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

Task 5 & Final Report

Hydrogen Hybrid Fuel Cell Bus and Hydrogen Fueling Station Demonstration

for:

New Technology Research and Development Program

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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 5 and the overall completion of their NTRD project. Task 5 includes the operation of the bus and hydrogen fueling station over a one-year period. Under this task, UT-CEM, along with project partners, operated the bus and station while performing passenger service on a Capital Metro UT Shuttle route. Data was collected on the operation, maintenance, and availability of the bus and refueling station during the demonstration project.

The overall project has successfully demonstrated 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

- 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 5, UT-CEM and project partners have operated the bus and hydrogen fueling station in passenger service. The bus arrived in Austin in March 2012 for pre-service trials and training and began passenger service in June 2012. Unfortunately several issues arose at the outset of the demonstration that limited the bus availability. The bus began performing routine, reliable passenger service in October 2012. The following report outlines the demonstration phase and completion of the project.

As proof of the project's success, the project partners have received follow-on funding from the Federal Transit Administration to develop a second generation Proterra fuel cell bus and demonstrate it in Austin, TX with the UT-CEM hydrogen fueling station. Lessons learned during this demonstration project will be used in upgrading the fuel cell bus design and improving reliability and production of the hydrogen fueling station.

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 project demonstrates two such technologies, both of which advance the commercial viability of hydrogen transportation. As a continuation of a previous TCEQ-funded project and in collaboration with the US Federal Transit Administration (FTA) National Fuel Cell Bus Program (NFCBP) (along with other state and federal agencies), the project partners 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) operating in Austin, Texas, by Capital Metro for at least one year. This important national vehicle demonstration program has been made possible by 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 (OEMs), 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 (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 are demonstrated in this field balidation 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
- 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:

1. 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 zero-emissions vehicles can and are being used in “real” operating conditions.
2. 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 is an electric hybrid merging the benefits of electric battery propulsion with the range extension of hydrogen 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 US Transportation, 1990-2003) while diesel exhaust is suspected to be the driving factor in rising childhood asthma, 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 proton exchange membrane (PEM) fuel cells and 54kilowatt-hour (kWh) energy storage from advanced lithium titanate 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

1) meeting or exceeding performance (acceleration, gradeability, range, braking distance, etc.) of its diesel counterparts, and
2) emitting no tailpipe pollutants thereby exceeding the 2010 heavy-duty bus emissions standards.

Also, this field balidation further demonstrates and validates 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:

1. 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.
2. 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. This report deliverable focuses on Task 5, which was completed in May 2013.

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 was completed in June 2012 with a report submitted 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 was completed in June 2012 with a report submitted 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 completed in May2012 with a report 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 are 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 completed in May2012 with a report submitted 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 operated the bus and fueling station for 12 months. The bus was operated by Capital Metro as part of their UT Shuttle passenger service, mostly performing a morning tripper service on the IF route. Capital Metro operators refueled the bus using the Pickle Research Campus hydrogen fueling station. During the demonstration, UT-CEM collected data to assess the performance of the fueling station and the bus. Details on the demonstration are presented in the following subtasks under the project.

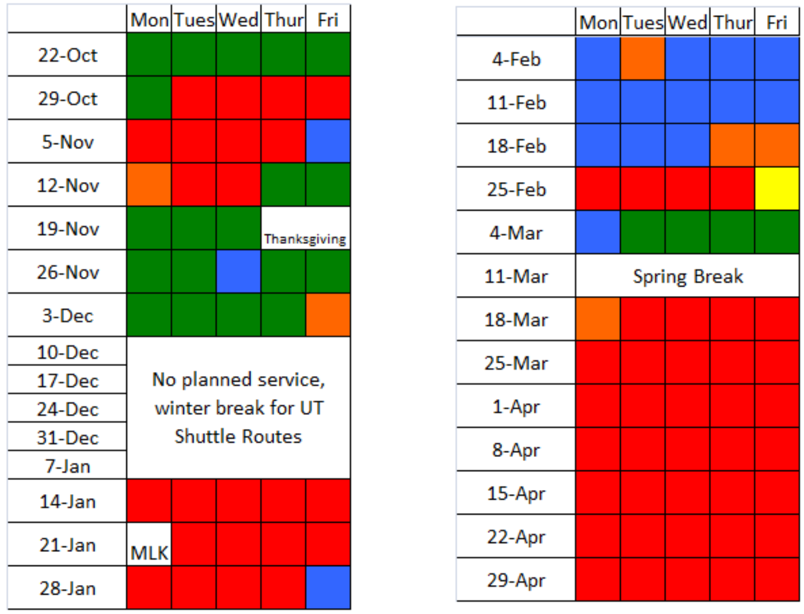
Task 5.1

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

> *" 2.5.1. Proterra bus demonstration.*
>
> *2.5.1.1. The PERFORMING PARTY will contract with Capital Metro for a twelve month operational demonstration of the Proterra bus. During the demonstration, the PERFORMING PARTY will ensure that data is collected and evaluated to better understand the bus's operating efficiency, reliability, performance, and maintenance requirements."*

UT-CEM, along with its project partner CTE, contracted with Capital Metro to operate and maintain the buses during the demonstration period. The bus was operated by Capital Metro as part of their UT Shuttle passenger service. The demo officially began in June 2012 and ended in May 2013. During the demonstration the bus experienced several issues that limited its availability during this time (Figure 3). The bus did not truly begin reliable service until October 2012. Data was collected by the team throughout the demonstration to document these issues, as well as the bus's operating efficiency and performance. Although availability was limited, UT-CEM and the project team, including the bus manufacturer, Proterra, worked to resolve issues as they arose. The lessons learned during the demonstration are key to furthering the commercialization of development of the fuel cell bus technology.

