Cleaning up:
Zero-emission buses in real-world use

A report on the XCELLSIS/Ballard Phase 3 Fuel Cell Bus Program.

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.

At XCELLSIS and Ballard, we believe the fuel cell engine is the most promising clean-energy source 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. Graciously participating with us in the testing process were two communities with an obvious commitment to clean-air solutions: Chicago, Illinois, under the Chicago Transit Authority, and Vancouver, British Columbia, through that region's Coast Mountain Bus Company.

This report presents the results of those tests.


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BALLARD Fuel Cell
NOVICE
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About the Phase 3 Test Program

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 started in July, 1997, followed by a non-revenue test phase in both cities in 1998.

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;
- To gain an understanding of vehicle performance, failures, and operating costs;
- To better understand the infrastructure required for the operation of this technology;
- To prepare the market for the entrance of fuel cell vehicles;
- To educate the public on the safety and reliability of fuel cell vehicles;
- To prepare and train potential transit customers to work with fuel cell vehicles.

About the participants

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 .5 million on the rail system. On a daily basis, the Authority travels over 190,000 miles (306,000 km) on 134 bus routes and over 181,000 miles (291,000 km) 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 B.C. 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, B.C., 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.

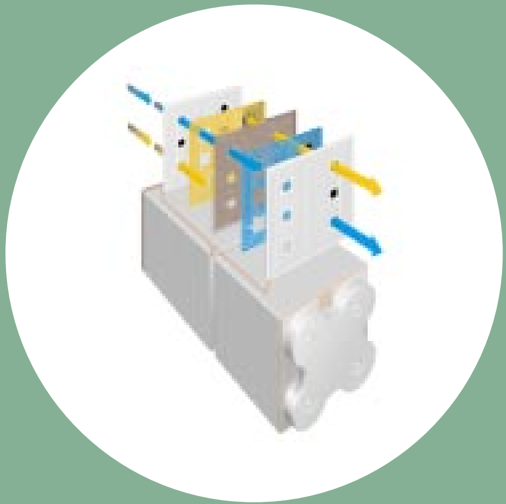
Stuart Energy is a world leader in the development and provision of electrolyzer hydrogen fuel appliances. It is based in Toronto, Ontario with additional offices in Grand-Mère, Québec; Vancouver, British Columbia, and Pasadena, California. Stuart Energy supplied the electrolyzer and fueling facilities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

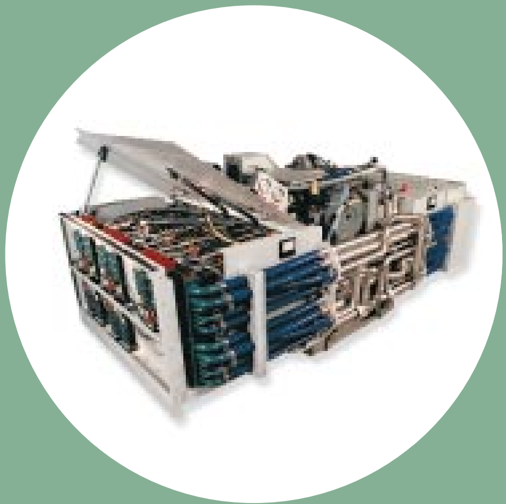
Other Partners

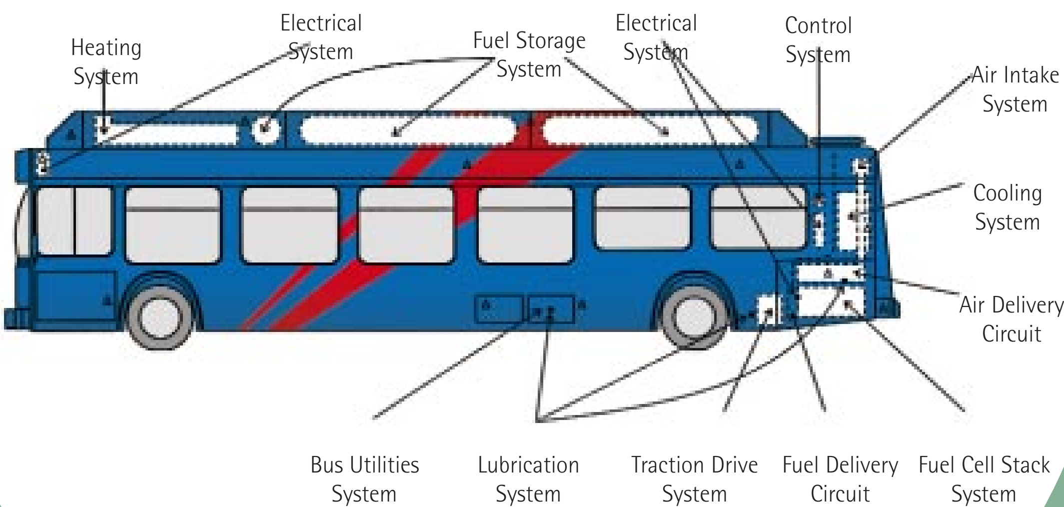
In addition to the transit authorities, funders of the Phase 3 program included the Province of British Columbia (Ministry of Employment and Investment), the Regional Transportation Authority of Northeastern Illinois, and the U.S. Federal Transportation Administration (FTA), utilizing Congestion Mitigation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

