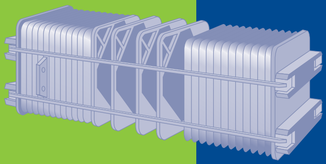

Hydrogen, Fuel Cells & Infrastructure Technologies Program

Fuel Cell Transit Buses

ThunderPower Bus Evaluation at SunLine Transit Agency

U.S. Department of Energy
Energy Efficiency and Renewable Energy

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. By investing in technology breakthroughs today, our nation can look forward to a more resilient economy and secure future.

Far-reaching technology changes will be essential to America's energy future. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a portfolio of energy technologies that will:

- Conserve energy in the residential, commercial, industrial, government, and transportation sectors
- Increase and diversify energy supply, with a focus on renewable domestic sources
- Upgrade our national energy infrastructure
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ThunderPower Bus Evaluation at SunLine Transit Agency

A U.S. Department of Energy Transit Bus Evaluation Project

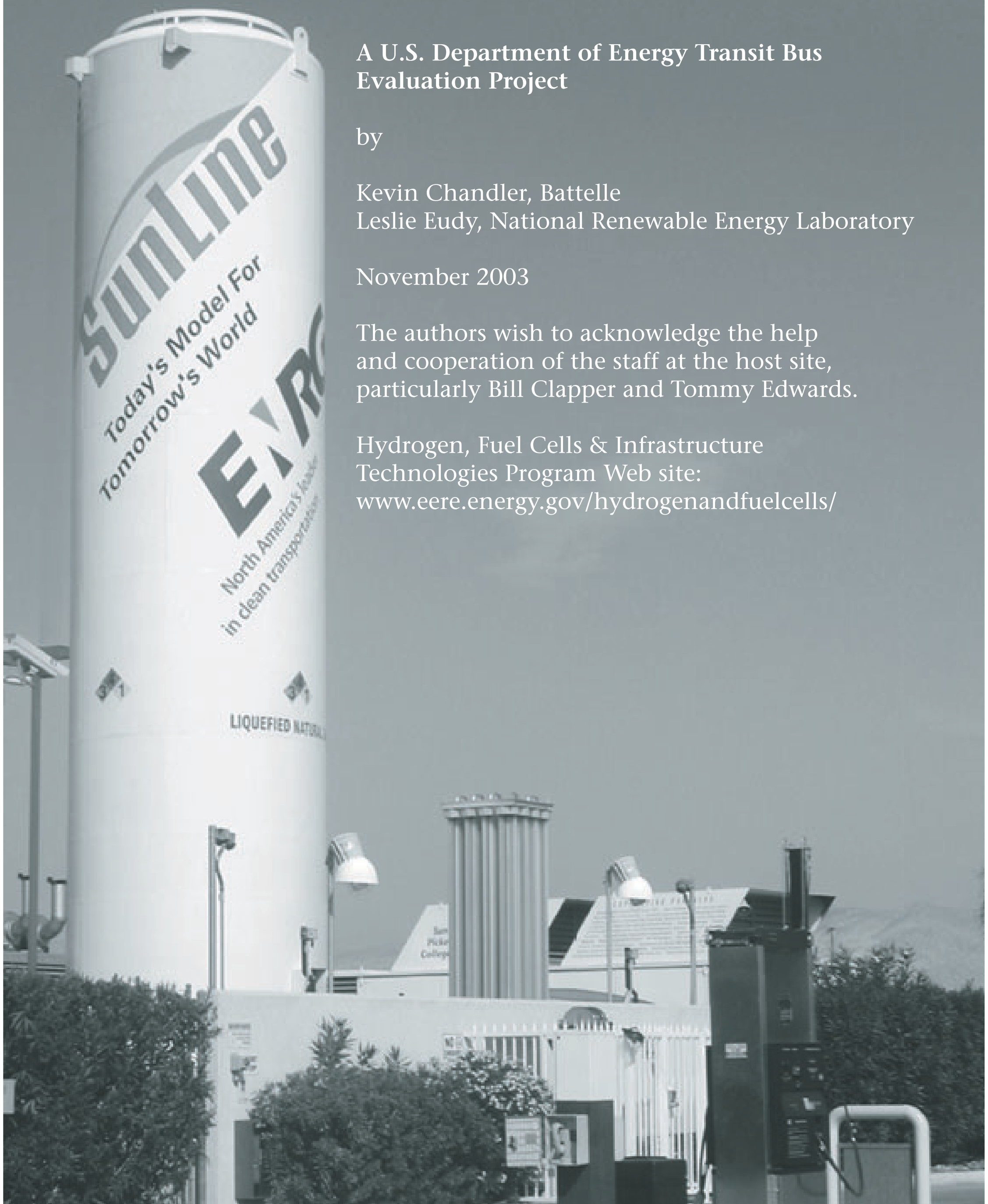
by

Kevin Chandler, Battelle
Leslie Eudy, National Renewable Energy Laboratory

November 2003

The authors wish to acknowledge the help and cooperation of the staff at the host site, particularly Bill Clapper and Tommy Edwards.

Hydrogen, Fuel Cells & Infrastructure Technologies Program Web site:
www.eere.energy.gov/hydrogenandfuelcells/



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Introduction

This report provides an overview of the ThunderPower fuel cell bus demonstration at SunLine Transit Agency in Thousand Palms, California. Under contract with the U.S. Department of Energy (DOE), the National Renewable Energy Laboratory (NREL) evaluated the bus while it was at SunLine for six months in late 2002 and early 2003.

Thor Industries and ISE Research developed and manufactured the 30-foot ThunderPower bus (an ElDorado coach). It uses a compressed hydrogen proton exchange membrane (PEM) fuel cell power plant developed by UTC Fuel Cells. The ThunderPower bus is one of a few fuel cell buses in the United States, and its use is a prelude to an upcoming demonstration program in California that will include seven more full-sized fuel cell buses. AC Transit, Santa Clara Valley Transportation Authority, and SunLine will participate in that program.

Designed and developed in 2001, the ThunderPower bus started service at SunLine in mid-2002. SunLine was chosen as the first demonstration site because of its desert climate and its experience with fuel cell buses and hydrogen production and dispensing capabilities.

This report describes the operation of the ThunderPower fuel cell bus during its six months of operation at SunLine, including an evaluation of the bus's performance during three months of revenue service. It also includes a description of the hydrogen production operations at SunLine.

Evaluation Programs at DOE and NREL

NREL evaluated the ThunderPower fuel cell bus in support of DOE's Hydrogen, Fuel Cells & Infrastructure Technologies (HFC&IT) Program, which integrates activities in hydrogen production, storage, and delivery with transportation and stationary fuel cell applications. The goals of the HFC&IT Program are to:

- Overcome technical barriers through research and development of hydrogen production, delivery, and storage technologies, as well as fuel cell technologies for transportation, distributed stationary power, and portable power applications.
- Address safety concerns and develop model codes and standards.
- Validate and demonstrate hydrogen and fuel cell technologies under real-world conditions.

