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

Task 4 Report

Bus Pre-Service Trials and General Operation and Maintenance Training

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 4 of their NTRD project. Task 4 includes pre-service trials and operator and maintenance training for the bus. Under this task, UT-CEM, along with project partners, has ensured all Capital Metro operators, fuelers, and maintenance personnel have been trained. Education and training was also provided to first responders that would respond to an incident along the chose route. In addition, the bus has undergone pre-service trials and testing. Validation of computer models was also performed to predict the buses ability to meet the duties of the selected route.

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 4, UT-CEM and project partners, have trained personnel and first responders on the first of these two technologies, the hydrogen hybrid bus. The bus arrived in Austin in March 2012, pre-service trials have been completed, and all personnel have been trained. The bus is scheduled to begin service 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 Transporation (DOT) 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 DOT 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 U.S. 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 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 Federal Transit Administration’s National Fuel Cell Bus Program (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 a separate report deliverable will be submitted in June 2012.

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 ensured that Capital Metro was provided with bus operational and maintenance manuals and was adequately trained on the operation of the bus prior to the demonstration. In addition, UT-CEM oversaw pre-service trials of the bus which aided the selection of bus routes for the demonstration. This task was complete in May 2012, and this deliverable report discusses below the accomplishment of this task.

Task 4.1

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

> *" 2.4.1. The PERFORMING PARTY will complete pre-service trials to verify that the Proterra bus can satisfy route trip times and route range on the planned demonstration routes."*

The bus arrived in Austin on March 12, 2012, with 6521 miles. As of the end of May 2012, pre-service trials and training sessions have accumulated 620 miles on the bus. The bus was operated on several candidate routes during the trials. These included the UT Shuttle routes known as Lake Austin (LA), Red River (RR), Forty Acres (FA), and Intramural Fields (IF). Currently, Capital Metro plans to begin operating the bus on the IF and FA routes during the Summer of 2012. The IF route schedule includes a trip per route which only lasts 4 hours between 7:00AM and 11:00AM. Capital Metro plans to begin

passenger service with the fuel cell bus on this route due to its limited duty cycle before placing it on a more demanding route.

Data was collected by UT-CEM from the bus on the selected routes to determine the bus's ability to complete the route. During the pre-service trials, UT-CEM saw some issues with the operation of both fuel cells on the bus. There were times when only one fuel cell was operational; however during these periods, the bus was able to complete 3-4 hours of operation on the single fuel cell. At times when both fuel cells were operational, the bus was able to easily complete 5-6 hours of operation. The limiting factor with only one fuel cell is the ability to recharge the batteries and extend their range. The bus becomes range limited with only one fuel cell because the battery state-of-charge falls too low. This occurs even though the hydrogen storage tanks are not empty.

The data from the pre-service trials was also used to validate computer models of the bus developed by UT-CEM. These models were then run to predict the ability of the bus to operate a full day on the chosen routes. The analysis shows that with two fuel cells in operation, the bus can achieve a full shift operation on any of the chosen routes. However, with only one fuel cell operating, the routes should be limited to 4 hours or less. The figures below show how the computer models match the energy consumption from the bus. Overall accuracy is within 5%.

Figure 3: Fuel cell and battery energy consumption comparison of actual bus data and simulation results.

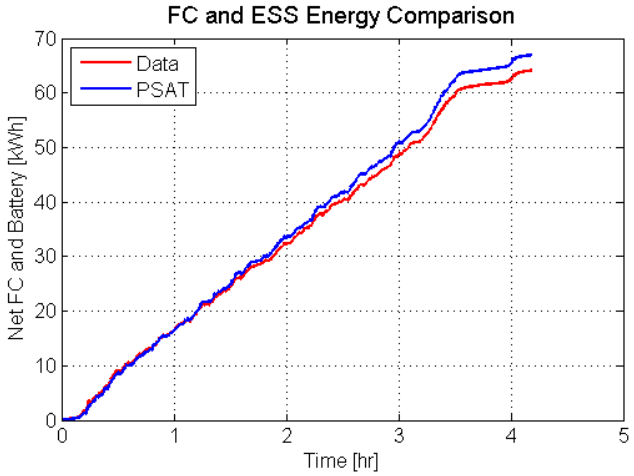


Figure 4: Bus data and computer simulation comparison of battery state-of-charge and energy.

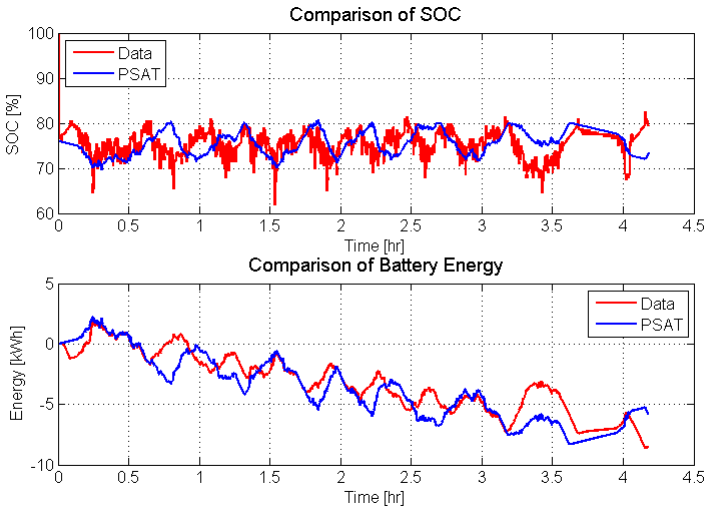


Figure 5: Fuel cell output power comparison between bus data and computer simulation.

