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Fuel Cell Bus Demonstration in Mexico City

by

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16. ABSTRACT The report discusses the performance of a full-size, zero-emission, Proton Exchange Membrane (PEM) fuel-cell-powered transit bus in the atmospheric environment of Mexico City. To address the air quality problems caused by vehicle emissions in Mexico City, a seminar on clean vehicles was held in the Mexico City area in June 1997. The seminar addressed the state of the art of several clean vehicle technologies, one of which involved PEM fuel cells. A PEM fuel-cell-powered bus was demonstrated by Ballard Power Systems as part of the seminar.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

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E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

In an effort to address the air quality problems caused by vehicle emissions in Mexico City, a seminar on clean vehicles was held in the Mexico City area in June 1997. This seminar addressed the state of the art of several clean vehicle technologies, one of the most promising being Proton Exchange Membrane (PEM) fuel cells. To showcase this technology, Ballard Power Systems displayed and demonstrated the world's first full size, zero-emission PEM fuel cell powered transit bus. This report describes the bus demonstration activity and discusses the bus performance in the atmospheric environment of Mexico City.

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Executive Summary

The Air Quality Problem

Among the most serious problems facing our modern world is air pollution. In the Mexico City Metropolitan Area (MCMA), addressing this problem has become a high priority because it affects both the quality of life of its more than 15 million inhabitants, and its environment. More than one-half of Mexico's industry is located in the 400-square-mile MCMA, with more than 20 percent of the nation's population residing in the city itself, consuming 150 times the national average for energy per unit area, and driving 60 percent of the nation's automobiles. Mexico City experiences nearly 30 million person-trips per day, generates 18,000 tons of garbage per day, and consumes water at a rate of more than 60 cubic meters (15,850 gallons) per second.

Mexico City lies in a basin at a latitude of 19°N, and at an elevation of 2240 meters (7400 feet). The city is nearly surrounded by mountains that rise an additional 1200 meters (4000 feet), that create a barrier to air circulation and isolate the area from the winds of regional weather patterns. For this reason, geography is an important contributor to the phenomenon of temperature inversion in which a cap of warm air sits over cooler air, trapping air polluting emissions.

Air pollution in Mexico City has increased along with the growth of the city, the movement of its population, and the growth of employment created by industry. The population of the Mexico City area is growing fast. From 1970 to 1980, the population of the MCMA grew at a rate of 4.3 percent with a corresponding 9.6 percent growth rate for the surrounding urban municipalities. The MCMA population is expected to grow at a 1.4 percent annual rate and total more than 20 million people by the year 2010.

The resource usage of transportation combined with industrial output results in the release of 11,700 tons of pollutants into the air each day or about 4.3 million tons per year. Trends over the last decade indicate that pollution levels could double in the next twelve years, with obviously serious pollution consequences for the population. The principal constituents of atmospheric air pollution are ozone, particulate matter, nitrogen oxides, sulfur oxides, and carbon monoxide.

Zero Emission Bus Demonstration Project

In June 1997 a seminar and exposition on clean vehicles was held in Mexico City to review the state of the art of several clean vehicle technologies, including one of the most promising, Proton Exchange Membrane (PEM) fuel cells. To showcase this technology, Ballard Power Systems displayed and demonstrated the world's first full size, zero-emission PEM fuel cell powered transit bus. This demonstration project was undertaken by Ballard Power Corporation and Science Applications International, with funding provided by the U.S. Environmental Protection Agency.

The general goal of the project was to raise public awareness of the existence, and advanced stage of development, of this technology that could contribute significantly to reducing pollution from transportation sources. The technical goal of the project was to document and characterize the performance of a transit bus using PEM fuel cells as its power source in the atmospheric environment of Mexico City.

The bus was successfully operated during the conference with considerable interest shown in it. The bus was demonstrated by providing rides to government officials, political leaders, members of the press, members of vehicle programs, and the general public. Data were collected throughout the operation of the bus to evaluate its performance at the elevation of Mexico City, and to determine if there is any effect from the ambient street-level pollution.

Zero-Emission Fuel Cell Technology

The Ballard Fuel Cell Engine that powers the bus uses a fundamentally different method of generating power; however, it retains many of the attributes of a conventional engine. Like traditional internal combustion engines, the fuel cell engine combines fuel and air to create power. The compressed hydrogen fuel is stored in an external tank that can be quickly and easily refilled, providing the vehicle with the required range.

A fuel cell converts the chemical energy in the fuel directly into electricity through a low-temperature electrochemical process. This direct conversion has no intermediate thermal or mechanical stages, so the efficiency is high. No combustion is involved, so there is no pollution. The only exhaust from a fuel cell is water vapor. The electricity produced by the fuel cell engine is supplied to electric motors that power both the vehicle's drive wheels and auxiliary equipment.

Technical Conclusion

Overall, the PEM fuel cell powered the Phase 2 Bus operated in Mexico City as anticipated, given the conditions present at that elevation. The performance of the fuel cell engine is significantly dependent on its air subsystem to provide oxidant to the fuel cell at the correct pressure and flow rate. Due to the high elevation of Mexico City, there was a reduction in air subsystem efficiency of about 28 percent. This reduced air flow caused a reduction of engine power output of about 22 percent. The atmospheric pressure at Mexico City's elevation is approximately 29 percent less than that at sea level. The contaminants in the Mexico City atmosphere did not have any apparent effect on the bus engine operation over the time frame of this demonstration project.

As a general conclusion of the operating experience in Mexico City, there does not appear to be any reason that fuel cell buses cannot be operated successfully in that environment. The air subsystem is the key to efficient and reliable operation of the fuel cell engine in any environment, and, provided that the unusual elevation of the city is taken into account in sizing the compressor, there should not be any particular limitation on bus operation under those conditions.

Project Overview

This report describes a project undertaken by Ballard Power Corporation, Science Applications International (SAIC), and the U.S. Environmental Protection Agency (EPA), to demonstrate Ballard's zero-emission fuel cell powered transit bus technology in Mexico City in June 1997.

The general goal of the project was to raise public awareness of the existence, and advanced stage of development, of this technology that could contribute significantly to reducing pollution from transportation sources. To accomplish this goal, the bus was demonstrated to government officials, political leaders, members of the press, members of vehicle programs, and the general public at a seminar and exposition on clean vehicles held June 3 and 4, 1997.

The technical goal of the project was to document and characterize the performance of the world's first full-sized prototype transit bus using proton exchange membrane (PEM) fuel cells as its power source in the atmospheric environment of Mexico City.

The bus was successfully operated during the seminar with considerable interest shown in it. Data were collected throughout the operation of the bus to evaluate its performance at the elevation of Mexico City and to determine if there is any effect from the ambient street-level pollution. As a general conclusion, the bus had a partially reduced level of performance due to the reduced atmospheric pressure at the city's elevation. This performance reduction is not unexpected, as the bus engine's air compressor system is optimized for operation at sea level.

