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

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Subcontractors:
- Protonex, LLC, Broomfield, CO
- International Truck & Engine, Fort Wayne, IN

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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 an 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

Cummins will develop an APU system 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. Our experience in the diesel genset APU market and initial response from customer surveys have been used to identify our overall system targets Our main goal is 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. This would make the systems comparable to current diesel generator based systems. Smaller size and lighter weight, while desirable, are not supported by higher price potential, nor do they justify incremental development cost or capital investment. We will 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. Table 1 lists the targets we believe are needed for market introduction.

TABLE 1. Proposed Targets for SOFC APU Market Introduction

Variable	Proposed Target
Cost	1,500 $/kW
Specific Power	17 W/kg
Power Density	8 W/L
Efficiency @ Rated Power	25% (lower heating value)
Cycle Capability	10 cycles
Durability	1,500 hours
Start-Up Time	60 min.

Accomplishments

- Created a design that fits the four stack module system with vibration isolation in a similar package to the Cummins compression ignition powered Comfortguard™ APU enclosure.

- Scale-up of existing 250 Watt fuel cell modules to a 600 Watt net module.
- Created an electrical system to hybridize the fuel cell and batteries to provide alternating current (AC) cabin loads, direct current (DC) loads, and starting battery charging.

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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 AC power for cabin loads, engine heating, and battery charging during rest periods.

Approach

The plan to complete the objectives of the project includes 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. These 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. CPG is responsible for project management, system design, packaging, all cold balance-of-plant (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 2008, we demonstrated and integrated an extremely compact modular CPOX reformer. This reformer is very small (only 1.5 inches diameter by 1.5 inches long) and requires no water for operation. Our work in 2008 included optimizing the reactor geometry to maximize the stable operating range, selecting catalysts that would give long life with commercial ULSD and demonstrating two different fuel feed options. In order to increase the reactor turndown ratio, the baseline reactor design was modified to reduce the inlet catalyst face temperature at low flow rates. These changes extended the operating range of the reactor by eliminating low-velocity regions. Three tests were conducted using this reactor configuration, two using B1 catalyst and one using B2 catalyst. A turndown ratio of 6:1 was achieved over both catalysts. At the lowest diesel feed rate tested (1 cc/min), the reactor was operated at oxygen-to-carbon (O/C) ratios as high as 1.5 without incurring significant gas-phase diesel combustion before the catalyst. Although the highest diesel feed rate used in the tests was 6 cc/min, it is likely possible to further increase the fuel feed rate before H_2 and CO concentrations begin to fall. Table 2 shows the reformate composition for the B1 and B2 catalysts at the different turndown ratios.

We tested the operating limits of the B2 catalyst in order to define the operating window for the CPOX reactor. The reactor operation is controlled by three parameters: firing rate, O/C ratio, and preheat temperature. Assuming a well mixed and completely vaporized fuel and air stream are fed to the reactor, these parameters must be maintained within certain limits to avoid catalyst deactivation and carbon formation within the reactor or downstream from the reactor.

The operating envelope for the reformer is shown in Figure 1. This operating range, in both fuel flow rate and O/C ratio is significantly larger than in previous models, and is among the widest envelopes ever demonstrated for a dry CPOX reactor on ULSD.

In addition to the reactor optimization, we also demonstrated two improved fuel feed systems for the CPOX reformer. Diesel fuel is very difficult to vaporize without forming deposits, as the final boiling point of the fuel is above the temperature at which the fuel begins to break down and form tars. Protonex demonstrated two fuel feed techniques that can give hundreds of hours between maintenance. One is an innovative vaporizer geometry that provides thorough mixing of the air and fuel prior to the reactor, and the other is a new, very-low-pressure-drop atomizer capable of producing <40 µm droplets with a feed pressure of <2 psi. Conventional atomizers typically require more than 30 psi air pressure to produce such small droplets. This pressure is too high for practical systems, as it would require very large, noisy and power-hungry compressor. With the new atomizer, a very small, low-power compressor can be used.

