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

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

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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.

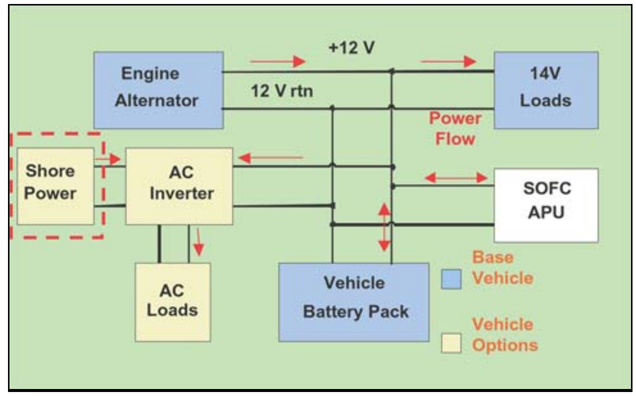

Figure 1. Vehicle Electrical System Diagram

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.

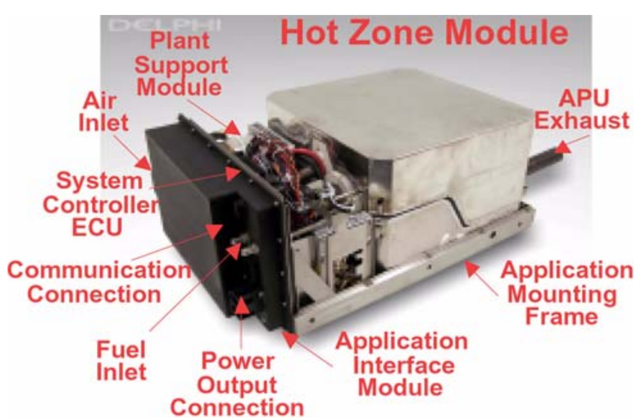

Figure 2. SOFC APU Hardware – Generation 3 APU System

- 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.

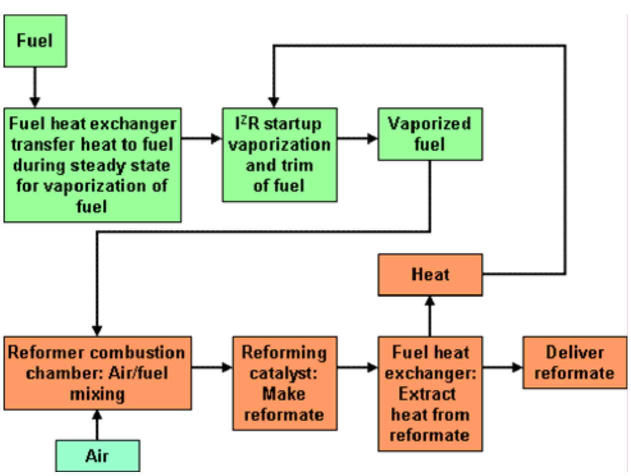

Figure 3. Fuel Delivery System Process Flow Block Diagram

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.