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Use of Hydrogen to Power the Advanced Technology Transit Bus (ATTB): An Assessment

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Final Report

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Phani K. Raj

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Technology & Management Systems, Inc.*
99 South Bedford Street, Suite 211
Burlington, MA 01803

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13. ABSTRACT (Maximum 200 words)

The Advanced Technology Transit Bus (ATTB), developed under primary funding from the U.S. DOT/Federal Transit Administration (FTA), currently uses a power plant based on a natural gas burning IC engine-generator set. FTA is interested in demonstrating the use of a hydrogen fuel cell-based power plant on the ATTB. This report analyzes several issues related to the proposed demonstration project including hydrogen safety, hydrogen storage options, and total hydrogen requirements.

A preliminary comparative assessment of the hazards and risks posed by useful energy equivalent quantities of hydrogen, methane, and gasoline, has been performed. This study indicates that hydrogen and methane have almost equal risks whereas gasoline has substantially higher risk. The reasons for a such a conclusion are indicated. The total quantity of hydrogen needed for a 120-km Central Business District operation cycle for an ATTB using a solid polymer electrode fuel cell is estimated to be 15.2-kg/day. This amount of hydrogen can be stored as a compressed gas on the bus in currently available CNG tanks at 25 MPA (3,600 psig) and be within the space and weight limitations of ATTB. The pros and cons of other types of hydrogen storage both on-board the bus and in the fueling station are discussed; only compressed gas storage is found to be technically and economically feasible.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (ha) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

°C=5/9(°F - 32)

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

°F=9/5(°C) + 32

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES 0 1 2 3 4 5

CENTIMETERS 0 1 2 3 4 5 6 7 8 9 10 11 12 13

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

Updated 8/1/96

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Chapter 1
Introduction

1.1 BACKGROUND

The Federal Transit Administration (FTA), in cooperation with the Los Angeles County Metropolitan Transportation Authority (LACMTA) and the Metropolitan Transit Authority (MTA) of Houston, Texas, is funding the design, prototype development, and demonstration of a new generation of lightweight, low-floor, high-technology transit bus—the Advanced Technology Transit Bus (ATTB). It was designed, developed, and fabricated by Northrop Grumman Corporation as the principal contractor. Six prototype units are being fabricated. The first prototype was rolled out in November 1996 and the sixth is due for delivery in December 1997, with the others being delivered at regular intervals.

The ATTB is designed with electric motor drives at the rear wheels. The prototype design implemented at present includes an electric generator directly driven by an internal combustion engine (Series DDC-30, Detroit Diesel natural gas engine) feeding power to the wheel motors. The prime mover part of the ATTB can be taken out relatively easily and replaced by another prime mover provided that the size, power, and weight limitations are satisfied.

One of the candidate alternate power sources is a fuel cell generating electricity by the electro-chemical action between hydrogen and oxygen. The advantage of using a fuel cell is that there are no tailpipe pollutant gas (or particulate) emissions. Fuel cells have higher chemical to electrical energy conversion efficiency. Also, there are no idling energy losses. Finally, with the provision of an energy storage device (battery, ultracapacitor, or flywheel), braking energy can be recovered resulting in improvement in the overall conversion of chemical energy to useful mechanical energy. Because of these potential beneficial characteristics of a fuel cell compared to that of an internal combustion engine, FTA is interested in testing one of the ATTB prototypes (Prototype 6) with a fuel cell powering the bus.

FTA directed Technology & Management Systems, Inc. (TMS) to perform a preliminary assessment of the various safety issues involved with the use of hydrogen-based fuel cell in an ATTB. This report details the analysis performed to satisfy the above objective.

1.2 SCOPE OF WORK

The scope of work included the preliminary evaluation of the following issues:

- Storage economy and safety properties of hydrogen.
- Energy balance in the production of hydrogen.
- Hydrogen requirements to operate an ATTB in a Central Business District (CBD) environment.
- Fuel cell type and size compatibility with the ATTB design.
- Types of hydrogen storage, both on-board the bus and in the fueling station.
- Preliminary safety assessment.
- Infrastructure issues.

The information obtained from published literature sources relevant to this study are indicated in Chapter 2. These include the principal design characteristics of ATTB, brief descriptions of types of fuel cells in commercial use and their features, fuel cells that are suitable for use in a bus, and the on-board hydrogen supply systems. Relevant properties of hydrogen are also discussed. A comparative safety/risk assessment among hydrogen, natural gas (methane), and gasoline is also indicated.

In Chapter 3, calculations are shown for determining the quantity of hydrogen required for operating a bus in transit service in a CBD. Peak power requirements on a fuel cell for a bus operation, energy budget required for producing hydrogen in a reformer, its use in a fuel cell to power a vehicle, and other overall efficiency issues, are also included.

Discussion and conclusions are provided in Chapter 4.

Chapter 2
Review of Technology and Preliminary Safety Assessment

2.1 IMPORTANT ATTB DATA

Important Advanced Technology Transit Bus (ATTB) data were obtained from Northrop Grumman Corporation, designers of the ATTB. The data refer to configuration 104 design. Except for minor changes, this represents the design implemented in Prototype 1 and rolled out in October 1996. These data are indicated in Table 2-1.

2.2 FUEL CELLS

There are five basic types of fuel cells that are in different stages of development and commercial viability. Table 2-2 describes these fuel cells, their characteristics, power density and present or potential applications. Currently, the phosphoric acid and the proton exchange membrane fuel cells are more suitable, technically as well as economically, for bus power plant application.

The two viable options for using a hydrogen-based fuel cell power plants in transit buses, therefore, are the Phosphoric Acid Fuel Cell (PAFC) and the Proton Exchange Membrane (PEM) fuel cell. The IFC Corporation of Hartford, Connecticut has built PAFCs in the 40 kW to 11 MW range, and is developing a 100 kW PAFC unit for use in a bus FTA-funded demonstration project at Georgetown University. This unit is integrated with an atmospheric pressure methanol reformer that supplies hydrogen to the fuel cell. IFC Corporation is also working on a PEM fuel cell capable of operating at atmospheric pressure. Ballard Corporation of Vancouver, British Columbia has developed and demonstrated the use of PEM fuel cells on a 30-ft bus. Currently, Ballard is fabricating a 250 kW PEM fuel cell for use in 40-ft buses to be used in revenue service in Vancouver and Chicago. These fuel cells are fed pure hydrogen at 35 psig from high pressure hydrogen storage tanks. Ballard is also developing a methanol reformer–PEM fuel cell integrated unit to work in the Georgetown University fuel cell bus program. Table 2-3 shows the power rating, weight, and dimensions of different types of fuel cells that are applicable to powering a bus.

Table 2-1

Relevant Data on ATTB*

Parameter		Value	Units
Length of Bus		12.2 (40)	m (ft)
Maximum Cross-Sectional Area of Bus		8	m^2
Gross Vehicle Curb Weight		9,441	kg
Seated Passenger Capacity		43	
Standing Passenger Capacity		29	
Engine = DDC Series 30, Natural Gas Engine Rating		156.6 at 2,600	kW rpm
Engine-Gen Set Weight		1,039	kg
Engine Skid Dimensions:	Length Width Height	0.8 2.0 2.2	m m m
Natural Gas (Fuel) Carried on Board		205.5 (7,256)	std m^3 (SCF)
Natural Gas Storage Pressure		25 (3,600)	MPa (psig)
Natural Gas Storage Tanks (Lincoln Composites)			
Total tank volume (2 tanks x 284.9 L + 1 tank x 116.2 L)		686	L
Total weight of 3 tanks (2 x 122 + 53.5)		297.5	kg
Tire Load Limits (Each Tire)	Front Rear	2,998 4,250	kg kg
Vehicle Weight Distribution on Axles	Front Rear	37 63	% %

* The data were provided by Northrop Grumman. These data refer to configuration design #104. The data are in English units. However, to maintain consistency, these data are presented in SI Units throughout this report.

