HYDROGEN FUEL CELL BUS EVALUATION

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Abstract

Global concern for the environment has been increasing throughout the last decade, and "green" technologies are being emphasized all over the world. Research and development of advanced technologies for the transportation sector has been growing at a rapid pace in an effort to reduce petroleum imports and lower emissions. Developing technologies have recently been incorporated into transit buses because of the additional space and volume that is available for packaging prototype equipment. In the late 1990s, preliminary studies on fuel cell buses were carried out by transit agencies in Chicago, IL; Vancouver, BC, Canada; and Georgetown University in Washington, DC. Although early results were promising, it was clear additional testing and evaluation was necessary before these new technologies could be successfully integrated into a transit fleet. One such evaluation is underway at SunLine Transit Agency in Thousand Palms, California on a bus equipped with a XCELLSiS Phase 4 fuel cell engine. The Department of Energy's National Renewable Energy Laboratory (NREL) is working with transit agencies and other partners to determine the test and evaluation protocols needed to advance implementation of these new technologies, as well as to document the necessary modifications to the transit agencies' maintenance and operation infrastructure. By evaluating SunLine, an "early adopter" of the technology, NREL will develop and carry out a test plan for evaluating the fuel cell buses, the hydrogen fueling infrastructure, and maintenance facilities. This paper describes the prototype bus, fueling infrastructure, and maintenance facility at SunLine and begins the process of determining what is needed to evaluate and characterize the bus' performance in service.

Introduction

Although buses make up less than 1% of the total vehicles operated in the U.S., their concentrated use in the urban environment results in disproportionate public health impacts. Most notably, buses are a major cause of human exposure to emissions of diesel particulate matter, which has been identified by the California Air Resources Board (CARB) as a toxic air contaminant. Transit buses are one of the best applications for alternative fuel or advanced technology vehicles for several reasons: they typically operate in highly urbanized areas where pollution is already a problem; they are centrally located/fueled; they are highly visible; and they are government subsidized. Due to the high visibility and pollution issues, buses have been the focal point for developing zero- and near-zero-emission fuel cell technology for heavy-duty vehicles. Several prototype fuel cell buses have been demonstrated in the U.S. and Canada in the past few years and are expected to be available commercially on a limited basis by 2003. Transit fleets considering advanced technology buses must have information on performance, maintenance, and infrastructure requirements before they can incorporate the buses into their fleet. Therefore, a comprehensive evaluation protocol will have to be developed for testing and evaluating fuel cell buses; and the necessary facility modifications and potential costs will need to be characterized.

California has traditionally led the way in implementing advanced transportation technologies, mainly due to severe air quality problems and the unique charter of CARB to adopt the world's most stringent emissions standards. Zero emission vehicles are a key element in CARB's plan to attain air quality standards, and its recently adopted state-wide urban bus fleet rule requires transit agencies that choose to follow the "diesel path" to begin demonstrations of zero-emission buses by July 2003. In conjunction with CARB and other members of the California Fuel Cell Partnership, a prototype fuel cell bus is currently being demonstrated at SunLine Transit Agency in Thousand Palms, CA. The Zero-Emission Bus, or ZEbus, is equipped with a direct-hydrogen proton exchange membrane fuel cell engine developed by XCELLSiS Fuel Cell Engines Inc. XCELLSiS partnered with SunLine to demonstrate the bus in real-world service. Data gathered from this demonstration will be used to validate the technology and to develop a commercial product. The SunLine demonstration provides an excellent opportunity for researchers to gain an understanding of the prototype bus, its systems, and facility modifications necessary for maintenance and operation. The information being gathered is aiding in the development of procedures for evaluating the next generation of fuel cell buses.

In 2003, AC Transit in Hayward, CA will procure up to 20 fuel cell buses for the California Fuel Cell Partnership's fuel cell bus demonstration program. (SunLine and AC Transit are currently the only two transit agencies that are associate members of the California Fuel Cell Partnership.) The buses from this procurement will be operated by AC Transit, SunLine Transit Agency, and possibly one or two other Bay Area transit properties. NREL plans an evaluation of these buses operating in revenue service.

