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Federal Transit Administration

National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2 Appendices



Alameda-Contra Costa Transit District
(AC Transit)



June 2010

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Introduction to the Appendices

The National Renewable Energy Laboratory (NREL) has reported evaluation results for fuel cell buses since 2003.¹ These reports include background on the transit agency, the buses, infrastructure, and overall experience operating fuel cell buses. Several reports are planned for each evaluation site. The first data report typically includes extensive background material plus an analysis of the first round of data. Update reports follow the initial publication, focusing on the newest data analysis and lessons learned since the previous report. The authors would like to provide more focus on the newer data without depriving new readers of the background and context on the transit agency and the technology. These appendices, referenced in the main report, are designed to provide the full background for the evaluation. They will be updated as new information is collected but will contain the original background material from the first report. Both parts can be downloaded separately. The report, *National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2* is available at www.nrel.gov/hydrogen/proj_fc_bus_eval.html, along with all other NREL publications on hydrogen and fuel cell buses.

¹Note that to save space, fuel cell bus has been abbreviated to FCB in the tables in these appendices.

Appendix A: NREL Transit Bus Evaluation Activities

Under funding from the U.S. Department of Energy (DOE) and in coordination with the Federal Transit Administration (FTA), the National Renewable Energy Laboratory (NREL) has been evaluating alternative fuel transit buses since the early 1990s. In 1996, DOE and NREL completed an evaluation of transit buses running on six different alternative fuels at eight transit agencies. As part of this alternative fuel transit bus evaluation, NREL and Battelle (NREL's contractor for this effort) developed a customized data collection and evaluation protocol. This protocol has evolved over time but is still based on the original effort.

NREL first began evaluating hydrogen-fueled transit buses in 2000 with SunLine Transit Agency. Since that time, NREL has published reports on fuel cell bus performance and fleet experience for several transit agencies in the United States. These evaluations were funded under the Technology Validation activity within DOE's Fuel Cell Technologies Program,¹ which is focused on addressing the technical challenges and accelerating the development and successful market introduction of fuel cells and related technologies. NREL supports DOE's Technology Validation activity by evaluating fuel cell vehicles in parallel with hydrogen infrastructure to determine the current status of the technology and to assess the progress toward technology readiness.

Although DOE has not funded the direct development of fuel cell buses, it has provided funding to NREL to conduct data collection, analysis, and reporting of existing fuel cell bus project evaluation results under its Technology Validation activity. Three hydrogen transit bus evaluations are currently active and six were completed in the last few years.

In 2006, FTA initiated its newest development program, the National Fuel Cell Bus Program (NFCBP).² The NFCBP was established as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) transportation authorization. The NFCBP program designated \$49 million in funding from 2006 through 2009 to help develop commercially viable fuel cell buses and technologies. The FTA competitively selected three nonprofit organizations—the Center for Transportation and the Environment (CTE), the Northeast Advanced Vehicle Consortium (NAVC), and CALSTART—to administer projects under the program. The FTA selected 14 separate projects in all, including 8 planned demonstration projects.

The FTA is collaborating with DOE and NREL to ensure that data are collected on all fuel cell bus demonstrations under the program. FTA has tasked NREL with evaluating the fuel cell bus demonstrations for the NFCBP. NREL uses the standard data collection and analysis protocol established for DOE heavy-duty vehicle evaluations. In May 2008, NREL published *Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*, which outlines the methodology for these evaluations.³ Table A-1 provides an overview of all the fuel cell bus evaluation projects planned under both

¹ DOE Fuel Cell Technologies Program Web site: www1.eere.energy.gov/hydrogenandfuelcells/

² FTA Bus Research and Testing Web site: http://www.fta.dot.gov/assistance/technology/research_4578.html

³ *Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*. NREL/MP-560-42781. Golden, CO: NREL, May 2008. Available online at <http://www.nrel.gov/hydrogen/pdfs/42781-1.pdf>

DOE and FTA funding. This overview is the estimated timing for NREL’s data collection and evaluation and does not reflect the early design, development, and construction phase for the buses. The plans for upcoming evaluations are subject to change as each project progresses. The projects are separated by funding agency; however, for the NFCBP evaluation sites, any detailed data collection and analysis of the fuel cell system or infrastructure will be funded by DOE. Table A-2 provides more details and status for the evaluation sites funded solely by DOE. Additional details on the eight NFCBP demonstrations sites funded by FTA are listed in Table A-3. FTA is also considering additional funding for one or two sites beyond the NFCBP sites, but this funding has not been determined.

Table A-1. Summary of NREL Hydrogen Bus Evaluations for DOE and FTA⁴

NREL Hydrogen Bus Evaluations for DOE and FTA																		
Site/Location	State	Eval. Funding	2009				2010				2011				2012			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
AC Transit/SF Bay Area	CA	DOE Technology Validation					CA ZEB Advanced Demo											
SunLine/Thousand Palms	CA		FCB															
SunLine/Thousand Palms	CA						Advanced FCB Project											
CTTRANSIT/Hartford	CT		FCB Demo															
City of Burbank/Burbank	CA						Burbank FCB											
AC Transit/Oakland	CA	FTA National Fuel Cell Bus Program	Accelerated Test															
SunLine/Thousand Palms	CA										American FCB Demo							
CTTRANSIT/Hartford	CT						Nutmeg Hybrid FCB Demo											
USC, CMRTA/Columbia UT/Austin	SC, TX						Hybrid FCB											
Logan Airport/Boston	MA										MA H2 FCB Demo							
Albany/NY	NY										Light-wt FCB							
SFMTA/San Francisco	CA						FC APU Hybrid											

Demonstration sites color coded by geographic area:

	Northern California		New England		Southeast
	Southern California		New York		South

⁴ For a current version of the summary table, see http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

