# FINAL TECHNICAL REPORT

DOE Assistance Award Number DE-EE0006093

**Fuel Cell Powered Airport GSE (Ground Support Equipment) Deployment**


**SUBMITTED BY**

Plug Power

968 Albany-Shaker Road

Latham, NY 12110

DUNS: 086908444

**INVESTIGATORS**

Joe Blanchard: jblanchard@plugpower.com


**SUBMITTED TO**

U. S. Department of Energy

Fuel Cell Technologies Office

Michael Hahn

michael.hahn@go.doe.gov

**REPORTING PERIOD**

01/01/2013 – 06/30/2019

March 9, 2020

***Acknowledgment:*** *"This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Fuel Cell Technologies Office (FCTO) under Award Number DE-EE0006093."*

## Table of Contents

## 1. Executive Summary

The Fuel Cell Powered Airport GSE (Ground Support Equipment) Deployment Project was initiated in 2013 between Plug Power and U. S. Department of Energy Fuel Cell Technologies Office (DOE). The project plan included development and deployment of fifteen fuel cell powered units for two years at an airport to understand the feasibility and economic viability of hydrogen powered GSE. Project participants were the Department of Energy, Plug Power, and FedEx. The Memphis, TN airport is the hub of FedEx's freight operation and was selected as the site for the demonstration portion of the project.

The project was established in 2 Phases with the first phase being the product development of a 20kW fuel cell to replace the lead acid battery in a Charlatte CT5E baggage tow tractor (tugs). This phase also included planning for hydrogen infrastructure at the Memphis airport. This initial phase spanned seven calendar quarters from Q2 CY2013 to Q4 CY2014. Fifteen fuel-cell powered tugs were delivered at the end of December 2014. The fuel cell powered tugs were commissioned and placed into service at the end of Q1 CY2015 starting the second phase or demonstration phase of the project.

During the first five quarters of service it was determined that the implementation and performance of the fuel cell stack and the overall architecture were not operating as expected. This resulted in significantly more maintenance and repair activity. Due to these issues, the failure rate and overall availability of the fuel cell powered tugs were not meeting the expected project objectives. However, all other performance and operational goals relating to power, ground speed, towing capacity, outdoor operation, hydrogen refilling, and runtime were satisfied with this first iteration of fuel cell power system. Significant learning was achieved and reported during this period of the project.

A decision was reached in Q2 CY2016 to redesign the fuel cell power system using Plug Power's internally developed fuel cell stack instead of the original externally sourced stack. During Q3 CY2016 to Q1 CY2017 the redesign of the fuel cell system was completed and the first three improved fuel cell powered tugs were put back into service. During the next three quarters through the end of CY2017 the fleet was upgraded with the new systems and performance reporting was provided. By the end of CY2017 all objectives established for the project had been successfully demonstrated and reported.

In Q1 CY2018, FedEx informed that the hydrogen system in Memphis was being repurposed and that the site would be decommissioned. The team immediately engaged in searching for a location to complete the demonstration of the fuel cell powered tugs. Decommissioning was completed in Q2 CY2018. A commitment from FedEx was also received in Q2 that two of the tugs could be relocated to their operation at the Albany, NY airport and planning commenced to accomplish this objective.

Activities to move the remainder of the project to Albany continued in Q3 and Q4 CY2018. In addition to Albany, other locations were explored to deploy a portion of the remaining fleet of fifteen hydrogen powered tugs. The impact and delays resulting from the shutdown at Memphis required negotiation with the DOE to adjust the project scope and extend the project duration. Agreement was reached to operate just the two tugs at Albany and collect an additional six months of data during winter months.

In Q1 CY 2019 the two tugs were fitted with cold weather cabs and put into service at FedEx's ramp operation in Albany in February. The two tugs continued to operate until the project completion at the end of Q2 CY 2019. FedEx decided not to continue to use the fuel cell tugs at the Albany operation.

The project successfully met the original objectives and demonstrated the viability of hydrogen powered ground support when compared with incumbent internal combustion powered equipment. The hydrogen powered tugs were able to meet all operational demands in the FedEx freight operation and demonstrated a cost effective, low emissions solution with favorable economics. The project provided valuable technical, economic, and operational learning toward using hydrogen power for ground support equipment applications.

## 2. Project Goals/Objectives

DOE Fuel Cell Technologies Objectives over Project Life

- To create a hydrogen fuel cell-based solution as a cost-competitive and more energy-efficient tugs compared to the incumbent internal combustion engine-powered vehicles.
- To enable airport end users to accomplish their daily tasks with a hydrogen fuel cell solution while reducing consumption of gasoline and diesel fuels, reducing U.S. demand for petroleum.
- To demonstrate lower carbon emissions with the fuel cell solution
- To demonstrate a value proposition that shows decreased energy expenditures when compared to diesel-powered airport vehicles

The objectives of this project are listed on the left side of the following graphic. The fuel cells will demonstrate viability in application. The implementation of fuel cells will reduce petroleum consumption and reduce emissions while validating alternative methods of supply energy to tugs at airports.

| DOE Project Objectives | Estimated Project Impact |
|---|---|
| **Reduce petroleum consumption** | Each tug uses ~2 gal/hr. Total tug run time of 15 tugs over 2 years will be upwards of 175,200 gallons of diesel fuel reduced. |
| **Reduce emissions at airports** | AT 10.1 kg CO2 per gal of diesel, there will be upwards of 1770 metric tonnes of CO2 eliminated at airports. |
| **Operate 10 hrs/day & 5,000+ hours** | Tug operation occurs during two shifts: day (10 AM-2 PM) and night (10 PM-2 AM). The total clock day is 10AM-2AM (16 hours). Actual tug activity is 8 hours per day. Total run time of 15 tugs over 2 years will be upwards of 87,600 fleet hours. |
| **Towing capability of 3,000 to 6,000 lbs.** | The tug will be able to tow 4 containers each weighing 10,000 lbs. The corresponding drawbar capacity of the fuel cell-powered tug is 5,000 lbs. |
| **Accelerated development of FC-powered GSE** | Fleet of 15 80V fuel cell systems in real world application in 2013 gaining significant field experience while allowing a premier tug end user to evaluate for larger deployments. |

## 3. Background

This project included deployment of 15 fuel cell powered units for two years at an international airport. Fifteen fuel-cell powered tugs were deployed in the FedEx operation at the Memphis, TN airport. The FedEx freight operation in Memphis uses a fleet of 1383 tugs to manage 270 flights per day.

The project was planned for two phases.

- **Phase 1:** The first phase was a one-year development phase where Plug Power developed, built and tested the 80V (~20 kW) fuel cell system for the tug application.
- **Phase 2:** The second phase was a two-year demonstration where a fleet of tugs were integrated into electric tow tugs and deployed in Memphis under real world conditions. The fuel cell fleet were originally to be fueled by another project partner's steam methane reformer and CSD (compression, storage, and dispensing) solution at the site. A cryogenic liquid to gas hydrogen system was ultimately installed and utilized at Memphis providing full hydrogen refueling capabilities.
- **Phase 2 +:** Due to decommissioning of the hydrogen system, the project demonstration at Memphis was terminated early. Two of the hydrogen powered tugs were redeployed at the FedEx operation at the Albany, NY airport to continue demonstration, including cold weather operation.