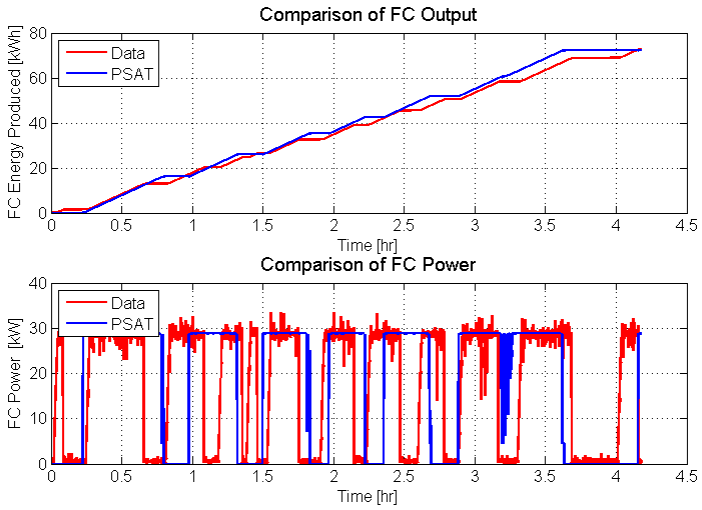
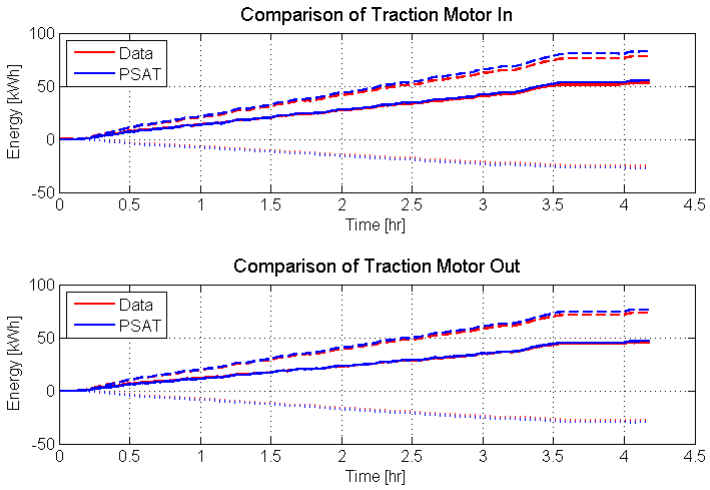


Figure 6: Traction motor power comparison between bus data and computer simulation.



Task 4.2

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

> *" 2.4.2. The PERFORMING PARTY will review and update the bus operations and maintenance manual and provide copies of manual to Capital Metro personnel."*

The maintenance and operator's manuals were updated by Proterra, the bus manufacturer, prior to delivery of the bus in March 2012. UT-CEM reviewed the manuals and saw that they were delivered to Capital Metro personnel. The manual provided the basis of the training for Capital Metro operators, fuelers, and maintenance personnel. Copies of the manuals will be submitted with this report as separate attachments but are not included in the appendix due to their length.

Task 4.3

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

> *" 2.4.3. The PERFORMING PARTY will provide at least 2-3 bus operation and maintenance trainings for project personnel involved in the bus operation and maintenance as well as for local emergency response officials."*

Throughout the month of May, UT-CEM and project partners conducted several training sessions for Capital Metro staff and emergency first responders. Drivers received a 4 hour bus introduction and basic operational training followed by 6-8 hours of on-road driving. The on-road driver training was overseen by Louis Fernandez with Signature Transportation, and the focus of the training was to teach the drivers how to drive the bus more efficiently.

Maintenance training was also provided to Capital Metro staff. In general, Capital Metro staff are not required to repair or maintain the fuel cell or high voltage systems. They were trained in hydrogen venting procedures for any situation in which the bus would need to be garaged and hydrogen needed to be removed from the storage tanks.

Additional training was provided to the Capital Metro fuelers who are responsible for refueling the bus each day. They were given an abbreviated version of the driver training class since they will need to drive the bus to the Pickle Research Campus for daily refueling. Figure 7 shows one of the fuelers receiving training at the hydrogen fueling station on the Pickle Research Campus.