Background on SunLine Transit Agency

Concerned with poor air quality in the surrounding Coachella Valley of Southern California, in 1992, SunLine's board of directors (all elected officials) mandated a conversion from diesel to alternative fuel buses. Investigation into alternatives to diesel showed that compressed natural gas (CNG) buses offered the lowest-emission commercially available technology available. With help from local partners, such as the Southern California Gas Company, who helped build the fueling infrastructure, and College of the Desert, who developed a training curriculum, SunLine converted its entire fleet to CNG. In May of 1994, SunLine became the first transit district in America to roll out for revenue service with a fleet of 100% CNG buses.

SunLine's management team believes that CNG is the best choice for the present, but also an excellent means to help make the transition to hydrogen as a major transit bus fuel. CNG used as a transportation fuel has storage, dispensing, and handing requirements similar to compressed hydrogen. In addition to the XCELLSiS fuel cell bus, SunLine operates two Hythane® fueled buses. Hythane® is a compressed gas mixture of 20% hydrogen and 80% natural gas (by volume). Adding the small percentage of hydrogen reduces CNG's already low NOx emissions by over 40%. The use of Hythane® can also help to gradually introduce hydrogen as a commonly used transportation fuel.

Sunline's single fuel cell bus and two Hythane® buses are fueled with hydrogen produced on-site by the transit agency. This paper describes the prototype fuel cell bus, the fueling infrastructure, and maintenance facility at SunLine and discusses some of the issues that need to be resolved for a transit agency to operate and maintain fuel cell buses in real-world revenue service.

Prototype Fuel Cell Bus

XCELLSiS Fuel Cell Engines, jointly owned by DaimlerChrysler, Ford Motor Company, and Ballard Power Systems, is focused on developing, manufacturing, and commercializing fuel cell engines for transportation applications. Their Phase 3 (P3) Test Program included a 2-year demonstration of P3 fuel cell buses at two locations: Chicago, Illinois, and Vancouver, British Columbia. The results from the demonstration were positive and led to many improvements in the Phase 4 (P4) bus design, including the following:

- Engine volume reduction of 50%
- Weight reduction of 3400 lb
- Eight fuel cell stacks (down from 20)
- Number of motors reduced to one (P3 had 12)
- Startup time reduced from 45 to 3 seconds
- Maintenance cost reductions (possibly as much as 90% compared to those of the P3 bus)

The P4 XCELLSiS fuel cell bus currently operated at SunLine is a standard low-floor transit bus purchased from New Flyer and converted by the XCELLSiS/Ballard Power Systems team to fuel cell power. Table 1 provides an overview of the XCELLSiS fuel cell engine and P4 fuel cell bus. Figure 1 shows a field engineer from XCELLSiS preparing to fuel the bus from the Stuart Energy/Fueling Technologies hydrogen/Hythane® dispenser (described later).

Table 1. Overview of the XCELLSiS fuel cell engine and P4 fuel cell bus

Fuel cell technology	Direct-H_2 Proton Exchange Membrane
Fuel cell engine make / model	XCELLSiS XCS-HY-205
Fuel cell engine volume / weight	5.32 cubic meters / 2,170 kg (4,774 lbs)
Net shaft power / peak net torque	205 kW @ 2100 rpm / 1,100 Nm @ 800 rpm
Net efficiency	44% to 37% (LHV)
Fuel type	Gaseous hydrogen @ up to 3,600 psig
Fuel storage system / capacity	Std. CNG cylinders / 17,500 SCF of CH_2*
Bus range	Approximately 225 miles
Air delivery system / max air flow	Two stage compressor / 600 SCFM
Nominal operating pressure	200 kPa (30 psig)
Cooling system	Water / glycol
Fuel cell operating temperature	$70^{o}C$ to $80^{o}C$
System voltage range	600 to 900 VDC
Power conditioning	IGBT inverter, liquid cooled
Electric traction drive	Brushless DC, liquid cooled
Power transmission	Fixed ratio, direct drive
Braking	Dynamic (no regenerative)

* Compressed gaseous hydrogen

Figure 1. XCELLSiS field technician fueling the P4 bus with hydrogen

Currently, XCELLSiS field engineers are handling the day-to-day operations of the P4 fuel cell bus and performing tests to verify and improve its commercial viability. The bus is not yet ready for revenue service. It is being driven over a similar street route each day, and is equipped with test instrumentation and water-filled tanks on the seats to simulate the curb weight of a loaded bus. Figure 2 shows the interior of the bus during such a test.