Table 2-2

Fuel Cell Types and Characteristics

Fuel Cell Type	Operating Temperature (°C)	Characteristics	Applications
Alkali	50-100	◆ High-power density (A/m^2). ◆ By-product is water. ◆ High platinum loadings on the electrodes needed. ◆ The KOH electrolyte reacts with CO_2 in the ambient to form K_2CO_3 which clogs the pores in the electrode. Hence, pure oxygen is required to be supplied. ◆ Very expensive fuel cell.	◆ In space vehicles, because of high reliability and high-power density.
Solid Polymer–Proton Exchange Membrane (PEM)	50-100	◆ Electrode being a solid provides great advantage for use in transportation sector. ◆ Requires platinum catalyst to promote reactions. ◆ Requires very high purity (>99.99%) hydrogen supply. ◆ Moderate current density.	◆ Currently being used in 30-40 ft prototype buses as a power source for propulsion.
Acid Electrolyte–Phosphoric Acid Fuel Cell (PAFC)	~200	◆ Commercially most successful. ◆ Fuel cells available in power range of a few kW to 300 kW. ◆ Cells are made of solid materials and the plate electrolyte is sandwiched between graphite plates. ◆ Very high reliability under industrial use conditions. ◆ High cost per kW ($2000 to $3000/kW)	◆ Used commercially to generate power in remote areas (near natural gas supply lines). 200 kW units have more than 20,000 hours of operating experience.

Table 2-2

Fuel Cell Types and Characteristics (continued)

Fuel Cell Type	Operating Temperature (°C)	Characteristics	Applications
Molten Carbonate	600	◆ Uses a mixture of lithium and potassium carbonate as the electrolyte. ◆ CO_2 is absorbed from the atmosphere and reacts with O_2 at the cathode to form carbonate ions which migrate towards the anode where they are neutralized by H_2 or CO producing water, CO_2, and electrons. ◆ Nickel catalyst is used in the electrodes. ◆ Electrolyte is hot and corrosive and impacts on the life of the components.	◆ Used in medium to large (2 kW - 2MW) power systems. ◆ Also used as load levelers in electric utilities. ◆ Not suitable for small power plants or for transportation use.
Solid Oxide	1,000	◆ Very high temperature. ◆ High temperature is utilized to reform natural gas in the cell itself. ◆ All materials are ceramic and are difficult to produce. ◆ High temperature waste heat can be used for other purposes. ◆ Very simple in design and operation.	◆ Few commercially operating units at present. ◆ Potential for use as a cogeneration plant because of the high temperature waste heat produced. ◆ Suitable for use in transportation sector if the cost, operating temperature can be reduced and material life and reliability are improved.

Table 2-3

Weight and Dimensions of Bus Fuel Cell Power Plants

Type of Fuel Cell Power Plant	Electrical Power Rating (kW)	Weight (kg)	Volume (m^3)	Features	Manufactured By
PAFC/Methanol, CNG, Naphtha Feed	100	1,720	5.70	Power plant is integrated with the reformer.	IFC
PEM/Methanol Power Plant	100	1,815	4.96	Power plant is integrated with the reformer.	Ballard
PEM/Methanol Unit for Georgetown Bus	150	1,091	4.96	Methanol reformer integrated with fuel cell. Mounts to the back of an RTS bus.	Ballard
PEM/Hydrogen Fuel Cell	205	—	—	All control and feed units integrated. Fits on the back of a 40-ft bus. H_2 gas is supplied from compressed hydrogen storage tanks.	Ballard

2.3 ON-BOARD HYDROGEN SUPPLY OPTIONS

The solid electrode fuel cells (PAFC, PEM) require the feed of hydrogen gas at the anode and oxygen (or air) at the cathode. To supply hydrogen to the fuel cell used on a bus there are two options. The first option is to store hydrogen on the bus as a highly compressed gas at pressures ranging from 25 MPa to 35 MPa (3,600 psi to 5,000 psi) in tanks certified for hydrogen duty. The second option is to produce hydrogen (of required purity) using on-board reformers. A reformer converts a hydrocarbon fuel such as natural gas, methanol, LPG, gasoline, naphtha, etc., to hydrogen and carbon dioxide. The advantages and disadvantages of either method of hydrogen supply on-board a bus are indicated in Table 2-4. At present, there is operational experience data only for the compressed hydrogen-PEM cell combination in a 30-ft demonstration bus operated by Ballard Corporation and PAFC-methanol on a 30-ft bus by Georgetown University. In December 1998 the buses with reformers on-board are expected to be placed in test service as a part of the FTA-sponsored Georgetown University fuel cell bus project.

2.4 HYDROGEN PROPERTIES

The important properties of hydrogen of interest to this study are its storage, energy content, safety/hazard, and handling characteristics.

Hydrogen is a gas at normal temperature and atmospheric pressure. It is the lightest of all gases (it is also the lightest element); hence, it rises rapidly in air when released into the atmosphere. Also hydrogen has a very high diffusion coefficient in air; hence it disperses in (and mixes with) air rapidly. Hydrogen liquefies at atmospheric pressure at 20 K (- 424 °F). Density of liquid hydrogen at the boiling point (20 K) is only 7% of the density of water. The density of hydrogen gas at standard conditions (293 K and 1 atmosphere) is also about 7% of the density of air at the same conditions. Density of hydrogen vapor at the liquid hydrogen boiling temperature is higher than ambient air density (by only about 12%).

The heat of combustion of hydrogen per unit mass is about 2.4 times that of a hydrocarbon fuel. A hydrogen flame in air is nearly invisible. Also, the flammability of hydrogen-air mixture has a wide range (4% to 75%) and the ignition energy is very low. These properties (compared with corresponding ones for a hydrocarbon fuel vapor) make hydrogen a potentially hazardous fuel. These and other properties of hydrogen are indicated in Table 2-5. Also shown in this table, for purposes of comparison, are the corresponding values for methane and gasoline.

Table 2-4

Advantages and Disadvantages of Different Types of Hydrogen Supply On-Board a Fuel Cell Bus

Type of On-Board Hydrogen Supply	Advantages	Disadvantages
Compressed Hydrogen Storage Tanks	◆ Very high purity hydrogen can be stored. ◆ Load-dependent hydrogen demand can be easily satisfied without any time lag. ◆ Fuel supply system maintenance is relatively easy. ◆ Relatively low weight of fuel supply components for a given duty cycle (when lightweight composite type tanks are used).	◆ Long-term high pressure hydrogen storage in lightweight composite tanks is still a developing technology. Leaks through valves and other appurtenances have been measured even in "leak proof" systems. ◆ Potential safety concerns are associated with large quantity, high-pressure hydrogen storage on a bus. ◆ Limited experience base on the behavior of safety valves and other equipment used in hydrogen duty and exposed to natural elements and road vibrations. ◆ Significant length of plumbing and number of plumbing connections between the bus roof tanks (of hydrogen) and inlet to the fuel cell poses higher potential for hydrogen leaks. ◆ Limited mass of hydrogen storage, even under high pressure. This results in reduced bus operating range and more frequent fueling events.

Table 2-4

Advantages and Disadvantages of Different Types of Hydrogen Supply On-Board a Fuel Cell Bus (cont.)

Type of On-Board Hydrogen Supply	Advantages	Disadvantages
Hydrogen-Generated On-Board Using a Reformer	◆ Hydrogen is generated where it is needed. Quantity of hydrogen gas at any instant is very small (gms). ◆ Because of storage of conventional fuels (and especially in liquid state for methanol and naphtha) on-board the bus the safety concerns are somewhat less. ◆ Liquid hydrocarbons (reformer feed) fuel storage provides larger operating range for a bus. Also, fuel handling and fueling are simpler. ◆ Less costly and lower technology demand on the fuel delivery infrastructure.	◆ Reformers are complex systems. None tried to date in the size and load demand variations of a typical transportation bus application. Hence, unproven technology for transit bus use. ◆ Inherently heavier equipment. ◆ Higher maintenance complexity (compared to gas storage tanks). ◆ High operating temperature in the reformer could pose safety problems. ◆ Load following characteristics for a bus reformer is untested. Because of the fluid flow and other equipment constraints, there may be significant phase lag between hydrogen demand and supply. (This may necessitate the provision of a hydrogen accumulator.) ◆ Generating a high purity hydrogen for a PEM cell requires additional complex equipment. ◆ A significant part of the chemical energy in the hydrocarbon fuel used by auxiliary equipment and is lost as waste heat (only in early designs).