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, B.C., 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 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 driveshaft. The hydrogen fuel cell engine is a zero-emission engine.





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 115 lb (52 kilograms) of hydrogen gas at 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.

Scope of the Phase 3 test program

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

1. To prove that H_2 fuel cell vehicles can work for commercial heavy-duty applications;

2. To set up and utilize the H_2 infrastructure for operating and maintaining small fleets of fuel cell vehicles, and;

3. To create a baseline of actual and projected lifecycle costs and performance information to improve future products.

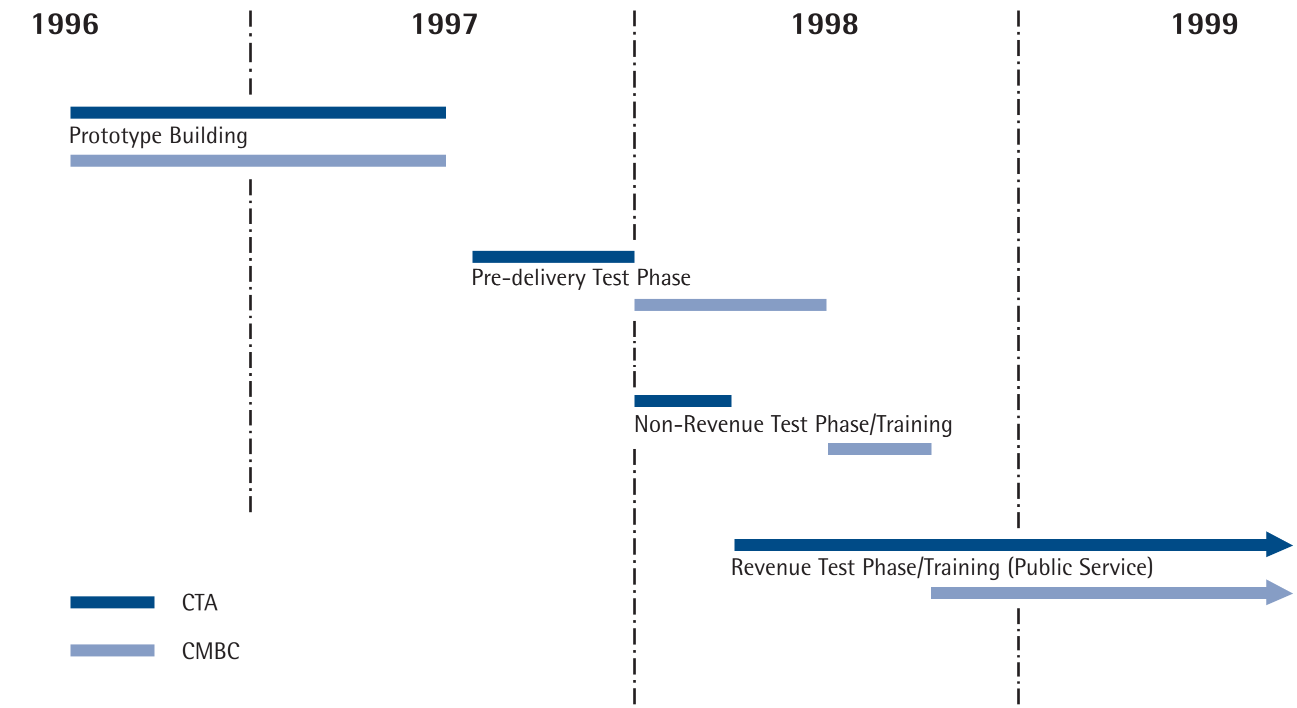
Each metropolitan area received three fuel cell-powered buses to use during the allotted test period. The six buses were deployed on existing routes under normal, revenue-generating conditions, regardless of weather or traffic. Owing to the unique fueling requirements of the Phase 3 fuel cell bus, maximum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

The total test mileage was 73,327 miles (118,000 km), with a total runtime of 10,559 hours and 205,000 riders.

