V.J.1 Diesel-Fueled SOFC System for Class 7/Class 8 On-Highway Truck Auxiliary Power

Dan Norrick (Primary Contact), Charles Vesely
Cummins Power Generation (CPG)
1400 73rd Avenue NE
Minneapolis, MN 55432
Phone: (763) 574-5301; Fax: (763) 528-7226
E-mail: Daniel.A.Norrick@Cummins.com

DOE Technology Development Manager: Donna Ho
Phone: (202) 586-8000; Fax: (202) 586-9811
E-mail: Donna.Ho@ee.doe.gov

DOE Project Officer: David Peterson
Phone: (303) 275-4956; Fax: (303) 275-4788
E-mail: David.Peterson@go.doe.gov

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

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Subcontractor:
Protonex, LLC, Broomfield, CO

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Project End Date: December 31, 2009

Objectives

Design, develop, and demonstrate a practically sized, diesel-fueled solid oxide fuel cell (SOFC) auxiliary power unit (APU) configured to provide electrical power for sleeper cab auxiliary loads of on-highway trucks to meet the requirements for cost, size, weight, fuel efficiency, and operation on diesel fuel.

- Develop ultra-low sulfur diesel (ULSD) fuel processor.
- Develop fuel cell that operates on ULSD catalytic partial oxidation (CPOX) reformate.
- Design, build and test APU under real-world conditions.

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
(B) Cost
(C) Performance

Technical Targets

This project is to develop APU systems for heavy truck applications to reduce idling of the main engine. Analysis and design(s) of fuel cell APU systems will lead to the build and test of an APU demonstration unit. The projected characteristics of the proposed system differ from the DOE solicitation targets. The planned CPG-Protonex LLC products (2006 and 2010), and market expectations were derived from our belief that the primary obstacle for market entry is economics – a combination of installed cost and operating efficiencies that demonstrate a payback in the 18-24 month time frame. Secondary factors are service interval, noise and vibration, weight, and size. In order to get “on the truck” we believe the APU needs to be in the range of 8 cubic feet (225 L), weigh less than 400 lbs (180 kg), and provide a base load of about 2,500 W to service heating and air conditioning loads. Smaller size and lighter weight, while desirable, are not supported by higher price potential, nor do they justify incremental development cost or capital investment. However, under this solicitation, we believe we can leverage our Solid State Energy Conversion Alliance SOFC development work to produce a diesel-fueled SOFC APU that will meet or exceed the performance required to be commercially successful in this market. The following lists the current DOE 2010 auxiliary power units and truck refrigeration unit targets and the actual 2006 proposal targets in ()s:

Cost:	$400/kWe	($1,500/kW)
Specific power:	100 W/kg	(17 W/kg)
Power density:	100 W/L	(8 W/L)
Efficiency @ rated power:	35% LHV	(25% LHV)
Cycle capability:	150 cycles	(10 cycles)
Durability:	20,000 hours	(1,500 hours)
Start-up time:	15-30 min	(60 min)

(LHV – lower heating value)

Accomplishments

- Fabricated complete modules and operated these modules on both hydrogen/nitrogen mixtures and on reformed liquid fuels.
- Thermally self-sustaining operation of complete modules was demonstrated.

- Completed the design and analysis of the power unit enclosure and complete balance of plant (BOP).
- Tested an inexpensive waste heat recovery exchanger that provides very high effectiveness at all operating conditions (≥95%) and very low pressure drop (<2" water on gas side) under all operating conditions.
- Designed and programmed a custom 6-layer printed circuit board (PCB) for interfacing and control of SOFC stacks and BOP components.
- Demonstrated the complete power electronics, inverter/battery charger/direct current (DC) boost system with a fuel cell power source simulator.
- Vibration tested a complete fuel cell module at 0.5 g over a frequency range of 5 Hz to 200 Hz in three directions.

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Introduction

With the onset of anti-idling legislation and the rising cost of fuel one potential early adopter for SOFC fuel cell technology is the on-highway truck APU application. First, an SOFC APU could provide the same electrical source as a conventional internal combustion engine-based APU. Second, it has the potential to improve exhaust emissions, fuel efficiency, reduced transmitted noise and vibration, and heating for both cabin and engine.

This project is directed at designing, building and demonstrating a ULSD-fueled SOFC APU installed in an on-highway truck to supply alternating current (AC) power for cabin loads, engine heating, and battery charging during rest periods.

Approach

The plan to complete the objectives of the project include identifying the overall truck system performance, power electronics, heating, battery, fuel cell system, and fuel cell hot zone requirements. Voice of Customer surveys will be used to identify and quantify the overall truck system requirements. This will flow down into detailed specifications for each sub-system/component. These specifications will be utilized to develop an overall system design that will detail the performance requirements for all sub-systems.

The APU design uses a novel dry CPOX reformer that requires no water. The APU is a modular design, based on four ~600 W (gross) modules, yielding ~2 kW net DC power. The scale up of fuel cell modules to 600 W and the development of the diesel CPOX reformer will be accomplished by modifications to a current 250 W product. Cummins Power Generation is responsible for project management, system design, packaging, all cold BOP equipment including air and fuel supply and metering, vibration isolation, power electronics and controls. Protonex is building the hot modules, including stacks, reformers, heat exchangers, tail-gas combustors and insulation packages.