Table 2-5

Properties of Hydrogen, Methane, and Gasoline

	Property	Temperature (K)	Temperature (°F)	Pressure Absolute (kPa)	Pressure Gage (psig)	Units	Hydrogen	Methane	Gasoline
1	Chemical Formula					—	H_2	CH_4	$(CH_2)_N$ $6 \leq N \leq 10$
2	Molecular Weight					kg/kmol	2	16	84-140 Avg. ~ 112
3	Normal Phase at NTP*						Gas	Gas	Liquid
4	Normal Boiling Point (NBP)†					K	20.3	112	—
5	Critical Temperature					K	33.0	190.6	—
6	Liquid Density at NBP					kg/m^3	70.8	422.6	700
7	Vapor Density at:								
	NBP:	20.3	-423.5	101.3	0	kg/m^3	1.34	1.82	4.5
	STP:	293	67.4	101.3	0	kg/m^3	0.083	0.65	4.4
		293	67.4	342.7	35	kg/m^3	0.283	2.14	—
		293	67.4	13,900	2,000	kg/m^3	10.7	110.5	—
		293	67.4	25,000	3,600	kg/m^3	17.7	189.0	—
		293	67.4	34,000	5,000	kg/m^3	23.0	245.0	—

Table 2-5

Properties of Hydrogen, Methane, and Gasoline (cont.)

Property	Units	Hydrogen	Methane	Gasoline
8 Flammability Limits in Air				
Lower	vol. %	4.0	5.3	1.0
Upper	vol. %	75.0	15.0	7.6
9 Detonability Limits in Air				
Lower	vol. %	18.3	6.3	1.1
Upper	vol. %	59.0	13.5	3.3
10 Diffusion Coefficient in Air	m/s^2	6.1×10^{-5}	1.6×10^{-5}	0.5×10^{-5}
11 Stoichiometric Concentration in Air	vol. %	29.53	9.48	1.76
12 Stoichiometric Air/Fuel Mass Ratio		34.33	17.17	14.7
13 Minimum Ignition Energy	mJ	0.02	0.29	0.24
14 Autoignition Temperature	K	858	813	501 - 744
15 Maximum Flame Temperature	K	1,800	1,495	1,520
16 Heat of Combustion				
Lower Value	MJ/kg	120.0	50.0	44.5
	MJ/m^3 of liquid	8,496	21,130	31,150
	MJ/m^3 of vapor at STP	9.96	32.5	195.8

Table 2-5

Properties of Hydrogen, Methane, and Gasoline (cont.)

Property	Units	Hydrogen	Methane	Gasoline
Higher Value	MJ/kg	142	55.5	48.0
	MJ/m^3 of liquid	10,054	23,454	33,600
	MJ/m^3 of vapor at STP	11.8	36.1	2,112
17 Standard Heat of Formation‡ (SHF)	MJ/kmol	0.0	-74.9	—

NOTES:

* STP = Standard Temperature (20 °C) and pressure (atmosphere)

† NBP = Normal Boiling Point. That is, the temperature of liquid boiling at 1 atmosphere pressure.

‡ SHF = Standard Heat of Formation is the enthalpy of the substance at its most natural state at 25 °C and 1 atmosphere pressure. A negative SHF indicates that heat is released to the environment during the formation of substance.

Sources of Data: Hord (1976), Burgess & Hertzberg (1974)

2.5 COMPARISON OF RELATIVE HAZARDS FROM HYDROGEN, NATURAL GAS, AND GASOLINE USED AS TRANSPORTATION FUEL

In this section, the relative hazards posed by the use of hydrogen and natural gas as alternative bus fuels and gasoline are compared. Diesel fuel is not considered because of the relatively high flash point for ignition, low flammability hazard, and higher overall safety.

Comparison of the relative hazards of hydrogen, methane, and gasoline is made on the basis of equal energy stored. The calculation of fuel storage requirements is based on the same mechanical energy being available at the wheels after considering the respective power plant efficiencies and the same bus duty cycle. We assume an overall hydrogen fuel cell efficiency of 45%, natural gas internal combustion engine (ICE)—genset efficiency of 30%, and a gasoline ICE power plant efficiency of 25%. On this basis, for every 1 kg of hydrogen stored, 3.6 kg of methane, and 4.9 kg of gasoline needs to be stored to obtain the same energy at the wheels.

Safety assessment can be performed for different storage systems and fuel release scenarios. Safety issues related to storage of the fuel on the bus as well as for the storage of fuel in the fueling station can be evaluated. These analyses can include the hazards associated with:

- Storage of fuel on the bus and
  - slow leaks of fuel to the atmosphere due to fuel line leaks
  - short duration, high pressure limited quantity releases from properly operating relief valves
  - long duration continuous releases from malfunctioning relief valves
  - major and relatively short-term releases of the entire contents of one or more tanks due to tank or tank component failures
  - low leak rate releases into the engine compartment of fuel due to fuel line or critical fuel side engine components

- Storage of fuel in the fueling station and
  - fuel release at low leak rate from gasket and valve packing failures
  - high rate, short-term releases from plumbing ruptures
  - spill or release of fuel due to bus overfill during a fueling process
  - very rapid release of a large quantity of fuel from the fuel tank failure

In the following section, the hazardous properties are compared and the magnitude of potential hazards arising from these properties for hydrogen, methane, and gasoline are reviewed. A qualitative to semi-quantitative assessment is performed of the relative magnitude of "risks" form a large-scale release of each of the fuels.[1] Considered in this summary safety assessment are such properties as flammability, explosivity, diffusion in the atmosphere, ignition energy, etc. Note that the consideration of each of the above release scenarios, together with a detailed calculation of the quantitative risks, is beyond the scope of this study.

The hazard comparisons below are made on the basis of the quantity of fuel required for an ATTB to operate for a distance of 120 km per day, in an Environmental Protection Agency CBD cycle. (This distance is typical of a bus operating range in a small-to-midsize town). On-site storage comparisons are qualitative.

2.5.1 Flammability

The range of fuel concentrations in air is considered as one of the indices of flammability hazard. Hydrogen has the widest flammability concentration range (4% to 75%) whereas methane has 5%-15% range that is only 14% of the range of hydrogen. Gasoline's flammability range is (1% to 7.6%) only about 10% of the range of hydrogen. On this basis, hydrogen is ten times more flammable than gasoline and seven times more flammable than methane.

However, in the case of a gas cloud release into the atmosphere and its potential ignition, the probability that a cloud ignites is not dependent only on the flammability range but on the complex interaction of the volume of cloud in the flammable range, duration of the persistence of cloud with

[1]Of equivalent quantity based on the same units of fuel energy being delivered at the vehicle wheel.

inflammable range, the location of ignition source(s) within this flammable volume and the probability that an ignition source is "on" when it is within the flammable cloud. If the focus is on a continuously "on" ignition source or an ignition source created by the release of the vapor cloud (such as a static electricity discharge) then the criterion for flammability index is only the lower flammable limit. This is because once the cloud is ignited even the rich portions (i.e., portions of the cloud with concentrations above the upper flammable limit) of the cloud will burn due to diffusional combustion in the open. Based on this criterion (of lower flammability limit) gasoline is more flammable, followed by hydrogen and methane. The ratio of gasoline lower flammability limit to the lower flammability limit of the other fuel is used as an index. The higher this index, the higher the potential hazard. Table 2-6 indicates these relative "hazard indices" for the three fuels.

Other hazardous properties of interest are shown in Table 2-6 and the corresponding relative indices of risk posed by the particular property are also indicated. In general, the indices are normalized to the value of the property of that fuel which causes the highest degree of hazard. Therefore, the lower the value of the relative hazard index, the lower is the degree of hazard posed by the property under consideration. Also indicated in Table 2-6 are the relative importance value (or the statistical weight) of each property as it contributes to the occurrence of a hazard by the release of a fuel. The overall hazard/risk index is then formed by the formula:

$$\text{Overall relative hazard index} = \sum \text{relative hazard index of a particular property} \times \text{statistical weight of the property} \qquad \textbf{(1)}$$

Where $\sum$ represents summation over all hazardous properties.

2.5.2 *Explosion*

The result of an explosion is the generation of locally high over-pressures. Explosions may result in injury to human beings exposed to over pressures, damage to buildings and other structures. There are two types of explosions: one in which the explosive energy is small and causes an increase in local gas pressure due to combustion in a confined or a semi-confined space, with damage here limited to structural failures; the second type involves the very rapid combustion of the fuel vapor resulting in the formation of a supersonic pressure wave (detonation wave) which can destroy structures and humans at large distances (hundreds of meters) from the source of gas. Which type of explosion occurs when a fuel vapor air mixture is ignited depends on the nature of the chemical, degree of structural containment of the vapor air mixture.