Specific areas of evaluation during the trial 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).

Phase 3 Program - timeline of operations



Phase 3 performance testing criteria

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.

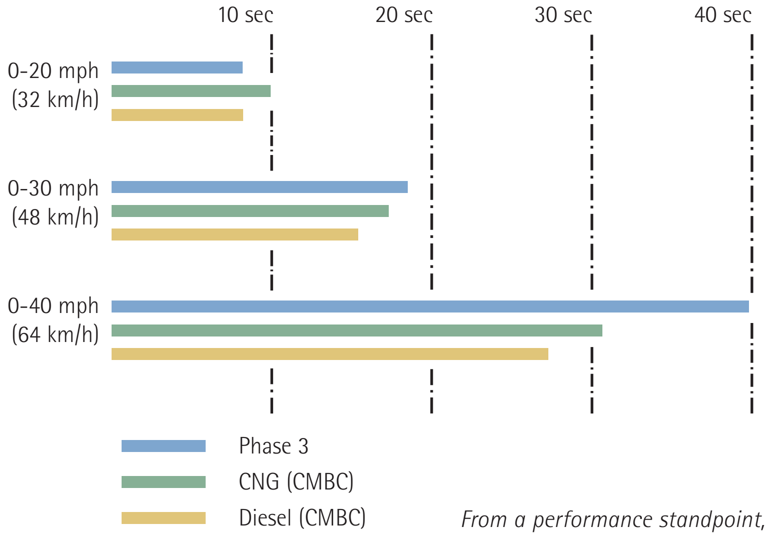
The test buses were run on regular routes, including high-volume downtown areas to maximize public visibility. Riders in both Vancouver and Chicago had very positive experiences from both a noise and a comfort level. In some cases, passengers would let diesel buses go by in order to ride a fuel cell 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 on page 17 shows, the Phase 3 bus was quieter than the diesel and CNG buses.

Acceleration to 20 mph (32 km/h) was about equal to diesel buses. Acceleration to 30 mph (48 km/h) and to 40 mph (64 km/h) 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, the Phase 3 fuel cell buses were considered better than CNG or diesel by both drivers and passengers.

"Paying for something that isn't causing a problem for the environment makes me feel good. I hope it continues."

— XCELLSIS Fuel Cell Bus passenger

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 0-20 mph range. In an acceleration test from a standstill, the XCELLSIS/Ballard Phase 3 bus was fastest from 0-20 mph, well ahead of design specifications of 10.5 seconds. 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.

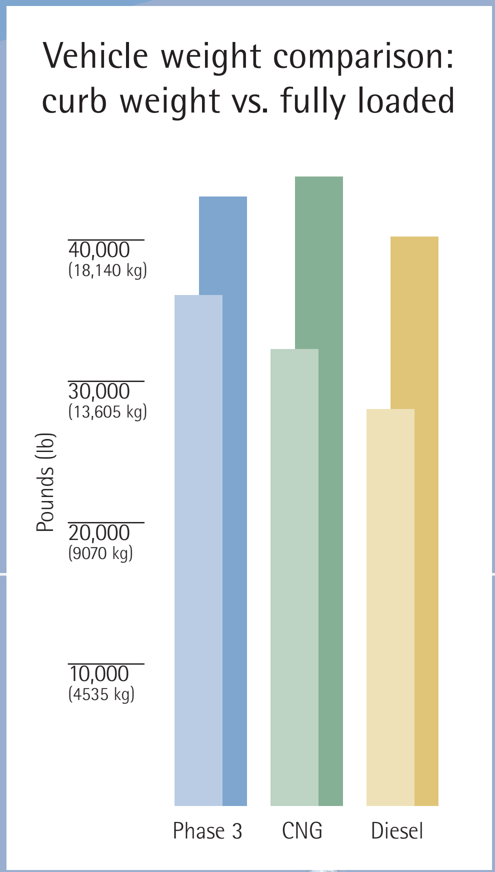
Weight and power

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. Substantial weight-saving refinements to the next phase bus (Phase 4) have expanded the fuel cell bus passenger capacity to 70 — see page 23.

