ZERO-EMISSION BUSES IN REAL-WORLD USE

1. PROJECT GOALS

As a result of the increasingly serious health dangers posed by urban air pollution, government agencies all over the world are mandating standards to reduce airborne emissions and greenhouse gases from motor vehicles. In the United States, for example, the Environmental Protection Agency (EPA), through the 1990 Clean Air Act, and CARB (California Air Resources Board) have both passed regulations to curb emissions. In Canada, the federal government has announced a CDN$ 500 million program to reduce emissions and greenhouse gases. European countries have also established emissions standards (Euro Standards) to reduce emissions, and the United Nations Development Program, Global Environment Fund and the World Bank are introducing programs to reduce greenhouse gases in developing countries.

XCELLSIS and Ballard have the firm belief that the fuel cell engine is the most promising clean-energy appliance to date. The XCELLSIS/Ballard Phase 3 Fuel Cell Testing Program sought to prove the validity of this statement in urban transit applications over an extended period of time, and in real-world conditions. Two communities with an obvious commitment to clean-air solutions participated in the testing process: Chicago, Illinois, under the Chicago Transit Authority, and Vancouver, British Columbia, through that region's Coast Mountain Bus Company.

Note: At the time of writing of the major part of this report, XCELLSIS was owned approximately 51% by DaimlerChrysler, 22% by Ford and 27% by Ballard. In December 2001, Ballard acquired 100% ownership of XCELLSIS. Any references to XCELLSIS/Ballard should be considered Ballard at the present time.

2. GENERAL DESCRIPTION OF PROJECT

The four-year-long Phase 3 program was conducted in two major urban transportation markets: Chicago, Illinois and Vancouver, British Columbia, under normal, real world, revenue-generating conditions, and in all types of weather. It began in June 1996 with construction of six prototype buses in cooperation with both transit authorities. A pre-delivery test phase began in July 1997, followed by a non-revenue test phase in both cities in 1998.

2.1 Objectives of the Phase 3 test program

The final part of the test was a two-year public service implementation with three buses in each city, starting March 16, 1998 in Chicago and ending June 30, 2000 in Vancouver. The objectives of the Phase 3 Program were to:

- Learn about fuel cell technology in real, everyday operation and to transfer that learning to subsequent engine and component development phases
- Gain an understanding of vehicle performance, failures, and operating costs
- Better understand the infrastructure required for the operation of this technology
- Prepare the market for the entrance of fuel cell vehicles (FCVs)
- Educate the public on the safety and reliability of FCVs
- Prepare and train potential transit customers to work with FCVs

2.2 Fueling infrastructure

Hydrogen is generally manufactured by one of two methods: from water via electrolysis, where electricity separates H_2O into its constituent parts of hydrogen and oxygen, and from fossil fuels, such as methanol or natural gas, where the H_2 is extracted from the hydrocarbon molecule.

In Vancouver, H_2 from electrolysis was manufactured and supplied by Stuart Energy. Taking nine months to design and build, Stuart delivered the electrolytic fuel appliance to BC Transit's bus garage in Port Coquitlam. Modifications included upgrading of two bus bays at the perimeter of the garage. The fuel storage system and refueling station were provided through a lease arrangement with Stuart Energy. The system was fully commissioned, with fueling receptacles and filling posts installed, by the end of March 1998. Shortly thereafter, the buses arrived at the site and underwent acceptance testing by BC Transit. In June 1998, the buses were accepted and deployed to routes. In September the buses entered revenue service. In the first year of revenue service, from September 1998 to October 1999, the station operated approximately 1500 hours producing over 100,000 Nm^3 of compressed hydrogen fuel. It took approximately four hours to fill a bus, because of limitations in production rate and ground storage capacity.

In Chicago, Air Products supplied hydrogen in liquid form from a process plant in southern Ontario. The refueling operation for hydrogen is essentially the same as for CNG. The fueling station used Air Products liquid storage (gaseous, on board the bus). It took approximately 15 minutes to fill a bus. In this case, modifications were required to upgrade a large covered bus garage where the buses were maintained and parked in the center of the garage. This included safety and ventilation systems. The fuel storage system and refueling station were leased from Air Products.

It should be noted that H_2 fueling systems are in early stages of development. Current systems have the capability of fueling a bus in less than 10 minutes. As is the case with any transit agency using fuel cell buses, fueling and maintenance facilities included safety systems comprising H_2 sensors and ventilation systems. Costs of the installations depend on the process selected, the number of fuel cell buses in the fleet and the extent of maintenance facility upgrades required.

2.3 Project partners

The Chicago Transit Authority (CTA) is the second-largest transit system in the United States. The CTA provides transportation to a service area population of 3.7 million people in Chicago and 38 surrounding suburbs with a fleet of 1875 diesel-powered buses and 1190 electric rail cars. On an average weekday, approximately 1 million passenger rides are provided on the bus system and over 0.5 million on the rail system. On a daily basis, the CTA travels over 306,000 km (190,000 miles) on 134 bus routes and over 291,000 km (181,000 miles) on seven major rail routes.

Coast Mountain Bus Company (CMBC) is a subsidiary of TransLink, the Greater Vancouver Transportation Authority, which is responsible for public transit, roads and bridges, transportation demand management and the AirCare vehicle emissions testing program in the region. The CMBC (formerly part of BC Transit) fleet is the third largest in Canada, consisting of 750 diesel-powered buses, 50 CNG-powered buses and 244 electrically powered trolleys.

XCELLSIS is jointly owned by DaimlerChrysler (51.5%), The Ford Motor Company (21.8%) and Ballard Power Systems (26.7%). XCELLSIS is the leading developer of fuel cell engines for light-and heavy-duty automotive applications. Its heavy-duty division in Burnaby, BC, and Ballard Power Systems were jointly responsible for developing and testing the Phase 3 bus fleet.

Ballard Power Systems is recognized as the world leader in developing, manufacturing and marketing zero-emission proton exchange membrane (PEM) fuel cells for transportation, electricity generation and portable power products. The fundamental component of these products is the Ballard fuel cell that combines hydrogen and oxygen without combustion to generate electricity.

Stuart Energy is a world leader in the development and provision of electrolyser hydrogen fuel appliances. It is based in Toronto, Ontario with additional offices in Grand-Mère, Québec, Vancouver, British Columbia, and Pasadena, California. Stuart Energy supplied the electrolyser and fueling facilities at Coast Mountain Bus Company.