Figure 3 shows the bus availability between October 2012 and May 2013. Task 5.1.1.2 will detail the maintenance issues that arose during the demonstration, which affected availability of the bus and made it not available (red blocks) on numerous days. The days shown in blue highlight times when the bus was available and in working order, but either a driver was unavailable or the bus needed inspections.



Description	Days	%	Description
In Service	23	22%	Bus is ready to go out, and completes full planned service
Not Available	61	58%	Bus does not go out due to bus problem
Road Call	6	6%	Bus is available, starts service, but does not complete planned service
Available, not in service	16	15%	Bus is available and ready, but for non-bus reasons does not go out in service
Hydrogen station down	1	1%	Bus is available and ready, but hydrogen station was not available

Figure 3: Bus availability tracking.

Task 5.1.1.1

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

> *"2.5.1.1.1. The PERFORMING PARTY will collect and compile route performance data from the bus's onboard data acquisition system."*

During the demonstration, UT-CEM worked with the bus manufacturer to obtain operational data from the bus. This was a laborious task since several operational parameters are recorded by the bus on a second-by-second basis and requires significant post-processing. For this reason, the detail bus performance data was only collected periodically. The purpose of this data collection process was to track any degradation seen in the performance of the bus throughout the demonstration. UT-CEM was able to assess performance degradation by comparing the bus's performance near the end of the demonstration to its performance at the outset of the demonstration. The computer models and simulations that were developed in Task 4 were instrumental in this comparison. Further details and results of the performance pre- and post- demonstration are discussed in Task 5.1.1.3.

In addition to collecting periodic detail bus operational data, Capital Metro staff used daily logs to track bus mileage and fuel consumption. The plot below show the cumulative mileage and hydrogen fuel consumption during the demonstration.

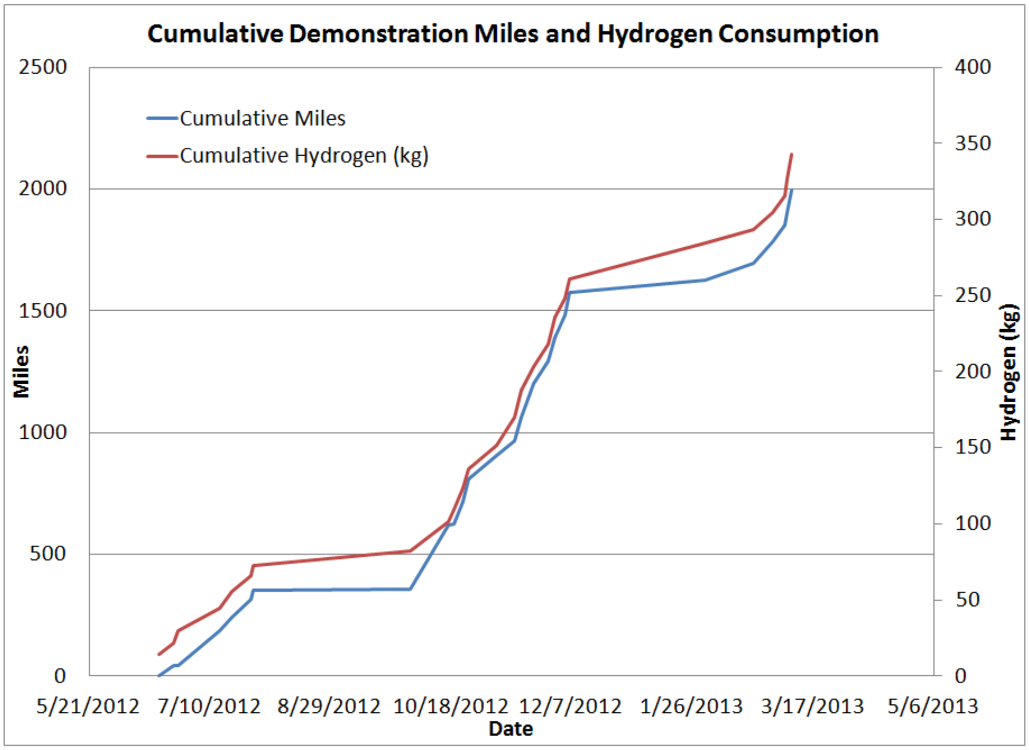


Figure 4: Mileage and hydrogen consumption during the demonstration.

Task 5.1.1.2

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

> *"2.5.1.1.2. The PERFORMING PARTY will collect maintenance data and records from Capital Metro and from the onsite Proterra personnel."*

UT-CEM, along with project partners, collected maintenance data from Capital Metro and Proterra during the demonstration. Figure 3 shows the overall bus availability during the demonstration, where the Red blocks denote times when the bus was down for maintenance. Highlights from the maintenance activities are summarized below

- During June 2012, the week of the demonstration start-up, the bus experienced a failure of one of its DC/DC converters. The DC/DC converter was replaced by Proterra and their supplier, US Hybrid.
- Between June 2012 and September 2012, the fuel cells on the bus required servicing. Initial diagnosis pointed to improper plumbing of the coolant circuit. This was then followed by the failure of an air blower, at which time Proterra replaced the air blower for each fuel cell stack. In September 2012, after still experiencing poor performance with the fuel cells, Hydrogenics inspected them at their facility and made minor repairs. During October 2012, both Proterra and Hydrogenics reinstalled the fuel cells and commissioned them successfully on the bus.
- During much of the early demonstration phase, October through November 2012, Fuel Cell 1 on the bus would experience intermittent shut downs during operation. For this reason, the service

route was limited to a morning UT tripper shuttle route, which would allow the bus to complete its service with only one fuel cell operating.