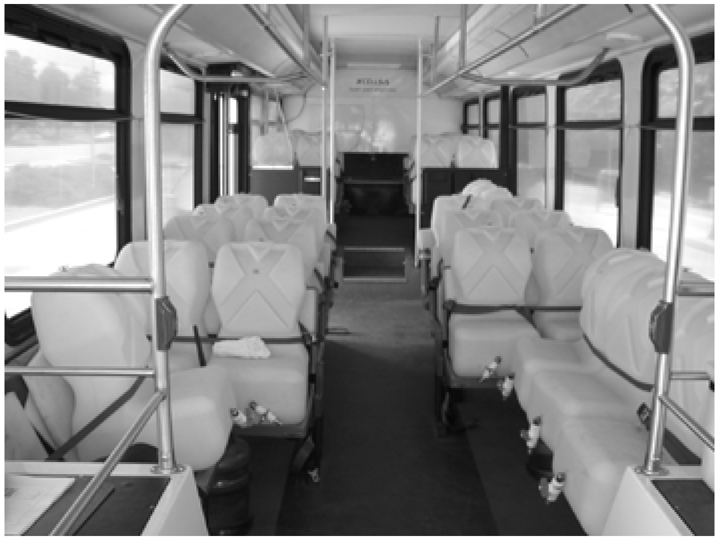

Figure 2. Water tanks in the XCELLSiS bus simulate curb weight during testing

Hydrogen Infrastructure

SunLine Transit Agency has adopted a two-pronged approach to its preliminary hydrogen fueling infrastructure. In April of 2000, SunLine opened a hydrogen generation, storage, fueling, and education facility to demonstrate these various approaches to hydrogen production. At the site, hydrogen is produced by solar-powered electrolysis as well as natural gas reforming. In an effort to test the viability of as many renewable sources of hydrogen as possible, SunLine is also interested in producing hydrogen from electrolysis powered by the Coachella Valley's abundant wind resources.

Currently, the hydrogen production, storage, and dispensing infrastructure at SunLine Transit Agency consists of the following main components:

- Three separate systems for onsite hydrogen production (two water electrolysis systems – one which provides fuel for SunLine's fuel cell golf carts and a neighborhood electric vehicle; the other provides fuel for the ZEbus and Hythane® buses; and partial oxidation reforming of natural gas)
- A tube trailer and American Society of Mechanical Engineers (ASME) tanks for storage of approximately 118,000 standard cubic feet (SCF) of compressed hydrogen

- A two-hose fueling station that dispenses compressed hydrogen from one hose and a Hythane® blend from the second hose

Stuart Energy Hydrogen Generator, Storage, and Dispensing System

Currently, all hydrogen used to fuel the XCELLSiS fuel cell bus is produced, stored, and dispensed through a complete system built and packaged by Stuart Energy. Hydrogen production in this system is accomplished by splitting water into hydrogen and oxygen using Stuart Energy's proprietary electrolysis technology. The resulting hydrogen gas is dried, purified, compressed, and sent to storage, while the oxygen is vented to the atmosphere. Hydrogen fueling of the XCELLSiS P4 fuel cell bus is accomplished with a specially designed dispenser similar to those used by SunLine to fuel its fleet of compressed natural gas buses. Energy to power the electrolyzer is currently provided by the grid with some of that power being offset by SunLine's photovoltaic arrays (totaling approximately 40 kW) and flat plate arrays.

Specific components of SunLine's complete "bus fueler" system include the following:

- Stuart Energy Model P3-1A CST multi-stack electrolyzer, with an output of 1400 standard cubic feet per hour (SCFH) of hydrogen

- Stuart Energy hydrogen processing module including a Comp-Air Reavell Model 5000 4-stage hydrogen compressor with an outlet pressure of 5,000 psi

- Modular hydrogen storage consisting of a FIBA tube trailer with 16 DOT tanks holding 104,000 SCF of hydrogen (3,130 psi), and two ASME tanks holding 14,000 SCF of hydrogen (4,000 psi)

- Fueling Technologies, Inc. Model HYDH5210 hydrogen/Hythane® dispenser, with mass flow metering, a separate mixer for Hythane®, and two fast-fill hoses