Table A-2. DOE/NREL Heavy Vehicle Fuel Cell/Hydrogen Evaluations

Fleet	Vehicle/Technology	Number	Evaluation Status
City of Burbank, CA	Proterra battery-dominant, plug-in hybrid bus using two Hydrogenics fuel cells	1	Evaluation began in April 2010
Bay Area Transit Consortia led by AC Transit (Oakland, CA)	Van Hool/UTC Power fuel cell hybrid	12	Evaluation to begin in 1st Quarter 2010
SunLine Transit Agency (Thousand Palms, CA)	Advanced FCB: New Flyer/ISE hybrid system/Ballard fuel cell	1	Evaluation began in May 2010
Completed Evaluations			
Connecticut Transit (Hartford, CT)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corporation (ISE Corp.)	1	Complete; reported in Oct. 2008, May 2009, and Jan. 2010
SunLine Transit Agency (Thousand Palms, CA)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	1	Extended testing with updated fuel cell system—complete; reported in Jan. and Aug. 2009
SunLine Transit Agency (Thousand Palms, CA)	New Flyer/ISE Corp. hydrogen internal combustion engine transit bus	1	Complete; results reported in Feb. 2007, Sept. 2007, and June 2008
	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	1	
Alameda-Contra Costa Transit District (AC Transit; Oakland, CA)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	3	Complete; results reported in March 2007, Oct. 2007, and July 2008
Santa Clara VTA ^a (San Jose, CA) and San Mateo (San Carlos, CA)	Gillig/Ballard fuel cell transit bus	3	Complete and reported in 2006
SunLine Transit Agency (Thousand Palms, CA)	ThunderPower hybrid fuel cell transit bus; ISE Corp./ UTC Power	1	Complete and reported in 2003

^aVTA = Valley Transportation Authority

Overall Evaluation Objectives

The objectives of the DOE and FTA evaluations are comprehensive, unbiased results of fuel cell and hydrogen bus development and performance compared with conventional baseline vehicles when available and appropriate. Baseline vehicles are typically diesel buses or occasionally compressed natural gas (CNG) buses. These evaluations also include information on the development and performance of hydrogen infrastructure and descriptions of the facility modifications required for safe operation of hydrogen-fueled vehicles.

The DOE and FTA demonstration and evaluation programs have two major goals:

- Supply credible data analysis results to the transit bus and fuel cell industries that go beyond “proof of concept” for fuel cell transit buses and infrastructure.
- Produce results focused on performance and use, including progress over time and experience from integrating vehicle systems, operations, and facilities for the fuel cell transit buses and supporting infrastructure.

DOE and FTA have both cited the lack of data and analysis results in real-world service as a challenge to moving the technology forward. These evaluations have proved useful for a variety of groups, including transit operators considering the technology for future procurements, manufacturers needing to understand the status of the technology for transit applications, and government agencies making policy decisions or determining future research needs.

Table A-3. Summary of FTA NFCBP Demonstration Projects

Project	Description
Dual Variable Output Fuel Cell Hybrid Bus Validation and Testing (CTE)	Proterra will develop a battery-dominant, 35-ft plug-in hybrid fuel cell bus (Hydrogenics) that will be demonstrated in Columbia, SC, followed by Austin, TX
Nutmeg/Connecticut Fuel Cell Bus Program (NAVC)	UTC Power and NAVC are leading a team to develop and demonstrate advanced version hybrid 40-ft fuel cell buses; enhanced UTC Power 120-kW proton exchange membrane (PEM) fuel cell with upgraded seals, catalysts, bipolar plates, balance of plant
Lightweight Fuel Cell Hybrid Bus (NAVC)	GE-led team to develop an advanced propulsion system integrated with a lightweight bus platform for field evaluation focused on advanced battery technologies for lower cost
Massachusetts Hydrogen Fuel Cell Powered Bus Fleet (NAVC)	Advanced bus development and in-service demonstration; integrate Nuvera 82-kW fuel cell with drive system from ISE Corp. and advanced energy storage; demonstration effort includes Nuvera's PowerTap fueling infrastructure
NY Hydrogen Powered FCB Program (NAVC)	The project team led by the New York Power Authority will develop and demonstrate two 40-ft buses for operation in upstate New York for up to 2 years
American Advanced Fuel Cell Bus Program (CALSTART)	A team led by SunLine will design and demonstrate a 40-ft fuel cell bus with design improvements that meets FTA "Buy America" requirements; revenue service evaluation in hot desert climate; Eldorado bus, BAE hybrid system, Ballard fuel cells
Compound Fuel Cell Hybrid Bus for 2010 (CALSTART)	A team led by BAE will develop a 40-ft hybrid bus with fuel cell auxiliary power unit (Hydrogenics, 16-kW PEM) coupled with a diesel engine; demonstrate for 1 year at San Francisco MTA; BAE Systems drive, electrically driven accessories, advanced energy storage (lithium ion)
AC Transit HyRoad: Commercialization of Fuel Cells for Public Transit (CALSTART)	Accelerated testing of existing fuel cell buses; team is Van Hool (bus chassis), ISE (hybrid drive system), and UTC Power (fuel cell system)

Appendix B: Transit Agency Descriptions

AC Transit: Host Site Profile

AC Transit⁶ provides public transit service in the East Bay of the San Francisco, California, area including Oakland, California. AC Transit was created in 1956, but public transit in Oakland dates as far back as 1869. The district is governed by a seven-member board of directors elected by East Bay voters. Five of these board members represent geographic wards; two are elected at large. The AC Transit service area of 364 square miles includes 13 cities and adjacent unincorporated areas in Alameda and Contra Costa counties. AC Transit operates 538 transit buses in peak service (682 active buses in the fleet including paratransit) on more than 105 fixed routes and also provides school bus service. In fiscal year 2006, annual ridership exceeded 67 million. Since 2000, AC Transit has operated HyRoad, a fuel cell demonstration program the transit agency developed. With a goal of demonstrating the viability of an emissions-free transit system, the HyRoad Program includes operating fuel cell buses and passenger cars; on-site hydrogen production, fueling, and vehicle maintenance; and public education and safety training.