- Educate key stakeholders whose acceptance of these technologies will determine their success in the marketplace.

The objective of DOE/NREL evaluation projects is to provide comprehensive, unbiased reviews of currently available advanced technology and alternative fuel vehicles. This objective is customized for each evaluation site based on the status of vehicle technology development and the site's expectations of these vehicles. Operators considering the use of these vehicles constitute the primary audience for this information.

Evaluation Strategy and Objectives

The objective of the ThunderPower bus demonstration was to verify that a fuel cell bus could be developed, integrated, and operated safely in service with comparable or better performance than a standard transit bus of the same size in the same service. ThunderPower, LLC, is a joint venture between Thor Industries and ISE Research. Thor Industries includes mid-size bus manufacturers Champion Bus and ElDorado National. ISE Research is a leader in developing and integrating electric and hybrid electric vehicle drive systems for sale and demonstration.

ThunderPower, LLC, is under contract to demonstrate the ThunderPower bus with at least two transit agencies in the Los Angeles area-SunLine was one of them. SunLine's objective was to show that a fuel cell bus could operate in revenue service and fulfill service demands from a performance and reliability standpoint. All participants reported that the bus met and, in some cases, exceeded their expectations. The ThunderPower bus left SunLine for Chula Vista Transit to complete further testing and operation. Chula Vista is located just south of San Diego and is near ISE Research's home offices.

NREL's objective was to review the demonstration of the prototype ThunderPower bus to provide useful background and operational information to those interested in the successful introduction of fuel cells into transit service. Throughout this document accomplishments and lessons learned from this project will be discussed.

NREL collected data on the operation, maintenance, and performance of the ThunderPower bus while in operation at SunLine. These data include fuel (hydrogen) fills, vehicle use (availability for service, route assigned, miles per day), and maintenance activities, such as warranty repairs.

The ThunderPower bus demonstration lasted six months—not enough time to study reliability and durability in-depth. The bus was built to meet the objectives defined for this demonstration and not necessarily as a commercial product. The intent of this demonstration is to assess how close this technology is to commercialization.

The evaluation approach was to study the entire operation of the ThunderPower bus at SunLine and separate the period when the bus operated in revenue service from other activities. The data are presented in three groups:

- All data collected during operation at SunLine (August 22, 2002 to February 24, 2003)
- Nonrevenue operation at SunLine (August 22, 2002 to November 5, 2002)
- Revenue operation at SunLine (November 6, 2002 to February 24, 2003)

Transit Buses Ideal for Fuel Cell Demonstrations

Transit bus demonstrations have typically been introduction points for new heavy-duty vehicle propulsion technologies. This is because[1]:

- Transit buses are centrally fueled and maintained.
- Transit buses are typically operated on fixed routes in urban stop-and-go duty cycles.
- Transit bus size and weight can easily accommodate new technologies.
- Capital purchases of transit buses and supporting infrastructure are federally supported (80% federal share and other funding programs).
- Transit buses have high visibility and impact because they operate in densely populated areas.

There have been several transit bus demonstrations over the past 10 years in the United States and Canada. These fuel cell bus demonstrations have identified areas of development to prepare fuel cell propulsion systems for heavy-duty vehicle service. Examples include:

- Reducing the size of the fuel cell stack.
- Increasing the power density of the fuel cell stack.
- Reducing overall weight of the fuel cell and electric propulsion system.
- Developing hydrogen infrastructure for vehicle use.
- Optimizing electric motors and control systems for heavy-duty vehicles.
- Demonstrating that electric propulsion systems are safe for transit vehicles and can perform well in environmental extremes (high and low temperatures and humidity).

Fuel Cell Bus Demonstrations

Timeframe	Details
1994-1995	FTA/Georgetown: three 30-ft fuel cell buses operating on methanol using 100 kW phosphoric acid fuel cell (PAFC) stacks from Fuji.
1998	FTA/Georgetown: 40-ft fuel cell bus operating on methanol using 100-kW PAFC from UTC Fuel Cells.
1998-2000	Ballard Phase III test program with six fuel cell powered, 40-ft transit buses using 275-hp PEM fuel cell stacks from Ballard that ran on compressed hydrogen; operated three at Chicago Transit Authority and three at Coast Mountain Bus (Vancouver).
2000-2001	Ballard Phase VI test bus operating on compressed hydrogen using 200-kW PEM fuel cell stack from Ballard, which was tested at SunLine; the bus currently resides at SunLine.
2001	FTA/Georgetown: 40-ft fuel cell bus operating on methanol using 100-kW PEM fuel cell stack from Ballard.
2002-2003	ThunderPower 30-ft fuel cell bus operating on compressed hydrogen using 60-kW PEM fuel cell stack from UTC Fuel Cells at SunLine then Chula Vista Transit.
2003-2005	Demonstration project just getting under way in Europe, Iceland, and Australia including 33 fuel cell buses using Ballard PEM fuel cell stacks and compressed hydrogen in 40-ft buses.
2004-2006	Planned demonstration project in the United States: Three fuel cell buses using UTC fuel cell stacks and compressed hydrogen in 40-ft buses at AC Transit, one fuel cell bus using UTC fuel cell stack and compressed hydrogen in a 40-ft bus at SunLine, and three fuel cell buses using Ballard fuel cell stacks and compressed hydrogen in 40-ft buses at Santa Clara Valley Transportation Authority.

[1] *Information excerpted from an FTA presentation by Shang Hsiung at the APTA Bus and Paratransit Conference committee meetings in Milwaukee, Wisconsin, May 2003.*

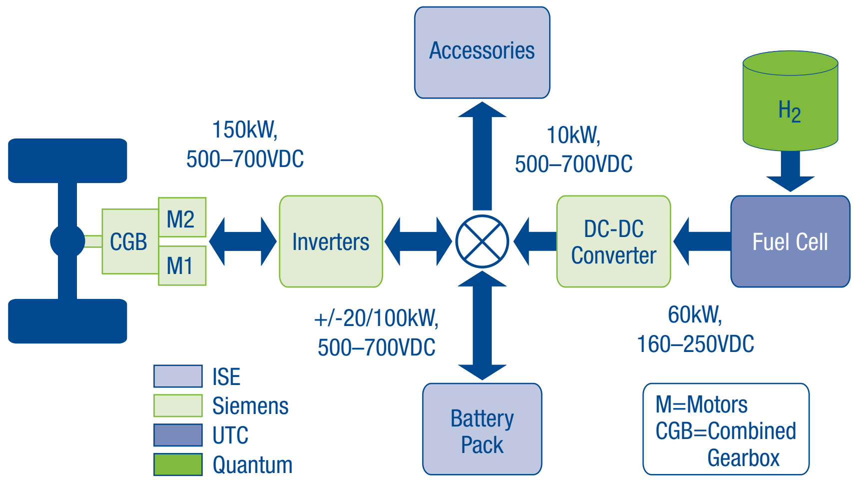


Figure 1. Block Diagram of the ThunderPower Fuel Cell Bus

Project Description

The ThunderPower fuel cell bus was developed under contract and was funded from several sources, including:

- Federal Transit Administration (FTA), U.S. Department of Transportation
- Sacramento Municipal Utility District
- Calstart-Westart
- South Coast Air Quality Management District
- DOE provided funding for this evaluation of the bus.

