Field Validation and Demonstration of Zero-NO_x Emission Hydrogen Bus and Fueling Infrastructure

Task 3 Report

Hydrogen Fuel Cell Hybrid-Electric Bus Preparation

for:

New Technology Research and Development Program

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Submitted by:

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Table of Contents

Table of Figures

Abstract/Executive Summary

The following report is provided to TCEQ by The University of Texas at Austin Center for Electromechanics (UT-CEM) to complete Task 3 of their NTRD project. Task 3 includes preparations of the hydrogen fuel cell hybrid-electric bus for the validation project. Under this task, UT-CEM, along with project partners, has ensured the bus, personnel, and support materials are ready for the demonstration. The team has installed the electrical charger, completed the bus wrap, and provided operation and maintenance manuals to Capital Metro staff.

The overall project will demonstrate two fuel cell technologies, both of which will advance the commercial viability of hydrogen transportation in the next few years and are critical to zero NO_x emissions vehicles. Texas can move to the forefront in commercializing and deploying zero emissions vehicle technologies, creating the foundation for a robust hydrogen economy. Two developed technologies to be demonstrated in this validation project are:

- A “ready for the road”, commercially available heavy-duty hydrogen fuel cell plug-in hybrid transit bus combining the clean energies of hydrogen and electric propulsion, and
- A cost competitive and commercially available hydrogen fueling station that is being commercialized and supported by Texas-based GreenField, an Atlas-Copco Brand.

Under Task 3, UT-CEM and project partners, have completed the necessary steps for addressing the first of these two enabling technologies, the hydrogen hybrid bus. The bus arrived in Austin in March 2012 and has undergone final inspections and training with operators and Capital Metro staff. The demonstration period is scheduled to begin in June 2012.

Introduction/Background

There has been significant progress over the past few years in developing more reliable and customer-friendly fuel cell vehicles and the infrastructure to support them. This proposal outlines a project that will demonstrate two such technologies, both of which will advance the commercial viability of hydrogen transportation in the next few years. As a continuation of a previous TCEQ-funded project and in collaboration with the US Department of Transportation's Federal Transit Administration (FTA) National Fuel Cell Bus Program (NFCBP), along with other state and federal agencies, the project partners will demonstrate a turnkey, self-contained, skid-mounted hydrogen fueling station (Figure 1) and an advanced, zero-emissions fuel cell hybrid electric transit bus (Figure 2) that will be operated in Austin, Texas, by Capital Metro for at least one year. The potential for this important national vehicle demonstration program to come to Texas has been made possible only by the ongoing support of the TCEQ and other forward-looking state organizations.

Figure 1. Hydrogen fueling station located at UT-CEM's facility at Pickle Research Campus for the validation project.

Figure 2. Hydrogen fuel cell plug-in hybrid transit bus for the validation project.

While well-publicized financial challenges have slowed fuel cell vehicle development by one or two domestic passenger vehicle original engine manufacturers (OEM), others have continued to develop

vehicles and set market launch projections for full-scale commercialization. For example, government leaders in Europe, Japan, China, Singapore, some US states, the US Department of Defense and the US Department of Transportation have maintained (and in some cases accelerated) research funding for hydrogen technologies. The number of commercial-ready products in the area of buses and industrial trucks (i.e. forklifts) has grown in recent years. There are contracts for over 300 hydrogen fuel cell forklifts to be deployed in Texas in the next two years. Deployment of fuel cell transportation demonstration projects continues to be supported by several state and federal initiatives and increasingly by private industry.

Texas can move to the forefront in commercializing and deploying zero emissions vehicle technologies, creating the foundation for a robust hydrogen economy. Two developed technologies critical to zero NO_x emissions vehicles will be demonstrated in this Field Validation program to further establish viability for full commercial acceptance:

- A "ready for the road", commercially available heavy-duty hydrogen fuel cell plug-in hybrid transit bus combining the clean energies of hydrogen and electric propulsion, and
- A cost competitive and commercially available hydrogen fueling station that is being commercialized and supported by Texas-based GreenField, an Atlas-Copco Brand.

