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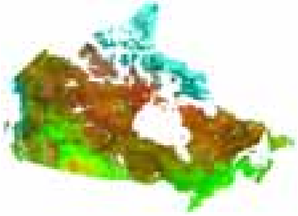

TRANSFORMING THE FUTURE:
MOVING TOWARD FUEL CELL-POWERED FLEETS IN CANADIAN URBAN TRANSIT SYSTEMS

DETAILED REPORT
FEBRUARY 2005

BC Transit
MARCON-DDM
Canada

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1 INTRODUCTION

1.1 BACKGROUND

In the year 2000, Canada, as part of a world community concerned about the environmental, social and economic consequences of increasing greenhouse gas emissions, announced its Action Plan 2000 on Climate Change.

As part of the plan, the Government of Canada committed to work with industry and other levels of governments to develop and demonstrate hydrogen-based technologies that would enable Canada to reduce greenhouse gas emissions while enhancing its innovative economy. A major part of this initiative is a focus on hydrogen applications in transportation.

In June 2001, Ottawa announced the creation of the Canadian Transportation Fuel Cell Alliance (CTFCA), a program to support the demonstration and evaluation of different processes for the production and delivery of hydrogen to fuel cell vehicles.

Urban transit systems, currently operating bus fleets fuelled almost exclusively by diesel, are a natural early adopter of hydrogen fuel cell technology that can reduce greenhouse gas emissions and urban air pollutants to zero.

Canadian urban transit systems (UTSs) are an ideal sector to engage because:

- They efficiently move large numbers of people – over 2.42 billion riders per year;
- The number of vehicles – approximately 12,000 buses across Canada – is a sizeable market;
- UTSs consume over 360 million litres of diesel and 17 million cubic metres of natural gas per year;[1]
- The transit application is visible to a public sympathetic to improving air quality;
- Transit properties have a centralized infrastructure that can be adapted to hydrogen; and
- Urban transit applications have global market relevance.

The societal benefits of hydrogen fuel cell-powered transit buses include:

- The health-related impacts of deploying zero-emission transport in inner city and other urban neighbourhoods;
- Significant reductions in noise pollution levels by replacing internal combustion engines with electric drive systems;
- Reduction of greenhouse gas emissions to zero; and
- The potential use of renewable sources of energy, e.g., solar, wind, geothermal and hydropower, to produce hydrogen fuel.

In 2003,The CTFCA made the decision to study the issues that face Canada's urban transit systems in making the transition from the diesel-powered fleets of today to the hydrogen fuel cell-powered fleets of the future. The need for this study was identified through the CTFCA's Heavy Duty Vehicle Fuelling Demonstration Working Group, comprised of representatives from transit operations, bus

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[1] Canadian Urban Transit Association, Canadian Transit 2003 Fact Book

manufacturers, equipment and technology providers, fuel suppliers and governments.

The group noted that, in addition to providing information to urban transit systems, the study would provide a knowledge base for industry to assist them in targeting business opportunities with regard to hydrogen fuel cell-powered transit systems.

In short, Canada's urban transit systems represent:

- An attractive market for the emerging fuel cell industry as it commercializes product;
- An opportunity for governments to meet a significant portion of their green house gas reduction commitments; and
- An opportunity for Canada to be a world leader in the transition to fuel cell-powered transportation.

1.2 METHODOLOGY

The findings presented in this report were derived from visits to 16 urban transit systems across the country, including special environmentally sensitive sites. As well, personal and telephone interviews were conducted with:

- bus manufacturers,
- hydrogen technology suppliers,
- technical training institutions,
- hydrogen industry experts,
- codes and standards developers,
- government agencies both in Canada and abroad, and
- fuel cell bus demonstration projects.

The findings were supplemented with secondary data obtained from a variety of sources, including industry associations, government agencies and industry analysts.

For the detailed methodology, see Appendix 1.

1.3 OBJECTIVES

This study was conducted to determine the challenges and the way forward for Canadian urban transit systems to make the transition to fuel cell-powered bus[2] fleets.

Specifically, it examines the following areas:

- The development of transit bus fuel cell technology in Canada and abroad;
- Canadian regulatory issues at all levels of government, in concert with the U.S. regulatory environment;
- Risk analysis compared to other technologies used in transit operations;
- Specifications for fuel cell-powered transit buses;
- The impact on operations and maintenance facilities;
- The impact on maintenance practices;
- The impact on operations and training budgets;

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[2] "Fuel cell-powered bus" defines all types of buses powered in whole or in part by a fuel cell on board the bus. The two major categories of fuel cell-powered buses discussed in this report are the fuel cell bus (a bus powered by a fuel cell only) and the fuel cell hybrid bus (a bus powered by a fuel cell and one or more other power sources).

- Fuelling infrastructure and technology;
- Supply chain impacts; and
- The need for external communications.

1.4 THE CANADIAN URBAN TRANSIT INDUSTRY

The Canadian urban transit industry serves 91 communities across Canada. Ninety of the 91 urban transit systems (UTSs) are members of the Canadian Urban Transit Association (CUTA), a source of statistical transit data used in this study.[3] Over 41,000 full-time and part-time staff are employed by the industry. By size, urban transit systems in Canada are broken down as follows:

• Group 1, serving populations of >400,000	13 UTSs
• Group 2, serving populations of 150,001 to 400,000	12 UTSs
• Group 3, serving populations of 50,000 to 150,000	32 UTSs
• Group 4, serving populations of <50,000	34 UTSs

Transit passenger service, which includes both bus and rail, is provided to over 2.42 billion riders per year. The combined fleets travel over 815 million kilometres in over 35 million hours, consume about 360 million litres of diesel fuel and over 17 million cubic metres of compressed natural gas (CNG) per year. The average revenue to cost percentage for all systems is 62%, meaning that, on average, various levels of government subsidize transit operations for 38% of their costs. Large urban centres, such as Toronto, have the highest number of rides per capita, (about 90, i.e., an urban resident averages about 90 rides per year). Smaller semi-urban/rural communities have the lowest rides per capita (about 14, i.e., a resident of a smaller community averages about 14 rides per year)[2]. The cost is inversely proportional to the level of ridership; i.e. it costs more to carry a passenger in less dense areas than in dense urban areas.

The Canadian transit industry operates over 12,000 buses of all types across the country. The average age of all active transit buses is 10.85 years and about 7,000 of the buses operating in Canada are over 15 years in age.[4] Approximately 96% of the Canadian transit fleet is composed of standard 12-metre buses. In total, 93.4% buses operate on low-sulphur or ultra low-sulphur diesel, 1.4% on bio-diesel, 2.8% on CNG, and 2.4% on electricity.

In the smaller transit communities, 8-metre, 9-metre and 11-metre diesel buses are common. Some of the companies operating transit in small communities are privately owned; they bid for service contracts with the community management and provide their own vehicles and infrastructure.[5] Other small communities operate their own transit fleets as part of the municipal structure or provincial agency but contract out the operation of these fleets to private operators.[6]

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[3] Canadian Urban Transit Association, Canadian Transit 2003 Fact Book.

[4] Ibid.

[5] For example, the Town of Banff.

[6] For example, the City of Kelowna.

1.5 THE PATH TOWARD FUEL CELL-POWERED BUSES

The transit industry in Canada, and in North America as a whole, has largely embraced diesel engine technology to power its bus fleets. Over the last ten years, several Canadian transit agencies have adopted CNG-fuelled engine technology as a means of reducing emissions. However, reliance on diesel technology is being reinforced with new designs and engine exhaust after-treatments that reduce air pollutant emissions to levels that are competitive with CNG-fuelled engines for many categories of emissions.

Diesel-electric hybrid and CNG-electric hybrid engine technologies are emerging at commercial levels, particularly in New York City where diesel-electric hybrid buses were introduced into regular transit service in 2001. By 2005, New York City transit expects to have 385 of these in service.[7] There are at least 19 other cities in the United States currently experimenting with hybrid buses.[8]

At the present time, fuel cell-powered buses are not available as a commercial product. Fuel cell technology is developing as the industry continues to actively pursue improvements to performance, reliability, costs and standards.

Fuel Cell Bus Demonstration Projects

Between 1991 and 2003, a number of fuel cell bus demonstration projects were implemented. Ballard Power Systems of Burnaby, British Columbia, with funding assistance from federal and provincial/state governments, built and demonstrated several fuel cell-powered buses.

Demonstration projects included:

- A proof-of-concept shuttle bus was built and demonstrated at the Los Angeles Airport;
- A 12-metre transit bus was built and demonstrated at several exhibitions;
- Two in-service transit bus demonstrations were then run in Vancouver, British Columbia, and Chicago, Illinois, between 1998 and 2000. (Both demonstration fleets, each composed of three 12-metre New Flyer-built coaches, operated successfully and proved during the demonstrations that the technology could meet all targeted objectives);
- A next-generation P4 fuel cell-powered bus was demonstrated for a year at SunLine Transit in Palm Desert, California in 2000/2001; and
- A European fuel cell-powered bus demonstration project, consisting of 30 buses, three in each of 10 cities, was launched in early 2003.

These demonstration projects will continue to provide lessons and experiences that will be instructive for fuel cell transit bus operation and maintenance.

As more than 7,000 of the transit buses currently operating in Canada will need replacement over the next 10 years, transit systems represent an attractive market for the fuel cell industry and an opportunity for government to achieve a significant share of its greenhouse gas reduction commitments.

An important issue for the transit industry is how to re-organize and re-structure to be ready for the introduction of fuel cell-powered fleets.

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[7] MTA Report "NYCT Operating Experience with Hybrid Transit Buses", delivered to APTA Bus & ParaTransit Conference, Minneapolis, MN, May 2002.

[8] TCRP Report 59, "Hybrid Electric Transit Buses: Status, Issues, and Benefits", 2000.

2 TOMORROW'S FUEL CELL-POWERED URBAN TRANSIT BUS

The hypothesis set out in the study mandate was: "*As an assumption, fuel cell transit buses will be commercially viable for regular transit service on or around 2010.*"[9]

Technology suppliers and bus manufacturers interviewed in the context of this study state that they do not realistically expect fuel cell-powered buses to be commercially available before 2015. They also report that:

- Fuel cell hybrid systems – combining a hydrogen fuel cell of smaller capacity, a system that recuperates energy from the brakes, and an efficient electric power storage system - are a promising technological development that reduces the consumption of hydrogen without increasing the cost of the power system.
- Other hydrogen technologies may present an intermediate phase to the introduction of fuel cell-powered buses[10] because they will be ready earlier and they will entail fewer operational changes for UTSs while moving fleets towards the hydrogen era.

The following sections describe the characteristics of tomorrow's fuel cell-powered urban transit buses, as described by the technology suppliers and bus manufacturers interviewed in the context of this study and in literature available at the time of the publication of this report.

2.1 FUEL CELL SYSTEM TECHNOLOGY

Considering the present state of advancement of proton exchange membrane (PEM) systems, the rapid progress of their performance, the significant reduction in costs and the intrinsic properties of the technology (i.e. weight-to-power ratio), PEM fuel cells are expected to power the first commercially available fuel cell transit buses.

Two main variations appear possible at this stage:

- A fuel cell system producing approximately 200 kW as the sole power source;
- A fuel cell hybrid system composed of: a smaller fuel cell system (90 kW to 125 kW), batteries or ultracapacitors[11] as a form of electricity storage, and a regenerative braking system that allows the recovery of the kinetic energy normally lost while braking.

The hybrid system may enter the marketplace first for the following reasons:

- Fuel cell hybrid buses consume less hydrogen fuel than fuel cell-powered buses and are therefore less expensive to operate;
- Fuel cell hybrid buses require fewer on-board storage tanks, thereby reducing the weight of the bus (compared to a fuel cell-powered bus) and improving its range and maximum carrying capacity or crush load;

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[9] See Annex A for information pertaining to current fuel cell technology.

[10] Technologies such as hydrogen internal combustion engines (HICE) and HICE-electric hybrid buses were not explored as they exceeded the scope of the study.

[11] Ultracapacitors are relatively new electronic devices, able to store and release large quantities of energy in a short period of time and acting somewhat like a rechargeable battery.

- Decreased fuel consumption translates into smaller and less costly hydrogen production and storage systems on UTS premises;
- Batteries or ultracapacitors are significantly less expensive than fuel cells;
- Regenerative brakes supply an appreciable quantity of energy to recharge batteries or ultracapacitors at very low cost, especially when used with vehicles that make frequent stops, such as urban transit buses; and
- The use of an electricity storage system for peak energy demand (typically during acceleration) and the use of regenerative brakes increase the life of the fuel cell.

Considering these advantages, fuel cell hybrid buses are included in the discussion of fuel cell-powered buses in this report. References made to fuel cells and fuel cell systems in this chapter apply to both fuel cell and fuel cell hybrid buses.

For a general overview of fuel cell system technology, see Annex A.

2.1.1 Cell Performance

Proton-exchange membrane (PEM) cell power densities in fuel cell stacks have improved in recent years, largely due to advancements in membrane/electrode technology. Power densities of 0.30 to 0.35 watts/cm^2 of cell active area have been reached (with near-ambient air delivery pressure). Since the cell components represent a substantial portion of the overall system cost, upgrades in power density will yield tangible cost reductions by reducing the cell component area required for the stack. Evolution in cell technology, mainly from improvements in catalysts and electrolyte-membranes, is expected to yield 0.50 to 0.55 watts/cm^2 by 2015.

2.1.2 Cell Component and Stack Designs

The design and technology developed for items such as bipolar plates, cooling plates, seals, reactant and cooling manifolds, current collectors and compressive loading hardware will be optimized for low-cost manufacturing. The stated goal is to reduce the cost to $66/kW[12] by 2015.[13]

2.1.3 Balance of Plant

As discussed in Annex A, a number of auxiliary components such as heat exchangers, interface modules, inverters and torque converters, are required to support stack operation. These currently constitute a major cost burden for the fuel cell systems built in low volumes. Tomorrow's fuel cell system will benefit from factors such as low-cost designs and opportunistic component selection to take advantage of existing high-volume sales.

2.1.4 Fuel Cell System Design

Fuel cell system design improvements will result in a marked preference for modular "plug & play" interconnected components. This approach will yield a system where components are easy to remove and install quickly, driving maintenance costs well below current levels. Resulting cost savings have been taken into consideration in the cost forecasts discussed in section 5.

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[12] This $66 (U.S. $50) benchmark, first published in a Merrill Lynch analysis of the fuel cell industry, reflects the cost of an automotive internal combustion engine. U.S. Department of Energy objectives were set at $59/kW (US$45) for 2010 and $40/kW (US$30) for 2015, including hydrogen storage.

[13] Unless otherwise stated, all currency figures in this report are in Canadian dollars. Where the costs were converted from U.S. dollars, the FX exchange rate used was CDN$1.33 to US$1.00. Dollar figures quoted for 2015 and beyond are expressed as "2015 dollars".

2.1.5 On-Board Fuel System

A number of fuel options are available to fuel cell-powered bus designers. These include "conventional" liquid fuels,[14] liquid hydrogen, gaseous hydrogen and gaseous hydrogen from metal hybrides.

Conventional liquid fuels belong to the hydrocarbon and alcohol families, both of which contain hydrogen. Accessing the hydrogen involves reformation of the feedstock and purification of the hydrogen stream on board the bus. For UTSs, conventional fuels are the simplest to procure, handle and store. However, their use in the context of fuel cell power generation would have negative repercussions on the performance, size, weight, cost, durability and reliability of transit buses.

This leaves hydrogen, either liquid or gaseous, as the preferred option for the fuel cell system manufacturer. The use of liquid hydrogen (LH_2) on board offers the possibility of storing large quantities of hydrogen in a relatively small space. As well, hydrogen purity and perceived dangers associated with high-pressure storage are not a consideration with this form of hydrogen. However, the problems associated with LH_2 on board include the higher cost of the fuel,[15] the cost of the additional fuelling station equipment required (vapourizer, cryogenic or vacuum tank, booster compressor) and the complexity of operating LH_2 fuelling stations.

Currently, gaseous hydrogen is the most appropriate fuel for the fuel cell system because additional power system components (e.g., reformers) are minimal. Gaseous hydrogen coupled with a fuel cell constitutes a "direct hydrogen fuel cell". The performance of a fuel cell stack using pure hydrogen is higher than that of one using diluted hydrogen, especially if the latter contains impurities. The use of pure gaseous hydrogen translates into a smaller, lighter, more efficient, lower cost and longer life fuel cell.

Applications using metal hydrides[16] are being developed but, given their weight and cost, they are not currently being considered for transit applications.

2.1.6 Durability

Fuel cell technology developments are currently focusing on increasing cell/stack power density and assuring adequate durability (and reliability) in an urban transit bus environment. Large swings in electrical load, internal temperature variations within the stack, and shutdowns (at least daily) are being factored into component design and operating conditions. Compromises are necessary between performance and durability. Performance/endurance characteristics of the fuel cell are monitored closely in fuel cell bus demonstration projects to gain valuable feedback for technology developers.

In 2015, it is expected that the life span of fuel cell stacks will allow for at least four years of continuous bus service (10,000 to 15,000 hours).

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[14] Diesel, gasoline or other liquid fuel such as methanol and ethanol.

[15] Energy equalling 30-40% of that in the fuel is needed in order to cool the hydrogen to the point of liquefaction.

[16] A hydride is a chemical compound involving hydrogen and a metal. It acts as a "hydrogen sponge", absorbing and releasing hydrogen with variations in temperature.

2.1.7 *Manufacturing and Supply Issues*

The challenges involved in commercializing the technology are multi-faceted, but all relate to making the fuel cell power system affordable and durable. The current fuel cell system cost is considered to be more than an order of magnitude beyond what will be acceptable in the marketplace. It is clear that no single breakthrough is likely to render the fuel cell-powered bus competitive with existing diesel technology. Advancements in technology and engineering over many fronts will be necessary.

Furthermore, the availability of state-of-the-art fuel cell technology will not be sufficient to attain competitiveness in the fuel cell-powered bus application. A low-cost manufacturing methodology must be established and high-volume production must be realized to attain the necessary per-piece component costs. Accordingly, it is necessary that fuel cell component manufacturing for transit bus applications dovetail with that of other heavy-duty fuel cell applications requiring high volume.

In terms of supply, bus manufacturers and urban transit operators claim that at least two companies with credible track records and warranties must be offering fuel cell systems under acceptable conditions by 2015 to allow market entry of buses equipped with that technology. This will create a market situation where transit systems will be able to compare bids and bus manufacturers will be able to build complete vehicles equipped with fuel cells on their own assembly lines, with warranties and service offered under terms as favourable as those now in place for diesel buses.

2.2 ELECTRICITY STORAGE SYSTEM

Urban transit buses powered by a combination of diesel engine and electric batteries are already being marketed. In these diesel-electric hybrid vehicles, batteries are charged both by the diesel engine and by regenerative braking. Their main advantages are the reduced consumption of fossil fuel and the reduced emission of pollutants and greenhouse gases. These vehicles are enjoying commercial success, even though their price is nearly two-thirds higher than that of conventional diesel buses (approximately $665,000 versus $400,000).

Batteries used for automotive propulsion are presently developing at a fast pace, with new products and applications continually emerging. However, the most promising electric storage and power technology for fuel cell hybrid bus propulsion appears to be ultracapacitors. While batteries store electricity by converting it to chemical energy, capacitors store electricity as it is, without carrying out any conversion. Although the storage capabilities of capacitors used to be much smaller than that of batteries, recently developed capacitors have much more storage capability.

Electric Double Layer Capacitors (EDLCs) are often called super or ultracapacitors. Ultracapacitors present the following advantages:

- Charge/discharge is faster than batteries;
- No chemical reaction;
- Longer material life;
- Higher cycle life than batteries (life is >100,000 cycles);

- Ability to deliver frequent pulses of energy without any detrimental effects (unlike batteries that experience reduced life if exposed to frequent high power pulses); and
- Greater voltage range than batteries.

But ultracapacitors also have their weaknesses:

- Lower specific energy than batteries; and
- No long-term energy storage.

Ultracapacitors, used in conjunction with batteries and/or fuel cell and regenerative brakes, provide the optimal combination of energy for both quick bursts and long-term energy storage.

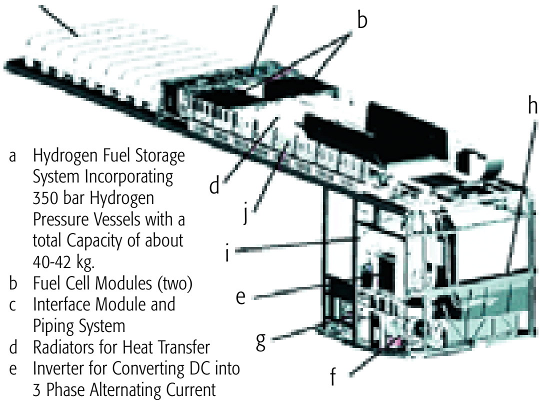
Ultracapacitors are already available commercially for applications requiring this type of power. They are now being refined for eventual use in vehicles. Their low cost and weight will make them a suitable option for combination with fuel cell systems and regenerative brakes. They are expected to last at least ten years with little or no maintenance.

It is currently expected that the fuel cells required for fuel cell hybrid buses will have a capacity of 90 to 125 kW.[17] Buses powered exclusively by fuel cells currently require 200 kW fuel cells.

2.3 ON-BOARD FUEL STORAGE TECHNOLOGY

According to technology suppliers and bus manufacturers, in order to attain adequate range, tomorrow's fuel cell-powered buses will carry up to 50 kg of gaseous hydrogen fuel on board at a pressure of at least 350 bar.

Figure 8. On-Board Fuel Storage System



a Hydrogen Fuel Storage System Incorporating 350 bar Hydrogen Pressure Vessels with a total Capacity of about 40-42 kg.
b Fuel Cell Modules (two)
c Interface Module and Piping System
d Radiators for Heat Transfer
e Inverter for Converting DC into 3 Phase Alternating Current
f Auxiliary Gear Case and Electric Drive
g Automatic Torque Converter
h Fuel Cell Control Device
i Air Supply System
j Cooling System

The HY-205 P5-1 Drive Train Main Subsystem Locations

Storage tanks capable of sustaining 700 bar of pressure and beyond are currently being developed and tested in laboratories. The development of 700 bar storage tanks will be a positive contribution if they make a significant impact on weight reduction in other areas.

It is expected that the first generation of commercial hydrogen fuel cell transit buses will store high purity hydrogen on board, in gaseous form, in high-pressure tanks that are similar to those presently used on demonstration buses and to those currently found on CNG-powered transit buses.

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[17] The preliminary design of Hydrogenics' fuel cell hybrid urban transit bus provides for 125 kW of ultracapacitors and a 125 kW fuel cell.

Currently storage tanks have a capacity of approximately 55 kg of hydrogen, stored at a pressure of approximately 350 bar. This capacity and pressure do not provide demonstration buses with the same range as present-day diesel buses. In the future, it is expected that technical improvements in fuel cell performance will provide commercial fuel cell-powered buses with a range comparable to that of today's diesel transit buses.

2.4 FUEL CELL TECHNOLOGY IN URBAN TRANSIT BUSES

2.4.1 Technical Specifications

The concept of operations (see Appendix 2) developed for the purpose of this study describes the technical specifications of a commercial version of the typical urban transit fuel cell bus. These specifications are supported by information provided by technology suppliers and bus manufacturers.

The basic bus design, specifications and configurations of the first commercial transit buses equipped with fuel cell technology are expected to be similar to those of present 12-metre, low-floor buses adapted for compressed natural gas (CNG) or those of the buses used for fuel cell bus demonstrations.

Fuel Cell Buses

Fuel cell bus configurations with engine/transmission systems vertically positioned in a corner at the back of the passenger compartment have proven to be particularly well suited to adaptation for fuel cell operation.

Passenger compartments of commercial fuel cell transit buses will not be noticeably altered from present diesel bus set-ups.

Fuel cell buses will be heavier than diesel buses. Present demonstration fuel cell buses carry more weight on front axles than that allowed by on-the-road regulations, mainly because of the hydrogen tanks on the rooftop. This, however, does not seem to present operational difficulties. In the first commercial vehicles, total weight will be more in line with axle capacities.

In the absence of standards specifically for fuel cell buses or their components, vehicles currently in use are permitted to use standards for CNG buses. It is expected that these CNG-related codes, complemented by hydrogen-specific safety and operating standards, will be used as models for hydrogen codes for future fuel cell-powered buses. It is also expected that hydrogen specificity will be incorporated into standards well before UTS fuel cell-powered bus fleets are procured.

Fuel Cell Hybrid Buses

Fuel cell system technologies are evolving quickly. In the meantime, the current shortcomings of fuel cell buses suggest that fuel cell hybrid buses will act as an intermediate or definitive step prior to the introduction of commercial fuel cell-powered buses. Some of the most expensive parts of a fuel cell bus are the stack and related equipment. Hybridization, by nature, reduces the core engine size and therefore minimizes the expensive components in a fuel cell vehicle.

It is too early in the development of fuel cell hybrid buses to predict their future configuration with a high degree of confidence. It can, however, be assumed that a commercial model would present technical specifications similar to those of the fuel cell buses described in this section and in the concept of operations (Appendix 2). On-board hydrogen storage will be similar in design to that used in fuel cell buses, although the quantity of hydrogen required will be significantly lower.

2.4.2 Performance/Operating Characteristics

Within the next several years, fuel cell efficiency and available power should allow fuel cell-powered buses to equal or surpass the existing requirements for 12-metre diesel buses.

Technology providers and industry experts predict the fuel cell-powered buses in 2015 will have the following operating characteristics:

- A range of 500 km;
- Maximum passenger capacity between 60 and 70 (comparable to the maximum load now carried by current buses in most UTSs);
- Braking distance similar to that of current buses;
- The same or better acceleration, speed and hill climbing capability;
- The same fuelling time (eight minutes or less);
- Reliability equal to or better than current buses;
- A gross vehicle weight of approximately 18,000 kg;
- A curb vehicle weight of approximately 14,300 kg;
- The same dimensions as those of buses in use today, with no additional limitations on turning radius, approach and departure angles, and ground clearance; and
- A noise level less than that of current buses.

These operating characteristics should allow urban transit systems to provide current levels of service with little or no adjustments to planning and operations. An exception may be the few transit routes that exceed 500 km.

The reliability of commercially available fuel cell-powered buses should be equal to or better than that of conventional diesel buses because of the nature of the fuel cell power system, with fewer moving parts, an electrochemical power generation system, solid-state technology and low-maintenance electric motor technology.

3 TOMORROW'S FUEL CELL TRANSIT PROPERTY

3.1 FACILITY REQUIREMENTS

3.1.1 Garage Space

Fuel cell-powered bus fleets will require the same number of maintenance bays as those required for a standard diesel or compressed natural gas (CNG)-fuelled bus fleets. However, there must be physical separation of specialty bays, such as welding and grinding, body, tire, battery charging and brake bays, from the garage area in which preventive maintenance inspection and repairs of the buses take place.

In addition to the physical separation of these bays, the entire facility must include:

- Hydrogen leak detection systems;
- Fire detection and suppression systems;
- Electrical classification for hazardous locations;
- Positive ventilation;
- An emergency disconnect apparatus that automatically shuts down all unessential electrical equipment in the event unsafe levels of hydrogen are detected;
- Designated parking and storage areas (these must be heated to above 5°C in cold climates);
- Ignition-free space heating equipment; and
- Removal of all electric panels from maintenance areas in which hydrogen will be present.

There is an ongoing Canada/United States program to develop a sound engineering basis for codes and standards that impact the extent to which the above risk mitigation procedures have to be implemented as well as the implementation process. An upcoming International Energy Agency Annex on Hydrogen Safety will also provide comparative data on hydrogen versus conventional fuels to ensure that the risk tolerance required for hydrogen is compatible with that accepted for fuels with which the public is already familiar.

3.1.2 Safety Systems

Although normal discharges of small quantities of hydrogen into a large facility are of no concern, fleet storage, service and refuelling facilities will require both detection and ventilation systems to deal with potential discharges of large quantities of hydrogen.[18] Ceilings should be sloped or contain cavities that direct any hydrogen spills to logical discharge points.

Hydrogen detection and control can be achieved by placing a ventilation discharge fan with hydrogen sensors at each discharge point. Normal air discharge rates should be about 0.3 $m^3/min/m^2$ of floor area.

To address concerns of heat loss in cold weather, external air inlets are placed at the bottom of the wall closest to the location of potential hydrogen discharge and extended inward in duct work along the floor area. Using this approach, a discharge fan can evacuate a selected floor area of a large room. The hydrogen detectors in the fan outlets should be rated for operation in Class 1, Zone 1 environments, control two-speed "sparkproof" fans, and have two pre-set alarm limits.

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[18] There are other means of eliminating unwanted hydrogen in a bus depot. For example, passive autocatalytic recombiners (PARs) have been used in the nuclear industry and could be adapted for UTS use in the future. Although it has been proven that PARs are not affected by atmospheric contaminants that may be present in bus garages, the engineering required to direct the potential hydrogen gas to the PAR has not yet been developed. Should this development be successful, it would reduce the costs associated with winter ventilation and the associated loss of heat.

At 10% Lower Explosive Levels (LEL), the ventilation system fan speed should double, while at 20% LEL, the electricity should be cut off to any hydrogen equipment in the facility.

All lights should be suspended far enough beneath the ceiling so as not to be immersed in hydrogen in the event of a hydrogen spill. This approach also allows all lights to be declassified.

Normal water-based fire suppression sprinklers, triggered by smoke detectors, are appropriate for facilities dealing with gaseous or liquid hydrogen.[19]

3.1.3 Specialty Equipment

Fuel cell-powered buses will have a curb weight of about 15 tonnes. Hoists used in maintenance bays must have the capacity to lift this weight with a sufficient margin of safety. As the fuel cell-powered bus will be about 3.7 metres tall, it will be essential to ensure there are no overhead obstructions once hoists are raised to the optimum height to allow servicing below the bus. The height will be between 1.5 and 2.0 metres off the ground.

As there is a requirement to service fuel storage systems and other components potentially located on the roof of the bus, all maintenance bays should be equipped with fall protection equipment and have access to portable gantries to allow maintenance personnel to safely access and work on the roof. Overhead lifting capability should also be provided by way of a track-mounted hoist or hoists that can be shared among bays.

The practice of using pits for maintenance, abandoned by many transit systems a few years ago because of the danger of fuel leakage, can be brought back to service fuel cell-powered buses (due to the fact that hydrogen is lighter than air). This less expensive way of reaching components located underneath the bus could save costs.

Bus wash facilities that do not have adjustable roof wash roller brushes will have to be modified to accommodate the increased height of fuel cell-powered buses.

3.1.4 Specialty Service Bays

A “clean room,”[20] centrally located and accessible from all maintenance and repair bays, will be required to ensure that the fuel cell stacks are not contaminated.

Between two maintenance bays or in each one of them, a clean work bench will be required to allow component repairs to take place without contamination.

A hydrogen venting area should be installed in the facility to allow the safe venting of hydrogen to proscribed on-board storage tank safety pressures before vehicles are brought into the garage for maintenance. This facility could be situated near the fuelling area to allow the vented hydrogen to be recycled and must be equipped with the required bus grounding capability.

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[19] Although open metal hydrides require special type D fire extinguishers and must not be exposed to water, this should be of no concern in a vehicle fuelled through hydride technology as the active metal hydrides are stored in durable metal containers.

[20] A “clean room” is one that is separated from the general work area and has its own ventilation system. It allows fuel cell system components that channel air, hydrogen or coolant to or from the fuel cell stacks to remain free from contaminants.