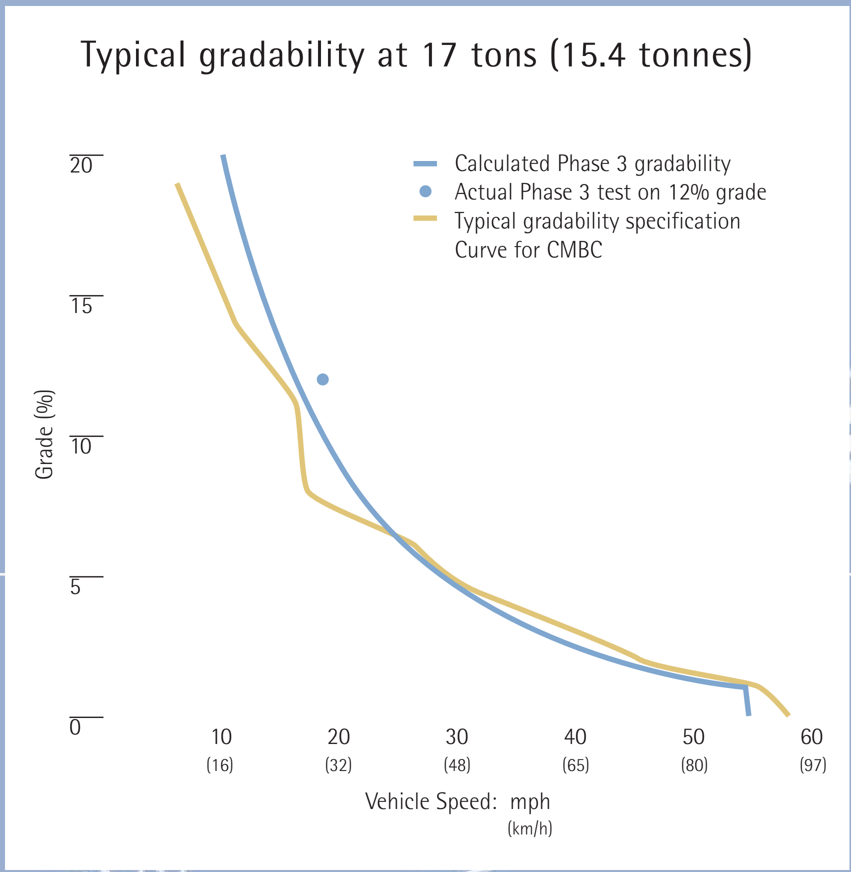
Typical gradability requirements set out in CMBC technical specifications are shown, as well as a curve of calculated performance of the Phase 3 bus. The measured data point for the Phase 3 bus shows that it exceeds specified requirements at 12% grade at 17 tons (15.4 tonnes) weight.

"I'm impressed. I prefer this bus over a diesel bus. It's much smoother and much quieter."

— Michael Simmons, CTA bus operator



Vehicle weight comparison: curb weight vs. fully loaded
Pounds (lb)
40,000 (18,140 kg)
30,000 (13,605 kg)
20,000 (9070 kg)
10,000 (4535 kg)
Phase 3
CNG
Diesel



Typical gradability at 17 tons (15.4 tonnes)
Calculated Phase 3 gradability
Actual Phase 3 test on 12% grade
Typical gradability specification Curve for CMBC
Grade (%)
20
15
10
5
0
10 (16)
20 (32)
30 (48)
40 (65)
50 (80)
60 (97)
Vehicle Speed: mph (km/h)

Noise output

"I think it's great! It's very quiet and it helps the environment."