This project addresses two immediate needs for lowering emissions in Texas non-attainment and near-non-attainment areas:

- Ultra-low or zero emissions vehicle platforms have not been commercially available for "real" working applications for heavy duty vehicles. Existing vehicles have typically been prototypes that are "test" vehicles not intended for public use. This project will put a zero-emissions bus in regular service with a transit agency to demonstrate that zero-emissions vehicles can and are being used in "real" operating conditions.
- Fueling supply infrastructure is unavailable, making the availability of vehicles irrelevant. This project demonstrates that the existing natural gas supply network can be leveraged to supply hydrogen for zero-emissions vehicles.

Mass transit has long been a transportation option that reduces energy usage and air pollution compared to private automobiles. Transit agencies are on the threshold of revolutionary change.

Transit agencies must find new, more environmentally responsive solutions for expanding their service. In an effort to reduce emissions, transit agencies in Texas are adopting electric rail, compressed natural gas (CNG) buses, liquefied natural gas (LNG) buses, and propane-fueled vehicles as alternatives to diesel. A growing number of transit agencies across the nation are moving toward zero-emission bus technologies for their urban circulator routes. All-electric vehicles are still cost-prohibitive due to the initial vehicle cost, maintenance cost, and the cost associated with the needed on-route electrical charging infrastructure due to limited range capabilities. A potentially lower cost alternative, offered here, is an electric hybrid merging the benefits of electric battery propulsion with the range extension of hydrogen proton exchange membrane (PEM) fuel cells.

This field validation project will help establish full commercial acceptance of a reliable, fuel efficient battery dominant, hydrogen fuel cell transit bus along with its cost-effective, efficient, and reliable onsite

hydrogen fueling station. The program team and partners have come together to demonstrate and promote the future of feasible and cost effective hydrogen transportation technologies.

Escalating petroleum prices and growing concerns with energy security, public health and global climate changes are accelerating technological innovation to continue economic growth while fulfilling environmental stewardship goals. Transportation contributes 27% of the US greenhouse gas emissions (EPA, Greenhouse Gas Emissions from U.S. Transportation, 1990-2003) while diesel exhaust is suspected to be the driving factor in rising childhood asthma and other respiratory complications and cancer. Moving toward a transit agency fleet-wide transition to zero NO_x emission and low greenhouse gas emission vehicle technologies will improve urban air quality.

This zero emission bus combines a lightweight composite chassis with a unique propulsion prime mover approach consisting of two 16 kilowatt (kW) hydrogen PEM fuel cells and 54 kilowatt-hours (kWh) energy storage from advanced Lithium Titanante batteries. The onboard batteries are charged overnight from the grid. This novel vehicle architecture provides a range of 300 miles with a documented fuel economy of about 10 miles per gallon (diesel energy equivalent) which is well over a doubling of fuel efficiency compared to commercial diesel transit buses.

It achieves this high efficiency while also meeting or exceeding performance (e.g. acceleration, gradeability, range, braking distance, etc.) of its diesel counterparts, and emitting no tailpipe pollutants thereby exceeding the 2010 heavy-duty bus emissions standards.

Also, this field validation will further demonstrate and validate increased collective hydrogen fuel cell stack life, reduced fuel cell stack replacement costs, lower operating costs, and increased reliability as well as ‘in service’ transit performance of a fuel cell powered vehicle.