- At the end of the Fall semester of service, on December 7, 2012, the bus experienced a catastrophic transmission failure. A leak had occurred which then caused the transmission to fail. Proterra worked through January 2013 to rebuild the transmission with spare parts it had available. The transmission was repaired and the bus was ready for service on February 1, 2013.
- At the beginning a February 2013 the bus was scheduled for a preventative maintenance inspection. This took several weeks to complete due to a brake system failure. This failure was due to a faulty air line valve, which was replaced and solved the issue.
- New driver training was required prior to resuming service in March 2013. The bus operated well during this time until a fire occurred on March 18, 2013. The cause of the fire was eventually traced to a failure in one of the DC/DC converters. The bus never returned to service after the fire event.

Task 5.1.1.3

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

> *"2.5.1.1.3. The PERFORMING PARTY will evaluate bus performance by correlating Powertrain System Analysis Toolkit (PSAT) bus models with route data."*

UT-CEM worked with Proterra to collect bus operation data throughout the demonstration. The purpose of this task was to track any performance degradation in the bus by using models developed during pre-service trials under Task 2.4. The plots below show the bus performance on March 8, 2013, versus the model predictions. In general, the actual bus performance matches the model predictions and shows little, if any degradation in overall bus performance. The model results match the actual bus performance within approximately 10%.

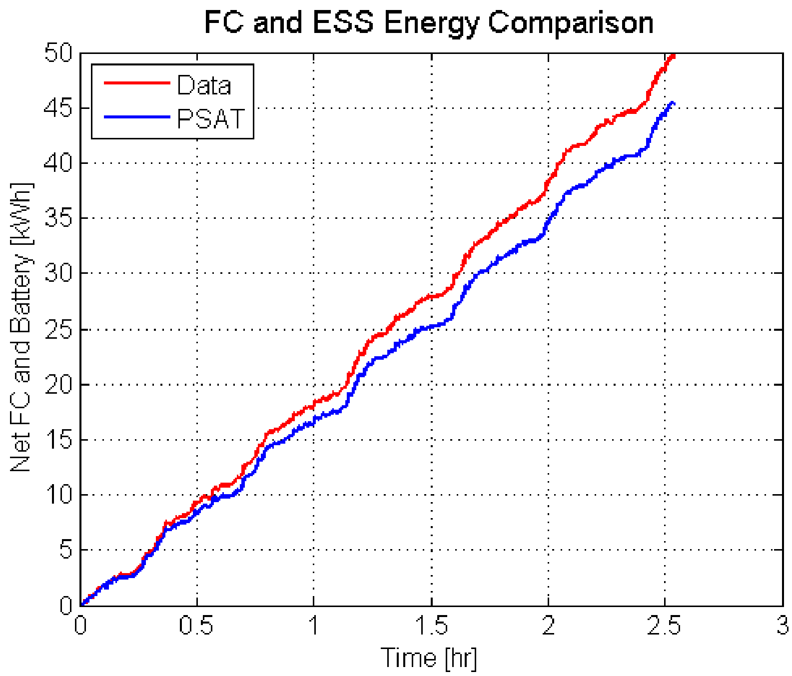


Figure 5: Comparison of overall energy consumption for data on March 8, 2013, versus the PSAT model.

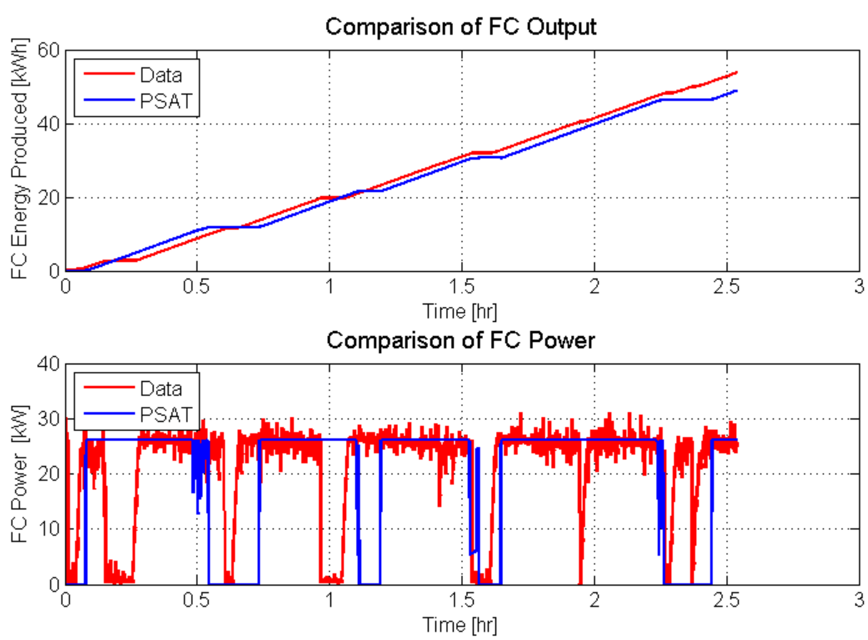


Figure 6: Comparison of fuel cell output power and energy produced for data on March 8, 2013, versus the PSAT model.