Air Products and Chemicals, Inc. is based in Allentown, Pennsylvania and employs more than 17,000 people in over 30 countries. A leading worldwide supplier of industrial gases, related equipment and selected chemicals, Air Products has applied its expertise to the safe production, storage and handling of hydrogen, as well as to fueling station design and construction. Air Products supplied fueling facilities for Chicago Transit.

Other Partners

In addition to the transit authorities, funders of the Phase 3 program included the Province of British Columbia (Ministry of Employment and Investment), the Regional Transportation Authority of Northeastern Illinois, and the U.S. Federal Transportation Administration (FTA), utilizing Congestion Mitigation and Air Quality Program (CMAQ) funds.

3. DESCRIPTION OF COMPONENTS

3.1 Fuel cell engine

The Ballard proton exchange membrane (PEM) fuel cell is the basis of the XCELLSIS fuel cell engine. Developed and manufactured by Ballard Power Systems Inc. of Burnaby, BC, it separates hydrogen electrons from the nuclei of hydrogen molecules through a thin polymer proton exchange membrane, harnesses the current they generate on their migration back to a cathode, then recombines them with the dissociated protons and oxygen from the air to create two byproducts: heat and pure water vapor. Individual fuel cells produce about 0.6 volts and are combined into a fuel cell stack to produce the amount of electricity required to power a vehicle.

The XCELLSIS fuel cell engine is shown in Figure 1. It consists of devices to regulate fuel and oxidant streams, generate electrical power, provide cooling, supply lubrication, manage electrical output and control the system processes. Electrical energy from the fuel cell engine is delivered to the traction motor, which provides mechanical power to turn a drive shaft. The hydrogen fuel cell engine is a zero-emission engine.

Figure 1: XCELLSIS fuel cell engine

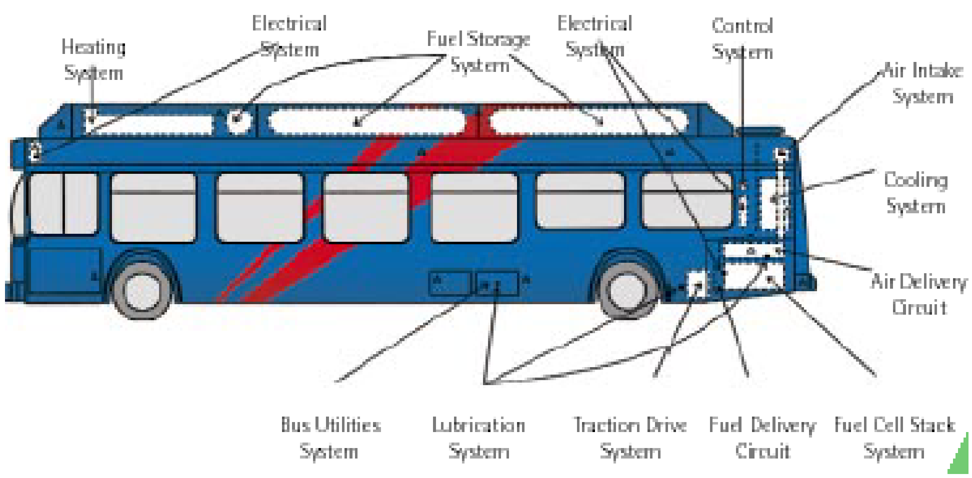

Figure 2: Schematic picture of XCELLSIS/Ballard fuel cell bus

3.2 Fuel cell buses

The Xcellsis/Ballard Phase 3 zero-emission fuel cell buses used for the test program were New Flyer Industries H40LF models, modified to accommodate the XCELLSIS Phase 3 Fuel Cell Engines and fuel storage systems. Exterior dimensions are identical to CNG models, with compressed gas fuel tanks (nine, for Phase 3) mounted on the roof, containing up to 52 kg (115 lb) of hydrogen gas at 250 bar (3600 psi). The interior was essentially unchanged, except the rear window area was modified to accommodate the radiator and some of the fuel cell system hardware and electronics. The fuel cell engine occupies parts of the bus chassis as well as a removable sub-frame within the engine compartment. The arrangement of the subsystems is shown in Figure 2 and the two bus fleets are shown in Figure 3 and **Figure 4**.

Figure 3: The Vancouver Ballard fuel cell bus

Figure 4: The Chicago fuel cell buses

3.3 Hydrogen fueling station in Chicago

The hydrogen fueling station for the CTA Hydrogen Bus Project was designed and constructed by Air Products and Chemicals (Allentown, PA). They adapted the industrial hydrogen distribution and supply technology base to design and construct the facilities for receiving, storing, processing and dispensing hydrogen to the buses. The fueling station consisted of two major systems:

- Hydrogen Receiving and Long-Term Storage System: to receive and store liquid hydrogen, vaporize liquid hydrogen to create gaseous hydrogen and compress and store compressed hydrogen for fueling operations
- Hydrogen Transfer System: for fueling the buses for revenue operation

Both systems are located at the Chicago/Palaski Bus Garage, but are physically detached from it for safety purposes. A picture of the hydrogen fueling facility is shown in Figure 5 and a schematic representation of both systems in Figure 6. The project included making modifications to the garage, which involved designing and installing hydrogen detection and evacuation systems, explosion proof lighting and fire suppression systems.