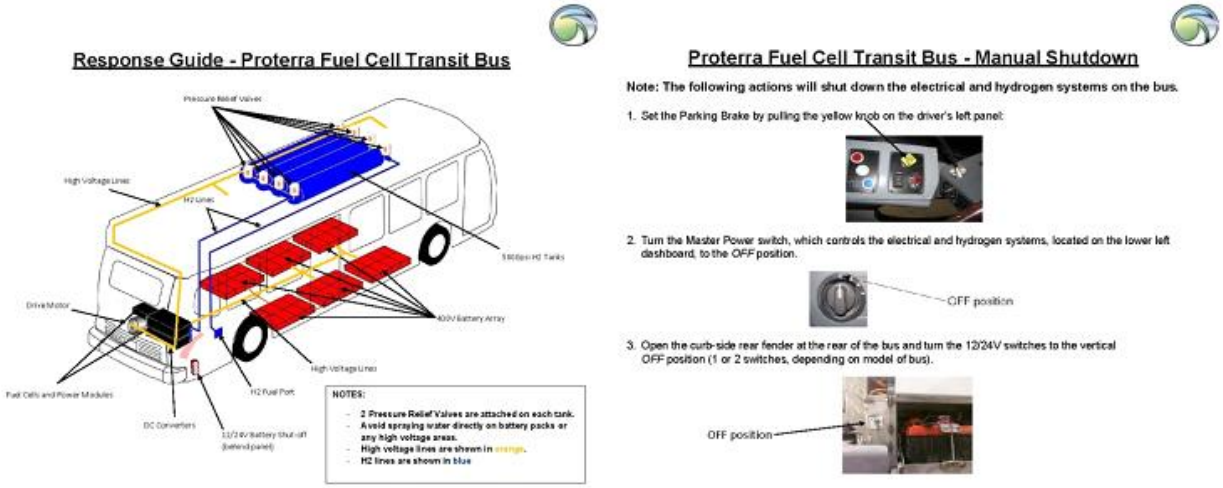
Figure 7. Capital Metro bus operator training at fueling station.

Six separate training sessions were also provided for emergency first responders such as the Austin Fire Department and EMS crews. These training sessions were held at Fire Station #3 near the UT Main Campus, as well as at Capital Metro's North Operational Facilities. Battalions all along the intended routes were called in for training, since the bus could potentially have an emergency anywhere along its route. Figure 8 shows the first responder training at Fire Station #3.

Figure 8. Emergency first responder bus training at Fire Station #3 near UT's main campus.

Provided during training to both Capital Metro staff and emergency first responders wasa quick reference card, Figure 9. The card outlines emergency shutdown procedures and shows the location of hazards, such as high voltage and hydrogen. One of these cards has been placed within each emergency first responder vehicle along the route.

Figure 9. First responder quick-reference card.



Task 4.4

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

> *"2.4.4. 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 4.5

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

> *" 2.4.5. 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 of bus performance in pre-service trials, a copy of the updated bus manual, and documentation of the bus operation and maintenance trainings."*

This report satisfies the report deliverable for Task 3.

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 4 was an additional step towards meeting the project's first goal of demonstrating a hydrogen hybrid fuel cell bus in Austin, Texas. Training sessions were held for all

Capital Metro personnel and emergency first responders prior to beginning in-passenger service for the demonstration. The pre-service trials show the bus can operate on any of the chosen routes for a full day's operation as long as both fuel cells are operational. If only one fuel cell is operational, then the bus should be limited to the four hour IF tripper route.

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

Critical issues

UT-CEM has identified the following critical issues for performance of the bus during the demonstration based on the pre-service trials.

Dual Fuel Cell Operation

As of the end of May 2012, Proterra was experiencing intermittent output power from one fuel cell and DC/DC converter. The bus is able to operate on a single fuel cell, but it is limited to four hour tripper routes and cannot complete a standard operating shift.

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 F, 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.

With these two known issues, UT-CEM has recommended the bus begin the demonstration on the IF morning tripper route that runs on weekdays from 7:00AM to 11:00AM . This will allow the bus to operate on one fuel cell over a four hour time period, and it also avoids the afternoon heat that is typical of a summer afternoon in Austin, Texas. If the bus performs well with adequate margin, or once the dual fuel cell operation is consistent, the demonstration may begin using a longer route.

Technical and commercial viability of the proposed approach

The accomplishment of Task 4 has not shown any large technical barriers that cannot be overcome and would limit commercial viability of the hydrogen hybrid bus. The fuel cells and DC/DC appear to be operating correctly, but a programming issue within the bus controller is not communicating to them correctly. Although resolving the programming error has been time consuming, this issue should not be a problem for eventual commercialization in a production bus.

In regards to the DC/DC converter issue in the previous section, 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 lessons learned during Task 4, would include upgrading the DC/DC converters as discussed in the previous section. Another upgrade would include the use of a newer generation fuel cell with twice the output power. 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. A single 32 kW module could replace the two 16 kW modules currently on the bus, or two 32 kW modules could be used to double the power available to extend the range of the batteries. 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 4 of the Grant Activities SOW. The hydrogen hybrid fuel cell bus has completed pre-service trials and all training of Capital Metro personnel and emergency first responders has been completed. The bus is set to begin passenger service in June 2012 on the morning tripper IF route operated by Capital Metro.

Completion of this task has the bus and personnel ready for 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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