X.4 Demonstration of Fuel Cell Auxiliary Power Unit (APU) to Power Truck Refrigeration Units (TRUs) in Refrigerated Trucks

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Subcontractors:
- Nuvera Fuel Cells, Billerica, MA
- Ballard Power Systems, Burnaby, BC, Canada

Project Start Date: June 1, 2012
Project End Date: September 30, 2018

Overall Objectives

- Demonstrate the viability of fuel cell-based transport refrigeration units (TRUs) for refrigerated Class 8 trailers.
- Assess the performance of the fuel cell-based TRUs by demonstrating these systems with 800–1,000 hours of commercial deliveries.
- Use the demonstration data and market assessment to develop a business case that will determine if lifecycle cost parity can be achieved with incumbent technologies.

Fiscal Year (FY) 2017 Objectives

- Direct subcontract teams led by Nuvera Fuel Cells and Ballard Power Systems as they each develop a fuel cell-based TRU for a refrigerated Class 8 trailer.
- Complete Phase I of the Ballard subcontract team development effort by producing a business case, a safety plan and a preliminary design.
- Complete Phase II of the Nuvera subcontract team development effort by performing an 8-hour integrated laboratory demonstration of the fuel cell system, power electronics, and TRU.

Technical Barriers

This project addresses the following technical barriers from the Market Transformation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

(B) High hydrogen fuel infrastructure capital costs for Polymer Electrolyte Membrane (PEM) fuel cell applications

(C) Inadequate private sector resources available for infrastructure development

(E) A lack of flexible, simple, and proven financing mechanisms

(F) Inadequate user experience for many hydrogen and fuel cell applications

Technical Targets

This project directly addresses the Market Transformation sub-program targets described in Section 3.9.4 of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan by developing a pathway for the introduction of fuel cell technologies into the transport refrigeration unit market. This niche market will increase hydrogen usage, reduce hydrogen cost, and further establish the hydrogen infrastructure at food distribution centers. The project involves the two primary U.S. TRU manufactures, Thermo King and Carrier Transicold. They will be actively involved in overcoming the logistical and other nontechnical challenges associated with implementing this new technology, resulting in a smoother adoption into the marketplace. The project involves demonstrations by two large potential customers, Walmart and WinCo Foods. These companies already use fuel cell-based lift trucks and as a result have experience with hydrogen infrastructure and safety issues. These demonstrations will provide valuable data on the performance of the technology in real-world operations and can be used to benchmark the benefits of the technologies. Both the TRU manufacturers and demonstrators will provide input into the business case to create a clear picture of the value proposition of this new technology.

FY 2017 Accomplishments

- Nuvera integrated the fuel cell system (stack and packaged balance of plant) and power electronics and tested it in a laboratory environment at low power in preparation for the real-world demonstration.
- Thermo King has identified WinCo as a new demonstration partner.
- Zen Clean Energy Solutions developed business case with assistance from Walmart, Carrier, and Ballard.

They developed a preliminary value proposition analysis to determine the tipping point between positive and negative net present values. This value proposition will help determine the conditions when lifecycle cost parity can be achieved with incumbent technologies.

- Ballard developed a preliminary system design and completed the Phase I go/no-go decision.

INTRODUCTION

A TRU is a high-powered air conditioning system used in cooling cold goods during on-road transport. It is generally powered by a separate diesel engine. Replacing this diesel engine with a fuel cell will address recent state and federal environmental mandates to reduce emissions, address noise restrictions found in many urban areas, reduce system maintenance, and improve the overall energy efficiency of the system. The initial market for this application would be food distributions centers where vehicles return to a central facility for refueling and where fuel cell lift trucks have already been established. This market will further expand the hydrogen usage at these sites and increase fuel cell market penetration.

The purpose of this project is to perform two demonstrations of fuel cell-based TRUs using two separate fuel cell teams as shown in Table 1. These demonstrations will provide user experience for over-the-road fuel cell applications that will mitigate commercial risk in developing this new technology.