Project Objectives/Technical Approach

With its partners in agreement, UT-CEM will increase the hydrogen fuel capacity of an integrated, self-contained, on-site hydrogen generation and fueling station to provide sufficient fueling infrastructure for an advanced hydrogen fuel cell hybrid-electric bus. UT-CEM will contract with the Gas Technology Institute (GTI) to increase the hydrogen fuel capacity of the hydrogen generation and fueling station, complete necessary enhancements for it, and maintain it. The hydrogen generation and fueling station will be located at the University of Texas at Austin's Pickle Research Campus. The Center for Transportation and the Environment (CTE), a partner in agreement with UT-CEM under a Memorandum of Agreement (MOA), is a grant recipient for the FTA’s NFCBP. Under the NFCBP grant, CTE contracted with Proterra, Inc. (Proterra) to build the fuel cell bus to be demonstrated under the grant. Using NFCBP grant funds, CTE will coordinate the use of the Proterra bus and will contract with Proterra for on-site labor support and spare parts for non-routine maintenance of the Proterra bus. The Capital Metropolitan Transportation Authority (Capital Metro), a partner in agreement with UT-CEM under a MOA, will operate the Proterra bus on a passenger service route in Austin, Texas, and perform routine bus maintenance. UT-CEM will ensure that data is collected and evaluated to better understand the Proterra bus’s and the hydrogen fueling station’s operating efficiency, reliability, performance, and maintenance requirements in order to further establish commercial viability.

The objectives for this work are:

- Twelve month demonstration of an advanced hydrogen fuel cell hybrid-electric bus on a public route to validate that the bus can support normal transit operations, and
- Demonstration of an integrated, self-contained, on-site hydrogen generation and fueling station in support of a hydrogen fuel cell bus in normal transit operations.

Tasks

The validation project consists of six tasks, as stated in the Grant Activities (Scope of Work). The first two tasks included upgrades to the hydrogen station and its preparation for the demonstration. Tasks 3 and 4 focus on the bus preparation and training of Capital Metro staff. The demonstration phase occurs in the fifth task where performance data for the bus and fueling station is collected and analyzed. The final task includes monthly reports and a final report deliverable to TCEQ. The project timeline consists of 24 months, ending in May 2013. The demonstration phase occurs over the last 12 months of the project.

For completeness, all tasks from the Grant Activities (Scope of Work) are shown in the following sections; however, this report deliverable focuses on Task 3, which was completed in May 2012.

Task 1: Hydrogen fueling station preparations

From the Grant Activities (Scope of Work), Amendment 03:

> *"2.1. Task Statement: The PERFORMING PARTY will contract with the Gas Technology Institute (GTI) to prepare the hydrogen fueling station and increase its hydrogen fuel capacity for use with the demonstration Proterra bus."*

Under this task, UT-CEM and GTI will perform upgrades to the hydrogen fueling station on the Pickle Research Campus and prepare it for the demonstration where it will be used to refuel the hydrogen hybrid bus operated by Capital Metro. A major part of this upgrade is the installation of additional storage capacity needed to refuel the bus. Other activities include upgrading cooling and exhaust systems and providing a back-up supply of hydrogen. This task will be completed in June 2012 with a report to follow in July 2012.

Task 2: Prepare hydrogen fuel station and staff for demonstration

From the Grant Activities (Scope of Work), Amendment 03:

> *"2.2. Task Statement: The PERFORMING PARTY will prepare the station operations and maintenance manual, train staff in operation of the station, and arrange for station maintenance during the demonstration."*

Under this task, UT-CEM and GTI will provide operations and maintenance manuals for the hydrogen refueling station on the Pickle Research Campus and train Capital Metro and on-site staff in fueling the

bus and maintaining the station. An additional component of the training that will be provided is to educate first responders on the use, design, and safety features of the fueling station. This task will be completed in June 2012 with a report to follow in July 2012.

Task 3: Hydrogen fuel cell hybrid-electric bus preparation

From the Grant Activities (Scope of Work), Amendment 03:

> *" 2.3. Task Statement: The PERFORMING PARTY will ensure that the Proterra bus, Capital Metro personnel, and support materials are prepared for the demonstration."*

Under this task, UT-CEM worked with Proterra and Capital Metro in preparing the bus and all support materials for the demonstration. This included the installation of the bus overnight electrical charger, as well as preparation of operator and maintenance manuals and spare parts inventory list. This task was complete in May 2012, and this deliverable report discusses below the accomplishment of this task.