Photo Credit: L. Eudy, NREL

Golden Gate Transit⁷ (GGT) is a participant in the AC Transit fuel cell bus demonstration. GGT is part of the Golden Gate Bridge, Highway, and Transportation District (The District), which is headquartered in San Francisco, California, and serves the North Bay area. The District includes GGT as well as the operation of the Golden Gate Bridge and the Golden Gate Ferry. GGT, which operates from San Rafael, California, a central location in its operating area, started fixed-route service in 1972 based on transportation planning aimed at reducing traffic congestion on the Golden Gate Bridge. GGT's current bus fleet totals 204 buses. During fiscal year 2008, the fleet operated more than 5.2 million miles. Figure B-1 shows the AC Transit and GGT operating areas.

AC Transit Fuel Cell Bus Program

AC Transit's interest in fuel cell buses started in October 1999, following a successful 1-week demonstration of the Ballard P4 ZEBus on scheduled routes in the AC Transit service area. This demonstration preceded Ballard operating the bus for a 1-year test at SunLine in 2000. Soon after, the California Air Resources Board (CARB) established a new fleet rule in February 2000 to significantly reduce emissions of existing and new transit buses in California. The rule set more stringent emissions standards for new urban bus engines and promoted advancement of the cleanest propulsion technologies—specifically, zero-emission buses (ZEBs). This ruling required transit agencies to choose a compliance path—alternative fuel or diesel.

⁶AC Transit Web site: www.actransit.org

⁷Golden Gate Transit Web site: www.goldengate.org

AC Transit and GGT agreed in 2001 to partner in the staff training and operation of fuel cell buses to meet the CARB requirements. AC Transit attempted to purchase fuel cell buses in 2000 and early 2001. The agency received only one bid, which was eventually withdrawn by the vendor. AC Transit set out in 2001 to learn all that it could about fuel cell buses, including operating the Ballard P4/ZEbus for 1 week for testing, joining the California Fuel Cell Partnership (CaFCP), and operating the ISE/UTC Power ThunderPower 30-ft fuel cell bus during part of 2003 and 2004.

During 2001 and 2002, AC Transit was looking for a new bus design to purchase for its planned bus rapid transit (BRT) project. AC Transit's next large purchase of diesel buses (approximately 190 buses) was from Van Hool through its distributor in the United States, ABC Companies. These new buses featured three doors for quick loading and unloading for the Rapid BRT service, which started in June 2003 with the San Pablo Rapid service.

At the end of 2001, AC Transit started discussions with ISE Corp. about developing a new fuel cell bus design. In April 2002, negotiations were started for a sole source contract with ISE and UTC Power with plans to use the same Van Hool bus chassis as was used for the diesel buses; however, this project stalled during most of 2002. After a major meeting of the project partners coinciding with an American Public Transportation Association (APTA) meeting in Las Vegas in September 2002, the project was re-energized. The contract for the new fuel cell buses was revised in April 2003, and the project was back on track. This order included three new Van Hool fuel cell buses for AC Transit and one new Van Hool fuel cell bus for SunLine. Rather than using a standard diesel chassis, as was originally planned, Van Hool designed and constructed an entirely new chassis (based on the existing A330 bus design) that could accommodate fuel cell and hybrid system components more effectively.

This new contract had several changes, and the delays required that the CARB deadline for demonstrating fuel cell buses be postponed. The first fuel cell bus was delivered to AC Transit in October 2005, and the other two AC Transit buses arrived in December 2005. The on-site hydrogen fueling station from Chevron was commissioned on March 13, 2006, and the three fuel cell buses went into service on March 20, 2006.

The HyRoad—Once the fuel cell buses were on order and being manufactured, AC Transit got to work putting together its hydrogen future and vision for its hydrogen fuel cell program. This comprehensive fuel cell program (HyRoad) aims to demonstrate the viability of an emissions-free transit system and features:

- Three zero-emission hybrid-electric, hydrogen fuel cell buses
- A fleet of fuel cell passenger vehicles (part of DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project)
- On-site hydrogen production and fueling
- On-site fleet maintenance
- Ongoing, outside evaluation (this report and future reports)
- Public education and safety training

The partners for the fuel cell bus program at AC Transit include the following:

- Van Hool Bus—manufacturer of the bus bodies and chassis
- UTC Power—maker of the fuel cell power systems
- ISE Corporation—integrator of the fuel cell power systems and hybrid-electric drive systems
- Chevron Technology Ventures (a division of Chevron USA)—builder of the hydrogen fueling station at AC Transit’s East Oakland Division.

Funding for this project included more than \$21 million from public agencies and private sector companies, as follows:

- State of California—\$8 million
- CARB—\$2.8 million
- Bay Area Air Quality Management District (BAAQMD)—\$1 million
- FTA—\$1 million
- California Energy Commission—\$1 million
- DOE—\$700,000 plus partial funding for the hydrogen station construction and operating expenses
- AC Transit matching funds—\$1.2 million
- CALSTART—\$200,000
- Chevron Technology Ventures—\$2 million (matching funds) plus additional funding for capital and operating expenses
- Miscellaneous contributions of more than \$3 million

AC Transit has operated the three fuel cell buses in revenue service since March of 2006. Under funding from DOE, NREL has tracked the performance of the buses in comparison with diesel buses in similar service. The results of the evaluation have been documented in four reports covering the data period from April 2006 through February 2010.⁸

Golden Gate Transit Profile

GGT is one of three divisions operated by the District, as described earlier. The mission of the District is “to provide safe and reliable operation, maintenance and enhancement of the Golden Gate Bridge and to provide transportation services, as resources allow, for customers within the U.S. Highway 101 Golden Gate Corridor.”⁹ The transit system has grown to the extent that more than 9 million customers rode the transit system in fiscal year 2008; more than 7 million of those customers were bus passengers. GGT operates 204 buses in various types of bus service, including intercounty, commuter express, and local. GGT operates primarily in Marin and

⁸ All NREL fuel cell bus evaluation reports are available on the Web at www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

⁹ Golden Gate Transit Web site: <http://goldengate.org>

Sonoma counties across the Bay northward from San Francisco. The service area covers 256 square miles. One of GGT's diesel buses is shown in Figure B-2.