3.1.5 *Spatial Implications*

Depot parking and circulation space for fuel cell-powered bus fleets will be the same as that required for diesel or CNG fleets, but the space required for fuel facilities may increase.

During the transition period, UTSs will likely require both hydrogen and conventional fuel facilities. Hydrogen fuel tanks will be located above ground and will require more ground space than diesel tanks located underground. This may pose a problem for urban transit depot sites that are filled to capacity with little room for expansion.

Studies are underway to establish criteria for hydrogen codes as well as quantitative risk assessment methods for specific sites such as UTS depots.

3.1.6 *Trades and Maintenance Implications*

Facilities/building maintenance trades will require skills upgrading that includes the testing and replacement of hydrogen sensors as well as fire detection and suppression systems in the building. The training cost is expected to be minimal (no more than one day per person). The cost of replacing hydrogen sensors should be included in facility maintenance budgets and is expected to be approximately $10,000 to $15,000 per building per year - assuming one maintenance building and one parking facility per depot.

Maintenance of the fuelling infrastructure should be contracted to the gas merchant[21] or the fuelling system manufacturer, where possible. If this is not possible, it will be necessary for the maintenance personnel to be high-pressure gas certified and to have the necessary training to repair and overhaul all fuel system components. Depending on the type of fuelling system selected, ten days of training per tradesperson or the hiring of additional tradespeople may be required.

3.1.7 *Facility Cost Implications*

Facility capital costs will be dependent on the status of existing maintenance and parking facilities. While older buildings will require upgrading, facilities that are designed to meet existing CNG standards will need minimal modifications, namely:

- Replacement of methane-detection systems with hydrogen-detection systems; and
- Upgrading of air handling equipment, where this is necessary to meet hydrogen safety requirements.

Other requirements will include the space to install the type of hydrogen refuelling system that has been chosen. Because many of the existing depots in Canada are already at maximum capacity, some systems will have no choice but to build a new hydrogen facility on a new site. It is estimated that a new facility could be built for an average of $1,300 to $1,400/m^2 for maintenance garage and parking areas (not including equipment) and $2,700/m^2 for finished areas.

Facility maintenance costs are estimated to increase by about $2.70/m^2/year to accommodate the maintenance of hydrogen-related safety equipment such as sensors and heating and ventilation systems.

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[21] Currently, only industrial gas merchants supply hydrogen commercially. Other suppliers may appear in the marketplace in the future. Shell, for example, has declared its intention to play a role in hydrogen distribution. In this document, the term "hydrogen fuel supplier" includes gas merchants as well as other potential hydrogen fuel suppliers.

3.2 FUELLING INFRASTRUCTURE REQUIREMENTS

There are now and will continue to be a variety of hydrogen fuelling system technologies available to transit bus fleet managers. The choice of a particular design for UTS fuelling infrastructure depends on:

- The size of the fleet and the number of buses at each fuelling location;
- The price of hydrogen by source;
- The degree of comfort of the UTS with new technologies;
- The space available to the UTS at each fuelling site, indoor and/or outdoor;
- The location of the fuelling facilities and its surrounding environment; and,
- The financial policies and resources of the UTS and its preferences concerning capital investment and cost of operation.

It is therefore difficult to generalize as to the extent of changes required by any given UTS. Firstly, the current conditions of UTSs vary widely from off-site fuelling of diesel buses to modern on-site CNG fuelling facilities. Secondly, the extent of the changes required also depends on the fuelling option selected by the UTS for its fuel cell-powered bus fleet. Each UTS will need to make site-specific assessments of the most appropriate fuelling approach.

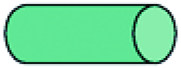
The preceding diagram summarizes the various combinations of fuelling equipment that can be used on a UTS site. These components are used to provide a source of hydrogen, to store it, and to bring it to a pressure of up to 430 bar to enable its dispensing into on-board storage cylinders at a pressure of 350 bar. One bar is the equivalent of 14.50 lbs/square inch.

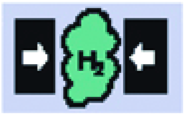
3.2.1 Fuelling Options

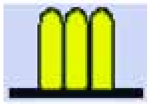
The major fuelling components presented above are discussed in detail in Annex B.

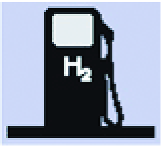
Four configurations from the above possibilities are deemed the most suitable for the range of UTSs in the Canadian industry. Two off-site sourcing options and two on-site production modules (water electrolysis and reformer-based hydrogen generators) are discussed in the following pages.

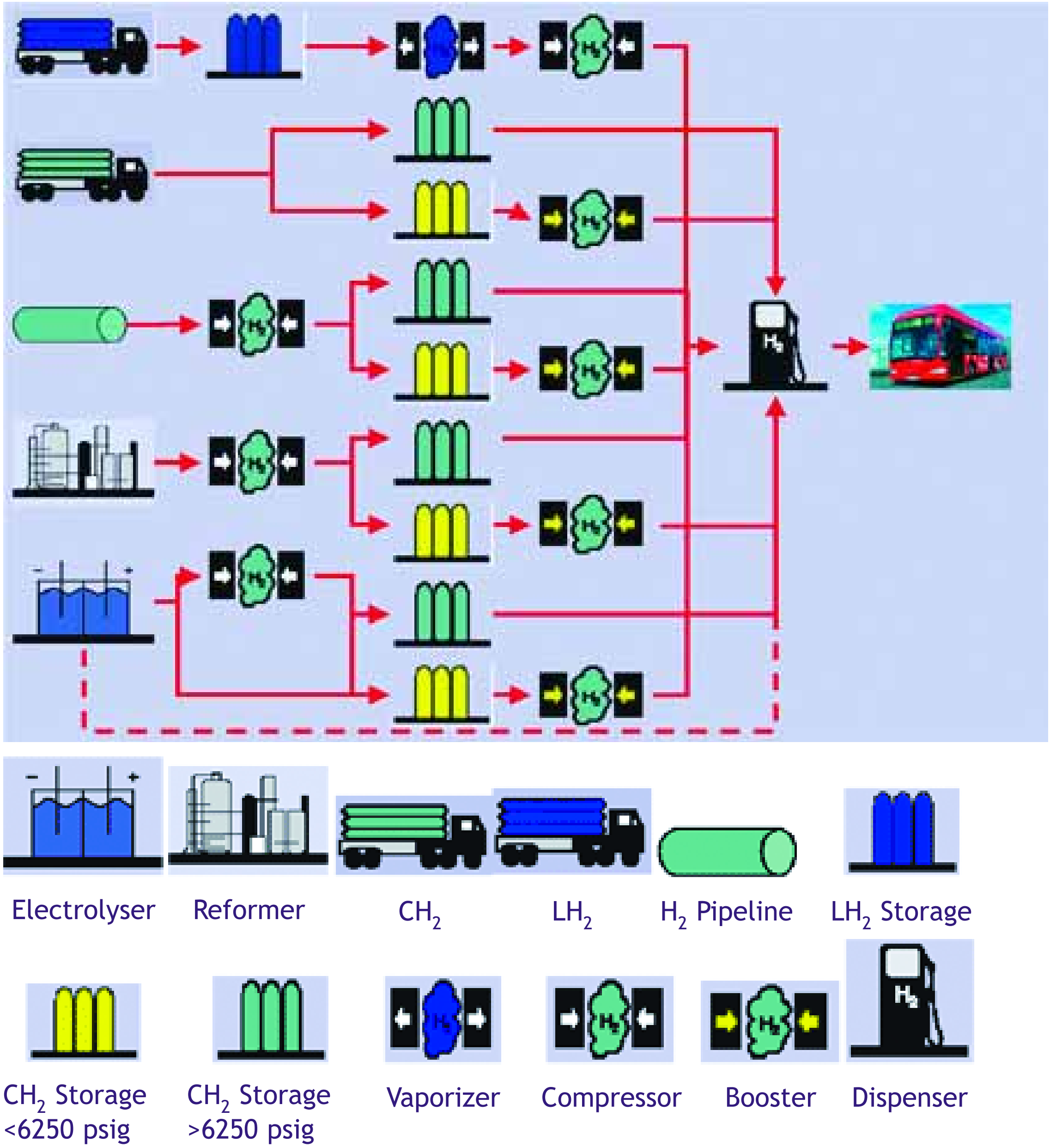
Fuelling Option 1:
Off-Site Sourcing of Gaseous Hydrogen
Large depots located in restricted areas (whether by physical space or residential circumstance) have limited hydrogen supply options. The size and relative complexity of the production equipment required to serve their needs exceeds the investment and efforts that can be expected from a transit system.


H_2 Pipeline


Compressor


CH_2 Storage
<6250 psig

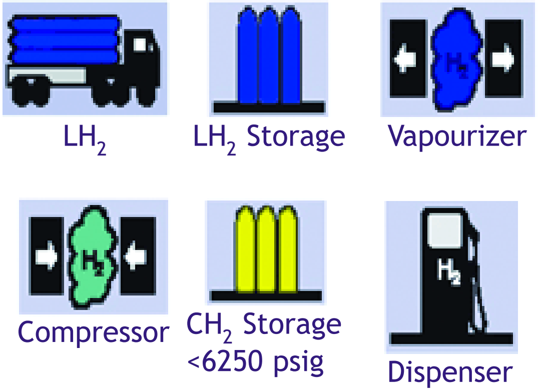

Dispenser


Electrolyser
Reformer
CH_2
LH_2
H_2 Pipeline
LH_2 Storage
CH_2 Storage <6250 psig
CH_2 Storage >6250 psig
Vaporizer
Compressor
Booster
Dispenser

Off-site production of hydrogen combined with pipeline delivery will be the most economical option open to these UTSs. The only equipment required at the UTS site would be compressors, relatively small storage tanks for high-pressure hydrogen,[22] dispensers and meters.

The availability of hydrogen pipelines, or the proximity to hydrogen by-product in quantities sufficient to supply the fleet by pipeline, should be investigated as an initial option. Construction of a large off-site hydrogen production facility and a pipeline may be necessary to fill the needs of very large UTSs.

The most appropriate approach, in this case, will likely be a partnership or a long-term agreement with a gas merchant. With this type of agreement, all equipment required can be supplied, installed and maintained by the gas merchant who will also bring the necessary experience and expertise to the project. The price of hydrogen would then include all peripheral and associated costs.



Fuelling Option 2:
Off-Site Sourcing of Liquid Hydrogen (LH_2)
The supply scenario for this option entails the daily (or once every second day) delivery of LH_2, produced off-site, likely by a gas merchant, and trucked to the UTS fuelling installations. Given the use of liquefied gas, this option involves differences in technology[23] at the UTS site. A LH_2 vacuum tank will be needed for storage. A vapourizer and a booster/compressor will bring the gaseous hydrogen to the dispenser where it will be metered as the refuelling takes place.

Here again, all equipment required will be supplied, installed and maintained by the gas merchant at a cost included in the price of hydrogen. The UTS must supply adequate space, easy access for replenishment, and some minimal infrastructure (e.g., electric connection to the grid) at its own expense. Dispensers and meters can be installed indoors or outdoors, as required.

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[22] Pipelines usually operate at very low pressure and would be too onerous if constructed to sustain 430 bar. For this option, on-site, high-pressure vessels will be required because compression on-board storage would take too much time for the standard refuelling process of a UTS.

[23] There are specific safety considerations associated with LH2 handling because of the extreme cold temperatures involved.

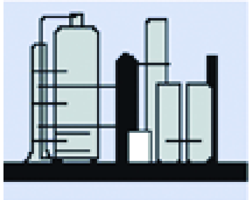
Fuelling Option 3: On-Site Reformer-Based Production

Reformers provide a third option for UTSs with easy access to bulk natural gas. In the case of methane reformers,[24] the technology that will be available to operators of small to medium-sized fuelling facilities in 2015 will be relatively inexpensive and easy to operate, will require a modest space, and will produce hydrogen at a competitive price.

Methanol reformers will also be available but will require the use of an additional on-site reservoir[25] for methanol storage. Methanol reformers have traditionally been custom made but packaging of this process is expected by 2015. Multi-fuel reformers will also be perfected by 2015, giving users the choice of natural gas, liquid propane gas or methanol as a feedstock and thus providing them with the flexibility to use the least expensive available fuel.

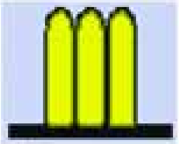
The configuration of Option 3 systems will include a packaged reformer (see illustration) with adequate production capacity, a purification system,[26] a compressor, a 430 bar storage ASME[27] reservoir[28] (or a 700 bar carbon fibre wrapped reservoir system) and a dispensing and metering system.

This configuration could be purchased and operated by the UTS directly. An energy provider such as a gas utility or an industrial gas merchant could also supply the package and factor the cost of equipment into the price of hydrogen. The price of hydrogen from this type of system would be largely dependent on the price of natural gas.

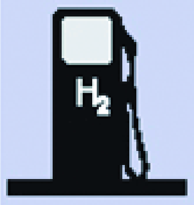


Reformer

Compressor



CH_2 Storage
<6250 psig



Dispenser

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[24] Conventional reformers are cumbersome, noisy, and often require much more space than is available on UTS depot sites.

[25] Current diesel reservoirs are usually adequate for methanol storage.

[26] Reformers produce hydrogen with impurities that are incompatible with PEM fuel cells.

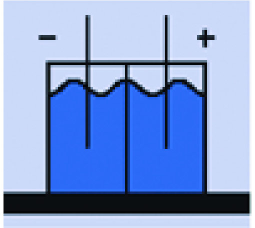
[27] American Society of Mechanical Engineers

[28] Currently there are no large high-pressure pre-built (packaged) reservoirs available on the market. They have to be custom-made to ASME specifications. The U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Program objectives for 2015 include *"the development and verification of low-cost, off-board hydrogen storage systems, as required for hydrogen infrastructure needs to support transportation, stationary and portable power markets by 2015."*

Fuelling Option 4:
On-Site Electrolysis-Based Production

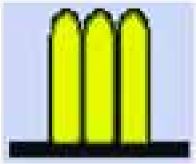
The system configuration of a water electrolysis hydrogen-generator-based fuelling station is similar to the previous option as it includes one or several electrolysis stacks adding up to adequate production capacity, a compressor, a 430 bar storage reservoir, and a dispensing and metering system.[29]

The industry anticipates delivering electrolyzers with considerably larger stacks by 2015, thereby making this option competitive with natural gas or methanol reforming. In this particular case, the cost of electricity is the single most important element affecting the total cost of hydrogen.

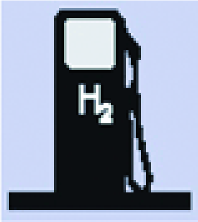


Electrolyzer

Compressor



CH_2 Storage
<6250 psig



Dispenser

3.2.2 Hydrogen Fuel Cost Components

Cost elements were developed for gaseous hydrogen delivered at the nozzle at a pressure of approximately 430 bar. All costs were calculated on a "per kilogram of hydrogen" basis, including capital and operating costs required by each production technology. In selecting fuelling cost parameters, two scenarios were considered, summarized as follows:

DOE Scenario:
After much consultation with the industry, the U.S. Department of Energy (DOE) published a Hydrogen, Fuel Cells & Infrastructure Program in June 2003. The program outlines goals and objectives reaching as far as 2015. The technical targets provided in the DOE publication were used as working hypotheses and as the basis for this scenario.

Conservative Scenario:
A second set of forecasts was developed from the U.S. DOE data to provide a more cautious estimate of anticipated 2015 costs.

The conservative scenario varies from the DOE scenario with respect to the following points:

- It assumes a higher price of energy (natural gas and electricity), given the current circumstances and trends;
- It takes into account new technological improvements such as electrolytic compression to 430 bar;
- It takes into consideration a longer lifecycle of electrolyzers for depreciation purposes;

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[29] A feed-water treatment system may be required if water quality does not meet the electrolyzer manufacturer's requirements.

- It accounts for 3% per annum inflation from 2010 to 2015.

Under these two scenarios, only three of the fuelling options described in section 3.2.1 were considered:

- Merchant LH_2 delivery (Option 2)
- On-site reforming of natural gas (Option 3)
- On-site water electrolysis (Option 4)

Cost elements for pipeline delivery of gaseous hydrogen (Option 1) were not developed, given the wide range of available factors to be considered, including the source of product hydrogen. Costs were not developed for reforming of alcohols or other hydrocarbon sources, as they were not included in the original four fuelling options.

In the following tables, the components in the cost of producing hydrogen vary from one technology to another, as some parts of one process do not apply to another process. For example, natural gas reforming (which includes the cost of natural gas and the operation of the process) is not required if water electrolysis is used. When cost components are not applicable to a given option, this is indicated by “n/a”.

The choice of a fuelling option will largely depend on the cost of feedstock, namely electricity or natural gas, as the former accounts for over 85% of the total cost of hydrogen and the latter accounts for nearly 65% (as indicated in the preceding tables). In Canada, natural gas prices are generally more volatile than electricity. As energy costs vary from one province to another, UTSs will need to consider the local cost and availability of energy in order to choose their source of hydrogen. It is likely that water electrolysis will be more attractive in provinces where hydroelectricity is prominent, such as Québec, Manitoba and British Columbia.

Table 1a. Cost Components of Hydrogen Fuel - DOE Scenario ($/kg)

Cost Components	**Option 2[30] Merchant LH_2**	**Option 3 On-Site Reformer**	**Option 4 On-Site Electrolysis**
Natural gas reforming	1.09	1.09	n/a
Cost of electricity	n/a	n/a	2.39[31]
Purification	0.04	0.04	n/a
Compression	n/a	0.32	0.21
Liquefaction	0.40	n/a	n/a
Handling, storage gasification, and dispensing	0.80	0.14	0.08
Delivery from a central production location to station	0.93	n/a	n/a
Other costs[32]	0.46	0.40	0.64

Source: MARCON-DDM HIT, 2004

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[30] Merchant gas prices were estimated using the cost of centrally reforming large quantities of natural gas without carbon sequestration and transporting it to the bus depot in liquid form.

[31] DOE calculations are based on $0.049/kWh (US$0.035/kWh) of electricity (FX exchange rate: CDN$1.33 for US$1.00)

[32] Includes site preparation, controls, capital costs, balance of plant, rent, utilities, maintenance, etc.

Table 1b. Cost Components of Hydrogen Fuel - Conservative Scenario ($/kg)

Cost Components	**Option 2[29] Merchant LH_2**	**Option 3 On-Site Reformer**	**Option 4 On-Site Electrolysis**
Natural gas reforming	2.42	2.42[33]	n/a
Cost of electricity	n/a	n/a	4.78[34]
Purification	0.04	0.04	n/a
Compression	n/a	0.37	0.23[35]
Liquefaction	1.19[36]	n/a	n/a
Handling, storage gasification, and dispensing	0.93	0.17	0.09
Delivery from a central production location to station	1.08	n/a	n/a
Other costs[37]	0.46	0.46	0.53

Source: MARCON-DDM HIT, 2004

Operational Considerations

Most UTSs prefer to have a security reserve of fuel on-site. While this is possible with hydrogen, it may be preferable (for capital cost or available space reasons) to negotiate emergency supply contracts with a gas merchant, or, for multi-garage UTSs, to add enough to each fuelling station to amount to a one-day supply for one garage.

3.2.3 Staff Training

While UTS staff using hydrogen fuelling systems will require specific training, hydrogen production and dispensing equipment suppliers do not foresee a need for staff to obtain certification training.

The maintenance of hydrogen equipment should be handled through a service contract with the fuel or fuelling technology supplier.

The most significant aspect of training will be safety. This can be conducted through the UTS Health, Safety and Environment (HSE) program. Safety training should be mandatory and should include Workplace Hazardous Materials Information System (WHMIS), Material Safety Data Sheets (MSDS), and the provision and use of specialized safety equipment and materials. It should address the safety of staff, clients and the general public and identify ongoing training requirements.

[33] Based on the price of natural gas in 2015, forecast at $0.73/m^3 (US$0.55/m^3) or $14.50/MMBtu (US$10.90/MMBtu) (FX exchange rate: CDN$1.33 for US$1.00). Source: Canadian Enerdata Ltd.

[34] Average industrial price of electricity in 2015, forecast at $0.140/kWh (US$0.105/kWh) by American Water Works Association. (FX exchange rate: CDN$1.33 for US$1.00).

[35] Assumes electrolytic compression at 430 bar where the only additional cost is related to an additional 0.2 kWh of electricity per cubic meter produced. Source: Summary of electrolytic hydrogen production, Johanna Ivy, NREL, April 2004, Appendix A.

[36] Source: Air Liquide Canada.

[37] Includes site preparation, controls, capital costs, balance of plant, rent, utilities, maintenance, etc.

3.3 THE UTS REGULATORY ENVIRONMENT

The Canadian model safety codes that currently form the basis of regulations affecting urban transit facilities are the:

- Canadian Electrical Code (CSA Standard C22.10);
- National Gas Codes (CSA Standards B149.1 and B149.2);
- National Building Code of Canada;
- National Fire Code of Canada;
- National Plumbing Code of Canada; and the
- Boiler, Pressure Vessel and Pressure Piping Code (CSA Standard B51).

If regulations for hydrogen were to be extrapolated from current analogous CNG codes, the space requirements for hydrogen refuelling might be significantly larger and might prohibit hydrogen from being produced and used economically on transit depot sites. This is a high-profile issue in the development of hydrogen codes and standards for hydrogen now underway.

3.3.1 Maintenance and Garage Facilities

The Canadian regulatory framework that controls the construction and operation of storage, maintenance, fuelling and repair facilities for urban transit fleets is based primarily on the above six model safety codes. These codes form the basis for most provincial, territorial and local regulations. Additional regulations that control the operation of transit vehicles but are not included in these six codes are under the authority of Transport Canada.

3.3.2 Fuelling Facilities

The above regulations also apply to indoor and outdoor fuelling facilities. As with all potentially flammable substances, the safe incorporation of hydrogen into an urban transit facility can be achieved by controlling the three elements required for combustion: ignition sources, combustibles and oxidants. The safe use of hydrogen includes:

- Prevention and control of leaks by designing facilities appropriately, incorporating detection and automated ventilation equipment to preclude the formation of combustible mixtures should accidental leaks occur, and maintaining proper safety procedures for handling them;
- Declassifying any hazardous locations by appropriate ventilation and eliminating ignition sources in any hazardous locations that cannot be declassified;
- Properly training all personnel in the appropriate procedures for handling hydrogen; and
- Performing an independent, third party safety audit of new facilities.

Performing these tasks for hydrogen systems does not present any significant problems for the proposed fuel cell-powered urban transit bus system.

3.3.3 Hazardous Materials Handling and Storage

Future hydrogen-ready transit facilities will require the same hazardous materials handling and storage installations as those currently mandated.[38]

While hydrogen is currently classified as a hazardous material, its emerging use as a fuel has created an interest in having hydrogen classified as a fuel. If and when this reclassification occurs, the handling and storage of hydrogen in UTS facilities will involve procedures similar to practices for familiar contemporary fuels such as CNG.

3.3.4 Risk Mitigation

The risks associated with hydrogen fuel on UTS sites can originate from: overpressure (explosion), thermal conditions, cryogenic conditions (for liquid hydrogen) and asphyxiation. (Although hydrogen is not poisonous, one cannot survive in a pure hydrogen atmosphere due to oxygen starvation.)

The requirements for gaseous hydrogen systems are based on the system's size and its potential for forming an explosive mixture in air. Confined hydrogen/air mixtures can detonate rather than burn. Hence, it is imperative to prevent the formation of flammable hydrogen/ air mixtures in the system. The usual requirements for hydrogen systems are: fire-resistant construction, special ventilation, explosion venting, spark prevention, and explosion-proof electrical systems.

Hydrogen molecules can also diffuse into steel and other metals. Depending on the material, this can cause embrittlement, resulting in structural defects such as cracks. This imposes important restrictions on the choice of materials for the storage and manipulation of hydrogen. However, cost-effective materials selection options are well established.

Besides system design criteria, risk mitigation includes requirements for emergency response plans for the employees of the hydrogen UTS, including co-ordination plans with fire and rescue authorities.

3.3.5 Hydrogen Certification for Personnel

Public education is a provincial responsibility and provinces should identify the personnel categories that will require hydrogen certification, e.g., installers, maintenance personnel, and owner/operators. It is anticipated that the program will be offered as a skills upgrade to tradespeople, e.g., pipe fitters and mechanics, with a "hydrogen endorsement" added to their basic tickets. There are similar trade certifications in the United States for welding and pipefitting, and there are certification models that can be used, perhaps from the gas or chemical industry, both in Canada and the United States.

3.4 MAINTENANCE REQUIREMENTS

3.4.1 Running Maintenance

Maintenance requirements for fuel cell-powered buses will differ from those of conventional diesel buses mainly for the engine, drive train and fuel system. Other on-board systems such as braking, steering, lighting, and heating, ventilation and air conditioning (HVAC) systems will largely be maintained using procedures currently in place. The new requirements will likely be broken down into four general areas:

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[38] At present, in all Canadian provinces, facilities storing or handling hazardous materials must implement a standardized system that ensures that all hazardous materials are appropriately labelled according to Workplace Hazardous Materials Information System (WHMIS) requirements. This system also requires that Material Safety Data Sheets (MSDS) are available for all hazardous materials. The system requires: staff training in hazardous materials handling, standardized labelling of all hazardous materials using the UN number, ready access to all MSDS for all staff, appropriate personnel safety equipment, appropriate storage facilities, and acceptable disposal techniques. Appropriate storage includes separation of corrosives, flammables and acids, as well as separation of stored hydrogen from oxidants or other stored fuels.

- Procedures unique to fuel cell systems;
- Procedures unique to the fuel system (these will be similar to any other gaseous fuel in use in the transit industry today, e.g., CNG);
- Procedures that will not be affected by the fuel cell technology but need some revision due to the changed safety environment associated with hydrogen gas; and
- Procedures that do not change regardless of the type of engine or fuel system on board.

Based on past fuel cell-powered bus demonstration projects, planned maintenance inspections for fuel cell buses may be categorized into those undertaken:

- daily;
- weekly;
- at 6,000 km;
- at 12,000 km;
- at 24,000 km; and
- at 48,000 km.

However, given that the configuration of commercial fuel cell-powered buses is not known today and the possibility that there may be several different designs, the inspection regime may differ somewhat from the above. In any case, these types of intervals could easily be integrated into current UTS inspection intervals.

While it may appear, at first glance, that fuel cell technology will add to the maintenance burden of transit properties, there will be a "netting out" of maintenance requirements. Some maintenance activities will be eliminated altogether (such as engine oil changes); some will be modified (such as filter replacements, which will require changing the various filters on the fuel cell system instead of the conventional diesel internal combustion engine); and some will remain unchanged (such as inspections of steering, lighting, suspension and brake systems). Brake reline intervals will likely change to those currently experienced on the heavier CNG buses, as the fuel cell-powered bus is likely to be about the same weight as a standard 12-metre CNG bus. In the case of fuel cell hybrid buses, there will be a significant increase in the brake reline intervals due to regenerative braking.

In terms of running maintenance, it is projected that commercial fuel cell-powered buses will be more economical to run, in the long run, than conventional diesel or CNG buses. Electric drive motors will require less running maintenance than diesel or CNG engines. Fuel cell systems, having few moving parts, will require less running maintenance and will not require frequent oil changes.

New or modified running maintenance inspection procedures will be required for:

- power inverters and controllers;
- air conditioning systems unique to fuel cell systems;
- electric motors;
- high pressure onboard hydrogen fuel storage;
- leak detection sensors;
- fire suppression systems;
- air and hydrogen humidifiers;
- condenser separators;
- fuel cell stack voltage;
- high voltage circuits;

- regulators;
- pressure reduction valves;
- hydrogen particulate filters;
- air system oil detectors; and
- grounding systems.

3.4.2 Overhaul Procedures

The principal difference in overhaul procedures for fuel cell-powered buses, as compared to buses now in use, will be the frequency and methods for system overhaul. Fuel cell stack replacement intervals will be shorter than current diesel or CNG engine overhaul intervals. The stack overhaul process will likely be contracted out as it will require special facilities such as clean rooms. However, the removal and replacement of fuel cell stacks is expected to be faster than the removal and replacement of a conventional internal combustion engine and the rebuild process is expected to be simpler. The labour required to remove and replace the fuel cell stacks will be approximately one-tenth of that required to remove and replace a diesel or CNG engine. Diesel engine rebuild trades may be dislocated in the transition.

Overhaul procedures for differentials and transmissions will remain unchanged unless the fuel cell drive train technology used incorporates a gearbox instead of a transmission. Given that engines will no longer be rebuilt, effort required in machine shops will be reduced and will be shift more to transmission and differential requirements.

Many other smaller component overhauls related to internal combustion engines, such as starters, will not be needed in the fuel cell environment. While there will be different ancillary components with fuel cell systems, these components will be mostly sealed, solid-state units that will be replaced rather than repaired.

3.4.3 Reliability and Spare Ratio

Given the significant reduction of moving parts in the core of the fuel cell system and the greater reliability of an electric motor, fuel cell bus reliability should be better than that of a diesel bus. However, the additional weight of a fuel cell bus, mainly attributable to the on-board storage of hydrogen, will result in slightly more wear on brake linings.

Otherwise, the performance of fuel cell-powered buses will be equal to or better than that of a standard diesel bus. It is also expected that a fuel cell-powered bus will carry up to 70 passengers, which means that no additional buses will be required to deliver the planned service.

3.4.4 Trade Skills

Maintenance personnel will need to have greater skills in electronic diagnosis as well as high-pressure gas training or certification. They will also need training in working with high-voltage systems. Specific skills will be required to maintain all the unique fuel cell system components listed earlier. These highly specialized systems will likely be modular and modules are likely to be replaced rather than repaired.

Transit systems that have conducted fuel cell bus demonstration projects estimate that the ratio of buses to mechanics could double and the ratio of buses to electronics technicians/electricians could be reduced by half to two-thirds. Consequently, where the current average ratio ranges from four to eight buses per mechanic, that ratio is expected to change to eight to 16 buses per mechanic. In Vancouver, where there is a large electric trolley fleet, the bus to electronics technician ratio is 13 coaches to one electronics technician in the trolley maintenance shop. This compares to a ratio of 26 diesel buses to one electronics technician or electrician. The transit systems that currently do not employ electronics technicians/electricians will have to re-train their current personnel or replace some of them with technicians qualified in electronics.

While this transition may appear to be a problem, transit systems participating in the study recognized that, by the time fuel cell buses are commercially available, many of their current mechanics will have retired. Mechanics graduating from technical colleges today already have greater electronics training and diagnostic skills than those trained in previous years (today's diesel buses demand some of these skills). What will also be required is training specifically related to the fuel cell systems and diagnostics. However, regular mechanics should be able to change/replace fuel cell system components once an electronics technician has identified the problem.

Service personnel will need training in the safe starting and operation of the fuel cell bus, safety procedures for checking fluid levels and pressures, and the correct procedures for fuelling the bus.

3.4.5 Trades Training

It is probable that the introduction of hydrogen fuel into a transit fleet will be a gradual process, with current buses being replaced with fuel cell-powered buses only as existing buses wear out. In most cases, specialized trades training can be introduced gradually.

UTSs that have already operated natural gas fleets will have a distinct advantage. The gradual introduction of fuel cell-powered buses will require specialist training in control systems and in electric drive technology. Since fuel cell repair or refurbishment will most likely be performed by the fuel cell stack manufacturer, the only required training for transit fleet trades will be removal and replacement.

Bus manufacturers and/or fuel cell system suppliers will likely offer training in diagnostic maintenance and use of their products. Gas merchants will likely offer general training in hydrogen pertaining to fuelling and safety.