## 4. Accomplishments

**Accomplishment Previously Reported**

**Q2 2013**

- Systems Engineering - Collection of Requirements
    - Data logging of CT5E in FedEx Express application (Ontario, CA)
    - Sharing of information with tug OEM
    - Component requirements and supply chain discussions
    - Identification of stack characterization and requirements for larger power (ex. pressure drop, polarization curve)
    - Identification of components with current component model lines
- System Modeling
- Coordination with FedEx Express Facilities Team for Hydrogen Prep / Permits
- Kickoff meeting with DOE and Partners in Latham on 3/27/13
- Receipt of Charlatte CT5E at Plug Power for weatherproofing and interconnect design
- Signing of hydrogen supply agreement with Nuvera (2 Power Tap units)

**Q3 2013**

- Data logging of Charlatte CT5E with FedEx dollies at Plug Power with 10,000 to 40,000 lbs. in tow at increments of 10,000 lbs.
- Receipt of first Hydrogenics 20 kW stack
- First prototype build
- Controls testing on Hydrogenics stack – pulse testing
- GSE P&ID
- System packaging solution
- First cut of the safety concept for GSE

- Discussions with FedEx Express and Charlatte about GSE modification / interfacing / weight distribution

**Q4 2013**

- GSE System Requirements Document complete
- GSE Safety Concept complete
- System Optimization: Selection of a custom-made low-pressure stack and receipt of the first stack build for testing and acceptance. Modified GenDrive architecture to adapt to a low-pressure stack alternative (improved efficiency from high 30's% to mid-40's%, which is critical to the value proposition and commercialization of the tugs. Fuel savings is the crux of the buyer's decision and we needed to slow things down to optimize this critical piece.)
- Configured the facility cooling loop to the electronic load bank
- Created a total of 30 documents outlining the system modules and integration of major components
    - Castings (2)
    - Covers (6)
    - Radiator Fan Shroud
    - Overflow tank
    - Battery enclosure parts (5)
    - Frame Members (3)
    - Tubing (3)
    - Bus-bars (2)
    - Brackets:
    - Electronics
    - Blower
    - Coolant pump
    - Coolant manifold/Polish filter
    - Relays
- Battery Design: Build and testing of a 3P24S Li-Ion battery to support the 20+ kW fuel cell module and provide buffer to huge, instantaneous power requirements, as needed when a truck accelerates with 40,000 lbs. of cargo behind it
- Packaging Design: Repackaging of the GenDrive system to accommodate a 3.75 kg hydrogen tank to ensure that the customer did not have to refuel during even the extreme shifts at the hardest run tugs at any airport in the United States. There will not be a reason for FedEx Express tug operators to take a break from their work to fill up, which was a top requirement discovered when finding voice of customer and creating system requirements.
- Packaging Design: Repackaging of the GenDrive system to move all major service items to the very top of the system, making it the easiest GenDrive ever to conduct service, both preventive maintenance items and to reach the stack and major balance of plant items.

**Q1 2014**

- Beta Prototype Testing

**Q2 2014**

- DOE visit to Latham for Go/No Go into Demonstration Builds on 6/26/14

- Passed go/no go decision with an action item list of follow-up to provide

**Q3 2014**

- Satisfied the action item list of follow-up to the first go / no go decision
- Site preparation for the start of the demonstration
- Operator training – Chris Ashley (service technician) provided training to FedEx Express training personnel for “train the trainer” activities.
- Safety training
- Service training – Fabern Andrews (dedicated service technician for Memphis) worked with Plug Power employees in Latham to build and test the demonstration units. Fabern also worked at a distribution center site to gain more experience with the general GenDrive architecture
- Creation of service parts consigned inventory – Parts are on order
- Arrangement for dedicated service area – A service tool kit has been stationed at Memphis for Plug Power service use
- Finalize operations & maintenance manual – The operator manual has been provided to FedEx Express for training purposes
- Modification of 15 CT5E trucks to accommodate fuel cell – This included: (1) Removal of site panels around the battery compartment, (2) a hole drilled into the side of the truck to allow for isolating the hydrogen tank during transport without removing the fuel cell, (3) holes drilled between the battery compartment and the Curtis controller to allow for routing of electrical cables through the body of the truck as opposed to outside the fuel cell, and (4)
- Start of fuel cell builds

**Q4 2014**

- Shipped 15 units to Memphis. FedEx Express received all by 12/29/14.
- The purchase order was received to pay for ½ of the fuel cell units.
- The hydrogen site has been fully installed. Flame detector and E-stop were the last remaining items. These last two were completed 12/16/14.
- Drawing updates are in process to support the permitting.
- The GenKey contract was submitted to FedEx Express on 10/10/14. (FedEx wanted to wait to execute the fueling contract until the site permit was received.)

**Q1 2015**

- Conducted operator safety training on fuel cell operation and hydrogen refueling
- Hosted the Memphis Fire Service Bureau for a review of the GenFuel site at the Memphis-Shelby County Airport.
- Received permitting from the Memphis Fire Service Bureau.
- Executed a contract between Plug Power and FedEx Express for the hydrogen fueling and service of the units over the demonstration period.
- Commissioned the 15 fuel cell units and GenFuel site on 03/29/15.
- Prepared for an event hosting the DOE, FedEx Express, Plug Power, and Steve Cohen (US Congressman for Tennessee, 9th District)

**Q2/Q3 2015**

- The fleet of 15 units has been operating in the operations at the airport. Plug Power has provided service support of the fuel cells and hydrogen infrastructure.

- Conducted an event with the DOE, FedEx Express, Plug Power, and Steve Cohen (US Congressman for Tennessee, 9th District)

**Q4 2015**

- Experience in FedEx application
- PRR (problem resolution record) created for each of top 10 failure modes
- Mitigation of 5 of the top 10 failure modes

**Market Outreach**


*Plug Power will retrofit 15 Charlatte CTGE cargo tractors with hydrogen-powered fuel cells as part of a Department of Energy grant project.*

- Presentation to Association of American Airport Executives in New Orleans on 4/21/15. Representatives from the DOE (Greg Moreland), FedEx Express (Thomas Griffin), and Plug Power (Jim Petrecky) were present.
- A program update was presented at the Annual Merit Review on 06/10/15.
- Data was collected and provided to National Renewable Energy Laboratory (NREL) for analysis.

**Q1/Q2 2016**

- Completed 15 months of operation with Hydrogenics stack
- Determined that the Hydrogenics stack did not meet the system requirements
- Determined that the stack failures were not attributed to the airport operation but failure to operate sufficiently in an architecture that directly couples the stack/battery to the vehicle load
- Fuel cell operation in application
    - Dealt with repeated issues with stack
        - Hard failures requiring refurbishment
        - Inability to start
        - Excessive purging
- Completed an evaluation of fuel cell requirements even though there was not a formal review to move into budget period 2:
    - Power: Capable of 5,000 lbs. drawbar capacity YES
    - Availability: > 80% NO
    - Run time: > 1 shift YES
    - Reliability (MTBF – Mean Time Between Failures): > 100 hours NO
    - Speed rating: 10 mph YES
    - Outdoor operation: no non-recoverable issues YES
    - Hydrogen Fills: 350 bar YES

Notes: Availability did not achieve 80% due primarily to stack issues. During the first month of the demonstration, availability met 70% but increasingly dropped as more issues arose. The main contributors to the lack of availability were 42% stack failures, 23% electronics failures, and 17% software failures. The goal for the second half of the demonstration is to reduce downtime to less than 11 calendar days per year.