ThunderPower, LLC, designed, specified, built, and integrated the ThunderPower bus. The design and component selection for the fuel cell bus were completed in 2001. This occurred in several steps, including:

- **Selection of the chassis:** The ElDorado National EZ Rider 2 chassis was chosen based on the experiences of Thor Industries and ElDorado National.
- **Selection of fuel cell systems:** UTC Fuel Cells' fuel power plant was chosen because it can operate at ambient pressures, eliminating the need for extra compression; it also has an integrated humidification system.
- **Selection of the hydrogen fuel system:** The hydrogen fuel system was selected based on the requirements and specifications provided by ISE Research.
- **Selection of compressed hydrogen storage system:** Quantum Technologies was chosen to supply its onboard system, certified at 3,600 psi. The company plans to certify the system to 5,000 psi.
- **Selection of the hybrid propulsion system:** Siemens ELFA™ technology was chosen because it is used commercially in Europe and has proven to be durable. The ThunderPower bus marks the first implementation of this drive system in the United States.
- **Selection of the energy storage system:** Panasonic lead acid batteries were chosen because they were designed specifically for hybrid vehicle use.
- **Design of the operating strategy:** This defines how much energy and power flow from the various systems for a given torque demand from the driver.
- **Development of a new charger:** Power Designers developed the charger; ISE Research developed the charger's controls and software.
- **Development of all-electric accessories:** These optimize the efficiency of non-fuel-cell systems on the vehicle, including the air conditioning system, scroll air compressor, and the hydraulic pump.
- **Incorporated safety systems:** These include ground fault interruption (GFI) for the fuel cell and propulsion systems. Dual Spectrum developed the sensors for hydrogen and heat.

Table 1 outlines some of the specifications of the bus. The ThunderPower bus's drive system includes

Table 1. ThunderPower Fuel Cell Bus Specifications	
Bus Manufacturer/Model	ElDorado National/EZ Rider 2
Bus Model Year	2002
Gross Vehicle Weight Rating	34,000 lb
Curb Weight	25,180 lb
Seats/Wheelchair Positions	26/two
Hybrid Type	Series/charge sustaining
Regenerative Braking	Yes
Energy Storage	Panasonic lead acid/48 12-V batteries in two modules
Electric Motor	Siemens 2 X 85 kW @ 650 VDC
Power Plant	UTC Fuel Cells/PEM
Power Plant Power Rating	60 kW continuous
Fuel Storage	Nine quantum cylinders with compressed hydrogen
Fuel Storage Capacity	25 kg hydrogen at 3,600 psi

Table 2. ThunderPower Fuel Cell Bus Performance Testing Results

Parameter	Results
Time for Acceleration (0-30 mph)	21 s
Time for Acceleration (0-45 mph)	48 s
Maximum Grade	17.5%
Top Speed	55 mph
Weight	25,180 lb
Interior Noise (Stopped)	62 dB (A)
Interior Noise (30 mph)	65 dB (A)
Interior Noise (55 mph)	71 dB (A)
Air System Charge Time	26 s
Range	150-200 mi
Efficiency	19,166 Btu/mi

Source: Fast Track Fuel Cell Bus, Final Report, ISE Research

two electric motors (which provide the bus with 170 kW to the drive axle), power inverters, and a gearbox. The hybrid system allows for regenerative braking, which captures braking energy and stores part of it in the Panasonic 600-V battery pack (includes 48, 12-V batteries) for later use by the electric drive system. The bus is primarily powered by UTC Fuel Cells' 60-kW PEM fuel cell, which is fueled by compressed hydrogen. Accessories for the vehicle are driven electrically through a DC-DC inverter (600 V down to 24 V/12 V). The vehicle is controlled through a multiplexing system that powers accessory operations, such as driver controls, air and hydraulic systems, cooling system, and the energy management controls (see Figure 1 on the previous page).

Compressed hydrogen is stored in Quantum Technologies tanks on the ThunderPower bus. The nine compressed hydrogen storage tanks have a capacity of as much as 25 kg of hydrogen at 3,600 psi. A full fuel load of hydrogen is the energy equivalent of approximately 25 gallons of diesel fuel. Based on this fuel capacity, the ThunderPower bus has an approximate range of 200 miles and a fuel storage capacity of 25 kg of hydrogen at 3,600 psi.

By the end of 2001, the ThunderPower bus was built. It was then tested for performance (the results are outlined in Table 2). The development process next focused on optimizing the propulsion system and supporting systems for the fuel cell stack operation.

In July 2002, the ThunderPower fuel cell bus was delivered to SunLine for testing in the grueling desert heat. The propulsion and fuel cell systems required a few minor adjustments. However, the issue of air conditioning for the passengers and propulsion system had to be addressed before the demonstration could begin.

Because SunLine's desert service area is so hot, the agency requires all vehicles to have oversized air conditioning for the passenger compartment. The original air conditioning planned for the ThunderPower bus could not cool both the propulsion system and the passenger compartment, so the bus was sent back to ISE Research for an upgrade. The fuel cell bus returned to SunLine in August 2002.

SunLine's onsite solar panels and tracking arrays produce electricity for electrolysis.

This hydrogen dispenser is one of several alternative fuel pumps at SunLine headquarters.

Host Site: SunLine Transit Agency

SunLine Transit Agency is located in Thousand Palms, California, in the Coachella Valley. The service area is more than 1,100 square miles and includes nine member cities (Desert Hot Springs, Palm Springs, Cathedral City, Rancho Mirage, Palm Desert, Indian Wells, La Quinta, Indio, and Coachella), as well as Riverside County.

SunLine was an early adopter of compressed natural gas (CNG) in bus operations. In 1994 it converted its entire bus fleet to CNG. The fleet currently consists of 46 CNG and two hydrogen/CNG blend (Hythane®) heavy-duty buses, plus ongoing fuel cell bus testing. SunLine provides service for 13 fixed routes and demand response with 24 natural gas powered vans.

SunLine's headquarters include administrative offices, training/meeting rooms, maintenance, fueling, and hydrogen fuel production facilities—all in one location. The agency operates 129 vehicles including light-, medium-, and heavy-duty vehicles. All but four of its vehicles operate on natural gas (compressed, liquefied, or Hythane®). The remaining four operate on electricity.