As for the overall trades, the introduction of new technologies can most appropriately be conducted through the UTS Health, Safety and Environment (HSE) program. As stated previously, staff participation in HSE safety training should be mandatory.

3.4.6 Speciality Tools and Equipment

Introduction of fuel cell buses will require the acquisition of some specialty tools and equipment that will either replace or be added to those on hand for the maintenance of standard diesel buses. These include:

- Non-sparking hand tools;
- Anti-static clothing;
- Gantry systems with fall protection to allow maintenance and removal and replacement of the roof-mounted fuel storage and other system components such as air conditioning;
- An overhead lifting capability (cranes);
- A calibration system for hydrogen sensors;
- Hydrogen detectors;

- Diagnostic equipment and software unique to the particular fuel cell system installed;
- "Clean" benches to allow maintenance of fuel cell system components;
- Nitrogen-purging equipment;
- Ground fault monitors;
- Mass flow meters;
- Digital manometers;
- Leak test equipment; and
- Fire suppression system test equipment.

3.4.7 Maintenance Cost Implications

The baseline maintenance cost for current transit fleets was determined from the interviews with the 16 transit properties that participated in this study. The average costs for current transit fleets are described in Annex C, section C3, with the average annual maintenance cost, including labour and material, for a standard 12-metre diesel bus being approximately $38,000.

Determining the future cost of maintaining fuel cell-powered buses whose designs have not yet been finalized is problematic. From discussions with representatives from fuel cell system manufacturers and UTSs hosting bus demonstration projects (in Vancouver, Chicago and Palm Desert), assumptions were developed to arrive at an approximate cost differential for maintaining fuel cell-powered buses. Wherever possible, classic production experience curves were applied to known current costs for fuel cell system components to derive an approximate "future" price for these items. The assumptions used for the analysis of the maintenance cost differential are as follows:

- Regularly scheduled preventive maintenance inspections will take the same amount of time to perform as those for diesel engines;
- Fuel cell system repairs will be fewer and less frequent, compared to diesel engines, due to fewer moving parts and components;
- Electric drive motors on fuel cell-powered buses will require less maintenance than the typical diesel internal combustion engine;
- Brake wear on a fuel cell-powered bus will be about 10% greater than on a diesel bus due to the increased weight;
- Brake wear on a fuel cell hybrid bus could be about half that of a diesel due to regenerative braking;
- If batteries are used on a fuel cell hybrid bus, they will require replacement twice during the lifecycle of the bus;
- Fuel cell stacks in a fuel cell-powered bus will be rebuilt a minimum of two, and possibly three, times during the lifecycle of the bus;
- Fuel system maintenance for fuel cell-powered buses will require three times the resources expended on diesel buses, but this is a minor element of the total maintenance costs;
- Tire maintenance of fuel cell-powered buses will be 10% more than that of a diesel bus due to the increased weight;

- Engine overhaul costs of a fuel cell-powered bus will be about one-third the cost of those of a diesel bus due to the simplicity of the stack rebuild process and the remove and replace process; and
- Maintenance of other bus components/systems other than the engine, drive train, brakes and fuelling system will continue to be performed as it is for diesel buses. Labour costs are expected to decrease significantly due to the replacement, instead of the repair, of defective electronic components.

Based on the preceding assumptions, and using the current baseline maintenance cost for a diesel bus, it is estimated that a fuel cell-powered bus will cost about 15% less to maintain on an annual basis than a diesel bus and that a fuel cell-electric hybrid bus will cost approximately 21% less. These costs do not take into consideration the capital and other operating costs over the life of a typical bus.

3.5 SUPPLY CHAIN IMPLICATIONS

Spare Parts

It is anticipated that bus manufacturers will continue to assume responsibility for all major components on their buses and will deal with spare parts for fuel cell buses in the same manner as they do for diesel buses. As in the past, this does not prevent individual transit systems from establishing direct contact with suppliers of components. Warranty items will continue to be supplied by bus manufacturers.

At the depot, spare parts specific to fuel cell-powered buses will be stocked and stored in the same manner as diesel bus parts. Fuel cell stacks will either be stored in current storage areas or ordered and delivered just in time.

Considerable space presently allocated to parts specific to diesel buses (engines, lubricants, etc.) will no longer be required. Generally, less storage space will be required for spare parts and their total value in inventory is likely to be less than at present.

Overhaul

In most UTSs, overhaul of fuel cell stacks will be completed under contracted service by fuel cell stack manufacturers. It is estimated that the rebuild of fuel cell stacks for a 200 kW fuel cell system will take approximately 50 hours, with remove and replace time being about six hours.

To minimize the downtime for a bus, UTSs will need to keep spare stacks on the shelf. The number of spare stacks that should be held in store will depend on the size of the fleet and the age of the buses within the fleet. Assuming that all buses are not procured at the same time and have different accumulated operating hours on the fuel cell system, fuel cell stack inventory, holding between 2% and 3% of the number of fuel cell buses in the fleet, should be maintained. In this scenario, the downtime for a bus requiring new fuel cell stacks should be no more than 48 hours.

Capital and Operating Cost Implications

Given the fewer number of mechanical components found on fuel cell-powered buses, the cost of operating the supply chain to support fuel cell buses will be similar to, if not less than, that of diesel buses.

3.6 ENVIRONMENTAL AND SAFETY ISSUES

Environmental and safety issues are most appropriately addressed through the Corporate Health, Safety and Environment (HSE) program.

4 MAKING THE TRANSITION

4.1 PRE-TRANSITION ISSUES

4.1.1 UTS Strengths

Today's transit properties share several characteristics. They tend to have:

- Political support at the provincial and municipal levels of government with respect to environmental initiatives;
- Increasing ridership and service growth;
- Progressive leadership, within the company, willing to support new technologies;
- Quality service with professional, skilled employees;
- Good labour relations; and
- Good fleet condition due to a regular replacement and maintenance schedule.

The current state of Canadian fleets is being challenged, however, due to budget constraints.

For a number of considerations (including their greater flexibility, relatively limited staff, and relatively closer working relationship between management and employees), smaller UTSs and those in environmentally sensitive areas are more likely candidates for conversion in a single wave to fuel cell-powered bus operations, assuming funding and other implementation issues are dealt with in the planning process. They are, therefore, attractive candidates for early conversion to fuel cell buses.

4.1.2 UTS Challenges

All transit properties interviewed, to a greater or lesser degree, reported tightly limited funding, constrained operating sites, and a workforce with no knowledge of fuel cell technology. These conditions create significant challenges even to meet existing service levels and the requirements of current technologies. In some cases, the pattern of urban development reduces the efficiency of transit services. Changing political situations, the separation of transit-related functions into different departments of local government, getting skilled and qualified tradespeople in some trades, and the lack of strategic vision (or external impediments to the vision) also present challenges.

The common constraint imposed by restricted funding means transitional funding will be essential to the successful introduction of fuel cell-powered bus fleets.

4.1.3 Structure

All transit fleets in Canada operate with local government oversight. While the smaller systems would be good initial candidates for conversion to fuel cell technology, some are operated by private organizations. This means that if contracts were awarded to new suppliers, the local government agency would have to buy the infrastructure from the private operating company and re-train all employees of the new supplier. This might prove to be a challenge.

Almost all urban transit systems are an "administrative unit" of their city organization, governed by a board of local politicians. Relationships with governing structures vary from "good and stable" to "improving". Smaller systems tend to have closer relationships with their governing body. While relations between UTSs and their respective governing bodies are generally good, the separation of responsibility for planning, procurement and operations (i.e., the responsibility is spread among different local government organizations) presents challenges for co-ordinating efficient and effective solutions to transit problems, given that the organizations often have competing, politically driven priorities.

4.1.4 Environmental Policies

Virtually all governing authorities of UTSs have formal policy statements regarding environment and climate change. Some communities, such as Banff, Kelowna, Sarnia and Whistler, have specific environmental policies related to transportation sustainability. All seem to be progressive in approaching environmental issues, making decisions within the constraints of existing budgets to decrease the amount of emissions in their fleets.

From an environmental perspective, most governing bodies are expected to look favourably on the introduction of fuel cell-powered bus technologies in the operation of urban transit systems. Most stakeholders, particularly the public, will embrace the environmental benefits of hydrogen technology.

4.1.5 UTS Knowledge of Fuel Cells

Except for UTSs that have had experience with hydrogen buses, knowledge of fuel cell technologies is generally poor. Most UTSs, however, are aware of hydrogen as a fuel. Some of the smaller Canadian transit systems, such as Sarnia, Banff, Niagara and Whistler, are seriously considering hydrogen fuel cell-powered fleets.

Canadian UTSs are more familiar with diesel-electric hybrid (DEH) and natural gas technologies and display varying degrees of knowledge and interest with regard to hydrogen/natural gas blends, low-emission diesel and bio-diesel. Many transit properties are looking at DEH technology.

While DEH could detract from, or postpone, the widespread adoption of fuel cell technology, the use of hydrogen internal combustion (HICE) or HICE-electric hybrid buses could be an intermediate step toward adoption of fuel cell-powered buses, one that would facilitate the installation of a hydrogen infrastructure before fuel cell technologies are commercially viable. The adoption of HICE-electric technology could also serve to make transit systems more aware of electric drive technology.

Although some transit properties have experience in dealing with gaseous fuels, such as CNG, hydrogen and hydrogen/CNG blends, there are currently no codes and standards related to using hydrogen as a fuel. Education in this area will be required when the standards become available.

4.1.6 UTS Concerns

There are three types of concerns with regards to the advent of fuel cell-powered buses in the transit industry: commercial availability at an affordable price, performance, and impact on operations.

Scepticism is widespread regarding the "advertised" pace of commercialization of fuel cell technologies, their capital and operating costs, and their reliability. Operators are wary of the use of high-pressure, on-board fuel storage. Funding remains the major concern for all transit systems and any technology that will result in a deterioration of their financial sustainability will not gain acceptance. All transit managers agree that the fuel cell-powered bus must perform as well as current diesel buses in order to be adopted by UTSs.

The introduction of hydrogen technologies into UTSs poses a number of challenges, including:

- adjusting the skill sets of the workforce;
- adapting current infrastructures to new requirements;
- occupational health and safety issues;
- training issues;
- winter operations with fuel cells;
- operating mixed fleets during transition; and
- the impact that fuel cell technology might have on service.

4.2 UTS OPTIONS

The operational concept that each UTS will adopt in the future will be driven largely by the technological options at its disposal in the following categories: buses, fuelling systems, and operations and maintenance.

Buses

Between now and 2015, four hydrogen-powered bus types could be made commercially available to UTSs (listed in order of market readiness):

- the hydrogen internal combustion engine (HICE) bus;
- the HICE-electric hybrid bus;
- the fuel cell hybrid bus (with ultracapacitors or batteries); and
- the fuel cell bus.

The latter two are expected to reach market almost simultaneously.

HICE buses were demonstrated in Montreal more than a decade ago. Their configuration is similar to conventional diesel buses with the fuel storage and fuel management systems being the two main differentiating characteristics. These buses could be brought in service quickly, if required, thereby providing UTSs with experience in handling the hydrogen value chain (supply/production, storage, fuelling and general manipulation).

Several demonstrations using HICE shuttle buses are currently being prepared in Canada. The environmental performance of HICE buses, however, does not meet Canada's long-term objectives regarding greenhouse gas emissions, nor is this bus technology as energy efficient as those that will be available shortly afterwards.

HICE-electric hybrid buses could also be made available quickly. There are currently plans for one HICE-electric hybrid bus demonstration project in the Canadian transit industry.

Fuel cell buses have decided advantages over diesel and CNG engine vehicles. They:

- produce no greenhouse gas emissions;
- produce no smog creating emissions;
- are quieter than conventional diesel or CNG vehicles; and
- have about twice the efficiency of internal combustion engines.

Fuel cell buses are currently in regular service in more than 15 cities world-wide on a demonstration basis. Most share a common design. Until recently, that design was expected to be the first commercially available offering to UTSs. However, there may soon be a more cost-competitive, reliable alternative to this large fuel cell bus.

Fuel cell hybrid buses, equipped with ultracapacitors (or another high-performance energy storage device) for peak power demand during acceleration is one possibility.

The first fuel cell hybrid buses will be demonstrated at AC Transit in Oakland, California, within the next two years. Fuel cell hybrid technology offers some advantages over fuel cell technology; in particular, a much smaller (50% or more), and therefore less expensive, fuel cell and a regenerative braking system. The smaller fuel cell allows for a longer range than fuel cell buses and the braking system significantly reduces maintenance costs. Electricity storage systems using ultracapacitors do not add to the maintenance burden of transit systems.

In making a decision regarding which technology to adopt, or which to adopt first, each UTS will need to conduct an analysis incorporating all factors that affect its particular circumstances, for example:

- Cost - capital, operating and lifecycle;
- Extent of infrastructure changes required;
- Personnel impacts;
- Environmental considerations;
- Societal benefits;
- Government policy;
- Public and government support for change; and
- Complexity of change required.

Fuelling Systems

All types of fuel cell-powered buses are expected to carry high-pressure compressed hydrogen fuel on board (350 bar) provided by one of the fuelling options already described in section 3.2:

- Gaseous hydrogen produced off-site, then delivered by pipeline and compressed on-site;
- A liquid hydrogen fuelling system with vapourization on-site;
- An on-site reformer fuelling system; and
- An on-site water electrolysis fuelling system.

The selection of a fuelling system by a UTS is primarily dependent on the economics of the available options (largely dictated by the cost of natural gas, electricity or other feedstock). But space constraints and location must also be considered. In a few cases, the large number of vehicles that need to be refuelled every day (over 200 to 250 buses) dictates that the only possible option would be a pipeline from an off-site source of hydrogen.

Electrolysis may be the most attractive option to UTSs with smaller fleets (less than 25 buses) and access to cost-competitive renewable power, as in the case of those located in British Columbia, Manitoba and Québec. Medium-sized fleets (25 to 150 buses) with ready access to natural gas would probably find on-site reforming a more attractive option. Larger UTSs would probably choose to deal with fuel suppliers for liquid hydrogen or pipeline deliveries.

Other factors may also influence the choice of fuelling systems, such as the availability of funds for capital expenses. Some UTSs may find that fuel production is not a core activity and will choose to outsource. In all cases, UTSs should ensure that backup fuel can be made available if and when required.

Operations & Maintenance

As there is no limitation imposed by either type of fuel cell-powered bus on service operations, the technological choice of UTSs will depend on the analysis of the impact each fuelling technology will have on the system's maintenance operations.

As discussed above, fuel production may be the only significant change in the daily operation. Traditionally, UTSs have not been fuel producers but fuel users, and some UTSs will not want to become producers. If a UTS prefers to remain a user, it has the option of sourcing its hydrogen fuel off-site or procuring a turnkey service from a hydrogen fuel provider. In the latter case, the price of hydrogen would include the use and maintenance of on-site production equipment.

Depots and Garages

The choice of renovating existing facilities or building new facilities will depend on a number of considerations, including:

- The age, condition and annual maintenance costs of existing facilities compared to the cost of building and maintaining new facilities;
- The level of congestion in the existing space;
- The functionality of existing space in meeting current organization and business processes;
- The amount of work (and cost) required to upgrade existing facilities to hydrogen safety standards;
- Whether sufficient space is available to accommodate hydrogen-related facilities such as hydrogen fuel production and/or storage facilities;
- Whether relocating the facilities to a new location will impact service delivery, and how;
- Whether relocating the facility will impact dead-heading costs, and how; and
- In large, dense urban centres, whether an affordable site is even available.

4.3 TIME REQUIRED FOR TRANSITION

Given the current financial position of most UTSs and their funding partners, it is unlikely that they will convert their fleets to fuel cell or fuel cell hybrid buses in a single wave, with the possible exception of very small systems (five buses or less). The time required to convert a complete fleet to fuel cell-powered buses could be as long as 16 to 20 years, the average lifespan of an urban transit bus. The complete transition of the Canadian transit fleet could be expected around 2035.

4.4 FACILITIES ADJUSTMENTS

In a transition period where the UTS will operate a mixed fleet of diesel or CNG buses and fuel cell or fuel cell hybrid buses, current procedures and those for fuel cell-powered buses (described in the preceding sections) will have to coexist. Multi-depot UTSs should segregate the two types of buses in two distinct facilities for an easier transition. Single garages will require conversion to a hydrogen-ready environment from the time the first fuel cell bus is put in service.

4.4.1 HVAC, Sensor & Monitoring Systems

The heating, ventilation and air conditioning (HVAC), sensor and monitoring system requirements have been described in section 3.1. The actual positioning of the detectors and the number of detectors required is currently being researched. Modelling of the dispersion of hydrogen releases in confined spaces is being carried out to simulate the dynamic behaviour of hydrogen. While hydrogen can be expected to rise to and accumulate on the ceiling, other locations may experience high concentrations during the release process.

4.4.2 Electrical Wiring

With appropriate ventilation design and the use of hydrogen sensors, declassified components can be used in most parts of the transit facility's electrical system. Lighting fixtures, however, must be the type that can be immersed in hydrogen in the event of a major hydrogen spill. Other exceptions are hydrogen detectors and discharge fans that need to be rated for operation in Class 1, Zone 1 environments.

4.4.3 Parts Storage Areas and Recycling

If parts storage areas are large enough to meet current operating needs, they should be large enough for fuel cell fleets. In fact, it is expected that less space will be required for fuel cell stacks compared to complete engine assemblies, as fewer spares will be required due to the faster rebuild times and the faster remove and replace times for fuel cell stacks. Because most of the components for fuel cell systems will be self-contained, no special storage areas will be necessary. Handling procedures may have to be adjusted because many of the parts and components for fuel cell systems will not be as robust as those for diesel or CNG-engine systems.

Current recycling practices will apply to any components or materials associated with fuel cell systems. Any hazardous materials found in hydrogen systems will be identified by their manufacturer and UTSs will be provided with any special handling instructions. Unique components that can be salvaged will likely be identified by the fuel cell systems and components suppliers, as are items found in current engine systems.

4.4.4 Maintenance Area Layout

Assuming that all related safety modifications are made to existing buildings, there will be no requirement to change current maintenance area layouts. New facilities expressly built for maintaining fuel cell-powered bus fleets will be built to hydrogen standards.

Tool modifications and special "clean" areas, as identified in section 3, will have to be accommodated within existing facilities or built into new facilities.

4.4.5 Fuelling Station and Fuel Storage

Although dispensing and metering hydrogen fuel requires special equipment, it does not necessitate additional space or any other changes to the facilities other than the general adaptations outlined in the previous sections.

Hydrogen is stored above ground, however, and storage systems for either liquid or gaseous hydrogen will occupy more land area than current diesel infrastructures. Appropriate separation distances for hydrogen components are still being researched. Initial approaches based on comparisons with natural gas have led to divergent and conflicting conclusions. The current approach is to develop independent criteria for hydrogen, based on a scientific database that is now under development. Results to date suggest that the space requirements will not exceed those for natural gas.

The area required will depend on fleet size. Depending on the fuel supply option chosen by the UTS, additional space may be required for fuel production on-site. Both reformers and electrolyzers are being packaged in increasingly compact self-contained units. The area required for fuel production on-site will also depend on fleet size.

In the transition phase, UTSs may prefer to source their hydrogen fuel off-site with a gas merchant until the number of fuel cell (or fuel cell hybrid) buses justifies the installation of a hydrogen fuel generator.

4.4.6 Tools

Introduction of fuel cell-powered buses will require the acquisition of some specialty tools and equipment for maintenance work. The additional tools needed to maintain fuel cell-powered buses are listed in section 3.1.

4.5 FLEET ADJUSTMENTS

Given the long life of a bus, most large transit systems operate with different models of engines, buses and other major components. Some of Canada's transit properties already operate with different types of fuels or propulsion systems (diesel, CNG, electric) and more will be doing so in coming years with the commercialization of diesel-electric hybrid buses.

Operating mixed fleets nearly always increases costs and the amount of work (more parts to store, more procedures to understand and apply, etc.) and transit managers are understandably reluctant to introduce additional models, suppliers or technologies. With fuel cell-powered buses, transit systems (even the few that operate CNG buses) will experience significant changes in maintenance facilities and procedures, e.g., no more oil changes or engine overhauls, different and more complex safety measures, more electrical and electronics work.

This was the experience of those transit systems that held demonstrations of fuel cell buses. They were, nevertheless, successful in operating fuel cell buses in conjunction with their regular fleets, sometimes in the same garages. The demonstrations, however, were temporary experiments without the constraints of daily service pressures.

Suggested strategies for introducing fuel cell-powered buses into transit bus fleets are:

- For very small fleets, change all buses at the same time if possible;
- For large, expanding fleets, transfer as quickly as possible to a garage redesigned or newly built and organized specifically for fuel cell-powered buses;
- For most other fleets (with a stable number of buses and limited garaging options), plan and organize for mixed operations and transfer gradually, one garage at a time.

4.5.1 Number of Buses Required

Fuel cell-powered buses are expected to have the same operating capability as standard diesel buses which means no additional vehicles will be required to deliver the same level of service as the current diesel fleets. The exception may be routes that are longer than 500 km.

4.5.2 Lead Times for Procurement

Most bus manufacturers need purchase orders two years before delivery dates for current diesel buses and no changes to this time frame are anticipated with the arrival of fuel cell-powered buses. This means that transit systems will need to initiate procurement processes for fuel cell-powered buses about three years prior to the desired in-service date to allow for governance approvals and the bidding process to take place.

4.6 MAINTENANCE OPERATIONS AND PROCEDURES ADJUSTMENTS

4.6.1 Personnel

In transitioning from diesel buses to fuel cell-powered buses, some impact on personnel is expected, namely:

- Readjustment of the ratios of buses to mechanics and buses to electronics technicians, increasing the former and reducing the latter. It is fully anticipated that this transition can be accommodated without significant disruption, due to the increased number of workers expected to retire over the next ten years.
- Changes in the way engines are overhauled will require the reduction of personnel currently holding positions related to engine overhaul. These reductions should be manageable through natural attrition in the maintenance workforce during the transition phase.

4.6.2 Training

All personnel who will be affected by the introduction of fuel cell-powered buses, including maintenance staff, bus operators, service persons, supervisors and managers, will require training.

Maintenance staff will require the most training. By 2015, however, it is anticipated that most graduates of technical training schools will have the electronics and computer diagnostic training required to maintain fuel cell-powered buses. This training will focus on procedures unique to fuel cell systems as well as on high-pressure and high voltage systems. All maintenance personnel, including those involved with stores and parts handling, will be required to have training in the handling of sensitive parts and equipment related to fuel cell system maintenance.

Service persons will require training on refuelling processes related to hydrogen fuelling infrastructure. Operators will require training on start-up and emergency shutdown procedures.

All personnel will require occupational health and safety training. Most UTSs should be able to accommodate this training within the resources currently allocated to training personnel on diesel engine technology upgrades. Where this is not possible, training costs can be incorporated in the capital project costs to acquire fuel cell-powered buses.

4.6.3 Tools and Equipment

UTSs transitioning to fuel cell-powered bus fleets will need to procure the tools and equipment identified in 3.4.6. Where the current tools owned by maintenance personnel do not meet the specifications for use with hydrogen (e.g. non-sparking tools), the UTS should absorb the cost of replacing them. Ongoing maintenance of personal tools would then become the responsibility of individual technicians. The tools required for fuel cell hybrid technology would be the same as those for fuel cell buses, except that a special battery maintenance area would be required.

4.6.4 Service Intervals

During the transition period, it will be necessary for UTSs to clearly identify and separate the processes and checklists for servicing/maintaining each type of bus technology during transition. While inspection intervals for fuel cell-powered buses will be similar to those of diesel buses (see section 3.4), the content of the checklists will be different. Maintenance personnel will need work orders that clearly state the type of maintenance to be performed for each bus type. Automated maintenance management information systems, if used by the UTS, can be adjusted to present or print out the appropriate maintenance checklist for each type of bus.

4.6.5 Overhauls

The operation of a mixed fleet of diesel or CNG buses and fuel cell or fuel cell hybrid buses will necessitate a phase-in/phase-out strategy that will be unique to each UTS, based on its current procedures and on the chosen future operations model. The phasing out of diesel bus overhaul processes, as fuel cell-powered buses are put into service, will affect personnel and contracting-out requirements and should be planned ahead of time to ensure that personnel are treated fairly and contracts for overhauling fuel cell system components are in place.

4.6.6 Spare Parts Inventory and Storage

There are no additional or separate requirements for spare parts storage with a fuel cell-powered fleet. As inventory for diesel or CNG buses is depleted, stocks for fuel cell-powered buses will increase. It is quite possible that less space will be required for fuel cell system components.

4.6.7 Warranty and After-Sales Service

No changes are anticipated with respect to warranties and after-sales service.

4.6.8 Capital and Operating Costs

The transition costs will depend on a number of factors, including whether a UTS chooses to convert their existing facilities or to build new ones.

4.7 FUELLING OPERATIONS

4.7.1 Options for Providing Fuel

There are basically two categories of options for procuring hydrogen fuel for the new buses: either the UTS will install its own hydrogen generator on-site, or it will source its hydrogen from fuel suppliers. Unless a specific facility is assigned to the new fuel cell-powered buses or, in the case of a smaller UTS, the whole fleet is converted to hydrogen, it would be advisable to use the services of a gas merchant at the beginning of the transition period until the number of buses and the economics warrant the purchase of a hydrogen generator.

Where electrolyzers and certain packaged autothermal reformer (ATR)-based fuelling systems are selected, it may be possible to procure modular units that can be added to one another in order to meet increasing hydrogen fuel requirements. Incremental purchasing, however, will be more expensive than sourcing a full-scale fuelling station from the outset.

4.7.2 Fuelling Station Configuration

Given that hydrogen refuelling can be performed within the standard eight minutes per bus, and that dispensers can be placed indoors or outdoors, the current configuration used for diesel or CNG buses can be replicated in terms of number of nozzles available to the fleet.

The only difference may be in dense urban centres with routes and schedules that exceed the range of fuel cell-powered buses, necessitating mid-day fuelling, additional buses or additional fuelling points and persons.

4.7.3 Personnel Adjustments

No additional personnel will be required for the transition period if the configuration of the new fuelling equipment has been carefully planned and the service facility can accommodate an additional dispenser in an appropriate location.

Where an additional location is planned for fuel cell-powered buses, a temporary increase in staffing would be expected for the transition period. In dense urban centres, additional permanent staff may be required.

Fuelling protocol will require some specialized training, as discussed in section 3.2.3.

4.8 FLEET SERVICING ADJUSTMENTS

No changes to fleet servicing are anticipated. An exception may be UTSs with routes that exceed the range of fuel cell-powered buses. These routes may require mid-day refuelling, additional fuelling points and personnel, or additional buses.

4.9 RISK MITIGATION & CODE COMPLIANCE

4.9.1 Comparative Risk Analysis

In a 2001 demonstration project of the Daimler Chrysler NEBUS in Oslo,[39] a risk assessment[40] was completed to compare the hydrogen fuel cell bus and the traditional diesel bus. The report concluded that any increased risk from hydrogen, beyond that presented by diesel, was insignificant. It supported the local transit authority's requirement that, *"No additional risks due to the usage of hydrogen as a fuel in buses will be accepted."*

To do a comparative risk analysis, the comparative fuel properties have to be considered. The following table presents selected physical properties[41] of hydrogen, natural gas, propane and gasoline vapour. These four fuels were selected as being representative of gases and vapours in automotive fuelling stations. As presented in the first row of properties in the table, hydrogen is much lighter than air, natural gas is lighter than air, propane is heavier than air, and gasoline vapour is much heavier than air. The selected data illustrate properties that are critical in determining the basic safety requirements of a facility.

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[39] This bus was equipped with four Ballard 50-kW Proton Exchange Membrane (PEM) fuel stacks, operating at 80°C, positioned at the rear of the bus. Fuel was stored in seven carbon fibre-reinforced aluminium cylinders, each with 150-litre capacity, placed within the roof of the bus and holding a total of 21 kg of hydrogen.

[40] *Stor-Oslo Localtraffic A.S., Safety Assessment of Hydrogen Bus Prestudy*, Report No. 2000-3525, Det Norske Veritas, 2001, 41pp.

[41] [1] Nyborg, E.O., Benard, P. and Hay, D.R. *Clearance Distance and Hazardous Zone Issues for Hydrogen Systems*, presented at the National Hydrogen Association's 14th Annual U.S. Hydrogen Meeting, Washington, March 4 to 6, 2003.

Table 2. Selected Properties of Fuel Gases or Vapours
(in air at normal temperature and pressure)

Property	**Hydrogen**	**Natural Gas**	**Propane**	**Gasoline Vapour**
Density relative to air	**0.07**	0.55	1.52	4.0
Molecular weight	**2.02**	16.04	44.06	107
Density (kg/m^3)	**0.084**	0.651	1.87	4.4
Diffusion coefficient (cm^2/s)	**0.61**	0.16	0.12	0.05
Explosive energy (MJ/m^3)	**9**	32	93	407
Flammability range (vol %)	*4 to 75*	5 to 15	2 to 10	1 to 8
Detonation range (vol %)	*18 to 59*	6 to 14	3 to 7	1 to 3
Minimum ignition energy (mJ)	*0.02*	0.29	0.26	0.24
Flame speed (cm/s)	*346*	43	47	42
Flame quench gap (mm)	*0.6*	2	2	2

Source: MARCON-DDM HIT, 2004

The wide flammability limits and detonation limits exhibited by hydrogen as compared to the other fuels, as well as its low ignition energy and high flame speed, are properties that can present a safety challenge. These properties, however, have been effectively managed at industrial sites for many years.

A number of hydrogen's physical properties enhance its potential safety as compared to the other listed fuels. The low density of hydrogen gas, in itself and in relation to air, as well as its high diffusion coefficient, means that accidental spills of gaseous hydrogen will rapidly rise and diffuse. As well, removing spills or declassifying hazardous zones by natural or artificial ventilation is more easily done with hydrogen than with the other fuels. Should a deflagration occur, the low explosive energy of hydrogen gas relative to the other fuels makes it a considerably safer fuel.

4.9.2 Changes to Procedures

Specific emergency preparedness and response plans, in the event of a significant hydrogen leak or a hydrogen fire, will need to be prepared. These plans must be incorporated into the overall training for all staff involved with fuel cell bus operation, including management. Training must address the differences between hydrogen, natural gas, propane and conventional liquid fuels.

4.9.3 Occupational Health and Safety

Occupational health and safety requirements are provincially controlled. Prior to the transition to fuel cell fleets, it will be necessary for provinces to determine the health and safety requirements for a hydrogen facility.

4.10 COMMUNICATIONS STRATEGY

For UTSs, the transition to fuel cell technology and tomorrow's fuel cell-powered urban transit fleets will require a communications strategy that targets both internal and external audiences. The communication strategy should be developed in two phases:

- Phase 1 – Decision Announcement: Communicate the decision to move to fuel cell-powered bus technology in such a way as to attract interest and gather support from target groups. Promote awareness of fuel cell-powered bus technology and its key advantages.
- Phase 2 – Service Introduction Announcement: Launch the new fuel cell-powered bus technology service. Develop and sustain interest and increase awareness.