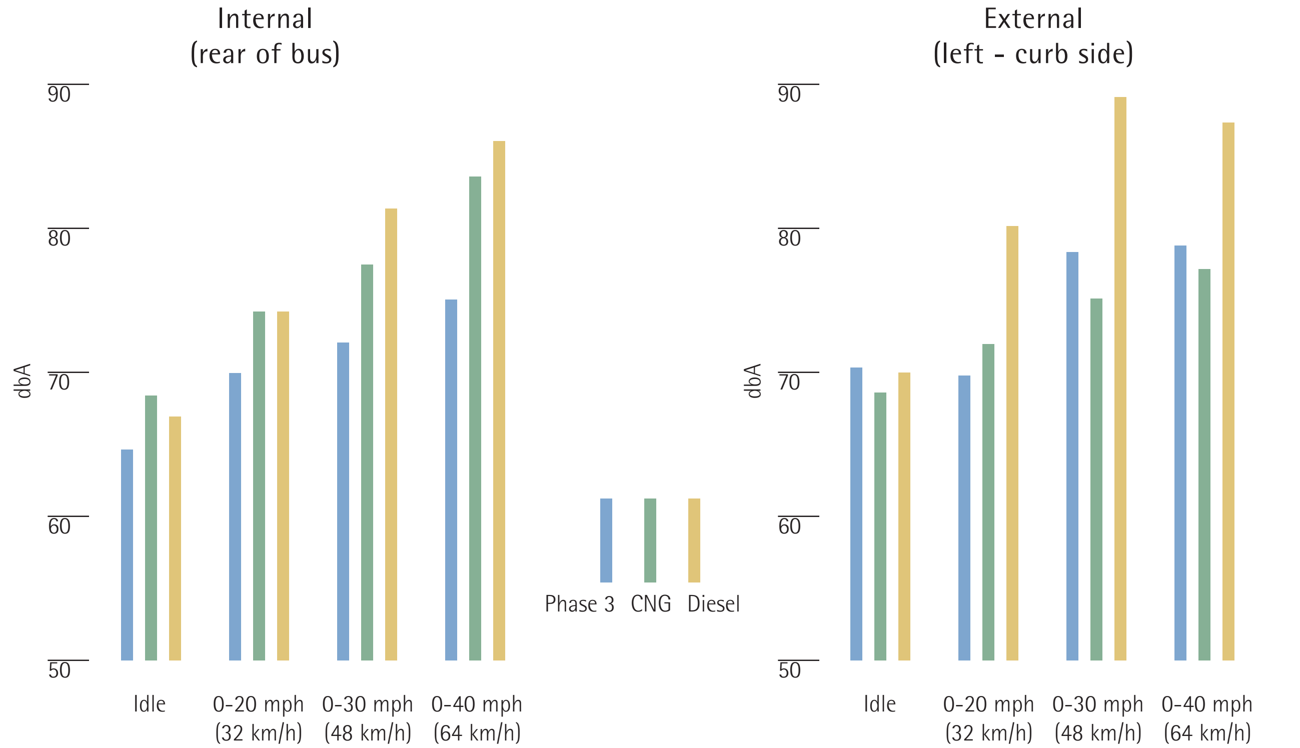
– Phase 3 Fuel Cell Bus passenger

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. As a comparison, typical sound pressure levels are:

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

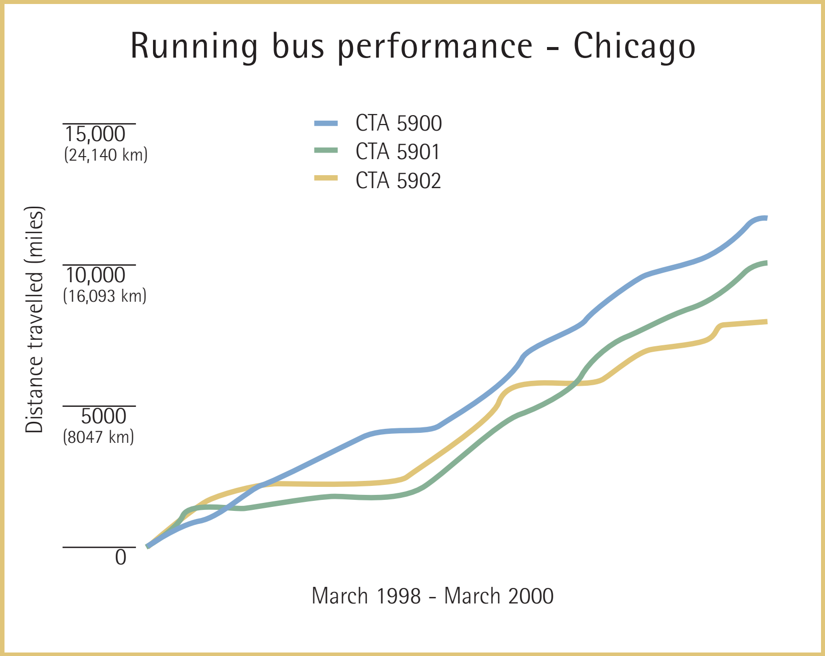
** data from Bruel & Kjaer*

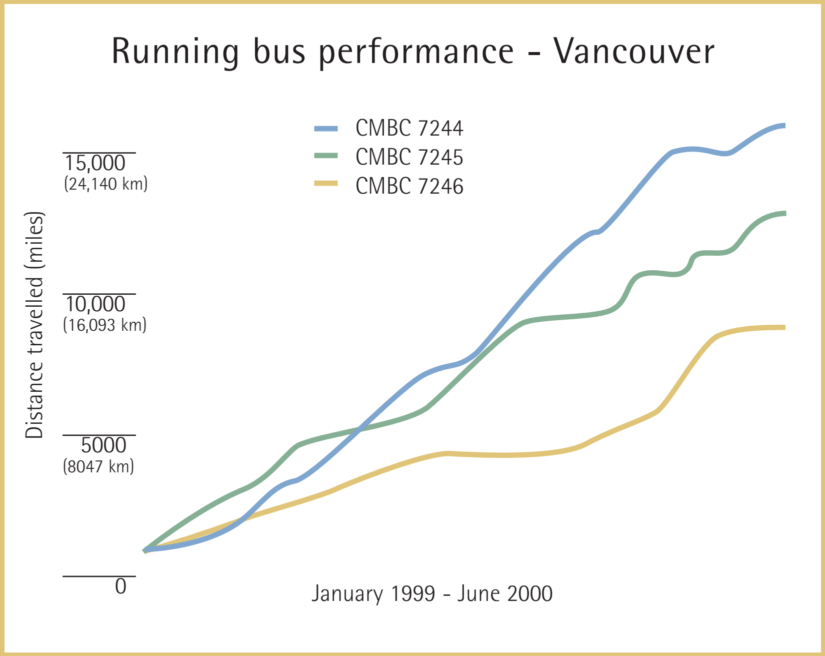
Noise tests


Internal
(rear of bus)
External
(left - curb side)
dbA
90
80
70
60
50
Idle
0-20 mph
(32 km/h)
0-30 mph
(48 km/h)
0-40 mph
(64 km/h)
Phase 3
CNG
Diesel

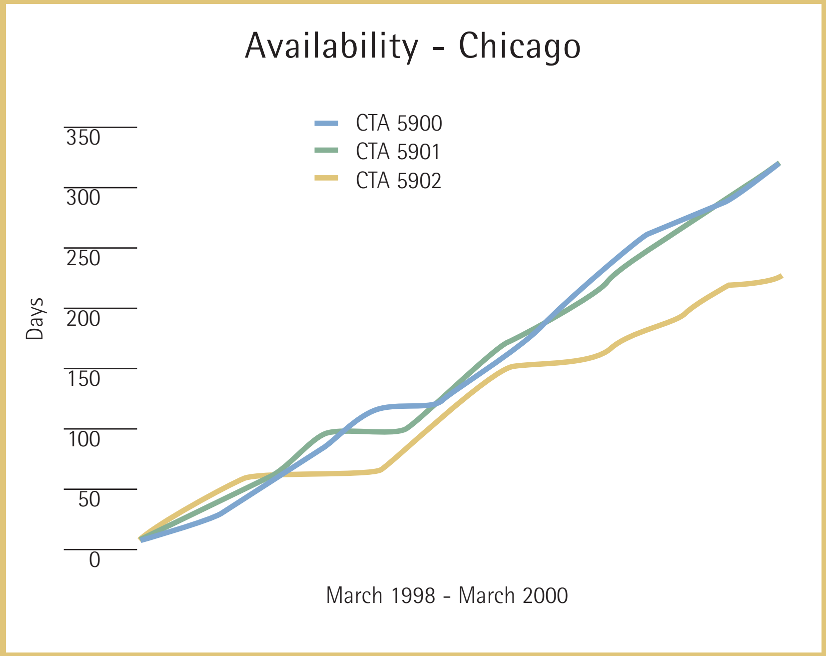
Running bus performance and availability