TABLE 1. Fuel Cell-Based TRU Demonstration Teams

Project Role	Nuvera Team	Ballard Team
Fuel Cell Supplier, System Integrator	Nuvera	Ballard
TRU Supplier	Thermo King	Carrier Transicold
Demonstration Partner	WinCo	Walmart

APPROACH

Each of the two demonstrations will be performed by a team consisting of a fuel cell system supplier and integrator, a TRU system manufacturer, and a demonstration site. Each demonstration will be 800 to 1,000 hours in duration and will consist of actual deliveries of cold goods. During the demonstration, data will be collected from the hydrogen refueling station, fuel cell system, TRU, and the trailer to allow an independent techno-economic analysis and a system evaluation relative to available DOE targets. These results will be used to develop a business case and commercialization plan that can be implemented at the conclusion of the demonstration.

In preparation for these demonstrations, a preliminary business case will be developed and safety and regulatory issues addressed. The system development will include appropriately sizing the fuel cell stack and hardening the system to be comparable in performance and robustness with the incumbent technology. These demonstrations may also require installation or augmentation of the on-site hydrogen infrastructure for refueling.

RESULTS

The Nuvera and Ballard team's progress with the fuel cell-based TRU demonstration projects are described below.

Nuvera Fuel Cell System Development. The Nuvera team completed packaging of the fuel cell system. It will be undermounted on a Class 8 trailer using the frame of an existing Thermo King SGSM 3000 diesel genset. The original components were removed and replaced with the fuel cell stack, balance of plant, and power electronics as shown in Figure 1. In addition to packaging the system hardware, the system controls, software and communication were finalized to allow integration with the Thermo King Precedent C-600 TRU. This particular TRU is a plug-in hybrid system that allows the use of either the diesel generated power or 480 VAC three-phase shore power during operations. As a result, the demonstration of this system requires that the fuel cell direct current (DC) power be converted to alternating current (AC) power to supply the TRU. The system also requires DC power boost convertors to supply DC power at other voltages for components such as the control system, sensors and the air compressor. The power conversions are one of the major challenges of this system integration.

The first integrated demonstration was performed at low power. It included an integrated test with the fuel cell and power electronics modules. The system included DC converters from 112 to 15 and 500 VDC. The DC/AC inverter and TRU were not included in this first integrated demonstration but 2.5 kW of power that would normally be used by the TRU was dissipated with resistors as surrogates. This first low power demonstration was successfully performed and results were as expected.

A follow-on demonstration included the DC/AC inverter and TRU at full power levels. Unfortunately, the fuel cell air compressor and the DC boost converter failed during the first 30 minutes of operation. The air compressor bearings failed and boost converter failed due to a software bug. These issues have been fixed and the diodes within the converter were replaced. To date, the required 8-hour integrated laboratory demonstration that will finalize the Phase II milestone has not been completed.

During this year, the original demonstration partner, H-E-B chose not to continue participation. As a result, Thermo King identified WinCo Foods in Modesto, CA as the new demonstration partner.

FIGURE 1. Photographs of the Nuvera packaged fuel cell system

Ballard Fuel Cell System Development. During FY 2017, the Ballard team completed their Phase I milestone. This milestone included a preliminary design, safety strategy, and market assessment. The preliminary design included system sizing, system balance of plant selection, packaging, and placement of the fuel cell system on the trailer. To perform the system sizing, Ballard and Walmart selected a demonstration site and used power usage and location data to size the fuel cell system and hydrogen tankage. Winter Haven, Florida, was the selected demonstration site to be a bounding case for Walmart distribution centers because of its high summer temperatures and humidity. Analysis of the data collected from 16 TRUs indicated that the Carrier electric hybrid TRUs required a peak power of 18 kW (see Figure 2). The highest hydrogen usage was 19 kg over the course of a 22-hour day, while 83% of the TRUs had less than 10 kg hydrogen consumption per day. Location data indicated that some of the trailers did not return to the distribution center of origin each day and as a result would require refrigeration longer than a single day. As a result of the disparity between the various trailer operations, Ballard and Walmart determined that 20 kg of hydrogen storage would be a reasonable for nearly all of the TRUs at this site.