This bus demonstration project was conceived by SAIC and funded by the EPA. Logistical planning was primarily undertaken by Ballard Power Systems and SAIC's Mexico City and San Diego offices. A major planning meeting was held in Mexico City during the week of April 21, 1997, that involved the U.S. Embassy Science, Commercial & Technology Counselor, Mexico City's Secretary of Environment and Undersecretary of Government, and representatives of the National Autonomous University of Mexico and Mexico's National Institute of Ecology.

Mexico City's Air Quality Problem

Among the most serious problems facing our modern world is air pollution. In the Mexico City Metropolitan Area (MCMA), addressing this problem has become a high priority because it affects both the quality of life of its more than 15 million inhabitants, and its environment. Mexico's government and commerce are concentrated in Mexico City. This centralization has combined with rapid growth, modernization, and industrialization over the last 40 years to intensify the city's air pollution problem. More than one-half of Mexico's industry is located in the 400-square-mile MCMA. More than 20 percent of the nation's population reside in the city itself, consuming 150 times the national average for energy per unit area and driving 60 percent of the nation's automobiles. About 40 percent of Mexico's gross domestic product is generated in the MCMA. Mexico City experiences nearly 30 million person-trips per day, generates 18,000 tons of garbage per day, and consumes water at a rate of more than 60 cubic meters (15,850 gallons) per second.

Mexico City's location, at high elevation and surrounded by mountains, combines with these other factors to result in unacceptable air quality. Mexico City lies in a basin at a latitude of 19°N, and at an elevation of 2240 meters (7400 feet). The city is nearly surrounded by mountains that rise an additional 1200 meters (4000 feet), that create a barrier to air circulation and isolate the area from the winds of regional weather patterns. For this reason, geography is an important contributor to the phenomenon of temperature inversion in which a cap of warm air sits over cooler air, trapping air polluting emissions.

Air pollution in Mexico City has increased along with the growth of the city, the movement of its population, and the growth of employment created by industry. The main cause of pollution in the city is energy consumption. Air pollution in the form of dust and particulate suspended in the air is an old problem. The pollution as is known today began about 50 years ago with the growth of industry, transportation, and population. The population of the Mexico City area is growing fast. From 1970 to 1980, the population of the MCMA grew at a rate of 4.3 percent with a corresponding 9.6 percent growth rate for the surrounding urban municipalities. The MCMA population is expected to grow at a 1.4 percent annual rate and total more than 20 million people by the year 2010.

The resource usage of transportation combined with industrial output results in the release of 11,700 tons of pollutants into the air each day, or about 4.3 million tons per year. Trends over the last decade indicate that pollution levels could double in the next twelve years, with obviously serious pollution consequences for the population.

The principal constituents of the atmospheric air pollution are ozone, particulate matter, nitrogen oxides, sulfur oxides, and carbon monoxide.

The primary air pollution problem that has been identified in the MCMA is the formation of photochemical smog, primarily ozone. These photochemical oxidants are gaseous substances formed in the atmosphere by reactions involving nitrogen oxides and organic compounds in the presence of solar ultraviolet radiation. The main photochemical oxidant is ozone accompanied by a range of other secondary pollutants. Photochemical smog can cause eye irritation, respiratory disorders, crop damage, and accelerated deterioration of materials. Ozone also acts as a greenhouse gas, and it has been calculated that doubling tropospheric ozone may increase the surface temperature by nearly 1C°.

Ozone levels in Mexico City are high and appear to be getting worse. The Mexican one-hour standard for ozone is 0.11 ppm. From 1986 to 1992, the standard was exceeded on 71 percent of the days in 1986 and increased in 1992 to 98 percent of the days in the year. Many occurrences exceeded the standard by up to 300 percent, with the highest concentration recorded being 398 percent of the standard. Unlike the majority of cities in the northern hemisphere, where the tropospheric ozone occurs primarily in the summer months when solar radiation is at its highest, the MCMA presents favorable conditions for ozone formation throughout the year. This explains why there were so many days in which the standard was exceeded.

Particulate matter includes a variety of suspended particles such as aerosols, organic and metal vapors, combustion particles, and road dust. PM-10 particles (particles smaller than 10μm) pose a greater threat than others because they can penetrate deeper into the lungs. Major types of PM-10 particles are those produced by combustion, and aerosol particles formed by photochemical reactions. PM-10 is associated with reduced visibility, soiling, and acid deposition damage to materials and buildings.

All nitrogen oxides (NOx) are a major contributor to the formation of ozone, with nitrogen dioxide being particularly prevalent and injurious to health. Nitrogen oxides reduce visibility by absorbing sunlight, producing smog with the typical brownish color. The acid deposition of nitrates damages the tissues of vegetation, corrodes some materials, and causes a decay of cement and other construction materials.

Sulfur oxides (SOx) occur as a result of combustion of sulfur containing fossil fuels. The dominant form of sulfur oxide, sulfur dioxide, reacts with water droplets to form acid precipitation. Ambient levels of sulfur dioxide have been declining, probably as a result of the reduction of the sulfur content in fuels.

Carbon monoxide (CO) is emitted in the MCMA in greater amounts than all other pollutants combined. It is emitted primarily by mobile sources, mainly as a result of incomplete combustion in gasoline engines. The concentrations of CO vary according to the time of day and occur in direct proportion with traffic variations. Concentrations generally vary between 2 and 15 PPM with occasional concentrations reaching as high as 24 PPM.

The atmosphere acts as a natural filter for the sun's energy before it reaches the earth. At Mexico City's elevation, the air is about 25 percent thinner than at sea level. This reduced air density results in a corresponding 25 percent reduction in protection from that of a city at sea level. The increased incidence of blue and ultraviolet rays due to the thinner atmosphere accelerates the photochemistry that leads to significantly higher ozone concentrations than would occur at sea level.

Due to Mexico City's latitude, the number of daylight hours and the direct angle of the sun are affected very little by seasonal variations. This burdens the city with year-round ozone problems that other cities are troubled with only seasonally.

Introducing Clean Vehicles

With the obvious need for clean vehicle technology for the world's nations in general, and emerging nations and Mexico City in particular, an internationally attended environmentally oriented conference is a good setting in which to showcase fuel cell powered bus technology. An opportunity to present this technology occurred during a seminar and exposition on clean vehicles held in June 1997 in the Mexico City area.

The seminar and exposition was an internationally attended forum to discuss and promote a variety of clean vehicle concepts and technologies. The conference included presentations describing:

- Clean vehicle policies of the U.S. Clean Air Act and California's Clean Vehicle Program, by members of the California Air Resources Board and South Coast Air Quality Management District.
- Mexican clean vehicle policies and efforts, by representatives of the Transportation and Highways Secretariat, National Institute of Ecology, and Environment Secretariat.
- Policies promoting clean vehicles in Germany, Japan, and Costa Rica, by representatives of the respective countries' programs.
- Review of the state of the art of a variety of clean vehicle technologies by representatives from Ballard Power Systems, General Motors, Chrysler, Ford, Volkswagen, and Motores de Difusión de Aire (DAMS). The technologies reviewed include fuel cell electric vehicles, battery electric vehicles, hybrid vehicles, compressed air powered vehicles, and natural gas powered vehicles.