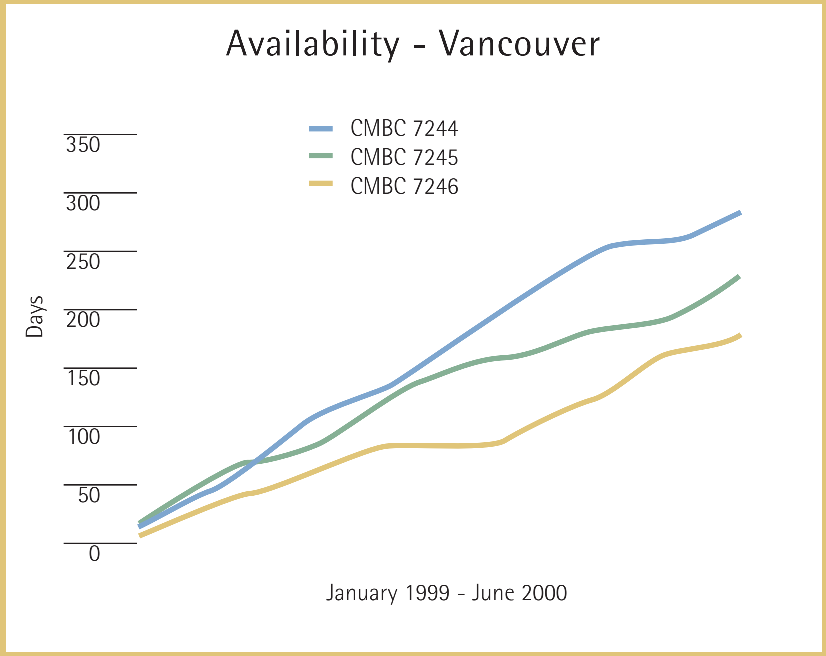
Considering its very intensive maintenance program, the objective of the Phase 3 test was for each bus to operate between four and six hours each day. The graphs show typical usage rates during revenue service in both areas. The significantly better run times and reliability in Vancouver reflect learning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





Total distances accumulated by all three buses in each region.





Shown is the individual availability of each bus in each region. 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.

Reliability

As expected, there were numerous incidents recorded during the program from which valuable experience was gained. 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 page 23). 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.

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 at CTA (see page 18) resulted in very encouraging road call results by the end of the program at CMBC.

	Hardware failures	Operator or maintenance errors	Non-failure incidents
CTA	143	13	217
CMBC	96	9	115

The incidents shown are identified under 3 classifications and cover fuel cells and systems only.

	Number of road calls	Distance between road calls
CMBC	23	1503 miles (2418 km)

Fueling infrastructure and performance

Hydrogen is generally manufactured by one of two different 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, and in Chicago it was supplied in liquid form by Air Products from a process plant in southern Ontario. The refueling operation for hydrogen is essentially the same as for CNG. The fueling station in Chicago used Air Products liquid storage (gaseous, on board the bus). It took approximately 15 minutes to fill a bus. The fueling station at Coast Mountain Bus was a Stuart Energy electrolyzer. It took approximately four hours to fill a bus, only because of limitations in production rate and ground storage capacity. 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 facilities upgrades required.

Infrastructure capital costs for hydrogen

Dedicated H_2 installations: Chicago (top) and Vancouver. In Chicago, 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.

In Vancouver, 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.

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 both projected vehicle and operating costs as this technology advances from the research and development phase to commercialization.

Vehicle costs

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.

Operating costs

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.

XCELLSIS' ZEbus is powered by the next-generation Phase 4 Fuel Cell Engine.

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: 31,700 versus 34,500 lb (14,376 versus 15,646 kg), 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 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 will be tested at SunLine Transit Agency in Thousand Palms, California, between July 2000 and October 2001.