Figure 5: CTA hydrogen fueling facility in Chicago

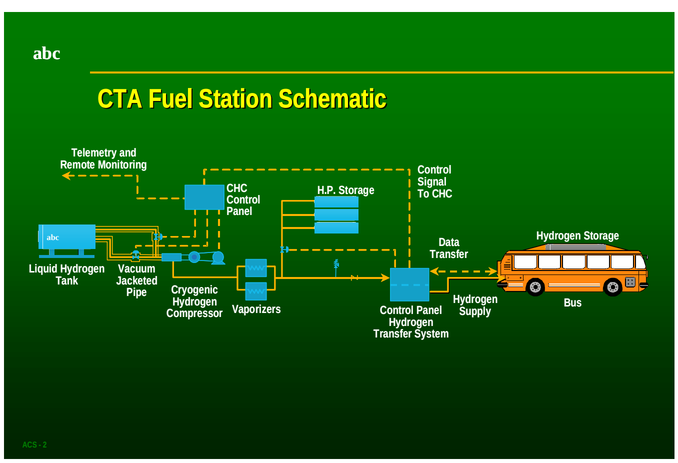

Figure 6: Schematic of the CTA hydrogen fueling facility

3.3.1 Hydrogen receiving and long-term storage system

For CTA, it proved to be most economical to deliver liquid hydrogen, use cryogenic liquid pumps, and vaporize it at the facility to achieve the high storage pressure needed for the gaseous hydrogen on the bus. Liquid hydrogen is transported to the garage in cryogenic 15,000-gallon liquid tanker trailers from an Air Products plant approximately 300 miles away. The hydrogen is stored on the site in a double-walled vacuum insulated tank with a liquid capacity of 9000 gallons. A cryogenic pump moves liquid hydrogen from the storage tank (pressure of 10 bar) through a vaporizer for refueling the buses with gaseous hydrogen at 250 bar. This pump requires less energy than needed to compress gaseous hydrogen to the same pressure. With high-pressure gas-buffer storage, it is possible to initiate bus fueling immediately, while the cryogenic compressor is cooling down and preparing to pump hydrogen into the bus storage tanks.

The station design is based on the use of a patented Cryogenic Hydrogen Compressor (CHC), which has wide applications for high-pressure hydrogen supply in the chemical industry. Air Products used a modified design of the compressor for the CTA fueling facility, which was designated as the CHC-6000. The compressor consists of a single-stage reciprocating, positive displacement pump unit, driven by a 30-kW AC motor.

Once a bus fueling sequence is initiated, a signal from the fuel transfer system control panel starts a timed process to cool the CHC-6000 compressor to operating temperatures. While this is happening, the bus is being filled from the bank of high-pressure gaseous storage tubes. Once pressures have equalized between the storage tubes and the bus tanks, an automatic valve is closed to isolate the storage tubes (see Figure 6)

After the cool down period, the CHC-6000 starts and begins to fill the bus directly. Typically, the bus can be completely filled within 15-20 minutes, depending upon the starting pressure of the bus. Once the bus is filled, the isolation valve is reopened and the storage tubes at the station are refilled in 5-10 minutes, so that it is available for the next bus. The single CHC pump system is capable of fueling two to three buses per hour on a continuous basis. However, it takes about two hours to move all three vehicles into place, fuel them, and move them out again, because there is only one fueling dispenser.

3.3.2 Hydrogen transfer system

The hydrogen transfer system receives pressurized hydrogen gas from and operates synchronously with the Hydrogen Receiving and Long-Term Storage System. The fueling process was designed to be user friendly. An automatic control system communicates with the person (called the "operator") who is fueling the bus, the bus itself and with the hydrogen source during the fueling process. The system measures the quantity of fuel in the vehicle tanks and stops the flow of fuel when the tanks are full or if an abnormal condition is detected (e.g., the bus is not grounded).

The station’s fast-fill capability allows each bus to be fueled within a 15-minute period. This required a maximum delivery rate capacity of 2000 Nm^3 of hydrogen per hour to achieve a final settled storage pressure of 250 bar at ambient conditions ranging from 188 to +38 ºC. Each bus consumed about 400-500 Nm^3 of hydrogen per day.

3.4 Coast Mountain Bus refueling station at Port Coquitlam

The Coat Mountain Bus fueling station is located at Port Coquitlam, BC. It was designed to generate up to 66 Nm^3/h of hydrogen. The hydrogen compression system was designed to compress the hydrogen to a pressure of 270 bars for storage. Three buses can be filled within a 12-hour period. The pressure in bus tanks being refueled was controlled to 250-bar temperature corrected to 15ºC. The station is shown in Figure 7.

3.4.1 Hydrogen generating system

The hydrogen generating system consisted of an air-cooled rectifier transformer and electrolytic cells connected electrically in series operating at 8800 A and at maximum 40 V. Power at 600 V (3 phase, 60 cycle) was supplied to the rectifier and transformer. In the rectifier, the voltage was reduced by the rectifier transformer and converted to direct current. A control knob on the control panel adjusted rectifier output.

DC current from the rectifier was supplied to the electrolytic cells through copper bus bars. At 8800 A (the maximum allowable current) the cells produced 66 Nm^3 of hydrogen and 33 Nm^3 of oxygen per hour.

The electrolyte in the cells was a 33% by weight solution of potassium hydroxide (KOH) in water. Potassium hydroxide levels were monitored quarterly and additions made to make up for mechanical losses due to spillage and carryover to the water-seal and mist eliminator. From the electrolytic cells, the hydrogen and oxygen flowed through collection manifolds to the water seal. The water seal served to equalize the hydrogen and oxygen gas pressures and to prevent the flow of hydrogen from the low-pressure gasholder when the cells were idle.

Automatic and/or manually operated valves were provided at the water seal for directing the hydrogen to the gasholder or atmosphere and the oxygen to atmosphere as desired. Gas was automatically diverted to vent when the gas purities fell below a minimum preset level. Two continuous gas analyzers were used to monitor the purity of the gas.