The Ballard fuel cell bus was demonstrated and displayed at the exposition that was held at the park-like setting of the Federal Electricity Commission Technology Museum at Chapultepec Park. The bus was introduced at this location and remained on display for 2 days with demonstration rides provided for the press and officials on the first day.

Following the event at Chapultepec Park, the bus was displayed for 2 days at the National Autonomous University of Mexico (UNAM). During this time, the general public was given an opportunity to examine the bus as well as ride in it.

Mexico City's Present Bus Fleet

The road infrastructure in the Mexico City Metropolitan Area is composed of 1371 km of primary roads that includes expressways, high priority avenues, and main roads. There are 8150 km of secondary roads.

An average of 29.5 million commuter trips made each day consist of 39 percent by private cars, 5.6 percent by taxis, 20 percent by small buses, 17.8 percent by suburban and urban buses, 16.3 percent by subway, and 1.3 percent by trolley and light rail.

The MCMA, with its over 15 million people, has close to 3 million motor vehicles. The population relies on several means of transportation to carry out their daily activities at offices, schools, shopping, entertainment, and commerce. The transportation sector is considered to be the main contributor to the gross emissions in the MCMA. Table 1 lists the types of transportation used in the MCMA.

Table 1. Transportation Types in the MCMA.

Transportation Type	Number of Units
Private cars	2,600,000
Taxi cabs	56,500
Urban buses	8,300
Mini-buses	52,000
Trolley buses	450
Subway cars	2,241
Transport trucks	196,000
Heavy diesel trucks	60,000

The estimated emissions from the bus fleet, which includes the urban and mini-bus fleets, are shown in Table 2. The estimates are based on the number of bus units shown in Table 1, with an average distance of 200 km traveled each day. Note that it is estimated that only about 80 percent of the mini-bus fleet are in operation at a given time.

Table 2. Bus Fleet Emissions.

	Emissions, per unit per day			Emissions, fleet per day		
	HC (kg.)	CO (kg.)	NOx (kg.)	HC (kg.)	CO (kg.)	NOx (kg.)
Urban buses:	1.6	4.9	4.2	13,280	40,670	34,860
Mini-buses:	2.2	20.6	0.48	91,520	856,960	19,968
Total daily emissions, bus types combined:				104,800	897,630	54,828

These figures show that Mexico City's bus fleet releases approximately 1,057 metric tons of pollutants into the air each day, or 380,520 metric tons each year. This amount represents approximately 10 percent of the city's total pollutant release. Total vehicle emissions (automobiles and trucks, as well as buses) are the source of 76 percent of all the pollutants released into the atmosphere of the MCMA. The high figure for mini-bus CO emission is due to the large number of gasoline fueled internal combustion engines used in this type of vehicle.

The majority of vehicles operating in the MCMA are characterized by old engines running at a high elevation. On average, the emissions from a typical vehicle in Mexico are three times higher than those of a typical vehicle operating in the United States.

The Ballard Fuel Cell Bus Engine

The Ballard Fuel Cell Engine that powers the bus uses a fundamentally different method of generating power; however, it retains many of the attributes of a conventional engine. Like traditional internal combustion engines, the fuel cell engine combines fuel and air to create power. Fuel is stored in an external tank that can be quickly and easily refilled, providing the vehicle with the required range.

A conventional internal combustion engine (ICE) produces power by burning a fuel to drive the engine's pistons that turn a crankshaft, providing rotational power for the drive train and auxiliary pumps, fans, alternators, and compressors. This high-temperature combustion process consumes non-renewable fuel and creates harmful pollutants (NOx, SOx, CO, and unburned HC). Additionally, because of the inherent limitations of the heat engine's Carnot cycle, and the frictional losses due to the mechanical nature of conventional engines, the overall efficiency of an ICE is about half that of a fuel cell engine.

Figure 1 illustrates the fundamental differences between an ICE and a fuel cell.

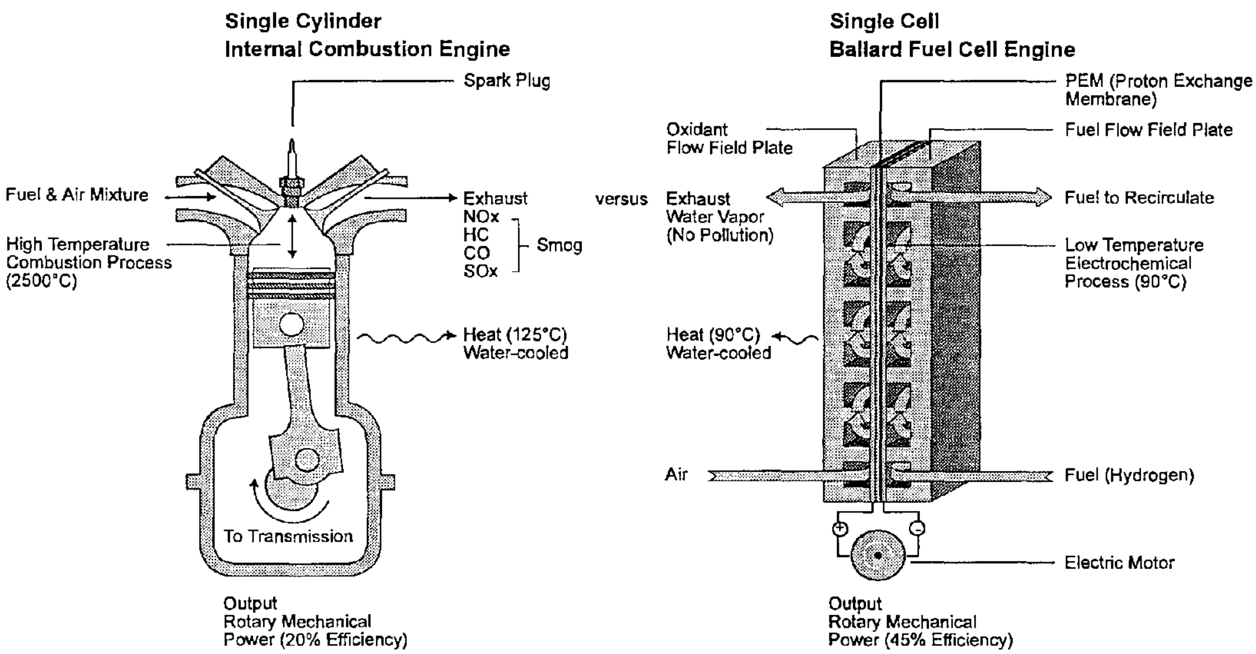
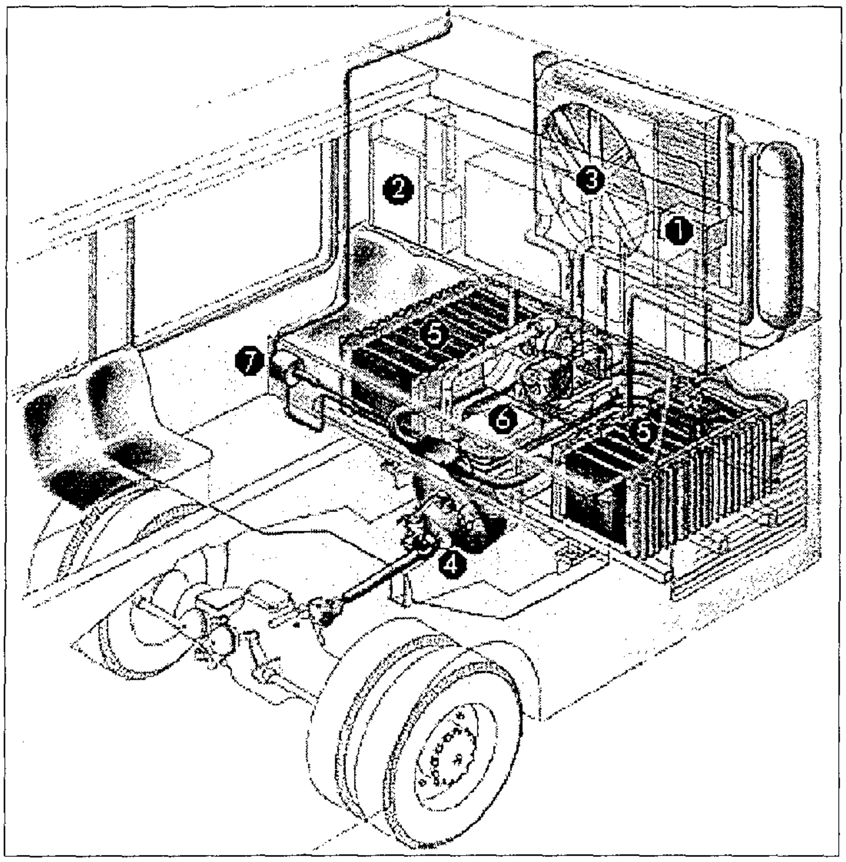