The District is unique among Bay Area transit operations because it receives no support from local sales tax measures or dedicated general funds. The District does not have the authority to levy taxes and relies on surplus bridge toll revenue as its only local support for the District's transbay transit services. Currently, GGT bus and ferry operations are funded approximately 50% by surplus Golden Gate Bridge tolls and 30% by transit fares. The remaining funds are covered by other sources, including federal, state, and local subsidies, and from advertising and property equipment rental revenues.



Figure B-2 GGT diesel bus (Photo credit: L. Eudy, NREL)

GGT Ride for the Environment

In response to the CARB Transit Rule established in late 2000, GGT selected the clean diesel path to meet emissions-reduction requirements. Those regulations called for an 85% reduction in particulate matter (PM) from a 2002 baseline by 2007. Since that time, GGT has taken aggressive steps not only to meet, but to exceed those regulations. GGT has employed a variety of improvements to its diesel fleet, including the following:

- Purchasing new buses with the cleanest available technology to replace older buses
- Replacing seven standard diesel buses with diesel-electric hybrid buses (Figure B-3)
- Switching to low-sulfur diesel fuel for the entire fleet
- Repowering older buses with low-emission engines
- Retrofitting buses with diesel-particulate filters
- Investigating new oil-filtration technologies to extend the oil change interval and reduce overall oil use.

GGT also has a rigorous inspection schedule to ensure that the fleet operates at optimal levels with the lowest emissions. These steps enabled GGT to achieve a 97% reduction in PM levels from 1992 levels.



Figure B-3 GGT diesel hybrid bus (Photo credit: L. Eudy, NREL)

The agency is also looking toward the future of bus technologies by partnering with AC Transit to demonstrate fuel cell buses. This partnership was initiated in 2003 when the two agencies signed an agreement outlining the collaboration. Under the agreement, AC Transit would provide access to training on the fuel cell bus and infrastructure, share information and lessons learned on the project, and periodically make available one of the three fuel cell buses for temporary demonstration in GGT's service. In response, GGT would provide funds to AC Transit for general support of the project, pay all direct costs associated with the bus while operating in its service, and actively participate in the information sharing and any data-collection activities. Working with AC Transit was extremely important to GGT because it provided the opportunity for hands-on experience with the technology without making the early investment in hydrogen infrastructure.

Early in the project, GGT's participation focused on learning what they could about the technology to prepare for eventual operation. AC Transit provided space for GGT personnel in training classes on general hydrogen awareness, specifics on operating and maintaining the buses, and hydrogen safety. GGT staff also participated in weekly conference calls on the project's progress and plans. All of this helped prepare the agency for finally operating a fuel cell bus.

Appendix C: Evaluation Bus Technology Descriptions

Table C-1 provides bus system descriptions for the fuel cell and diesel buses that were studied in this evaluation. The prototype fuel cell bus in service at AC Transit (Figure C-1) was developed in collaboration between ISE Corporation,¹ UTC Power,² and Van Hool.³ AC Transit unveiled its hydrogen fuel station and hydrogen fuel cell buses on March 13, 2006. The buses started in passenger service on March 20, 2006. The purchase, manufacturing, and packaging of the Van Hool fuel cell buses took about two years and cost approximately \$3.2 million each.

The Van Hool diesel buses were ordered in 2002 with delivery in 2005. To provide a baseline, six of the diesel Van Hool buses were selected from the 21 buses of that type operating from the East Oakland Division. These six diesel buses are operated alongside the fuel cell buses. The diesel buses, one of which is pictured in Figure C-2, cost \$323,000 each.

The diesel and fuel cell buses at AC Transit are the same bus model, but the diesel buses are slightly older. The fuel cell bus is a little more than 8,000 lb heavier than the diesel bus, and this added weight results in a reduced passenger capacity. The price of the fuel cell bus is essentially ten times more than the diesel bus.

Table C-1. Fuel Cell and Diesel Bus System Descriptions

Vehicle System	Operation from East Oakland Division	
	Fuel Cell Bus	Diesel Bus
Number of Buses	3	6
Bus Manufacturer and Model	Van Hool A330 Low Floor	Van Hool A330 Low Floor
Model Year	2005	2003
Length/Width/Height	40 ft/102 in./139 in.	40 ft/102 in./121 in.
GVWR/Curb Weight	43,240 lb/36,000 lb	40,800 lb/27,800 lb
Wheelbase	228 in.	235 in.
Passenger Capacity	30 seated or 26 seated and 2 wheelchairs; 15 standing	32 seated or 28 seated and 2 wheelchairs; 53 standing
Engine Manufacturer and Model	UTC Power PureMotion ⁴ 120 Fuel Cell Power System	Cummins ISL
Rated Power	Fuel cell power system: 120 kW Two Electric Drive Motors: 170 kW total (continuous)	280 hp @ 2200 rpm
Accessories	Electrical	Mechanical
Emissions Equipment	None	Diesel Oxidation Catalyst
Transmission/Retarder	Gearbox/Flenders Regenerative braking	Voith Integrated retarder
Fuel Capacity	50 kg hydrogen	92 gal
Bus Purchase Cost	\$3.2 million	\$323,000

¹ ISE Corporation Web site: www.isecorp.com

² UTC Power Web site: www.utcpower.com

³ Van Hool Web site: www.abc-companies.com/sales_vh.htm

⁴ PureMotion is a registered trademark of UTC Power.



Figure C-1. AC Transit fuel cell bus (Photo credit: L. Eudy, NREL)



Figure C-2. Diesel bus at AC Transit (Photo credit: L. Eudy, NREL)

Table C-2 provides a description of some of the electric propulsion systems for the fuel cell buses. Note that the diesel buses are not a hybrid configuration and do not have regenerative braking or energy storage for the drive system.