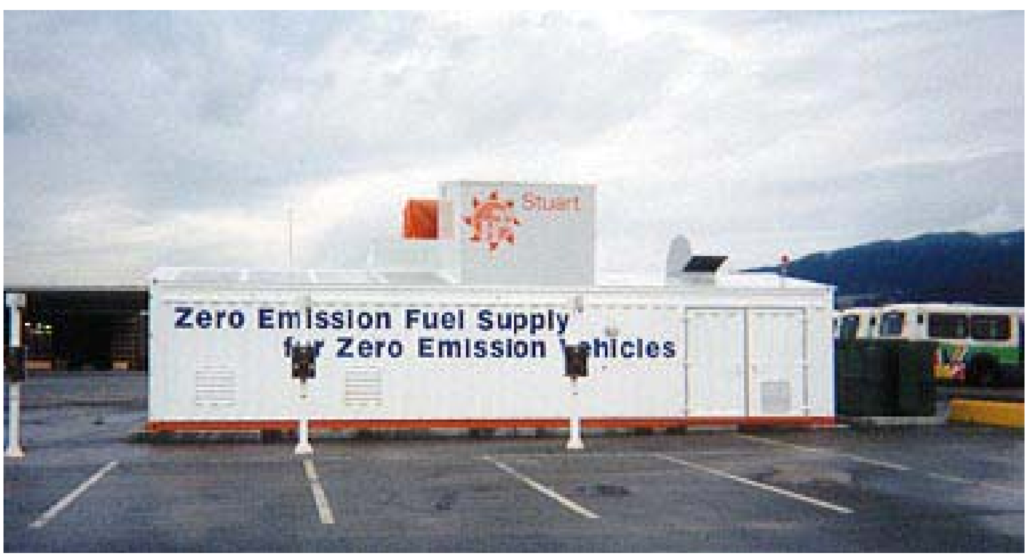

Figure 7: Hydrogen refueling station at Port Coquitlam

3.4.2 Feed water system

The feed water system was supplied and maintained by a third party. Using an ion exchange resin bed type system, regeneration occurred on site. A low-pressure switch was supplied to shut down the plant if water pressure fell below a minimum preset value. A solenoid valve was used to stop the flow of water to the electrolytic cells whenever the rectifier was shut down. An automatic feed system consisting of two loops, solenoid valves activated by level switches, and a mechanical “float” system, was used to maintain the level in the cells. Plant shutdown occurred if minimum levels or maximum levels were exceeded.

3.4.3 Hydrogen compression and purification system

The hydrogen compression and purification system was designed to compress the hydrogen produced by electrolytic cells to a pressure of 270 bar, then filter, purify and dry it before it was delivered to the end user. Hydrogen from the water seal went to the hydrogen mist eliminator, which removed the potassium hydroxide electrolyte mist entrained in the hydrogen gas. From the mist eliminator the hydrogen went to a hydrogen gas holder having a normal capacity of 6 m^3 and a working pressure of approximately 0.012 bar (18 psi). Fitted at the gas holder were five level switches for controlling the hydrogen compressors. From the gas holder the hydrogen flowed to the hydrogen compressors.

The hydrogen compressors were CompAir Reavell liquid-cooled, 4-stage reciprocating compressors, designed to operate at a speed of 1800 rpm and driven by 45 kW (60 hp) motors. At this speed each of the two compressors had a capacity of approximately 90 standard cubic meters per hour of hydrogen at a maximum discharge pressure of 270 bar. Each compressor was fitted with a temperature switch, pressure switch and low oil pressure switch. Two compressors were used; one was put on line, and the other was put on standby.

From the compressors the hydrogen flowed through a series of coalescing filters to remove oil and condensate and then a dryer. A three cartridge, heatless pressure swing type dryer was used. From the dryer filter the hydrogen flowed to an after filter where any desiccant particles entrained in the hydrogen are filtered out. A backpressure-maintaining valve controlled pressure in purification process. This valve holds a minimum of 270 bar on the dryer regardless of the downstream pressure.

3.4.4 Cooling water system

The electrolytic cells were water cooled with a combination of glycol and water. The cooling system consisted of two parallel paths:

- Each cell was fitted with two water-cooled gas scrubbers, one for each gas. The gases leaving the cell were passed through the scrubbers before entering the collection manifold.
- Attached to the end of each cell were cooling water jackets. Cooling water, supplied to the distribution manifold, flowed through the two jackets in series and then through a discharge hose to the cooling water collection header. The cooling system was a closed loop design incorporating transfer pumps and heat exchanger.

3.4.5 *Other components*

The stationary gas storage system, supplied by the customer, consisted of 4 banks of "T" cylinders (approximately 5 Nm^3 at 270 bar) connected to a single manifold. Each cylinder had its own pressure relief device.

A "dome loaded" pressure regulator was used to control pressure to maximum value of 250 bar at 15ºC in the hydrogen refueling operation. The delivery line was protected from over-pressurization by safety relief valve. A "fail safe" pneumatically operated shut-off valve was installed to stop flow of hydrogen to the buses if the process was upset or if the operator pushed the emergency stop (E-stop) button.

Buses were refueled by connecting to one of three filling posts. Each filling post was equipped with a manual shut-off valve, pressure gauge and quick connect nozzle

The process flow of the whole facility is depicted in Figure 8.

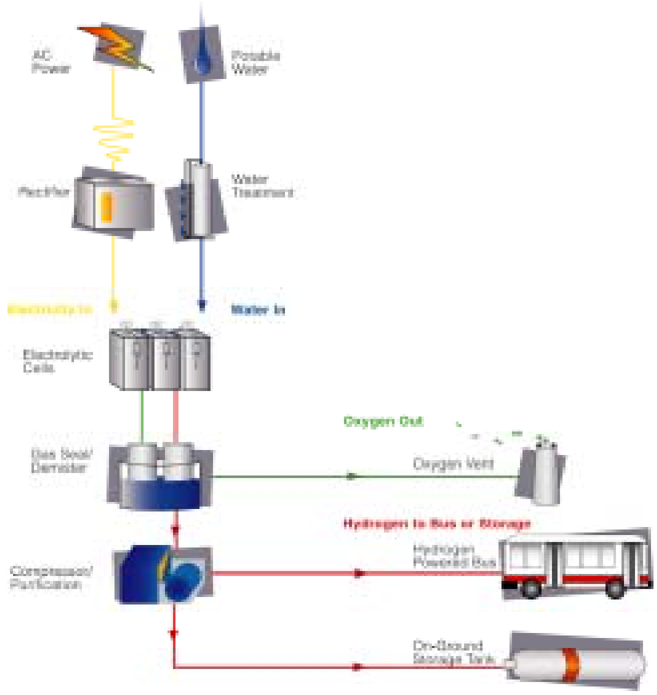

Figure 8: Process flow of fuel appliance

4. PERFORMANCE AND OPERATIONAL EXPERIENCE

Beyond the main objectives of the program, XCELLSIS and Ballard designed the testing to address three specific areas of concern; namely to:

- Prove that H_2 fuel cell vehicles can work for commercial heavy-duty applications
- Set up and utilize the H_2 infrastructure for operating and maintaining small fleets of fuel cell vehicles
- Create a baseline of actual and projected lifecycle costs and performance information to improve future products

Each metropolitan area received three fuel cell-powered buses to use during the allotted test period. The six buses were deployed on existing routes under normal, revenue-generating conditions, regardless of weather or traffic. Owing to the unique fueling requirements of the Phase 3 fuel cell bus, maximum time between refuelings on the test units was about six hours.