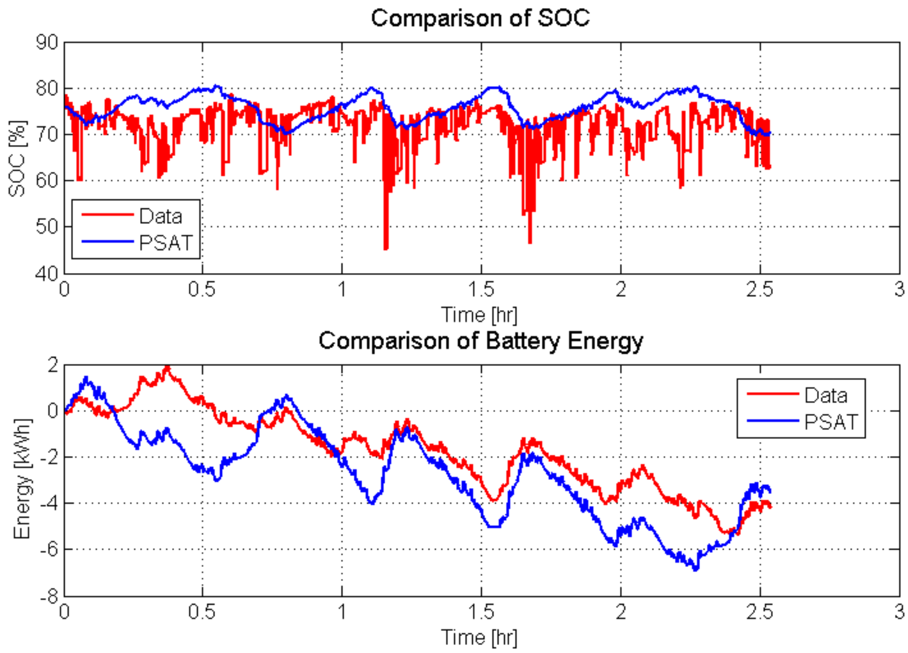


Figure 7: Comparison of battery performance for data on March 8, 2013, versus the PSAT model.

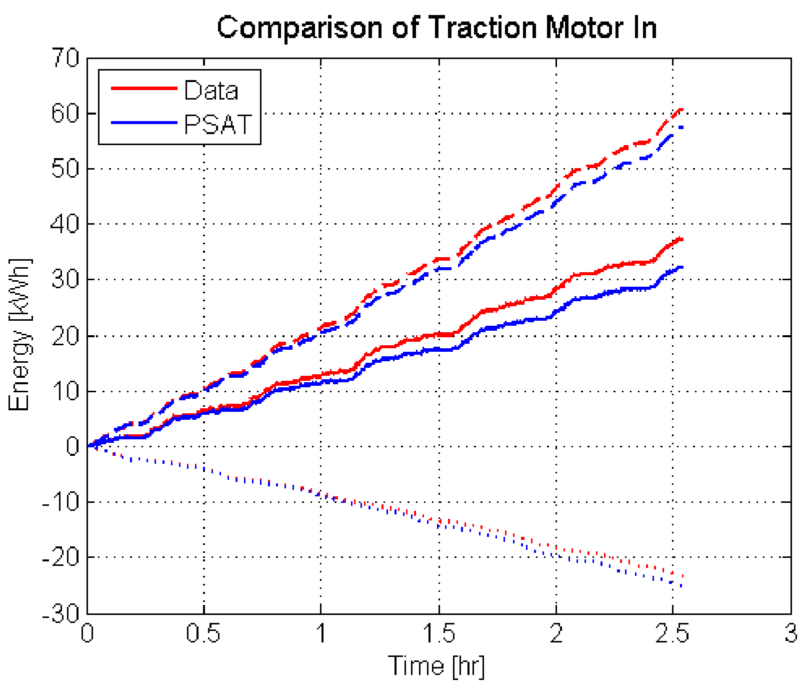


Figure 8: Comparison of traction motor energy for data on March 8, 2013, versus the PSAT model. Solid lines show overall energy use, while dashed lines show energy to the wheels and the dotted lines show regenerative braking energy.

Task 5.1.1.4

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

> *"2.5.1.1.4. The PERFORMING PARTY will calculate bus performance metrics and cost metrics to evaluate the commercial viability of the bus technology."*

At this time, the economics of running and operating a hydrogen fuel cell hybrid bus exceed those of traditional diesel engine buses. Although fuel economy is greatly improved by using an electric vehicle platform with a hydrogen fuel cell range extender, initial capital cost, availability of hydrogen, and cost of hydrogen hurts the economic case for fuel cell buses.

Daily fuel economy seen during the demonstration was somewhat sporadic with days as high as 13miles per kilogram (mi/kg) and other days as low as 4 mi/kg, with an overall average fuel economy of 7 mi/kg. This could be explained by the variety of operational scenarios seen by the bus. For example, on days with low fuel economy, the bus and its fuel cell were in a maintenance or testing phase with the fuel cell running while the bus remained parked. However, on days with more reliable operation in passenger service, the bus fuel economy was on the high end of the spectrum with an average fuel economy of 8 mi/kg, which is in agreement with computer models and simulations of the bus. This is approximately twice the fuel economy seen with traditional diesel engine buses, which typically operate at 3 to 4 mi/gallon, and is on track with the US Department of Energy (DOE) fuel cell bus fuel economy targets.

Although the fuel economy benefit is substantial, the current cost of hydrogen fuel at present, prevent the fuel cell bus from being cost competitive with traditional diesel buses. As shown in the list below, depending on how and where hydrogen is obtained can greatly affect the price.

- Today's delivered hydrogen via high pressure tube trailer - $20/kg
- Demonstrated hydrogen production with UT-CEM fueling station - $9.72/kg
- As-designed hydrogen production with UT-CEM fueling station - $3-4/kg
    - The UT-CEM hydrogen station was designed to produce 50 kg of hydrogen per day at a cost of $3-4/kg. During the demonstration the production rate of the station was intentionally lowered to match the fuel consumption of the bus. This resulted in additional electrical energy consumption per kilogram of hydrogen produced, and led to higher energy costs during the demonstration.
- DOE targets for hydrogen production - $3.10/kg (central) and $3.70/kg (distributed)

In order to be cost competitive with diesel engine buses, the fuel cell bus capital cost must decrease greatly and hydrogen fuel cost must approach that of diesel. Today's fuel cell bus costs approximately $2,000,000, while hydrogen costs can vary greatly as previously shown. However, the as-designed specification for the UT-CEM fueling station is capable of achieving the DOE cost targets for hydrogen, which would put the cost of hydrogen on par with that of diesel. This would allow the more efficient fuel cell bus to achieve a fuel savings of $300,000 over its life. Therefore, to be cost competitive with diesel buses, the capital cost of the fuel cell bus must reach $600,000, or just $300,000 more than a traditional diesel bus.