Improvements: Phase 4 vs. Phase 3

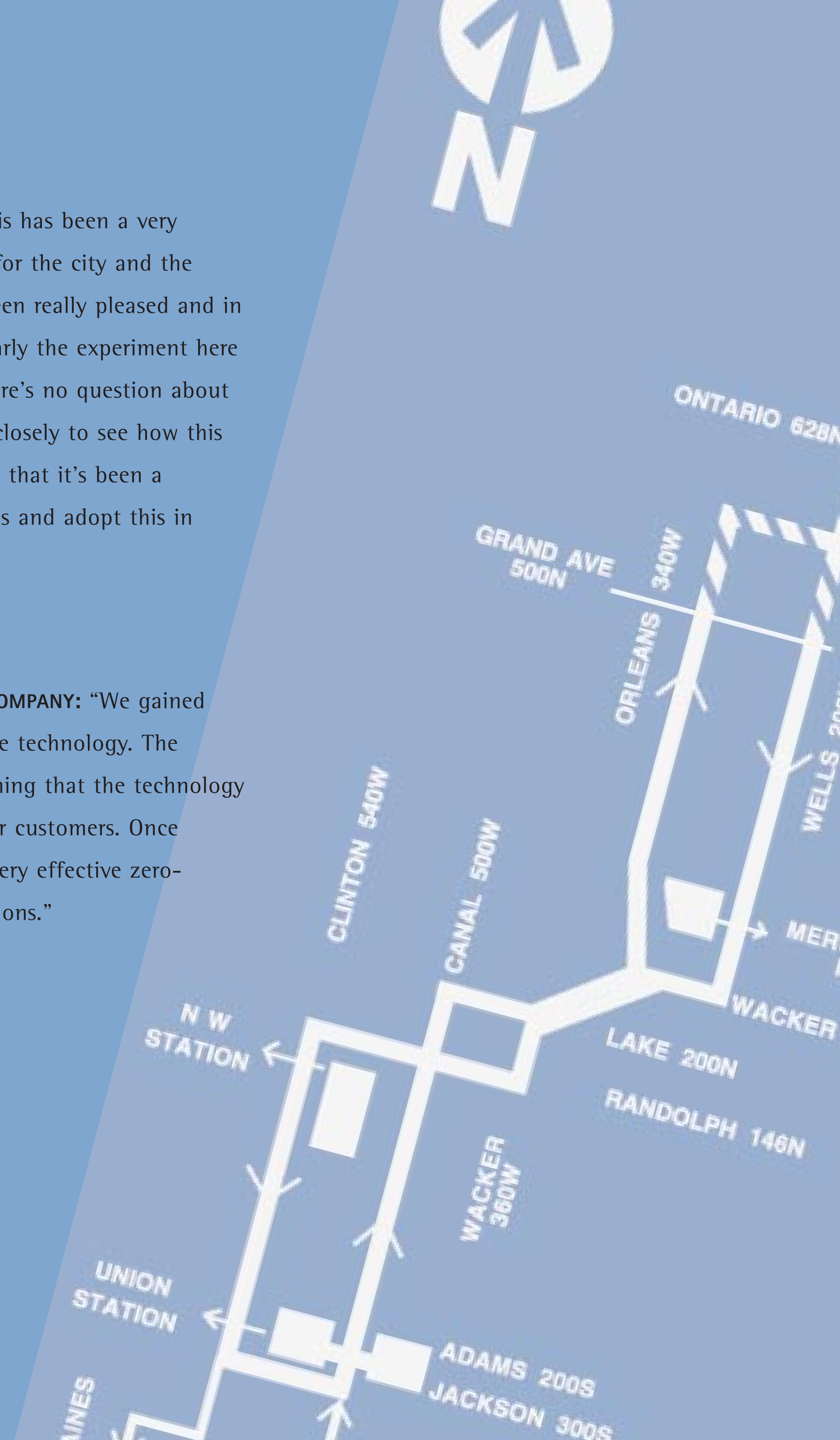
	Phase 4	Phase 3
Engine volume reduction	50% of Phase 3	
Weight reduction	3400 lb	
Fuel cell stacks	8	20
Recommended maintenance and repair	1/10 of Phase 3	
Number of motors (traction and auxiliary)	1	12
Startup time	3 seconds	45 seconds

XCELLSIS Phase 4 Fuel Cell Engine.

Test Program Conclusions

Frank Kruesi, President, Chicago Transit Authority: "This has been a very successful experiment… for the Chicago Transit Authority, for the city and the region and for our customers and employees. Everyone's been really pleased and in fact excited to be on a bus, which is unusual in buses. Clearly the experiment here proves that a hydrogen fuel cell works on transit buses, there's no question about that. 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 is how soon we can continue this and adopt this in fleets around the country and the world."

Dave Stumpo, President and CEO, Coast Mountain Bus Company: "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."

Chris Lythgo, Senior Vice President, Service Support, Coast Mountain Bus Company: "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."

The rationale for fuel cell vehicles

The U.S. Environmental Protection Agency has established emissions standards to 2010, and some states have already begun implementing plans for zero-emission buses (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 will put 20 fuel cell buses in operation by 2003. 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 will be delivered starting in late 2002/early 2003. Other possible locations for ZEBs with commercial XCELLSIS Phase 5 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.

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

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