The total test mileage was 118,000 km (73,327 miles), with a total runtime of 10,560 hours and 205,000 riders.

Specific areas of evaluation during the Phase 3 test program were:

- Engine development
- Chassis integration
- Garage adaptation — modifications to handle and store hydrogen
- System safety program (to ensure safety during handling and refueling)
- Training program – drivers, maintenance personnel and supervisors
- Documentation – operating and maintenance manuals
- Pre-delivery tests
- Non-revenue tests
- Revenue service tests
- Field service support
- Involvement of transit agencies (garage modifications, training for fuel, maintenance and building systems)

4.1 Phase 3 bus performance testing

A major component of the XCELLSIS/Ballard Phase 3 test program was a head-to-head comparison against existing transit options. Thus, the performance of the Phase 3 bus was measured against diesel and compressed natural gas (CNG), and from every aspect of interest to a major transit authority. These included (among other criteria) acceleration, initial cost, operating costs, reliability, noise levels, fueling infrastructure and passenger capacity.

The test buses were run on regular routes, including high-volume downtown areas to maximize public visibility. Riders in both Vancouver and Chicago had very positive experiences from both a noise and a comfort level. In some cases, passengers would let diesel buses go by in order to ride a fuel cell bus. Some would call ahead to request scheduled routes so they could ensure their next ride was on a zero-emission bus. As the noise comparison chart in Figure 12 shows, the Phase 3 bus was quieter than the diesel and CNG buses.

4.1.1 Acceleration from rest

From a performance standpoint, the Phase 3 fuel cell-powered buses meet or exceed the performance figures of diesel- and CNG-powered buses, especially in the important 0-32 km/h range. As the acceleration test results in Figure 9 illustrate, from a standstill, the XCELLSIS/Ballard Phase 3 bus was fastest from 0-32 km/h, well ahead of the design specification of 10.5 seconds.

Acceleration to 32 km/h (20 mph) was about equal to diesel buses. Acceleration to 48 km/h (30 mph) and to 64 km/h (40 mph) was lower than diesel and CNG primarily due to Phase 3 buses being heavier. Interior space, seating and other aspects were unchanged from standard diesel-powered buses. Overall, both drivers and passengers considered the Phase 3 fuel cell buses better than CNG or diesel.

Current developments (Phase 4 bus) will result in acceleration that is expected to be equal to or better than a diesel or CNG bus to any speed.

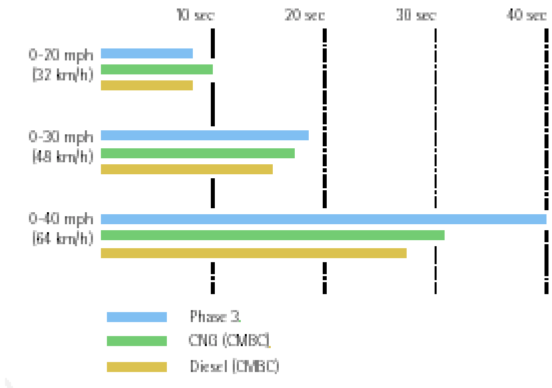

Figure 9: Acceleration from rest

4.1.2 Weight and power

Most external and internal dimensions are identical to those of the standard New Flyer buses and are therefore not repeated here. Loaded to its maximum of 40 passengers (GVW limited), Phase 3 buses are approximately equal in weight to a CNG bus loaded with 70 passengers (see Figure 10). Substantial weight-saving refinements to the next phase bus (Phase 4) have expanded the fuel cell bus passenger capacity to 70 (see Table 4).

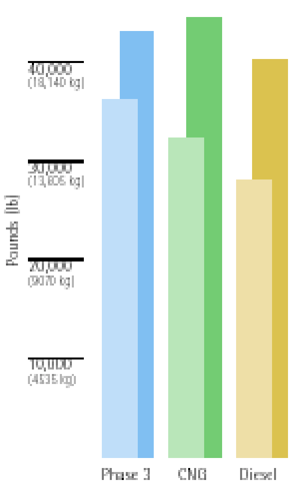

Figure 10: Vehicle weight comparison: curb weight vs. fully loaded

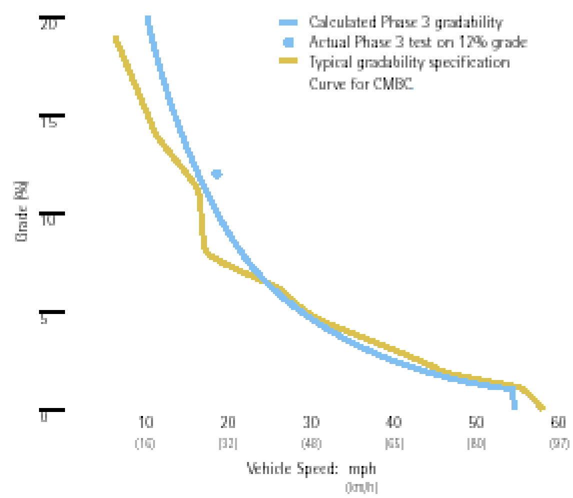

Figure 11: Typical gradability at 17 tons (15.4 tonnes)

Figure 11 compares the typical gradability requirements set out in CMBC technical specifications with the calculated performance of the Phase 3 bus. The measured data point for the Phase 3 bus shows that it exceeds specified requirements at 12% grade at 17 tons (15.4 tonnes) weight.

4.1.3 Noise output

Most passengers noticed the considerably quieter interior of the XCELLSIS/Ballard Phase 3 bus as compared to a conventional diesel bus. It is important to note that a sound level difference of 3 dbA is significant. Examples for typical sound pressure levels are given in Table 1.

Table 1: Comparison of sound pressure levels

Noisy workplace (factory)	88 dbA*
Diesel bus at 30 mph (48 km/h)	80 dbA
Phase 3 Fuel Cell Bus at 48 km/h (30 mph)	72 dbA
Business office	67 dbA*

* data from Bruel & Kjaer

The results of noise tests under various conditions are displayed in Figure 12.