In April 2000, SunLine opened a hydrogen generation, storage, fueling, and education facility to demonstrate various approaches to hydrogen production. Hydrogen at SunLine is produced, stored, and dispensed through a system built and packaged by Stuart Energy.

Hydrogen is made in two ways at SunLine. One method separates pure water into hydrogen and oxygen using Stuart Energy's proprietary electrolysis technology (called an electrolyzer). The hydrogen gas is then dried, purified, compressed, and sent to storage, and the oxygen is vented to the atmosphere. The second method uses a reformer by Hyradix, which produces hydrogen by stripping it from methane molecules in natural gas. This process produces carbon dioxide, which is also released into the atmosphere. The hydrogen is distributed using a specially designed dispenser and fill nozzle (Sherex 5000), which is similar to those used by SunLine to fuel CNG buses.

Electricity to power the electrolyzer and reformer is provided by the electric grid, with some of that power being offset by SunLine's solar panels and tracking arrays with a total installed capacity of 37.5 kW.

All SunLine's buses and support vehicles are stored outside. The agency built a special facility onsite for hydrogen vehicle maintenance. The building, which was originally constructed for the demonstration

Fuel Options

While SunLine uses pure hydrogen in the ThunderPower bus, other fuels are available for fuel cell vehicles. These include hydrogen-rich fuels, such as methanol, gasoline, and diesel. Each fuel has advantages and disadvantages.

Pure Hydrogen: Fuel cell vehicles powered with pure hydrogen (in gaseous or liquid form) produce only water vapor and heat as emissions, making them zero emission vehicles. Storing hydrogen onboard the vehicle has been a challenge because hydrogen has low energy density. Storing enough hydrogen to attain a comparable range to conventional vehicles requires large pressurized cylinders, which adds weight to the vehicle. Bulky cylinders on a smaller vehicle can usurp cargo space. Another challenge is building the infrastructure needed to support travel throughout the United States.

Hydrogen-Rich Fuels: Fuel cell vehicles that run on hydrogen-rich fuels must have a reformer onboard to extract hydrogen. The advantage to this system is that the vehicle can be fueled with a conventional fuel, such as gasoline or diesel. The higher energy content of these fuels would enable the vehicle to travel farther on less fuel. A reformer, however, adds complexity and weight to the vehicle, and results in some emissions of carbon dioxide and other pollutants.

of the ZEBus (a Ballard Phase 4 fuel cell bus), is essentially a tent designed to vent hydrogen through its roof. The building is also equipped with sensors that sound an alarm if a hydrogen leak is detected. Construction costs were approximately $50,000 ($21,000 for the building, doors, and ventilation system, and $29,000 for fire and combustible gas sensors and the alarm system).

Table 3. Components of SunLine's Hydrogen Fueling System

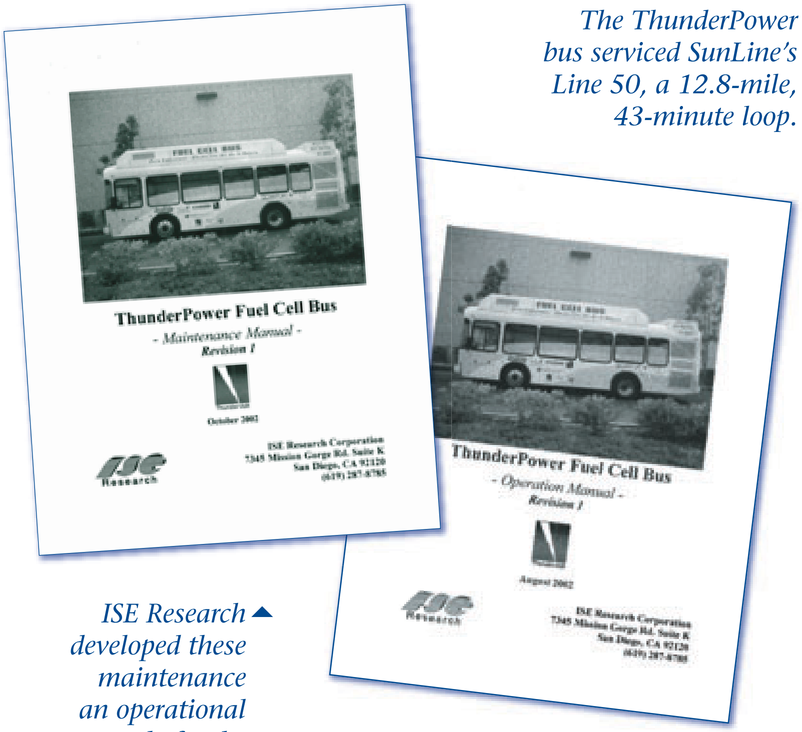
Electrolysis Production of Hydrogen Equipment	
Electrolyzer	Stuart Energy model CFA-450 multi-stack with a maximum hydrogen output of 450 standard cubic feet (scf)/h
Compressor	Stuart Energy hydrogen processing module, includes a CompAir model 5409H.2.H2, four-stage hydrogen compressor with an outlet pressure of 5,700 psig
Bulk Storage	Modular hydrogen storage consisting of a FIBA tube trailer with 16 DOT tanks that hold 104,000 scf of hydrogen (3,130 psig) and nine ASME tanks that hold 79,992 scf of hydrogen (6,000 psig)
Natural Gas Reformer Equipment	
Reformer	Hyradix natural gas reformer uses 110 psig natural gas as a feedstock and produces 3,500 scf/h hydrogen
Compressor	PDC Machine (model GDC-5) is a two-stage diaphragm compressor with an outlet pressure of 3,600 psig
Dispensing Equipment	
Dispensers	Fueling Technologies, Inc., model HYDH5210, hydrogen/Hythane(r) dispenser with mass flow metering, a separate mixer for Hythane(r), and two fast-fill hoses; model H5411D52 hydrogen dispenser with mass flow metering and two Sherex 5000 fill nozzles

Project Start-Up at SunLine

The ThunderPower fuel cell bus was delivered to SunLine on August 21, 2002, for initial service. Before and since the bus's arrival, mechanics and operators have been trained on the basics and specifics of fuel cell operations. SunLine produced training videos for employees, and staff was given maintenance and operations manuals on the ThunderPower fuel cell bus.