Notes: For the first 9 months of the demonstrations, there were 230 failures. Over this time there were 22,700 hours of the fuel cell being available for operation. This yielded a failure rate of 20 failures/year and a MTBF of 98 hours.

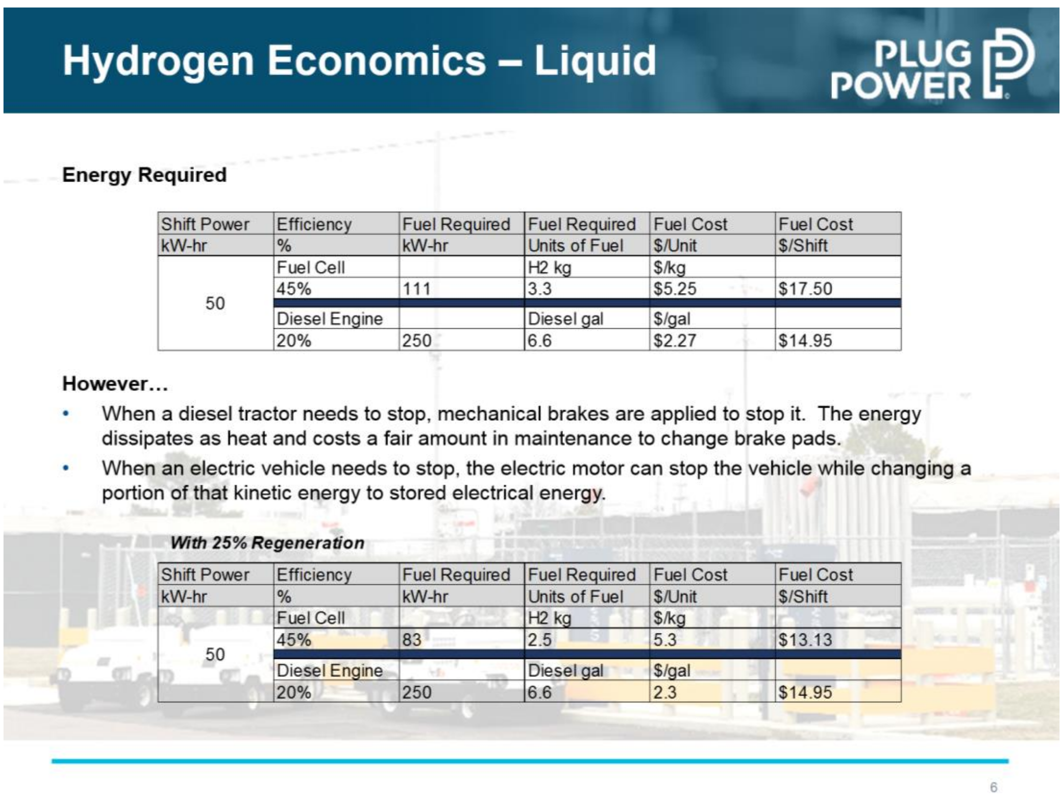
- The metrics from the first year were compiled and sent to NREL, as follows:

| System | Time (GMT) | Stack Hours | Stack Starts | System Hours | System Starts | Power | Total H2 | Tank Fills |
|---|---|---|---|---|---|---|---|---|
| GD76B01 | 2/15/2016 | 75.9 | 3514 | 1053.7 | 227 | 746.9 | 107552 | 105 |
| GD76B02 | 12/6/2015 | 71.2 | 1757 | 1869 | 304 | 643.6 | 80844 | 139 |
| GD76B03 | 3/6/2016 | 87.4 | 5598 | 2103.6 | 277 | 746 | 72957 | 167 |
| GD76B04 | 1/21/2016 | 141 | 2879 | 1811.9 | 284 | 594.1 | 127266 | 120 |
| GD76B05 | 2/10/2016 | 151 | 3646 | 2278.6 | 346 | 1659.7 | 215498 | 153 |
| GD76B06 | 3/16/2016 | 154.1 | 3861 | 2382.9 | 363 | 1666.9 | 129363 | 154 |
| GD76B07 | 3/14/2016 | 54.5 | 1660 | 1298.5 | 226 | 497.9 | 66622 | 111 |
| GD76B08 | 1/28/2016 | 83.1 | 2624 | 1508.5 | 229 | 760 | 74420 | 126 |
| GD76B09 | 7/29/2015 | 4.5 | 89 | 186.9 | 29 | 49 | 10998 | 22 |
| GD76B10 | 3/16/2016 | 100 | 3009 | 1604.8 | 393 | 1035.6 | 81782 | 177 |
| GD76B11 | 1/21/2016 | 93.5 | 2306 | 1326.1 | 348 | 1005.8 | 96403 | 159 |
| GD76B12 | 8/25/2015 | 34.2 | 1133 | 759.2 | 141 | 374.8 | 53706 | 67 |
| GD76B13 | 3/16/2016 | 78.7 | 2624 | 1554.9 | 273 | 754.1 | 66692 | 92 |
| GD76B14 | 3/16/2016 | 81.4 | 2560 | 1429.3 | 287 | 762.3 | 78037 | 144 |
| GD76B15 | 2/24/2016 | 71.1 | 3908 | 1521.6 | 239 | 651.4 | 74328 | 95 |

| Fleet | Stack Hours | Stack Starts | System Hours | System Starts | Power | Total H2 | Tank Fills |
|---|---|---|---|---|---|---|---|
| Units | hrs | # | hrs | # | kW-hr | kg | # |
| Parameter | 1281.6 | 41168 | 22689.5 | 3966 | 11948.1 | 1336 | 1831 |

- Failure Metrics
    - Stack 42%
    - Electronics 23%
    - Software 17%
    - Coolant 7%
    - Miscellaneous 5%
    - Operator Error 4%
    - Actuators/Regulators 2%
- Investigated other material handling applications at the airport
    - Data logging of 48V Taylor-Dunn tug to expand the use of hydrogen fuel cells at Memphis airport
    - Investigation of electric forklifts to expand the use of hydrogen fuel cells at Memphis airport (3 different uses)
- Testing with Hydrogenics in Memphis regarding stack failures (MTBF: 61 hours)
    - Recommendations from stack OEM is to implement a DC/DC converter and/or large stack resistors to raise the stack current at a slower pace
- Summarized learning from Year 1
  - Tug handles application load
  - Operating outdoor 24/7 is not a problem
  - Weatherproofing strategy works well
  - Air filtration protects the system from airport hydrocarbon emissions

- Tug can operate worst route for full shift without needing to refuel
- Handful of components that had a drastic effect on reliability
  - Problem components have been identified
  - Alternates have been identified and tested
  - Plan for retrofitting is in place
  - Executing plan toward a revision to the tug design
- Created a list of design improvements to optimize serviceability
- Decision to migrate to a Plug Power stack for the second version and incorporate learning from Year 1
- Value Proposition Analysis **-** Economic analysis of fuel cells vs. diesel with different hydrogen supply methods



