Center for Transportation Infrastructure and Safety

Show Me the Road to Hydrogen

by

John W. Sheffield

NUTC
R204

A National University Transportation Center
at Missouri University of Science and Technology

Disclaimer

Technical Report Documentation Page

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16. Abstract

The Missouri University of Science and Technology (Missouri S&T) and Ford Motor Company demonstrated a shuttle bus service and hydrogen fueling facilities in rural Missouri near Ft. Leonard Wood. Initiated by a request from the U.S. Army Maneuver Support Center (MANSCEN) at Ft. Leonard Wood (FLW), Missouri S&T helped establish a commuter bus service between FLW and the neighboring town of Rolla which is located about 25 miles from the military base on Interstate-44. With funds provided by the Defense Logistics Agency through the Air Force Research Laboratory, this hydrogen initiative contracted with Air Products and Chemical, Inc. to supply a temporary hydrogen fueling facilities and later with Gas Technology Institute to design and build a hydrogen fueling facility with on-site generation of hydrogen in Rolla. The NUTC matching funds were used to offset the cost of two hydrogen-fueled Ford E-450 shuttle buses.

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1. Background

The Missouri University Science and Technology (Missouri S&T), through a hydrogen internal combustion engine vehicle evaluation participation agreement with the Ford Motor Company, operated a shuttle bus service and a hydrogen refueling station in rural Missouri. Initiated by a request from the U.S. Army Maneuver Support Center at FLW, Missouri S&T initiated a broad research, training, and education agenda for the rural hydrogen transportation test bed is to develop, demonstrate, evaluate, and promote safe hydrogen-based technologies in a real-world environment. With additional funds provided by the Defense Logistics Agency through the Air Force Research Laboratory, this hydrogen initiative built and operated a hydrogen fueling facility that includes on-site generation of hydrogen. The NUTC matching funds were used to offset the cost of two hydrogen-fueled Ford E-450 shuttle buses.

2. Objectives

The Missouri rural hydrogen transportation test bed has the following technical objectives:

- To collect and evaluate real-world data to address safety and environmental issues, develop statistically validated codes and standards, formulate policies and regulations, and understand reliability and large-scale deployment of hydrogen technology under diverse operating conditions;
- To develop, validate, and transition to a manufacturing environment, commercially ready, non-destructive testing technologies for hydrogen storage and transport systems;
- To test, demonstrate, and validate hydrogen vehicles, hydrogen transportation infrastructure, and vehicle and infrastructure interfaces for complete system solutions;
- To gain public acceptance to the use of safe alternative energy sources to power the transport system that is independent of the fossil fuel supplies;
- To integrate research results into a comprehensive undergraduate and graduate curriculum to educate the future workforce on hydrogen technologies;
- To develop and implement an outreach program, in collaboration with other national programs, which has a special emphasis on safety training for operators, maintainers, code officials, and first emergency responders at the local and state levels.

3. National University Transportation Center

The recent establishment of the National University Transportation Center (NUTC) at the Missouri University Science and Technology (Missouri S&T) under the "Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users," expands the research and education activities to include alternative transportation fuels and other issues that are at the forefront of society and the national agenda. A holistic approach will be taken to address not just the technology but also public perception, permitting, safety standards, and education and training. A key partner already engaged is the National Association of State Fire Marshals (NASFM) that regards this initiative as an "excellent candidate for the model approach to introducing hydrogen to communities." The tasks identified in five areas, viz., Infrastructure Development and Deployment, High-Pressure Composite Cylinders, Inspection and Monitoring, Statistically Validated Codes and Standards, and Safety, constitute a comprehensive research, development and demonstration program to address some of the challenges described in the U.S. Department of Transportation (DOT) Hydrogen Roadmap 2005 "Research, Development, Demonstration, & Deployment Roadmap for Hydrogen Vehicles & Infrastructure to Support a Transition to a Hydrogen Economy".

This initiative built on previous studies on manufacturing of composites, non-destructive testing and evaluation, expands the current theme of the NUTC at Missouri S&T. The preliminary activities were aimed at initiating the research related to the development of a rural hydrogen transportation test bed that will demonstrate, evaluate and promote hydrogen-technologies in a real-world environment, including:

- On-site generation of hydrogen from ethanol
- Modeling of composite hydrogen storage cylinders using finite element analysis
- Non-destructive testing and evaluation (NDT&E)
- High voltage disconnect systems (HVDS)
- Statistically-validated codes and standards - stationary fuel cells
- Hydrogen safety of transportation vehicles
- Blast wave modeling

The NUTC strategic plans seek to address national needs in the area of transportation infrastructure and safety focusing on the following topical areas:

- Advanced materials
- Transition-state fuel vehicle infrastructure
- Non-destructive evaluation (NDE) technologies and methods

Within the topical area of "Transition-state fuel vehicle infrastructure" which focuses on hydrogen as a transportation fuel, two critical tasks have been identified as follows:

- Development of safety codes, standards, and regulations
- Infrastructure development and deployment

The NUTC plans to support proposals in the areas of advanced materials, transition-state fuel vehicle infrastructure, and NDE technologies and methods with the objective of advancing the state-of-the-art of transportation infrastructure and safety. One example is the modeling of composite hydrogen storage cylinders as pressurized hydrogen storage cylinders are a critical component of hydrogen transportation systems (vehicle fuel systems, bulk commodity transport, portable storage, and stationary storage). These cylinders also have pressure/thermal relief devices (P/TRDs) that are activated in case of an emergency. Recent studies illustrated the ongoing development of comprehensive finite element analysis tool for the modeling, simulation, and design optimization of composite hydrogen storage cylinders for safe installation and operation. For example, by using of a neural network model, one can effectively predict the burst pressure of these composite hydrogen storage cylinders undergoing thermal loading. To date, the researchers at Missouri S&T have applied their two-dimensional, shear deformable, composite shell model for static finite element analysis, thermo-mechanical analysis, dynamic analysis and failure analysis. Their ongoing tasks include the extension to three-dimensional analysis accounting for hydrogen with fluid-structure interactions; three-dimensional failure analysis/life prediction due to thermo-mechanical dynamic loading; impact analysis; nonlinear analysis with geometric nonlinearity (large deformation) and material nonlinearity (plasticity for aluminum liner and visco-plasticity for polymer liner); and the design optimization using neural network models.

4. Energy trends in the U.S.

In the U.S., it should be noted that DOT has authorities, regulatory responsibilities and expertise for vehicle safety and fuel economy, and for pipeline and hazardous material safety, including the safety of hydrogen fueled vehicles and hydrogen storage in vehicles, as well as the safe transportation and distribution of hydrogen. While the U.S. Department of Energy (DOE) is the federal government agency responsible for light-duty vehicles in U.S., it is the DOT which is responsible for heavy-duty vehicle research and provides capital funds to support, and to maintain the safety of the Nation's transportation infrastructure including the development of the hydrogen distribution and delivery system. Because DOT has primary responsibility for pipeline safety and transportation of hazardous materials, it must also coordinate the concurrent development of the infrastructure to support the pace of commercially available vehicles, and the pact of local production, storage and protection of energy using hydrogen.