12-Cell Subscale Bundle Testing. A 12-cell stack was tested as a proof of concept for several design

TABLE 2. Performance of Catalysts B1 and B2 at Different ULSD Feed Rates

	Diesel ml/min	O/C	Wet Reformate Composition (%)							Yield (%)	
			N_2	H_2	CO	CO_2	CH_4	Ar	H_2O	H_2	CO
B1	6.0	1.1	51.2	20.9	23.3	0.75	0.47	0.61	2.8	88	93
B1	5.0	1.1	50.7	21.7	23.7	0.59	0.40	0.61	2.3	92	96
B1	1.0	1.5	56.5	15.8	17.1	3.6	0.42	0.68	6.0	82	84
B2	6.0	1.1	50.6	21.9	23.9	0.50	0.24	0.61	2.2	93	97
B2	5.0	1.1	50.8	21.5	23.8	0.49	0.40	0.61	2.5	91	96
B2	1.0	1.5	57.0	15.9	16.9	4.2	0.05	0.68	5.4	82	83

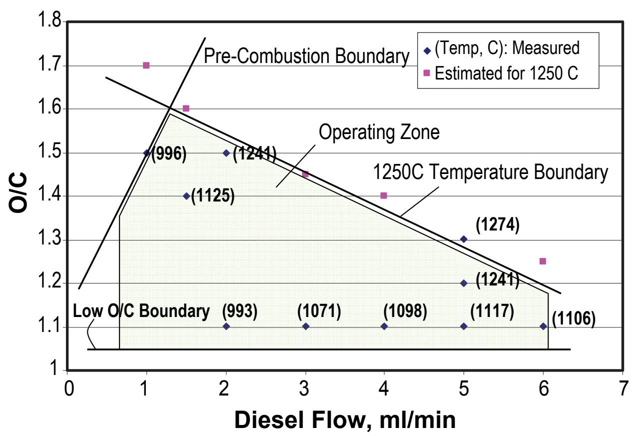

FIGURE 1. O/C vs flow rate which determines the estimated operating window for the B2 catalyst at a feed preheat temperature of about 325°C.

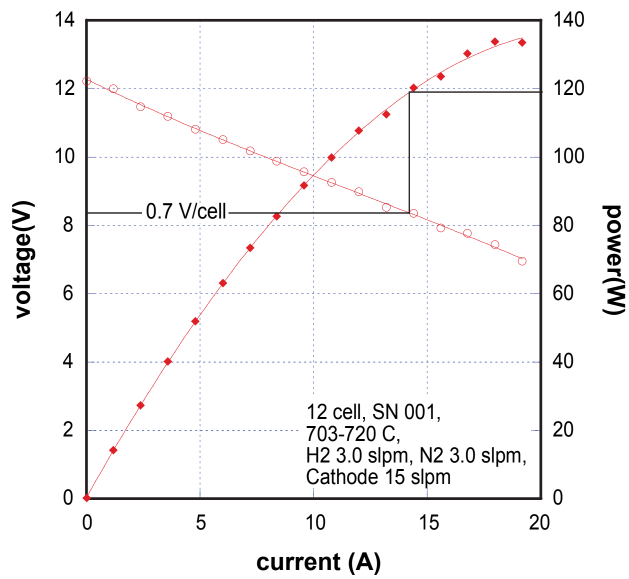

FIGURE 2. Polarization Plot and Power for 12-Scale Bundle

features. The cathode air feed system was redesigned from past generations. Improvements were made to the interconnects and their attachments. This test was the first multiple cell stack to use the Ø10.2 mm diameter tubes. All of these improvements resulted in good performance that will scale-up to meet the power requirements of the full-scale modules. A representative polarization plot is shown in Figure 2. Power at 0.7 V/cell and ~50% fuel utilization is just under our project goal of 10 W/cell. With planned cell and interconnect improvements, we expect to achieve over 10 W/cell in our full-scale stacks.

Subsequent tests, including one on a 3-cell stack that lasted for 180 hours, have provided more concrete evidence on degradation mechanisms within the stack. This data is being used to further develop interconnect designs, fabrication, and assembly techniques that would increase the power margin and potentially reduce performance degradation rates.

CPG is evaluating a high-volume blower for the SOFC APU project. The chosen blower is a low-cost, relatively high efficiency, single-stage blower powered by the inverter 200 to 350 volt DC bus. This blower will not only deliver the cathode air for the four SOFC modules, but also provide the first stage compression for the anode air for the four SOFC modules. Figure 3 and Figure 4 show the performance of the blower at various conditions. The blue line in Figure 3 shows the system requirements of the SOFC system over a range of running conditions. At normal running condition (342 standard liters per minute, SLPM), the blower is working at ~25% efficiency. At maximum running condition (570 SLPM) the blower can attain ~30% efficiency.