Table 2-6
Relative Hazard Indices for Hydrogen, Methane, and Gasoline for Each Hazard Property

Property	Index Calculation	% of Weight of the Property for Initiating a Hazard	Relative Hazard Indices		
			Hydrogen	Methane	Gasoline Vapor
1 Flammability	$\frac{\text{LFL of Gasoline}}{\text{LFL of Other Fuel}}$	10	0.25	0.19	1.00
2 Explosivity (confined conditions)	$\frac{\text{Detonation Range of Fuel}}{\text{Detonation Range of } H_2}$	10	1.00	0.18	0.05
3 Explosivity (partial confinement)	$\frac{\text{Prob of Explosion of Fuel}}{\text{Prob of Explosion of } H_2 \text{ in Air}}$	10	1.00	0.10	0.10
4 Energy of Explosion*	$\frac{\text{Explosion Energy Released by Fuel}}{\text{Explosion Energy Released by Gasoline}}$	10	0.49	0.82	1.00
5 Minimum Energy of Ignition	$\frac{\text{Energy of Ordinary Ignition Sources}}{\text{Minimum Ignition Energy of the Fuel}}$	5	1.00	1.00	1.00
6 Vapor Density at Release** (STP)	$\frac{\text{Vapor Density of Fuel}}{\text{Vapor Density of Air}}$	20	0.07	0.54	1.00
7 Diffusivity in Air†	$\left[\frac{\text{Diffusivity of Gasoline Vapor}}{\text{Diffusivity of Fuel}}\right]^{3/4}$	20	0.15	0.42	1.00

Table 2-6
Relative Hazard Indices for Hydrogen, Methane, and Gasoline for Each Hazard Property (cont.)

Property	Index Calculation	% of Weight of the Property for Initiating a Hazard	Relative Hazard Indices		
			Hydrogen	Methane	Gasoline Vapor
8 Flame Temperature‡	$\left[\frac{\text{Flame T of Fuel}}{\text{Flame T of Gasoline}}\right]^2 x \left[\frac{\eta_{fuel}}{\eta_{gas}}\right]^{1/2}$	15	0.68	0.67	1.00
9 Absolute Weighted Risk Index	$\sum$ Weights x Individual Hazard Index	100	0.47	0.47	0.82

* Based on TNT equivalent/kg of fuel x total kg for 120 km service. It is estimated that 15.2 kg of hydrogen, 54.7 kg of natural gas, and 73.7 kg of gasoline, are needed for 120 km service. Theoretical TNT equivalents are 24, 11, and 10, respectively, in kg/kg.

** Indices greater than 1 are changed to 1.

† The rate of air entrainment (and, therefore, of vapor dilution) into a free convection buoyant plume in which the turbulence is self generated is proportional to the $(3/4)^{ths}$ power of the molecular diffusivity.

‡ For identical size (diameter) fires, the hazard distance is proportional to the square of flame temperature and square root of fraction of energy emitted (η).

Hydrogen is more explosive (per unit mass) than either methane or gasoline. On a theoretical basis, the effect of 1 kg of hydrogen exploding is equivalent to 24 kg of TNT. Corresponding TNT equivalence numbers for methane and gasoline vapor are 11 and 10, respectively. However, in a given vapor cloud, the mass of fuel within the explosive concentration is variable (with time and ambient mixing conditions). The fraction of the cloud vapor mass that can actually explode is small (5% to 10%); this fraction is called the yield. The yield factor for hydrogen is smaller than for methane or gasoline vapor due to rapid dispersion.

One important explosion-related property distinguishes hydrogen from other fuels: hydrogen has the greatest propensity to explode even under very modest confinements. It is generally impossible to have hydrogen-air, methane-air, and gasoline-air mixtures explode when ignited in the open. However, very modest confinement will be sufficient to have a hydrogen-air mixture explode if ignited. For methane and gasoline vapors, a much higher degree of confinement (approaching unity) is needed to initiate an explosion. However, for equivalent energy storage in the fuels, hydrogen has the least theoretical explosive potential of the three fuels.

2.5.3 *Ignition Energy*

Hydrogen has the lowest ignition energy (0.02 mJ) which is about 10 times lower than that for methane or gasoline vapor. However, the ignition energies for all three fuels are so low that the energy in a static spark is significantly higher than required to ignite any of the three fuels. Hence, it can be safely argued that all three fuels are "equally easily" ignitable.

2.5.4 *Vapor Density*

The density of hydrogen vapor at standard temperature and pressure (STP) is only 7% that of air, whereas the density of methane at STP is 54.2% that of air and gasoline vapor is 367% that of air (i.e., heavier than air). Hydrogen released at STP conditions will rise very rapidly, being very buoyant. Methane at STP will also rise, but at a lower rate. However, when hydrogen is released from a very high pressure (say, 3,600 psi) it expands and cools to a low temperature; but the gas exiting will still be lighter than air and should rise. On the other hand, a high pressure release of methane results in a heavier than air gas which will not rise, but, after mixing with air, become, at best, neutrally buoyant. This means that hydrogen released from a high pressure tank poses less hazard (because of its relatively rapid rise), especially in the open, compared with methane released from similar storage conditions. Also, for equivalent energy stored in the gases, the cloud formed by methane will be larger than from an equivalent hydrogen release. Therefore, the low vapor density of hydrogen results in reduced hazards at lower elevations compared with that posed by equivalent energy methane. Gasoline poses the most serious and longer term ignition and fire hazard at lower levels (i.e., close to the ground).

2.5.5 Diffusivity

The magnitude of diffusivity determines the rate at which a cloud of vapor mixes (or is diluted) in the atmosphere. While the dilution of a vapor cloud in the atmosphere is governed by the level of atmospheric turbulence (independent of the vapor diffusivity) in cases where the turbulence is generated by a buoyant, rising plume, diffusivity is an important property. The higher the value of the diffusivity, the more rapidly the vapor plume is diluted.

Hydrogen has the highest diffusion coefficient (0.61 cm^2/s) in air followed by methane (0.16 cm^2/s), and gasoline vapor (0.05 cm^2/s). Therefore, compared to gasoline vapor, hydrogen is about 12 times more easily dispersed and diluted. It is also noted that hydrogen ***rises*** in the air whereas gasoline vapor tends to stay close to the ground.

2.5.6 Flame Temperature and Fire Radiation

The extent of the hazard zone surrounding a fire depends on the fire temperature, its emissivity, and the size of the fire. Alternately, these parameters can be contained in two parameters, namely the rate of heat energy generation by a fire and the fraction of this energy that is emitted to the surroundings. The latter number varies between 15% and 40% (17%-25% for hydrogen, 23%-33% for methane, and 30%-42% for gasoline). Gasoline fires have the highest (adiabatic) flame temperature (2,470 K) followed by hydrogen (2,320 K), and methane (2,150 K). Hydrogen and methane vapor fires are very short-lived because they burn essentially in an unconfined diffusion flame without the flame bottom being anchored to a "base." Gasoline fires, on the other hand, can be large pool fires and persist for a long time. Without a whole sequence of calculations, it is not possible to predict whether a short-lived hydrogen fire or a longer burning gasoline fire create a larger hazard area. However, it can be anticipated that the gasoline fire will burn longer and may lead to higher levels of hazard.

Table 2-6 shows the relative hazard indices calculated for each of the fuels for each property. Also provided in the table are the (subjective) statistical weights for each property. The total weighted average hazard index of each fuel in also given. It is seen that the relative hazards of hydrogen and methane are almost the same, whereas gasoline is about twice as hazardous when assessed on the basis of equal energy storage in each of the fuels.

2.6 ENERGY REQUIREMENTS FOR HYDROGEN GENERATION

Hydrogen is commercially produced on a large scale by a process of steam reforming of a hydrocarbon feedstock (natural gas naphtha) in an industrial reformer. Several questions related to the energy requirement arise in the use of hydrogen as a transportation fuel. Some questions include:

1. How much energy is consumed in producing a unit mass of hydrogen?

2. Is it beneficial (i.e., energy-wise more efficient) to use hydrogen rather than conventional hydrocarbon fuels in a transport vehicle even when there is an energy penalty in producing hydrogen?