## Hydrogen Economics – Liquid

**Energy Required**

| Shift Power kW-hr | Efficiency % | Fuel Required kW-hr | Fuel Required Units of Fuel | Fuel Cost $/Unit | Fuel Cost $/Shift |
|---|---|---|---|---|---|
| 50 | Fuel Cell | | H2 kg | $/kg | |
| | 45% | 111 | 3.3 | $5.25 | $17.50 |
| | Diesel Engine | | Diesel gal | $/gal | |
| | 20% | 250 | 6.6 | $2.27 | $14.95 |

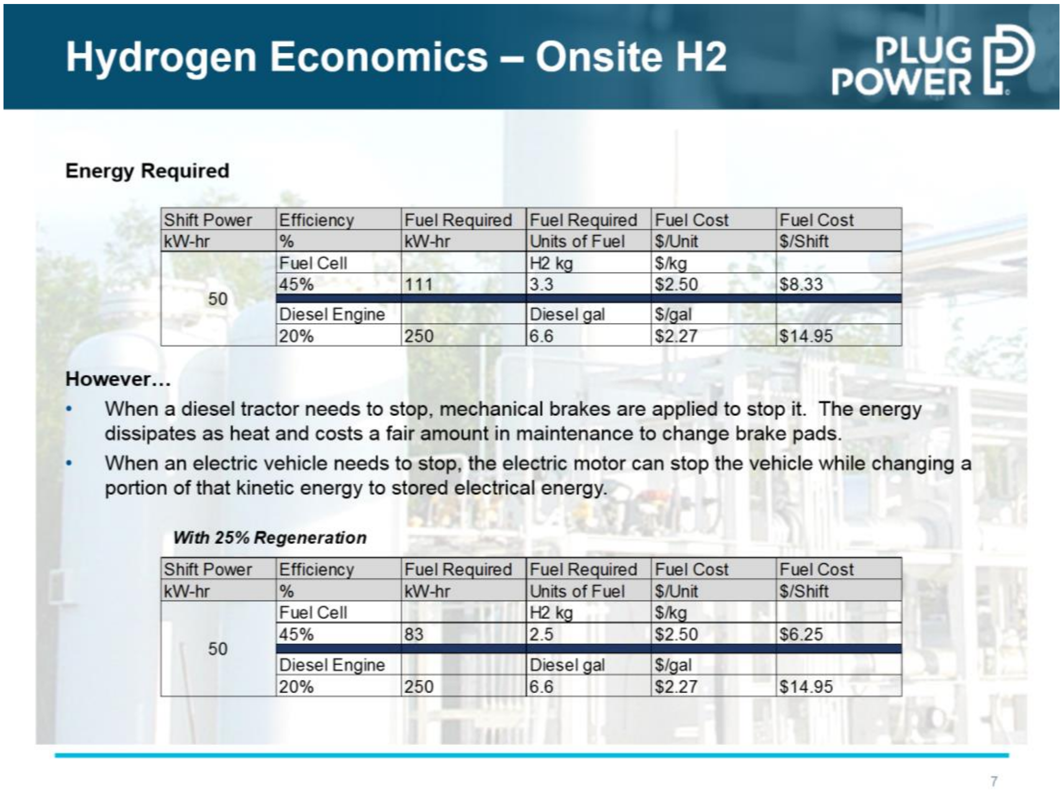
**However…**

- When a diesel tractor needs to stop, mechanical brakes are applied to stop it. The energy dissipates as heat and costs a fair amount in maintenance to change brake pads.
- When an electric vehicle needs to stop, the electric motor can stop the vehicle while changing a portion of that kinetic energy to stored electrical energy.

***With 25% Regeneration***

| Shift Power kW-hr | Efficiency % | Fuel Required kW-hr | Fuel Required Units of Fuel | Fuel Cost $/Unit | Fuel Cost $/Shift |
|---|---|---|---|---|---|
| 50 | Fuel Cell | | H2 kg | $/kg | |
| | 45% | 83 | 2.5 | 5.3 | $13.13 |
| | Diesel Engine | | Diesel gal | $/gal | |
| | 20% | 250 | 6.6 | 2.3 | $14.95 |

6



## Hydrogen Economics – Onsite H2

PLUG POWER

**Energy Required**

| Shift Power kW-hr | Efficiency % | Fuel Required kW-hr | Fuel Required Units of Fuel | Fuel Cost $/Unit | Fuel Cost $/Shift |
|---|---|---|---|---|---|
| 50 | Fuel Cell | | H2 kg | $/kg | |
| | 45% | 111 | 3.3 | $2.50 | $8.33 |
| | Diesel Engine | | Diesel gal | $/gal | |
| | 20% | 250 | 6.6 | $2.27 | $14.95 |

**However…**

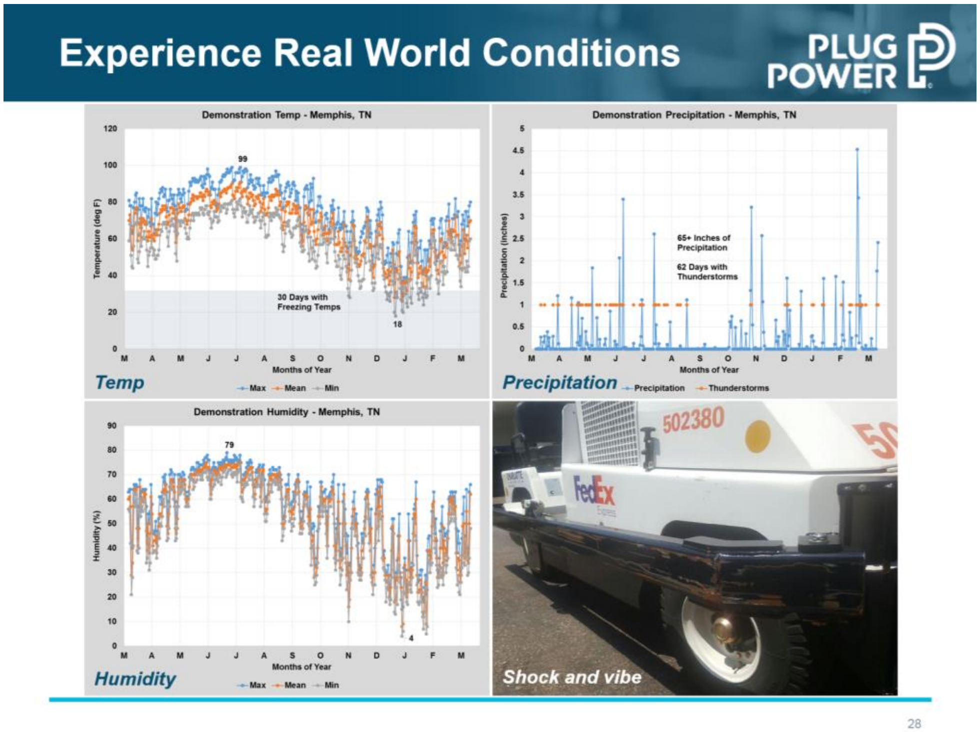
- When a diesel tractor needs to stop, mechanical brakes are applied to stop it. The energy dissipates as heat and costs a fair amount in maintenance to change brake pads.
- When an electric vehicle needs to stop, the electric motor can stop the vehicle while changing a portion of that kinetic energy to stored electrical energy.