4.11 SCHEDULE FOR TRANSITION

The transition process for any of the technology options selected will follow the critical path of the acquisition of the buses, this being the longest process, given the assumption that bus manufacturers cannot deliver fuel cell-powered buses in less than two years. Using this assumption, the time required for each major group of activities in the transition process is presented in the following chart:

Figure 1. Transition Process Timetable

MONTH:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Requirements definition and project approval process	■	■	■	■	■	■	■	■	■	■	■	■																								
Contract award and delivery of buses													■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Facilities modification design, contract award and concentration													■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	←	←	←	←	←	←
Fuel station design, contract award and construction													■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	←	←	←	←	←	←
New facility design, contract award and construction							■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	←	←	←	←	←	←
Negotiations with bargaining unit representatives, as appropriate, to deal with any dislocation issues affecting employees							↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	■	■	■	■	■	■												
Development of technical training program for employees																									■	■	■	■	■	■	←	←	←	←	←	←
Development and writing of corporate health, safety and environment policy applicable to the hydrogen/fuel cell environment													↔	↔	↔	↔	↔	↔	■	■	■	■	■	■												
Development of health, safety and environment training program																									■	■	■	■	■	■						
Training the trainer program																									↔	↔	↔	↔	■	■						
Training for supervisory and management personnel																															↔	↔	■	■	■	←
Technician training																															■	■	■	■	■	■
Facility maintenance staff training																															■	■	■	■	■	■
Service person training																															↔	↔	↔	■	■	■
Internal stakeholder education and communication program development													↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	■	■										
Internal stakeholder education and communication																												■	■	■	←	←	←	←	←	←
External stakeholder education and communication program development													↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	■	■										
External stakeholder education and communication																												■	■	■	←	←	←	←	←	←

Note: The arrows indicate the flexibility in scheduling the named activity, identifying the earliest start time and the latest completion time. Where there is no arrow preceding or following the activity bar, the activity should not commence or continue later than the time shown. The above time estimates will vary, depending on the unique circumstances of each urban transit system and the readiness to transition to the hydrogen environment. For smaller systems, the time periods may be reduced significantly. The sequence of each activity may also vary by transit system. All activities, however, will have to be completed prior to fuel cell-powered buses entering into revenue service. All training programs will include the necessary health, safety and environment components applicable to the role of the person receiving the training.

5 CONVERSION COSTS

The costs associated with converting a transit bus fleet to fuel cell technology will vary from one UTS to the other depending on a number of factors, including the status of current facilities, the fleet size, and labour agreements. Consequently, the costs presented in this document are generic and should be used as a general guideline only. All costs are expressed in 2015 dollars.

5.1 COST COMPONENTS

The main cost components affected by the introduction of fuel cell or fuel cell hybrid buses will be:

- The capital cost of the buses, usually amortized over their 16-20 year lifecycle (18 years used for the purposes of this study);
- Maintenance operating costs (including spare parts);
- Fuel costs; and
- The capital and operating costs of the depot and, for most Canadian properties, an indoor parking garage. These are usually amortized over 20 years or more.

This section presents an overall evaluation of the cost equation for fuel cell and fuel cell hybrid buses, considering all major aspects and taking into account all information gathered from UTS representatives in the context of this study.

For the purpose of this evaluation, a cost model[42] was developed that takes into account all variables and projects them over the lifecycle of the first commercial fuel cell-powered buses.

5.2 CAPITAL COST OF FUEL CELL-POWERED BUSES

Bus manufacturers were not able to provide firm prices on fuel cell-powered buses since fuel cell technology will continue to evolve between now and the time it makes its commercial entry.

The costs of fuel cell-powered buses sold for demonstration projects are not reliable as a base for estimating future commercial prices, for two reasons:

- Commercial fuel cell technology buses may be technically quite different from present demonstration models.
- Each past sale has required custom financial packaging, including public funding and fuel cell manufacturer contribution. Publicly available prices are unlikely to reflect the full cost of these buses.

The assumptions used in this report regarding the prices of commercial fuel cell and fuel cell hybrid buses in 2015 are therefore based on a combination of publicly-available sources and information gathered in the context of this study. They are:

1) Reliable industry sources indicate that the actual direct cost of a fuel cell stack (direct material, direct labour and direct overhead) is $4,788/kW (US$3,600), which represents 70% of the total price of $9,097/kW (US$6,840).[43]

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[42] The lifecycle cost model, designed by MARCON-DDM HIT, incorporates all the characteristics of a classic cost evaluation model for alternative fuels. It also takes into consideration economies of scale in forecasting the price of major equipment and components such as fuel cell stacks.

[43] FX exchange rate: CDN$1.33 for US$1.00

2) Published prices ranging between $7,980 (US$6,000) and $11,970/kW (US$9,000),[44] for an average of $9,975/kW.

3) U.S. Department of Energy technical target for 2015: $40/kW (US$30),[45] including storage. An average of $50/kW was used (storage not included) as a conservative figure;

4) Evobus (Clean Urban Transit In Europe [CUTE]) price, in 2003, of $1.84 million (1.2 million Euros)

5) Recent North American transactions at $1.86 million (US$1.4 million)[46](Chicago Transit) and $1.2 million (BC Transit), for an average of $1.53 million.

Resulting price estimates are presented in the following table:

Table 3. Sources of Fuel Cell System and Bus Costs

	Cost of 200 kW Fuel Cell System ($)		**Fuel Cell Bust cost ($)**	
	2004	**2015**	**2004**	**2015**
Sources				
1	1,368,038	144,923	2,001,198	1,021,365
2	1,995,000	211,340	2,628,160	1,087,782
3		10,000		886,442
4	1,202,240	127,358	1,835,400	1,003,800
5	1,228,840	130,177	1,862,000	1,006,619
Average			**2,081,690**	**1,001,201**

Source: MARCON-DDM HIT, 2004

The average costs for a fuel cell bus in 2004 and 2015, based on the preceding sources, are $2,081,700 and $1,001,201 respectively. The 2015 forecasts take into account the standard learning curve effects on the fuel cell system cost.

With the same rationale applied to fuel cell systems destined for fuel cell hybrid buses, and when resulting cost is substituted for a hybrid diesel power plant, the forecast price of a fuel cell hybrid bus in 2015 averages $1,005,615. Present and forecast bus prices do not take into account taxes, rebates and subsidies.

Table 4. Sources of Fuel Cell Hybrid Bus Costs

	Cost of 120 kW Fuel Cell Hybrid System ($)		**Fuel Cell Hybrid Bust cost ($)**	
	2004	**2015**	**2004**	**2015**
Sources				
1	820,823	86,954	1,493,223	1,017,713
2	1,197,000	126,804	1,869,400	1,057,563
3		6,000		936,759
4	721,344	76,415	1,393,744	1,007,174
5	737,304	78,106	1,409,704	1,008,865

Source: MARCON-DDM HIT, 2004

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[44] Idem.

[45] Idem.

[46] Idem.

The following table summarizes the current and forecast prices used in the cost model.

Table 5. Forecast Prices for Low-Floor 12-Metre Transit Buses

Bus Type	2004 Price ($)	2015 Price ($)	Rationale & Calculations
Diesel	390,000	600,387	Impact of inflation
Diesel-electric hybrid	665,000	920,515	Reliable bus manufacturing industry sources and sales to Seattle, SEPTA, NYCTA and BC Transit. NY City Transit Authority paid $512,000 (US$385,000[47]) for its diesel-electric hybrid buses. This early adopter special price will not be offered to other transit systems. The next commercial bids are expected to be approximately $665,000 (US$500,000).
Fuel cell hybrid	1,541,518	1,005,615	See Table 4
Fuel cell	2,081,690	1,001,201	See Table 3

Source: MARCON-DDM HIT, 2004

5.3 MAINTENANCE OPERATING COSTS

As discussed in section 3.4.7, the baseline maintenance cost for current fleets was estimated from the results of interviews with representatives from the 16 transit properties participating in this study.

Assumptions were developed to estimate the approximate cost differential for maintaining fuel cell-powered buses. These assumptions are also presented in section 3.4.7.

Using the current baseline maintenance cost for a standard 12-metre diesel bus, it is estimated that a fuel cell bus would cost approximately 15% less to maintain, on an annual basis, than a diesel bus and that a fuel cell hybrid bus would cost approximately 21% less to maintain than a diesel bus.

Taking inflation into account, the following table shows the maintenance costs, input into the cost model:

Table 6. Annual Maintenance Cost ($)

Maintenance Cost per Bus	2004	2015[48]
Diesel bus	38,000[49]	52,601
Diesel-electric bus	Not available	No forecast
Fuel cell bus	32,222	44,603
Fuel cell hybrid bus	29,892	41,378

Source: MARCON-DDM HIT, 2004

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[47] FX exchange rate: CDN$1.33 for US$1.00.

[48] 2004 figures adjusted for inflation (3% per annum).

[49] Annex C provides detailed information on maintenance costs obtained from UTS interviews. On average, maintenance costs are $0.64/km. Urban transit buses travel an average of 60,000 km/year.

The forecasted maintenance cost of fuel cell buses was derived from the assumptions described in section 3.4.7.

There should be no significant increase in maintenance personnel salaries associated with fuel cell fleets. The modified skill sets required from UTS employees who will be affected by the introduction of fuel cell-powered buses should not necessitate any substantial increase in total wages, salaries or benefits for most UTSs across the country.

5.4 FUEL COSTS

Future prices for diesel fuel were forecast using the actual prices paid by UTSs (taxes included) participating in this study and projecting them to 2015 and beyond using two basic scenarios:

- The same price increases as those experienced over the last 30 years (that is, approximately the rate of inflation), resulting in a price forecast of $0.77/litre by 2015; and
- A faster rate of increase, corresponding to twice the rate of inflation and reflecting the present expectation of increasing demand and decreasing supply, resulting in a price forecast of $1.05/litre by 2015.

Three supply methods (reforming, electrolysis and off-site fuel supply) were developed to estimate the future price of hydrogen fuel[50] to input into the cost model. Two scenarios resulted from these calculations:

- The first corresponds to the technical targets established by the U.S. Department of Energy[51] for 2010 (DOE scenario).
- The alternate forecast is based on DOE targets adjusted to take into consideration more current energy price forecasts (natural gas at $0.73/m^3 [US$0.55] and electricity at $0.140/kWh [US$0.105]) as well as new technological developments (conservative scenario). (FX exchange rate: CDN$1.33 for US$1.00.)

Only the conservative scenario has been input into the model for cost forecasting purposes. No taxes have been added to the price of hydrogen.

The cost model takes into account an anticipated fuel consumption of 10 kg of hydrogen per 100 km of operation for a fuel cell bus in 2015. A fuel cell hybrid bus is anticipated to consume 34% less hydrogen fuel than a fuel cell bus.

Table 7. Cost of Hydrogen in 2015

Costs per kg of Hydrogen ($)	DOE Scenario	Conservative Scenario
On-site reforming of natural gas	2.10	3.47
On-site water electrolysis	3.50	5.63
Off-site merchant LH$_2$	3.85	6.12

Source: MARCON-DDM HIT, 2004

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[50] See Section 3.2.2 for detailed cost breakdown.

[51] Hydrogen, Fuel Cells & Infrastructure, Department of Energy, Draft, June 2003, Section 3, Technical Plan.

The following table presents the fuel costs per kilometre in 2015, taking into account the various assumptions made for the development of a 2015 fuel price.[52]

Table 8. Cost of Fuel per km ($)

Hypothesis:	Diesel price* per litre: $0.77	Diesel price* per litre: $1.05
Diesel bus (55.8 litres/100 km)	0.43/km	0.59/km
Diesel electric bus	Not available	No forecast
Hypothesis:	**Hydrogen price** per kg: $3.47**	**Hydrogen price** per kg: $6.12**
Fuel cell bus (10 kg/100 km)	0.35/km	0.61/km
Fuel cell hybrid bus (6.6 kg/100 km)	0.23/km	0.40/km

Source: MARCON-DDM HIT, 2004

* All taxes included
** Assuming there will be no taxes on hydrogen

5.5 FACILITIES CAPITAL COSTS

With regard to capital expenditures that UTSs will incur to accommodate a fuel cell technology based bus fleet, two major possibilities were evaluated and included in the cost model:

- Building a new maintenance depot (with or without indoor parking facility) for a 250-bus fleet; or,
- Transforming an existing 250-bus garage (with or without indoor parking) to hydrogen requirements.

The expected additional capital costs for building a new 250-bus garage and indoor parking facility for fuel cell or fuel cell hybrid buses, above those required for the same number of diesel buses, were estimated using experiences with CNG, as well as recent maintenance depot planning and construction experiences at BC Transit and Société de Transport de Montréal (STM).

Capital costs for modifying an existing depot were estimated based on an updated version of the costs incurred for the fuel cell bus demonstration in Vancouver.

These capital expenditures relate mainly to the installation of safety-related equipment in facilities where fuel cell-powered buses are maintained or garaged.

Building design, ventilation, and sensor installation with an alarm threshold for interruption of operations were described in section 3.1.

The major requirement for facilities and operations when moving toward hydrogen is accommodating hydrogen's buoyancy and dispersion properties that move the focus of the hazard from the point of release to areas where hydrogen can accumulate, generally at higher points in the building near the ceiling. This requires removal of both hydrogen and potential ignition sources from these points. The latter are generally electrical fixtures

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[52] A key assumption here is that there will be no improvement to the average fuel consumption of the regular diesel bus.

such as lights that must be dropped down from the ceiling and the former is addressed through ventilation.

Installation of an appropriate ventilation system could be a major one-time cost in facilities that have unsuitable ceiling designs. In other facilities, it may be relatively inexpensive. Replacement of electrical fixtures is a nominal cost, as is the installation of hydrogen detectors. Winter heating costs may increase.

The capital costs for adapting a large (250-bus) facility for fuel cell-powered buses used in the cost model are as follows (2015 estimate adjusted for inflation):

Table 9. Hydrogen Facilities Upgrade Costs

	Upgrading ($)	
	2004	**2015**
Garage	1,500,000	2,076,351
Bus Barn	3,000,000	4,152,702

Source: MARCON-DDM HIT, 2004

Should a UTS choose to build a new garage or bus barn for reasons that are unrelated to transitioning to a hydrogen fleet, building a facility to anticipated hydrogen codes and standards will be more expensive than building one to diesel standards because of the additional equipment required (as detailed in section 3). The **incremental** cost of building fuel cell-powered bus facilities (i.e., the amount exceeding the cost of building diesel bus facilities) is presented in the following table:

Table 10. Hydrogen Facilities Building Costs

	Building* ($)	
	2004	**2015**
Garage	1,000,000	1,384,234
Bus Barn	2,000,000	2,768,468

* Incremental cost over that of a regular building for 250 diesel buses

Source: MARCON-DDM HIT, 2004

Costs will vary according to each specific situation (urban area, garage capacity, etc.) but the variations, amortized over 20 years, will not have a significant impact on the overall cost differential between facilities for a fuel cell-powered bus fleet and facilities for a diesel bus fleet, over the life cycle.

Costs for adapting a CNG facility for hydrogen fuel cell-powered buses will be significantly lower than those for a diesel facility. In all cases, these costs do not include fuel production and storage facilities.

Facility maintenance operating costs are estimated to increase by about $2.70/m^2/annum to accommodate the maintenance of hydrogen-related safety equipment such as sensors and heating and ventilation systems. This amounts to about $250 per bus per year (less than 0.6% of total maintenance costs).

In most municipalities, buildings and vehicles are not insured for damages, theft and fire. Consequently, the introduction of hydrogen in buildings and vehicles should not have a financial impact on normal operating costs. As for health and safety insurance, the potential impact of hydrogen has not been factored into the cost model. It is anticipated that any insurance premium increases will be temporary and that uneventful safety records will resolve any insurance premium issues that may arise.

5.6 NON-RECURRING COSTS

Retraining

It is anticipated that the introduction of fuel cell-powered buses into a transit fleet will be a gradual process, with fuel cell-powered buses gradually replacing buses as they age. Specialized trades training will therefore be introduced gradually.

The introduction of fuel cell vehicles will require specialist training in control systems and electric drive technology. Since fuel cell repair or refurbishment requires clean room technology, the fuel cell stack supplier will often perform this operation. The only likely required training for most transit fleet trades will be how to remove and replace fuel cell stacks, not how to repair them. It appears that training will therefore result in ongoing costs similar to those presently incurred in operating a diesel transit fleet. No additional allowance has been taken into consideration in the cost model for retraining activities.

Implementation of New Procedures

New procedures for maintenance of both fuel cell-powered bus fleets and maintenance facilities will have to be developed concurrently with the procurement of the new fleet and infrastructure. Where possible, suppliers will need to establish the new procedures and set up training programs for both trainers and maintenance personnel within the UTS. Occupational health and safety training will also have to be scheduled for all personnel affected by the introduction of the new technology.

The costs for developing the new procedures and for the training required can be included in the capital procurement budget or may be absorbed in the current operating budgets of UTSs. Of necessity, the introduction of new procedures will be phased in with the acquisition of the new fleet and the upgrade/replacement of the maintenance facilities.

Environmentally Safe Disposal of Equipment

A transit facility equipped for hydrogen fuelling should require no additional hazardous materials handling or storage requirements than those that are currently necessary for existing facilities and there should be no additional one-time transition costs.

Communications

For most UTSs, the communications costs associated with the transition to fuel cell-powered bus technology represent a small portion of the overall annual communications budget. Therefore, the cost model assumes no incremental costs related to communications.

5.7 SUMMARY OF COSTS

The following table summarizes all relevant 2015 cost forecasts contained in this report and uses a reference case of a 250-bus garage.

The lifecycle cost of each bus is therefore:

• Diesel bus	$ 2,169,290
• Fuel cell bus	$ 2,170,748
• Electric/fuel cell hybrid bus	$ 1,992,429

Costs for larger or smaller facilities will vary accordingly but will be the same proportionately. No facilities related costs are factored in the preceding lifecycle costs. All costs are expressed in 2015 dollars.

Table 14. Summary of Key Costs, in 2015 dollars

Lifecycle Cost Components for 250 Buses over 18 Years		
Bus Acquisition Cost		
	Diesel	$150,096,770
	Fuel cell	$250,300,279
	Fuel cell hybrid	$251,403,664
Operations Cost		
Maintenance Cost		
	Diesel	$236,704,005
	Fuel cell	$200,714,570
	Fuel cell hybrid	$186,199,881
Fuel Cost		
(Diesel @ $1.05/l)	Diesel	$155,521,825
(Hydrogen @ $3.47/kg)	Fuel cell	$91,672,162
(Hydrogen @ $3.47/kg)	Fuel cell hybrid	$60,503,627
Total Cost		
	Diesel	$542,332,600
	Fuel cell	$542,687,012
	Fuel cell hybrid	$498,107,172

Source: MARCON-DDM HIT, 2004

The lifecycle cost of all types of buses is dependent on the cost of fuel used. Scenarios outlined earlier take into account diesel prices of $0.77 and $1.05/litre. The cost of hydrogen depends on the fuelling option considered among the three possibilities. The fuelling option and the price of diesel results in six possible combinations for the fuel cell bus and six for the fuel cell hybrid bus.

The lifecycle cost of fuel cell buses ranges from the same as diesel buses (when diesel sells for $1.05/litre and hydrogen fuel is produced using on-site reforming) to 23% more than diesel buses (when diesel sells for $0.77/litre and hydrogen fuel is sourced off-site in liquid form).

The lifecycle cost of fuel cell hybrid buses can be 8% less than that of a conventional diesel bus (if diesel sells for $1.05/litre and hydrogen is generated using on-site reforming). Under different circumstances (if diesel sells for $0.77/litre and liquid hydrogen is provided by a merchant), the lifecycle cost of a fuel cell hybrid bus can be almost 9% higher than that of a conventional diesel bus.

The following table summarizes the range of possible cost differentials between fuel cell-powered buses and diesel buses based on two levels of diesel fuel prices.

Table 15. Lifecycle Cost Differentials Relative to Diesel Buses (based on natural gas at $ 0.55/m^3 and electricity at $ 0.105/kWh)

Hydrogen Source	**Fuel Cell Bus Fuel Diesel price ($/l)**		**Cell Hybrid Bus Diesel price ($/l)**	
	$0.77	**$1.05**	**$0.77**	**$1.05**
Reforming	8.49%	0.07%	-0.42%	-8.15%
Electrolysis	19.92%	10.61%	7.12%	-1.20%
Merchant LH_2	22.51%	12.99%	8.83%	0.38%

Source: MARCON-DDM HIT, 2004

6 CHALLENGES

Numerous technical, economic, political and administrative challenges have to be resolved before fuel cell-powered buses can be made commercially available and before urban transit systems (UTSs) can begin to acquire fuel cell-powered buses. All stakeholders will need to address these challenges as soon as possible in this pre-transition phase if Canadian UTSs are going to make an accelerated transition to fuel cell-powered fleets.

6.1 TECHNICAL CHALLENGES

There are several technical issues with fuel cell-powered buses that need resolution before they can be made commercially available. The following key success factors need to be satisfied to ensure fuel cell-powered buses find their market:

- The range of buses must reach at least 500 km;
- Passenger carrying capacity must be between 60 and 70 persons;
- Reliability as good as that of current diesel buses must be achieved;
- Bus performance parameters must be as good as those for diesel buses;
- Buses must meet U.S. Department of Transport future testing standards; and
- Fuel cell system manufacturers must develop system architecture that bus manufacturers can easily integrate into coach structure designs.

While fuel cell system manufacturers are clearly critical to the successful introduction of their technology to the Canadian UTSs, fuelling systems and hydrogen fuel providers also have a key role. The latter must quickly adapt their current demonstration-type technologies to the industrial standards required by transit operators.

Electrolyzer technology must evolve to meet the challenges of larger demand. Electrolysis-based fuelling systems must also be engineered to reduce their capital cost by using larger stacks, providing higher electrolytic pressure and simplifying control modules while ensuring they can adapt to additional stacks to meet growing demand at any given site. Manufacturers must also devote technical resources to minimizing electrical consumption, integrating the systems with renewable electricity sources,[53] and increasing reliability.

For reformers, manufacturers must master the packaging of standard units in a modular form. Capital costs must be reduced for smaller units and carbon sequestration must be included in future technologies. Multi-feedstock systems would be preferable. Finally, attention must be given to the aesthetics of future systems as some will be situated in non-industrial environments.

Fuel suppliers will also face technical challenges. Production capacity, currently under-utilized, would be insufficient to meet UTS demand if a massive conversion were to occur. In some areas of the country, there may an opportunity to serve UTSs with existing pipelines; in some cases, a new pipeline might be the best way to meet additional demand. The main focus of fuel suppliers should be less expensive delivery methods.

Stationary storage technologies must also evolve beyond small cylinders linked by a manifold at 350 bar. Resources must be devoted to the development of large, on-site storage reservoirs at a

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[53] The U.S. Department of Energy targets call for hydrogen from "large plant" electrolysis using a renewable source at a cost of $2.66/kg (US$2.00) by 2010.

reasonable cost. While higher-pressure cylinders are desirable on transit buses to provide them with a range that is identical to that of diesel buses, focus should be placed on stationary or transportable storage at pressures exceeding 700 bar. This will eliminate the need for costly hydrogen liquefaction and vapourization in the supply chain.

As a whole, the industry must ensure that a sound, cost-effective codes and standards structure will be in place for hydrogen-fuelled UTS bus fleet facilities well before 2015.

Regarding training and education, training programs for operating and maintenance personnel are being developed at several institutions. In the early transition projects, custom training programs by hydrogen experts will be required. Within the timeframe considered in this project for implementation of fuel cell-powered transit fleets, the training process for accommodating hydrogen in the related trades will likely be institutionalized.

For UTSs, the technical challenges are relatively few and easily manageable. The challenges pertain mainly to the transition period where facilities, equipment and personnel will need to be adapted to the new reality of fuel cell-powered buses.

6.2 ECONOMIC CHALLENGES

A variety of reliable industry sources, as well as published data, was used to develop five fuel cell-powered bus scenarios (section 5.2), resulting in a 2015 forecast price of slightly more than $1 million for both a fuel cell and a fuel cell hybrid bus. This price is approximately two-thirds greater than that of a diesel bus. These costs assume that the technical challenges outlined in the preceding sub-section will be overcome. The cost of the fuel cell system for an urban transit bus must not exceed $125,000 for a fuel cell model and $75,000 for a fuel cell hybrid model. The challenge is to bring the cost of fuel cell systems down by 90% over the next 10 years. Obviously, economies of scale and learning curve effects will play a considerable role in this process, but much work remains to be undertaken by fuel cell system suppliers.

For bus manufacturers, the major challenge will be maintaining the cost of bus shells and other fuel cell peripherals at a price competitive with those for diesel buses, forecast at $550,000 per shell.

Hydrogen fuel suppliers and hydrogen production system suppliers will also have their share of challenges. Major performance improvements described earlier must be made while considerably diminishing capital costs. In the case of reformer equipment, according to U.S. Department of Energy (DOE) technical targets, costs must decrease by 50% by 2010. According to the cost model used in the context of this report, this 50% decrease must be realized by 2015. Electrolysis-based fuelling equipment suppliers will also need to lower the capital cost of their systems by 60% by 2015. Given the strategic importance of hydrogen fuel costs to the successful implementation of fuel cell-powered buses in Canada, there is a need for further study of the projected cost of hydrogen fuel. This will provide UTSs with better tools for assessing the future operations cost of their fuel cell-powered fleet.

Without financial incentives, urban transit operators will have a major, if not insurmountable, challenge in introducing fuel cell-powered buses into service. The actual cost of purchasing and operating the buses in 2015 will be dependent on the chosen technology, the chosen fuel supply, and the evolution of fuel prices.

6.3 PUBLIC POLICY CHALLENGES

All transit managers interviewed in the context of this study stated that the issue of funding UTSs appropriately is the single most critical success factor in the conversion of the Canadian transit fleet to fuel cell-powered buses. Currently, various levels of government support transit systems in a variety of ways, including operating budgets and capital expense financial incentives. The present level of funding, however, barely allows transit fleets to keep operating at the breakeven point financially.

With the acquisition cost of fuel cell-powered buses anticipated to exceed that of diesel buses by two-thirds, UTSs cannot absorb the capital cost of these buses within their current budgets. This will be particularly true during the transition period, where the cost of operating a mixed fleet will increase the overall operating expenses and there will be one-time costs related to adapting facilities and equipment and training personnel.

There are three measures by which governments can support the introduction of fuel cell-powered buses in Canadian UTSs:

- Financial incentives such as subsidies, rebates and tax holidays;
- Regulatory standards for vehicles, operating facilities and fuelling standards; and
- Legislated obligations such as mandatory adoption of zero-emission buses.

6.4 ADMINISTRATIVE CHALLENGES

In the transition to fuel cell-powered fleets, it is the UTSs that will be responsible for preparing all aspects of their operations to accommodate the changes. The transition will involve administering changes to facilities, operations and planning, equipment, maintenance operations, fuelling infrastructure, the regulatory environment, training, budgeting, and environmental and safety issues. With resources within UTSs already strained, help from outside sources will be required through the transition period.

In addition to internal changes, UTSs will need to secure the commitment of key stakeholders to facilitate and support the transition. Effective communication with all stakeholders will be important during the transition period and as fuel cell-powered buses are introduced.

7 CONCLUSION

Fuel cell-powered buses, expected to be commercially available by 2015, are a viable technology for use in Canada's urban transit fleets.

Fuel cell-powered buses are expected to be able to carry out urban transit duties with performance and reliability that are comparable to or better than their diesel counterparts. Although the acquisition cost of a fuel cell-powered bus will be more than that of a diesel-powered bus, the lifecycle cost, including the cost of acquisition, maintenance and fuel, will be comparable.

Closing the gap between the current reality and what can be possible in 2015 is feasible only if all stakeholders focus on the opportunity that presents itself at this juncture in Canadian transit history.

For the fuel cell and related equipment industry, the Canadian transit fleet represents a critical target market and an ideal first large-scale market segment, as well as a stepping stone to other markets.

A crucial part of closing the gap in the next ten years will be the support of government, at all levels, in accelerating the introduction of fuel cell-powered transit vehicles and acting as a catalyst for increased co-operation among stakeholders.

The introduction of fuel cell-powered buses into transit fleets cannot be achieved without increased government intervention, particularly with regard to transition costs. While fuel cell buses are expected to be cost-competitive on a lifecycle basis, the cost of acquisition (anticipated to exceed that of a diesel bus by two-thirds) is more than most urban transit systems can afford. As well, the one-time cost of adapting facilities, tools and equipment is outside the normal scope of transit system budgets. While this transition is feasible, it will require new arrangements with funding partners to ensure that additional support for capital costs is available.[54]

In the final analysis, it will be governments, with their financial incentives, policies, legislation, and regulatory standards that will be the most critical players in accelerating the transition to fuel cell-powered bus fleets in Canada's urban transit systems.

If this goal is achieved in a timely manner, Canada could become a world leader and innovator in sustainable energy technology and expertise. In turn, Canadian stakeholders in the hydrogen and fuel cell industry would have a sustainable competitive advantage in the global marketplace.

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[54] In Canada, there is no federal funding support for the purchase of transit buses. By contrast, in the U.S., the Department of Transportation's Federal Transit Administration (FTA) can fund up to 80% of the capital cost of transit buses. In Canada, individual UTSs fund new bus purchases through their funding partners, i.e., the province and/or local municipal entities. (Source: Manitoba Energy Development Initiative.)

8 RECOMMENDATIONS

A significant collaborative effort involving all stakeholder groups is imperative if there is to be a successful transition to fuel cell-powered bus fleets in Canadian urban transit systems.

All stakeholders – urban transit systems (UTSs), bus manufacturers, fuel cell system suppliers, fuel storage system suppliers, fuel and fuelling station providers, training institutions, and governments – have a critical role to play. Following is a list of recommended activities by stakeholder group:

For the Canadian UTS Industry

It will be important for urban transit systems to work collaboratively in the development of fuel cell-powered transit bus technology. In advance of fuel cell-powered buses being commercially available, there are a number of activities UTSs can undertake to ensure that fuel cell technology will meet their operational requirements.
These are:

1. Clearly determine current operations and maintenance costs to use as a baseline when considering a transition to fuel cell technology;
2. Determine the current skills profile of their maintenance workforce to use when planning for the changes in competencies required to maintain a fuel cell-powered bus fleet;
3. When hydrogen codes and standards are available, examine the changes that will be required to existing facilities to accommodate and operate fuel cell-powered buses;
4. Within the context of individual UTS strategic plans, determine if the transition to fuel cell technology needs to be addressed by building new facilities at a green-field site; if so, identify potential sites within the service area;
5. Assess the impact of gaseous hydrogen use on current occupational health and safety programs in the UTS environment;
6. Review hydrogen-related emergency response plans;
7. Identify opportunities for shared fuelling facilities, i.e., small UTSs and city fleets;
8. Enlist the Canadian Urban Transit Association (CUTA) to be a clearing house for the sharing of information and experience related to hydrogen and fuel cell-powered buses;
9. Using CUTA as a reference base, establish a centre of knowledge and expertise for UTSs with regard to alternative fuel technologies and particularly hydrogen fuel cell technology developments;
10. Keep UTS governing boards informed of fuel cell technology developments relevant to urban transit;
11. Sponsor the development of a transition cost model that UTSs can readily use to assess their specific situation when considering fuel cell-powered buses; and
12. Continue participation in cost-shared demonstration programs.

For Bus Manufacturers

It is recommended that bus manufacturers take a more proactive role in the technical integration of fuel cells in urban transit buses. In particular, it is recommended that they:

13. Work in collaboration with fuel cell system suppliers;
14. Develop bus design guidelines for fuel cell system suppliers;

15. Continue participation in cost-shared demonstration programs.

For Fuel Cell System Suppliers

In addition to resolving technical challenges and focusing on cost reduction, it is recommended that fuel cell system suppliers:

16. Co-operate with all industry stakeholders to advance the anticipated date of market readiness;
17. Ensure continued co-operation with bus manufacturers to facilitate the smooth integration of fuel cells in new bus design and optimal manufacturability;
18. Develop field training programs for UTS maintenance and operations personnel;
19. Consider developing "stack rebuilding" services, procedures and pricing;
20. Continue participation in cost-shared demonstration programs;
21. Consider cross-application designs to standardize parts requirements; and
22. Study the possibility of balance-of-plant standardization throughout the fuel cell industry in an effort to simplify maintenance for UTSs and decrease costs for fuel cell suppliers.