Table C-2. Additional Electric Propulsion System Descriptions

Propulsion Systems	Fuel Cell Bus
Manufacturer/Integrator	ISE Corporation
Hybrid Type	Series, charge sustaining
Drive System	Siemens ELFA/ISE
Propulsion Motor	2-AC induction, 85 kW each
Energy Storage	Battery: 3 modules/216 cells; sodium/nickel chloride ZEBRA; 53 kWh capacity
Fuel Storage	Eight, roof mounted, SCI, type 3 tanks; 5,000 psi rated
Regenerative Braking	Yes

Fuel Cell Bus Propulsion System Description

The fuel cell buses use the PureMotion 120 Fuel Cell Power System manufactured by UTC Power in a hybrid electric drive system designed by ISE. The Van Hool A330 transit bus chassis was redesigned to integrate the fuel cell system. The bus has a low floor from front to back and three doors for easy passenger boarding.

ISE’s hybrid system is a series configuration—the fuel cell power system is not mechanically coupled to the drive axle. The fuel cell power system and energy storage system work together to

provide power to two electric drive motors, which are coupled to the driveline through a combining gearbox. The hybrid system is also capable of regenerative braking, which captures the energy typically expended during braking and uses it to recharge the energy storage system. Each component of the propulsion system is controlled through an ISE-developed operating system.

The primary power source for this hybrid system is UTC Power's PureMotion 120 Fuel Cell Power System, which produces 120 kW from its PEM fuel cell stacks. UTC Power's fuel cells operate at near-ambient pressure, which eliminates the need for a compressor. This configuration not only increases the efficiency of the system, but also results in very quiet operation. The energy storage system consists of three ZEBRA (sodium/nickel chloride) batteries.⁵

⁵ Web site: http://www.cebi.com/cebi/content/index_en.html?a=5&b=9&c=19&d=72

Appendix D: Evaluation Infrastructure Description

AC Transit operates its bus fleet from four divisions—Richmond, Emeryville, East Oakland, and Hayward. To demonstrate fuel cell buses, the fleet needed to install hydrogen fueling infrastructure at one of these bus operating divisions. As a diesel-path fleet, AC Transit had no prior experience with gaseous fuels. Joining the CaFCP provided an opportunity for the fleet to accelerate the learning curve and gain valuable hydrogen fuel experience before the buses were delivered. AC Transit's first hydrogen-related project was in partnership with the CaFCP and was a demonstration of an electrolyzer and hydrogen dispenser at the Richmond Division. This station was mainly intended as a satellite station for light-duty fuel cell vehicles (FCVs) being tested by the automotive partners of the CaFCP. AC Transit also used this station to fill the ThunderPower fuel cell bus during its demonstration. The project provided AC Transit with valuable experience as it began development for its larger-scale hydrogen station.

Oakland Energy Station

AC Transit selected the East Oakland Division as the site for demonstrating its fleet of fuel cell buses. This selection was due to its location in a light industrial area and because space was available for the added fueling infrastructure. AC Transit operates more than 200 vehicles from this division, including the three fuel cell buses, twenty-one 40-ft diesel Van Hool buses, 41 paratransit shuttles, and six University of California, Berkeley (UC Berkeley) vans. Of the buses at the site, 138 are required for peak service.

In March 2004, AC Transit partnered with Chevron Technology Ventures to design and build a hydrogen energy station at the East Oakland Division.⁶ Plans for a station were already in process as part of the DOE light-duty FCV demonstration. Chevron leads one of the teams demonstrating FCVs and hydrogen infrastructure for the DOE project. AC Transit serves as one of the demonstration sites, operating a small fleet of Hyundai/Kia FCVs.

As the fuel cell bus demonstration plans began to solidify, the project partners decided it would be cost effective to combine the needs for both demonstrations into one station. Construction on the station began in June 2005 and was completed by November. The station was operational by mid-December. On March 13, 2006, AC Transit and local officials formally inaugurated the Chevron–AC Transit Hydrogen Energy Station, kicking off the demonstration project. All of the HyRoad project partners participated in the event, which included facility tours and a ribbon-cutting ceremony.

The station design includes two reformers that are capable of producing a total of 150 kg of hydrogen per day. One of the reformers is a standard design and is the primary production reformer for hydrogen at the station. The second reformer is an advanced technology design that Chevron used to investigate ways to further refine production methods and increase efficiency.

The purified hydrogen is compressed to 6,250 psi and stored in a series of cascade pressure vessels. Total storage capacity at the station is 366 kg of hydrogen. The station is equipped with two dispensers that supply the compressed hydrogen to the buses and light-duty vehicles. The

⁶ Information on the Chevron–AC Transit Hydrogen Energy Station was provided in part by Chevron Technology Ventures, a division of Chevron USA.

system connections monitor the tank-fill status and provide an appropriate fill at 5,000 psi. The dispensing system is designed to enable simultaneous fills for two buses (or light-duty FCVs). Figure D-1 shows the hydrogen fueling dispensers at the station. AC Transit's agreement with Chevron includes all operation and maintenance of the station for two years.



Figure D-1. Dispenser at Chevron—AC Transit Energy Station (Photo credit: L. Eudy, NREL)

The design of the station includes various safety devices to alert AC Transit and Chevron of any potential problems. These devices include hydrogen detectors, flame sensors, emergency stop buttons, and alarm indicator lights (Figure D-2). The alarm indicators reflect the condition of the station as follows:

- **Green light**—normal operating conditions
- **Yellow light**—a problem is occurring or has occurred
- **Red light**—hazardous condition exists, evacuation from area required
- **Strobe and siren**—fire condition, fire department notified



Figure D-2. Condition indicator lights (left) and hydrogen flame sensor (right) at the Chevron-AC Transit Hydrogen Energy Station (Photo credit: L. Eudy, NREL)

Maintenance Facility Modifications

AC Transit chose to modify an existing facility to enable staff to maintain the hydrogen-fueled buses safely. The required modifications (~\$1.5 million) were completed, and the maintenance bay was cleared for use in January 2006. The selected bay was isolated from the rest of the facility by a firewall. There is space for servicing two buses at a time. Figure D-3 shows the bay with and without a fuel cell bus.