***With 25% Regeneration***

| Shift Power kW-hr | Efficiency % | Fuel Required kW-hr | Fuel Required Units of Fuel | Fuel Cost $/Unit | Fuel Cost $/Shift |
|---|---|---|---|---|---|
| 50 | Fuel Cell | | H2 kg | $/kg | |
| | 45% | 83 | 2.5 | $2.50 | $6.25 |
| | Diesel Engine | | Diesel gal | $/gal | |
| | 20% | 250 | 6.6 | $2.27 | $14.95 |

7

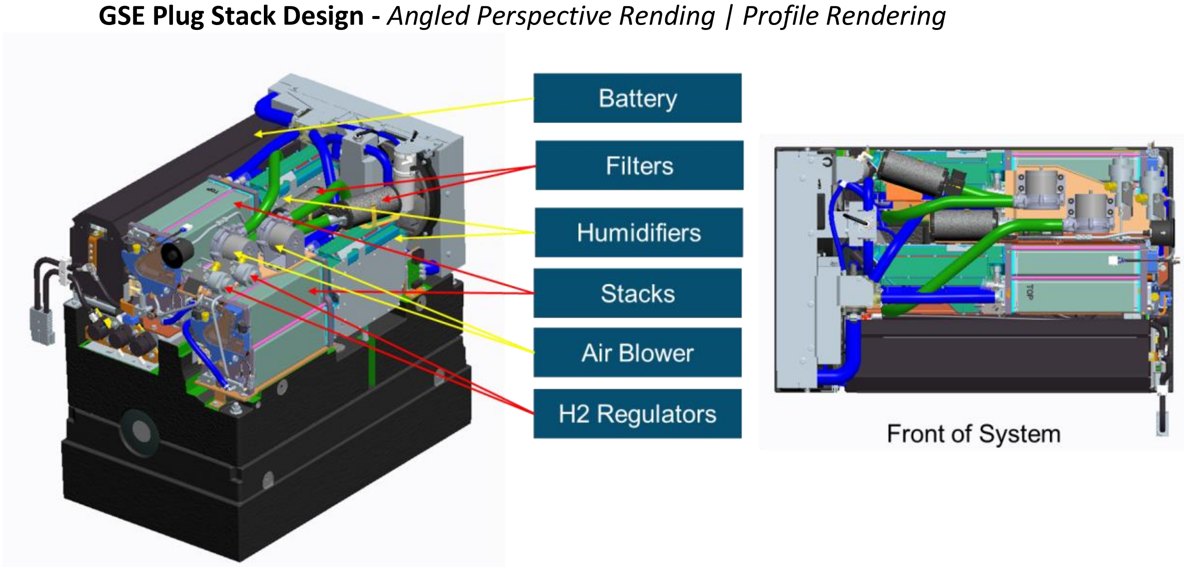
- Summarized the real world conditions the GSE units experienced during the first year
  - 30 freezing days
  - Temperature range: 18 - 99 deg. F
  - Humidity: 4 – 79%
  - Thunderstorms averaged 1/week
  - Regulator shock and vibe




- Annual Merit Review presentation given in Washington D.C.

**Q3 2016**

- Completed re-design of GSE fuel cell system with Plug Power stack
  **GSE Plug Stack Design -** *Angled Perspective Rending | Profile Rendering*




**Q4 2016**

- Completed remanufacture of first fuel cell systems with Plug Power stack

**Q1 2017**

- Redeployed 3 fuel cell systems in Memphis
- Started on-ramp demonstration with Plug stack architecture

**Q2 2017**

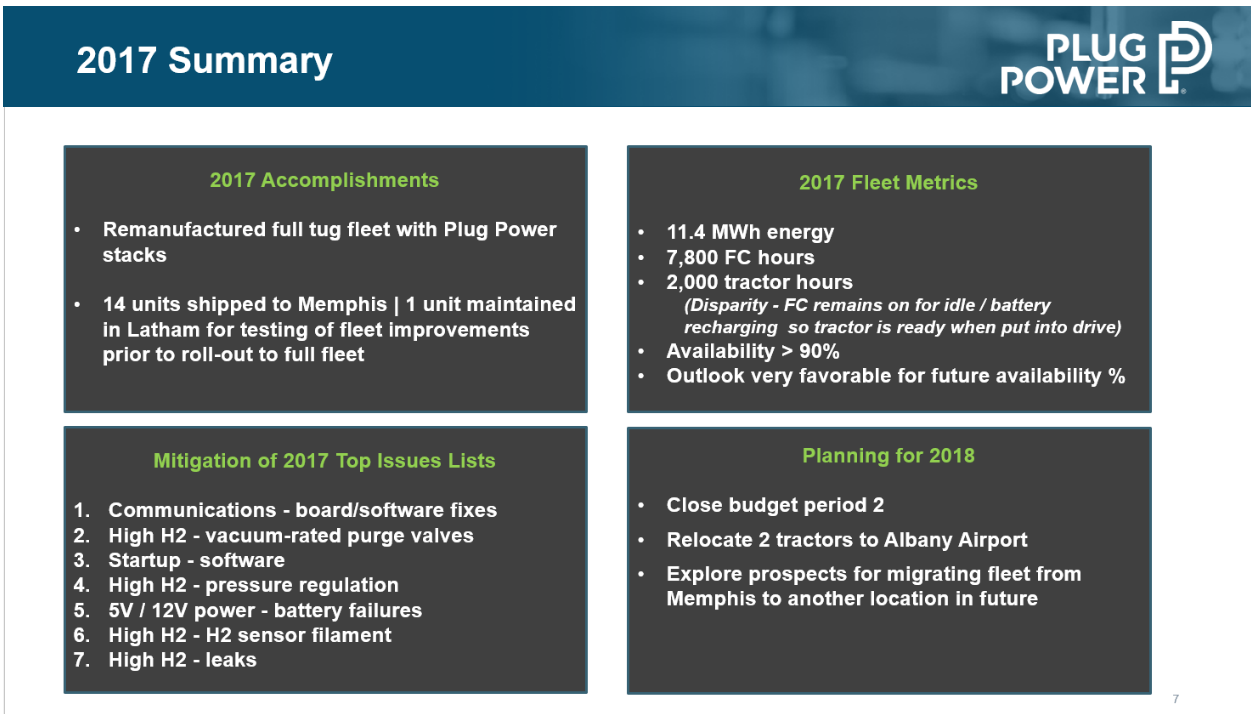
- Continued to expand fleet of Plug stack-based fuel cell units in Memphis

**Q3 2017**

- Continued to expand fleet of Plug stack-based fuel cell units in Memphis
- Sent data to NREL covering first 5 months of redeployment

**Q4 2017**

- Continued to expand fleet of Plug stack-based fuel cell units in Memphis
- Summarized fleet results covering February 2017 through December 2017