4.1.4 Running bus performance and availability

Considering its very intensive maintenance program, the objective of the Phase 3 test was for each bus to operate between four and six hours each day. The graphs in Figure 13 show typical usage rates during revenue service in both areas. The significantly better run times and reliability in Vancouver reflect learning experience and ongoing improvements implemented during the course of the testing, which were conducted six months earlier in Chicago.

In Figure 14, the individual availability of each bus in each region is shown. For this program, availability is defined as percentage available for scheduled revenue service operations. Average availability in Chicago was 56%; in Vancouver, it was 55%. Factors affecting availability were system or coach failures, upgrade work and higher maintenance levels than anticipated.

The incidents shown in Table 2 are identified under three classifications and cover fuel cells and systems only.

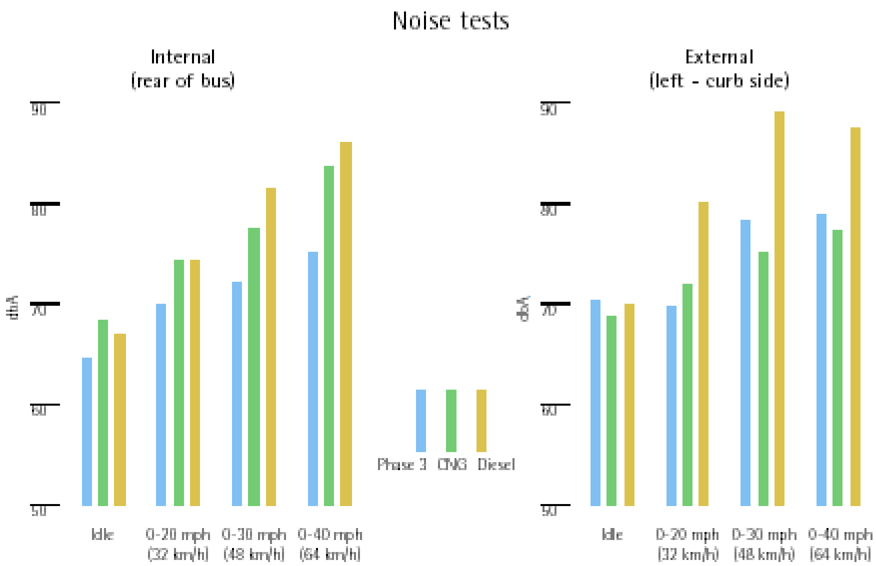

Figure 12: Noise tests

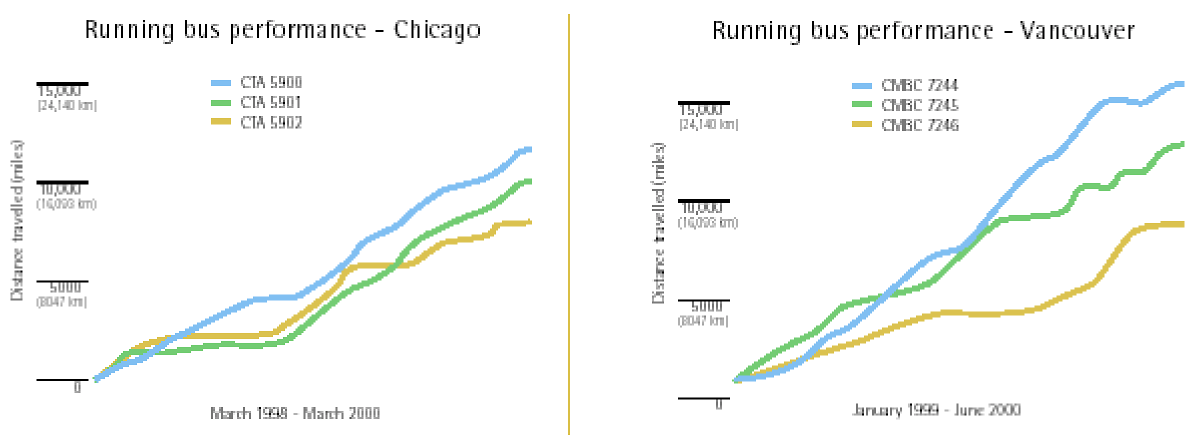

Figure 13: Running bus performance in Chicago and in Vancouver

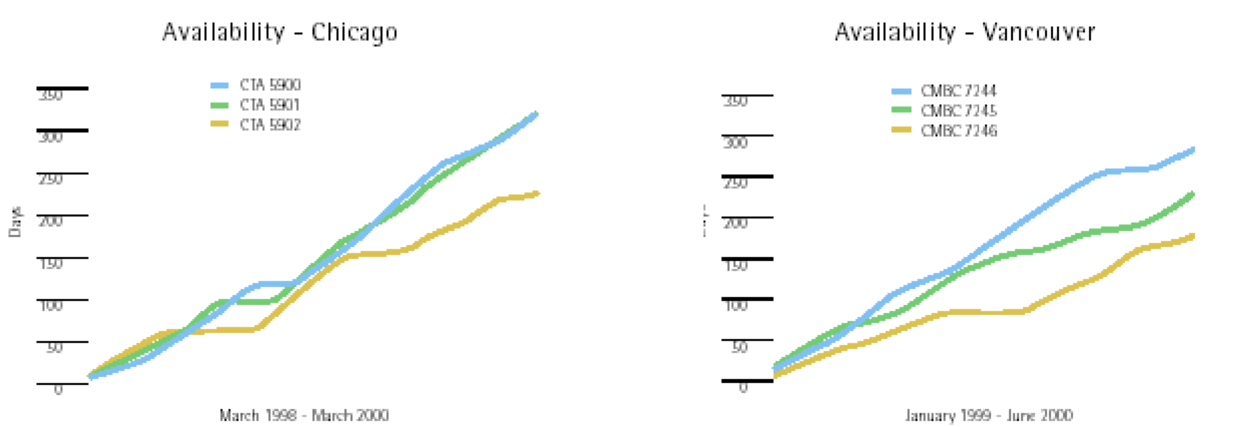

Figure 14: Availability of buses in Chicago and in Vancouver

4.1.5 Reliability

As expected, there were numerous incidents recorded during the program from which valuable experience was gained. A summary of these incidents is shown in Table 2. Gathering information and subjecting the buses to rigorous duty cycles and actual harsh transit-environment conditions was the intended scope of this project. This stage of technology development process typically yields more incidents and failures from which significant improvements are made to subsequent generations of fuel cell buses. The Phase 3 program accomplished that goal by providing data and information that enabled the realization of Phase 4 fuel cell bus technology and design advances in all areas of the engine and supporting systems (see Table 3). As such, because the Phase 3 Fuel Cell Buses were early prototypes, consisting mostly of prototype components, a detailed analysis based on technical data would not have a basis in comparison to current technology. Some components have since been replaced with simpler, newer-generation components; others are no longer required. Nonetheless, XCELLSIS and Ballard established a very aggressive plan to keep the buses in operation, which included monitoring all elements of the fuel cell system — a total of close to 1500 per bus.