Figure D-3. Modified maintenance bay at AC Transit East Oakland Division (Photo credit: L. Eudy, NREL)

The detection system in the maintenance bay is configured to trigger specific actions if a leak or fire is detected. At 20% lower flammability limit (LFL), the garage doors automatically open, ventilation fans are turned on, the heating system is shut down, and the magnetic doors release. If a leak is detected at 40% LFL or a fire is detected, the fire department is automatically notified, all electrical power to the bay is disconnected (except for ventilation and emergency equipment), and a fire alarm is activated to signal evacuation of the building. These safety measures are all in place to ensure maximum protection for staff and facilities in case of a hydrogen-related incident. None has been recorded to date.

Other safety features include the following:

- Two-hour firewall
- Ignition-free space heating system
- Antistatic, nonskid, grounded floor covering
- High-speed roll-up doors
- Magnetic door release
- Audiovisual strobe alarms
- Three-fan ventilation system capable of providing up to four to six air exchanges per hour
- Class 1 Division 2 electrical classification

Because the specially equipped maintenance bay is co-located with the rest of the maintenance building, maintenance staff is required to depressurize the buses prior to entering the facility. To accomplish this depressurization, the hydrogen in the tanks is vented down to 600 psi. The hydrogen removed from the vehicle is ultimately vented to the atmosphere in a controlled and safe manner. This decision to lower the fuel pressure in the vehicle was made early in the design process to reduce the overall cost of the facility modifications. The safety requirements for a facility capable of maintaining buses with full hydrogen tanks are more costly. Although capturing the vented hydrogen for future use is possible, early investigation showed it was not cost-effective using available methods. For a fleet of only three buses, the amount of hydrogen vented was deemed not significant enough to warrant the cost of the equipment to capture and reuse the fuel.

In preparation for full-day fuel cell bus operation, AC Transit upgraded its electrical access for charging the ZEBRA batteries overnight to allow faster charging. These upgrades were completed in June 2007. Each fuel cell bus is plugged into a charge station (shown in Figure D-4) overnight to balance the charge between batteries, top off the charge, and provide heat for the batteries and freeze protection for the fuel cell when temperatures are 2°C or less.



Figure D-4. Fuel cell bus/battery charging station at AC Transit (Photo credit: L. Eudy, NREL)

Appendix E: Fleet Summary Statistics

Fleet Summary Statistics: Alameda-Contra Costa Transit District (AC Transit) Fuel Cell Bus and Diesel Study Groups and Evaluation Periods Fleet Operations and Economics

	Fuel Cell All Revenue	Fuel Cell Accel Test	Fuel Cell Clean Point	Diesel
Number of Vehicles	3	3	3	6
Period Used for Fuel and Oil Op Analysis	3/06–02/10	11/07–02/10	Thru 2/10	01/07–2/07
Total Number of Months in Period	47	28	~25	12
Fuel and Oil Analysis Base Fleet Mileage	220,314	160,116	155,666	264,575
Period Used for Maintenance Op Analysis	3/06–2/10	11/07–02/10	Thru 2/10	01/07–2/07
Total Number of Months in Period	47	28	~25	12
Maintenance Analysis Base Fleet Mileage	224,871	164,673	160,027	266,514
Average Monthly Mileage per Vehicle	1,595	1,960	2,101	3,702
Availability	61%	62%	66%	N/A
Fleet Fuel Usage in Diesel gal/H ₂ kg	36,368	26,685	25,918	62,976
Roadcalls (RCs)	186	139	134	62
All MBRC	1,209	1,185	1,194	4,299
Propulsion RCs	147	107	104	25
Propulsion MBRC	1,530	1,539	1,539	10,661
Fleet Miles/kg Hydrogen (1.13 kg H ₂ /gal Diesel Fuel)	6.06	6.00	6.01	
Representative Fleet mpg (energy equiv.)	6.85	6.78	6.79	4.20
Hydrogen Cost per kg	8.00	8.00	8.00	
Diesel Cost per Gallon				2.29
Fuel Cost per Mile	1.32	1.33	1.33	0.55
Total Scheduled Repair Cost per Mile	0.13	0.11	0.10	0.09
Total Unscheduled Repair Cost per Mile	0.57	0.64	0.64	0.40
Total Maintenance Cost per Mile	0.70	0.75	0.74	0.49
Total Operating Cost per Mile	2.02	2.08	2.07	1.04

Maintenance Costs

	Fuel Cell All Revenue	Fuel Cell Accel Test	Fuel Cell Clean Point	Diesel
Fleet Mileage	224,871	164,673	160,027	266,514
Total Parts Cost	64,376.76	53,664.12	52,999.35	86,635.00
Total Labor Hours	1,851.4	1,377.9	1,311.6	877.0
Average Labor Cost (@ \$50.00 per hour)	92,568.50	68,895.00	65,580.00	43,850.00
Total Maintenance Cost	156,945.26	122,559.12	118,579.35	130,485.00
Total Maintenance Cost per Bus	52,315.09	40,853.04	39,526.45	21,747.50
Total Maintenance Cost per Mile	0.70	0.75	0.74	0.49