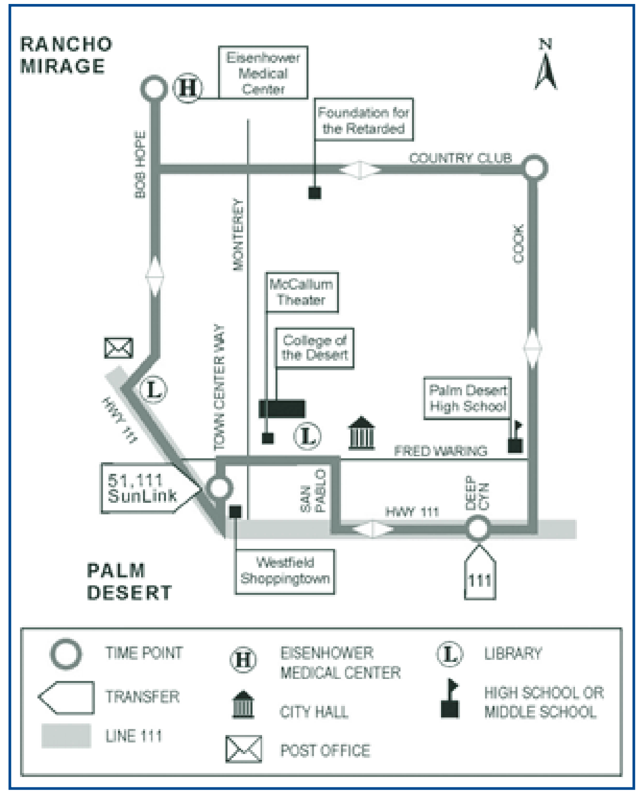
The day after the bus arrived at SunLine it was put into simulated service. It shadowed a SunLine bus in service to create a record of safe and reliable service (required by SunLine's insurance carrier since SunLine didn't own the ThunderPower bus). The demonstration bus passed the test and was put into service—and covered by the insurance company—on November 6, 2002, two weeks ahead of the insurance company's original schedule.

The simulated service of the ThunderPower bus included loading it to half the seated capacity and operating it behind a bus in actual revenue service on Line 50. The fuel cell bus was loaded with 150 lb per simulated passenger to half the seated capacity, plus the driver, for approximately 2,100 lb.



ISE Research developed these maintenance an operational manuals for the ThunderPower bus.

SunLine Line 50
The ThunderPower bus serviced SunLine's Line 50, a 12.8-mile, 43-minute loop.



Fuel Cell Bus Use

During its time at SunLine, the ThunderPower bus was assigned to Line 50, which can be described as light city driving on flat terrain through the cities of Rancho Mirage and Palm Desert. A typical bus schedule for Line 50 was two buses driving 17 loops (one for each direction) that totaled 230 miles and took 14 hours per bus to complete. A full shift for the ThunderPower bus included nine to 10 loops or 115 to 128 miles on route, plus travel time to and from SunLine, which added seven more miles to the shift. The route usually required a scheduled driver change in the middle of the day.

The total on-route time for the ThunderPower bus operating a full shift was approximately 7.5 (9 loops) to 8.3 hours (10 loops). A typical loop on Line 50 took 43 minutes with 7 minutes of rest or "catch-up" time at the end of the route. The average speed for the bus cycle was about 17 mph. The ThunderPower fuel cell bus drove Line 50 on weekdays and was off on weekends and holidays.

During the nonrevenue period (August to November), the ThunderPower bus rarely completed a full shift. The time not spent on route was used to further test and optimize the bus to prepare it for revenue service. During the revenue period (November to February), the fuel cell bus nearly always completed a full shift. It was limited by range (about 150-200 miles), so it couldn't complete an entire day's work without being fueled.

ISE Research assigned a technician to be onsite at SunLine to monitor the bus and ensure that data collection from the bus systems went smoothly. The bus had to be out of service so the technician could collect data on its systems. To keep the technician in line with an eight-hour workday, the ThunderPower bus was operated on Line 50 for a half day instead of a full day. The limited use of the bus worked best for SunLine and ISE Research. Based on the availability calculation, the

Table 4. Availability of the ThunderPower Fuel Cell Bus While Operating at SunLine

Availability	All Data While at SunLine	Nonrevenue Operation (August to November 2002)	Revenue Operation (November 2002 to February 2003)
Possible Days Available	134	54	80
Days in Operation	78	33	45
Holidays/Vacation	7	1	6
Days Scheduled Off	17	9	8
Days out of Service for Maintenance	32	11	21
Percent Bus Available for Service	**71%**	**75%**	**68%**

fuel cell bus was available for service 68%-75% of the time (average 71%).

Although the availability of the bus was calculated based on its operation at SunLine, scheduled publicity events and holidays were not counted against the bus or the fuel cell technology. Availability is one measure of reliability for this technology, as it measures the up time of the fuel cell bus as indicated by whether the bus was available for service. All partners in this demonstration focused on making sure that as much of the operations information was collected as possible. Table 4 summarizes the availability of the fuel cell bus and the numbers used to calculate that availability.

As shown in Figure 2, the ThunderPower bus accumulated 8,800 miles and 640 fuel cell stack hours of operation at SunLine. These numbers take into consideration the service time lost when the bus was down because of problems with the fuel cell cooling system in December 2002.

The ThunderPower bus was occasionally featured at conferences for display and rides and made available for tours. These activities took the bus away from operation on Line 50 but were good opportunities to demonstrate the technology. Publicity events for any demonstration of new technology are important to the product development process. The ThunderPower bus was featured at the following events:

- American Public Transportation Association (APTA) Annual Meeting, September 22-26, 2002
- Maintenance training video shoot, October 3, 2002

Table 4 Definitions

- **Possible Days Available**: All weekdays during the operating period.
- **Days in Operation**: Days the fuel cell bus was in operation at SunLine for at least three hours.
- **Holidays/Vacation**: The bus was not used on holidays and for a few days when the ISE technician was on vacation.
- **Days Scheduled Off**: Days the bus was used for public relations or training activities at SunLine.
- **Days Out of Service for Maintenance**: Days the bus was being repaired and not available for service at SunLine.
- **Percent Bus Available for Service**: A calculation of Days in Operation at SunLine divided by the Possible Days Available minus Holiday/Vacation and Days Scheduled Off, multiplied by 100%.

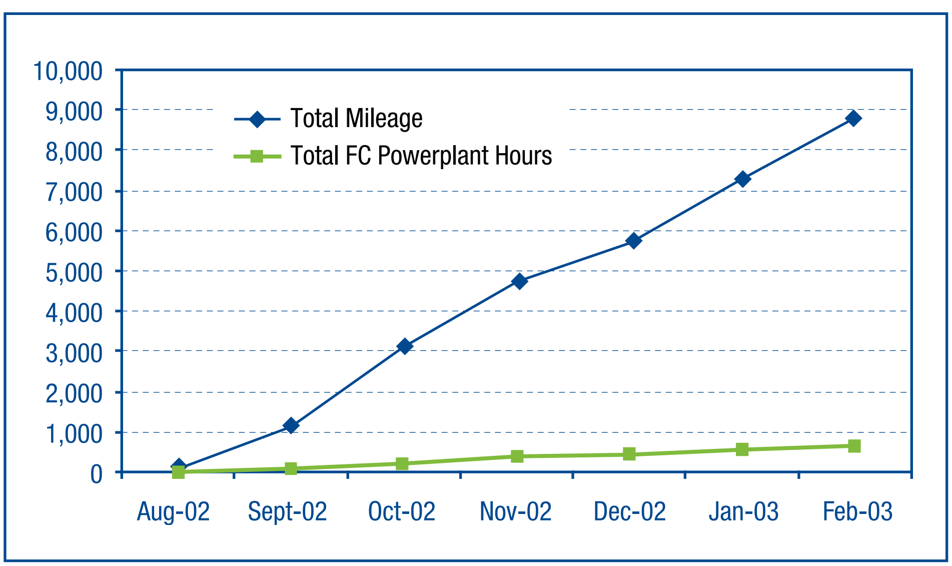


Figure 2. Total Mileage and Fuel Cell Stack Hours Accumulated by the ThunderPower Bus