The safety of the entire transportation system will be essential for the success of hydrogen as an emerging alternative transportation fuel. Accordingly, DOT has a vital role in developing, promulgating, and enforcing regulations in various aspects of transportation operations. In a small way, the rural hydrogen transportation test bed in Missouri will be addressing the issues and processes important for the transition to a hydrogen economy while maintaining the current high standard of safety, reliability, and public confidence in this rural transportation system. The project seeks to confirm the validity of the procedures and standards for the safe use and transport of hydrogen in transportation vehicles. Many believe that hydrogen safety codes and standards should be performance-based and systems-oriented and that the hydrogen safety codes and standards be designed to apply to general product applications as opposed to prescriptive, type-specific regulations for each application. Thus these new hydrogen codes and standards are being developed based on sound scientific knowledge of hydrogen effects on material properties and behavior. Finally, these new hydrogen codes and standards must address both the design and operation of transportation systems, subsystems, components, and consumer devices.

Public acceptance of hydrogen fueled vehicles will dictate fuel system integrity, vehicle safety, and crashworthiness performance equal or superior to the existing petroleum fuel currently in use. The challenges for developing safety codes, standards, and regulations for hydrogen fuel systems include the need for substantial research in understanding and anticipating the effects of hydrogen on various materials. The full-scale demonstration projects must be designed to research the complex systems operations, performance, reliability, and costs. Cross-cutting research is also required to examine the effects of hydrogen on conventional and composite materials (i.e., stainless steel alloys and carbon composites, respectively) including the effects of temperature, pressure ranges, and fluctuations. In addition, the effects of atmospheric and vehicle environmental stressors such as humidity, temperature, airborne and waterborne contaminants (acids, salt compounds, etc.), dirt, vibration, and shock on material integrity need to be fully understood before the standards for hydrogen use and transport can be promulgated. Inspection technologies must also be developed to detect and maintain the integrity of hydrogen fuel and commodity transport systems. The standards and regulations actions will rely on data collected from a diverse set of research and demonstration projects, including those conducted or funded by DOE, Environmental Protection Agency (EPA), Department of Defense (DOD), and DOT in U.S. as well as others international sources. Although basic knowledge and early research and development on materials behavior can be shared across the modes and used for many purposes, regulations should be specific to the application and will be developed independently by the appropriate operating organizations, in collaboration with relevant standards organizations.

5. Hydrogen demonstration project

Although significant demonstration projects are on-going with hydrogen highways in California, Florida and urban locations such as Washington DC, there is still much to do to address issues related to the real-world and practical applications of standards, safety, and public acceptance of these new systems in rural applications. The state of Missouri is ideally suited to develop and demonstrate the proper operation of hydrogen highways in a rural setting which represents over 25% of the nation's transportation needs and which is not well-represented in the current major national projects in the U.S. Missouri S&T is especially well positioned to focus on rural applications. Based on the interest and encouragement from DOT, the NUTC at Missouri S&T redirect significant resources toward initiating this important task. Other key partners include the National Association of State Fire Marshals, the Missouri State Fire Marshall, the Missouri Department of Transportation (MoDOT) and the Missouri Transportation Institute (MTI).

A new rural commuter bus service was established in May 2007 serving a large military installation (FLW) from the neighboring town of Rolla located about 25 miles away on U.S. Interstate-44 highway. The need for this commuter bus service has resulted from a significant growth in the FLW population, which has almost doubled to around 40,000 people at FLW. The increase in commuter traffic, coupled with the U.S. Army's interest in reducing single-occupant auto trips to FLW and its willingness to provide each federal employee with a monthly tax-free benefit, make the long-term operation of this commuter bus service viable. The hydrogen shuttle buses were used in a local service within the Rolla community because of range limitations.

The hydrogen internal combustion engine (H2ICE) vehicle participation agreement with the Ford Motor Company provided two Ford E450 H2ICE shuttle buses with the following specifications:

1.	Vehicle description	E450 Cutaway Shuttle Bus
2.	Configuration	Shuttle Bus (Body by Corbeil Enterprises)
3.	Wheelbase	176" WB
4.	Body style	Shuttle Bus Body on E450 Chassis
5.	Passenger capacity	12 passengers
6.	Vehicle length	301.5 inches
7.	Vehicle width	96 inches
8.	Vehicle height	112.5 inches
9.	Frontal overhang	30 inches
10.	Rear overhang	95.5 inches
11.	Fueling location	Left rear side
12.	Engine displacement	6.8L V10 Engine , Supercharged
13.	Engine horsepower	235 HP
14.	Engine torque	310 ft.-lbs.
15.	Transmission	Automatic, 5R110W
16.	Final drive ratio	4.56:1
17.	GVW	14,050 lbs./ 6375 kg
18.	Emission level	0.2 gm / BHP-hr NOx (target)
19.	Fuel capacity	30 kg of gaseous hydrogen at 5000 psi
20.	Vehicle range	150 miles
21.	Tank configuration	Rear of vehicle above frame
22.	Fuel tanks	Dynetek W205 Type 3 (carbon fiber, metal liner)

In order to achieve public acceptance of hydrogen-fueled vehicles, an outreach program is being developed and implemented that promotes production, distribution, and use of hydrogen as a transportation fuel, integrates with existing structure, regulatory processes, public understanding, and emergency response systems, and has a special emphasis on safety training for local and state officials, first responders, general public, and operators/maintainers in collaboration with other national programs. A broad range of safety education and training activities on best practices was implemented for effectively supporting the deployment of hydrogen vehicles and related infrastructure.

Table 1 provides a summary of the major milestones for the ShowMe the Road to Hydrogen project.

Table 1. Major Milestones of the ShowMe the Road to Hydrogen Project

No.	Major Milestone of Project	Date
1.	Commuter Bus Service (non hydrogen) for FLW Established	May 07
2.	Temporary Hydrogen Air Products HF 150 Mobile Refueler Utilized	May 07
3.	Ford H2 Internal Combustion Engine Buses Utilized for Missouri S&T Campus Shuttle	June 07
4.	First Responder Training Completed (St. Robert and Rolla)	July 07
5.	Air Products Contract Negotiations for Fixed H2 Fueling Station Deemed Unsuccessful	Oct 07
6.	Contract Signed with Gas Technology Institute for Fixed H2 Fueling Station - Steam Methane Reforming (15 kg/day)	Dec 07
7.	US DOT RITA Administrator Paul Brubaker Toured Facilities (21^{st} - 22^{nd})	Feb 08
8.	H2 Bus Showcased at Ozarks New Energy Conference in Springfield, MO (22^{nd})	Feb 08
9.	FLW H2 Commuter Bus Service Initiated	Aug 08
10.	H2 Caravan Stop at FLW for Hydrogen Road Tour 2008 (Aug 19^{th})	Aug 08
11.	H2 Caravan Stop and Ride-&-Drive at Rolla for Hydrogen Road Tour 2008 (Aug 19^{th})	Aug 08
12.	Gov. Blunt Sign Energy Proclamation on 1^{st} Day of Energy Month in Missouri	Oct 08
13.	Hydrogen Station Off-line for Steam Methane Reformer Retrofit (Safety Redesign)	Nov 08- Mar 09
14.	Steam Methane Reformer Mobile Hydrogen Unit Re-installed (22^{nd})	April 09
15.	H2 Bus Showcased at Missouri Energy Summit in Columbia, MO (22^{nd} – 23^{rd})	April 09
16.	H2 Production Start-up via Steam Methane Reformer (23^{rd})	April 09
17.	FLW H2 Commuter Bus Service Re-initiated	April 09
18.	Conclude Project	Dec 09

The Appendix provides a set of twenty-six figures documenting numerous details of the project.