Figure 1. ICE - Fuel Cell Comparison.

The Ballard Fuel Cell Engine, by contrast, converts the chemical energy in the fuel directly into electricity through a low-temperature electrochemical process. This direct conversion has no intermediate thermal or mechanical stages so the efficiency is high. No combustion is involved so there is no pollution. The only by-product from the electricity-producing reaction is water vapor. The water vapor combines with the unused air from the intake to form clean exhaust. The electricity produced by the fuel cell engine is supplied to electric motors that power both the vehicle's drive wheels and auxiliary equipment.

A number of subsystems are required to make the fuel cell engine operate. Evaluation of the operation of these subsystems at the elevation of Mexico City was the primary technical objective of this demonstration. Figure 2 shows the layout of the various engine subsystems.



(1) Electrical System
(2) Control System
(3) Cooling System
(4) Electric Traction Drive
(5) Fuel Cells
(6) Air Delivery
(7) Fuel Delivery

Figure 2. Fuel Cell Bus Engine.

The **Fuel Cell Array** is at the heart of the Ballard Fuel Cell Engine. It is composed of a number of PEM fuel cell stacks arranged to provide the required power at the desired voltage and amperage. Internal manifolding directs the flow of fuel, air, and coolant through the array.

The **Air Delivery System** is one of the most critical subsystems. It provides air to the fuel cell array at a flow and pressure corresponding to the power demand. As more power is demanded from the fuel cell array, higher air pressure and flow must be provided to generate the power. The Ballard Fuel Cell Engine is designed to provide maximum power at a pressure of 30 psig. Air from the outside is drawn in through a filter by an electrically driven compressor and increased to full operating pressure by a turbocompressor powered by energy recovered from the exhaust air from the engine. The air flow through the engine is also used to remove the water that is produced by the electrochemical reaction.

The **Fuel Delivery System** is relatively simple. High pressure compressed hydrogen gas that is stored in lightweight composite cylinders is regulated in two stages to 30 psig. The flow is controlled with valves, and is recirculated within the system to ensure complete utilization.

The **Cooling System** maintains the fuel cell operating temperature at 85°C with a simple thermostatically controlled radiator and electrically driven fan. An auxiliary cooling loop controls the temperature of the high-power electrical components.

The **Electrical System** provides power interface between the fuel cell array and the electrical equipment for the engine and vehicle. Main system power is provided at 650 Vdc.

The **Control System** uses an on-board computer and industry standard programmable logic controller to coordinate the operation of mechanical, process, and electrical power systems.

The **Electric Traction Drive** motor is coupled through a speed reducer to the vehicle axle. Dynamic braking from the motor reduces wear on the vehicle brakes. Because the fuel cell bus does not have a battery for energy storage, the energy generated from dynamic braking is dissipated as heat through a resistive load.

Table 3 provides details about the subsystems used in the bus.

Table 3. Fuel Cell Engine Specifications.

Performance	
Horsepower	275 HP
Electric Power	205 kW (650 Vdc @ 315 A)
Efficiency/Idle	60%
Efficiency/Full Power	40%
Emissions	Zero
Fuel Cell Array	
Fuel Cell Stacks	13 kW x 20
Electrical Connection	2 Parallel/Series Strings
Voltage Range	450-750 Vdc
Pressure - Fuel/Air	30 psig (207 kPa)
Operating Temperature	185°F (85°C)
Air Delivery	
Type	Motor + Supercharger + Turbocharger Oil-lubricated/Intercooled
Pressure	30 psig (207 kPa)
Capacity	530 scfm (0.3 kg/s)

(continued)

(Table 3. Continued).

Fuel Delivery	
Fuel	Compressed Hydrogen Gas (CHG)
Delivery Pressure	Regulated to 30 psig (207 kPa)
Recirculation Type	Ejector
Storage Pressure	3600 psig (24800 kPa) Compressed Natural Gas (CNG) Standard
Cooling System	
Type	Dual Circuit - Water/Antifreeze
Fuel Cell Array	Water-cooled (Heated below Freezing)
Power Components	Liquid-cooled
Radiator/Fan	Transit Standard/15 HP Electric-drive
Pump Drive	Dual Shaft 5 HP Electric-drive
Heat Output	240 kW to 105°F (40°C)
Electrical System	
Main DC Link Voltage	650-750 Vdc with Up-chopper
Alternator	24 Vdc/300 A
Auxiliary Voltages	460 Vac, 24/12 Vdc
Starting Battery	24 Vdc/220 Ampere-hour Lead-Acid
Control System	
Hardware	Allen Bradley SLC - 5/04 PLC
Software	PLC Ladder Logic
Electric Traction Drive	
Motor	Induction Ac, Liquid-cooled
Controller	0-400 Hz IGBT Inverter, Liquid-cooled
Input Voltage	100-800 Vdc
Motor/Controller Efficiency	93%
Power Output (Continuous)	215 HP (160 kW)
Motor Speed	Base 1800 rpm; Maximum 12000 rpm
Gear Reducer	Planetary 4.29:1
Power Transmission	Fixed Ratio, Direct Drive
Torque	2700 lb ft (3650 N•m)
Dynamic Braking	Liquid-cooled Resistor

The Ballard Fuel Cell Bus

The bus used for this project is Ballard's Phase 2 Fuel Cell Bus. The Phase 2 Bus is the world's first full-size transit bus powered with PEM fuel cells. The Phase 2 Bus was constructed and became operational in 1995, following the successful demonstration of Ballard's prototype Phase 1 Bus. Both buses have been extensively and successfully demonstrated all over North America. The purpose of the Phase 1 Bus was to demonstrate the concept of a PEM fuel cell powered bus, while the purpose of the Phase 2 Bus is to show practical application of the technology in a full-size city bus that meets transit authority performance criteria and Department of Transport regulations.