3. How can one quantify the ecological benefit arising from the use of hydrogen in vehicles in light of significant improvements in reducing emissions from conventional fuel burning in vehicles?

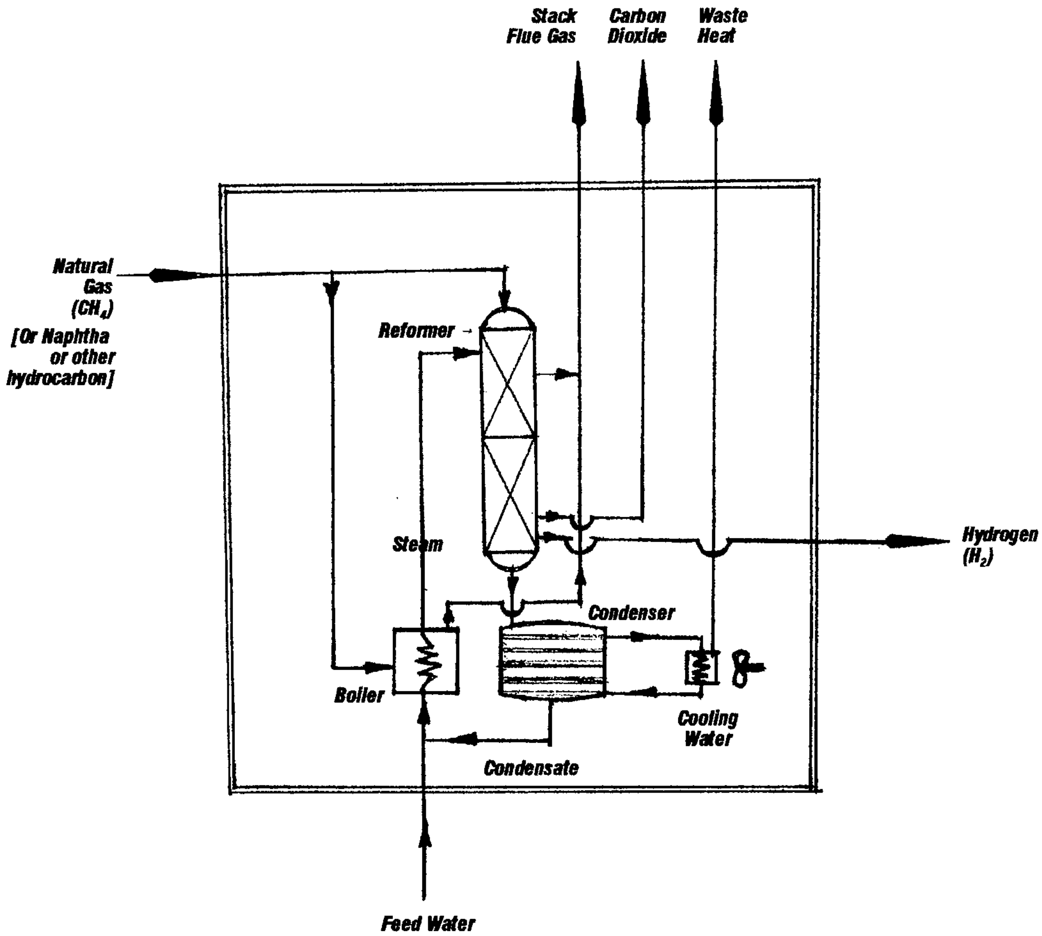
The first two questions are addressed in this section. Developing an answer to the third question is beyond the scope of this study.

2.6.1 *Hydrogen Production Energy Calculation*

Hydrogen production energy calculations are shown below assuming natural gas at the feed stack to the industrial reformer. A schematic representation of the steam reformer for producing hydrogen is shown in Figure 2-1. The overall ideal reaction in a reformer can be represented by the following equation.

$$CH_4\,(gas) + 2H_2O\,(liquid) \rightarrow 4H_2\,(gas) + CO_2\,(gas) - \Delta H_f^{o} \qquad (2)$$

In the above equation it is assumed that all reactants and products are in their standard states at 25 °C and atmospheric pressure. The parameter ΔH_f^{o} represents the net increase in standard heat of formation at standard conditions. (Note if ΔH_f^{o} is positive, heat is absorbed by the reaction from the "surroundings.") The above net heat of formation represents the minimum heat exchange with the environment and, therefore, represents an ideal value.



Overall Reformation Reaction

$$CH_4\ (gas) + 2H_2O\ (liquid) \rightarrow 4H_2\ (gas) + CO_2\ (gas) - Heat$$

Figure 2-1

Schematic Representation of a Hydrogen Reformer

$$h_f^\circ(CO) = -108.9 \quad \text{MJ/kmol}$$

$$h_f^\circ(H_2O\,;\, vapor) = -242.0 \quad \text{MJ/kmol}$$

$$h_f^\circ(H_2O\,;\, liquid) = -286.0 \quad \text{MJ/kmol}$$

Using the above standard heat values and equation **(2)** we can show that:

$$\Delta H_f^\circ = 253.2 \quad \text{MJ/kmol of } CH_4$$

$$= 63.3 \quad \text{MJ/kmol of hydrogen produced}$$

$$= 31.7 \quad \text{MJ/kg of hydrogen produced}$$

That is, for every kg of hydrogen produced, 31.7 MJ of energy is "absorbed" from the environment. We now define the theoretical maximum thermal efficiency of the process as follows:

$$\eta_{Th} = \begin{matrix}\textit{Process Thermal Efficiency}\\ \textit{(based on LHV values)}\end{matrix} = \frac{\textit{Heat Content of Hydrogen Produced}}{\left[\begin{matrix}\textit{Heat Content of}\\ \textit{Natural Gas}\end{matrix} + \begin{matrix}\textit{Additional Heat Provided}\\ \textit{From Environment}\end{matrix}\right]} \qquad \textbf{(3)}$$

Noting from equation **(2)** that every kg of hydrogen produced requires the use of (1 x 16)/(2 x 8) = 2 kg of methane, and using the lower heating values for hydrogen and methane from Table 2-5, we get:

$$\left(\eta_{Th}\right)_{max} = \frac{120}{(2 \times 50 + 31.7)} = 91.1\% \qquad \textbf{(4)}$$

The value for the reformation thermal efficiency calculated in equation (4) is the theoretical maximum efficiency because we have neglected taking the actual heat losses due to hot stack gas flow, cooling water circulation, convective and radiative heat losses, energy consumed by pumps, fans, etc. Therefore, the actual efficiency will be less. The thermal efficiency of an industrial reformer[2] is indicated to be (Kirth-Othmer, 1995)

$$\eta_{Th} = 78.5\%$$

Using the above practical efficiency value, the external heat to be provided is

$$Q_f = 52.87 \; MJ/kg \; of \; hydrogen \; produced$$

It is anticipated that a reformer of the size that can fit on a bus will be less efficient than the industrial size reformer. Therefore, in the case of smaller reformers, external energy input per kg of hydrogen produced will be higher than the above indicated value.

2.6.2 Overall System Thermal Efficiency

The metric which indicates whether one system is better or economical in energy use, than another comparable system for developing motive power is the overall (system) thermal efficiency. This overall efficiency is defined by the following equation:

$$System \; Thermal \; Efficiency = \frac{Useful \; Mechanical \; Work/Energy \; Output}{\left[\begin{array}{c} Energy \; in \; Feedstock + All \; Other \; Process \\ Energy \; Input \; External \; Sources \end{array} \right]} \quad (5)$$

[2] Industrial reformer efficiency is expected to be significantly higher than that of a reformer which can fit into a bus engine compartment. Attempts to obtain data on bus reformer efficiency values were unsuccessful.

The overall system thermal efficiencies of hydrogen fuel cell-based bus system and the natural gas burning internal combustion engine bus system are calculated in the following paragraphs.

In performing the calculations, the following assumptions are made:

- Hydrogen is produced by reforming methane (natural gas).
- Energy in transporting (either by pipelines or in tank trucks) hydrogen or natural gas is not considered.
- Energy required to compress the gas is taken into account. Both hydrogen and natural gas are compressed to 25 MPa (3,600 psig).
- Different values for the thermal efficiencies for the hydrogen fuel cell and natural gas-burning internal combustion engine are assumed.