Task 3.1

From the Grant Activities (Scope of Work), Amendment 03:

> *" 2.3.1. The PERFORMING PARTY and CTE will install the bus's overnight electrical charger at Capital Metro's facilities, and complete an operational check-out of the charger."*

The overnight electrical charger for the bus was installed in July 2011 at Capital Metro's North Operations Facilities near the Pickle Research Campus. Figure 1 shows the charger installation. Part of the installation included an electrical meter on the input of the charger. This meter will be monitored to track electrical energy consumption during the demonstration.

Figure 3. Installed overnight electrical charger Capital Metro's facilities including an electrical meter.

Operational checkout of the charger was completed on May 28, 2012, after Proterra completed software upgrades that were necessary to recharge the batteries on the bus. The batteries were connected to the charger at 44% state-of-charge (SOC) and were recharged overnight to 95% SOC. The electrical energy consumption during this charging event was 28 kilowatt-hours.

Task 3.2

From the Grant Activities (Scope of Work), Amendment 03:

> *" 2.3.2. The PERFORMING PARTY and CTE will coordinate with the bus manufacturer's, Proterra, personnel on a bus operations and maintenance manual and spare parts inventory to ensure adequate bus maintenance during the demonstration."*

With delivery of the bus in March 2011, Proterra and CTE provided operations and maintenance manuals for the bus. These manuals were submitted at the time of this report to TCEQ but are not provided as attachments to this report due to their length. Also provided were relevant spare parts for routine bus maintenance during the demonstration (Appendix A). Routine bus maintenance that will be handled by Capital Metro staff includes all systems that are typical of conventional diesel engine buses. This includes lights, brakes, steering, and coolant, among others. All maintenance of high-voltage and hydrogen systems will be done by Proterra during the demonstration.

Figure 4. The Proterra hydrogen hybrid bus at Capital Metro's North Operations Facilities in Austin, Texas.

Task 3.3

From the Grant Activities (Scope of Work), Amendment 03:

> *" 2.3.3. Schedule: The PERFORMING PARTY shall complete this task within 12 months of the signed Notice to Proceed Date as issued by TCEQ."*

This task was completed in May 2012, which is 12 months after the TCEQ signed Notice to Proceed Date of May 26, 2011.

Task 3.4

From the Grant Activities (Scope of Work), Amendment 03:

> *" 2.3.4. Deliverables: The PERFORMING PARTY shall submit a report to the TCEQ upon completion of this task. This report will include but is not limited to documentation, including pictures, of the operational overnight charger and installed bus wrap, as well as a copy of the bus operations and maintenance manual and spare parts inventory agreed on between CTE and Proterra."*

This report satisfies the report deliverable for Task 3.

Task 4: Complete bus pre-service trials and general operation and maintenance training

From the Grant Activities (Scope of Work), Amendment 03:

"2.4. Task Statement: The PERFORMING PARTY will complete pre-service trials with the Proterra bus and ensure that all Capital Metro personnel are trained in the bus's operation and maintenance."

Under this task, UT-CEM will ensure that Capital Metro is provided with bus operational and maintenance manuals and are adequately trained on the operation of the bus prior to the demonstration. In addition, UT-CEM will oversee pre-service trials of the bus which will aid in the selection of bus routes for the demonstration. This task was completed in May 2012 and will be detailed in a separate report in June 2012.

Task 5: Proterra bus and fueling station demonstration

From the Grant Activities (Scope of Work), Amendment 03:

"2.5. Task Statement: The PERFORMING PARTY will operate the hydrogen fuel cell hybrid-electric bus in a realistic working environment over a twelve month period, including using the hydrogen generation and fueling station as the bus's primary fuel source."