Figure 3. SunLine's FIBA tube trailer and ASME tanks for CH_2 storage

Figure 4. Stuart Energy's modular compressed hydrogen station

HbT Natural Gas Reformer

A second source of hydrogen for SunLine's fleet of fuel cell buses will be produced through on-site partial oxidation reforming of natural gas. In mid 2000, the California Air Resources Board approved a grant to HbT (formerly known as Hydrogen Burner Technology) to build and install such a system at SunLine. The HbT system uses HbT's Under-Oxidized Burner (UOB^{TM}) technology and a QuestAir purifier to reform pipeline natural gas into high-purity (99.999%) hydrogen. This system, which is currently undergoing checkout testing, will be able to fuel four or five hydrogen buses per day. The system includes the following components:

- Model 4200 NG-A UOB^{TM} reformer/CO shift reactor skid
- Pressure Swing Adsorption (PSA) purification unit
- Integrated automatic Programmable Logic Controller (PLC) controls
- Pressure Dynamics 2-stage hydrogen compressor
- Pressure vessels for hydrogen storage

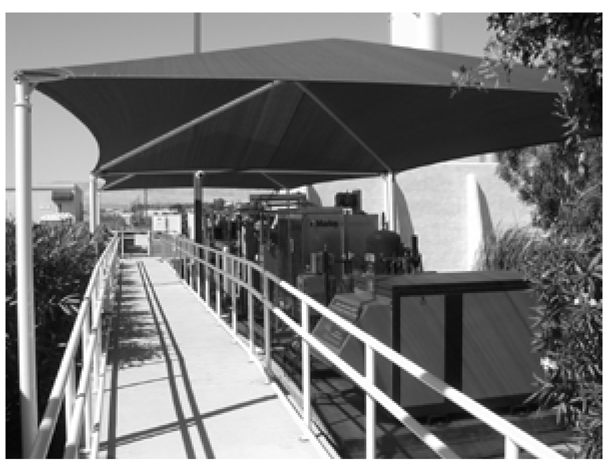

Figure 5. HbT's Model 4200 NG-A natural gas reformer system at SunLine Transit Agency

As the first U.S. transit agency to build a hydrogen fueling infrastructure, SunLine has broken new ground. Table 2 gives the estimated cost for the infrastructure installed at SunLine. Because this facility is a first of its kind, these costs should be considered preliminary. Some components and systems are essentially pre-commercial, while others are "off-the-shelf." The cost of adding infrastructure to another transit agency could be different depending on their approach, the specific equipment, the number of buses serviced, and other factors. The costs listed here reflect SunLine Transit Agency's current experience with providing fuel for its bus fleet.

Table 2. Cost of Hydrogen Fueling Infrastructure Installed at SunLine

Infrastructure Component	System	Manufacturer / Model	Estimated Equipment Cost
H_2 Production, Clean-up, and Compression	Electrolyzer	Stuart Energy P3-1A	**Unknown / Proprietary**
	Compressor	CompAir Reavell 5000	**Included in Stuart Energy package**
	Nat. Gas Reformer	Hydrogen Burner Technologies 4200 NG-A	**$450,000**
	Compressor	Pressure Dynamics	**Included in HBT package**
H_2 Storage	Tube Trailer Cylinders (104,000 SCF)	Fiba Technologies	**$104,000**
	Stationary Cylinders (14,000 SCF)	Not Available	**$54,000**
H_2 / Hythane Dispensing	Hydrogen / Hythane Mixer and Dispenser	Fueling Technologies Inc. HYDH5210	**$32,000**

Maintenance Facility for Hydrogen Buses

Currently, SunLine Transit Agency maintains its fleet of CNG buses in a large indoor facility. By contrast, XCELLSiS personnel perform maintenance on the hydrogen fuel cell bus in a separate, smaller facility. As Figures 6 and 7 show, this "outdoor-style" facility consists of an aluminum frame, fireproof canvas, and explosion-proof light fixtures. The "tent" structure is ventilated along the ridgeline to allow hydrogen gas to safely escape if it is inadvertently released from the vehicle. In the near future, hydrogen sensors may be installed along the peak of the structure to alert maintenance staff of a possible leak. This $95,000 facility is sufficient to maintain the existing XCELLSiS fuel cell bus and possibly up to four additional buses, but it is essentially an interim solution for SunLine Transit Agency. It is also important to note that SunLine's maintenance facility, while perfect for the agency's operating climate, would not work for transit agencies in all climate zones. Eventually, transit districts making a serious commitment to hydrogen fuel cell buses will need to construct state-of-the-art maintenance facilities that meet all applicable safety codes and standards.