Table 2: Summary of incidents and road calls

	CTA	CMBC
Hardware failures	143	96
Operator or maintenance errors	13	9
Non-failure incidents	217	115
Number of road calls		23
Distance between road calls		2418 km (1503 miles)

Not all failures indicated resulted in road calls, which is one of the key measures to transit in evaluating bus performance. The earlier changes, implemented due to the improved learning experience at CTA as mentioned above, resulted in very encouraging road call results by the end of the program at CMBC.

4.2 Operation of Port Coquitlam fueling station

Since the start of regular operation in June 1998, the appliance provided hydrogen to the buses without fail. The buses, which operated five days a week, Monday through Friday, never missed a day of revenue service due to fuel supply problems. Because the fueler could operate during non-peak periods, on an "interruptible basis", Stuart was able to take advantage of lower electricity rates. Operating data for the period September 14, 1998 to October 21, 1999 of the hydrogen refueling station at Port Coquitlam are summarized in Table 3:

Table 3: Plant Operation (September 14, 1998 – October 21, 1999)

Total operational time for cells	1515 hours
Total number of buses filled	430
Electrolyser current	8800 A
Electrolyser voltage (DC)	35 – 36 V
Amount of hydrogen fuel produced during this time	100,430 Nm^3
Oxygen purity	99.54 – 99.85%
Hydrogen purity	99.64 – 99.90%
KOH concentration	31 – 39% by weight
Cell temperature	59ºC - 75ºC

The bus filling operation was carried out by BC Transit. Stuart employed students from the University of Victoria to collect performance data. These students were also trained by Stuart staff in the operation of the equipment and maintenance of the site.

Over the course of the project, the site was visited numerous times by individuals from varying backgrounds. All major auto companies, including Daimler/Chrysler, Ford Motor Company, General Motors, Honda and energy companies (BP and Shell), visited the site during the demonstration period.

The operating data obtained from this project have been essential to Stuart and have been incorporated into the design of subsequent fuel appliances. The demonstration was an important proof of concept and confirmed that direct on-site hydrogen production is a viable and reliable option.

5. ENVIRONMENTAL ASPECTS AND SAFETY ISSUES

5.1 Hydrogen fueling operations at the CTA station

Fueling was performed only by operators that have completed the Hydrogen Transfer System Environmental training program and while wearing fire-resistant clothing, gloves and eye protection.

Multiple levels of protection were designed into the fueling station to insure that the bus did not move during refueling. In addition to the breakaway fitting within the fuel hose, the traction motors of the bus were de-energized when the fuel door on the bus was opened. Also, a small depression was made in the pavement at the fueling station to accommodate the left front tire of the bus - again, to prevent movement.

Fueling operations are not conducted under the following conditions:

- Fueling equipment is defective or damaged (e.g., damaged fuel nozzle, wet nozzle, etc.)
- Present or impending threat of an electrical storm
- Intense storm conditions that impede the operator's ability to move into, out of or within the refueling area (e.g., hail, blizzard, wind, heavy rain, etc.)
- Bus not properly grounded
- Unauthorized person or vehicles in the refueling area
- There is a fire or hydrogen leak

5.2 Process safety specifications at the Port Coquitlam fueling station

Plant equipment was housed in a ventilated, positive pressurized steel shipping containers with explosion relief roof. The ventilation rate provided greater than one air change per minute.

The hydrogen concentration in the cell and compression rooms was monitored on a continuous basis. The cell and hydrogen compression areas complied with Class 1 Division II, Group B specifications, and were approved by the Canadian Standards Association

Two dual wavelength IR flame detectors monitored the storage and refueling process.

An automatic fire detection and suppression system was supplied for the control room. The system was designed to automatically shut down the plant and extinguish the fire if one was detected.

The control system was equipped with data logging capability using a standard personal computer. The computer was connected to a modem giving it remote monitoring capability.

6. REGULATORY ASPECTS AND LICENSING PROCEDURES

6.1 Hydrogen Refueling Facility in Chicago

CTA worked with the Chicago Fire Department and the Department of Environment to address codes and standards issues. The following National Fire Protection Association (NFPA) codes and standards were considered in the project:

- NFPA 50A: Standard for Gaseous Hydrogen Systems at Consumer Sites
- NFPA 50B: Standard for Liquefied Hydrogen Systems at Consumer Sites
- NFPA 54: National Fuel Gas Code
- NFPA 70: National Electric Code
- NFPA 88A: Standard for Parking Structures
- NFPA 88B: Standard for Repair Garages
- NFPA 497A: Recommended Practice for Classification of Class I Hazardous Locations for Electrical Installations in Chemical Process Areas

The CTA Emergency Response Plan complies with the requirements specified in:

- National Response Team, Guidance for an Integrated Emergency response Plan, 1996
- Occupational Safety and Health Administration (OSHA) 29 CFR 1910 for Hazardous Waste Operations and Emergency Response
- Metropolitan Water Reclamation District of Greater Chicago for Spill Prevention, Containment and Countermeasures Plan 40 CFR 403 8(f2)v

The experiences of CTA in planning and executing their hydrogen fuel cell bus project was used by the US Department of Transportation in generating the report "Clean Air Program: Design Guidelines for Bus Transit Systems Using Hydrogen as an Alternative Fuel " (DOT-FTA-MA-26-7021-98-1).

7. ECONOMIC CONSIDERATIONS

Although a transit agency normally considers both capital and operating costs when purchasing a bus for its fleet, the focus of the Phase 3 program was not to address the purchase price of the buses, but to establish a baseline of operating costs for fuel cell buses. Nonetheless, this report does address the projected vehicle and operating costs as this technology advances from the research and development phase to commercialization.