Under this task, UT-CEM and project partners will operate the bus and fueling station for 12 months. The bus will be operated by Capital Metro as part of their UT Shuttle passenger service. Capital Metro operators will refuel the bus using the Pickle Research Campus hydrogen fueling station. During the demonstration, UT-CEM will collect data to assess the performance of the fueling station and the bus. This task will be completed in May 2013.

Task 6: Reporting

From the Grant Activities (Scope of Work), Amendment 03:

"2.6. Task statement: The PERFORMING PARTY will prepare and submit monthly detailed project reports and a comprehensive final report while ensuring compliance with all TCEQ program requirements"

Under this task, UT-CEM will submit monthly progress reports and billing statements to TCEQ. The monthly reports are on-going. Upon completion of the project, UT-CEM will submit a final project report summarizing the results of the project. All reports are to be submitted on time and within budget per NTRD program requirements. The final report will be completed following the end of the project in May 2013.

Discussion/Observations

Objectives vs. Results

Accomplishment of Task 3 was the first step towards meeting the project's first goal of demonstrating a hydrogen hybrid fuel cell bus in Austin, Texas. Delivery of the bus included all relevant manuals and

maintenance items needed by Capital Metro to complete the 12-month demonstration. The electrical charger is also in place, which will provide increased fuel economy during the demonstration by allowing the bus to begin a day's operation on electrical power for the first part of the route.

Delivery of the bus was delayed multiple times during the project and caused the team to amend the Grant Activities (Scope of Work) twice to realign task deliverables.

Critical issues

Several issues caused delays in delivery of the bus. They are summarized below.

Transmission

The original bus transmission was not suitable for a 12-month demonstration. It required servicing/rebuilding every 1500-2000 miles. Proterra worked with Borg-Warner to develop a new transmission that was suitable for their entire line of buses. Converting their buses to the new transmission was problematic and took several months and caused delays in delivering the bus.

DC/DC Converters

The two DC/DC converters, which provide the power interface between the fuel cells and the batteries, are undersized in regards to thermal heat rejection. The space allocated for the converters within the bus did not allow for an adequately sized converter that could remove heat generated during operation. The solution was to limit the power output of the converters as their temperature approached thermal limits. In practical terms, this means that at ambient temperatures above 87 Fahrenheit, the output of the fuel cells through the DC/DC converters begins to be derated. Rather than a total output of 32 kW, the DC/DC converters provide only 29 kW of power to the batteries.

Electrical Noise

Another intermittent problem with the bus has been electrical noise from the traction motor. This was part of the issue with early transmission problems, although not the only issue with the transmission upgrade. A separate electrical noise isolation device was used to help mitigate the noise seen by the transmission controller. This problem is unique to the Austin demonstration bus since it uses an earlier version of the traction motor. Proterra's newer buses use a newer generation motor with improved shielding.

Technical and commercial viability of the proposed approach

The accomplishment of Task 3 has not shown any large technical barriers that cannot be overcome and would limit commercial viability of the hydrogen hybrid bus. The transmission and electrical noise issues identified in the previous section have either been identified and correct by Proterra. The one outstanding item is the DC/DC converter. An alternative DC/DC converter design has been developed which would not see the same thermal limitations; however, it is too large to fit in the currently available space on the Austin demonstration bus. A next generation bus design should be able to rework the layout of the bus to allow integration of the larger converters. Depending on the success of the Austin demonstration and the ability of the current DC/DC converters to perform well, the research team may install the new converters

on the bus, in an alternative location, to assess their viability. The alternative location may be an isolated compartment within the passenger area of the bus. This is not an ideal location as it presents technical and safety concerns, and the team will evaluate all other alternatives if this upgrade is needed.