6. Conclusions

This Missouri Rural Hydrogen Transportation Test Bed builds on previous studies on manufacturing of composites, non-destructive testing and evaluation, and expands the current theme. This initiative initiated research related to the development of a rural hydrogen transportation test bed that will demonstrate, evaluate and promote safe hydrogen-based technologies in a real-world environment. Lessons learned and technologies developed will be transferred to support larger efforts, and critical links will be maintained with other hydrogen centers.

Appendix

2006 E-450 H2ICE Shuttle Bus Performance

Vehicle: USAMissouri-Rolla035
Time Zone: America/Indiana/Vincennes

Status: No Service Required
Created: Sun 14 Oct 2007 01:10:05

Serial Number 035-VP-0005

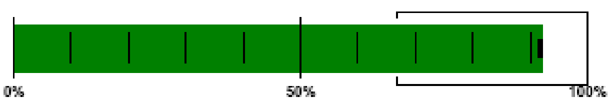
Messages

Average statistics: 11.4 mi/day, 58.00 kRevs/day (computed over last 28 days)

*Note: The fuel economy calculation algorithm is still in development - fuel economy data plotted in the fuel consumption graph may contain outliers (perhaps 2% of the points).

Maintenance

Oil Level



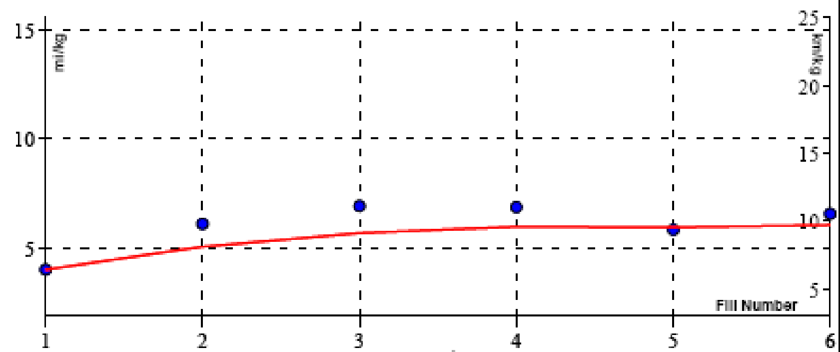
Last OilChange 01 Jan 2007 1mi 2km

Oilchange due at

Oil Life Used: Not Calculated

Fuel

Post Refuel Keyon	Fuel Used kg
10-Oct-07 13:15	7.1
08-Oct-07 10:17	5.8
08-Oct-07 07:52	10.5
30-Sep-07 14:33	16.6
20-Sep-07 07:44	20.9
11-Jul-07 10:39	2.6



Fuel Consumption* (Last 6 fills)

Time and Distance

		Sun 07 Oct	Mon 08 Oct	Tue 09 Oct	Wed 10 Oct	Thu 11 Oct	Fri 12 Oct	Sat 13 Oct	Sum	Life Totals
Time (engine running)		-	02h 03m	-	02h 36m	-	01h 46m	-	06h 26m	33h 41m
Dist	mi	-	19.4	-	46.3	-	29.0	-	94.7	616.2 mi
	km	-	31.2	-	74.4	-	46.7	-	152.4	991.7 km
Revs	k	-	157.76	-	209.27	-	144.99	-	512.02	2551.7 kR

Questions/Comments: h2bus@ford.com
Document Version: VP-1-0

Figure A-1. Hydrogen Bus #35 Performance Report

2006 E-450 H2ICE Shuttle Bus Performance

Serial Number 036-VP-0005

Vehicle: USAMissouri-Rolla036
Time Zone: America/Indiana/Vincennes

Status: No Service Required
Created: Sun 14 Oct 2007 01:10:05

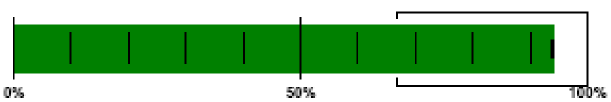
Messages

Average statistics: 11.8 mi/day, 60.00 kRevs/day (computed over last 28 days)

*Note: The fuel economy calculation algorithm is still in development - fuel economy data plotted in the fuel consumption graph may contain outliers (perhaps 2% of the points).

Maintenance

Oil Level



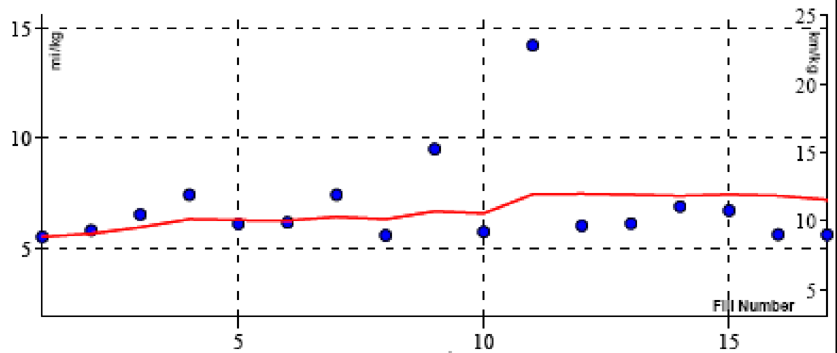
Last OilChange 01 Jan 2007 1mi 2km

Oilchange due at

Oil Life Used: Not Calculated

Fuel

Post Refuel Keyon	Fuel Used kg
11-Oct-07 10:09	5.1
10-Oct-07 13:29	5.3
05-Oct-07 10:23	14.7
30-Sep-07 14:16	12.7
20-Sep-07 10:47	5.2
19-Sep-07 10:25	4.3
18-Sep-07 10:26	4.1
12-Sep-07 10:32	4.8
10-Sep-07 10:42	5.4
06-Sep-07 10:28	2.9



Fuel Consumption* (Last 17 fills)

Time and Distance

		Sun 07 Oct	Mon 08 Oct	Tue 09 Oct	Wed 10 Oct	Thu 11 Oct	Fri 12 Oct	Sat 13 Oct	Sum	Life Totals
Time (engine running)		-	-	01h 45m	00h 00m	01h 57m	-	-	03h 44m	60h 55m
Dist	mi	-	-	23.0	0.2	28.4	-	-	51.6	1205.6 mi
	km	-	-	37.0	0.3	45.7	-	-	83.0	1940.2 km
Revs	k	-	-	132.89	0.77	155.79	-	-	289.45	4727.1 kR

Questions/Comments: h2bus@ford.com
Document Version: VP-1-0

Figure A-2. Hydrogen Bus #36 Performance Report

2006 E-450 H2ICE Shuttle Bus Performance

Vehicle: USAMissouri-Rolla035
Time Zone: America/Indiana/Tell_City

Status: No Service Required
Created: Sun 19 Apr 2009 11:00:01

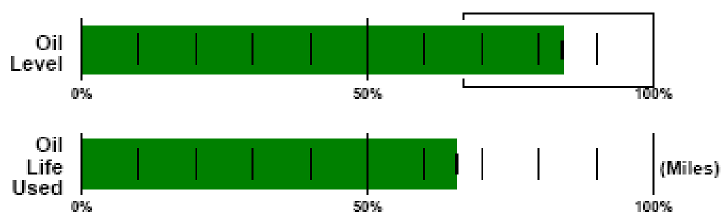
Serial Number 035-VP-0089

Messages

Average statistics: 1.2 mi/day, 4.00 kRevs/day (computed over last 28 days)

*Note: The fuel economy calculation algorithm is still in development - fuel economy data plotted in the fuel consumption graph may contain outliers (perhaps 2% of the points).