The Phase 2 Bus, shown in Figure 3, is built on a New Flyer Industries model H40LF advanced low floor coach chassis. The fuel cell engine is based on Ballard's second generation fuel cell stack design, and fits into the existing engine compartment normally occupied by an internal combustion engine. The hydrogen fuel is stored in the form of compressed gas in cylinders on the roof. The Phase 2 bus is the design basis for the fuel cell bus fleets presently being delivered to the Chicago Transit Authority and the British Columbia Transit Authority.

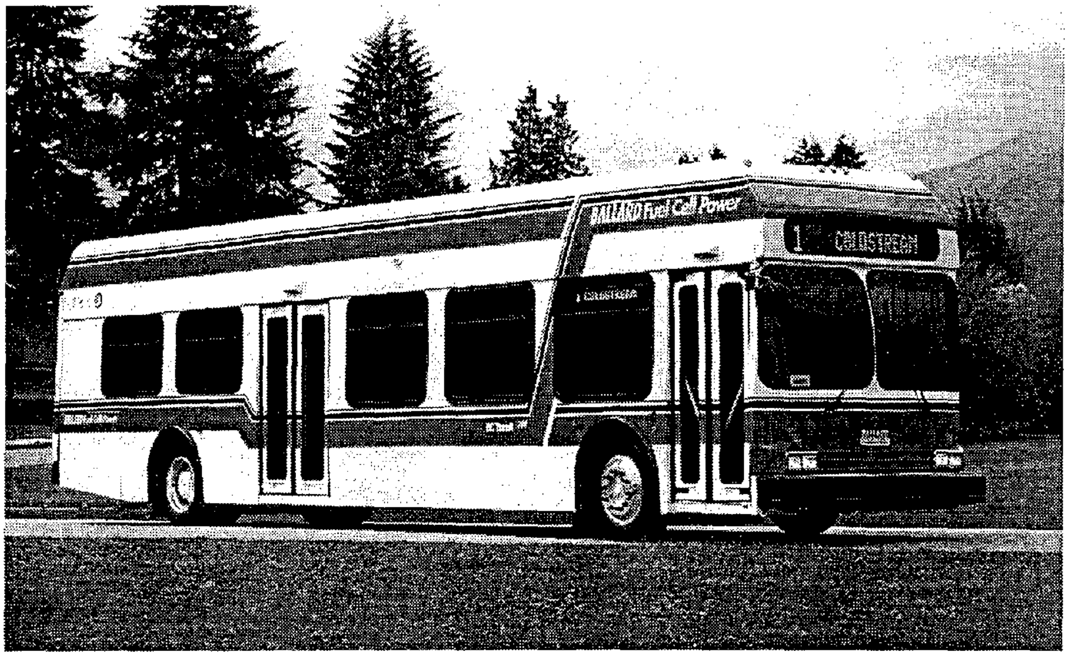


Figure 3. Phase 2 Bus.

During the conference, the bus was primarily on static display. The bus was also operated for the purposes of demonstration rides for dignitaries and members of the press, public demonstration rides, and for moving between locations. During all operation, data for over 65 different operating conditions and parameters were logged by computer. These data allow the following assessment of the bus performance with a comparison to data obtained during operation of the same bus in Vancouver, BC immediately prior to shipping to Mexico City by truck.

Summary of Bus Operation

The performance data shown in the following figures were logged during dynamic operation of the bus and are composed of thousands of data points in each graph. The apparent scattering of points is a result of the transient conditions present during the operation of the bus in actual on-road conditions.

Performance

The common method of interpreting the performance of a PEM fuel cell is with a graph plotting voltage vs. current, commonly known as a polarization curve. The polarization curve shows the relationship of the fuel cell voltage to the current demanded by a load. The power produced can be determined from the voltage and current at a given load point. Figures 4 and 5 show polarization curves for bus fuel cell operation in Vancouver, BC, as a sea-level baseline, and in Mexico City.

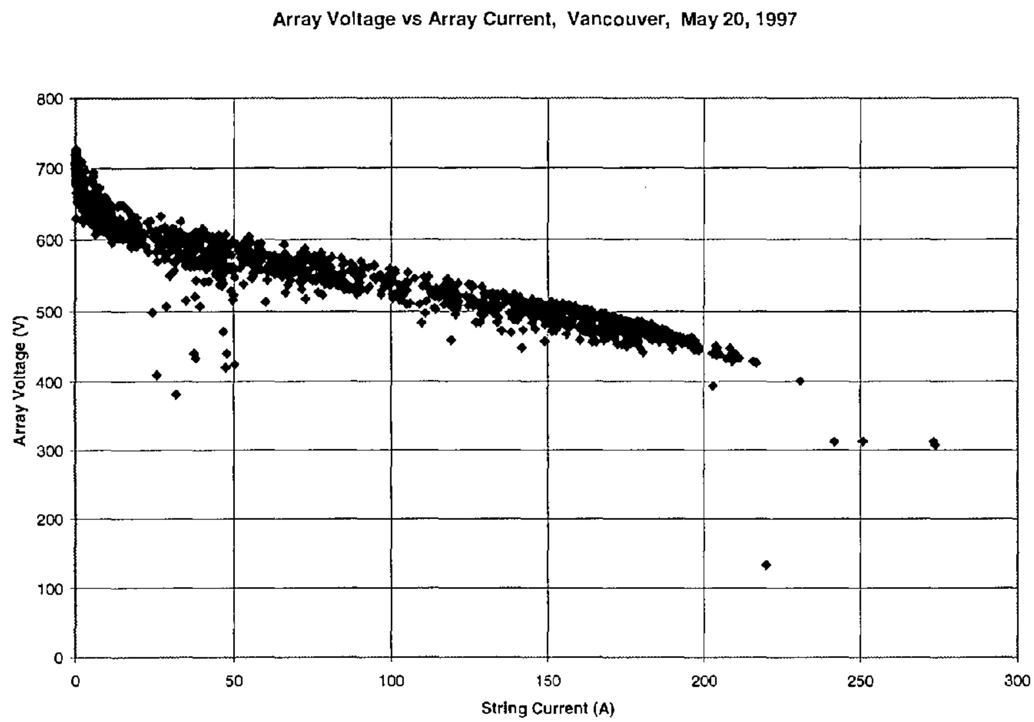


Figure 4. Fuel Cell Polarization, Vancouver.

Typical and expected performance is shown in Figure 4, representing data taken during a test run in Vancouver. This plot shows that the engine provided about 220 A of electric current per stack string at 432 V. There are two stack strings in parallel; therefore power of 190 kW was produced.