For Hydrogen Fuel Storage System Suppliers

The major challenge facing storage system suppliers is reducing the weight of on-board storage cylinders. It is recommended that they also:

23. Continue development of 700-bar storage and dispensing systems;
24. Develop larger units for fixed on-site storage and transportable systems for hydrogen fuel suppliers;
25. Work with bus manufacturers on the design of on-board storage;
26. Continue participation in cost-shared demonstration programs.

For Hydrogen Fuel and Fuelling System Providers

In addition to resolving technical challenges, it is recommended that fuel and fuelling system providers:

27. Determine what is required and plan for the expansion of centralized production units to meet the anticipated increase in demand from UTSs;
28. Identify opportunities for pipeline delivery and additional by-product recovery;
29. Identify opportunities for shared fuelling facilities (i.e., small UTSs and city fleets);
30. Provide information to the Canadian Association of Motive Power Educators (CAMPE) on the integration of hydrogen-related training into existing apprenticeship and licensing programs;
31. Continue participation in the development of hydrogen-specific standards and codes;
32. Continue participation in cost-shared demonstration programs; and
33. Acquire, review and share performance data from demonstration projects.

For Training Institutions
Training institutions will be faced with many tasks in the coming years. It is recommended that they:

34. Coordinate with provincial and inter-provincial apprenticeship programs regarding hydrogen and fuel cell-related trades training; for example, through the Canadian Association of Motive Power Educators (CAMPE);
35. Use a centralized training and certification body for hydrogen and fuel cell-related training and certification;
36. Integrate hydrogen and fuel cell-related training into existing apprenticeship and licensing programs rather than creating new training programs;
37. Revise hazardous material technician training under provincial fire marshal programs;
38. Co-operate with the United States in creating standardized hydrogen-related fire safety programs throughout North America;
39. Prepare hydrogen and fuel cell-related emergency response training.

For Governments
Governments have a crucial role to play in the future of both the fuel cell and urban transit industries. It is recommended that they:

40. Consider changing or enacting legislation to encourage commercial application of fuel cell technologies;
41. Continue to develop appropriate funding strategies to support the transition to hydrogen fuel cell–powered applications through:
    - incentives for bus acquisition
    - incentives for facilities building or conversion (including fuelling stations) and
    - incentives for education to facilitate adoption of fuel cell technologies.
42. Continue participation in cost-shared demonstration programs;
43. Complete the assessment of the overall cost-benefit comparison of fuel cell-powered buses to diesel buses by taking into account social costs such as air pollution, noise, and greenhouse gas emissions;
44. Develop regulations and processes regarding fuel cell-powered bus registration;
45. Continue to develop regulatory standards for vehicles, operating facilities and fuelling systems based on hydrogen and fuel-cell technology;
46. Survey health and safety regulations in the various provinces and territories to determine the implications of introducing hydrogen in the workplace;
47. Increase the quantity and level of information for various publics in order to improve their awareness, e.g., citizens, media, insurance companies and labour groups;
48. Gauge Canadian public support for the use of fuel cell technology in urban transit systems and continue monitoring over time;
49. Articulate a national strategy for providing incentives to accelerate the commercialization of fuel cell-powered heavy duty vehicles in Canada; and
50. Target environmentally sensitive areas and smaller UTSs with clear and definitive policies to encourage the early adoption of fuel cell-powered bus fleets.

ANNEX A: GENERAL OVERVIEW OF FUEL CELL TECHNOLOGY

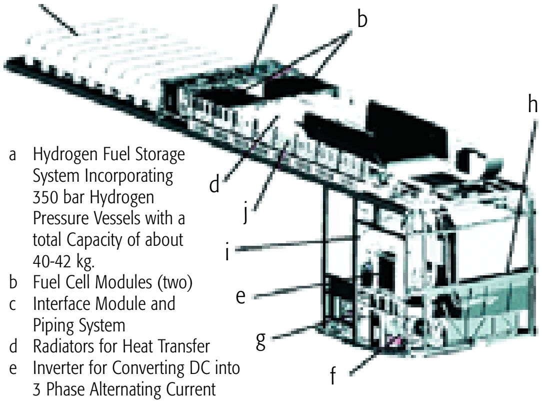
A1 FUEL CELL SYSTEM TECHNOLOGY

Fuel cell power systems consist of:

- On-board fuelling provisions for delivering hydrogen or a hydrogen-rich gas;
- The fuel cell system itself, comprising the fuel cell stack and its auxiliaries;
- A power conditioner that converts the raw DC power from the fuel cell stack to a form suitable for the AC or DC motor controller, depending on whether the vehicle uses AC induction motors (more typical) or DC motors; and
- A microprocessor-based system controller.

In addition to the power-generating fuel cell stack, the fuel cell system requires several auxiliaries to support stack operation. Some are related to the need to provide internal cooling within the stack. These are comprised of: a pump for circulating a liquid coolant; a heat-rejection heat-exchanger/fan apparatus (similar to an automotive radiator) for dissipating heat from the coolant; a coolant reservoir; and, where water is used as the coolant, a deionizer-based purifier to maintain water quality. Other auxiliaries include: a reactant-air delivery blower (or compressor), a system for air humidification; and product-water-recovery condenser apparatus. In hydrogen-fuelled systems, the remaining fuel cell system component requirements are relatively minor. However, in systems with hydrocarbon-based fuels, substantial integration between the fuelling subsystem and the fuel cell system is required and additional heat exchangers are generally needed.

Figure A-1. Fuel Cell Power System



a Hydrogen Fuel Storage System Incorporating 350 bar Hydrogen Pressure Vessels with a total Capacity of about 40-42 kg.
b Fuel Cell Modules (two)
c Interface Module and Piping System
d Radiators for Heat Transfer
e Inverter for Converting DC into 3 Phase Alternating Current
f Auxiliary Gear Case and Electric Drive
g Automatic Torque Converter
h Fuel Cell Control Device
i Air Supply System
j Cooling System

The HY-205 P5-1 Drive Train Main Subsystem Locations

The illustration opposite shows the general layout of the main components of a fuel cell power system.

The fuel cell stack technology being targeted for urban transit bus application is proton-exchange membrane (PEM) technology (shown in the illustration). This is due to several factors, including development status, power density capability, operating temperature range, and start-up and response time. These issues are addressed in the discussion of PEM cell and stack technology.

A1.1 Membrane Electrolyte

PEM fuel cell technology is characterized by the proton-exchange membrane electrolyte, generally represented by the trifluoromethane sulfonic acid proton conductor embedded in a polytetrafluoroethylene matrix. This electrolyte conducts protons (hydrogen ions) from the anode (hydrogen oxidation electrode) to the cathode (oxygen reduction electrode) of the cell, in beneficial conjunction with water molecules that are "dragged" with the protons. This process is relatively efficient provided that the moisture level in the cell is high enough to prevent the membrane from drying out.

Most fuel cell stack suppliers indicate that the operating temperatures of cells can range from a few degrees above freezing to more than 80°C. However, it has been recently demonstrated that some fuel cell stacks can operate at temperatures below freezing.[1]

Current development efforts seek to extend this range, even beyond the boiling point, using pressurized operation and/or novel electrolyte chemistry. Membrane thickness is typically in the 25-125 micrometer range. Thinner membranes yield higher performance because of reduced through-plane resistance. This is partially attributable to enhanced back-migration of liquid product water from cathode to anode. Compromises in membrane thickness are often made to promote durability.

A1.2 Electrocatalysts

PEM cells generally utilize platinum-based catalysts. The cathode catalyst is usually platinum-only, supported on carbon black. However, development work is being carried out on platinum alloys in search of enhanced activity. Anode catalysts are almost always platinum-only (also on a carbon black support). When trace concentrations of carbon monoxide are present (e.g., 10-100 ppm), however, platinum alloys, typically platinum-ruthenium, are used to mitigate poisoning.

Platinum loadings are generally in the 0.25 to 1.0 mg/cm^2 range at the cathode and at the lower end of that range at the anode, provided that carbon monoxide (CO) is not present. With CO-containing anode feed, the platinum loading is usually at least 0.5 mg/cm^2, along with additional ruthenium at about half that loading.

A1.3 Electrodes

The PEM electrodes consist of the carbon-black-supported catalyst and binder, comprising the catalyst layer, deposited on a porous, conductive substrate. Alternatively, the catalyst layer can be deposited directly onto the electrolyte-membrane. Either way, the substrate serves as a gas-diffusion layer through which the reactant gas migrates from distribution channels within the adjacent bipolar plate to the catalyst layer.

The catalyst layer binder is generally a dispersed form of the ionomer that is present in the membrane, serving to promote ionic conduction within the catalyst layer. The substrate is usually a highly porous carbon paper or carbon cloth.

A1.4 Bipolar Plate

The bipolar plate in the PEM fuel cell functions to conduct electrons from one cell to the next, to separate the fuel gas on one side from the oxidant gas (air) on the other, and to distribute reactant gas on each side to the respective adjacent electrode. Accordingly, this plate must be electronically conductive, be impermeable and have channels (or porous elements) on opposite surfaces. Bipolar plates are generally fabricated out of graphite via compression moulding. Alternatively, they can be formed from metal,

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[1] "Honda Motor Co. Ltd. today announced the development of the Honda FC Stack, a remarkably compact, next-generation fuel cell stack that delivers high performance yet operates at temperatures as low as -20°C (-4°F)." Source: Honda Motor Co. Press Release, Tokyo, October 10, 2003.

an approach that could yield a thinner, stronger, and possibly lower-cost component, but the plates must be kept free of corrosion.

A1.5 Stack Technology

The component technologies described above must be fabricated and incorporated into a series-connected "stack" of cells in order to generate a voltage high enough for practical use. In addition to the cell components, provisions must be made for: implementing edge seals and manifolding seals for reactants in each cell; internal cooling to control temperature within the stack; current-collector plates at the ends of the stack; outboard end-plates upon which to apply compressive load to the stack, copressive-loading means, internal and/or external reactant manifolds; and possibly external thermal insulation.

A1.6 Stack Cooling

The cooling provisions are a major consideration in stack design. Except in the case of very small stacks, cooling to remove waste heat generated within the stack is generally accomplished via forced convection of a liquid (usually water) through cooling plates that are uniformly spaced throughout the cell stack. There is usually one cooling plate per cell, especially in high-power-density operations (as would be expected in an urban transit bus), in order to maintain an acceptably uniform temperature throughout the stack. In this regard, liquid flow is delivered at a high rate to minimize liquid temperature increases. As in the case of bipolar plates, cooling plate materials are usually graphite-based to avoid corrosion. In addition, unless a dielectric liquid is used, the coolant must be continuously treated to prevent impurity build-up; ions in the water could otherwise cause enough ionic conductivity to create appreciable "shunt" current within the water phase that communicates with all cells in the stack.

A1.7 Stack Performance

In the fuel cell-powered urban transit bus arena, the greatest emphasis to date has been on PEM fuel cell technology. As discussed, the operating temperature range is broad and it extends to temperatures low enough to foster reasonably short start-up times. The transit application benefits from the comprehensive PEM fuel cell development activity that has been carried out in the portable, stationary and, above all, automotive areas. PEM cell technology has advanced to the stage where achievable power densities are at least competitive with those of other fuel cell types.

Although there is little specific information available regarding performance from fuel cell system manufacturers involved in urban transit bus development, assumptions can be made based on the general state-of-the-art PEM technology. Operating current densities for relevant stacks are typically in the 0.3 to 0.6 ampere/cm^2 range at voltages of 0.6 to 0.7 volt/cell (hydrogen fuel; air at near-ambient pressure). Higher levels of stack power density can be achieved through the use of pressurized air. However, this requires an air compressor, which consumes substantial parasitic power and generates far more noise compared to a blower operating at near-ambient conditions. Fuel cell system manufacturers are divided in terms of preference for low-pressure versus high-pressure operation. A representative power density at rated power (near-ambient air pressure) may be assumed to be at about the 0.30 to 0.35 watt/cm^2 range (where cm^2 represents active cell area).

There is a great deal of PEM fuel cell stack development and testing that is directed toward achieving and confirming the necessary durability of these stacks. It may be assumed that significant progress is being made, but any evidence is limited to laboratory stacks at this time.

It should be noted that, while the required life for an automotive fuel cell is less than 5,000 hours, the operating life of an urban bus is much higher (equivalent to about 1.6 million km of driving). Accordingly, the voltage decay rate for a fuel cell operating for the life of the bus would need to be less than about 2 mV/cell per 1,000 hours. At the time of preparation of this study, no published data has been found to indicate that this decay rate has been realized in representative stacks.

A1.8 Fuel Cell System Costs

The discussion of fuel cell system technology provides a framework for projecting the capital cost of the cell-related components of the system. The principal components are the platinum-based electro-catalyst, the electrolyte-membrane and the bipolar plates.

For this exercise, it will be assumed that the platinum catalyst loading of each electrode will be the predominant factor affecting electrode cost and that the loading will be 0.5 mg/cm^2 at the cathode and 0.25 mg/cm^2 at the anode (assuming no CO is present in the fuel gas). It is further assumed that the cell power density will be 0.3 W/cm^2. Projecting the market cost of platinum at $20/g, the overall catalyst cost would then be $50/kW.

The electrolyte-membrane cost can be projected based on the expected cost of reasonably high volumes (i.e., assuming there is a substantial PEM fuel cell market upon which the urban transit bus application can piggyback). For this exercise, the membrane cost will be assumed to be $100/m^2. Using the same power density as above, the membrane cost would be $33/kW.

The bipolar plate cost will depend on the fabrication process and, of course, the manufacturing volume. Once again, projecting reasonably high volumes, the type of fabrication process involved (see earlier discussion of cell components) can be projected at $50/m^2. The cooling plates that are required for the stack are expected to be manufactured in a similar fashion and are required in similar quantities. On the other hand, savings could be realized via integration of functions between these types of plates, thereby reducing the required plate count, albeit with a more complex configuration. Taking these issues into consideration, it can be assumed that the overall plate cost per cell would be $75/m^2. At the assumed power density, the plate cost would then be $25/kW.

All of the additional provisions required for the fuel cell stack (cited in the preceding discussion of stack technology) constitute what could be considered an “overhead” cost for the stack in relation to that of the cell components. These provisions are a function of the design approach of fuel cell system manufacturers. However, assuming effective optimization with respect to cost and reasonably high volume, this “overhead” cost can be expected to be low. If the “overhead” costs are assumed to be 15% of the cell costs, they would amount to $16/kW. The overall stack cost would then be $24/kW. In the meantime, such designs have not yet been optimized and volumes are still low. Volumes for cell component manufacturing are also low. Hence, stack costs today are considered to be several times this figure.

The auxiliary components required in the fuel cell system to support the stack are discussed in A1. Many of the relevant components are specific to the particular fuel cell application, and their ultimate cost will depend on design and volume issues. Other components are commercial or near-commercial but are not manufactured in volume for any existing applications. Some components, and most of the hardware items, are common items of commerce and therefore readily available at competitive prices. It will be up to fuel cell system manufacturers to lower their costs by taking advantage of high-volume manufacturing. They can minimize the cost of auxiliary components by using commercially available designs or by piggybacking on designs targeted at other upcoming high-volume applications.

A2 FUEL CELL SYSTEM MANUFACTURERS

The degree of interest in urban transit buses demonstrated by fuel cell system manufacturers has been growing over the last decade, spurred on by several factors:

- Transit buses operate within a relatively short, closed-loop pattern;
- They are maintained by a well trained and stable team;
- They are refuelled in one or a few central locations;
- Urban transit systems belong, for the most part, to governments or government agencies;
- They are already heavily subsidized with public funds;
- They serve the public in general and a good share of environmentally-sensitive citizens;
- There is a relatively small number of bus manufacturers serving a manageable number of potential customers with a large number of vehicles; and
- The number of government-funded demonstration programs for urban transit applications is growing world-wide.

A2.1 North American Fuel Cell System Manufacturers

In North America, there are presently at least three potential suppliers of PEM fuel cell systems for transit buses: the Canadian companies Ballard and Hydrogenics and the United States' United Technologies Corporation (UTC). Interviews were conducted with representatives from these three manufacturers regarding their involvement in demonstration activities.

Ballard Power Systems

Ballard Power Systems has been developing heavy-duty fuel cell systems since the early 1990s. The company provided three hydrogen-fuelled 90-kW PEM fuel cell systems for New Flyer buses that were tested from 1997-2000. The company is now providing three hydrogen-fuelled 205-kW PEM systems for Gillig buses that will be demonstrated in California, as well as a 65-kW PEM fuel cell that will be part of a fuel cell/battery hybrid system for a MAN bus.

Ballard has recently completed delivery of 27 heavy duty fuel cell systems for the Clean Urban Transit in Europe (CUTE) program running in nine European cities, and has supplied a further nine systems (three each) for demonstrations in Iceland, Australia and China. The CUTE demonstration data will be used to refine Ballard's commercial heavy duty fuel cell system design.

Hydrogenics

Hydrogenics supplied a 10-kW PEM fuel cell for a Hawaii-based project that carried out tests on a fuel cell hybrid bus. The power system has provisions for supplying electricity to the grid when the bus is idle. Hydrogenics will also supply a 180-kW PEM fuel cell that comprises several stacks for a New Flyer bus. This system will also have grid-power capabilities. The company plans to continue participating in demonstrations and is working aggressively on the integration of ultracapacitors into its power system.

United Technologies Corporation (UTC)

UTC has been active in the fuel cell-powered bus area since the 1990s. In conjunction with the fuel cell-powered bus program championed by Georgetown University, a 100-kW phosphoric acid fuel cell, operating on methanol fuel, was tested in a 12-metre vehicle from Nova Bus, as part of a fuel cell/battery hybrid system. In 2002, a 75-kW PEM fuel cell, operating on hydrogen, was tested in a nine-metre bus from Thor Industries, as part of a fuel cell hybrid system. UTC has also supplied systems for projects in Torino, Italy.

UTC is providing a hydrogen-fuelled 170-kW PEM fuel cell system for a North American Bus Industries vehicle in a California-based project. It is also supplying a 60-kW PEM fuel cell, as part of a fuel cell/battery system, for each of five 12-metre Irisbus buses to be tested in Europe. UTC will also supply 120-kW PEM fuel cells, as part of a fuel cell/battery hybrid system, for four Van Hool buses to be tested under the auspices of the California Fuel Cell Partnership.

UTC representatives confirmed that the organization will continue its involvement as long as it can find shared funding for its efforts. UTC considers the California vehicle initiative to be a major factor in the commercialization of fuel cells in the urban transit bus market.

A2.3 Other Fuel Cell System Manufacturers

Proton Motor Fuel Cell GmbH

This German company, located in Strarnberg, is one of the leading European companies for PEM fuel cell technology and has been developing and producing PEM fuel cells and fuel cell systems since 1998. Proton Motor is providing Volvo with a system for a 15-metre, double-decker bus.

Siemens

Siemens supplied a hydrogen-fuelled 120-kW PEM fuel cell system, composed of four stacks, for testing in a MAN bus during 2000-2001.

Toyota

Toyota installed and tested a hydrogen-fuelled 90-kW PEM fuel cell hybrid system in a bus in 2001. In 2002, Toyota provided a power system consisting of two 90-kW fuel cells. In 2005, Toyota plans to have an upgraded version of this bus operating in Japan.

A3 ON-BOARD FUEL STORAGE TECHNOLOGY

The great majority of fuel cell-powered buses are equipped with gaseous compressed hydrogen cylinders that are placed on bus rooftops. These buses carry 40 to 50 kg of hydrogen fuel in eight to 11 cylinders, at a pressure of 350 bar.

There are two cylinder constructions currently available: a plastic core (weighing 46 kg) or an aluminium core wrapped in carbon reinforced fibre (weighing 87 kg). The filling capacity of both cylinder types is comparable (5 kg/unit), with plastic-core cylinders accommodating 10% less hydrogen than aluminium-core cylinders. Operating temperatures for both cylinder types range from –40°C to +85°C. Currently, plastic cylinders have received NGV2-1998 and TÜV[2] certifications while the aluminium technology is CSA (B51-97), NGV2 and TÜV (505) certified. The life expectancy of both types of cylinders is 15,000 fills or approximately 20 years. The cylinders themselves require no maintenance, but valves and manifold assembly may result in annual costs of 3% of the initial system cost.

In terms of performance, the current on-board storage technologies provide fuel cell-powered buses with a range that varies from 300 to 400 km. Replenishment of hydrogen fuel can be completed in eight to 10 minutes, although one supplier claims it can be completed in five minutes. Fuelling time is obviously dependent on the type of fuelling equipment used.

On-board storage system costs, installed, range from $65,000 to $80,000 per bus, depending on the technology and the system configuration used.

By 2015, on-board storage system suppliers expect to reduce the weight of their cylinders and be able to provide 700 bar capability, if required. During this same period, prices of storage systems are expected to drop by almost half.

A4 FUEL CELL-POWERED TRANSIT BUSES

To date, most of the effort in integrating fuel cell systems into urban transit has been carried out by fuel cell suppliers. Bus manufacturers have provided shells for experimentation purposes.

With the supply of 27 Citaro buses to the Clean Urban Transit in Europe (CUTE) demonstration program, Daimler-Chrysler leads in the production of fuel cell buses with the support of Ballard. The data from these demonstration programs shows an average price of 1.2 million Euros ($1.84 million). However, it has been difficult to obtain the precise cost of Citaro buses or that of any other fuel cell or fuel cell hybrid bus provided for

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[2] TÜV is a leading technical service company active in the industrial, product and transportation sectors worldwide. Its range of services encompasses consultancy, inspections, tests and expert opinions as well as certification and training.

demonstration purposes. Some of the costs related to the fuel cell system and the integration of bus components, as well as the cost of warranted repairs and maintenance, have been borne by the main provider of fuel cell systems (Ballard/ XCELLSIS) as part of its development investment.

None of the bus manufacturers contacted in the context of this study (New Flyer, Nova Bus, Orion, Gillig, North American Bus Industries Inc. and Van Hool) were able to provide a price for a complete fuel cell-powered bus, mainly because the cost of the power plant and its integration are still unknown.

Outside the CUTE project, the most current demonstration project reviewed in the context of this study is the one involving Van Hool (fuel cell system) and International Fuel Cells Inc. (integrator) for four buses delivered to AC Transit and Sunline in California.

While few new fuel cell bus demonstration projects are currently taking place, large-order sales of diesel-electric hybrids are being concluded. This may reflect the preference of governments and UTSs to wait for improvements in fuel cell bus performance and costs before committing to further investments.

Based on the research and interviews conducted, the present cost of a 200 kW fuel cell system/ propulsion system is estimated to be between $1.2 and $2.0 million (this would be in line with the $6,000 price of Ballard's commercially available fuel cell). This price must be compared to the commercial price of about $70,000 for a diesel engine transmission on an urban transit bus.

A4.1 Favourable Factors and Trends

An encouraging environmental factor for the industry is the proclaimed intent of many governments to undertake actions that will result in cleaning the air, slowing climate change and implementing the Kyoto Accord. Another favourable factor is the industry's perception that public transit systems represent one of the best short-term opportunities to introduce fuel cell technology to the market. The demonstration projects of the last decade are being followed by more elaborate projects such as the Canadian Transportation Fuel Cell Alliance project and the "H_2 Early Adopters Program" from Technology Partnerships Canada. The industry sees these programs as an essential first step to a hydrogen economy, and it sees the transit bus market as a cornerstone for establishing a favourable environment for fuel cells.

Over the past two years, many governments, including Canada, have dramatically increased funding support for hydrogen and fuel cell research, development, demonstration and deployment. Hydrogen and fuel cell systems, whether for stationary power generation or transportation applications, are perceived as an answer to some of the issues arising from the ever-increasing use of fossil-based fuels, such as climate change, urban air pollution and energy security. For countries like Canada that have established expertise in hydrogen and fuel cell technology, the advent of the global hydrogen economy presents an economic opportunity: the deployment of products and technology expertise abroad.

Gasoline, diesel and CNG-fuelled vehicles are major fuel users and consequently major emitters of greenhouse gases, primarily carbon dioxide, which is responsible for the warming of the earth's atmosphere, and air contaminants, such as carbon monoxide and particulates, which are responsible for the poor air quality in major cities around the world. Governments currently encourage the use of mass transit as an energy efficient alternative to passenger cars. The potential for pollution-free, more energy-efficient transit systems makes that option even more attractive.

For the fuel cell system manufacturing industry, favourable factors include improvements in fuel cell system life and reliability. These have resulted, in part, from basic PEM technology advancements. An example is membrane/electrode improvements leading to enhanced stack life characteristics.

A4.2 Unfavourable Factors and Trends

The most pressing challenge for the fuel cell-powered bus industry is system cost reduction. The industry is aware that much work remains to make fuel cell systems commercially competitive.

In the context of the public transit market, the industry recognizes that there is a great deal of pressure on operators to reduce operating costs. Besides fuel cell system costs, other factors, such as the cost of upgrading transit infrastructure and the cost of hydrogen, must be taken into consideration. These factors are not within the industry's control.

A4.3 Infrastructure

The fuel cell system manufacturers see their role as being providers of ready-to-integrate power systems. Partners will be required for bus manufacturing as well as for integrating the power system with the vehicle drive train.

Hydrogen Fuel

Fuel cell system manufacturers prefer the use of compressed, high-purity hydrogen for their buses, as opposed to a liquid fuel. This implies that the establishment of a hydrogen supply infrastructure for vehicle refuelling will be a key factor for the successful introduction of fuel cell-powered buses in the urban transit market. The scope of the hydrogen delivery infrastructure is limited compared to that of personal vehicle fuelling. Nevertheless, UTSs cannot bear the burden of developing such infrastructure. Consequently, government support for hydrogen production, storage, and transportation infrastructure will be imperative.

Capital Costs

Government-sponsored programs involving fuel cell-powered buses currently are and will increasingly become key to the successful integration of this technology in the urban transit systems in Canada and abroad. Early-stage quasi-commercial purchases cannot occur without some form of government intervention through legislation, financial incentives or a combination of both.

The current high cost of fuel cell systems for urban transit buses must also be offset by cost reductions before full-scale commercialization is possible. Some reductions will be achieved through technological advances, but government programs must also help to address the lack of economies of scale in the industry.

Ultimately, market potential for fuel cell-powered buses must be driven by a value proposition based on lifecycle cost.

A5 URBAN TRANSIT BUS MANUFACTURERS

Currently, the participants most involved in developing fuel cell-powered buses are fuel cell system suppliers. With few exceptions, bus manufacturers are reluctant to work on the integration of these systems much before they are fully developed.

The three Canadian manufacturers of transit buses (New Flyer, Orion and NovaBus) presently supply nearly all the 12-metre, low-floor buses acquired by Canadian transit systems. While New Flyer has taken the most proactive stance with respect to fuel cell-powered buses, it is expected that all three manufacturers will participate in the market by 2015. In the commercial phase, fuel cell suppliers will relinquish their leadership to bus manufacturers

There is currently no indication that foreign bus manufacturers will gain a significant share of future fuel cell-powered bus purchases in Canada, but that possibility cannot be totally discounted as manufacturers like Van Hool and Alexander Dennis have already sold specific bus models to Canadian UTSs. As well, consolidation or ownership changes could lead to supply arrangements that are substantially different from those in place today.

The manufacturers that will be the most successful in marketing fuel cell transit buses in Canada will be those that make the transition from bus shell providers to full-scale integrators of fuel cell propulsion systems.

Furthermore, to be commercially successful, transit bus manufacturers must have a product they can market throughout North America, which means they must develop fuel cell-powered transit buses that meet the standards established by the Federal Transit Administration of the U.S. Department of Transportation. Compliance testing for these standards is conducted at the Altoona Research and Testing Centre in Altoona, Pennsylvania. Without this testing, commercial products cannot be sold in the United States.

The areas of testing at Altoona include:

- maintainability;
- reliability;
- safety;
- performance;
- structural integrity and durability;
- fuel economy;
- noise;
- emissions testing; and
- brake testing.

To date, bus manufacturers have shown little interest in arms-length commercial exploitation of the fuel cell-powered bus. The basis for their participation has been government-supported programs.

A6 DEMONSTRATION SITE EXPERIENCE

Demonstrations with urban transit buses, using various types and stages of fuel cell systems and hydrogen fuelling and storage equipment, have been staged since the early 1990s. Over the course of the demonstrations, the performance of fuel cell-powered buses has improved dramatically.

Reports from the demonstrations, before the Clean Urban Transit in Europe (CUTE) experiments in Europe, can be summarized as follows:

- Fuel cell buses almost reached the stage where they could be operated on a daily basis on regular transit bus lines. However, they required more frequent maintenance and repairs than commercially sold diesel or CNG buses (fuel cell stacks and components not directly included in fuel cell systems but required for their operation necessitated the most time).

- The organization of on-board systems (electrical, plumbing, etc.) was not optimized for easy access and maintenance.
- Service availability was lower than that required by transit systems and range was limited to 200 to 300 km.

It should be noted, however, that preliminary results from the first year of operations of the 27 Citaro fuel cell buses in Europe show major improvements with regard to all of these shortcomings. Fuel stack durability has improved to at least 3,000 hours and stacks can be replaced in a shorter timeframe. Availability for service is now compatible with that of a diesel bus. Maintenance costs and downtime (excluding fuel stack replacements) are now in line with commercially available buses.

ANNEX B: GENERAL OVERVIEW OF HYDROGEN FUELLING SYSTEMS

Fuelling systems are composed of all or some of the following:

- A source or production unit;
- A storage system;
- A compression system; and
- A dispensing and metering system.

There are multiple configurations of these components, with the majority of these configurations not relevant to the context of this report.

Gaseous fuel uses technologies that are different from traditional diesel-fuelling systems. The space requirements may therefore differ substantially from current installations, especially where production and storage of hydrogen are concerned. The operating conditions, however, are dictated by parameters for handling gaseous fuels, conditions that are similar to the handling of compressed natural gas (CNG). Safety systems are described in section 3.1 of the report.

Section 3.2 of the report presents four generic fuelling options based on the most common needs of a UTS and the most practical combination of the six factors described previously. A description of the main technologies identified at the time of the writing of this report[3] and the options available to transit system operators within the timeframe of this roadmap are presented below.

B1 OFF-SITE SUPPLY

Industrial hydrogen suppliers have been producing and delivering high-quality hydrogen for several decades with a high degree of reliability. Pricing has varied, mainly due to supply and demand issues. At the time of the writing of this report, there is a surplus of capacity in North America, mainly due to the decrease in demand from the food industry. However, refineries are driving demand upward because of their need for hydrogen in the desulphurization of fossil fuel processes. The current strength of the construction industry also creates a sustained demand for hydrogen for the flat glass industry.

A substantial increase in the demand for hydrogen, such as the one that would result from a massive adoption of hydrogen-fuelled buses by Canadian transit systems, would force hydrogen suppliers to build additional capacity, mainly using natural gas as a feedstock. Prices for hydrogen would then be closely linked to the price of natural gas. Note that hydrogen prices are also influenced by the distance between the source of supply and the customer, at an approximate rate of \$0.01/100 km/Nm^3 when trucking is used to deliver hydrogen.