Currently, the DOE has a 2016 cost target of $1,000,000 for fuel cell buses with an ultimate goal of $600,000. These targets are based on current estimates of operational and maintenance costs for both diesel and fuel cell buses, as well as current energy costs. In the future, as the cost of energy is expected to rise and reliability of fuel cell systems improve, the ultimate cost target for the fuel cell bus may be adjusted. Demonstration programs such as this TCEQ NTRD project are working to advance hydrogen and fuel cell technologies so that these efficient, zero emission vehicles can be cost competitive with existing fossil fuel vehicles in the future.

Task 5.1.1.5

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

> *"2.5.1.1.5. The PERFORMING PARTY may conduct meetings and information sessions on the technology for the public, media, educational organizations, and potential commercial partners. However, NTRD grant funds may not be used for this subtask."*

During the demonstration, UT-CEM held a kick-off event in June 2012 to signify the start of passenger service. In addition, UT-CEM and project partners attended an EV-TEC center event hosted by Dr. Ross Baldick at The University of Texas at Austin in December 2012. At this event, the bus was on display and Michael Lewis participated in a question and answer panel regarding electric vehicles. In addition, several tours of the UT-CEM refueling facilities were conducted for various visitors during the project, including guests from the Texas Railroad Commission who were interested in UT-CEM's alternative fuels projects. NTRD funds were not used in conducting these meetings or engagements.

Task 5.2

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

> *" 2.5.2. Hydrogen fueling station demonstration.*
>
> *2.5.2.1. The PERFORMING PARTY will contract with GTI for a twelve month operational demonstration of GTI's hydrogen fueling station in conjunction with the Proterra bus. During the demonstration, the PERFORMING PARTY will ensure that data is collected and evaluated to better understand the hydrogen fueling station's operating efficiency, reliability, performance, and maintenance requirements in order to further establish commercial viability."*

UT-CEM finalized a subcontract with GTI in September 2011 for the operation and demonstration of the UT-CEM hydrogen refueling station. The subcontract included upgrades to the existing hydrogen station to allow refueling of the Proterra bus. This work was detailed in the Task 1 and Task 2 reports. In addition, the subcontract included operation support and maintenance for the station throughout the demonstration. Data was also collected during the demonstration to assess the station's performance and fuel delivery to the bus, which is detailed in discussion under Task 5.2.1.1.

Throughout the demonstration, UT-CEM and GTI had to address several maintenance issues. The majority of the issues centered around various valve components (check valves, solenoid valves, and flow control valves) which would periodically fail. Over time, the valves were replaced with alternatives from other vendors and their durability will be determined beyond this demonstration. An additional problematic component was the chiller unit on the station, which experienced intermittent flow control problems and unexpected shut downs. The flow control issues were solved by adding a reservoir for the coolant, which allows trapped air to escape the coolant lines, while the random shut down events were traced to a faulty control relay. The final maintenance item during the demonstration were random failures of various control logic modules. The failure of these modules was not unexpected as they had been in operation for several years.

Task 5.2.1.1

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

> *"2.5.2.1.1. The PERFORMING PARTY and GTI will collect and compile data utilizing remote and manual data collection tools."*

During the demonstration UT-CEM and GTI collected data from the station to assess its performance and troubleshoot any issues that arose. GTI was able to do much of their efforts remotely with appropriate data acquisition and network tools.

The plot shown in Figure 9 shows the hydrogen fueling station during a production mode in which hydrogen was being generated and stored in the high pressure tanks. The station can store 80 kg of hydrogen in six composite, Type 3 tanks at 6,000 pounds per square inch gauge (psig). The tanks are grouped in pairs into three separate banks: high, medium, and low. As the plot shows, by the end of the production cycle, all three banks are full at 6,000 psig.