Results

In 2009, we fabricated complete modules and operated these modules on both hydrogen/nitrogen mixtures and on reformed liquid fuels. In addition to tests of full-scale stacks and modules, we also tested sub-scale modules and fuel processor components.

Each module in the APU is a complete, independent hot zone containing a tightly-integrated stack, fuel processor, recuperative heat exchanger and tail-gas combustor inside an insulation package. The stacks use 66 tubes, each 10x135 mm. Typical performance of a module on a 50% H_2/N_2 mixture is shown in Figure 1. Figure 2 shows a photograph of one of the modules. The first modules were delivered to Cummins Power Generation in the third quarter of Fiscal Year 2009.

The system uses a novel dry CPOX reformer capable of efficiently processing ULSD. During this fiscal year, we demonstrated long-term operation of the reformer using both vaporizer and atomizer feed systems. Stable operation of the CPOX for more than 500 hours between maintenance was demonstrated, with no carbon deposition on the CPOX with oxygen-to-carbon (O/C) ratios as low as 1.1. We observed carbon deposition in downstream stack and hot zone components for O/C ratios below 1.2; an O/C ratio of 1.3 was chosen for system operation. At this O/C ratio, we have been able to demonstrate more than 500 hours of stable continuous operation of reformers and subscale stacks.

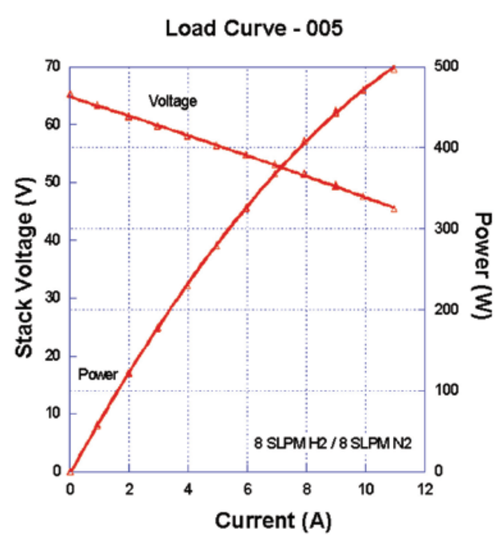

FIGURE 1. Stack Load Curve on H_2/N_2 Mixture

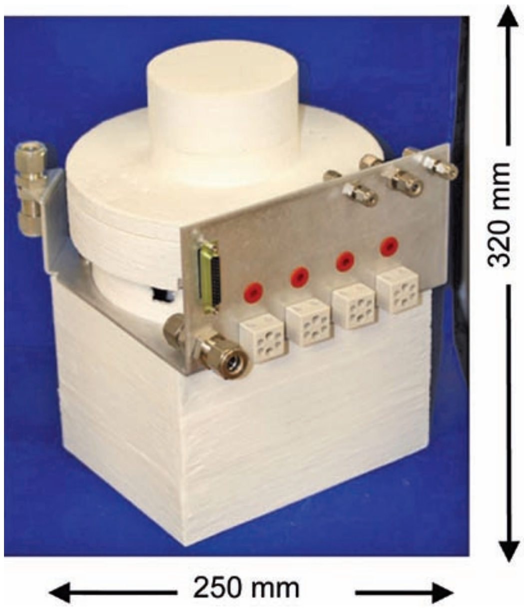

FIGURE 2. Photograph of Module

Thermally self-sustaining operation of complete modules was demonstrated this fiscal year. Target operating temperatures can be achieved at less than 45% of target fuel flows, corresponding to a “hot idle” condition; we do not anticipate difficulties in achieving target temperatures at full power and fuel flow rates.

In FY 2009, we began testing sub-scale stacks on liquid fuels to determine the proper setpoints for the fuel processor and cathode air flow to enable reliable start-up and shut-down of stacks on liquid fuels. These tests included operation on both ULSD and low-sulfur kerosene fuels. Each thermal cycle was between 180°C and 720°C with heating and cooling times of approximately 40 minutes each. The power was very stable over these cycles, with less than 1% power loss over 10 thermal cycles. This is excellent thermal cycling performance, particularly given these relatively rapid heating and cooling rates. Although these tests were conducted with a sub-scale stack, they used a full-scale fuel reformer, so they provide a complete test of the fuel processor and a high-fidelity simulation of the conditions inside a full-scale module.

Also in FY 2009, Protonex continued work on atomizers for feeding fuel to the modules. Two fuel feed technologies are being developed in this project: fuel vaporization and fuel atomization. Fuel vaporization is currently more mature and has been selected for the initial demonstrations on this project, but atomization has the potential for longer maintenance intervals. During FY 2009, we demonstrated atomizers capable of achieving very small droplet sizes with low feed pressures. Low feed pressures are required to minimize the pumping power required to feed the fuel and air to the CPOX reactor. Compared to state-of-the-art nozzles, this atomizer achieves small droplets at less than one-fifth the pressure drop. Low feed pressure is critical to minimizing the parasitic power draw of the fuel feed system; at a design pressure of 12 kPa, this atomizer would consume only 5% of the stack gross power while producing droplets with a Sauter mean diameter (D[3,2]) of ~24 μm. The current atomizer design operates well over a limited range of fuel and air flows. In the remainder of the project we plan to implement design changes that will extend the operating range to include startup and shutdown conditions.