Figure 2-2 shows schematically the hydrogen fuel cell bus system and the natural gas engine bus system. The various energies generated or consumed are indicated. It is noted that the energies indicated are on the basis of 1 kg of hydrogen (note: 2 kg of methane is required to produce 1 kg of hydrogen in an ideal reaction). Hydrogen is produced by the reformation of methane. The thermal efficiencies of various components or subsystems are indicated on the figure. The efficiency value for the reformer is assumed to be 78.5% which is typical for an industrial hydrogen reformer. The efficiency for a smaller reformer to be used on a bus will be substantially lower than the value.[3]

It is seen that the overall hydrogen system efficiency is about 33% (assuming a fuel cell efficiency of 45%) whereas the overall efficiency with a natural gas engine system is only 29.5%. Therefore, the overall energy performance of the hydrogen fuel cell power plant-based bus and the CNG burning bus seem to be close to each other. (The overall efficiency values are, of course, very dependent on the individual component efficiency values). The hydrogen system has, however, the added advantage that the tailpipe emissions from the vehicle are practically zero, thereby providing an ecological advantage.

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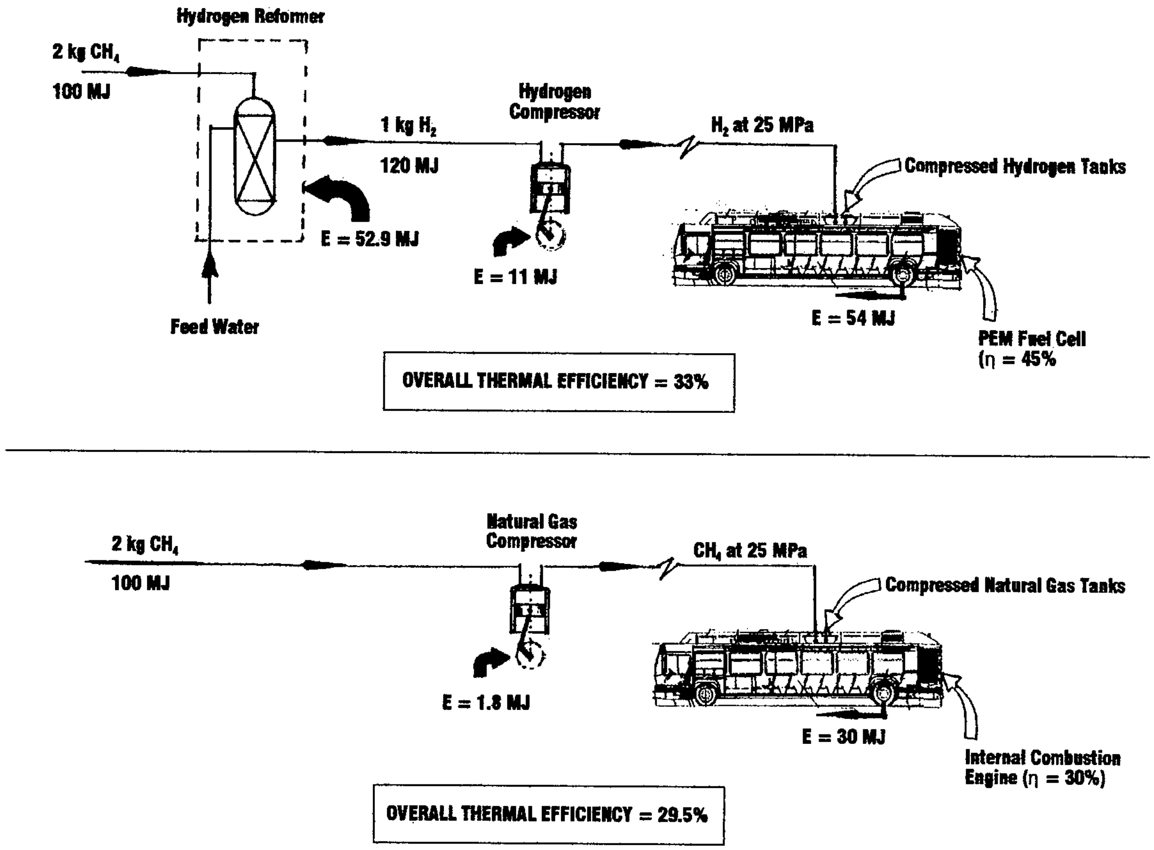
[3]As of the date of finalization of this report, data/information on the actual bus size reformer efficiencies were not available.



Note: A 4-stage, 4500 psig, natural gas compressor is (on average) rated at 2.75 Scfm/hp (i.e., to compress 1 kg, 915 kJ of energy is needed). Hydrogen compression energy is estimated to be 11 MJ/kg.

Figure 2-2

Comparison of Overall Thermal Energy Requirements and System Efficiency Between Hydrogen and Natural Gas-Based Transportation Systems

Chapter 3
Hydrogen Requirements Analysis

In this chapter the fuel (hydrogen) requirements to operate an ATTB in a typical Central Business District (CBD) environment with the bus propelled by a PEM fuel cell power plant are analyzed. To perform the necessary calculations, the following assumptions are made:

3.1 BUS DUTY CYCLE ASSUMPTIONS

(i) ATTB Characteristics

- Configuration 105 design is assumed.
- Only seated passenger load is considered.
- No credit is taken for differences in weight between the natural gas engine/gen set and a PEM fuel cell power plant or the weight savings in the weight of fuel carried[4] or the differences in weights of gas tanks.

(ii) Bus Duty Cycle

- Daily Operating Range = 120 km.
- Five percent (5%) of this distance is on a 4% grade.
- Bus operates according to the EPA-specified CBD 15 cycle depicted schematically in Figure 3-1a and Figure 3-1b.
- None of the braking energy is recovered.
- The bus operates all the time with the full load of seated passengers.

(iii) Fuel Cell Characteristics

- No reformer on-board the bus.
- PEM fuel cell is used.
- Fuel cell overall efficiency is 45%.

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[4]Prototype 1 ATTB carries an inventory of 134 kg of natural gas (7,256 SCF).

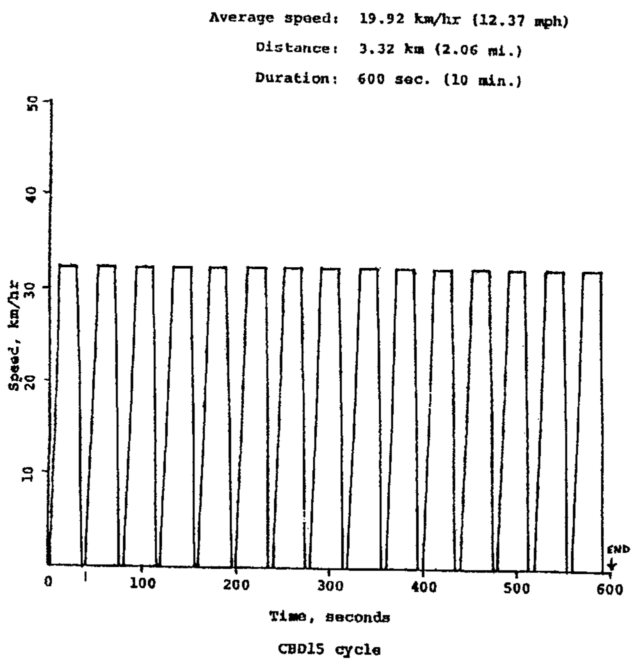

Figure 3-1a
EPA-Designated CBD Driving Cycles

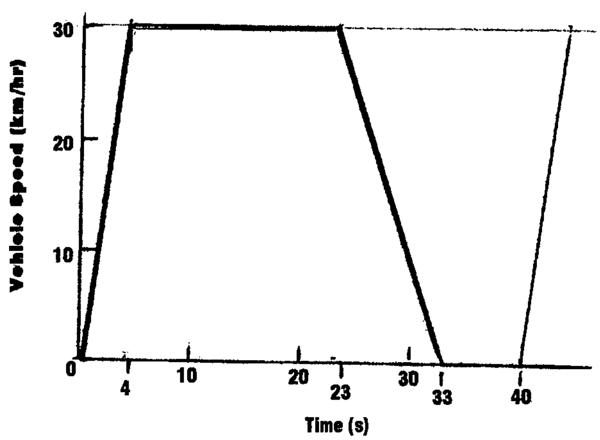

Figure 3-1b
Details of a Single CBD Cycle

(iv) Other Parameters

- Values for aerodynamic drag and rolling friction coefficients are assumed. These are indicated in Table 3-1.