Table 5: Fuel Cell Bus Duty Cycle	
Terrain	Flat, light city driving
Climate (Yearly averages)	
Average Low Temperature	56ºF
Average High Temperature	89ºF
Average Rainfall	5.8 in/year
Route	Line 50
Loop Distance	12.8 miles
Number of Loops per Shift	9-10
Time per Loop	43 minutes, with a 7 minute layover between loops
Length of Operation	7.5-8.3 hours
Distance per Shift	122-135 miles
Average Speed	17 mph

Table 6. Hydrogen Fuel Consumption and Economy for SunLine Operations

Category	All Data While at SunLine	Nonrevenue Operation (August to November 2002)	Revenue Operation (November 2002 to February 2003)
Fuel Economy Mileage	8,019	2,985	5,034
Hydrogen Used (kg/lb)	789/1,739	316/696	473/1,043
DGE	698	279	419
Miles per DGE	11.5	10.7	12.0
GGE	779	312	467
Miles per GGE	10.3	9.6	10.8

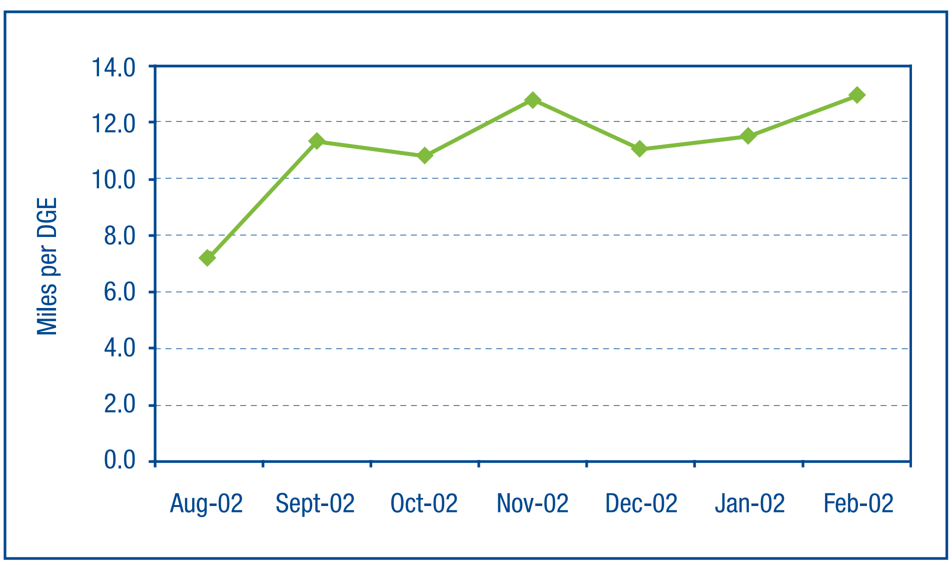


Figure 3. ThunderPower Bus Fuel Economy by Month

- Training for maintenance personnel, November 4-5, 2002
- Tours in San Diego, November 14-15, 2002
- Tours at SunLine, November 18 and 22, 2002
- Fuel Cell Seminar at SunLine, November 19-21, 2002

Fuel Consumption and Economy

The ThunderPower bus uses compressed hydrogen and air for the fuel cell stack. Hydrogen's low energy density limits the range of a bus. This measure is used to determine how efficiently the bus (and specifically the fuel cell stack) uses hydrogen. Table 6 shows the ThunderPower bus's hydrogen consumption and economy during the SunLine demonstration.

The diesel gallon equivalent (DGE) fuel economy for the ThunderPower bus was 10.7 miles per DGE during the nonrevenue period and 12 miles per DGE during the revenue period, as shown in Table 6. SunLine reports that its CNG ElDorado buses average around five miles per DGE on the same route (Line 50). The fuel economy for the hybrid fuel cell bus is nearly 2.4 times higher than that of the CNG buses currently used on the route. The gasoline gallon equivalent (GGE) fuel economies are also shown in Table 6.

Figure 3 shows the average DGE fuel economy of the ThunderPower bus at SunLine. The chart shows that the fuel economy slowly rose. This increase coincides with an increase in bus use over time with significant use coming during the revenue period.

Maintenance

ISE Research was responsible for maintaining the ThunderPower bus propulsion and fuel systems during the SunLine demonstration period of August 2002 to February 2003. SunLine was responsible for operating the bus, performing hydrogen fueling, and maintaining the bus and all systems other than propulsion and fuel. Everyone involved with this demonstration said the bus operated better than expected. In fact, SunLine reported that it expected to work on the bus more than it did.

The ThunderPower bus was first brought to SunLine in July 2002 to check the design and make sure the bus was ready to operate in the desert climate. At that time, ISE Research discovered that the air conditioning system did not have quite enough capacity for the hot, dry environment. The bus was then returned to ISE Research for upgrades until August 21, 2002, when it was brought back to SunLine for the demonstration. Table 7 lists problems that were discovered and resolved during the SunLine demonstration. Table 8 features the minor maintenance work performed on the bus.

Table 7. Maintenance Issues that Kept the ThunderPower Bus Out of Service

Dates	Problem Description
August 26 to September 4, 2002	Battery management system redesigned
September 6-9, 2002	Air conditioning malfunction serviced
October 10-11, 2002	Fuel cell cooling fan problem, DC-DC converter adjusted
December 5-18, 2002	Fuel cell cooling system problems repaired
January 6-9, 2003	DC-DC converter component replaced
January 28 to February 4, 2003	Fuel cell system repairs, inverter problems
February 6, 2003	Relay board replaced

Table 8. Maintenance Repairs Performed by SunLine

Maintenance Date	Action Description
November 4-5, 2002	Preparation for revenue service (safety inspection and farebox inspection)
December 2, 2002	Repair farebox
January 9, 2003	Replace stepwell lamps
January 11, 2003	Perform preventive maintenance inspection for 6,500 miles
January 31, 2003	Support ISE Research in inverter repairs
February 22, 2003	Check brakes

Emissions

A fuel cell bus is considered a zero-emissions vehicle. Its only emission is water vapor. However, producing, distributing, and dispensing hydrogen creates a total emission that is commonly referred to as "well-to-wheel."