Breakdown of Maintenance Costs by Vehicle System

	Fuel Cell All Revenue	Fuel Cell Accel Test	Fuel Cell Clean Point	Diesel
Fleet Mileage	224,871	164,673	160,027	266,514
Total Propulsion-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 65)				
Parts Cost	4,122.66	3,455.34	2,898.40	18,794.62
Labor Hours	687.2	592.0	542.0	173.1
Average Labor Cost	34,361.00	29,598.50	27,098.50	8,653.50
Total Cost (for system)	38,483.66	33,053.84	29,996.90	27,448.12
Total Cost (for system) per Bus	12,827.89	11,017.95	9,998.97	4,574.69
Total Cost (for system) per Mile	0.17	0.20	0.19	0.10
Exhaust System Repairs (ATA VMRS 43)				
Parts Cost	0.00	0.00	0.00	5,091.03
Labor Hours	8.0	8.0	8.0	28.0
Average Labor Cost	400.00	400.00	400.00	1,400.00
Total Cost (for system)	400.00	400.00	400.00	6,491.03
Total Cost (for system) per Bus	133.33	133.33	133.33	1,081.84
Total Cost (for system) per Mile	0.00	0.00	0.00	0.02
Fuel System Repairs (ATA VMRS 44)				
Parts Cost	0.00	0.00	0.00	2,561.24
Labor Hours	15.4	4.0	4.0	17.8
Average Labor Cost	770.50	200.00	200.00	890.00
Total Cost (for system)	770.50	200.00	200.00	3,451.24
Total Cost (for system) per Bus	256.83	66.67	66.67	575.21
Total Cost (for system) per Mile	0.00	0.00	0.00	0.01
Powerplant (Engine) Repairs (ATA VMRS 45)				
Parts Cost	387.84	261.16	261.16	3,549.02
Labor Hours	72.5	57.5	57.5	56.4
Average Labor Cost	3,623.00	2,875.00	2,875.00	2,819.50
Total Cost (for system)	4,010.84	3,136.16	3,136.16	6,368.52
Total Cost (for system) per Bus	1,336.95	1,045.39	1,045.39	1,061.42
Total Cost (for system) per Mile	0.02	0.02	0.02	0.02
Electric Propulsion Repairs (ATA VMRS 46)				
Parts Cost	476.93	238.54	28.82	0.00
Labor Hours	384.4	320.5	318.5	0.0
Average Labor Cost	19,217.50	16,023.50	15,923.50	0.00
Total Cost (for system)	19,694.43	16,262.04	15,952.32	0.00
Total Cost (for system) per Bus	6,564.81	5,420.68	5,317.44	0.00
Total Cost (for system) per Mile	0.09	0.10	0.10	0.00

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell All Revenue	Fuel Cell Accel Test	Fuel Cell Clean Point	Diesel
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts Cost	1,720.15	1,720.15	1,499.95	1,809.52
Labor Hours	139.0	137.0	137.0	33.4
Average Labor Cost	6,950.00	6,850.00	6,850.00	1,669.00
Total Cost (for system)	8,670.15	8,570.15	8,349.95	3,478.52
Total Cost (for system) per Bus	2,890.05	2,856.72	2,783.32	579.75
Total Cost (for system) per Mile	0.04	0.05	0.05	0.01
Air Intake System Repairs (ATA VMRS 41)				
Parts Cost	1,433.75	1,139.30	1,041.15	959.66
Labor Hours	0.00	0.0	0.0	0.0
Average Labor Cost	0.00	0.00	0.00	0.00
Total Cost (for system)	1,433.75	1,139.30	1,041.15	959.66
Total Cost (for system) per Bus	477.92	379.77	347.05	159.94
Total Cost (for system) per Mile	0.01	0.01	0.01	0.00
Cooling System Repairs (ATA VMRS 42)				
Parts Cost	104.00	96.20	67.32	4,372.69
Labor Hours	66.0	65.0	17.0	35.0
Average Labor Cost	3,300.00	3,250.00	850.00	1,750.00
Total Cost (for system)	3,404.00	3,346.20	917.32	6,122.69
Total Cost (for system) per Bus	1,134.67	1,115.40	305.77	1,020.45
Total Cost (for system) per Mile	0.02	0.02	0.01	0.02
General Air System Repairs (ATA VMRS 10)				
Parts Cost	603.64	591.30	591.30	340.34
Labor Hours	9.0	9.0	9.0	13.2
Average Labor Cost	450.00	450.00	450.00	660.00
Total Cost (for system)	1,053.64	1,041.30	1,041.30	1,000.34
Total Cost (for system) per Bus	351.21	347.10	347.10	166.72
Total Cost (for system) per Mile	0.00	0.01	0.01	0.00
Brake System Repairs (ATA VMRS 13)				
Parts Cost	33,129.13	29,030.18	29,027.80	25,031.61
Labor Hours	113.0	111.0	111.0	112.2
Average Labor Cost	5,650.00	5,550.00	5,550.00	5,609.50
Total Cost (for system)	38,779.13	34,580.18	34,577.80	30,641.11
Total Cost (for system) per Bus	12,926.38	11,526.73	11,525.93	5,106.85
Total Cost (for system) per Mile	0.17	0.21	0.22	0.12

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell All Revenue	Fuel Cell Accel Test	Fuel Cell Clean Point	Diesel
Transmission Repairs (ATA VMRS 27)				
Parts Cost	0.00	0.00	0.00	451.46
Labor Hours	2.0	0.0	0.0	2.5
Average Labor Cost	100.00	0.00	0.00	125.00
Total Cost (for system)	100.00	0.00	0.00	576.46
Total Cost (for system) per Bus	33.33	0.00	0.00	96.08
Total Cost (for system) per Mile	0.00	0.00	0.00	0.00
Inspections Only—No Parts Replacements (101)				
Parts Cost	0.00	0.00	0.00	0.00
Labor Hours	451.6	324.8	308.8	381.3
Average Labor Cost	22,579.00	16,241.50	15,441.50	19,066.50
Total Cost (for system)	22,579.00	16,241.50	15,441.50	19,066.50
Total Cost (for system) per Bus	7,526.33	5,413.83	5,147.17	3,177.75
Total Cost (for system) per Mile	0.10	0.10	0.10	0.07
HVAC System Repairs (ATA VMRS 01)				
Parts Cost	3.52	3.52	3.52	1,000.46
Labor Hours	28.3	19.2	19.2	9.5
Average Labor Cost	1,412.50	957.50	957.50	475.00
Total Cost (for system)	1,416.02	961.02	961.02	1,475.46
Total Cost (for system) per Bus	472.01	320.34	320.34	245.91
Total Cost (for system) per Mile	0.01	0.01	0.01	0.01
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts Cost	19,255.07	13,914.96	13,809.50	36,342.22
Labor Hours	488.2	254.9	254.6	117.7
Average Labor Cost	24,410.50	12,746.00	12,731.00	5,882.50
Total Cost (for system)	43,665.57	26,660.96	26,540.50	42,224.72
Total Cost (for system) per Bus	14,555.19	8,886.99	8,846.83	7,037.45
Total Cost (for system) per Mile	0.19	0.16	0.17	0.16
Lighting System Repairs (ATA VMRS 34)				
Parts Cost	855.96	589.55	589.55	608.70
Labor Hours	10.6	9.0	9.0	15.2
Average Labor Cost	530.5	450.00	450.00	759.50
Total Cost (for system)	1,386.46	1,039.55	1,039.55	1,368.20
Total Cost (for system) per Bus	462.15	346.52	346.52	228.03
Total Cost (for system) per Mile	0.01	0.01	0.01	0.01