Cummins Power Generation completed the BOP air delivery system fabrication for the four fuel cell module. The system includes one cathode air blower, one CPOX air boost blower, four cathode flow control valves, four anode control valves, and eight air mass flow sensors. The system achieved the required flow rate, flow adjust response time, and flow measuring resolution. A 3-dimensional printer was incorporated and significantly accelerated the air manifold and flow control valve fabrication and allows Cummins Power Generation to use low cost automotive components in the fuel cell development application.

A custom designed 6-layer PCB for interfacing and control of SOFC stacks and BOP components was completed. A Freescale microcontroller was selected as the computing core of each control board. SOFC specific software was written for execution on these microcontrollers which implemented the required operating steps outlined by Protonex.

Cummins Power Generation revised the power electronics topology after further investigation determined that the DC-DC boost was not necessary. The revised topology has the SOFC stack directly inverted to AC using a modified, Cummins Power Generation commercially produced, hybrid DC/AC/inverter/battery charger. In addition to an overall simpler topology, system efficiency has been improved 3-4% by removing the losses caused by the earlier DC-DC boost.

The sheet metal housing consists of an inner (Figure 3) and outer frame with vibration isolators in between the two frames. The inner frame has two compartments (or sides) – the hot side (or module side) which consists of the fuel cell modules and waste heat exchangers and the cold side (or BOP side) which consist of blowers and pumps (for air and fuel handling respectively) and control boards.

Stress analysis was conducted in ANSYS® using Cummins internal standard. A load of 5 g was applied in the longitudinal, transverse and vertical directions of the APU frame (longitudinal being parallel to the truck rail). The stress plots were studied and the sheet metal frame was reinforced as appropriate. In order to have high structural rigidity to weight ratio, square tubes (¾” x ¾”) were used as structural members. The stresses in the

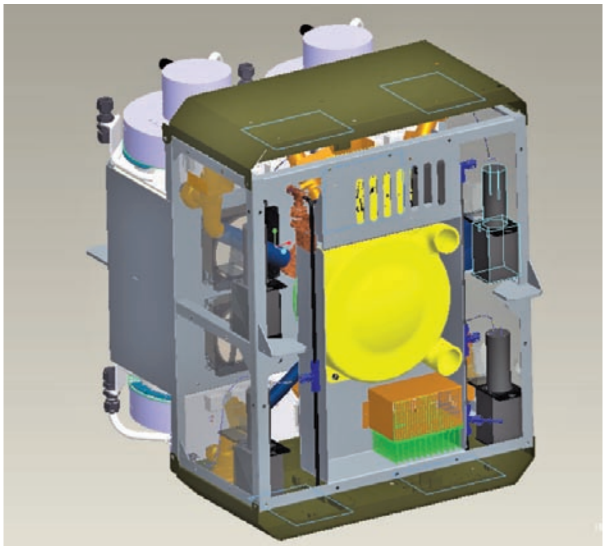

FIGURE 3. Fuel Cell – Inner Frame

longitudinal direction were found to be the most critical. In order to have sufficient room for the inner frame to sway inside the APU box (especially at low frequencies) a swaying clearance calculation was performed. Military standard 810 was used as a reference. The maximum accelerations and displacements at the extreme points of the frame at all operating frequencies were determined and appropriate vibration isolation mounts were selected.

Identified and tested a group of inexpensive waste heat recovery exchanger designs that provide the required cab heating with an effectiveness of ≥95% and pressure drop of <2" water over the required range of operating conditions. Tests were conducted on the heat exchangers by simulating the fuel cell exhaust using an in-house designed and fabricated natural gas burner. The simulated exhaust gas flow was adjusted to nominal operating conditions of the fuel cell and the temperature of the stream was 600°C which is typically the temperature reached by SOFC exhaust at the exit of the module. From a previous study it is known that the cab requires about 5 kW of heat during a peak winter event. The heat exchanger is capable of transferring the required amount of heat at a very high effectiveness at all flow conditions.

A 66-cell stack was tested at room temperature as a preliminary test to capture the module's vibration behavior. The tests were performed in the 5~200 Hz frequency range in three directions with vibration level of 0.5 g. Test results showed the fuel cell stack module had fairly symmetric vibration behavior about its vertical axis. With the current mounting design the module demonstrated a resonant peak at frequency about 75 Hz.

Conclusions and Future Directions

- This year we have fabricated complete modules and operated them on both hydrogen and reformed liquid fuels.
- We have demonstrated the viability of a dry CPOX approach at the stack and module level.

Future work

- Build and test full-scale bundles and complete 4-module sets for testing.
- Extend atomizer operating range to include start-up and shut-down conditions.
- Complete conceptual design of higher-power (~1 kWe) module.
- Complete SOFC APU unit fabrication and demonstration.