Hydrogen suppliers offer a turnkey solution to their customers. Their "contract price" for hydrogen therefore covers most costs, including amortization of capital investments for fuelling infrastructures and routine maintenance costs. The following costs are generally not included in the price of hydrogen:

- Land or space for infrastructure at the customer site;
- Civil work required for infrastructure such as cement bases, electrical lines, fences;
- Electricity; and

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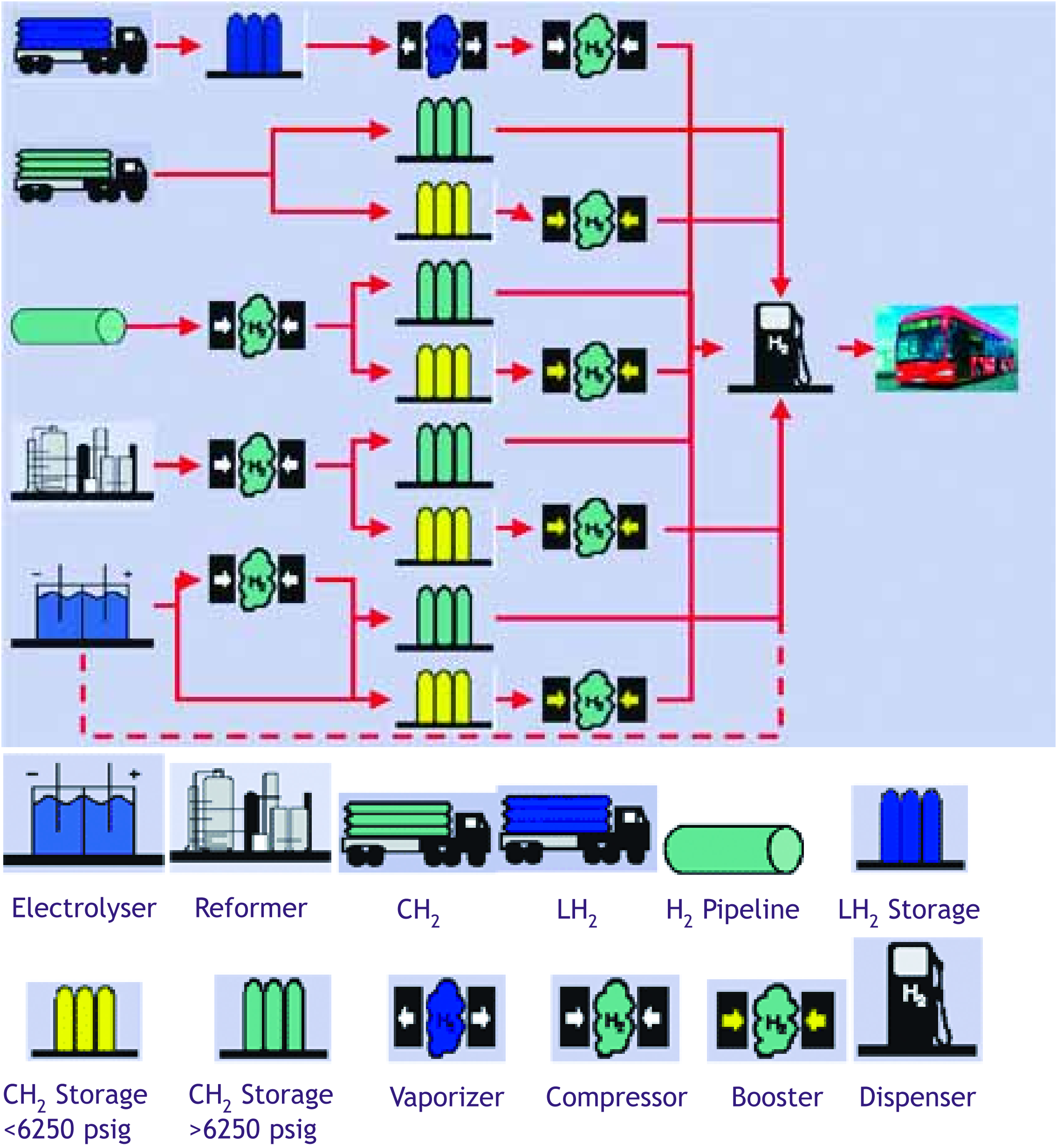
[3] Hydrogen production technologies, such as pyrolysis of biomass and algae photosynthesis, have been excluded from this discussion as they are considered impractical for use by UTSs in the study timeframe.

Figure B-1. Fuelling Systems



- Relocation of any customer installations not related to the system.

It is understandable, therefore, that hydrogen suppliers would encourage UTSs to sign a long-term contract for their hydrogen supply and select the most economical way of ensuring supply continuity. The price of hydrogen would likely include the supply of an on-site storage system, dispensers and meters, as well as other peripheral equipment required to ensure the proper operation of the fuelling system.

The current price of hydrogen for the large quantities required by UTSs is approximately \$0.85/Nm^3 but may vary from \$0.50/Nm^3 to more than \$2.00/Nm^3 depending on the:

- Delivery system selected by the hydrogen fuel supplier, based on the location of the client relative to production facilities;
- Quantities;
- Distance from the production facilities;
- Type of installations required;
- Contract duration;
- Supply security provisions required;
- Timing of negotiations; and
- Trends in the price of natural gas.

Hydrogen suppliers today would resort to one of the following three methods of delivering hydrogen to transit systems:

- Liquid hydrogen produced off-site, trucked to the site and stored on-site;
- Gaseous hydrogen produced off-site and delivered by pipeline; or
- Gaseous hydrogen produced off-site and delivered by truck.

Liquid hydrogen is available in several locations in Canada and, because of its comparative density, travels long distances relatively economically when large quantities are involved. Where pipelines are not available, it is the delivery method preferred by hydrogen suppliers. Wherever liquid hydrogen is used, a cryogenic or vacuum tank is required on-site. Other equipment, such as a vaporizer and a compressor, are also needed to produce adequate pressure for fuelling.

Currently, there are only three hydrogen pipelines in Canada, located in Bécancour (Québec), Sarnia (Ontario) and Fort Saskatchewan (Alberta). These pipelines serve refineries and a few large users. All three feed off a by-product gas stream recuperated from another chemical process. These pipelines may have excess capacity that could serve local transit companies. The low pressure of gaseous hydrogen in pipelines is such that one or two compressors are required on-site to pressurize the fuel to 350 bar for on-board storage.

Gaseous delivery is practical only when a UTS is located within about 300 km of the hydrogen production site. In this case, exchanges of gaseous reservoirs up to 250-bar pressure are the most common method in use today. In the future, however, large 700-bar storage tanks will become available for hydrogen transportation purposes and are likely to displace liquid hydrogen, given that the density of the hydrogen they will contain is comparable to that of liquid tankers and that the costly procedure of liquefaction is avoided. This option is discussed later in this annex.

Hydrogen suppliers can also offer on-site production. Under the right conditions, they could propose electrolysis or reformer-based hydrogen generators to their customers. The choice of "delivery method" is wholly dictated by the economics involved and the rate of utilization of the supply base at the time of the decision. On-site production is discussed in the following section. The technologies used by hydrogen suppliers are the same as those described for use by UTSs. The cost of on-site equipment and its operation and maintenance are all wrapped into the cost of hydrogen and a monthly service charge. There is therefore no need for capitalization on the part of the UTS.

Under specific circumstances, when large bus fleets are fuelled in a central location where there is no available space for the construction of a large reformer, it will be possible and likely economical to build a steam methane reformer (SMR) off-site and a connecting pipeline to bring the hydrogen to the UTS.

B2 ON-SITE PRODUCTION OF HYDROGEN

Generally speaking, there are two technologies that would reasonably allow a UTS to produce its own hydrogen, given the right set of circumstances and economic factors: water electrolysis and on-site reforming of hydrocarbon gases or alcohols.

B2.1 Water Electrolysis-Based On-Site Production

These fuelling stations have a water electrolysis hydrogen generator (commonly known as an electrolyzer) as their source of hydrogen. The storage systems, compression systems, dispensers and meters are quite similar to all other technologies and do not warrant further explanation in the context of this report.

Electrolyzers apply a continuous current to water to split the molecule of hydrogen from the molecule of oxygen. The amount of electricity per cubic meter of usable hydrogen required varies depending on the electrolyzer's design efficiency and the nature of the peripheral equipment required to operate the reactor (i.e., cooling system) and to purify the hydrogen (i.e., drying system).

Electrolysis systems produce hydrogen gas with only oxygen gas as a vented co-product. The resulting hydrogen stream is purer than reformer-derived hydrogen and there is less chance of the presence of contaminants detrimental to fuel cells. Consequently, a purification system is generally not required.[4]

Typically, electrolyzers consume 56 to 67 kWh/kg of hydrogen. This represents the single largest cost component of the hydrogen produced by electrolysis. The following table demonstrates the impact of the cost of electricity on the cost of hydrogen.

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[4] Some electrolyzers present traces of potassium hydroxide in the hydrogen stream and therefore require a purification system.

Table B-1. Impact of Electricity Prices on Cost of Hydrogen

Cost of Electricity per kWh	Hydrogen Cost @ 56 kWh/kg ($ per kg)	Hydrogen Cost @67 kWh/kg ($ per kg)
$ 0.04	2.24	2.68
$ 0.05	2.80	3.35
$ 0.06	3.36	4.02
$ 0.07	3.92	4.69

Source: MARCON-DDM HIT, 2004

In addition to electricity, other cost components of producing hydrogen by water electrolysis are:

- The initial investment to purchase the equipment;
- The installation costs (including commissioning and local approvals);
- The cost of maintenance;
- The cost of an adequate supply of water;
- The cost of operation (other than power);
- The cost of supplies (water filtration agents, catalyst, etc.); and
- Insurance costs.

Depending on the supplier and the size of equipment, the cost components can add another $5.50 to $11.00/kg to the cost of electricity, bringing the total cost of hydrogen to about $13.00/kg.

Although large custom-made units are available, the maximum output of today's standardized commercially available electrolyzers (single unit with multiple stacks) is 260 kg/day. Several such units can be used together but at this time, this results in few economies of scale.

Prototypes able to produce hydrogen at an electrolytic pressure exceeding 350 bar are already being tested. It is expected they will be commercially available well before 2015, thereby eliminating the need for compression systems.[5]

Future developments will allow larger standardized units to enter the market, as a result of larger diameter electrolysis stacks and common peripherals and controls for larger quantities of stacks. Simplified designs of the electrolyzer module and integrated manufacturing methods, along with increased efficiency, will also reduce manufacturing and operating costs.

These developments will contribute significantly to driving the cost of hydrogen produced by water electrolysis toward U.S. Department of Energy technical targets for 2015. These include 10-15% energy efficiency improvements and capital cost reductions of 20% or more.

The major drawback associated with the use of electrolyzers is that there is not yet a large marginal decrease in the cost of hydrogen as the quantities required increase.[6] Consequently, there is a fairly narrow range of fleet sizes where water electrolysis-based fuelling stations can be operated at a cheaper cost than that of competitive technologies (discussed in section 3.2 of the report).

On the other hand, some UTSs located in environmentally-sensitive areas may consider electrolyzers the only acceptable means of hydrogen generation as they can produce totally "green

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[5] Cost elements used in the cost model, therefore, assume there will be no need for compressors in an electrolysis-based fuelling system.

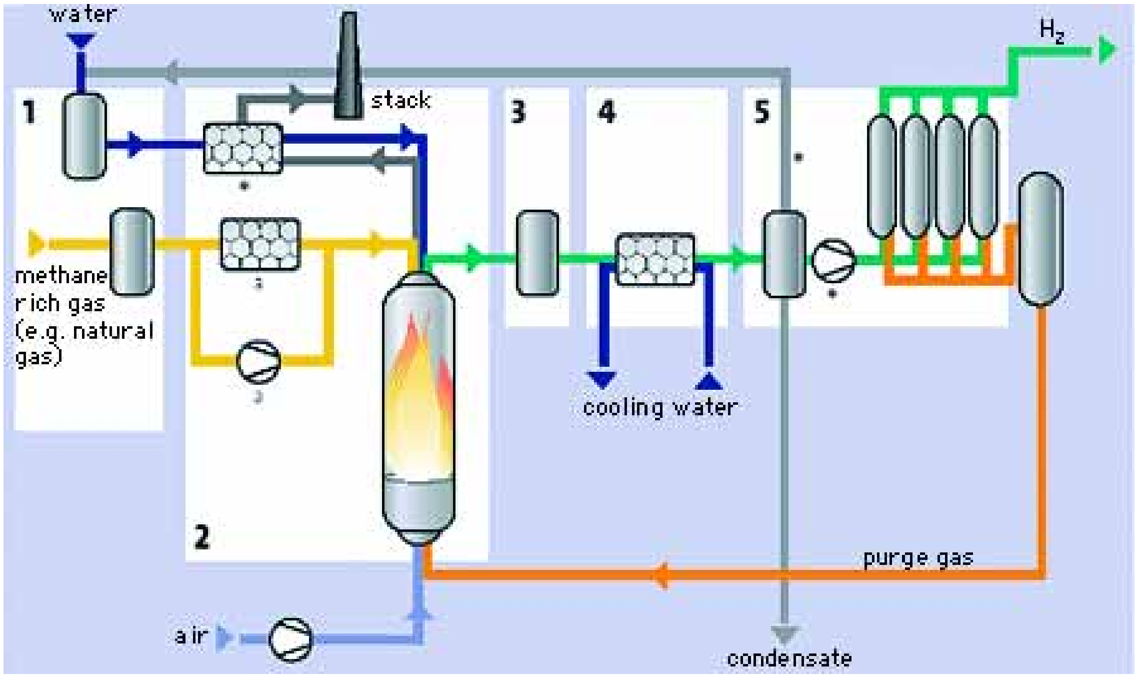
[6] Up to 60% of the cost of producing hydrogen is electricity. At least two thirds of this electricity is used to split the water molecule. Therefore, the minimum operating cost amounts to $0.20/Nm^3 at a $0.05/kWh rate.

hydrogen" when the electricity is procured from a renewable source.

B2.2 Hydrocarbon/Alcohol-Based On-Site Production

There are several reforming technologies, each with significant differences in yield, complexity and capital cost. In general, hydrocarbon/alcohol-based fuelling stations use reforming technologies to extract hydrogen from natural gas or methanol. To generate a hydrogen product from the feedstock, the hydrogen is liberated from the carbon by breaking the carbon-hydrogen bond. Reformers accomplish this by using a combination of heat and catalysts. After the initial step of breaking down the hydrocarbon, further steps are taken to "clean

Figure B-2. Flow Chart of Steam Methane Reformer



1 Feed Pre-Treatment[7]
2 Reforming and Steam Generation
3 High Temperature Conversion
4 Heat Exchanger Unit
5 Purification Unit

* Optional, depending on reformer design, either a heat exchanger for low-pressure reformer or compression to 16 bar for high-pressure reformer

Source: CUTE, Hydrogen Supply Infrastructure And Fuel Cell Bus Technology, 2004

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[7] Natural gas available from utilities has a sulphur-based odorant added for safety reasons. Any such contaminant needs to be fully removed, given the possible detrimental impact on the reforming process and the potential poisonous impact on PEM fuel cells if such contaminants were present in the hydrogen stream.

up" by-product components that would hinder fuel cell performance. Figure B-2 illustrates the functioning of a typical steam methane reformer.

There are four main categories of reforming technologies:

- Steam reforming of hydrocarbons, usually natural gas, yields relatively cost-competitive hydrogen in large quantities but does not eliminate the production of CO_2 – it simply relocates CO_2 production upstream.
- Partial oxidation (POx) is a large-scale production method that is most often used for heavy oil (low value) refinery by-products.
- Auto-thermal reforming (ATR) is often considered a sub-category of partial oxidation.
- Alcohol reformation takes advantage of liquid's (e.g., methanol and ethanol) benign shipping and storage properties for localized hydrogen production. These liquids are easily reformed to hydrogen. As in natural gas reforming, alcohol reformation yields CO_2.

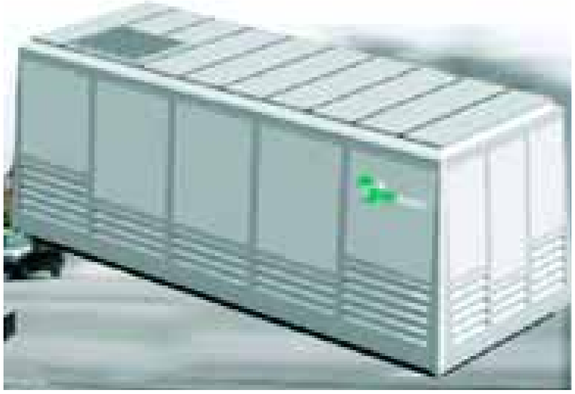
The highest possible yield of hydrogen is obtained from steam methane reforming (SMR) of natural gas, which is the dominant hydrogen production technology on a large scale. Of the four technologies, it is the most complex and to date has been difficult to downscale.

Depending on their relative efficiency, current SMRs use four to six Nm^3 of natural gas to produce one kg of hydrogen. With prices for natural gas varying from $2.00 to $8.00, the direct cost of producing one kg of hydrogen ranges from $3.35 to $20.88. The investment costs must then be added ($7.48 to $13.39/kg, depending on the SMR size), for a total cost varying from $10.83 to $34.27/kg of hydrogen.

Traditionally, reformers have been custom-built to user specifications using widely-known processes. Most units are fairly large, have a long response time and are able to produce several tons of hydrogen per day. Usually located in heavy industrial areas, aesthetics and footprint have not been an important concern in the design of these reformers.

ATR and POx are simpler technologies but with significant yield penalties. For example, the hydrogen yielded by POx conversion of methane is approximately half that yielded by SMRs.

Recently, packaged units have been introduced to the marketplace. They are usually much smaller with attention paid to external appearance. To achieve compactness, reforming technologies, such as auto-thermal reforming and partial oxidation, have been and continue to be perfected. Currently, these packaged generators can produce a maximum of 100 Nm^3/hour per single unit) and several units can be used together. Contrary to electrolyzers, these reformers benefit from important economies when scaled up to larger output units, as their cost of capital per kg of hydrogen represents a larger share of the total cost of hydrogen.



Future technological improvements will increase the thermal efficiency of these generators to 75 or 80%, increase their operating pressure (currently near atmospheric), and further decrease the sensitivity of the steam reformer to multiple start ups and shut downs. Much needed size reductions, about 25 to 40%, are also expected.

Much work is being done to simplify the design of certain components and to decrease equipment cost by 20 to 30% with the use of integrated manufacturing methods. Mass production could further reduce these costs by as much as 50%. In terms of operating cost, an increase in the reformer's efficiency should reduce costs.

B3 BALANCE OF PLANT

The balance of a fuelling plant is comprised of storage systems, compression systems, dispensers and meters.

B3.1 Compression System Configurations

If hydrogen is stored on board at 350 bar, an inlet pressure of 430 bar is usually required. There are two methods of doing this: overflow filling and booster filling. **Overflow filling** occurs when the rated pressure of the station storage is higher than that of the vehicle tank after refuelling. Refuelling is achieved by gas overflow from the station into the vehicle vessels and pressure levelling between the two. **Booster filling** occurs when the station storage has a rated pressure below that of the vehicle tank. In this case, a "booster compressor" is required to make up for the difference prior to filling the bus cylinders. It is installed between the storage reservoir and the dispenser.

Another piece of equipment is the vaporizer, used to bring liquid hydrogen to gaseous form under controlled conditions. This operation cannot provide 430 bar of pressure; therefore, either a booster or a compressor must be used in the supply chain where liquid hydrogen is the source.

B3.2 Storage System Configurations

There are two types of storage systems: vacuum tanks for liquid hydrogen and high-pressure reservoirs for gaseous hydrogen (GH_2).

Vacuum Tanks for Liquid Hydrogen

Liquid hydrogen storage is a proven technology that has been used by hydrogen suppliers for several decades. However, it requires equipment, i.e., a vaporizer, booster, and compressor, that is costly and consumes considerable space and energy.

Energy costs represent the bulk of the expenses associated with cooling hydrogen to the point of liquefaction. Industry sources state that the equivalent of 30 to 40% of the energy contained in hydrogen is required to liquefy it.

BMW has studied the use of liquid hydrogen in combustion engines in automobiles for over 20 years and claims that using liquid hydrogen in automobiles is a good alternative. The German company Linde has developed a tank for liquid hydrogen where the cold from some of the liquid hydrogen is used to cool down the insulation surrounding the tank (completed using cooling elements). In this way, the tank keeps the hydrogen in a liquid state for up to 12 days.[8]

High-pressure Reservoirs for Gaseous Hydrogen

High-pressure gaseous reservoirs can be designed and custom-fabricated using American Society of Mechanical Engineers guidelines. Reservoirs are preferred to vacuum tanks because they are expected to use less space and be less expensive to acquire (see section 3.2). However, this may not be the case if hydrogen is sourced off-site and delivered in carbon-fibre-wrapped cylinders at a pressure of 430 bar or higher.

At the time of the preparation of this report, these cylinders are rated at 430 bar and are therefore adequate for on-site storage of gaseous hydrogen. However, for stationary applications with requirements for large quantities, carbon-fibre-wrapped cylinders are expected to be too expensive and space consuming.

If 700-bar storage technology is commercially available by 2015, the density of hydrogen would then compare to that of LH_2. (This would make a considerable difference to the scenarios described in section 3.2.) With the cost of compression being less than the cost of liquefaction, it would then become efficient to operate with exchanges of containerized high-pressure gaseous hydrogen and to overflow refill the bus tanks directly from these. (Note that this alternative was not retained for fuelling cost calculations in section 5.)

B3.3 Other Components

When considering on-site production of hydrogen, there is yet another difference between the components required for reforming and those required for electrolysis: the peripherals used to bring hydrogen to a purity level adequate for use in fuel cells.[9] The selection of this equipment depends on the content of the feedstock and the production process used. Typically, hydrogen produced by reforming requires purification to ensure there are no traces of carbon or other contaminants in the hydrogen stream. Electrolysis-based fuelling stations must deal with the possibility of electrolyte contamination.

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[8] Hyweb, 2000.

[9] Currently, fuel cell manufacturers are proposing a maximum of 10 ppb S, 1 ppm CO, 100 ppm CO_2, 1 ppm NH_3, 100 ppm NMHC on C-1 basis, <2% O_2, N_2, Ar, and that particulates conform to ISO 14687. Revisions are under consideration based on durability data and experience in fuel cell vehicle validation.

ANNEX C: TODAY'S TRANSIT OPERATING ENVIRONMENT

C1 FLEETS IN SERVICE

The Canadian transit industry operates over 12,000 buses across the country. Of these, about 11,500 are standard 12-metre buses. The remainder are a variety of articulated buses, double-decker buses, electric trolley buses, and small community buses. A little more than 93% of the buses operate on low-sulphur or ultra low-sulphur diesel, over 1% on bio-diesel, almost 3% on natural gas, and the remainder on electricity. About 7,000 of the buses operating in Canada are over 15 years of age and it is likely these buses will be replaced before fuel cell-powered buses are commercially available.[10]

In the smaller transit communities, eight-metre, nine-metre and 11-metre diesel buses are common. Some of the companies operating transit systems in these communities are privately owned; they bid for service contracts with the community and provide their own vehicles and infrastructure.[11] Other small communities operate their own transit fleets as part of the municipal structure or provincial agency but contract out the operation of these fleets to private enterprise.[12]

C2 OPERATING AND PLANNING PARAMETERS

The table below summarizes the findings of the interviews conducted with representatives of the UTSs that participated in the study. With few exceptions, the planning parameters are similar for small, medium and large-sized transit systems, despite the variety of operating environments ranging from large, dense urban areas to low-density rural areas.

The planned bus life averages 18 years, with larger systems averaging 17.4 and smaller systems averaging 18.8. This is explained by the greater wear and tear on large system buses due to higher average passenger loads and more congested, stop-and-go city driving conditions.

Major overhaul intervals for the three categories of systems differ, with larger transit systems having a lower frequency. This is likely due to the different maintenance practices at each of the system categories.

C2.1 Route Planning Parameters

The number of routes operated is directly proportional to the size and density of the transit service area. The larger the geographic area, the greater the number of routes.

The length of transit routes is a function of the geography of the service area and the density of traffic. The less dense the traffic is, the higher the average operating speed of the buses will be, allowing them to be more efficient. Traffic density also affects the average planning speed for scheduling and the daily range requirement for the buses.

C2.2 Passenger Carrying Capacity

While maximum passenger capacities are similar for all systems, the length of time for which the maximum passenger carrying capacity is required is much shorter for the small systems and much longer for the large systems.

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[10] CUTA Transit Data 2002.

[11] For example, the Town of Banff.

[12] For example, the City of Kelowna.

Table C-1: UTS Operating and Planning Parameters

	OPERATING AND PLANNING PARAMETERS		
	Small-Sized Systems	**Medium-Sized Systems**	**Large-Sized Systems**
Planned Bus Life (yrs)			
Average	18.8	18.0	17.4
Range	10 to 20	16 to 20	16 to 18
Major Overhauls Planned			
Engine			
Average	2.50	2.50	1.25
Range	2 to 3	1 to 4	1 to 2
Transmission			
Average	2.85	3.25	2.5
Range	1 to 4	2 to 6	2 to 4
Planning Spare Ratio (%)			
Average	27.0%	14.0%	17.5%
Range	15 to 50%	12 to 17% CNG 17%	12 to 18.2% CNG 25%; ETB 18%
Max. Passenger Capacity			
Average	57	65	65
Range	40 to 75	60 to 80	55 to 75
Min. Passenger Capacity			
Average			
Range	10 to 65	20 to 65	20 to 49
Desired Seating Capacity			
Average	40	40	40
Range	30 to 45	30 to 45	30 to 45
No. of Routes Operated			
Average	11	40	191
Range	2 to 17	30 to 54	85 to 265
Length of Routes (km)			
Average	27	18	21
Range	2 to 74	2.5 to 57	2 to 80
Max. Service Hours/Bus/Day			
Average	19	19.90	22.1
Range	17 to 22.5	18.5 to 21.2	19 to 25
Avg. Planning Speed (kph)			
Average	30	20.65	21
Range	20 to 40	19.3 to 23.3	17 to 24
Max. Range Required (km)			
Average	480	460	500
Range	250 to 700	400 to 470	450 to 700

Source: MARCON-DDM HIT, 2004

The a.m. and p.m. peaks in large cities, for example, can last several hours. In some cities, there is only a slight dip in the peak at the mid-day period.

Minimum passenger carrying capacities will also vary from small to large systems. If there are fewer than 25 passengers per hour on any given route, it is inefficient to use a standard 12-metre bus. This is why some of the smaller systems only use small community-type shuttle buses. Larger systems that need to have the high carrying capacity during peak periods will use the larger buses all day, as it is ineffective and inefficient to have small buses during off-peak periods and large buses for peak periods. The desired seated passenger capacity is 40 and the maximum passenger carrying capacity required is 65 passengers for most systems, which is generally below the number possible with the gross vehicle weight of the buses.

C2.3 Bus Performance Requirements

The **range** a bus will achieve is related closely to the loads it is carrying, the topography of the routes it is using and the density and nature of traffic. Transit systems operating in dense urban areas will find that the buses consume more fuel per kilometre than those in rural areas. Weather also impacts fuel consumption. A range of 500 km will meet the needs of almost all transit systems. In smaller systems, buses may need refuelling every second day, whereas in larger systems daily fuelling is required.

All UTSs surveyed indicated their buses need to have the ability to climb typical urban hills at a maximum 12% grade at 32 kph with a full load to meet their operating requirements. Acceleration to 32 kph must take no more than 10.5 seconds to facilitate merging into traffic when pulling away from a bus stop. Interior noise levels should not exceed 85 dba.

C3 MAINTENANCE

All surveyed UTSs collect maintenance data, some manually and some electronically. All UTSs interviewed are able to provide high-level data on costs for labour and materials for general maintenance categories. Only a few, however, have effective maintenance management information systems that allow for the planning and scheduling of work; the tracking of performance against standard times; analysis using activity-based costing for every maintenance activity for each bus or category of bus in a fleet; and the tracking of consumption of spare parts, inventory, fuel and lubricants for the fleet and by bus. While most are able to compare high-level performance against time, very few are capable of performing detailed analyses of productivity, efficiency, and cost of labour and materials against activity. Under such circumstances, it is difficult for management to identify efficiencies or measure effective use of resources.

Every transit operating environment is different, with maintenance demand being driven by a large variety of variables such as passenger loads, type of technology, climate, topography and traffic density. For the purposes of this study, a baseline maintenance environment was established, using averages from the UTSs that participated in this study. The following table shows the average number of maintenance activities required over the lifecycle of a bus in different size systems.

Table C-2: Maintenance Activities by Size of UTS

	Number in Lifespan of Bus		
Maintenance Activity	**Large-Sized System**	**Medium-Sized System**	**Small-Sized System**
Preventive Maintenance and Repair	Average: 15 Range: 14 to 16	Average: 9 Range: 5 to 10	Range: 8 to 22 Average: 15.2
Component Overhaul	Average: 2.5 Range: 1.5 to 4	Average: 4.9 Range: 2 to 9	Average: 6 Range: 4 to 8
Total Average	17.5	13.9	21.2

Source: MARCON-DDM HIT, 2004

C3.1 Spare Ratio Requirements

The spare ratio requirement is the percentage of the total fleet that is required to accommodate all maintenance (scheduled and unscheduled), taking into account an allowance for buses that may be out of service for other reasons (such as an accident) while allowing the deployment of the correct number of buses to deliver the published service levels.

With larger systems having mixed standard and articulated diesel fleets, and perhaps even alternative-fuel fleets such as CNG, spare ratios will tend to be higher than those of homogenous fleets with single-fuel technology.

The planning of spare ratios is determined largely by the maintenance demands of the operating environment. Bus fleets that service large cities and experience large passenger loads, traffic congestion, etc., tend to require more maintenance effort for braking, suspension and steering systems, as well as wheelchair lifts and coach bodies. Smaller systems have higher spare ratios due to the fact that they operate fewer buses and have less flexibility in deploying their fleets.[13] CNG and electric trolley buses tend to have a higher maintenance requirement and higher spare ratios.

Across all participating UTSs, spare ratios for maintenance ranged from 13.9% to 21.2%, with small systems having the highest spare ratio. One small system interviewed has a spare ratio of 50% because it operates only three buses and runs only two routes.

C3.2 Inspection Intervals

The table below summarizes the planned maintenance inspection intervals reported by participating transit systems. A range of data is provided because UTSs face differing operating environments.[14]

All transit systems interviewed had established at least two categories of planned maintenance inspection: minor and major. Some had broken the minor inspection schedules into three subcategories: check-over, minor, and minor with oil change. Some conducted two types of major inspection: Major 1 and Major 2.

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[13] A system with only two routes and three revenue vehicles, for example, will have a spare ratio of 50% to enable maintenance schedules to be met.

[14] Where all respondents reported the same figure, only that figure is presented.

Table C-3: Inspection Intervals by Size of UTS

	Range of Inspection Intervals (km)		
Maintenance Activity	**Large-Sized System**	**Medium-Sized System**	**Small-Sized System**
Minor	3,000 to 10,000	10,000	5,000 to 15,000
Major	9,000 to 72,000	36,000 to 80,000	15,000 to 40,000
Brake Relines	35,000 to 70,000	45,000 to 90,000	40,000 to 80,000
Engine Overhaul			
Diesel	300,000 to 750,000	400,000 to 600,000	400,000 to 550,000
CNG		450,000	
Differential Overhaul	900,000	750,000 to 900,000	750,000 to 800,000
Transmission Overhaul	240,000 to 500,000	360,000 to 425,000	350,000 to 550,000

Source: MARCON-DDM HIT, 2004

C3.3 *Maintenance and Labour Data*

Other categories of maintenance effort include component overhaul, body repairs, fuelling, cleaning, bad orders, road calls, repairs and training. Table C-3 presents the average allocation of overall labour and material costs to the major maintenance categories.