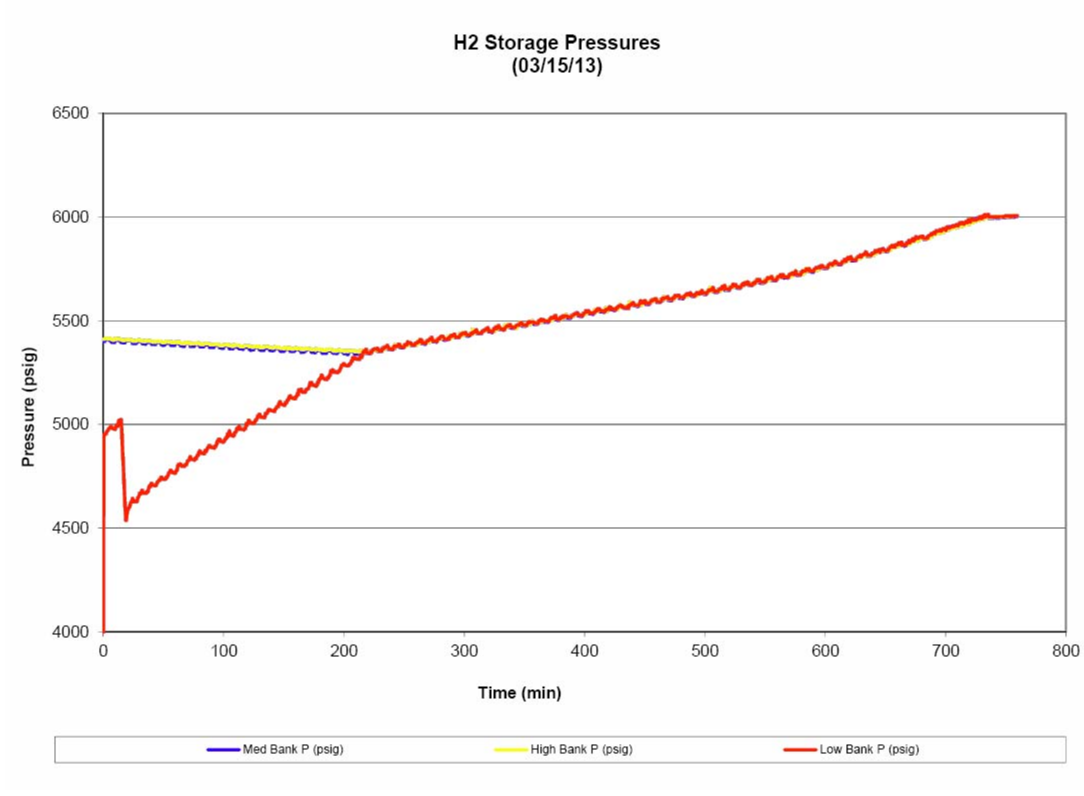


Figure 9: Hydrogen storage pressures during hydrogen production.

Using a three bank system allows the station to dispense hydrogen gas to the bus, or any other vehicle, using a cascade process in which the vehicle is filled from the storage banks sequentially. Cascading the fill allows for more hydrogen to be delivered to the vehicle. Figure 10 shows the pressures for each bank during a refueling event for the bus. The low bank initially equalizes with the bus storage tanks to a pressure of approximately 3500 psig. The medium bank follows and increased the bus storage pressure up to approximately 4300 psig, while the high bank completes the fill up to approximately 4700 psig. As shown in Figure 10, during this refueling event, the pressure in the station's storage vessels was below 6,000 psig and a complete fill of up to 5,000 psig was not possible.

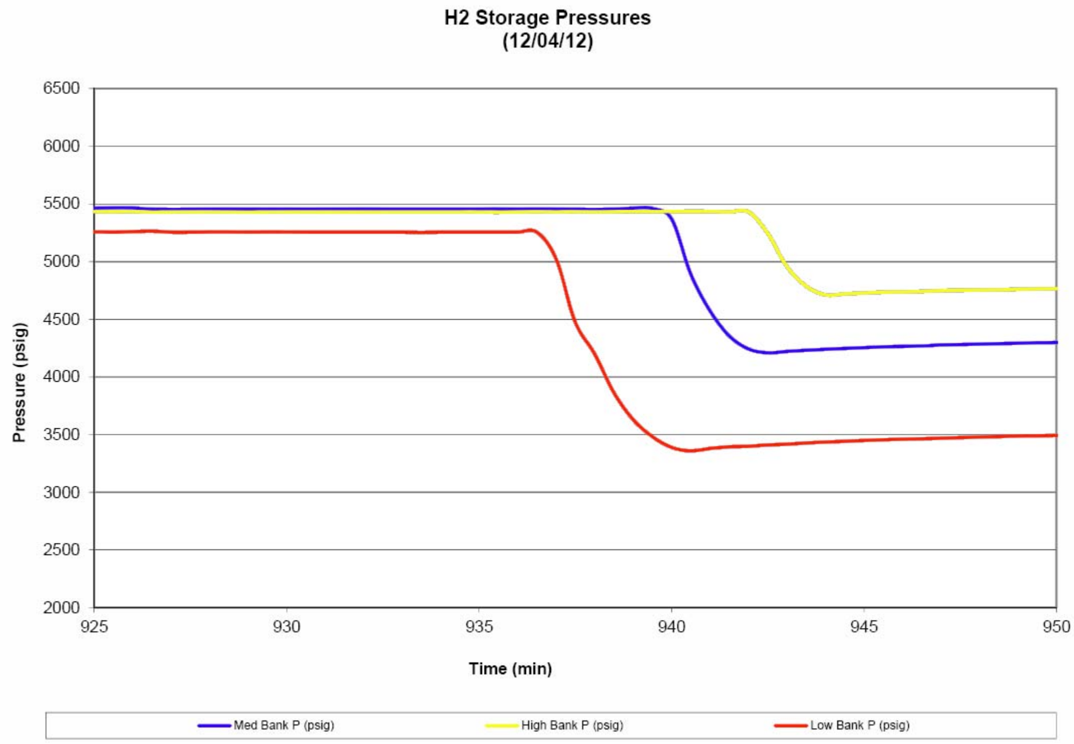


Figure 10: Hydrogen storage pressures during bus refueling.

Task 5.2.1.2

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

> *"2.5.2.1.2. The PERFORMING PARTY and GTI will measure energy use and assess station operating costs."*

During the demonstration, UT-CEM and GTI installed power and utility metering equipment on the station to determine the cost of hydrogen generation. This resulted in an average cost of $9.72/kg when considering the electrical energy, natural gas, and water consumption while producing, compressing, and storing the hydrogen gas (assuming utility cost assumptions of electricity at $0.10/kWh, natural gas at $12.50/1000 SCF, and water at $2.00/1000 gallons). Consumption rates for each utility are as follows:

- Electricity consumption / kg of hydrogen = 50.5 kWh (compression accounts for 50-60%)
- Natural gas consumption / kg of hydrogen = 373 SCF (This consumption rate includes recycling of tail gas to the burner on the natural gas reformer. If recycling of tail gas is not implemented, the consumption rate increases by approximately 75%.)

- Water consumption / kg of hydrogen = 2.3 gallons

During the demonstration, the station was setup to produce hydrogen at 20 kg/day in order to better match the fuel consumption seen by the bus. This resulted in higher overall energy consumption than would be expected during full scale hydrogen production, where the station is capable of producing hydrogen at 50 kg/day at a cost of approximately $3 to $4/kg.