3.2 CALCULATIONS OF HYDROGEN REQUIRED

The total energy required in each phase of a single CBD cycle (namely, acceleration, coasting, deceleration, and idle) is calculated separately. These energies include those to overcome inertia, road friction, and aerodynamic drag. These energies are summed over all of the CBD cycles to cover 120 km. This total energy is added to the energy expended in going over grade (i.e., increase in bus potential energy). Knowing the total energy required, the energy value of a unit mass of hydrogen, and thermal efficiency of the fuel cell the hydrogen requirement for a single day is calculated. The details of the calculations and results are indicated in Table 3-1. The energy requirements for an RTS bus in a CBD cycle are also calculated and compared with actual diesel bus performance data from NREL study.

It is seen that an average 15.2 kg of hydrogen is needed per day. With a 5% reserve, a 16.0 kg capacity storage on the bus is necessary. If the gas storage is assumed at 25 MPa (3,600 psi), then 904 liter storage volume is needed which can be fulfilled by three tanks of Lincoln Composite tanks each of 284.9 liters and one tank of 72.3 liters.

The ATTB has space on its roof to accumulate four tanks of 10-ft length. With this in view, calculations were made to determine the changes in the bus operating range with the provision of different size compressed hydrogen storage tanks. These results are presented in Table 3-2. It is seen that with the largest size (diameter) tanks available, the hydrogen that can be stored at 25 MPa (3,600 psig) is 27.8 kg. This increases the range to 208 km in a CBD environment with a 5% reserve capacity. The weight of tank + hydrogen for the baseline 120 km service is about 420 kg, comparable to the weight of tank + CNG currently used on an ATTB. For the 210-km range, the tank + hydrogen weight increases to about 660 kg.

Table 3-1

Calculation of Fuel Consumption to Operate a Bus in a CBD Cycle

Parameter	Symbol	Formula	Bus Type	
			ATTB	RTS
I. ASSUMED PARAMETER VALUES				
Gross Vehicle Weight (including engine)	W_v		9,440 kg	13,840 kg (30,510 lbs)
Passenger Weight (44+1)	W_p	45 x 70.22	3,160 kg	3,160 kg
Total Loaded Bus Weight	W	$W_v + W_p$	12,600 kg	17,000 kg
Frontal Area	A		8.0 m^2	8.0 m^2
Rolling Friction Coefficient	μ		0.01	0.01
Drag Coefficient	C_D		0.5	0.5
Density of Air	ρ_a		1.2 kg/m^3	1.2 kg/m^3
II. ENERGY REQUIRED IN MOTION				
A. Acceleration Phase				
Maximum Speed	U_m		32 km/hr 8.89 m/s	32 km/hr 8.89 m/s
Duration of Acceleration	t_1		4 s	4 s
Acceleration Magnitude	a	$\frac{U_m}{t_1}$	2.22 m/s^2	2.22 m/s^2
Distance Travelled in Acceleration Phase	S_1	$\frac{U_m t_1}{2}$	17.8 m	17.8 m
(i) Energy to Overcome Inertia Used During Acceleration	E_1^K	$\frac{1}{2} W U_m^2$	497.8 kJ	671.6 kJ

Table 3-1

Calculation of Fuel Consumption to Operate a Bus in a CBD Cycle (cont.)

Parameter	Symbol	Formula	Bus Type	
			ATTB	RTS
(ii) Energy to Overcome Aerodynamic Drag	E_1^D	$\frac{1}{2} \rho_a C_D A \frac{U_m^3 t_1}{4}$	1.69 kJ	1.69 kJ
(iii) Energy to Overcome Rolling Friction	E_1^R	$W x \mu x S_1 x g$	22.0 kJ	29.7 kJ
B. Constant Speed Phase				
Duration	t_2		19 s	19 s
Distance Travelled	S_2	$U_m x t_2$	168.9 m	168.9 m
(i) Aerodynamic Energy Used	E_2^D	$\frac{1}{2} \rho_a C_D A U_m^2 x S_2$	32.03 kJ	32.03 kJ
(ii) Rolling Friction Energy Used	E_2^R	$W g \mu S_2$	208.5 kJ	281.3 kJ
C. Deceleration Phase				
Duration	t_3		10 s	10 s
Deceleration Rate	d		-0.89 m/s^2	-0.89 m/s^2
Distance Travelled in Decelerating Phase	S_3	$U_m t_3 + \frac{1}{2} d t_3^2$	44.4 m	44.4 m
D. Stop/Idling Phase				
Duration of Stop	t_4		7 s	7 s
Idling Energy (at 1/20th max power of 185 kW)	E_4^I	1/20 * 185 x 7 (for RTS only)	0	64.75 kJ
III. TOTAL ENERGY PER CYCLE				
Duration of Cycle	t		40 s	40 s
Accessory Load (Assumed)			15 kW	15 kW
Accessory Load Energy/Cycle	E^A		600kJ	600kJ

Table 3-1

Calculation of Fuel Consumption to Operate a Bus in a CBD Cycle (cont.)

Parameter	Symbol	Formula	Bus Type	
			ATTB	**RTS**
Total Energy Consumption per Cycle	E_C	$\sum \left(E^K + E^D + E^R\right)_{1,2,3,4} + E_A$	1,362.0 kJ	1,681.1 kJ
Total Distance Traveled in a Cycle	S_C	$S_1 + S_2 + S_3$	231.1 m	231.1 m
IV. DAILY DUTY CYCLE TOTAL ENERGY				
Total Daily Distance	S		120 km	120 km
Number of CBD Cycles	N	$\frac{S}{S_C}$	520	520
A. Energy Required for Overcoming Potential Energy Due to Grade				
Steepness of Grade			4% (2.29°)	4% (2.29°)
Assumed Fraction of Distance Involving Grade	f		5%	5%
Cumulative Distance Traveled on Grade	S_G	f*S	6 km	6 km
Potential Energy Gained	E_P	$W\, g\, S_G \tan\left(2.29^{\circ}\right)$	29.64 MJ	39.98 MJ
Total Energy Consumed Daily	E	$N\, E_C + E_P$	737.9 MJ	914.1 MJ
Average Energy Consumption/km	e_1	$\frac{E}{S}$	6.15 MJ/km	7.62 MJ/km
Average Wheel Motor/Transmission Efficiency	η_T		90%	90%
Assumed Fuel Cell/IC Engine Brake Thermal Efficiency	η_{EN}		45% (fuel cell)	30% (IC Engine)

Table 3-1

Calculation of Fuel Consumption to Operate a Bus in a CBD Cycle (cont.)

Parameter	Symbol	Formula	Bus Type	
			ATTB	RTS
Average Chemical Energy Required for/km	e_2		15.2 MJ/km	28.2 MJ/km
NREL Measured Diesel 2 Bus Performance Values			—	26.8 MJ/km (3.2 mpg of diesel #2)
V. HYDROGEN REQUIREMENT				
LHV of Hydrogen	LHV		120 MJ/kg	120 MJ/kg
Total Hydrogen Required	M_{H_2}	$e_2 \times \frac{S}{LHV}$	15.2 kg/day	—
Includes a Drawdown Reserve of ~ 5%			16.0 kg/day	—
Volume of Tanks at Storage Pressure of 34 MPa (5,000 psi) 25 MPa (3,600 psi)		 $\frac{16.0}{23.04}$ $\frac{16.0}{17.7}$	 0.694 m^3 = 694 L 0.904 m^3 = 904 L	—
Standard Hydrogen Gas Volume		$\frac{M_{H_2}}{0.083}$	183.2 m^3/day 6,467 SCF/day	—
Number of 3,600 psi Lincoln Tanks 15.9" x 120" 15.9" x 35"	V_T	 3 x 284.9 L + 1 x 723 L	927 L	—
Assume 4 days/week x 8 weeks of bus Operation H_2 Storage Required		32 x 15.2 kg/day	486 kg = 5,860 m^3 std = 207,000 SCF	

Table 3-2
Comparison of the Bus Operating Range* with Different Hydrogen Storage Tank** Configurations

	Details of Tank		Number of Tanks	Total Quantity of Hydrogen Stored (kg)	Range† (km)	Combined Weight of Tank and Gas Stored In It (kg)	Remarks
1	15.9" D x 120" L	(122 kg)	3	16.4	123	418.7	
	15.9" D x 35" L	(36.3 kg)	1				
2	15.9 " D x 120" L	(122 kg)	4	20.2	150	508.2	
3	18.4" D x 120" L	(158 kg)	4	27.8	208	659.8	
4	15.9" D x 120" L	(122 kg)	2	133.6 ‡	—	431.1	Current ATTB system with natural gas
	15.9" D x 52" L	(53.5 kg)	1				

* Assumes that the bus follows the EPA's CBD cycle throughout its operating range together with 5% of distance being on 4% grade.