System integration continued this quarter with progress towards packaging the four modules and BOP within the desired physical envelope. Figure 5 shows the latest arrangement and outer cosmetics for the SOFC APU.

Conclusions and Future Directions

Conclusions

- CPOX reformation of ULSD can be achieved over the required range of O/C ratios and meets turndown ratio requirements for APU operation.

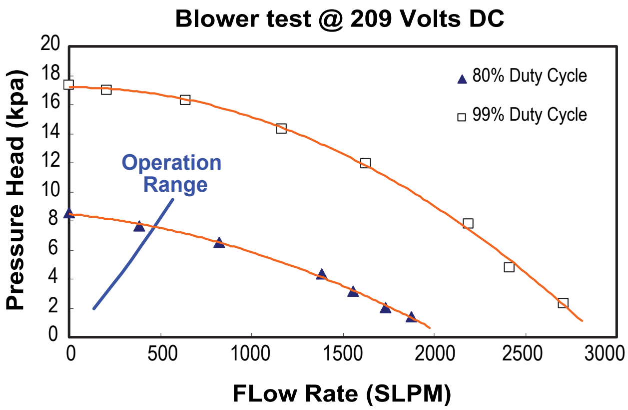

FIGURE 3. Flow vs. Pressure Head for Cathode Air Blower (Operation Range: 136 to 570 SLPM)

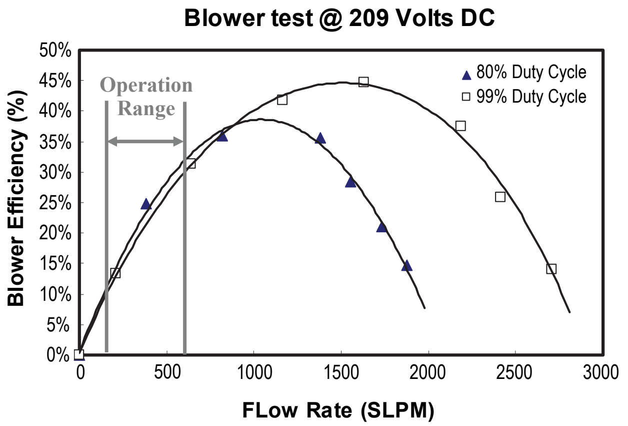

FIGURE 4. Flow vs. Efficiency for Cathode Air Blower (Operation Range: 136 to 570 SLPM)

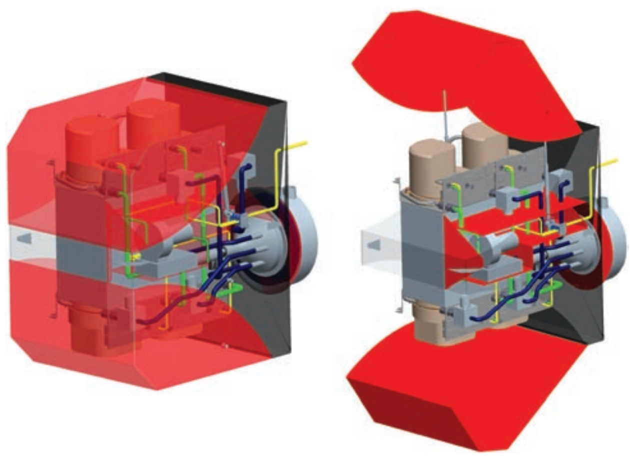

FIGURE 5. Latest SOFC APU Packaging and Integration

- An APU architecture based on modular SOFCs can be packaged within the target metrics for size and weight.· A cathode air blower capable of meeting the requirements for flow and pressure has been identified but further optimization is desirable.
- A hybrid system architecture capable of supporting the identified electrical loads has been conceptualized.

Future Work

- Build and test full-scale bundles and complete 4-module sets for testing.
- Scale atomizer to size for 600 W module.
- Final down-select of atomizer or vaporizer for final build.· Analysis and testing of APU shock and vibration response.
- Design and development of optimized cathode air blower.
- Move to near-net-shape manufacturing of some stack components.