Maintenance

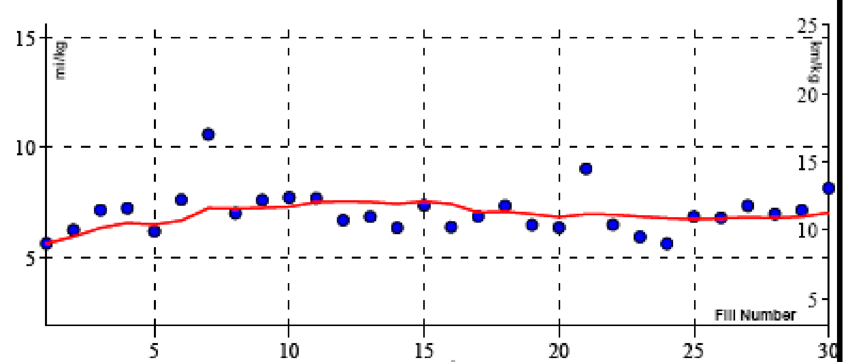


Last OilChange 20 Jun 2007 110mi 177km

Oilchange due at 09 Aug 2011 3110mi 5005km

Fuel

Post Refuel Keyon	Fuel Used kg
16-Oct-08 14:51	9.4
19-Aug-08 05:41	5.3
09-May-08 10:23	5.3
07-May-08 08:38	11.0
29-Apr-08 10:05	8.9
25-Apr-08 08:31	22.8
15-Apr-08 12:20	13.1
22-Feb-08 20:59	1.3
14-Feb-08 10:14	3.5
14-Feb-08 08:36	6.1



Fuel Consumption* (Last 30 fills)

Time and Distance

	Sun 12 Apr	Mon 13 Apr	Tue 14 Apr	Wed 15 Apr	Thu 16 Apr	Fri 17 Apr	Sat 18 Apr	Sum	Life Totals
Time (engine running)	-	-	-	-	-	-	-	-	109h 36m
Dist mi	-	-	-	-	-	-	-	-	2073.0 mi
Dist km	-	-	-	-	-	-	-	-	3336.1 km
Revs k	-	-	-	-	-	-	-	-	8720.3 kR

Questions/Comments: h2bus@ford.com
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Figure A-3. Hydrogen Bus #35 Performance Report

2006 E-450 H2ICE Shuttle Bus Performance

Vehicle: USAMissouri-Rolla036 | Status: See Messages
Time Zone: America/Indiana/Tell_City | Created: Sun 19 Apr 2009 11:00:01

Serial Number 036-VP-0089

Messages

Insufficient operational time over the last 28 days to compute full statistics.

*Note: The fuel economy calculation algorithm is still in development - fuel economy data plotted in the fuel consumption graph may contain outliers (perhaps 2% of the points).

Maintenance

Oil Level 0% 50% 100%

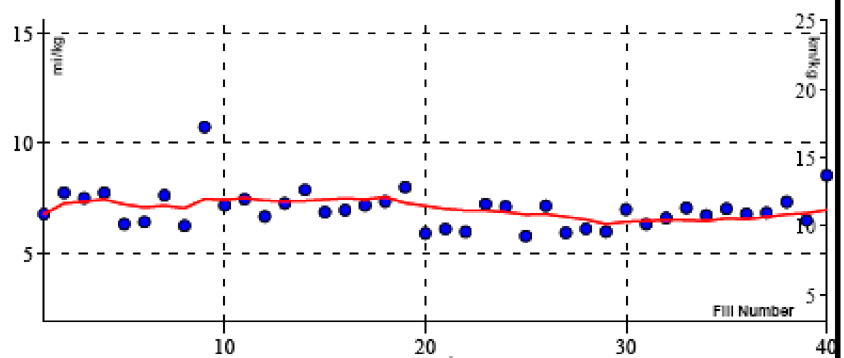
Last OilChange 20 Nov 2007 1493mi 2403km

Oilchange due at

Oil Life Used Not Calculated

Fuel

Post Refuel Keyon	Fuel Used kg
16-Oct-08 14:51	6.7
19-Aug-08 08:10	18.6
11-Apr-08 08:34	6.8
07-Apr-08 08:28	13.7
31-Mar-08 08:34	3.1
21-Mar-08 08:29	7.3
19-Mar-08 13:03	9.0
12-Mar-08 10:19	8.7
05-Mar-08 10:14	22.0
25-Feb-08 08:30	0.3



Fuel Consumption* (Last 40 fills)

Time and Distance

	Sun 12 Apr	Mon 13 Apr	Tue 14 Apr	Wed 15 Apr	Thu 16 Apr	Fri 17 Apr	Sat 18 Apr	Sum	Life Totals
Time (engine running)	-	-	00h 24m	-	-	00h 26m	-	00h 51m	130h 04m
Dist mi	-	-	-	-	-	6.4	-	6.4	2413.9 mi
Dist km	-	-	-	-	-	10.2	-	10.2	3884.7 km
Revs k	-	-	28.70	-	-	32.92	-	61.62	10337.4 kR