Figure 6. Outside of existing maintenance facility for hydrogen buses.

Figure 7. Interior of the hydrogen bus maintenance facility

Issues

The single P4 XCELLSiS bus operated at SunLine Transit Agency is one of a kind and currently the world's most technologically mature on-road fuel cell vehicle. SunLine is among the most progressive transit agencies in America regarding early adoption of advanced low-emission bus technologies and the use of alternative fuels. The existing hydrogen generation, storage, and dispensing systems at SunLine are essentially state-of-the-art for compressed hydrogen use in vehicle applications. Involvement of the California Fuel Cell Partnership will help the program progress to the next stages of deployment when additional buses become available in 2003. Clearly, the right players have been assembled for the SunLine Transit Agency fuel cell bus demonstration, and the program is on track for success.

However, to optimize the program's full potential for success, a number of issues will need to be addressed over the next two years. These include the following:

- Currently, SunLine Transit Agency has a limited role in testing, operating, maintaining, and fueling the fuel cell bus. SunLine provides motor coach operators, preventative maintenance on the bus, and some equipment replacement. At this early stage, XCELLSiS field engineers are performing most other functions on a day-to-day basis. This is necessary in order for XCELLSiS to further the commercial viability of its emerging direct-hydrogen PEMFC technology. However, if fuel cell buses are to be deployed in normal revenue service at

SunLine Transit Agency and other California transit agencies by 2003, it will soon be necessary to increase the hands-on involvement of transit personnel in these processes. A "master plan" for this transition is needed, perhaps through the California Fuel Cell Partnership.

- The existing facilities at SunLine Transit Agency to generate, store, and dispense hydrogen appear sufficient to meet SunLine's current fuel cell bus program, including plans for modest expansion (~2 or 3 buses). Significantly expanding the fleet beyond a demonstration scale will likely require significant upgrades to key systems, such as expanded fuel storage and an improved maintenance facility. SunLine Transit Agency is already addressing some of these concerns.

- According to SunLine personnel, the biggest barrier to expanding its hydrogen fuel cell bus operations is the current lack of hydrogen-specific regulations addressing safety. Without new codes and standards specifically designed for the unique characteristics of hydrogen, it's possible that fire-protection and code and safety officials will raise issues that could delay the commercial introduction of hydrogen fuel cell buses by many years.

- There are many logistical issues to be worked out before SunLine Transit Agency can optimize the emerging subsystems in its hydrogen infrastructure. For example, the HbT reformer system produces large volumes of wastewater each day during full operation. This effluent is not hazardous but nonetheless must be disposed of in an efficient, non-disruptive manner. It's possible that beneficial uses for the effluent can be identified.

Future Work

The goal for the NREL Hydrogen Bus Evaluation Program is to evaluate the performance and operating characteristics of fuel cell buses in revenue service and characterize the maintenance and fueling infrastructure needed to fuel and maintain them. Because fuel cell buses are not commercially available, we will use the prototype fuel cell bus demonstration project at SunLine to understand the technology and plan for the future evaluation. Using the preliminary data collected, NREL plans to:

- Develop and document the procedures necessary to evaluate fuel cell buses
- Perform baseline performance testing of the XCELLSiS fuel cell bus and document the results
- Define and document infrastructure and facility modifications required to add hydrogen fueling and bus maintenance to the AC Transit site
- Evaluate the performance, emissions, cost, and operating characteristics of the Hythane buses

The information collected will be made available on the World Wide Web.

References

Cleaning Up: Zero-Emission Buses in Real-World Use. 2001. A Report on the Phase 3 Fuel Cell Bus Program by XCELLSiS/Ballard Power Systems. http://www.ballard.com/fcb_report.asp

Information provided to NREL and Arthur D. Little by staff from SunLine Transit Agency and XCELLSiS Fuel Cell Engine Company.