## 2017 Summary

| | February | March | April | May | June | July | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Monthly Availability | 95.9% | 97.2% | 97.0% | 94.7% | 97.7% | 77.1% | 92.0% | 87.1% | 81.9% | 86.1% | 84.6% |
| Monthly Day Utilization | 49.4% | 30.6% | 15.0% | 11.3% | 19.3% | 13.7% | 19.2% | 15.7% | 22.0% | 55.8% | 47.6% |
| Monthly Night Utilization | 56.5% | 53.2% | 32.4% | 31.2% | 43.3% | 36.1% | 49.7% | 49.5% | 46.3% | 56.1% | 47.4% |
| Total Energy | 613.6 | 751.1 | 850.8 | 1121.9 | 1814.1 | 1527.6 | 1580.0 | 1452.2 | 1482.9 | 304.9 | 359.6 |
| Total # of Sorts | 90 | 104 | 86 | 94 | 146 | 102 | 126 | 137 | 140 | 318 | 274 |
| Average Energy per Sort | 6.8 | 7.2 | 9.9 | 11.9 | 12.4 | 15.0 | 12.5 | 10.6 | 10.6 | 1.0 | 1.3 |

**Notes:**

- Energy usage per sort increased in early months, mainly attributed to " taking the training wheels off " and using the tractors throughout the airport.
- July was a tough month for service (previously reported, communications issues). The high energy per sort is attributed to counting the complete sort as unit down (red) when some usage occurred during the sort, artificially raising the average.
- Energy per sort appears to be between 10 and 12 kWh as a net of energy out and energy recovery. Data collection in November and December was intermittent. Resulting estimations of usage led to higher sort counts.
- Night sort tends to use the tractors more regularly with night utilization approaching 50%.

8

## Failure | Resolution Summary

GSE Memphis Failures - February to October 2017

| | Shutdown | Count | % | Root Cause | Failure Description | Improvements |
|---|---|---|---|---|---|---|
| 1 | CAN communication | 11 | 31% | Motor Controller Board | Board fails, which causes air blower to stop working and stops stack power generation. | 1. Board re-work (containment)<br>2. Board redesign (long-term fix)<br>3. Software improvements (long-term fix) |
| 2 | High H2 detection (Safety shutdown) | 9 | 25% | Purge Valve | Purge valves exhaust impurities in hydrogen stream from stack. Sometimes purge valves stick open longer than desired, resulting in excessive hydrogen overboard. Safety system shuts down system. | 1. Clean purge valves with alcohol solution to remove impurities that gum up seating of valve (containment)<br>2. Identification of alternate solenoid solutions that have a strong spring to seat the valve in spite of accumulation of impurities (long-term fix) |
| 3 | System does not advance through startup sequence | 5 | 14% | Software | Software gets hung up on a condition not being met for proper stack power export. | 1. Sequence and condition improvements (long-term fix) |
| 4 | Low/high H2 pressure to stack | 3 | 8% | H2 Pressure Regulator | Regulators reduce hydrogen tank pressure down to a specified stack inlet pressure. If the regulation is too low, there is insufficient hydrogen flow, resulting in low stack performance and shutdown. | 1. Monitor H2 pressure in data (containment)<br>2. Adjustment as needed during regular PM checks (long-term fix) |
| 5 | Loss of 5V / 12V to System Control Boards | 3 | 8% | Battery | Battery does not provide the 5V or 12V voltage to power the boards to operate the system. | 1. Rework (containment)<br>2. Root cause analysis on 2 failed batteries |
| 6 | High H2 detection (Safety shutdown) | 2 | 6% | H2 Sensor | The sensor drifts over time due to the materials used. The value in the presence of no hydrogen increases over time. | 1. Monitor H2 value when H2 tank valve is closed (containment)<br>2. Material change in the hydrogen sensor to greatly reduce the sensor drift over time (long-term fix) |
| 7 | High H2 detection (Safety shutdown) | 1 | 3% | H2 tubing leak | Hydrogen leaks from a fitting or tube. | 1. Replacement of failed tubing (containment)<br>2. Redesign of tubing with thicker walls (long-term fix) |
| - | Other | 2 | 6% | | | |
| | **Total** | **36** | **100%** | | | |

10

| Hydrogen Tug Performance Evaluation - Year 1 | | |
|---|---|---|
| Criteria | Metric | Demonstrated Performance |
| Power | Capable of 5,000 lbs. drawbar capacity | Tugs demonstrated the ability to pull up to 50,000 lbs. |
| | | |
| Availability | > 80% | 90.1% (February - December 2017) (Mitigation actions of all failures has been identified, leading to improved availability) |
| | | |
| Run Time | > 1 shift | Tugs achieved 3-4 shifts before running out of fuel. |
| | | |
| Reliability MTBF (Mean Time Between Failures) | > 100 hours | 218 hours (36 failiures over 7,844 hours) |
| | | |
| Speed Rating | 10 mph | 10 mph<br><br>(Tugs could be increased to 19 mph unloaded and 16 mph fully loaded. End user limits speed to 10 mph.) |
| | | |
| Outdoor Operation | No non-recoverable issues | Containment and long-term fixes identified for all failures. |
| | | |
| Hydrogen Fills | 350 bar | 350 bar |
| | | |

**As a result of the redeployment starting February 2017, the fleet demonstrated performance that met or exceed the technical evaluation criteria.**

**Q1 2018**

- Submitted data up to January 2018 showing positive progress with new design.
- Was informed by FedEx that hydrogen infrastructure property was to be repurposed ASAP.
- Began decommissioning of Memphis operation and Hydrogen infrastructure.
- Began investigation of alternate opportunities to deploy fleet (Northeast, Southern California)

**Q2 2018**

- Completed decommission of Memphis operation and Hydrogen infrastructure:
    - Deconstruction and removal of all hydrogen infrastructure.
    - Return of fuel cell systems to Plug Power headquarters.
- Received commitment from FedEx to relocate 2 Fuel Cell Systems at Albany Airport for expanded weather testing.
    - Met with Albany facility Manager of Fleet Maintenance and Ramp Operations Manager to observe facility and discuss operational logistics.
    - Developed a low-risk/obligation fueling plan approved by FedEx and signed contract for fueling transportation services.
    - Cleanup and prep of fuel cells.
    - Awaiting delivery of reconditioned tractors from Charlatte (expected delivery by 8/31). Cabs are being added for cold weather operation.
- Requested project extension.
- Continued exploration of locations and infrastructure funding for further fleet testing in Southern California and Hawaii.

**Q3 2018**

- Planning and coordination with relevant parties for Albany Airport operation of FedEx and Plug Power Latham, NY hydrogen fueling station.
- Submitted request of for approval of completion of Budget Period 2 and commencement with Budget Period 3 with a revised scope and project extension to allow 6 months of operation.

**Q4 2018**

- Received approval of Budget Period 2 completion.
- Charlatte reconditioned CT5E baggage tractors received in Latham, NY for fuel cell integration.
- Fuel cells completed verification.
- Conducted hydrogen refueling testing and training of personnel.
- Updated project Safety Plan for Budget Period 3 and received approval from DOE.
- Submitted revised SOPO and associated documents to DOE.
- Continued to explore other locations in the FedEx network to deploy remaining hydrogen powered ground support equipment.