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell All Revenue	Fuel Cell Accel Test	Fuel Cell Clean Point	Diesel
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts Cost	4,355.72	4,216.83	4,216.83	2,506.26
Labor Hours	58.5	53.0	53.0	41.2
Average Labor Cost	2,925.00	2,650.00	2,650.00	2,061.50
Total Cost (for system)	7,280.72	6,866.83	6,866.83	4,567.76
Total Cost (for system) per Bus	2,426.91	2,288.94	2,288.94	761.29
Total Cost (for system) per Mile	0.03	0.04	0.04	0.02
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts Cost	2,051.06	1,862.44	1,862.44	2,010.78
Labor Hours	5.0	5.0	5.0	8.5
Average Labor Cost	250.00	250.00	250.00	425.00
Total Cost (for system)	2,301.06	2,112.44	2,112.44	2,435.78
Total Cost (for system) per Bus	767.02	704.15	704.15	405.96
Total Cost (for system) per Mile	0.01	0.01	0.01	0.01
Tire Repairs (ATA VMRS 17)				
Parts Cost	0.00	0.00	0.00	0.00
Labor Hours	0.0	0.0	0.0	4.1
Average Labor Cost	0.00	0.00	0.00	204.50
Total Cost (for system)	0.00	0.00	0.00	204.50
Total Cost (for system) per Bus	0.00	0.00	0.00	34.08
Total Cost (for system) per Mile	0.00	0.00	0.00	0.00

Notes

1. To compare the hydrogen fuel dispensed and fuel economy to diesel, the hydrogen dispensed was also converted into diesel energy equivalent gallons. Actual energy content will vary by locations, but the general energy conversions are as follows:

Lower heating value (LHV) for hydrogen = 51,532 Btu/lb

LHV for diesel = 128,400 Btu/lb

1 kg = 2.205 * lb

51,532 Btu/lb * 2.205 lb/kg = 113,628 Btu/kg

Diesel/hydrogen = 128,400 Btu/gal / 113,628 Btu/kg = 1.13 kg/diesel gal

2. The propulsion-related systems were chosen to include only those systems of the vehicles that could be affected directly by the selection of a fuel/advanced technology.
3. ATA VMRS coding is based on parts that were replaced. If there was no part replaced in a given repair, then the code was chosen by the system being worked on.
4. In general, inspections (with no part replacements) were included only in the overall totals (not by system). 101 was created to track labor costs for PM inspections.
5. ATA VMRS 02-Cab and Sheet Metal represents seats, doors, etc.; ATA VMRS 50-Accessories represents things like fire extinguishers, test kits, etc.; ATA VMRS 71-Body represents mostly windows and windshields.
6. Average labor cost is assumed to be \$50 per hour.
7. Warranty costs are not included.

Appendix F: Fleet Summary Statistics—SI Units

Fleet Summary Statistics: Alameda-Contra Costa Transit District (AC Transit) Fuel Cell Bus and Diesel Study Groups and Evaluation Periods Fleet Operations and Economics

	Fuel Cell All Revenue	Fuel Cell Accel Test	Fuel Cell Clean Point	Diesel
Number of Vehicles	3	3	3	6
Period Used for Fuel and Oil Op Analysis	3/20/06-02/10	11/07-02/10	Thru 2/10	01/07-12/07
Total Number of Months in Period	47	28	~25	12
Fuel and Oil Analysis Base Fleet Kilometers	354,551	257,675	250,513	425,781
Period Used for Maintenance Op Analysis	3/20/06-2/10	11/07-2/10	Thru 2/10	1/07-12/07
Total Number of Months in Period	47	28	~25	12
Maintenance Analysis Base Fleet Kilometers	361,885	265,008	257,531	428,901
Average Monthly Kilometers per Vehicle	2,567	3,155	3,381	5,957
Availability	61%	62%	66%	N/A
Fleet Fuel Usage in Diesel L/H ₂ kg	36,368	26,685	25,918	238,364
Roadcalls	186	139	134	62
Kilometers Between Roadcalls (KBRC)	1,946	1,907	1,922	6,918
Propulsion Roadcalls	147	107	104	25
Propulsion KBRCs	2,462	2,477	2,476	17,156
Fleet kg Hydrogen/100 km	10.26	10.36	10.35	
Representative Fleet mpg (L/100 km)	34.36	34.69	34.65	55.98
Hydrogen Cost per kg	8.00	8.00	8.00	
Diesel Cost per Liter				0.61
Fuel Cost per Kilometer	0.82	0.83	0.83	0.34
Total Scheduled Repair Cost per Kilometer	0.08	0.07	0.06	0.05
Total Unscheduled Repair Cost per Kilometer	0.35	0.39	0.40	0.25
Total Maintenance Cost per Kilometer	0.43	0.46	0.46	0.30
Total Operating Cost per Kilometer	1.25	1.29	1.29	0.64

Maintenance Costs

	Fuel Cell All Revenue	Fuel Cell Accel Test	Fuel Cell Clean Point	Diesel
Fleet Kilometers	361,885	265,008	257,531	428,901
Total Parts Cost	64,376.76	53,664.12	52,999.35	86,635.00
Total Labor Hours	1,851.4	1,377.9	1,311.6	877.0
Average Labor Cost (@\$50.00 per hour)	92,570.00	68,895.00	65,580.00	43,850.00
Total Maintenance Cost	156,946.76	122,559.12	118,579.35	130,485.00
Total Maintenance Cost per Bus	52,315.59	40,853.04	39,526.45	21,747.50
Total Maintenance Cost per Kilometer	0.43	0.46	0.46	0.30