Questions/Comments: h2bus@ford.com
Document Version: VP-1-0

Figure A-4. Hydrogen Bus #36 Performance Report

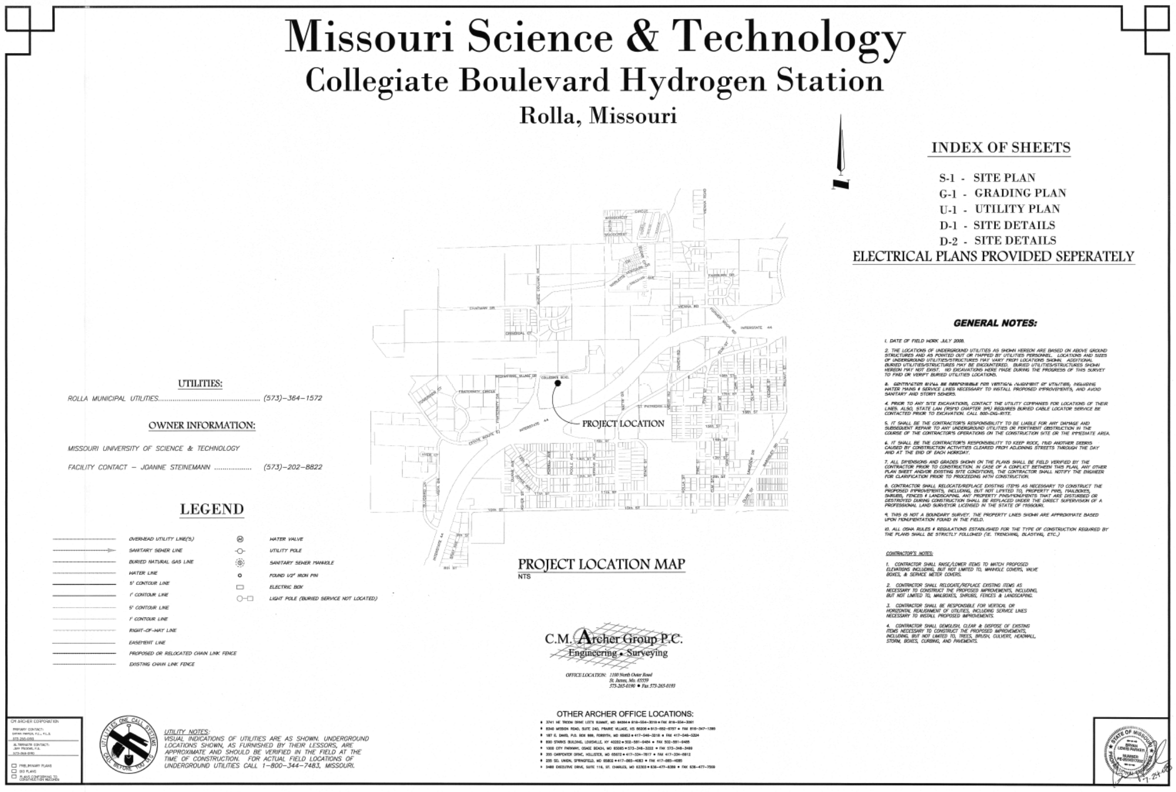


Figure A-5. Permanent Hydrogen Fueling Station Project Document Cover Page

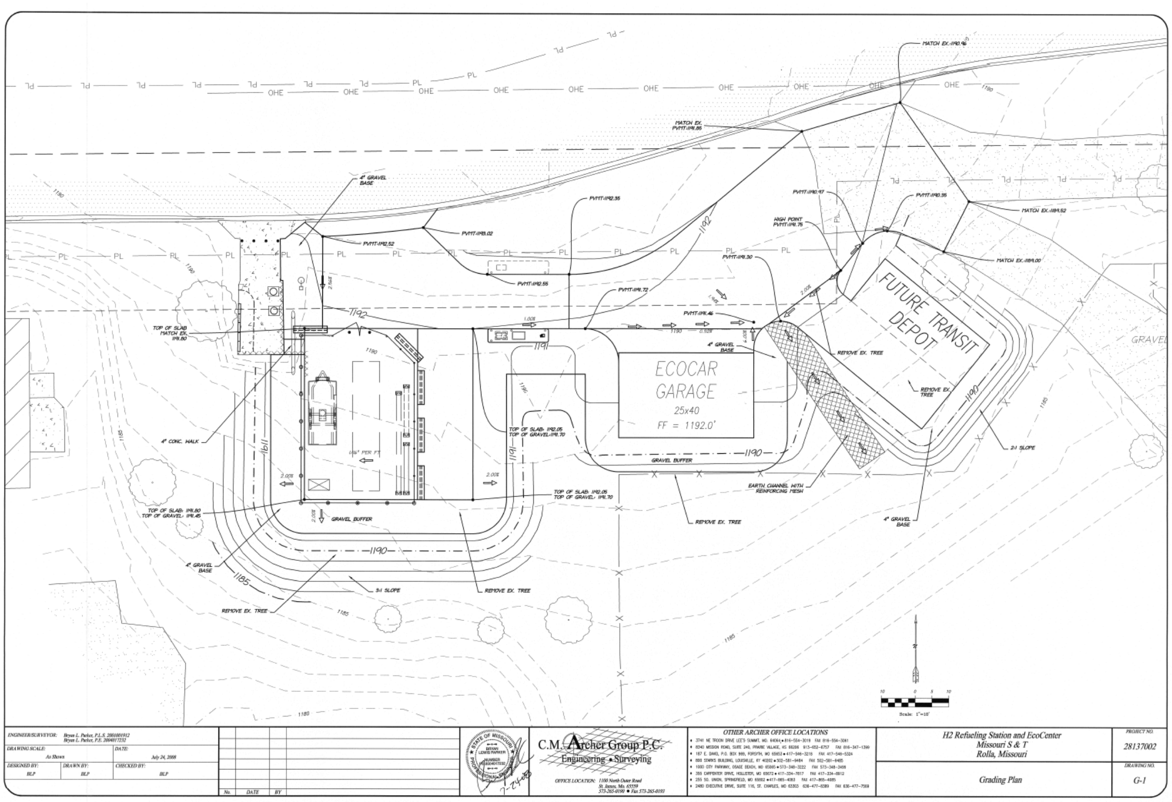


Figure A-6. Permanent Hydrogen Fueling Station Grading Plan

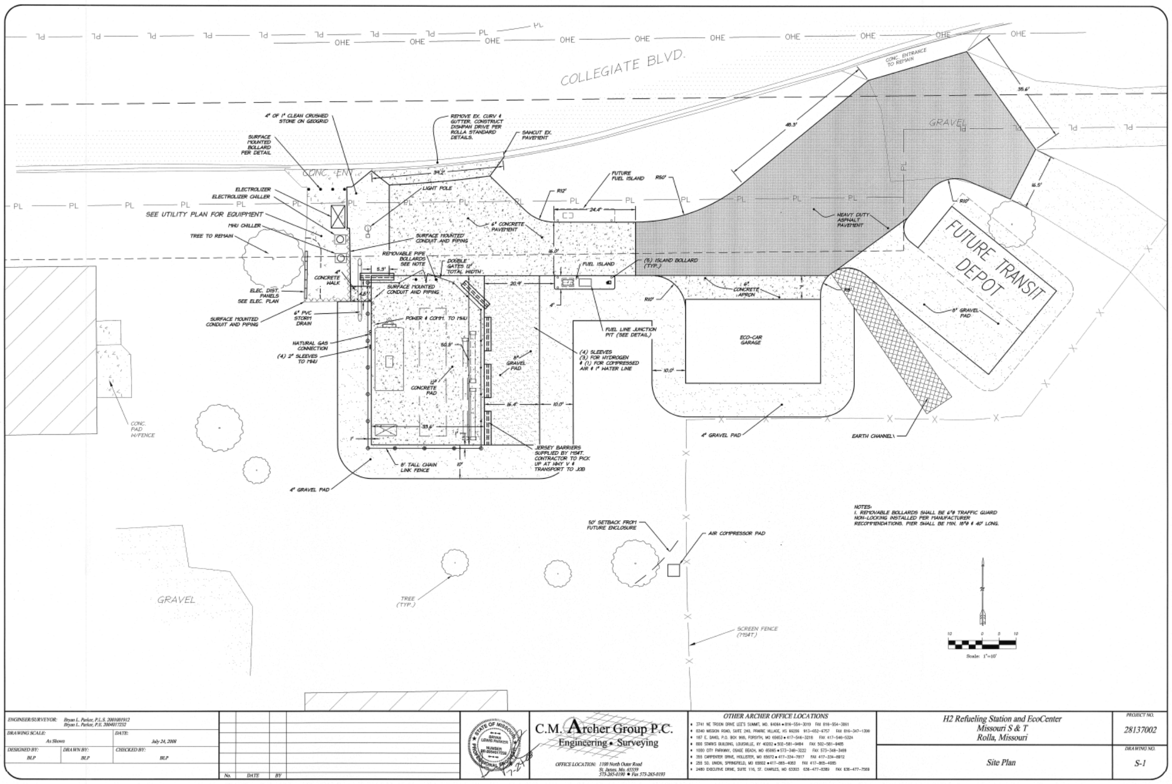


Figure A-7. Permanent Hydrogen Fueling Station Site Plan