In addition to system sizing, Ballard used the Winter Haven TRU data to determine if hybridization of the fuel cell is required. Based on the data provided, the system runs at maximum power for many hours and transients are relatively slow. As a result, hybridization would not benefit such a design, therefore batteries are required only for startup. During the design process, the best location of

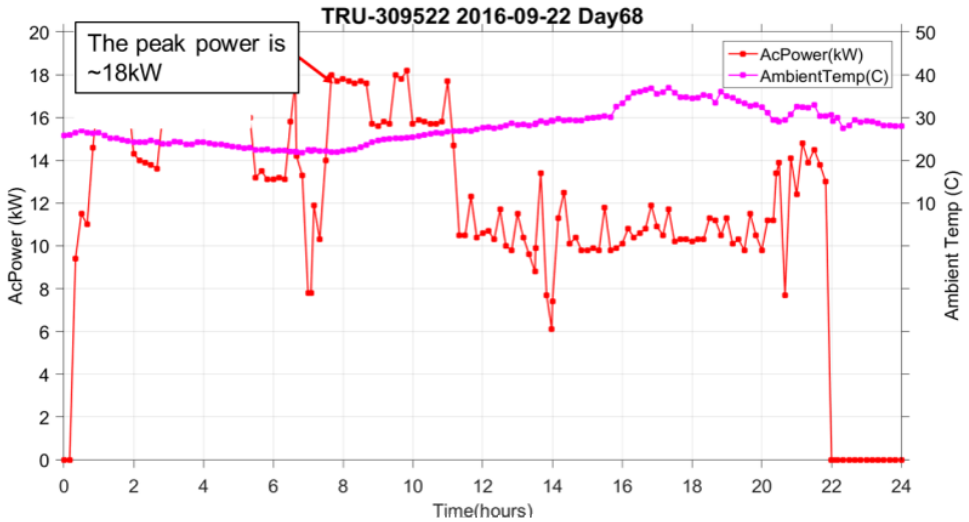

FIGURE 2. AC power required and ambient temperature for bounding TRU at the Winter Haven, Florida, Walmart Distribution Center

the fuel cell system and tankage was determined to be the bottom of the trailer. No other location could be found that would not impact tractor or trailer operations. Although space is available under the trailer, this location does require additional shielding to protect the system from on-road projectiles.

Ballard developed a safety strategy that incorporated input from applicable codes and standards and a Product Potential Hazard Analysis. A risk reduction plan was developed that recommended design approaches and features to mitigate the hazards identified.

Zen Clean Energy Solutions developed a market analysis for the Class 8 trailer TRU. This analysis identified three recent changes that may impact the business case favorably: (1) increased availability of hydrogen at distribution centers with the deployment of fuel cell forklifts; (2) availability of higher-efficiency, all-electric TRUs; and (3) reduction of fuel cell cost. The market analysis estimated the total cost of ownership comparing a diesel-based TRU with a "clean sheet design" fuel cell TRU over a 10-year lifecycle. In this analysis, the cost of fuel and capital cost of the system are the driving factors. Using a cost of $3.27/gallon for diesel fuel and $4.00/kg for hydrogen, the net present value (NPV) comparison of the two systems is -$25,000, or the fuel cell system costs are higher than the incumbent technology. Table 2 compares the NPV difference between a fuel cell and a diesel system. The green highlighted cells are where this difference is positive and the fuel cell system has economic benefits over the incumbent technology.

The fuel cell system capital cost has been estimated at nearly twice that of the diesel engine. It is not only the fuel cell itself that drives this increased cost, but also the tankage required for storage of 20 kg of hydrogen and the power electronics, including DC/DC and DC/AC conversion. These non-fuel cell items make up more than half of the total capital cost of the system (58%). As a result, additional cost reduction research should be done not only on the fuel cell but on the tanks and power electronics as well.