Task 5.2.1.3

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

> *"2.5.2.1.3. The PERFORMING PARTY may conduct meetings and information sessions on the technology for the public, media, educational organizations, and potential commercial partners. However, NTRD grant funds may not be used for this subtask."*

During the demonstration, UT-CEM held a kick-off event in June 2012 to signify the start of passenger service. In addition, UT-CEM and project partners attended an EV-TEC center event hosted by Dr. Ross Baldick at The University of Texas at Austin in December 2012. At this event, the bus was on display and Michael Lewis participated in a question and answer panel regarding electric vehicles. In addition, several tours of the UT-CEM refueling facilities were conducted for various visitors during the project, including guests from the Texas Railroad Commission who were interested in UT-CEM's alternative fuels projects. NTRD funds were not used in conducting these meetings or engagements.

Task 5.3

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

> *"2.5.3. Schedule: The PERFORMING PARTY shall complete this task within 24 months of the signed Notice to Proceed Date as issued by TCEQ."*

The demonstration was completed in May 2013 within 24 months of the Notice to Proceed Date issued by TCEQ.

Task 5.4

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

> *"2.5.4. 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 reporting of data, costs, and performance information on the bus and the hydrogen fueling station."*

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. They are not included in the report due to their length.

In addition, GTI delivered manuals on the operation and maintenance of the fueling station to UT-CEM. These manuals reside at UT-CEM and are not included is this report due to their length.

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"*

Monthly reports were submitted in a timely fashion, as were the interim final reports. The final report will be completed in June 2013.

Discussion/Observations

Objectives vs. Results

Accomplishment of Task 5 met the project's goal of demonstrating a hydrogen hybrid fuel cell bus and hydrogen fueling station in Austin, Texas. The demonstration officially began in June 2012, but was immediately hampered by performance issues with the bus. During the first week of service, the bus experience a DC/DC converter failure that was then followed up by issues with one of its fuel cells. By October 2012, the bus was in good operating order and completed several days of service through the remaining Fall semester on a University of Texas shuttle route.

At the start-up of the Spring semester, issues with the transmission on the bus limited it's operation. The transmission was eventually repaired and the bus resumed operation in February 2013 as new driver's were trained for the spring semester. During March 2013, a failure within one of the DC/DC converters led to a minor fire on the bus. No passengers or personnel were injured during this event, but the fire did take the bus out of service. At the conclusion of the demonstration, the exact cause of the DC/DC converter was still being investigated and the bus never returned to service.

The demonstration had mixed success, but ultimately led to a better understanding of the technologies onboard the bus. The bus manufacturer worked through their transmission issues and has a new supplier which will provide a more reliable system. In addition, Proterra has gained valuable insight into design and layout of the fuel cell and DC/DC converter systems. These lessons have led to packaging redesign which will alleviate thermal issues seen during the demonstration. This new packaging concept will place the fuel cell power system (now integrated with the DC/DC converter) on the roof of the bus with better access for wire and plumbing, as well as better ventilation.

The hydrogen station demonstration involved several upgrades to the system, resulting in reliable operation during the demonstration. Only once during the demonstration was the bus not able to refuel due to the station being under maintenance. Lessons learned during the demonstration have led to replacement of several minor components, such as check valves and solenoids, with more reliable components.

Critical Issues

Bus

UT-CEM has identified the following critical issues for the bus during the demonstration. Each of these issues limited service at some point during the demonstration.

Dual Fuel Cell Operation

Proterra experienced intermittent output power from one of the fuel cells during the demonstration. The bus was able to operate on a single fuel cell, but it was limited to four hour tripper routes and could not complete a standard 8-hour operating shift. The cause of the problems was traced to improper plumbing of the coolant system and poor performance of the air blower system.

DC/DC Converters

The two DC/DC converters, which provide the power interface between fuel cells and 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 to remove heat generated during operation. The solution for the demonstration was to limit 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 began to be de-rated. Rather than a total output of 32 kW, the DC/DC converters provided only 29 kW of power to the batteries.

Transmission

The transmission used during the demonstration was a prototype system developed by Proterra in conjunction with their vendor. At the time of fabrication, an off-the-shelf transmission was not available that would fit the bus and traction motor specifications. During the project, Proterra has worked with vendors to provide a more reliable solution for newly constructed buses.

Overall

With these issues experienced during the demonstration, the project team has a better understanding of the fuel cell technologies on the bus. Proterra revised their packaging concept for their latest fuel cell bus design. This new concept will package the fuel cell and DC/DC converters into a single skid package that will be installed on the roof of the bus. This will allow more space for adequately sizing components and routing cables and plumbing. In addition, placement on the roof will allow for better air flow and ventilation.

Fueling Station

During the demonstration UT-CEM also identified critical issues for the fueling station. Some issues caused downtime at some point during the demonstration, while others are areas that need to be proven in the future to achieve full production capacity at the hydrogen station.

Valves and Solenoids

These components included check valves, solenoid valves, and flow control valves. During the demonstration, multiple failures of these items occurred. In some cases replacement valves failed prematurely after replacement. By the end of the demonstration, GTI replaced all troublesome components with alternative valves. However, the true durability and reliability is unknown at this time as more hours are needed on each of them.

Blower Capacity / Cooling

The original cooling systems on the hydrogen station were not adequately sized to cool electrical enclosures within the station. A new blower was installed early during the demonstration. However, since there was limited operation during Summer months due to downtime of the bus, the true effectiveness of this blower is unknown at this time.

Chiller

The chiller experience two intermittent issues during the demonstration. The first issue was due to trapped air pockets within the coolant lines. A coolant reservoir was installed, which solved this problem. The second issue was traced to a faulty control relay. Upon replacing this relay and adding the coolant reservoir, the chiller's performance was flawless for the remaining demonstration period.