**Q1 2019**

- Cold weather cabs for the CT5E baggage tractors were delivered on 1/7. Initial inspection showed 1 cab had the windshield broken in transit.
- Initial fit-up of cold weather cabs showed they were not properly designed for the required side hitch arrangement used on the tractors at the Albany airport. Additionally, the Operator Interface for the GenDrive had to be routed into the cab. The modifications and repairs to the cabs delayed the start date of the demonstration phase by 1 month.


- Completed hydrogen safety training with FedEx on 2/11.
- Completed tow truck driver training and had CT5E tractors delivered to Albany Airport on 2/14.
- First exclusive use of CT5E tractors at Albany was on 2/19.

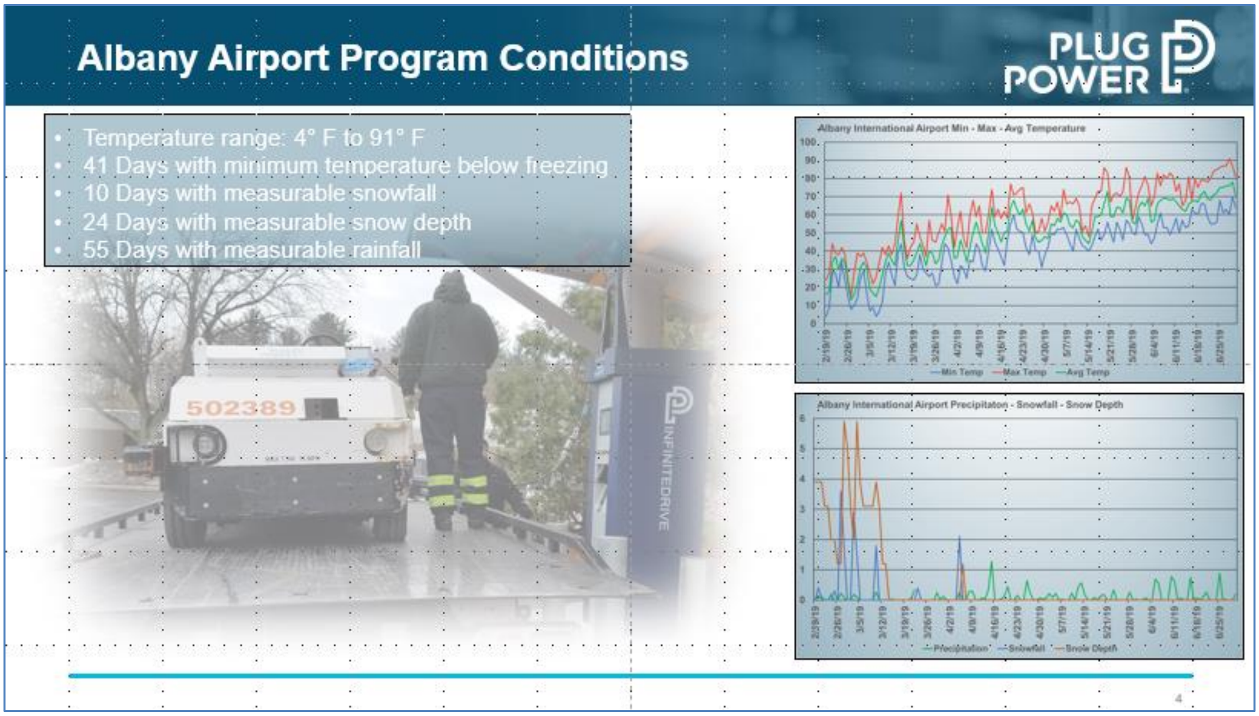

- Continued operation of the 2 CT5E tractors through end of quarter.

**Accomplishments During Final Reporting Period**

**Q2 2019**

- Continued operation of the 2 CT5E tractors through end of quarter.
  - Limited hours logged during quarter due to the low usage of FedEx's operation
    - 2 shifts Tuesday-Friday & 1 shift Saturday – limited aircraft
    - Many days/shifts only required single tractor
  - Shuttled to Plug Power Facility for refueling
  - Met all operational requirements at FedEx Albany
  - Used dispatch resources for any fuel cell maintenance tasks
- Completion of Task 7B at the end of the 6 months demonstration phase in Northern climate.
  - 41 operational days with temperatures below freezing

- 10 days with measurable snowfall
- Provided further verification of the redesigned fuel cells performed as expected in the duty cycle at the airport and in the Northern climate.
- Were unable to place any additional fuel cells into GSE service.




- Completion of Task 9.
  - FedEx's decision on continuing operation was weighted heavily on available hydrogen infrastructure and the fact that Albany operation was very small. Ultimately, FedEx decided to return to their normal baggage tractors for the Albany operation. A more demanding operation than Albany requiring multiple shifts and more baggage tractor hours per shift would improve the value to the end operator.
    - Decision factors of continued operation:
      - Not viable to install hydrogen infrastructure for two or even one baggage tractor
      - Limited use of baggage tractors at Albany is served by internal combustion tractors even though on a per unit basis the internal combustion tractors are less efficient and have significant emissions
      - No implications of cold weather operation
  - The economics of operation at Albany did not prove a business case for FedEx. Acknowledgement of more demanding airports with continuous operations and a larger number of baggage tractors would be feasibly supported with hydrogen and fuel cells. The economics from the earlier demonstration phases of the program were updated with current cost factors and are shown in Section 6 of this report.

## 5. Lessons Learned

This project has spanned enough time to see evolution in the technology and market conditions. From a technical perspective, there has been generational improvements in the Proton Exchange Membrane (PEM) fuel cell technology used in this program. As demonstrated in the program, selecting the correct fuel cell components and architecture are critical to a successful application of the technology. Plug Power's experience with using an "shrink-wrapped" stack in the initial design was, in fact, a tough lesson in adapting components for a specific product architecture. The migration to the Plug Power internally developed stack showed marked improvement in reliability and serviceability of the fuel cell units in the GSE tugs. During the elapsed time of the program other product and technology improvements have been made by Plug Power and other suppliers of fuel cell technology.

Tied partially to the improvements in technology are significant component level and system cost reductions in the same timeframe. Additional, supply chain cost reductions have also been achieved. Results of these improvements have reduced initial CAPEX on the fuel cell solution by about 30% over the project duration.

The market conditions have certainly changed during this project. The sustainability pressures have increased dramatically over the last few years. This project originally was focused on a fuel cell to diesel internal combustion power comparison. This is still a valid and valuable comparison therefore the financial comparison is refreshed in Section 6 of this report. However, the rate of change in the market moving from internal combustion to electric has dramatically changed from 2013 to 2019. Freight carriers like FedEx as well as passenger carriers at airports around the world are much more focused on sustainability and emissions today than 2013, thus moving entire fleets to electric power. The OEMs of ground support equipment are also providing an accelerating number of their total portfolio as electric. With fully electric ground support equipment, the migration from battery electric to hydrogen fuel cell is significantly simplified over converting internal combustion directly to hydrogen power.