Hydrogen is produced in two ways at SunLine:

- Electrolysis (separating hydrogen and oxygen from water). The only emission from electrolysis is oxygen; however this process requires a significant amount of electricity. The production of electricity may result in significant emissions, unless it is from a renewable source such as wind or solar.
- Reforming natural gas. This process, which is performed onsite at SunLine, requires electrical energy and has carbon dioxide as a by-product.

Because both of these hydrogen production processes use electricity, the source must be considered when calculating well-to-wheel emissions for the fuel cell buses. SunLine uses solar power for a portion of electricity production, which would add no emission. The source of any grid-supplied electricity would need to be determined to report well-to-wheels emission.

Summary and Conclusion

Based on the results of this analysis and the response from the project partners, the SunLine demonstration was a complete success. The ThunderPower bus was designed, developed, integrated, and operated successfully at SunLine for six months. Although it was a prototype (or precommercial) vehicle, the ThunderPower bus operated in revenue service at a reliable level for most of the evaluation period. To summarize the accomplishments and lessons learned:

- The bus met or exceeded all goals set for the demonstration at SunLine.
- Availability for service was 71% for the six-month demonstration period. This availability level may have been higher with quicker response to a couple of the problems experienced.
- The bus ran for six months at SunLine with some public relations activities and still accumulated 8,800 miles and 655 fuel cell fuel power plant hours.
- The hybrid fuel cell bus operated in revenue service with an energy equivalent fuel economy 2.4 times higher than a similar CNG bus operating in the same service at SunLine.
- One unexpected issue was covering the ThunderPower bus under SunLine's insurance. The problem for the insurance carrier was that SunLine did not own the bus and the hydrogen fuel cell propulsion system was not proven safe. SunLine was requested to operate the bus in a simulated service to provide a safety record for the insurance carrier to consider before covering the bus in revenue service. The bus completed the requested simulated service with no safety incidents and went into revenue service on November 6, 2002.
- SunLine was pleased with the support provided by ISE Research and the project team for the demonstration of the fuel cell bus. This type of commitment and the creation of a good support team are required to make a demonstration successful.
- There is a need to learn more about the reliability and durability of this type of propulsion system in transit buses. A longer-term demonstration and evaluation would be helpful in understanding how close to commercialization this technology is. This type of demonstration can be difficult because of the cost of supporting the maintenance. Another issue is a potential complaint that once the longer-term demonstration is complete, new technology would have advanced considerably. However, the information and knowledge gained from the experience of a longer-term demonstration would benefit future products tremendously.

Plans for the ThunderPower Bus

The ThunderPower bus finished its demonstration operation at SunLine on February 24, 2003. It then went to UTC Fuel Cells for work on the fuel cell system and upgrades before being demonstrated at Chula Vista Transit in Chula Vista, California, just outside San Diego. Chula Vista Transit opened its hydrogen fueling station on May 26, 2003. The ThunderPower bus demonstration at Chula Vista was expected to last a month. The bus will then be sent to several other California transit agencies.

Other DOE/NREL Evaluations

DOE and NREL plan to evaluate the fuel cell buses that will be demonstrated in California starting in mid-2004. AC Transit, Santa Clara Valley Transportation Authority, and SunLine plan to operate seven full-size (40-ft) transit buses for two years starting as early as mid-2004. This group of buses will include two bus manufacturers (Gillig and Van Hool) and two fuel cell power plant manufacturers (Ballard and UTC Fuel Cells).

Contacts

SunLine Transit Agency

SunLine Transit Agency
32-505 Harry Oliver Trail
Thousand Palms, CA 92276
Phone: 760-343-3456
Fax: 760-343-0576

Tommy Edwards
Director of Maintenance
E-mail: tedwards@sunline.org

Gayl Biondi
Director of Business Development
E-mail: gbiondi@sunline.org

ISE Research

David Mazaika
President and CEO
7345 Mission Gorge Road, Suite K
San Diego, CA 92120
Phone: 619-287-8785
Fax: 619-287-8795
E-mail: dmazaika@isecorp.com

DOE

Christopher Bordeaux
Technology Development Manager
Hydrogen, Fuel Cells, & Infrastructure Technologies Program
1000 Independence Ave., S.W.
Washington, DC 20585
Phone: 202-586-3070
Fax: 202-586-5860
E-mail: christopher.bordeaux@ee.doe.gov

NREL

Leslie Eudy
Senior Project Leader
1617 Cole Blvd.
Golden, CO 80401
Phone: 303-275-4412
Fax: 303-275-4415
E-mail: leslie_eudy@nrel.gov

Battelle

Kevin Chandler
Program Manager
505 King Avenue
Columbus, OH 43201
Phone: 614-424-5127
Fax: 614-458-5127
E-mail: chandlek@battelle.org

Partner Web Sites

ElDorado National
http://www.enconline.com/

Hyradix
www.hyradix.com

ISE Research
www.isecorp.com

Quantum Technologies
www.qtww.com

Stuart Energy
www.stuartenergy.com

SunLine Transit Agency
www.sunline.org

Thor Industries
www.thorindustries.com

UTC Fuel Cells
www.utcfuelcells.com

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Appendix A - ThunderPower Fuel Cell Bus

Bus Description	
Manufacturer	ElDorado National/ThunderPower LLC
Model	EZ Rider 2
Length	40 ft
Width	102 in.
Height	137.5 in.
Wheelbase	160 in.
Gross Vehicle Weight Rating	34,000 lb
Curb Weight	25,180 lb
Seats	26
Wheelchair Positions	2
Wheelchair Ramp/Lift	Ramp, rear door
Hybrid Drive System	
Hybrid Type	Series, charge sustaining
Regenerative Braking	Yes
Generator/Inverter	ELFA™/IP 65 (2 x 85 kW @ 600 VDC)
Controller	EV control
Energy Storage Type	Lead acid battery
Energy Storage Manufacturer	Panasonic (48, 12-V batteries in 2 modules)
Energy Storage Location on Vehicle	Under floor in rear
Electric Motors	Siemens (2 x 85 kW @ 650 VDC)
Electric Motor Location	Under bus, connected to gearbox
Gearbox	ELFA™/4.05:1 ratio
Number of Driven Axles	One (rear)
Power Plant Description	
Manufacturer	UTC Fuel Cells
Model	PC36/PEM
Year of Manufacture	2002
Power Rating	60 kW continuous
Power Plant Accessories (All Electric)	
Hydraulic Pump	Vickers/V10/6 gpm @ 1,800 psi
Heating	Water/glycol/97,000 Btu/h
Air Conditioning	ACT/electric/50,400 Btu/h
Air Compressor	Scroll type/14.7 scfm @ 100 psi
Fuel Storage	
Type	Compressed hydrogen
Storage	Nine quantum high-pressure cylinders
Maximum Operating Pressure	3,600 psi
Total Storage Capacity, Usable	25 kg
Safety Equipment	
Fire Detection	Dual spectrum, using infrared sensors
Fire Suppression	Dual spectrum, using halotron agent
Vapor Detection	RKI Instruments, metal oxide sensors