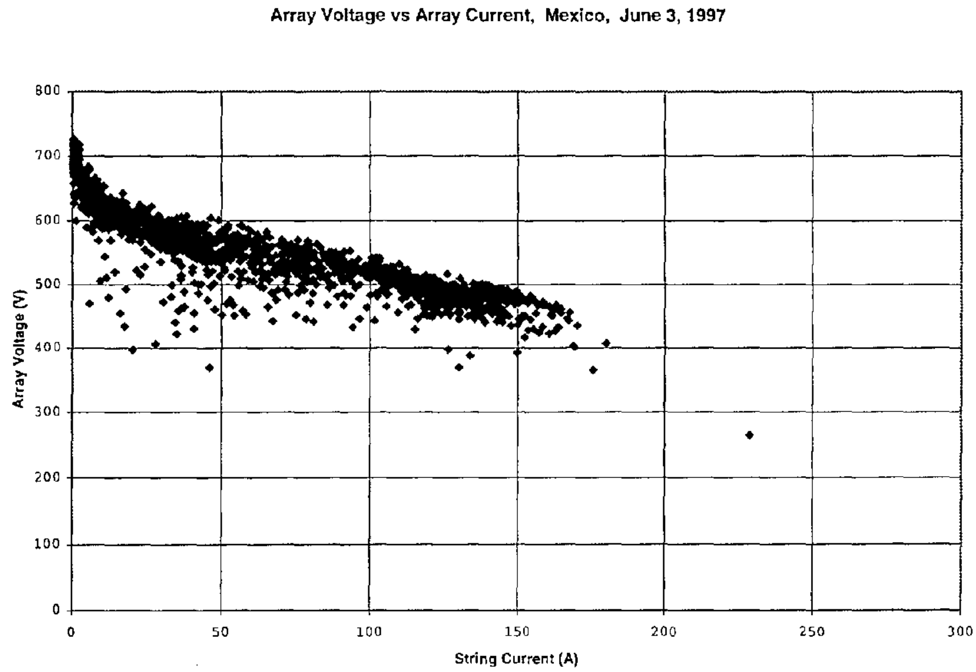


Figure 5. Fuel Cell Polarization, Mexico City.

The graph in Figure 5 shows voltage and current measured during operation in Mexico City during this project. As can be seen, the current output of one fuel cell string is only about 172 A at 430 V. This corresponds to a total power of 148 kW.

These performance data show a 22 percent decrease in peak power during operation in Mexico City. The obvious differences between the environments of Vancouver and Mexico City are the air quality and atmospheric pressure. Prior to this project, it was expected that there would be a reduction in performance due to lower system air compressor efficiency at the high elevation.

Compressor Outlet Pressure Vs Compressor Speed, Vancouver, May 20, 1997

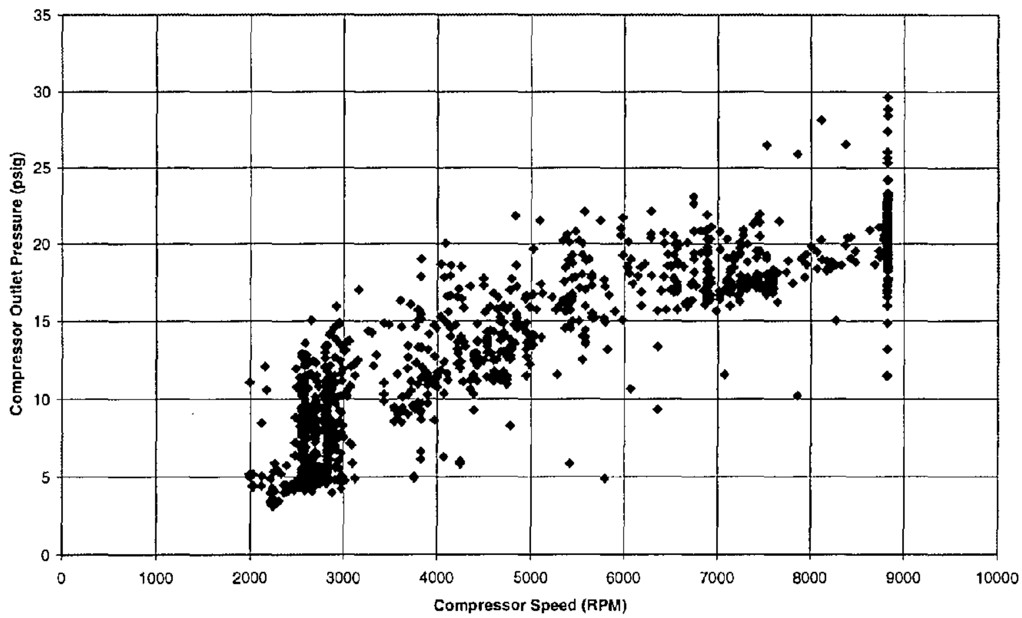


Figure 6. Compressor Pressure, Vancouver.

Compressor Outlet Pressure Vs Compressor Speed, Mexico, June 3, 1997

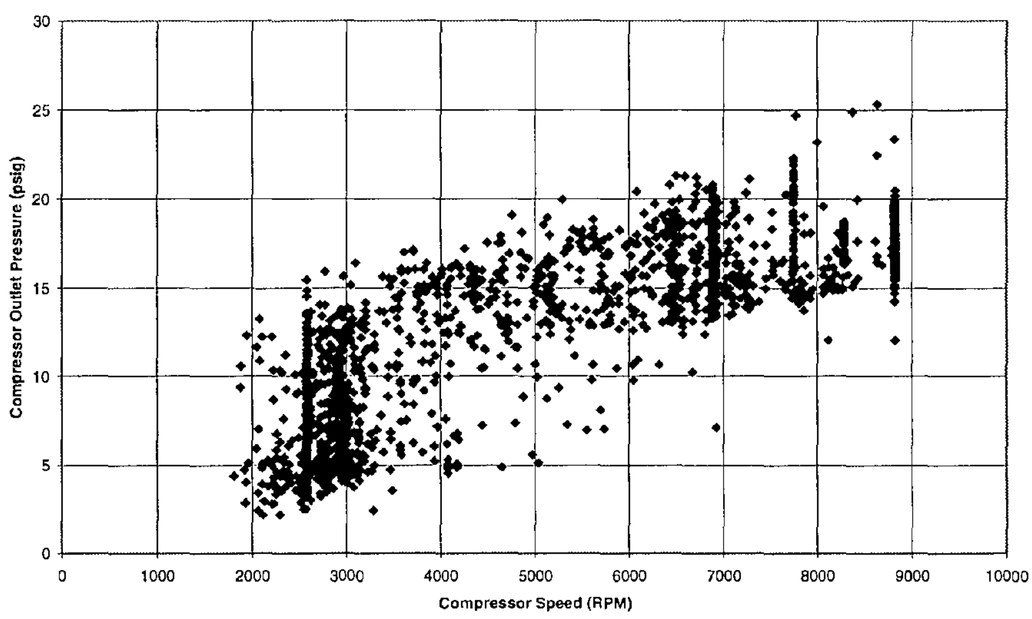


Figure 7. Compressor Pressure, Mexico City.