Summary of Lessons Learned

- Definition of and knowledge a product's application is critical to bring robust products to market.
- Generational product improvements are sometimes necessary to match market expectations
  - 2nd generation redesign was faster to market and met more requirements
- The fuel cell powered tugs performed as well or better than internal combustion powered equipment
  - **Even initial design met operational goals relating to power, ground speed, towing capacity, outdoor operation, hydrogen refilling, and runtime**
  - **2nd generation redesign met reliability and availability goals**
- Operator feedback in almost all cases was positive regarding using the fuel cell power tugs, being preferred over internal combustion
- Proved outdoor operation of fuel cell power over wide range of conditions and temperature at both Memphis and Albany
- Hydrogen is a viable fuel solution for airports
  - Permitting process was not significantly different than other applications
  - It can be safely used on airports, like other widely used liquid or gaseous fuels

- The market conditions are not static and evolve from economic, regulatory, and sustainability influences
- New technology cost reduction curves help compete against incumbent technology
- Integration of the fuel cell system/controls more tightly with the GSE will improve the user experience
- To be a ubiquitous power solution for airports, a fuel cell must have cold storage/cold start capability
  - The proposed development of this feature was not approved when the project scope change was done in 2018
- Validated energy requirement for full-shift operations
- Validated power requirements for starting, acceleration, and steady speed operation at different towing loads
- Gathered data and provided comparison on value proposition between fuel cell and diesel-powered tugs
- Airport operations and needs are different even with the same Operator, e.g. Memphis and Albany were not carbon copies

FedEx provided the following summary statement of their experience with the fuel cells: ***"During this project there have been many stumbling blocks. While in Memphis, the Users at FedEx liked the Fuel Cell cargo tractors because they were quiet, did not smell of diesel exhaust and took only as long as a traditional ICE tug to fuel. Once the Fuel Cells were rebuilt with a Plug Power stack, the reliability of the fueling system improved and showed a lot of promise. Due to operational changes, the tugs were moved to Albany, New York to continue the evaluation and prove themselves in colder weather. Their performance was very reliable, and the Users seemed very accepting of the technology."***

## 6. Conclusions

This project experienced two significant and unforeseen issues requiring adjustments and revisions to accomplish the original objectives. The original fuel cell design had reliability issues that required redesign, and in the end, Plug Power replaced all fuel cell systems with internally developed technology. The second hurdle was the change in plans at the Memphis airport requiring the project shutdown, revisions, and restart. The relocation of two individual tugs to the Albany was realistically just a consolation to garner some cold weather data. The last six months of operation at Albany did provide some real-world experience in a cold climate but generated very limited statistical data due to limited run hours.

Even with challenges, the project was able to meet the original objectives, restated below, and demonstrate the viability of hydrogen powered ground support when compared with incumbent internal combustion powered equipment.

- To create a hydrogen fuel cell-based solution as a cost-competitive and more energy-efficient tugs compared to the incumbent internal combustion engine-powered vehicles.
- To enable airport end users to accomplish their daily tasks with a hydrogen fuel cell solution while reducing consumption of gasoline and diesel fuels, reducing U.S. demand for petroleum.

- To demonstrate lower carbon emissions with the fuel cell solution
- To demonstrate a value proposition that shows decreased energy expenditures when compared to diesel-powered airport vehicles

The updated financial comparison model is shown below reflecting updated capital costs, Tax Credit information, and fuel costs. The model continues to show the advantages of hydrogen powered ground support equipment over internal combustion in a realistic high-demand application.

**GSE Economics - Updated 2019/2020**

| | | | | |
|---|---|---|---|---|
| Fuel Cell CapEx | | Usage | Days/Year | 312 |
| Tractor | $25,000 | Usage | Shifts/Day | 2 |
| Fuel Cell | $35,000 | Regeneration | % | 20% |
| Tax Credit** | -$9,100 | | | |
| Total FC Solution | $50,900 | * Assumes maintenance is a wash | | |
| | | ** Fuel Cell Tax Credit =26% in 2020 | | |
| Diesel CapEx | | | | |
| Base Tractor | $30,000 | | | |
| Emissions Upgrade | $10,000 | | | |
| Diesel Solution | $40,000 | | | |
| | | | | |
| CapEx Premium* | $10,900 | | | |

**Liquid H2 vs. Current Diesel Price**

| Shift Power | Efficiency | Fuel Required | Fuel Required | Fuel Required | Fuel Cost | Fuel Cost |
|---|---|---|---|---|---|---|
| kW-hr | % | kW-hr | kW-hr | Units of Fuel | $/Unit | $/Shift |
| 50 | Fuel Cell | | w/ Regen | H2 kg | $/kg | |
| | 45% | 111 | 89 | 2.7 | $5.25 | $14.00 |
| | | | | | | |
| | Diesel Engine | | | Diesel gal | $/gal | |
| | 20% | 250 | 250 | 6.6 | $3.00 | $19.76 |

**Onsite H2 vs. Current Diesel Price**

| Shift Power | Efficiency | Fuel Required | Fuel Required | Fuel Required | Fuel Cost | Fuel Cost |
|---|---|---|---|---|---|---|
| kW-hr | % | kW-hr | kW-hr | Units of Fuel | $/Unit | $/Shift |
| 50 | Fuel Cell | | w/ Regen | H2 kg | $/kg | |
| | 45% | 111 | 89 | 2.7 | $2.75 | $7.33 |
| | | | | | | |
| | Diesel Engine | | | Diesel gal | $/gal | |
| | 20% | 250 | 250 | 6.6 | $3.00 | $19.76 |

The original plan for this project has proven quite insightful to the evolving market and commercial potential for hydrogen powered ground support equipment. Numerous commercial evaluations and demonstrations are underway as of 2019. The motivation for low or zero emission power and propulsion systems on airports is much greater today than at project inception and this project and its findings established baseline for ongoing work with hydrogen powered ground support equipment.

## 7. Products

### A. Publications, Conference Papers, and Presentations

A presentation entitled “MT011_PETRECKY_2013_o” was given at the 2013 Annual Merit Review in Washington, DC. The DOE has a record of this presentation.

A 2-page summary was provided for the 2013 DOE Hydrogen and Fuel Cells Annual Progress Report to Lindsay Steele at Pacific Northwest National Laboratory (PNNL)

A presentation entitled “MT011_PETRECKY_2014_o” was given at the 2014 Annual Merit Review in Washington, DC. The DOE has a record of this presentation.

A 2-page summary was provided for the 2014 DOE Hydrogen and Fuel Cells Annual Progress Report to Lindsay Steele at Pacific Northwest National Laboratory (PNNL)

A presentation entitled “MT011_PETRECKY_2015_o” was submitted in preparation for the 2015 Annual Merit Review in Washington, DC. The DOE has a record of this presentation.

A presentation entitled “MT011_PETRECKY_2016_o” was submitted in preparation for the 2016 Annual Merit Review in Washington, DC. The DOE has a record of this presentation.

A presentation entitled “MT011_PETRECKY_2017_o” was submitted in preparation for the 2017 Annual Merit Review in Washington, DC. The DOE has a record of this presentation.

A presentation entitled “MT011_PITTS_2018_p” was submitted in preparation for the 2018 Annual Merit Review in Washington, DC. The DOE has a record of this presentation.

### B. Inventions, Patent Applications, and Licenses

None.

### C. Website(s)

None.