Over 78% of all maintenance efforts are allocated to three categories of activity: preventive maintenance inspections, repairs including bad orders and road calls, and component overhaul. The following table summarizes the allocation of effort by percentage of total cost of labour and materials. Large systems tend to have a higher preventive maintenance allocation, but this is likely due to a difference in allocation of repairs to preventive maintenance work orders.

Table C-4: Average Labour and Material Costs, Major Maintenance Work

Maintenance Category	Average (%)
Preventive Maintenance Inspections	18.9
Component Overhaul	11.8
Body Repairs	6.2
Fuelling	5.3
Cleaning	9.3
Repairs (including bad orders and road calls)	47.4
Training	0.5

Source: MARCON-DDM HIT, 2004

Table C-5: Maintenance Effort for the Three Major Categories

	% of Maintenance Effort			
Category	**Large**	**Medium**	**Small**	**Average**
Preventive Maintenance Inspections	35.4	14.2	14.6	21.4
Repairs (including bad orders and road calls)	53.4	68.8	70.9	64.4
Component Overhaul	11.2	17	14.5	14.2

Source: MARCON-DDM HIT, 2004

The average allocation to maintenance activities (expressed as a percentage of total costs) within each of the three major categories is presented in the following table:

Table C-6: Maintenance Activities as a Percentage of Total Costs

	% of Total Costs		
Maintenance Activity	**Preventive Maintenance**	**Repairs Including Road Calls and Bad Orders**	**Component Overhaul**
Fuel System	1.4	1.1	4.1
Braking System	26.1	7.5	N/A
Tires	22.1	8.5	N/A
Engine	19.5	18.0	35.9
Drive Train	16.7	11.4	26.8
Other	14.2	53.5	33.2

Source: MARCON-DDM HIT, 2004

The average percentage allocation of maintenance labour costs by maintenance activity is presented in the following table:

Table C-7: Average Allocation of Maintenance Labour Costs

Category	**Average Allocation (%)**
Minor Inspections	14.6
Major Inspections	6.6
Brakes	20.9
Repairs (including bad order and road calls)	43.4
Transmission Re & Re	0.5
Differential Re & Re	1.1
Component Overhaul	15.0

Source: MARCON-DDM HIT, 2004

Contracting policies vary from system to system. However, in those systems where the work force is certified, provisions for contracting are in the collective agreements. Generally, all systems perform preventive maintenance internally. Generally, all **large** systems perform repairs and overhauls internally, with a few exceptions in the area of engine and transmission overhaul and major repairs, where small amounts of work may be contracted out. As systems get smaller, more and more of the major repair and overhaul work is contracted out. In properties with CNG buses, fire detection and suppression systems maintenance tends to be contracted out. Maintenance is contracted out when it is believed to be cost effective.

C3.4 *Maintenance and Fuel Costs*

Operating costs are directly affected by the mix and age of the fleet within a transit system, as well as other variables in the operational environment. Consequently, it is difficult to compare one UTS to another. Fuel prices vary widely within the country and fuel contracts differ from UTS to UTS.

While there is significant variation in the costs between systems, following are the average total maintenance costs (including labour and material) and fuel costs (including applicable taxes) per kilometre for a standard 12-metre diesel bus:

• Maintenance cost per kilometre	$ 0.64
• Fuel cost per kilometre	$ 0.31

A 12-metre transit bus travels an average of 60,000 km per year. The annual total maintenance costs per bus for the 16 UTSs interviewed, including labour and materials but not fuel, ranged from $20,700 to $62,100, with the median cost being $39,200 and the average cost being $38,000, not including fuel.

C3.5 *Maintenance Employees*

The number of maintenance employees by trade varies significantly for all UTS categories. Variables that affect the number of employees include: size and mixture of fleet, passenger loads, climate, topography, overhaul requirements, labour contracts in effect and contracting policies.

The three groups of transit system maintenance employees are mechanics, electricians/ electronic technicians and service persons. Smaller systems do not have electronics technicians/electricians; this work is performed by mechanics. Vancouver, with its fleet of electric trolley buses, has a larger than normal complement of electronic technicians/electricians and may indicate the type of ratio one would find with the introduction of fuel cell-powered buses.

The average ratio of buses per mechanics ranges from four to eight. In smaller systems the ratio is lower because the employees are multi-tasked and multi-skilled. In Banff, for example, the mechanics also service the buses and perform electrical repairs.

The ratio of buses to service persons is more consistent across different sized transit systems, with smaller systems again having smaller ratios. The number of service persons required is directly related to the number of buses, the size of the depot yard, and the amount of time available to fuel and service the buses required for the following day. Large fleets that have a greater proportion of buses in service for a longer portion of the day tend to have more service persons in order to process the buses through the servicing cycle in the time available and thus have a lower ratio of buses to employee.

C3.6 *Emergencies and Hazardous Products*

The transit systems participating in the study indicated they generally well prepared to handle emergencies and hazardous products.

Spill kits include various hydrophobic and hydrophilic absorbents (pads, towels, brooms, particulate), catch basin drain covers, basic personal protective equipment and fire blankets. The kits are located in the garages, on each bus and auxiliary vehicle, and at the fuel islands. Most systems are equipped with auto shut-offs and oil-water separators on all storm sewers and catch basins, with automatic valves that shut down if a spill occurs on the property. Transit employees generally respond to minor situations. When the situation requires the intervention of provincial and federal emergency and regulatory agencies, services are often contracted. Provincial emergency programs must be notified if there is a spill of 200 litres or more, or if any type of spill threatens ground water or streams.

Safety data sheets and waste generator regulations are available at most UTSs. At most sites, hazardous material waste (e.g., batteries) is stored in drums and collected and removed by contractors. Hazardous wastes are handled in accordance with WHMIS, Transportation of Dangerous Goods, WCB and various environmental regulations. Some UTSs track hazardous waste on a computerized database.

Safety training is provided to personnel on a regular basis, with frequencies varying from UTS to UTS. Some of this training is unique to maintenance personnel. These courses include WHMIS, first aid, spill response, earthquake response and fire safety and last from three to four hours to a full day.

C3.7 Occupational Health and Safety

Occupational health and safety requirements are provincially controlled. It is doubtful if these requirements currently address workplace health and safety in a hydrogen facility. A survey of health and safety regulations is required in each province to determine the range of possible implications.

C4 FUELLING INFRASTRUCTURE AND PROCESSES

C4.1 Space Allocation

All transit systems have either interior or covered fuelling stations. Those in cold climates have interior fuelling stations. All medium and large-sized UTSs have two diesel dispensing points per operating garage; small-sized systems have one diesel dispensing point. Very small systems, such as Banff, use a card-lock contracted service.

C4.2 Indoor/Outdoor Fuelling

Fuelling stations are conveniently located along the servicing route, normally between the parking area (indoor or outdoor) and the bus wash facility (where one exists). Bad order buses must go through a repair process before being serviced and refuelled.

Indoor fuelling is used in most of the country and fuelling points are located within the bus parking facility.

C4.3 Fleet Refuelling

Fuelling is performed during the fleet servicing cycle by service persons working the late afternoon and night shifts. While fuelling a diesel bus with a “posilock” system takes an average of 3.5 minutes, the servicing cycle takes between 8 and 15 minutes, depending on the size of the fleet, the size of the depot property and the number of service persons available. Buses are usually fuelled daily. Exceptions occur where buses are in service 24 hours per day. In some UTSs, buses used for "trippers"[15] are serviced every second day. In all cases, fuelling operations and servicing must take place after buses have returned to the depot for the day and before they are dispatched the following day. A large portion of all fleets is available for fuelling only five or six hours per day.

Once the bus is connected to the fuel hose, the service person checks engine and transmission oil levels and the coolant level and, if necessary, tops them up. Tire pressures are checked, the interior of the bus is swept or vacuumed, the operator's station is cleaned, the bus is moved through the wash rack, and then back to the designated parking area.

C4.4 Service Person Requirements

The servicing function varies greatly from fleet to fleet in terms of who performs the work. The smaller the system, the more multi-tasked maintenance employees become. In some UTSs, there are no service persons and the work is performed by the mechanics. In large-sized UTSs, the ratio ranges from 11 to 22 buses per service person; in medium-sized systems, from 13 to 16 buses per service person; and in small-sized systems, four to 18 buses per service person, except for those systems where mechanics service the buses.

C5 FACILITIES AND TOOLS

C5.1 Facilities

Of the 35 depot and garage locations occupied by the transit properties participating in the survey, only eight garages conform with current or future building standards. Sixteen locations are ageing or have obsolete facilities and do not conform to current codes. The remaining garages are built to standards that existed in the '80s and '90s. Only three facilities are designed for CNG fuel and have made the heating, lighting and ventilation system modifications required for hydrogen. Most have air recirculation of about four changes per hour, with the exception of the new buildings that have six air changes per hour. The Port Coquitlam facility in Vancouver is the only facility in the country that, in addition to conforming to standards for CNG, has two self-enclosed bays rated for the use of hydrogen gas. Approximately half the garages have open-flame heating systems within the roof structure.

Maintenance bays and hoists are adequate for most facilities except a few smaller properties that have obsolete buildings and have to rely on portable hoists or hoists that barely have enough capacity to lift current diesel buses. Hoist capacities range from 16 tonnes to 30 tonnes. Access to maintenance bays is generally 4.3 metres or taller. Only a few of the transit systems operating out of old

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[15] Buses that are only used for one or two runs during peak service periods to augment service schedules (e.g., to provide additional capacity on routes serving schools in the morning and afternoon).

facilities are restricted to 3.7-metre doors. Only one garage reported overhead obstructions in the garage that would prevent hoisting of a bus taller than the average diesel bus of today.

In most garages, circulation space is adequate. Some of the smaller systems have cramped quarters and have limited, if any, spare parking space. The obsolete garages have no room for potential expansion of the buildings or the fleet.

C5.2 UTS Site Characteristics

Larger, multi-depot, transit systems have a variety of sizes of sites, in a variety of neighbourhoods, ranging from those depots filled to capacity in dense urban areas to those with spare capacity in suburban areas. Zoning, in all cases, ranges from a mixture of residential for the older depots to industrial and commercial for newer facilities.

For medium-sized systems, space tends to be more limited in urban locations. Smaller-sized UTSs tend to have depots located in commercial/light industrial areas; a few are in residential neighbourhoods.

Transit systems in cold climates generally have both a maintenance facility and an indoor parking facility for their buses. As a result, there is limited circulation space around these facilities.

C5.3 Electrical and Other Systems

At all UTSs surveyed, electrical capacity at their sites is three-phased: 480 volt to 600 volt. All sites can be easily upgraded, as necessary, provided sufficient funds are available.

Electrical panels in the UTSs surveyed are almost all situated on the interior walls of the facilities. A few newer buildings have the panels isolated in electrical/utility rooms.

Other than the transit systems operating vehicles fuelled with natural gas, explosion-proof lighting is not used.

Heating, ventilation and air conditioning (HVAC) systems have air changes ranging from three to eight per hour. In some smaller facilities using radiant heat, the only air change is when the garage doors are open. Most HVAC systems use open-flame heaters in ceiling-mounted units. A few have roof-mounted units that force warm air into the building.

The only transit facilities that have sensors for air quality monitoring are those that operate CNG bus fleets. A few have carbon monoxide alarms. All facilities have a form of fire and heat detection system that automatically triggers sprinklers. One garage uses manual fire extinguishers.

C5.4 Emergency Systems

Emergency system requirements in current transit garages and maintenance facilities are largely dependent on local regulatory requirements and therefore vary. However, given that most local regulations are based on requirements of the Canadian building code, a reasonable amount of consistency can be expected.

The Canadian Electrical Code (CEC) provides hazardous zone classification data and ventilation requirements for commercial garages that are storing, fuelling or repairing vehicles using volatile liquid fuels, propane or natural gas. Based on CEC requirements, the zone immediately above floor level and in-service pits in most facilities will be classified as *Class 1, Zone 1*, thus requiring special wiring because of the density of liquid fuel vapours or propane. For a facility dealing only with diesel fuel, local regulations may differ because of the flash point. The National Fire Code of Canada requires that in the absence of special provincial regulations for such facilities, the requirements of the CEC must be followed.

Required emergency systems include full sprinkling for fire suppression, fire detection and alarm systems, and automated alerting of the fire department.

C5.5 Tools

In addition to the standard kit of hand and air tools found in all garages, following is a list of typical equipment and tools found in a diesel bus maintenance garage:

- Diagnostic readers for engines and transmissions;
- Decibel meter;
- Smoke meter;
- Viscosity comparator;
- Oil conductivity tester;
- Injector comparator;
- Injector pop pressure tester;
- Cooling system temperature test unit, pH meter;
- Surface temperature thermocouple;
- Headlight aimer;
- Ultra-sonic leak detector;
- Battery tester/charger, hydrometers, voltmeters and ohmmeters;
- Engine block crack detector;
- Pressure and flow gauges;
- Digital multi-tester;
- Tapley brake test meter;
- Static and dynamic wheel balancers;
- Motor dynamometer;
- Chassis dynamometer;
- Electric test benches;
- Transmission valve body tester;
- Electric test bench to test all DC and AC motors, generators and solenoids under full load and no load conditions; and
- Air test bench to test valves, compressors and regulators.

Only transit systems having CNG fleets have the requisite gantries and fall prevention equipment available for working on the roofs of buses. The garages also have overhead lifting equipment to assist in the removal of roof-mounted equipment such as high-pressure fuel storage tanks.

C6 TRAINING PROCESSES

Training in the maintenance trades is primarily carried out in the community colleges or CEGEPS (in Québec). For the established trades, licenses are provided in the appropriate specializations. It will be some time before the market for hydrogen-related licenses is large enough to warrant hydrogen-specific programs. In the transition period, it is anticipated that individual instruction in hydrogen technologies will be necessary for demonstration and early-adopter sites. Course content has been developed for such programs and will likely be adopted by community college trade programs as the market grows.

C7 COMMUNICATIONS

C7.1 Reaching Target Audiences

All transit systems appear to have similar methods of communicating with their stakeholder groups. External groups include transit clients, the general public, the media, and local and provincial regulatory and emergency agencies. Internal groups include employees, management, bargaining units, where applicable, and governing boards. The study shows that large and medium-sized UTSs are able to communicate "somewhat to very effectively" with all groups. Smaller systems communicate "very effectively to extremely effectively" with all groups because of small staffs and closer community ties. Managers know their employees and their stakeholders on a personal level and have a closer relationship with the media.

For all transit systems, transit riders are reached through:

- Customer service centre;
- Manned switchboard;
- Focus groups;
- Open houses;
- Web sites;
- Media releases;
- On-board advertising, such as rider alerts, interior ads, posters, and pamphlets; and
- Quarterly rider surveys.

The general public is reached through:

- Open houses and press releases;
- Media advertising; and
- Media stories.

Media are reached through:

- Personal knowledge of media personalities in newspapers, TV and radio;
- Regular meetings;
- Media releases, sometimes through a PR/media consultant;
- News releases;
- Press conferences; and
- Visits to the transit base.

Communication with regulatory and emergency agencies at the local and provincial levels is carried out in various ways:

- In many jurisdictions, the transit control centre is part of the City Emergency Response Centre, allowing frequent meetings with fire, EMS, and police services;

- Where transit control centres are not physically part of the local emergency co-ordination centre, transit staff regularly meet with counterparts in local emergency service organizations (there is often a direct line to the emergency co-ordination centres);
- Regular meetings are held with emergency responders; and
- Various staff maintain close contact with municipal regulatory authorities.

Employees are contacted through:

- Newsletters;
- News clippings sent out electronically;
- Notices at dispatch for the drivers;
- Posters in garages;
- Face-to-face meetings;
- Quarterly newspapers sent to homes;
- TV news service in depots;
- Moving weekly executive team meetings among operating depots to allow executive contact with employees;
- Intranet and an employee web site run by unions;
- Mailings sent to homes for important messages; and
- Information notices with pay stubs.

Management is contacted through:

- E-mail notices;
- Face-to-face meetings;
- Newsletters delivered to offices;
- Newsletters sent out monthly to homes;
- Daily “coffee klatches” for direct reports in office;
- Division heads weekly staff meetings;
- Annual management “show and tell” to roll out the business plan for the year;
- Senior management team meetings held on a regular basis; and
- Informal meetings.

Communication with governing bodies varies greatly from one transit system to another, depending on the governance structure. In some city organizations, the general manager reports directly to the City Council, while in others there are boards appointed by the provincial or regional authority, and communication occurs through personal contact, briefing papers and regularly-scheduled meetings. In some systems, the senior executive of the transit system reports to a standing committee composed of members of City Council, and communication is usually conducted through the senior executive of the UTS.

In addition to the regular communication channels with employees, communication with bargaining unit representatives is through:

- Regularly scheduled joint committee meetings on operational issues;

- Quarterly meetings held to review service levels/changes; and
- Regular joint meetings of union and company executives held to inform each other of on-going or up-coming events.

C7.2 Communications and Change Management

Change is managed differently from property to property. In smaller transit systems, and to some degree in medium-sized ones, there is greater personal contact and communication between management and employees, and employees' bargaining unit representatives if employees are certified. Change tends to be managed well with good two-way communication regarding change issues. All the above communications mechanisms are used to facilitate the change.

In larger transit systems, particularly those with multiple depots, change management presents a greater challenge. In many of these UTSs, employees are not seen on a regular basis by their supervisors because shifts are frequently started while the bus is in service. Bargaining unit representatives tend to negotiate with management and thus management does not have as much direct contact with employees. In larger systems, management must expend greater effort to communicate the change issues to affected employees. According to some employees in some of the larger systems, this is not always done well.

C7.3 Advocacy

Until recently, hydrogen was perceived as unique and it was "regulated" accordingly with unique handling requirements. Hydrogen systems built in the past were burdened with high real estate costs due to the perceived need for large set-back distances and many safety devices from hydrogen detectors to fail-safe «valving» for hydrogen containment. There was also the fear that a single accident could irreparably set back the use of hydrogen as a fuel. This approach to safety at any cost was adopted without quantitative comparison of the relative risk of hydrogen compared to other fuels and, through this comparison, the risk the public was willing to accept.

The more current attitude, which is still evolving, is that hydrogen systems should not burden the public with safety concerns beyond those which it already accepts with contemporary fuels. Monitoring detectors, automatic interruption of fuel flow and other impositions are no longer considered necessary for emerging hydrogen systems. Demonstration projects for hydrogen, particularly for filling stations, now exceed 80 documented cases. They have helped to build a comfort level so that "avoiding failure at all costs" is now being replaced with "providing an equivalent level of safety".

The evolving attitude about hydrogen is also moving toward another concept: hydrogen is as safe as conventional fuels and it may actually be safer. For example: during fuelling, hydrogen will be transferred in a closed system, whereas with gasoline the fumes signal a substantial release of fuel into the atmosphere (a few grams of hydrogen during disconnect compared to hundreds of grams in the case of gasoline). Another example: release of gasoline from a vehicle tank spreads and upon ignition may engulf the vehicle in a high-temperature flame. Gaseous hydrogen, on the other hand, is released upward, disperses rapidly and upon ignition burns with a low-luminosity flame. Generally, hydrogen releases are more survivable than gasoline releases, particularly in the case of ignition.

To further support the "equivalent level of safety" concept and ensure economic competitiveness, studies are underway to look at the level of risk the public is currently willing to accept with conventional fuels and the level of risk that will be associated with hydrogen systems. These quantitative risk assessments, which are taking place in Canada and internationally through the International Energy Agency, will have an impact on the way hydrogen is deployed in the urban transit systems of the future.

To date, industry has been particularly successful in obtaining press coverage for hydrogen innovations. The industry is evolving rapidly and, during this transition period, there continues to be a need to advocate for hydrogen and its role in environmental protection, resource security and conservation.

ANNEX D: REGULATORY ENVIRONMENT FOR MAINTENANCE FACILITIES

D1 CANADIAN REGULATORY PROCESS

For maintenance and garage facilities and indoor and outdoor fuelling facilities, the Canadian model safety codes apply. These are identified in section 3 of the report. The Canadian model safety codes define an "Authority Having Jurisdiction" as the governmental body responsible for enforcement of any part of a regulated code or standard or an agency designated by that body to exercise such a function. The Canadian authorities having jurisdiction are primarily the provincial and territorial governments, who, in turn, assign the responsibilities for development of regulations and enforcement to their related departments. These regulations are then utilized by local officials, such as building inspectors or fire chiefs, who may be employed by a provincial or federal government department, a city, a municipality or a planning district. The person delegated with local responsibility for the regulatory decision varies from location to location.

Canadian electrical, gas and pressure vessel codes are developed by the Canadian Standards Association (CSA), while the building, fire and plumbing codes are developed at the Codes Centre, Institute for Research in Construction, National Research Council of Canada. CSA is an accredited standards development organization. For the first five codes, the authorities having jurisdiction have formed advisory councils to co-ordinate the development and application of their codes. Given that the individual codes regulate the use of many specific safety standards, the advisory councils also liaise directly with the accredited certification bodies that certify products for Canada. The advisory councils are:

- The Canadian Advisory Council on Electrical Safety (CACES);
- The Interprovincial Gas Advisory Council (IGAC);
- The Provincial/Territorial Policy Advisory Committee on Codes (P/TPACC);
- The Council of Canadian Fire Marshals and Fire Commissioners (CCFM/FC); and
- The Canadian Advisory Council on Plumbing (CACP).

The Canadian Boiler and Pressure Vessel Code (BPVC) is administered and co-ordinated in a somewhat different manner. While the CSA is the standards development organization producing Canadian pressure vessel standards, these standards are based primarily on the requirements of the Boiler and Pressure Vessel Code of the American Society of Mechanical Engineers (ASME/BPVC). The base Canadian standard is CSA B51, which governs the design, registration and inspection of pressure vessels, related components and piping. The "Authority Having Jurisdiction" (a provincial government department) approves new vessel designs and allocates a Canadian Registration Number to new designs. This number allocation is co-ordinated among provinces through the use of a unique numbering system. A committee of chief provincial inspectors also meets on an annual basis to co-ordinate activities among the provinces and territories.

Additional CSA standards relate to the highway transport of dangerous goods and are based on ASME/BPVC, U.S. Department of Transportation and Transport Canada regulations. The CSA accepts equipment designs similar to those of the United States for the highway transport of compressed gaseous hydrogen and cryogenically cooled liquid hydrogen, allowing both commodities to be transported between the two countries.

D2 SAFETY PROGRAM

A critical step in the development of a hydrogen energy system is the incorporation of a safety program, with the objective of providing safety for everyone in contact with the system (passengers, employees, general public). The safety program must be operational during all project stages, including design and planning, system construction, operation and maintenance, and must emphasize the prevention of accidents through hazard identification, assessment and resolution.[16]

An initial requirement is the completion of a hazard analysis that considers the physical and chemical properties of hydrogen as well as the specific properties of the storage and hydrogen delivery system. The roles and responsibilities of all personnel must be clearly defined. Hazard resolution procedures must be established to identify and resolve hazards at every stage of the project. Hazard resolution includes:

1) *System definition:* The functions and characteristics of the hydrogen system and subsystems are established and classified. Interactions between system elements should also be identified.

2) *Hazard identification:* The purpose is to find the hazards and determine their cause.

3) *Hazard assessment:* This involves grading the hazards in terms of likelihood (probability of occurrence) and severity (consequences of the hazards).

4) *Hazard reduction:* Once the hazards are assessed, they can be resolved by elimination, control or risk assumption. Hazards can be eliminated by appropriate system design. When the hazards cannot be avoided, they should be controlled by the following means:[17]

- Designing for minimum hazard;
- Installing safety devices;
- Installing alarms and warning devices;
- Developing administrative controls, including special procedures and training; and
- Providing protective clothing and equipment.

5) *Follow-up:* This involves monitoring the effectiveness of hazard reduction, performing a hazard analysis of the modified system or procedures (making sure that new hazards have not been introduced), and documenting the hazard resolution process. The safety program should also establish how compliance to standards and personnel certification requirements will be achieved and provide for adequate controls and verifications.

As discussed below, typical safety elements in an indoor fuelling facility will include a sloped ceiling with hydrogen detectors at ventilation discharge locations, suspended lights and a two-speed ventilation system triggered by the hydrogen detectors.

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[16] For example: *Clean Air Program: Design Guidelines for Bus Transit Systems Using Hydrogen as an Alternative Fuel*, U.S. Department of Transportation, Federal Transit Agency, DOT-FTA-MA-26-7021-98-1, DOT-VNTSC-FTA-FTA-98-6, October 1998, 67pp.

[17] *NASA Glenn Safety Manual*, Revision 9-03, Chapter 6 ‘Hydrogen’.

D3 RISK MITIGATION REQUIREMENTS

Hydrogen has wide flammability limits in air (4 to 75%) and very low ignition energy at stochiometric concentration (at about 30% in air by volume). Hydrogen has one of the highest energies of combustion *per unit of mass*. The lower heating value of hydrogen per unit of mass is 120 MJ/kg, compared to about 50 MJ/kg for hydrocarbon fuels such as gasoline, propane and natural gas. Because of its low density, however, hydrogen *under ambient conditions* has one of the lowest energy of combustion *per unit of volume*.

Hydrogen requires low ignition energy at stochiometric concentration in air. A 20-µJ spark can ignite this mixture, 10 times less than what is required to ignite a gasoline/air mixture. Such sparks can be generated by static charges. A hydrogen flame is nearly invisible and may be difficult to detect due to the absence of soot. The auto-ignition temperature for hydrogen is 585°C. A mixture of hydrogen and air may detonate in confined or partially confined areas. The energy content per weight of a stochiometric mixture of hydrogen and air is about the same as that for TNT, although only part of the hydrogen within the flammable cloud contributes to the detonation.

The density[18] of hydrogen at ambient pressure and temperature is 0.0838 kg/m^3, compared to 0.668 kg/m^3 for methane, 1.292 kg/m^3 for air[19] and 1.866 kg/m^3 for propane. Hydrogen is therefore buoyant at room temperature. The density of hydrogen vapour is 1.339 kg/m^3 at 101.3 kPa and 20.28 °K. In fact, cold hydrogen gas remains heavier than ambient air up to temperatures of 190 K at 101.3 kPa. The buoyancy of room temperature hydrogen tends to limit the spread of combustible air-hydrogen mixtures resulting from a hydrogen release.

Hydrogen disperses more quickly than other fuels in air. The properties in the table below show that the hydrogen molecule in air has a diffusivity[20] of 0.61 cm^2/second, compared to 0.11 cm^2/second for propane[21, 22] and 0.16 cm^2/second for methane. The diffusion rate of hydrogen in air is about 3.8 times faster than air in air. The presence of turbulence will increase the rate of hydrogen diffusion.

Hydrogen, in both its gaseous and liquid phases, is particularly subject to leakage because of its low viscosity and low molecular weight. Leakage is inversely proportional to viscosity.[23] Hydrogen leaks are undetectable to the human senses as they are colourless and odourless. The leakage rate of liquid hydrogen is roughly 100 times that of JP-4 fuel,[24] 50 times that of water, and 10 times that of liquid nitrogen.[8]

Hydrogen-air mixtures can burn as either a deflagration or a detonation. Deflagrations generally occur when an unconfined cloud of hydrogen-air

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[18] Thermodynamic and Transport Properties of Pure Fluids, E.W. Lemmon et al, NIST Standard Reference Database 12, version 5, ©2000.

[19] Handbook of Chemistry and Physics, 62nd Edition, CRC Press, Boca Raton, Florida, p. F-9, 1981.

[20] Werner Zittel, Reinhold Wurster, Safety Hydrogen in the Energy Sector, Ludwig-Bölkow-Systemtechnik GmbH, 1996.

[21] From 'Guidelines on Remediation of Contaminated Sites', Environmental Guidelines No 7, Danish Environmental Protection Agency, p 224 (2002) calculated from data taken in Lugg, G.A. 1968: *Diffusion Coefficients of Some Organic and Other Vapour in Air*. Analytical Chemistry, 40, 1072-1077.

[22] http://www.eere.energy.gov/hydrogenandfuelcells/codes/.

[23] NASA Glenn Safety Manual, Revision 9-03, Chapter 6 'Hydrogen'.

[24] A military version of a kerosene type of fuel.

Table D-1: Properties of Gaseous Hydrogen Related to Leakage

PROPERTY	HYDROGEN	METHANE	PROPANE	GASOLINE
Molecular Weight	2.02	16.04	44.06	~ 107
Density of Gas (kg/m^3)	0.0838	0.6512	1.87	4.4
Viscosity of Gas at NTP (g/cm-s)	$8.9*10^{-5}$	$11.17*10^{-5}$	$8*10^{-5}$	$5.2*10^{-5}$
Diffusion coefficient in still air at NTP (cm^2/s)	0.61	0.16	0.12	0.05
Buoyancy (density realtive to air)	0.07	0.55	1.52	3.4-4.0

Source: MARCON-DDM HIT, 2004

mixture is ignited by a small ignition source. The rapid expansion of the hot gases of fast deflagrations may produce a significant pressure wave, which may harm personnel or damage structures.

Detonations travel at supersonic speeds. The pressure across a hydrogen detonation wave is about 20 times the atmospheric pressure and significantly greater than a deflagration. The pressure ratio seen by obstacles in the path of a detonation is between 40 and 60. A detonation generally results from a deflagration that has been ignited in a confined or partly confined area. A powerful ignition source is required to produce detonation in an unconfined hydrogen-air mixture.

Questions of risk and safety therefore can never be considered singularly. They must be considered in context or as compared to other fuels.

Hydrogen does pose risks, but when compared to other fuels, it also has benefits. A comparison of the basic safety characteristics of hydrogen with other fuels used in similar applications is a useful starting point to assess potential hazards of hydrogen in new applications as well as its acceptability to the general public. Hydrogen can be compared to existing gaseous and liquid fuels and energy carriers, especially combustible gases such as methane (natural gas), propane, gasoline, diesel, kerosene and methanol, as well as new gaseous mixtures such as Hythane™.

The wide range of flammability of hydrogen-air mixtures compared to other fuels has been considered a disadvantage. An accidental leak of hydrogen is more likely to result in a fire or explosion than a leak of Hythane, propane, gasoline or diesel. For example, hydrogen can ignite when the atmosphere is at 50% hydrogen while at the same percentage Hythane propane cannot. However, the differences between hydrogen, methane and Hythane are minor for the lower limit and the lower limit of propane is even less. Gasoline and diesel fuels are not compared because the rate at which the vapours mix with air depends partly upon the buoyant effect and the diffusion coefficient. The buoyant effect does not exist for the liquid and the diffusion coefficient is very low in liquid form.

After a leak, however, the ignitable fuel concentration builds up from zero, and ignition (if the ignition source is present) is most likely to occur when the concentration first reaches the lower flammability limit (LFL). Comparing property values in the table below, the values for LFL are almost the same for hydrogen and Hythane but smallest for diesel, gasoline and propane.

Comparisons among fuels can produce different conclusions, depending on the nature of the release. For example, the dissipation or dispersion of fuel vapour in air is a function of its diffusivity coefficient, vapour density at room temperature, vapour density at the normal boiling point, and its buoyancy in air. Dissipation is affected by mass flow and turbulence of the atmosphere above a fuel spill, such as wind velocity and direction. The fuel vapour density relative to the density of air at room temperature determines whether the fuel vapours have positive or negative buoyancy.

In a confined area, such as a room where the ascent of fuel vapours is restricted, buoyancy is less important than a spill in an unconfined area where rapid dissipation reduces the concentration and duration of fuel-air mixtures. The properties in the table below combine to show that hydrogen is the least hazardous in an open area. In a confined area, however, it is the most hazardous, followed by methane and propane. Table D-4 explains the five-level ranking system.