Figures 6 and 7 show compressor pressure characteristics during operation in Vancouver and Mexico City respectively. The wide scatter range of the data points in these charts illustrates the dynamic nature of the air compressor system. The air compressor system is a load-following subsystem; that is, its output varies directly with the total system load to produce high power when needed, but to reduce the system parasitic loss during low power conditions such as idling and cruising. Every time the driver accelerates, the compressor motor speed increases to increase the air flow, and when the driver eases off the throttle, the compressor motor speed and compressor air flow reduce. This high frequency cycling produces the data point scatter seen in these charts.

A comparison of the compressor pressures obtained in Vancouver and Mexico City shows that the general characteristics are similar but that the maximum pressure obtained in Vancouver is somewhat higher than in Mexico City.

The compressor pressure charts also illustrate a typical feature of an urban bus driving cycle. The density of the data points is highest at the low and high ends of the plot with lower density in the mid-range. This shows that a bus tends to be operated from idle to high power demand (acceleration), then back to low power to cruise or decelerate to a stop. Only a small amount of time is spent at a steady mid-power condition.

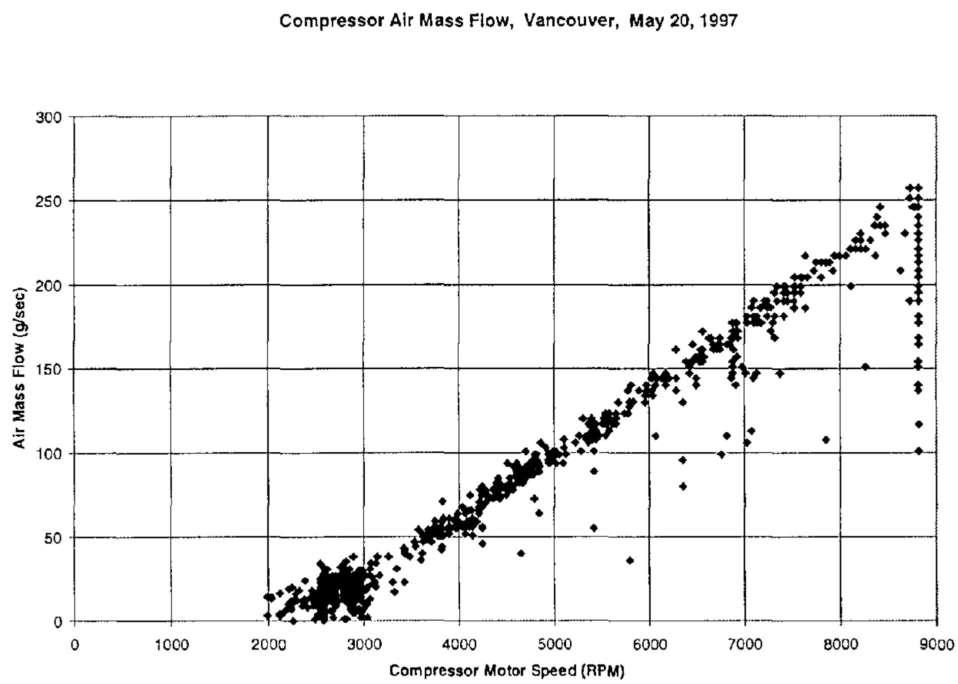


Figure 8. Air Flow, Vancouver.

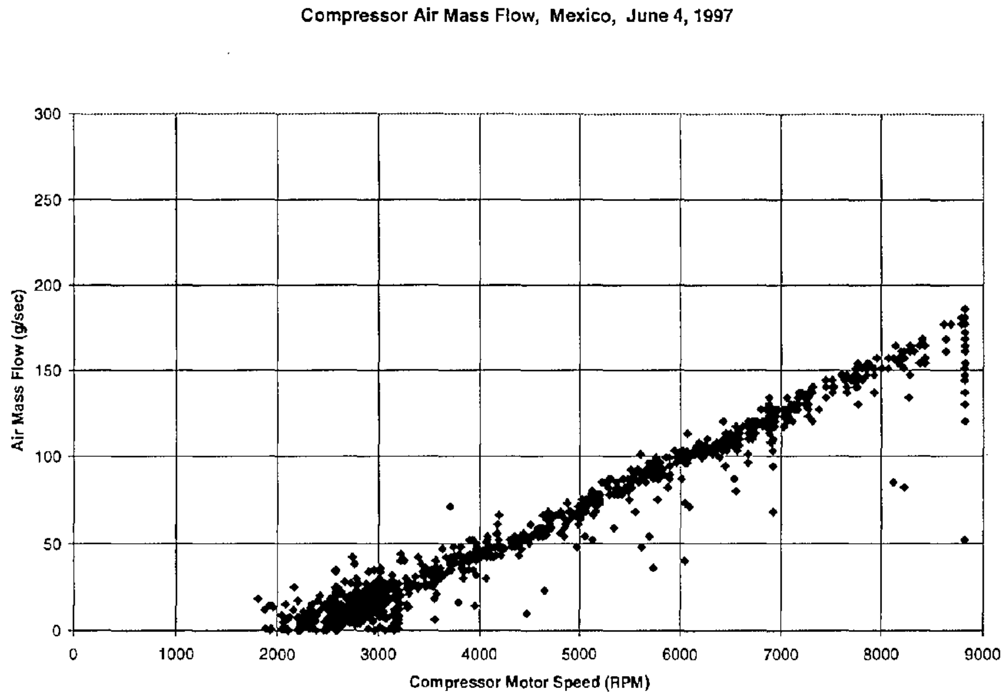


Figure 9. Air Flow, Mexico City.

Fuel cell designs are optimized for operation at a specific air pressure, but equally important is the air flow rate. The air flowing through the fuel cell provides oxygen necessary to sustain the electrochemical reaction, and also carries away the water that is produced by the reaction. If the air flow is inadequate, the power output of the fuel cell may be reduced by insufficient reactant being present (oxygen) in the air, and by the presence of excess water that blocks the air passages within the fuel cell, also resulting in reduced power output.

During operation of the bus in Mexico City, reduced air flow rate was the most significant factor contributing to the reduction in bus engine performance. Figures 8 and 9 show the air flow provided by the compressor system across the compressor motor rotational speed range. Both graphs show that the output is linear across the speed range, but at any speed above the low end of about 3000 RPM, the relative flow rate is substantially lower in the case of the Mexico City data. The output across most of the RPM range is about 28 percent lower than the Vancouver data, which would account for the lower performance shown in the Mexico City polarization curve.

The reduced flow of the air subsystem has obvious implications for fuel cell performance, but an additional complication occurred during the Mexico City operation as a result of the lower air flow rate. The air flow through the air system is one of the factors that contributes to compressor temperature regulation. It was found that the reduced air flow, particularly at high power levels, caused the compressor temperature to increase to a point where the system instrumentation would go into alarm mode. This problem was not caused by general system overheating, but occurred specifically to the air compressor. The primary cooling system that controls the fuel cell temperature, and the secondary cooling system for power electronics and other ancillaries, both functioned normally in Mexico City's summer ambient temperature.