Fuel cell buses with XCELLSIS engines will be on the streets of Europe and North America by late 2002/early 2003. With further development and volume production, fuel cell buses with XCELLSIS engines and Ballard fuel cell stacks are expected to drop in price to a figure comparable to a CNG bus — after approximately 1500 units have been produced.

The current operating costs for the Phase 3 bus are higher than either diesel or compressed natural gas. Through identified technological refinements, they are expected to be comparable to those of a CNG bus – again, after about 1500 units have been produced.

Table 4: Improvements reached in Phase 4 vs. Phase 3

	Phase 4	Phase 3
Engine volume reduction	50% of Phase 3	
Weight reduction	1540 kg (3400 lb)	
Fuel cell stacks	8	20
Recommended maintenance and repair	1/10 of Phase 3	
Number of motors (traction and auxiliary)	1	12
Startup time	3 seconds	45 seconds

8. THE NEXT STEP: PHASE 4

Overall, the Phase 3 test results were excellent. Most mechanical problems were minor and easy to fix. Purchase and operating costs are expected to drop dramatically over the next several years, as system complexity and parts counts are reduced and reliability improves. The Phase 4 portion of the XCELLSIS fuel cell engine development, now in progress, has already resulted in lighter vehicle weight: 14,400 versus 15,600 kg (31,700 versus 34,500 lb), with better acceleration and lower complexity, reduced part count and weight, and improved power density — all of which point to lower capital and operating costs. Owing to improvements summarized in Table 4 in technology and the reduction in the number of components, maintenance and repair costs are expected to be about 1/10th the requirement of Phase 3 engines.

The Phase 4 bus has been tested at SunLine Transit Agency in Thousand Palms, California, between July 2000 and October 2001.

9. CONCLUSIONS

The following conclusions have been formulated by some of the leading executives:

Frank Kruesi, President, CTA:

“This has been a very successful experiment… for the Chicago Transit Authority, for the city and the region and for our customers and employees. Transit agencies around the world are watching very closely to see how this experiment has worked, and we’re happy to make it known that it’s been a success. The real question now is how soon before the technology is available, and affordable, for fleets around the country and the world.”

Dave Stumpo, President, CMBS:

“We gained invaluable experience and knowledge of the fuel cell engine technology. The project was a great success from our point of view, confirming that the technology is viable for use in public transit and very acceptable to our customers. Once commercialized, it will provide the transit industry with a very effective zero emission engine technology to meet environmental obligations.”

Craig Lang, President, Technology Consulting Group, Inc. (former Senior Vice President, Technology Development, Chicago Transit Authority, responsible for CTA's Phase 3 program):

"Through the dedicated efforts of CTA and XCELLSIS/Ballard employees, the Fuel Cell Bus Program at CTA exceeded its goals and resulted in a tremendously successful technology development effort. Not only a world-first event, the CTA program set the stage for further development of the technology and introduction of the fuel cell bus as the environmentally friendly/alternative-propulsion transit vehicle of the very near future. This program clearly indicated that fuel cell technology will yield significant benefits to our customers, the transit industry and the environment."

Christ Lythgo, Senior Vice President, Service Support, CMBS:

"The results of the Phase 3 fuel cell bus demonstration project far exceeded our expectations. The project confirmed that fuel cell technology is viable for a public transit application notwithstanding the acknowledged requirement to reduce both capital and operating costs to acceptable levels. Fuel cell powered buses provide a very clean technology that will help in addressing urban air quality issues. Hydrogen electrolysis fueling technology worked without service failure and proved that it is a viable alternative for the supply of hydrogen fuel."

Kevin Casey, Vice President and General Manager, Transportation, Stuart Energy:

"This project was a tremendous success not only from a fuel cell perspective but also from a hydrogen fueling infrastructure point of view. It has facilitated the development of a safe, practical approach to providing hydrogen fuel based on water electrolysis. It has provided "real life" experience in dealing with the many complex issues in the planning, design, installation, and operation of a fueling station for use in revenue service. Knowledge gained from this exercise has been a springboard to the development of a commercially viable hydrogen fueling station solution that will enable the future commercialization of fuel cell vehicles."

10. PLANS

Ballard Power Systems continues to develop its fuel cell technology for transit buses and will be evaluating the results in two key projects:

In Western Europe, where 10 cities are also looking to environmental solutions to address Euro Standard emissions reduction initiatives, a total of 30 fuel cell EvoBus Citaros with Ballard fuel cell engines will be delivered starting in mid 2003. The second program will operate three Gillig buses at Santa Clara Valley Transit Authority starting mid 2004. Other possible locations for zero-emission buses (ZEBs) with fuel cell engines include Chicago, Canada, and – through the United Nations Development Fund/Global Environment Fund program to address greenhouse gases – Brazil, Mexico, China, India and Egypt.

The U.S. Environmental Protection Agency has established emissions standards to 2010, and some states have already begun implementing plans for ZEBs. For example, CARB (California Air Resources Board) recently passed a regulation requiring fleets of 200 or greater to choose one of two paths: a diesel path requiring demonstration of at least three ZEBs starting in 2003, and 15% of new bus purchases starting in 2008 to be ZEBs. The alternative-fuel path requires 85% of new purchases to be alternative fuel starting in 2001 and 15% of new purchases to be ZEBs starting in 2010. The California Fuel Cell Partnership is supporting California's placement of fuel cell buses to meet the Air Resources Board's ZEB requirements. This will begin with the placement of seven buses by mid-2004.

With its zero emissions, the fuel cell vehicle is quickly emerging as one of the best solutions to urban air-quality issues.

11. REFERENCES

The main part of this case study is based on the report "Cleaning up: Zero-emission buses in Real-World Use" which has been published on the XCELLSIS/Ballard Phase 3 Fuel Cell Bus Program. It has been supplemented by information on the hydrogen fueling stations of the Chicago Transit Authority in Chicago (Sections 3.3, 5.1 and 6; provided by CTA and by Air Products) and of the Coast Mountain Bus Company in Port Coquitlam, BC (Sections 3.4, 4.2 and 5.2; provided by Stuart Energy).

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