Another challenge identified with the fuel cell system is that it is much heavier than conventional technology. With the weight of the 20 kg hydrogen tanks, fuel cell system, and the shielding needed to protect the system on the undercarriage of the trailer, it is more than 1,000 lb greater than a typical TRU. Due to weight constraints on the Walmart trailers, this additional weight results in an equal amount of product that cannot be shipped. This loss of capacity was a significant concern for Walmart.

A final challenge is the expiration of the federal Business Energy Investment Tax Credit for fuel cells that expired in December 2016. This tax credit provided 30% tax credit to offset the cost of using a fuel cell option.

As a result of the negative estimated NPV lifecycle cost comparison to the diesel engine TRU, the loss of carrying capacity, and the less favorable federal incentives, the Ballard team (including Walmart and Carrier) decided to not continue the project into Phase II. This team will not build a fuel cell TRU nor perform their originally planned demonstration. Instead, they will write a final report and close out the subcontract.

CONCLUSIONS AND UPCOMING ACTIVITIES

The development and demonstration of a fuel cell auxiliary power system for Class 8 refrigerated trailers is a first step in expanding fuel cell use to TRUs. This demonstration will increase fuel cell market penetration and further break down technical and nontechnical barriers to hydrogen and fuel cell use.

During FY 2017 the Nuvera team packaged and tested the integrated fuel cell system in the laboratory at low power and attempted testing at high power. In FY 2018,

TABLE 2. Impact of Diesel and Hydrogen Fuel Costs on NPV Difference between Fuel Cell and Incumbent TRU Technology

		Hydrogen Cost ($/kg)						
		$ 2.00	$ 3.00	$ 4.00	$ 5.00	$ 6.00	$ 7.00	$ 8.00
Diesel Cost ($/gallon)	$ 2.00	$ (15,925)	$ (31,286)	$ (46,648)	$ (62,009)	$ (77,371)	$ (92,732)	$ (108,093)
	$ 3.00	$ 973	$ (14,389)	$ (29,750)	$ (45,112)	$ (60,473)	$ (75,834)	$ (91,196)
	$ 4.00	$ 17,870	$ 2,509	$ (12,853)	$ (28,214)	$ (43,575)	$ (58,937)	$ (74,298)
	$ 5.00	$ 34,768	$ 19,406	$ 4,045	$ (11,316)	$ (26,678)	$ (42,039)	$ (57,401)
	$ 6.00	$ 51,665	$ 36,304	$ 20,942	$ 5,581	$ (9,780)	$ (25,142)	$ (40,503)
	$ 7.00	$ 68,563	$ 53,201	$ 37,840	$ 22,479	$ 7,117	$ (8,244)	$ (23,606)
	$ 8.00	$ 85,460	$ 70,099	$ 54,738	$ 39,376	$ 24,015	$ 8,653	$ (6,708)
	$ 9.00	$ 102,358	$ 86,997	$ 71,635	$ 56,274	$ 40,912	$ 25,551	$ 10,189
	$ 10.00	$ 119,256	$ 103,894	$ 88,533	$ 73,171	$ 57,810	$ 42,448	$ 27,087

Nuvera will finalize Phase II by performing the 8-hour laboratory demonstration at high power with the fuel cell system integrated with the TRU. They will then upgrade the system for on-road operations by installing a stack cover and redesigned external enclosure for on-road projectiles. They will also improve component connections for the higher-than-anticipated levels of vibration. The Nuvera team can then move to Phase III where they will perform the on-road demonstration with WinCo as their new demonstration partner.

Work performed by the Ballard team this fiscal year includes the development of a preliminary design based on TRU data at the Walmart distribution center at Winter Haven, Florida, a safety plan, and a market assessment. The market assessment was not considered favorable enough for the Ballard team to continue into Phase II. As a result, the team will not develop the fuel cell system, integrate it with the TRU, or perform the demonstration. Instead, Ballard will complete its final reports and conclude this work in the upcoming months.