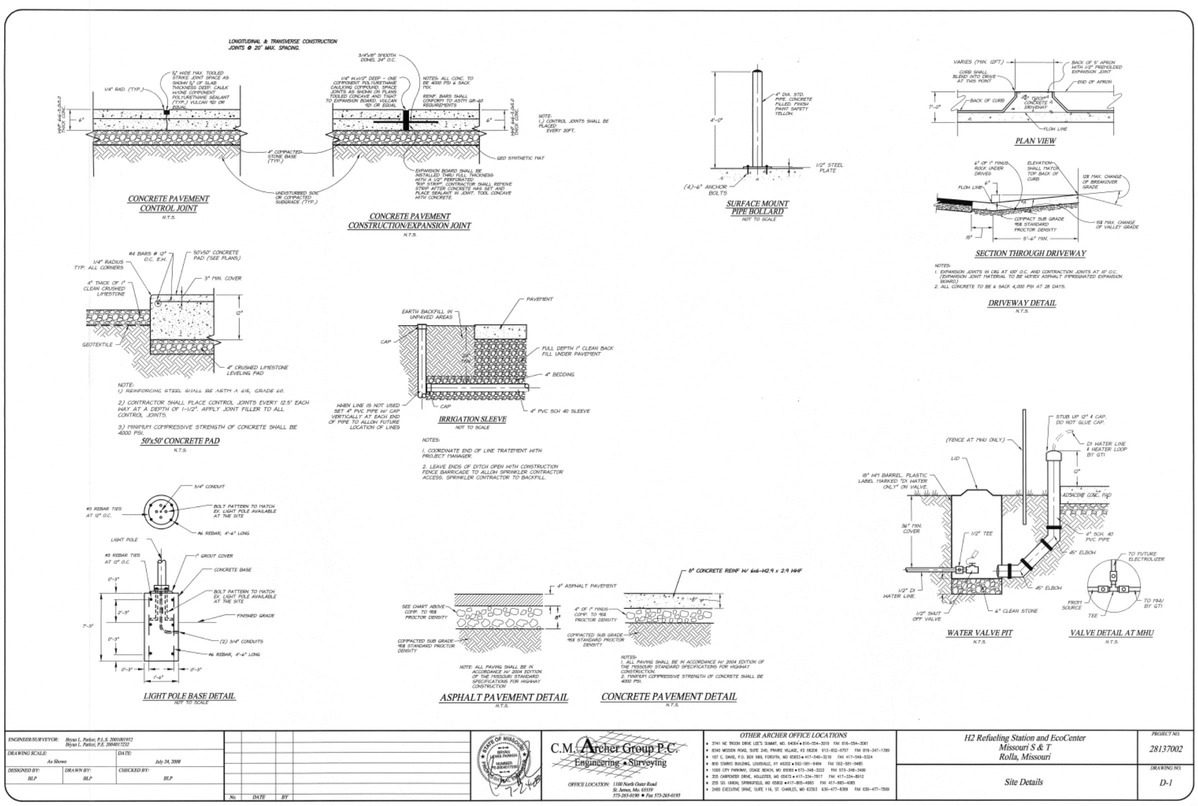


Figure A-8. Permanent Hydrogen Fueling Station Site Details D-1

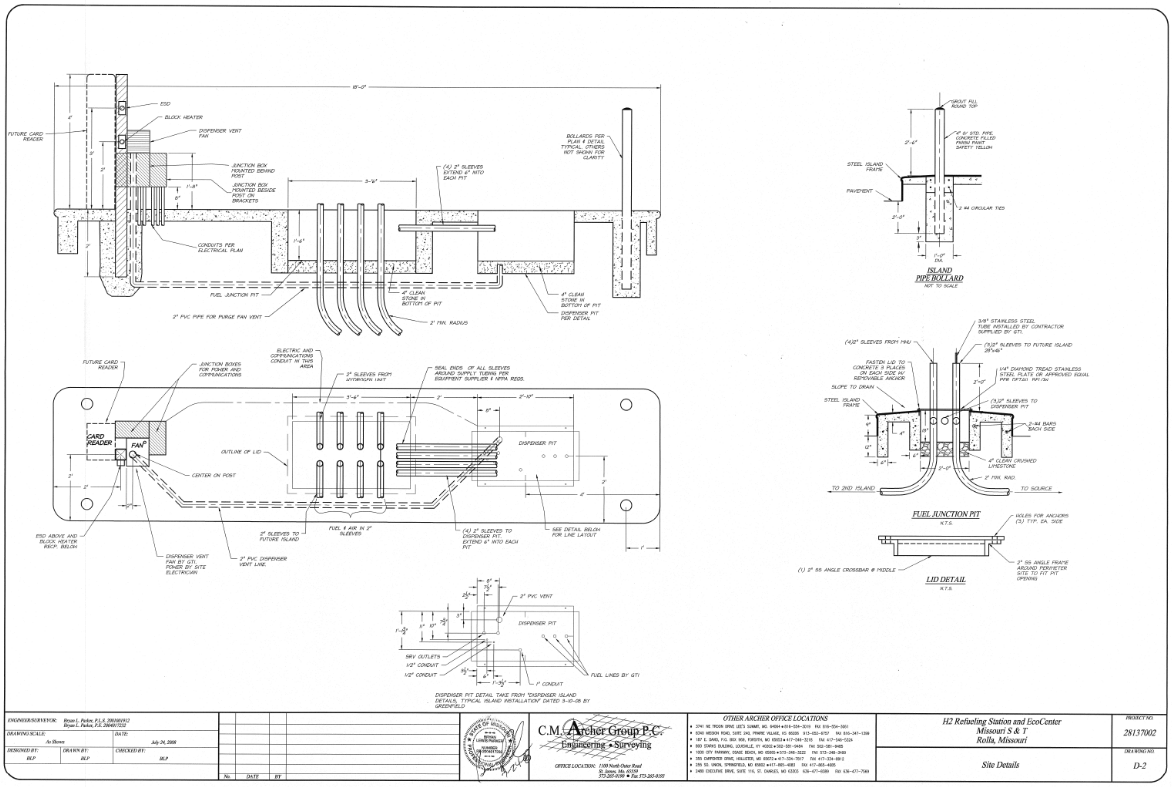


Figure A-9. Permanent Hydrogen Fueling Station Site Details D-2

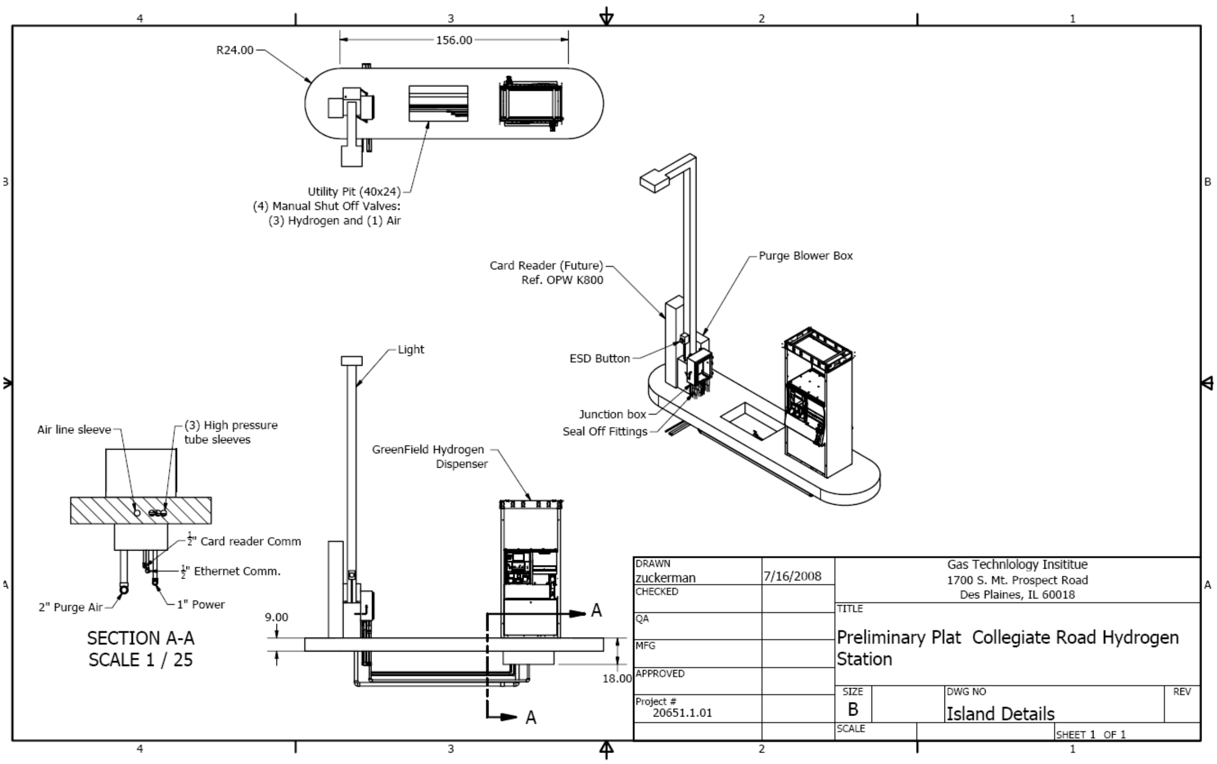


Figure A-10. Hydrogen Dispenser Details

Figure A-11. US DOT RITA Administrator Paul Brubaker at Ribbon Cutting

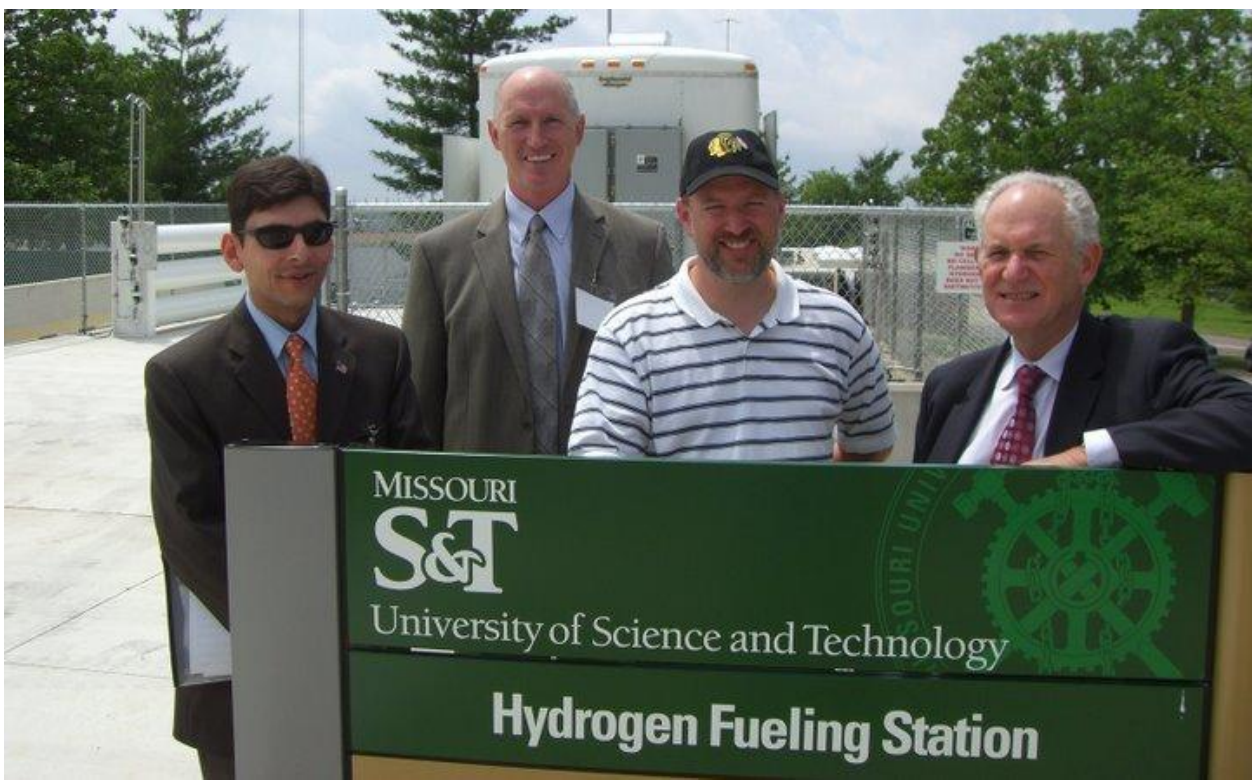