Scope for future work

Future work related to Task 3, preparation of the bus for the demonstration, would include upgrading the DC/DC converters as discussed in the previous section. Another upgrade would include the use of a newer generation motor with improved EMI shielding to reduce electrical noise. A future proposed project using FTA funds, would also double the size of the fuel cell modules by replacing the two 16 kW units with two 32 kW units. Hydrogenics, the fuel cell manufacturer, has made recent advancements in their packaging and can now provide a 32 kW fuel cell module in nearly the same footprint as the 16 kW modules currently on the bus. The upgrade in fuel cell power would allow the bus to operate for longer periods of time at higher average speeds.

Intellectual Properties/Publications/Presentations

Proterra and GTI have both previously filed patents on their technologies prior to this project. No new IP has been generated during the project.

Summary/Conclusions

This report completes Task 3 of the Grant Activities SOW. The hydrogen hybrid fuel cell bus has been in Austin since March 2012 and has been prepared for the demonstration. Preparations include installation of the overnight electrical charger, as well as documentation and parts needed to maintain the bus during the demonstration. The next task under the SOW will include operator training and bus pre-service trials prior to beginning the 12-month demonstration.

Completion of this task marks the first step in achieving a twelve month demonstration of an advanced hydrogen fuel cell hybrid-electric bus on a public route to validate that the bus can support normal transit operations.

Acknowledgements

UT-CEM would like to acknowledge the following project partners:

- Gas Technology Institute - hydrogen station implementation
- Capital Metro Transit Authority - in-service passenger demonstration
- Proterra, Inc - bus manufacturer
- Federal Transit Administration - funding source through the National Fuel Cell Bus Program
- Center for Transportation and the Environment - program management under the FTA funding

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Appendices

Appendix A: Spare Parts Inventory

Quantity	Description
1	142 pc. Crescent tool case
4	JKS-50 Limitron Fuses / ProT # 3430
3	JKS-60 Limitron Fuses / Prot # 3428
2	Tyco Elect P/N EV200AAANA / ProT # 274
1	9005 Headlamp Lo / NAPA
1	9006 Headlamp Hi / NAPA
1	tif TIF8800 Combustible Gas Detector w/Charger
1	NAPA Solder & Seal Assortment P/N 770767
3	SEW Eurodrive MDX60B/61B Opers Manual
1	JKS-20 Limitron Fuses / ProT # 3431
2	Shawmut CNN150 fuse / ProT # 3545
10	Coopere Bussmann LP-CC-3 amp Fusses / ProT # 2584
3	AmpTrap 20amp/600vac fuses ATQR20 / ProT # 6757
10	FERRaz Shwmut 20A/600vac fuses ATMR20 / ProT # 6757
1	Toggle switch on/off
Misc	Deutsch 2 position connectors/ pins/seals/locks
Assort	Resistors
5	NAPA ATC-5 amp fuses
2	15amp 32v glass fuses
3	Dash indicator lamps
1	Set pos/neg clamps
assort	Deutsch connectors/ pins/seals/locks/ pin remover tool
assort	Nuts/Bolts/Screws and air chuck for bus

1	Hacksaw
6	Ferraz Shawmut 200amp 500V p/n A50QS200-4 / ProT #901
1	12vdc air pump w/plug for 12vdc system connect Clamp
1	MUX2-B Siemens VDC-78052 VS-Villingen
1	Small Bottle Fab Bubble Indicator 8oz
1	DeWalt 1/2 cordless drill w/charger one battery
1	Paladin Tool CrimpAll (orange color)
1	Klein Tool wire cutter and striper
1	Klein Tool neddlenose pliers
2	Klein Screwdrivers
1	Green Screwdriver
1	10" Husky adjustable wrench
1	Safety Glasses
1	dill and tap set 13pc Magna (red Box)
1	7 pc Husky Nutdriver set
1	Box cutter (black & gray)
1	Special ratchet wrench for inserts
1	small black flashlight
2	Small screwdrivers
1	Wireless remote mic Radio Shack
1	Registration papers
1	10" Eee computer
1	set of speakers for computer