Table D-2: Properties of Gaseous Hydrogen Related to Flammability

PROPERTY	HYDROGEN	METHANE	HYTHANE™	PROPANE	GASOLINE	DIESEL
Density (kg/m^3)	0.0838	0.6512	0.56609	1.87	4.4	~7
Molecular weight	2.02	16.04	13.94	44.06	~107	~150
Limits of flammability in air (Vol. %)	4.1 to 75	5.3 to 15.0	5.0 to 17.0	2.1 to 9.5	1.0 to 7.6	0.5 to 4.1
Flame temperature in air (K)	2,318	2,148 to 2,227	2,234	2,385	2,470	2,200
Lower heating value (kJ/g)	120	50	60.5	46.4	44.5	43
Higher heating value (kJ/g)	142	55.5	68.5	50.4	48	N/A
Burning velocity at NTP (cm/s)	265 to 325	37 to 45	49.6	N/A	37 to 42	35
Toxicity	non-toxic	non-toxic (asphyxiant)	non-toxic (asphyxiant)	non-toxic (asphyxiant)	slight (asphyxiant)	slight (asphyxiant)

Source: MARCON-DDM HIT, 2004

Table D-3: Relative Dissipation Hazard of Hydrogen

Fuel	**Diffusion Coefficient in air at NTP**	**Vapor density at NTP in g/m³**	**Buoyancy in air at NTP**	**Vapor Density at NBP in g/cm³**	**Buoyancy in air at NBP**	**Rank in confined, unconfined areas**
H_2	0.61	83.76	Positive	0	Negative	Level 5, 1
CH_4	0.16	651.19	Positive	0	Negative	Level 4, 1
C_3H_8	0.12	1,870	Negative	unknown	Negative	Level 2, 3
Gasoline	0.05	4,400	Negative	0	Negative	Level 1, 4
Diesel	<0.10	7,000	Negative	unknown	Negative	Level 1, 5
Air		1,208		0	Negative	

Source: MARCON-DDM HIT, 2004

In fact, these comparisons relate to all but one dimension of risk: the probability of occurrence. Risk is a combination of the probability of the incident and its potential impact (burning or exploding).

This again is scenario-dependent. One case of interest to the UTS operator is the release of hydrogen from a bus in an accident. Here, a comparison with a liquid fuel such as diesel can be quite dramatic. A liquid fuel spill can result in a rapid spread of the fuel and, if it ignites, the envelopment of the vehicle in an extremely hot flame. A similar experience with hydrogen would have significantly less impact. Hydrogen is buoyant and its dispersion properties will lead to a vertical flame from the release point with much less intense radiation. In general, a release of hydrogen with ignition is considered to be a more survivable incident.

Comparison of Hydrogen and Conventional Fuel Hazards

To compare the relative hazards of conventional fuels with respect to leakage, volatility, dissipation, ignition, flammability, deflagration, radiation, detonation, and physiological hazards a five-level system can be used where the significance of the Level 1 to Level 5 ranking is:

Level 1 means low (negligible effects)

Level 2 means minor (marginal effects)

Level 3 means moderate (moderate effects)

Level 4 means high (critical effects)

Level 5 means severe (catastrophic effects)

Source: Sourcebook on Hydrogen Applications, TISEC Inc., 2004

Thus, it is essential that hydrogen systems, both mobile and stationary, be designed to compensate for properties that tend to facilitate conditions such as ignition and detonation and to fully exploit its properties that mitigate consequences. When this is done, hydrogen systems can be made as safe as or safer than conventional fuels.

ANNEX E: TERMINOLOGY AND ABBREVIATIONS

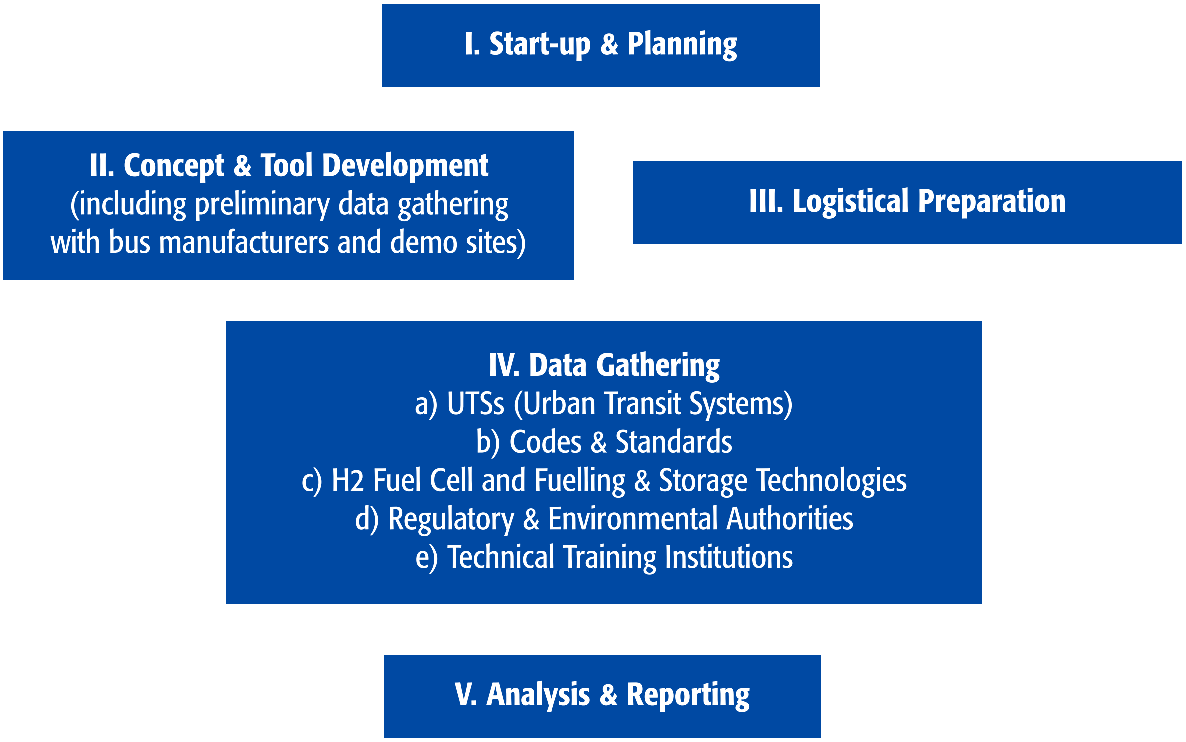
ASME	American Society of Mechanical Engineers
ATR	Auto-thermal reformer
BO	Bad orders
BPVC	Canadian Boiler and Pressure Vessel Code
CACES	Canadian Advisory Council on Electrical Safety
CAMPE	Canadian Association of Motive Power Educators
CACP	Canadian Advisory Council on Plumbing
CCFM/FC	Council of Canadian Fire Marshals and Fire Commissioners
cm/s	Centimetres per second
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CRN	Canadian Registration Number
CTFCA	Canadian Transportation Fuel Cell Alliance
CUTA	Canadian Urban Transit Association
DEH	Diesel-electric hybrid bus
DOE	Department of Energy (U.S.)
EDLC	Electric double-layer capacitors
Fuel cell hybrid buses	Electric-fuel cell hybrid buses using electricity storage and regenerative braking
g/cm-s	Grams per centimetre second
GDL	Gas-diffusion layer
GH_2	Gaseous hydrogen
GHG	Greenhouse gas
HCNG or Hythane™	Mixture of hydrogen and compressed natural gas
HD fuel cell	Heavy-duty fuel cell
HICE	Hydrogen internal combustion engine
HSE	Health, safety and environment
HVAC	Heating, ventilation and air conditioning
Hybrid HICE~Battery	Hydrogen internal combustion engine coupled with unspecified batteries and regenerative braking
IC	Internal combustion
ICE	Internal combustion engine
IGAC	Inter-provincial Gas Advisory Council
°K	Degrees Kelvin
kJ	Kilojoule

km	Kilometre
KOH	Potassium hydroxide
kW	Kilowatt
kWh	Kilowatt hour
kPa	KiloPascal
LEL	Lower explosive levels
LH_2	Liquid hydrogen
m^3, Nm^3, Nm^3/hr	Cubic metre, normal cubic metre, normal cubic metre per hour
MJ	Megajoule
MMBtu	Million British thermal unit
MSDS	Material Safety Data Sheets
NBP	Normal boiling point
NTP	Normal temperature and pressure
NGV	Natural gas vehicle
PEM	Proton exchange membrane; polymer electrolyte membrane
PM	Preventive maintenance
P/TPACC	Provincial/Territorial Policy Advisory Committee on Codes
Re & re	Remove and replace
Regenerative braking	A system that recovers some of the energy lost while braking, using the motor as a generator and capturing expended kinetic energy that an electrical storage system accumulates for future use
SCC	Standards Council of Canada
SDO	Standards Development Organization
SMR	Steam methane reformer
UTS	Urban transit system
W	Watt
WHMIS	Workplace Hazardous Materials Information System

APPENDIX 1: METHODOLOGY

The methodology used to complete this study was composed of five principal phases, as outlined in the following diagram.

Figure 1-A. Methodology Overview



I. Start-up & Planning

II. Concept & Tool Development
(including preliminary data gathering
with bus manufacturers and demo sites)

III. Logistical Preparation

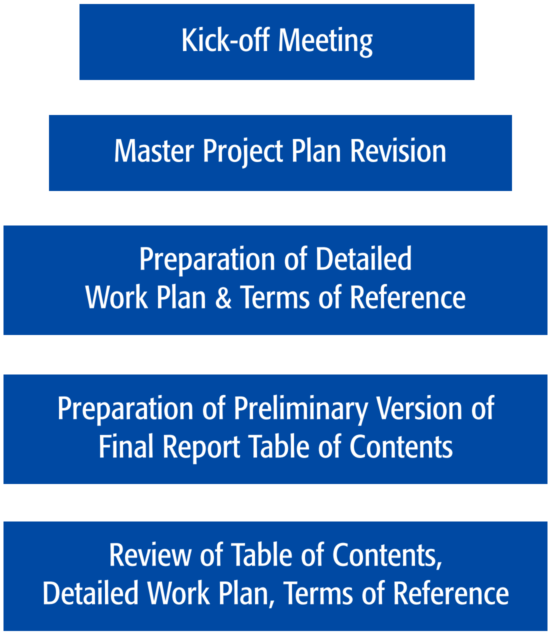
IV. Data Gathering
a) UTSs (Urban Transit Systems)
b) Codes & Standards
c) H2 Fuel Cell and Fuelling & Storage Technologies
d) Regulatory & Environmental Authorities
e) Technical Training Institutions

V. Analysis & Reporting

PHASE I. START-UP & PLANNING

The first phase of the methodology was essentially composed of start-up activities aimed at setting the groundwork for phases II through IV of the methodology.

Figure 1-B. Phase I: Start-up & Planning



Phases II and III of the methodology were undertaken simultaneously as both were preparatory steps to the data-gathering phase (Phase IV). In Phase II, interviews were undertaken with three North American and one CUTE[25] demonstration sites as well as with six bus manufacturer representatives. The list of organizations interviewed is presented in Appendix 3.

Phase III complemented Phase II by providing all the logistical support required to undertake data collection.

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[25] CUTE: Clean Urban Transport for Europe project - Fuel cell bus project partially funded by the European Union.

PHASE II. CONCEPT & TOOL DEVELOPMENT

Figures 1-C and 1-D summarize the second phase of the methodology.

Phase II began with a documentary search and review aimed at identifying UTS operating parameters (including costs, operations) as well as helping uncover issues related to changes required to adopt alternative fuel technologies such as CNG, Hythane™ and others.

Figure 1-C. Phase II: Concept & Tool Development

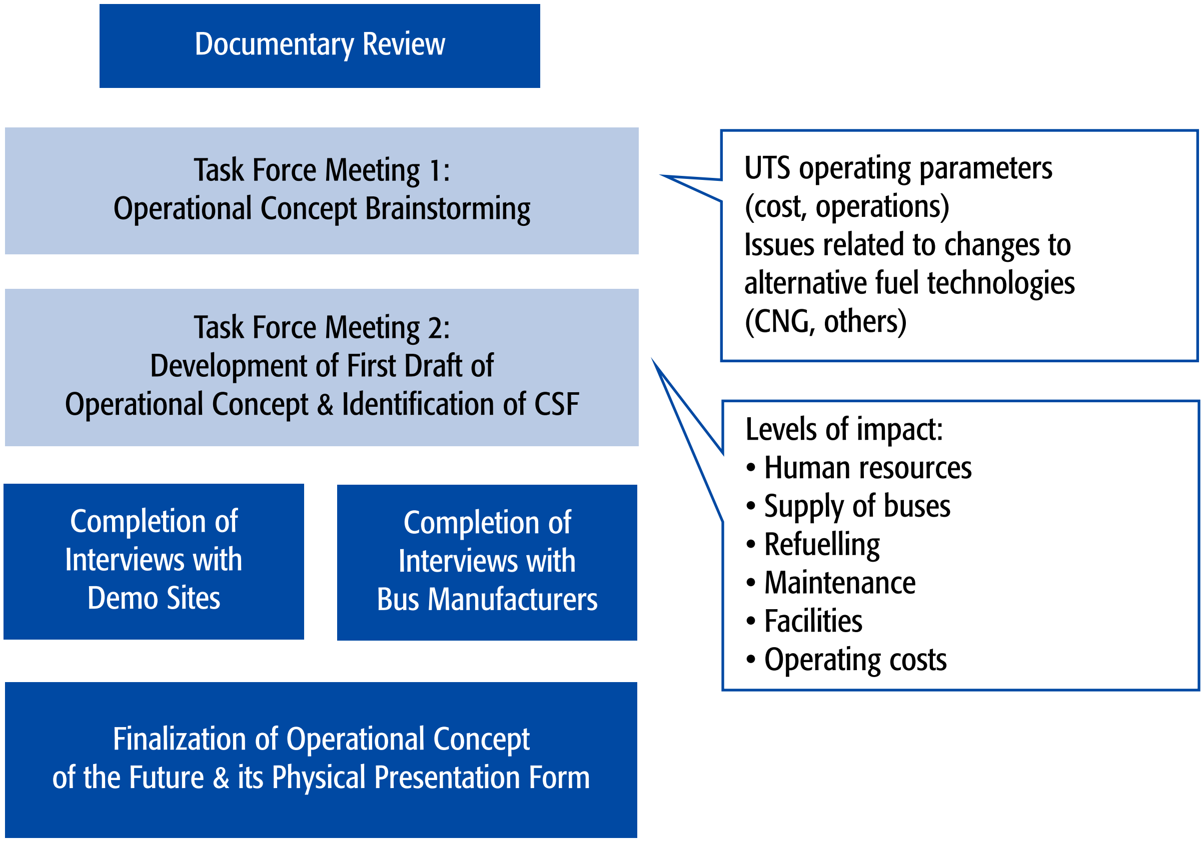


Figure 1-D. Phase II: Concept & Tool Development (2nd Part)

Design & Testing of Face-to-Face
UTS Interview Questionnaire

Design of Other Interview Guides for:
- Fuel cell engine suppliers
- H_2 technology players
- Technical training institutions
- Codes & standards & regulatory authorities

Development of Analytical Tools
(including costing model)

Testing of Data Collection Instruments
with UTSs (small, medium, large,
environmentally sensitive areas)

Review & Modifications
to Data Collection Instruments

Following the completion of this documentary review, an internal team of experts held two meetings:

- **Task Force 1 Meeting: Operational Concept Brainstorming**

  The brainstorming session looked at the Operational Concept from a variety of perspectives, including but not limited to personnel, supply of buses, refuelling, maintenance, facilities and operating costs.

- **Task Force 2 Meeting: Development of First Draft of Operations Concept & Identification of CSF**

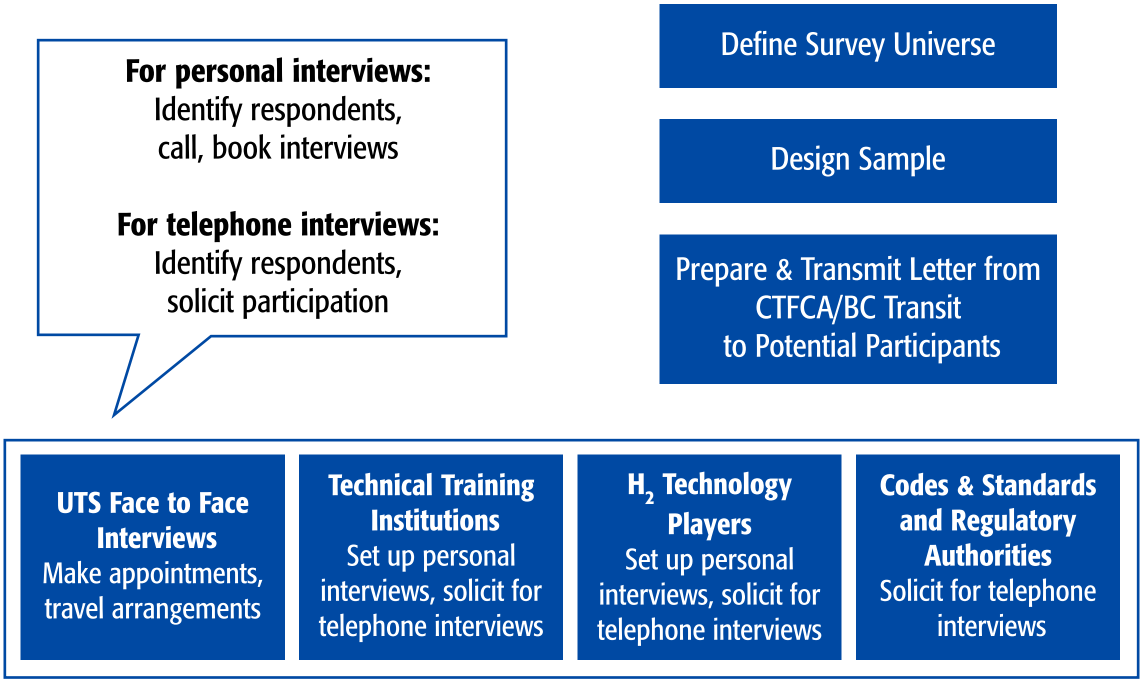
At the Task Force 2 meeting, a decision was made to undertake the demo site and bus manufacturer interviews prior to finalizing the Concept of Operations. (For Concept of Operations, see Appendix 2.)

Having developed the “Operational Concept of the Future”, MARCON-DDM HIT proceeded to the design of the instruments used to undertake the data gathering (phase IV of the methodology). A copy of the data collection instruments is presented in Appendix 3.

PHASE III. LOGISTICAL PREPARATION

Phase III involved all the logistical and co-ordination activities in preparation for the data collection work.

Figure 1-E. Phase III: Logistical Preparation

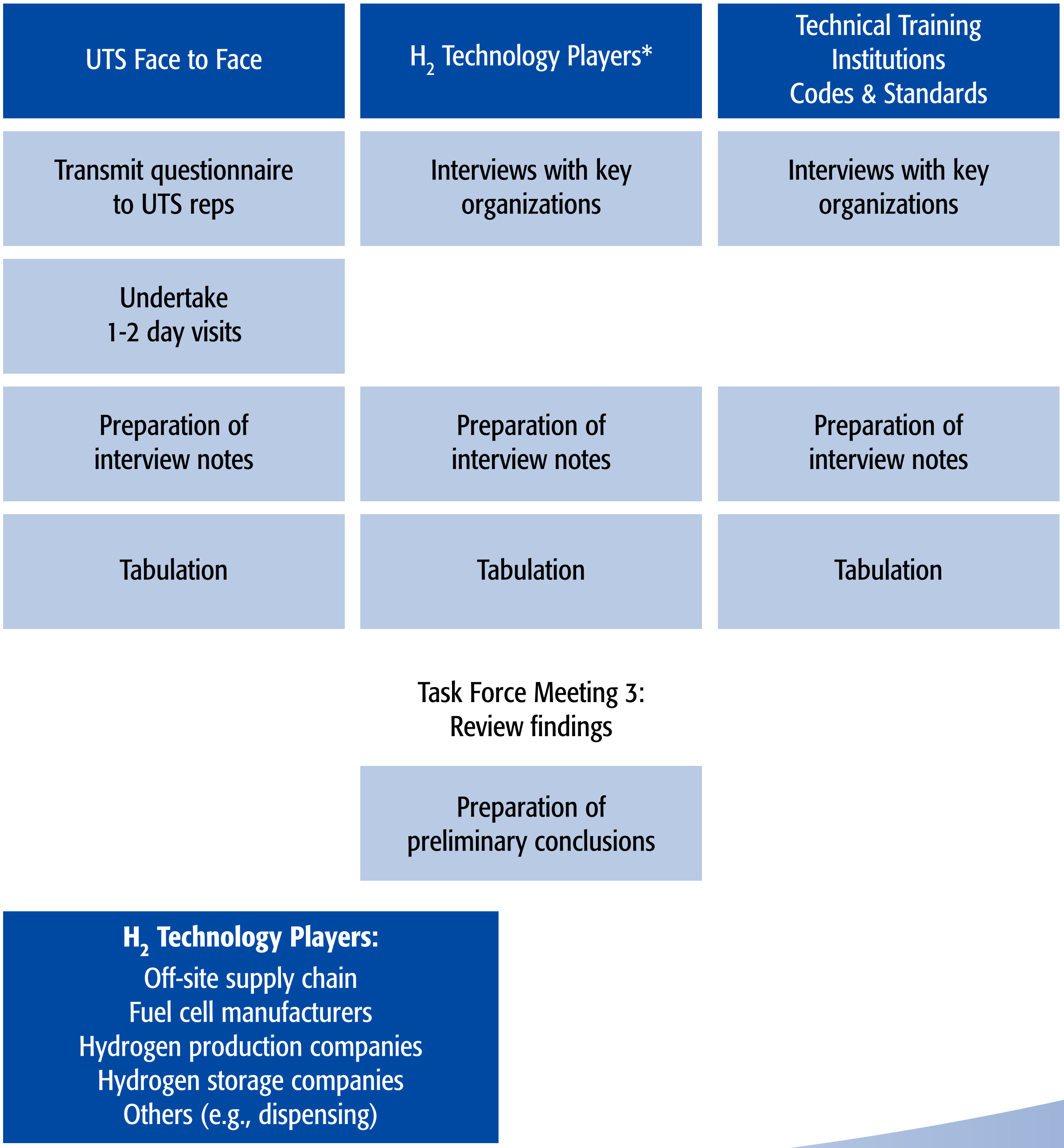


PHASE IV. DATA GATHERING

The fourth phase represents the research phase of the methodology. Data was gathered from UTSs, technology providers, fuel suppliers, unions, training institutions, industry associations and regulatory bodies.

The activities of this phase are shown in Figure I-F.

Figure 1-F. Phase IV: Data Gathering



UTS Face to Face	H_2 Technology Players*	Technical Training Institutions Codes & Standards
Transmit questionnaire to UTS reps	Interviews with key organizations	Interviews with key organizations
Undertake 1-2 day visits		
Preparation of interview notes	Preparation of interview notes	Preparation of interview notes
Tabulation	Tabulation	Tabulation

Task Force Meeting 3:
Review findings

Preparation of preliminary conclusions

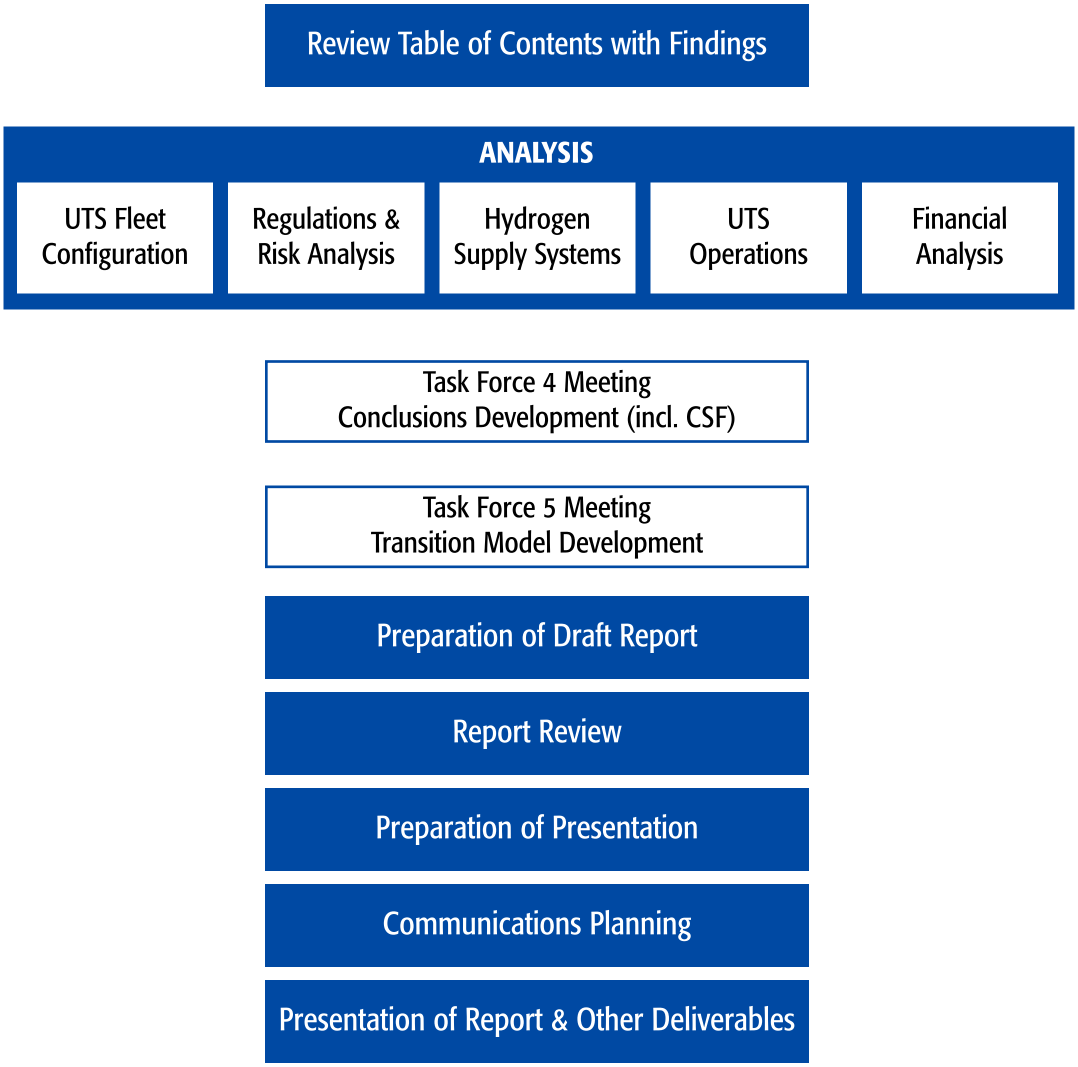
H_2 Technology Players:
Off-site supply chain
Fuel cell manufacturers
Hydrogen production companies
Hydrogen storage companies
Others (e.g., dispensing)

After having completed the research, a third task force meeting was held in order to review the findings and develop the preliminary conclusions for reporting purposes.

PHASE V. ANALYSIS & REPORTING

The last phase of the methodology is outlined in the following diagram.

Figure 1-G. Phase V: Analysis & Reporting



MARCON-DDM HIT analyzed all significant costs of the participating transit systems that would be affected by the transition to fuel cell-powered buses, collected available data and indications on present and future costs related to fuel cell-powered bus operation (including bus and facility capital expenditures, maintenance and other operating expenses, and other one-time transition costs), and organized them into a model to derive a total cost differential between diesel and fuel cell-powered bus fleets over the standard lifecycle of a transit bus.

APPENDIX 2: CONCEPT OF OPERATIONS

The **Concept of Operations** is a PowerPoint presentation that outlines the approach of the study, describes hydrogen applications for transit systems, and discusses the transit system operating parameters that will be directly impacted by the transition to fuel cell-powered transit fleets.

APPENDIX 3: QUESTIONNAIRE/ INTERVIEW GUIDE

The **Questionnaire/Interview Guide** lists the questions that interviewers posed to the various members of the transit systems that participated in the study. This included members of: the executive team, planning and operations, maintenance and vehicle engineering, sites and facilities, finance, communications, and union representatives.

APPENDIX 4: LIST OF ORGANIZATIONS INTERVIEWED

Demonstration Sites

- Vancouver (Coast Mountain Bus Company)
- Chicago (Chicago Transit Authority)
- Oakland (AC Transit)
- London CUTE[26]

Bus Manufacturers

- Gillig
- NABI
- New Flyer
- Nova Bus
- Orion
- Van Hool

UTSs

The following table shows the UTSs that participated in the study. The objective was to undertake interviews with UTS representatives in every region of the country and within each of the four basic UTS categories defined (50 units or less, 150 – 250 units, multi-250 units and special environmentally-sensitive areas).

Table 4-A. UTSs that Participated in the Study

UTS Category	UTS
50 units or less	Whistler, Kelowna, Saint John, Sarnia
150 – 250 units	Halifax, Outaouais, Victoria, Hamilton
Multi 250 units	Calgary, Winnipeg, Ottawa, Vancouver, Montreal
Special Environmentally-Sensitive Areas	Banff, Niagara, Cape Breton

Hydrogen Technology Industry

Interviews were undertaken with hydrogen technology industry players covering a range of specializations: fuel cell system suppliers, hydrogen and fuelling systems suppliers and hydrogen storage companies. The players interviewed are listed in Table 4-B.

Table 4-B. Interviews with Hydrogen Technology Industry

Category	Players Interviewed
Fuel cell system suppliers	• Ballard Power Corporation • United Technologies Corporation • Hydrogenics
Hydrogen and fuelling systems suppliers (including main components suppliers)	• Stuart Energy Systems Corporation • IMW • Air Liquide • Hyradix • Chevron-Texaco • Hydrogenics Corporation • OnQuest • Membrane Reactor Technologies • Methanex
Hydrogen storage companies	• Dynetek • Quantum
Electricity storage	• Maxwell Technologies

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[26] CUTE: Clean Urban Transport for Europe.

Technical Training Institutions

A number of technical training institutions were contacted, including College of the Desert in California, Hydrogen Safety LLC in Connecticut, Advanced Transportation Technology in California, University College of the Fraser Valley in B.C., and The National Alternative Fuels Training Consortium in West Virginia. Given the limited availability of hydrogen-related training programs, a small number of institutions agreed to participate in this study. Organizations interviewed were:

- Red River College (Winnipeg)
- Air Products
- Schatz Energy Research Centre (California)
- Department of Environmental Resources Engineering (California)
- University of California (Davis)
- Hydrogen Research Institute (Trois-Rivières)

Codes & Standards Organizations and Regulatory Authorities

- Chair of Canadian Advisory Council on Electrical Safety (CACES)
- Chair of the Inter-provincial Gas Advisory Council (IGAC)
- Chair of TISEC Inc.

APPENDIX 5: LIST OF MARCON-DDM HIT MEMBERS

MARCON-DDM HIT
- Pierre Ducharme, Project Director
- Catherine Kargas, Project Coordinator
- Jules Gagné
- Dr. Frank Gibbard
- Dr. Art Kaufman
- Jean-Marie O'Hearn
- Roy Duncan
- Paul Moreau
- Francis Fontaine

SEAJAY Consulting
- Chris Lythgo, Client Liaison

H2 Option
- Dr. Tapan K Bose
- Dr. Pierre Benard

TISEC
- Dr. Robert D. Hay
- Dr. Erling Nyborg

CryoNord
- Elie Shama