Figure A-12. Missouri S&T Permanent Hydrogen Fueling Station

Figure A-13. Ford F450 Hydrogen Shuttle Buses

Figure A-14. Missouri S&T E-cubed Commons with Hydrogen R&D Garage

Figure A-15. Project Sponsors

Figure A-16. Missouri Governor Matt Blunt

Figure A-17. Passengers from Rolla Riding Hydrogen Bus to Ft Leonard Wood

Figure A-18. 2007 Mobile Fueling Station

Figure A-19. Air Product's HF150 Mobile Hydrogen Fueling Station

Figure A-20. First Responders' Training 2007

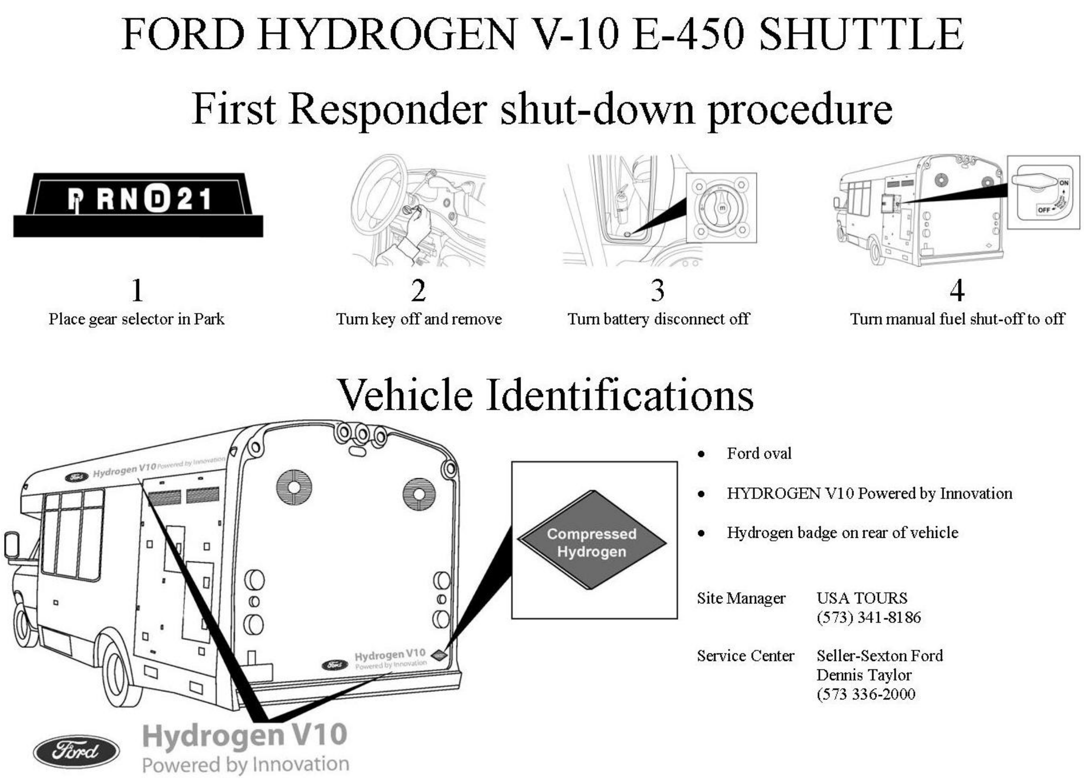


Figure A-21. First Responder Shut-Down Procedure

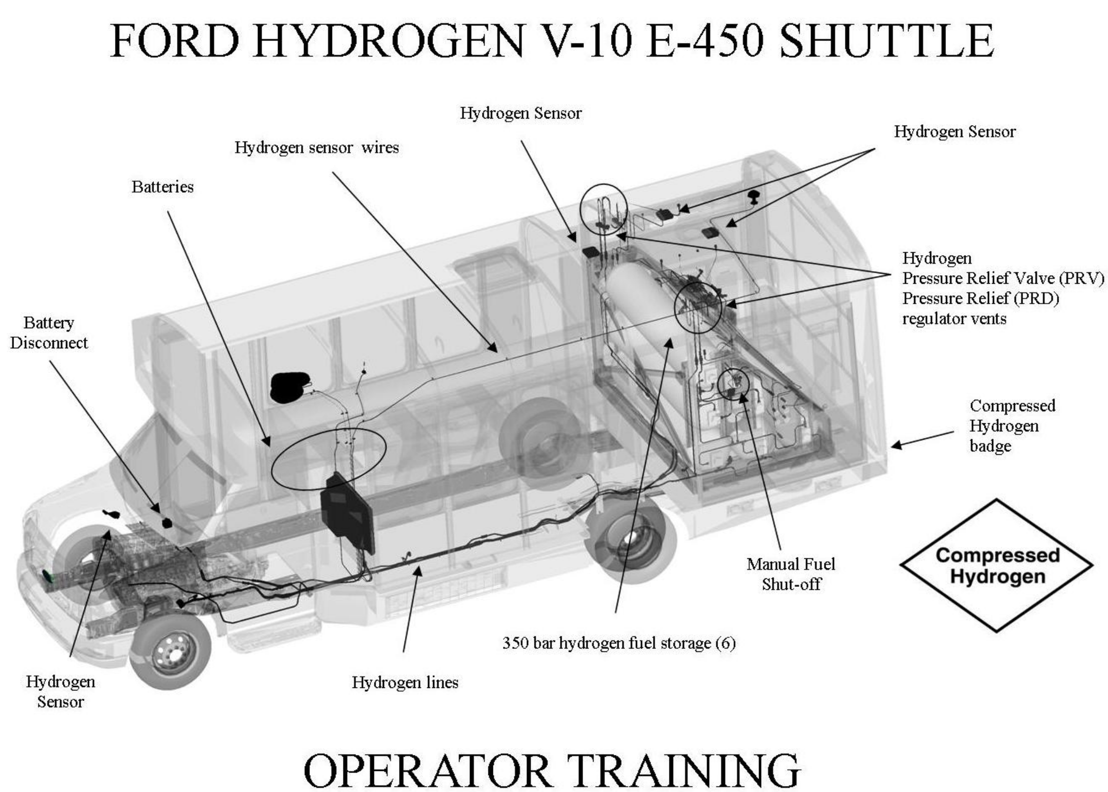


Figure A-22. Hydrogen Safety System

Figure A-23. Liquid Hydrogen Tanker Filling Mobile Fueler

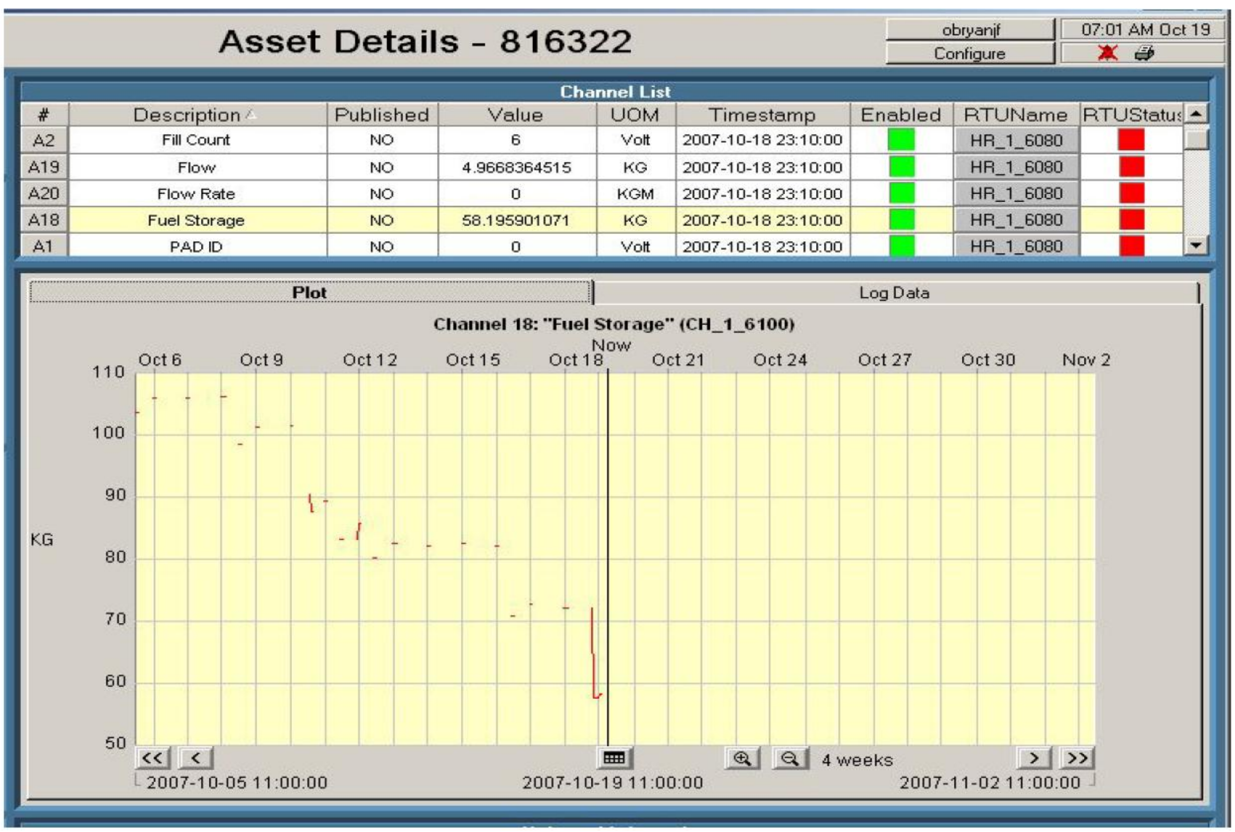


Figure A-24. Hydrogen Asset Detail Chart

Figure A-25. 2008 Hydrogen Road Tour with Stops in Missouri

Figure A-26. NEXT STOP: Missouri's Hydrogen Highway