiber sheet molding compound (SMC) hood system, conforming to the manufacturer's quality standards and reducing hood system mass by at least 30%, for a class 8 tractor. ORNL will provide technical management of the project by monitoring a contract between UT-Battelle and Volvo Trucks North America.

Figure 7. Example of SMC heavy duty truck hood.

The project team, led by Volvo Trucks North America, had the objective to design, manufacture, test, and commercialize a carbon fiber SMC hood system for Volvo's class 8 tractor. A carbon fiber SMC hood system is expected to be 21 – 35 kg less massive than a traditional SMC hood system (30% - 50% mass reduction). Volvo originally planned to utilize carbon fiber SMC in a hood that is offered as a standard product. However, such a strategy requires cost parity with the conventional SMC hood, and achieving cost parity is deemed highly improbable for at least the next several years because of current carbon fiber pricing. Therefore, the current plan is to investigate using carbon fiber SMC on a hood that is part of a weight-sensitive option package that couples the hood with an optional large displacement engine that satisfies 2007 emission regulations. FY 2006 tasks focused principally on tooling procurement and validation. Figure 7 shows a picture of the current SMC glass fiber reinforced hood that was evaluated for this project.

21st CENTURY TRUCK
PARTNERSHIP

2005 DOE Merit Review and Peer Evaluation Report for Heavy Vehicle Materials Program (link)

WEBLINK

The 2005 DOE Merit Review and Peer Evaluation Report for Heavy Vehicle Materials Program can be found at:

http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2005_heavy_vehicle_merit_review.pdf

21st CENTURY TRUCK
PARTNERSHIP

FY2005 Progress Report for High Strength Weight Reduction Materials (link)

WEBLINK

The FY2005 Progress Report for High Strength Weight Reduction Materials can be found at:

http://www1.eere.energy.gov/vehiclesandfuels/resources/fcvt_hswr_fy05.html

THERMAL MANAGEMENT, FRICTION & WEAR

21st CENTURY TRUCK
PARTNERSHIP

2006 Heavy Vehicle Systems Optimization Merit Review and Peer Evaluation (link)

WEBLINK

The 2006 Heavy Vehicle Systems Optimization Merit Review and Peer Evaluation can be found at:

http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2006_hvso_merit_review.pdf

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

For more information contact:
EERE Information Center
1-877-EERE-INF (1-877-337-3463)
www.eere.energy.gov