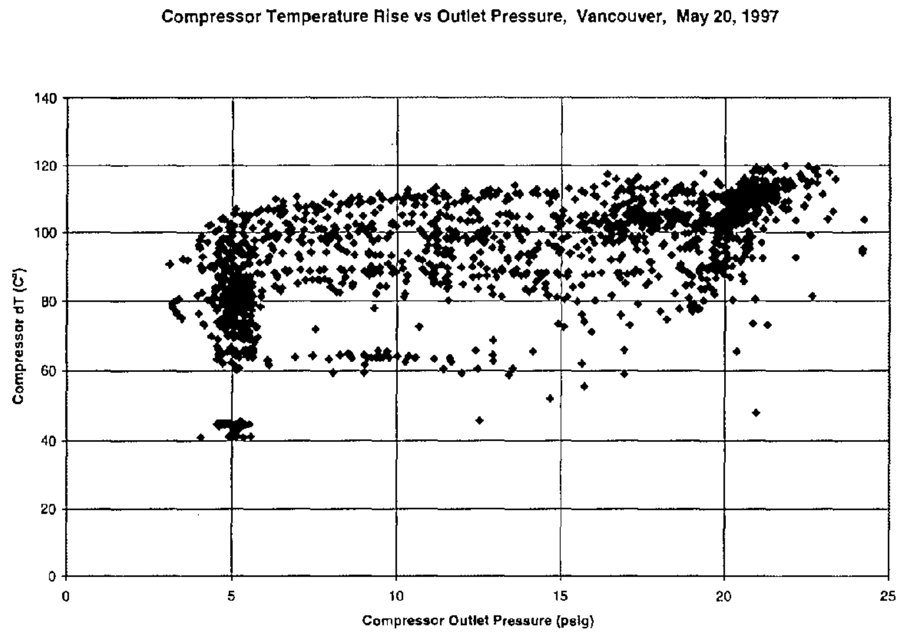


Figure 10. Compressor Temperature, Vancouver.

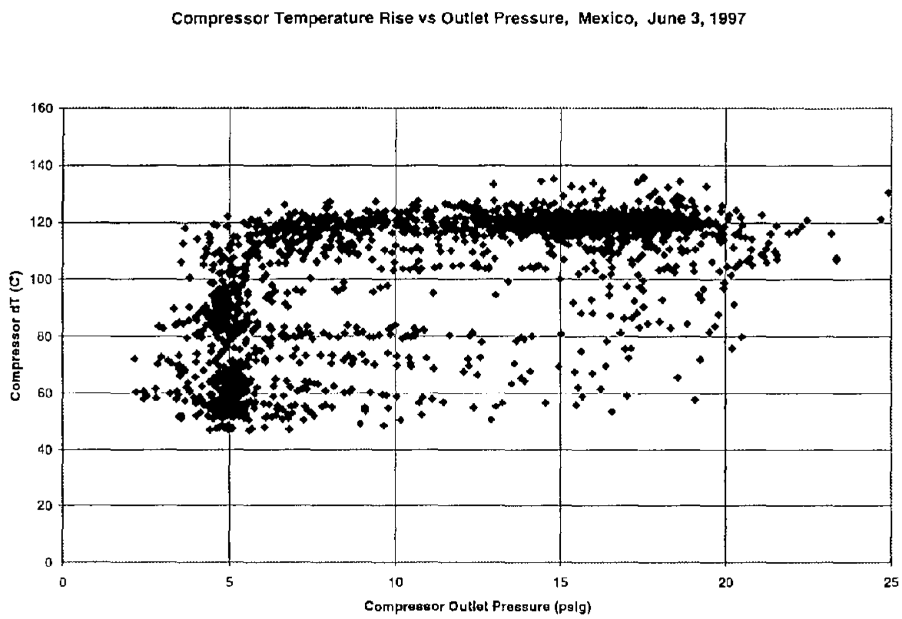


Figure 11. Compressor Temperature, Mexico City.

Figures 10 and 11 show the temperature rise of the air compressor as related to the outlet pressure for operation in Vancouver and Mexico City. In Vancouver operation, the temperature is well distributed between about 80° and 115°C across the entire pressure range of 5 to 25 psig, only briefly approaching 120°C at the highest power level. In the case of Mexico City operation, it can be seen that, at any pressure above 5 psig, the temperature quickly rises to about 120°C, and in many cases approaches 130°C. This level of air compressor temperature increase necessitated adjustment of the system electronic governor to limit the power output to minimize the occurrences of the compressor's going into an over-temperature alarm state.

Bus Performance Summary

Overall, the PEM fuel cell powered Phase 2 Bus operated in Mexico City as anticipated, given the conditions present at that elevation. The reduction in power as a result of the lower atmospheric pressure was expected. However, the degree of the air compressor temperature problem caused by the reduced air flow rate was less anticipated.

The data presented here suggest that the overall fuel cell engine performance loss is in the order of 22 percent, and the loss in compressor air flow rate is about 28 percent for a given compressor motor speed. These decreases are directly attributable to the reduced atmospheric pressure at the 2240 meter (7400 foot) elevation of Mexico City. The atmospheric pressure at Mexico City's elevation is approximately 29 percent less than that at sea level. This performance variation is summarized in Table 4.

Table 4. Bus Performance Variation With Elevation.

	Engine Output (kilowatts)	Compressor Air Flow (grams/second)	Atmospheric Pressure (millibars)
Sea level	190	257	1010
Mexico City (2240 m)	148	186	713
Reduction due to elevation	22%	28%	29%

The performance loss experienced in Mexico City is not due to any fundamental limitation of the PEM fuel cell technology, but is the result of operating outside of the normal operating conditions of the engine's air subsystem. The air subsystem in the Phase 2 Bus is carefully designed to provide a given air flow and pressure range while minimizing the parasitic loss to the overall system. The system is designed to accomplish this with ambient atmospheric pressures found from sea level up to modest elevations.

Given the significantly reduced density of the atmosphere at 2240 meters, proportionally less air mass moves through the compressor for each revolution, resulting in lowered air flow rates that inhibit fuel cell performance and compressor cooling. The solution to this situation is a relatively straightforward re-sizing of the air subsystem to provide adequate air flow in an environment of reduced ambient pressure.

The contaminants in the Mexico City atmosphere did not have any apparent effect on the bus engine operation over the time frame of this demonstration project. Carbon monoxide (CO) is present in the Mexico City air but, while this compound can be a concern if it is present in the fuel, its presence in the air that passes through the fuel cell did not seem to have a detrimental effect. The levels of CO in the Mexico City air, while potentially hazardous to human health, are within the levels generally tolerated by a PEM fuel cell even when present in the fuel. It should be noted, however, that extensive testing has not been done to evaluate the long term effect of operating a PEM fuel cell with significant levels of CO in the air.

As a general conclusion of the operating experience in Mexico City, there does not appear to be any reason that fuel cell buses cannot be operated successfully in that environment. The air subsystem is key to efficient and reliable operation of the fuel cell engine in any environment and, provided that unusual elevation is taken into account in the design of the compressor, there should not be any particular limitation on bus operation in Mexico City.

Reference/Acknowledgement

Mexico City air quality data and transportation statistics from: "Mexico City Air Quality Research Initiative" (MARI), a report published by Los Alamos National Laboratory, June 1994.