Appendix B - Fuel Cells and Hydrogen

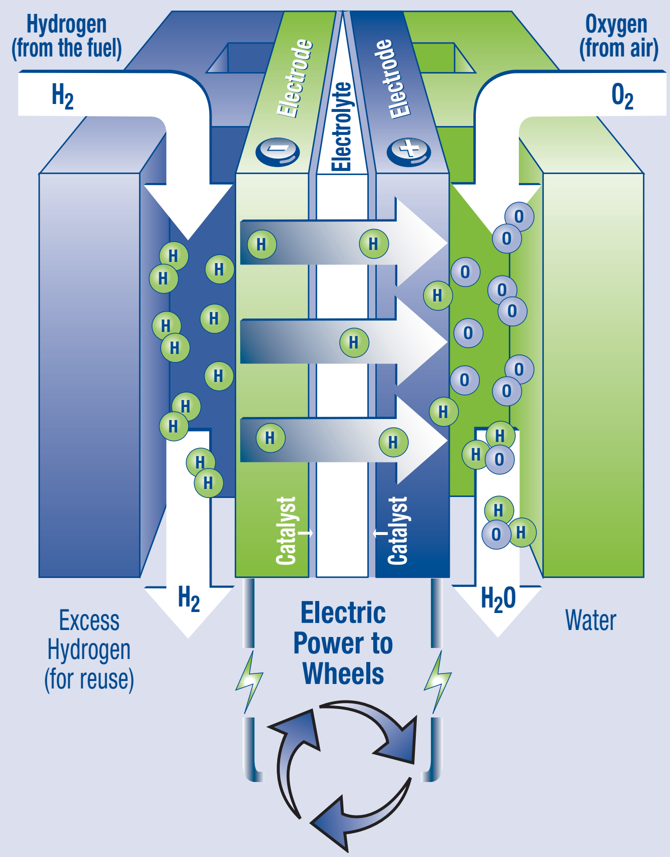
A fuel cell is an electrochemical device that uses hydrogen and oxygen to produce electricity. It consists of two electrodes (a cathode and anode) and is separated by an electrolyte. The ThunderPower bus uses PEM fuel cells, which are most commonly used for vehicle applications because they offer high power density and can operate at low temperatures. However, other types of fuel cells also show promise.

The principle of fuel cell operation is simple. Hydrogen is fed to the anode, where a catalyst-coated membrane separates the hydrogen electron from the proton. The proton passes through the membrane to the cathode side and combines with oxygen to form water. Because the electron cannot pass through the membrane, it is forced through the electrical circuit to create electricity. It then flows to the cathode where it is reunited with the proton in forming a water molecule.

A single fuel cell generates a small amount of electricity and must be combined in a series to power applications, such as transit buses. These fuel cell stacks can consist of hundreds of individual fuel cells.

There are several types of fuel cells, which are characterized by the type of electrolyte used. The chemical makeup of each type determines its operating characteristics. The following table lists characteristics of each type of fuel cell.

Individual Fuel Cell



Fuel Cell Properties

Fuel Cell	Electrolyte	Catalyst	Operating Temperature	Fuel for Anode/Cathode
PEM	Solid polymer membrane	Platinum	80ºC	Hydrogen/pure or atmospheric oxygen
Phosphoric Acid	Liquid phosphoric acid	Platinum	200ºC	Hydrogen/ atmospheric oxygen
Direct Methanol (DMFC)	Solid polymer membrane	Platinum	50º-100ºC	Methanol solution in water/atmospheric oxygen
Alkaline (AFC)	Solution of potassium hydroxide in water	Nonprecious metals	100º-250ºC	Hydrogen/pure oxygen
Molten Carbonate (MCFC)	Molten carbonate salt	Nonprecious metals	650ºC	Hydrogen, methane/ atmospheric oxygen
Solid Oxide (SOFC)	Ceramic oxide	Nonprecious metals	800º-1,000ºC	Hydrogen, methane/ atmospheric oxygen

Sources: DOE HFC&IT Program (www.eere.energy.gov/hydrogenandfuelcells), Rocky Mountain Institute (www.rmi.org/sitepages/pid556.php), Fuel Cells 2000 (www.fuelcells.org/fctypes.htm)

Appendix C - Calculating Energy Equivalent Gallon Fuel Economy for Hydrogen

Hydrogen is measured in mass units when it is delivered to the bus's storage system. In the United States, these mass units are typically measured in pounds-mass and abbreviated "lb" (sometimes lbm). In the rest of the world, this measure of mass would be in kilograms (kg). In the United States, fuel economy is usually presented in miles per gallon (mpg). For compressed hydrogen, the hydrogen measured in lb needs to be presented in units similar to gasoline or diesel so it can be compared to something familiar.

The fuel economy calculation starts with an energy conversion with standard energy content values[2] for each fuel:

- Hydrogen: 51,532 British thermal units (Btu)/lb
- Diesel: 128,400 Btu/gallon
- Gasoline: 115,000 Btu/gallon

The next determination is which comparison fuel to use: diesel or gasoline. There is a slight energy content difference based on volume for gasoline and diesel fuels, so this will change the fuel economy calculation slightly.

Diesel MPG Comparison Calculation

Distance traveled, miles/(hydrogen mass dispensed, lb x 51,532 Btu/lb/128,400 Btu/gallon)

Gasoline MPG Comparison Calculation

Distance traveled, miles/(hydrogen mass dispensed, lb x 51,532 Btu/lb/115,000 Btu/gallon)

A fuel economy calculation is performed between two separate fuel fills for the bus. On the second fuel fill, the difference in mileage between the two fuel fills is divided by the amount of fuel added in the second fuel fill:

Miles per gallon = (odometer second fill - odometer first fill)/(fuel added in second fill)

One major assumption is made in this calculation-both fills provided a complete fill of the tank. Only this way can the calculation be used accurately—the fuel tank level must be known at the beginning and the end of the operation between the two fill-ups. This is not always the case, and therefore the calculation can have some significant error at each fill. However, the accuracy of this calculation improves with multiple and consecutive fuel fills (in other words, this error tends to average out as long as there are several fuel fills and none of the fuel fill information is missing).

[2] *Source: Alternative Fuels Data Center Web site (www.afdc.doe.gov/pdfs/fueltable.pdf)*

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Produced for the U.S. Department of Energy
by the Center for Transportation Technologies and Systems
at the National Renewable Energy Laboratory (NREL),
a U.S. Department of Energy national laboratory

NREL
1617 Cole Blvd.
Golden, CO 80401-3393

DOE/GO-102003-1786
November 2003

Printed with a renewable-source ink on paper containing
at least 50% wastepaper, including 20% postconsumer waste