PLC Modules / Computer hardware

The station's computer hardware, including programmable logic control (PLC) modules, experience random failures during the demonstration. The likely cause of these failures were age of the components and their susceptibility to high temperatures. More ruggedized hardware may be needed for a commercialized product.

Pressure Swing Absorber (PSA)

The pressure swing absorber is responsible for purifying the hydrogen production stream to standards necessary for fuel cells. During the demonstration, hydrogen production rates were limited by the PSA's ability to purify the hydrogen. A refurbishment of the PSA would likely restore the station to full production capacity; however, during the demonstration this was not pursued since the station's 20 kg/day production rate exceeded the bus's average 10 kg/day consumption rate.

Reformer

At the beginning of the project, GTI rebuilt the reformer and installed it in the station. During the demonstration the reformer performed flawlessly, producing hydrogen at a rate of 20 kg/day. Unknown at this time, is the ability of the reformer to produce its rated capacity of 50 kg/day. This was never tested during the demonstration and would need to be proven in future development work.

Overall

In general, the UT-CEM hydrogen station performed well and only once during the demonstration was it unable to refuel the bus as needed. The majority of the issues encountered during the project were minor component failures that are not anticipated to be major obstacles to commercialization. The only remaining question at the end of the demonstration is the true production capacity of the station.

Technical and commercial viability of the proposed approach

The accomplishment of the demonstration of the bus and fueling station under Task 5 has not shown any large technical barriers that cannot be overcome and would limit commercial viability of the hydrogen hybrid bus or hydrogen fueling station.

The major bus component issues have revolved around the fuel cell, DC/DC converters, and transmission. Proterra continues to work with fuel cell and DC/DC converter manufacturers to solve issues with these components. Proterra believes repackaging the fuel cell and DC/DC converters into a separate module placed on the roof will eliminate many of the thermal and plumbing issues seen during the demonstration. Proterra is currently underway with a second round FTA NFCBP project to deliver a new fuel cell bus to Austin for a future demonstration that will implement this new fuel cell and converter packaging. In addition, the bus transmission used in the program was a prototype transmission that was never designed for long life. Over the past 24 months of the project, Proterra has worked with multiple transmission suppliers to identify a suitable transmission for their future bus builds.

The issues that were experienced with the fueling station during the demonstration were mostly minor and impose no threat to further commercialization of the product. However, the true hydrogen production rate is unknown. It is anticipated that UT-CEM and GTI will be able to ramp up production during the next FTA NFCBP demonstration in Austin and prove its true capability.

Although the bus and fueling station show no technical barrier to commercialization, a large economic barrier remains. The current cost of the bus and hydrogen fuel does not support an economic case when compared to traditional diesel engine buses. The UT-CEM hydrogen station has the potential to produce hydrogen at a cost comparable to diesel. This implies, when considering the increased efficiency and fuel economy of the fuel cell bus, that over its life, a fuel cell bus would potentially save $300,000 in fuel costs. Therefore, the fuel cell bus capital cost must not exceed the cost of a diesel bus by more than $300,000. Over time, as energy costs rise and fuel cells become more reliable, the fuel cell bus cost target will need to be adjusted.

Scope for future work

The lessons learned during the demonstration of the bus and fueling station during Task 5 have led to a path forward for both technologies. This path forward includes a future demonstration of a next generation fuel cell bus in Austin, Texas, through the Federal Transmit Administration's National Fuel Cell Bus Program. In this future demonstration, Proterra will deliver a new fuel cell bus based on their current all-electric bus platform. The new fuel cell bus will include a 60 kW fuel cell power system which will provide greater performance over more demanding duty cycles. In addition, the upgraded fuel cell module will be packaged with the DC/DC converters in a roof mounted skid. By locating these components on the roof, Proterra expects to solve thermal issues encountered during the demonstration. Finally, the new bus will included a commercial transmission that Proterra has developed with vendor's throughout the 24 months of the current project.

During this next demonstration, which is scheduled to begin in early 2014, the bus will continue to be fueled by the GTI and UT-CEM hydrogen fueling station. The goals in the next demonstration are to:

- test reliability and robustness of various valves and computer hardware,
- test the new blower and cooling systems during Summer operation, and
- show the station's fuel production capability.

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

UT-CEM's Field Validation and Demonstration of a Zero-NOx Emission Hydrogen Bus and Fueling Infrastructure was completed in May 2013. The project successfully demonstrated two enabling technologies for reduced emissions transit buses:

- 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
- A cost competitive and commercially available hydrogen fueling station being commercialized and supported by Texas-based GreenField, an Atlas-Copco Brand.

During the project, several issues arose with the operation and maintenance of the bus, but the lessons learned have proven valuable in further the commercialization of the fuel cell bus technology. These lessons will be implemented in a future demonstration of a next generation Proterra fuel cell bus supported through the FTA NFCBP. This future demonstration is scheduled to begin in early 2014.

The recently completed field demonstration, also saw the successful implementation of a hydrogen refueling station, making use of existing natural gas networks. The station was able to produce, store, and dispense hydrogen which was generated through steam reformation of natural gas. The Field Validation project highlighted several components with reliability issues, but alternative suppliers were readily located and have proven to be more reliable to date. The fuel station will continue to be demonstrated during the next FTA NFCBP project slated for early 2014. In this upcoming demonstration, the lessons learned in the recently completed NTRD project will be implemented and help advance the technology and its commercialization.

Continued field validation projects are needed to continue advancement of these technologies and to overcome current financial and hydrogen supply barriers. Through the Field Validation and Demonstration of a Zero-NOx Emission Hydrogen Bus and Fueling Infrastructure, Texas has been able to position itself within the hydrogen and fuel cell community and industry, providing a basis for a future, robust hydrogen economy and continued advancement of the technologies.

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- 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

References

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fceb_status_2012.pdf

http://www.nrel.gov/hydrogen/production_cost_analysis.html#fn3

http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf

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