** All tanks are assumed to be the TUFFSHELL® composite tanks manufactured by Lincoln Composites, Inc.

† Operating range is calculated on the basis of a 5% reserve left in the tank. That is, only 95% of the mass of gas in the tank is used.

‡ Refers to the methane inventory in the tanks.

3.3 PEAK POWER REQUIREMENTS

The peak power required of the power plant is calculated based on the design requirements for ATTB that it be able to go at 72 kph (45 mph) on a 4% grade. These calculations are shown in Table 3-3. A peak power of 173 kW is needed if the auxiliary power load of 15 kW is assumed to also be applied during the above grade climb.

Table 3-3

Peak Power Requirement Calculations

Parameter	Symbol	Formula	Bus Type	
			ATTB	RTS
Grade Slope Angle	γ		2.59°	2.59°
Slope			0.04	0.04
Maximum Speed	U_m		20 m/s (45 mph)	20 m/s (45 mph)
Fully Loaded Bus Weight (45 passengers)	W_m		12,600 kg	17,000 kg
Aerodynamic Drag Force	F^D	$\frac{1}{2} \rho_a U_m^2 C_D A$	960 N	960 N
Rolling Frictional Force	F^F	$\mu W x g \cos \gamma$	1,230 N	1,670 N
Weight Component Parallel to Road	F^I	$W g \sin \gamma$	4940	6,660 N
Total Resistive Force	F	$F^D + F^F + F^I$	7,130 N	9,290 N
Prime Mover Power Output Needed (with 90% efficiency for drive train)	P^M	$\frac{F U_{max}}{\eta}$	158 kW (212.5 hp)	206.5 kW (277 hp)
Auxiliary Power (assumed)	P^A		15 kW	15 kW
Total Power Needed	P	$P^M + P^A$	173 kW (232 hp)	221.5 kW (297 hp)

Chapter 4
Requirements of Regulations for a Hydrogen Storage Installation

In this chapter the requirements in the Code of Federal Regulations (29 CFR) for the design and operation of a hydrogen storage installation are discussed.

4.1 CODE OF FEDERAL REGULATIONS (CFR)

The design and operation of hydrogen storage installations (both gaseous hydrogen and liquefied hydrogen) are regulated under Occupational Safety and Health Administration's (OSHA) Regulations in 29 CFR, Subpart H ("Hazardous Materials"), section 1910.103. OSHA Regulations are primarily concerned with the safety and health of workers and employees on the premises of the activity. However, public safety is also within the purview of these regulations.

The regulatory requirements related to a gaseous hydrogen storage installation, with storage capacity of greater than 400 cft. of gas, are indicated in 29 CFR §1910.103(a) and for an installation with liquefied hydrogen storage are indicated in 29 CFR §1910.103(b).

4.2 GASEOUS STORAGE INSTALLATIONS

The regulations in 29 CFR §1910.103(a) stipulate the design (performance) specifications and other requirements for gaseous hydrogen storage installations under the following major headings.

- **Containers**—including its supports, building materials, marking, safety relief devices, piping and tubing, etc.

- **Equipment Assembly** —including mobile trailers, valves, gages, regulators, and other accessories.

- **Testing**—protocol for testing the various components of the installation once it is in place.

- **Location of Installation**—safety distances to various objects and areas of people congregation from the gaseous storage installation.

- **Installation Building**—location of the storage container and other appurtenances in a separate but enclosed building is permitted only for hydrogen storage volumes less than 3000 cft.

The minimum safety distance to be provided between the installation and people or property depends on the size of storage. For storage of hydrogen in excess of 15,000 scf (425 m^3) the minimum distance to "concentration of people" (i.e., people in offices, lunch rooms, locker rooms, etc.) is 50 ft (15.3 m).

In case the storage is inside a building the regulations stipulate the ventilation and electrical system requirements. For example, explosion venting is to be provided in exterior walls and on the roof only. Also, the electrical systems must conform to the Class I, Division 2 specifications.

4.3 LIQUEFIED HYDROGEN STORAGE INSTALLATIONS

The regulations in 29 CFR §1910.103(b) indicate the requirements and performance specifications for liquefied hydrogen storage installations under the following major headings.

- **Containers**—including its supports, building materials, marking, safety relief devices, piping and tubing, etc. The container should conform to the ASME Unfired Pressure Vessel Code.

- **Equipment Assembly** —including mobile trailers, valves, gages, regulators and other accessories and their testing.

- **Testing**—protocol for testing the various components of the installation once it is in place.

- **Liquid Vaporizers**—design should be of the indirect heat source type.

- **Electrical Systems**—including bonding and grounding as well as the classification of the equipment and other electrical systems in the facility.

- **Location of Installation**—safety distances to various objects and areas of people congregation from the gaseous storage installation.

- **Operating Instructions**—instructions on the facility operation, maintenance, security, etc. in written form.

- **Installation Building**—The location of the storage container and other appurtenances in a separate but enclosed building is permitted only for storage volumes less than 600 gallons.

- **Control of Ignition Source**—Ignition sources are to be identified and either eliminated or controlled.

Installations with storage capacities of larger than 600 gallons (2.27 m^3) are not allowed to be located within buildings. Also, all electrical systems within 3 ft (1 m) of where regular connection and disconnection of a transfer pipe is made are to conform to Class I, Division 1 specifications. Those electrical systems which are within 25 ft (7.6 m) of a regular connection or disconnect of a hydrogen flow in a pipe or from a liquid hydrogen container must conform to Class I, Division 2 specifications. The safety distance to locations of concentrations of people should be at least 75 ft (23 m) from a liquid hydrogen storage container. Non-fire proof buildings should be farther than 100 ft (30.5 m).

It is unclear whether the 29 CFR §1910.103 regulations are applicable to a hydrogen dispensing facility, especially to a facility in which vehicles are filled often. For example, the definition given for "a gaseous hydrogen system," in §1910.103 (a) (1), indicates that the "system terminates at the point where hydrogen at service pressure first enters the consumer's distribution piping." There is no reference to hydrogen exiting from the installation. Also, there are also no explicit references in these regulations to a vehicle refueling facility. In addition, the definition of the "consumer" is not very clear. When a transit system owns (or leases) storage facility equipment and dispenses hydrogen into the vehicles the definition of the consumer is unclear. However, since the purpose of the regulations is to enhance personnel safety at the bulk hydrogen storage facilities, it is reasonable to assume that the requirements of 29 CFR §1910.103 are applicable to a transit facility which operates a hydrogen storage and refueling facility.

Chapter 5
Discussion and Conclusions

In this report, several different types of analyses have been performed to assess the feasibility of using hydrogen in a fuel cell to power an ATTB. These analyses have included comparison of hydrogen, natural gas, and gasoline safety, energy requirements and thermal efficiencies of hydrogen production systems, and hydrogen requirements for a CBD operation of an ATTB. The results from these analyses and conclusions follow.

5.1 DISCUSSION

The feasibility of using hydrogen as an alternative bus fuel with a hydrogen-oxygen fuel cell has been demonstrated in practice. Different types of fuel cells (solid polymer electrode types) are available for use in ATTB. The principal question for the use of a fuel cell on a bus is not whether the fuel cells will perform, but how the hydrogen is supplied to the fuel cell. Hydrogen can be stored as a pure (compressed) gas on the bus or can be generated *in situ* using a reformer and a hydrocarbon fuel (such as methanol). Detailed data on the performance, reliability, and life cycle costs for bus-mounted hydrogen reformers are not yet available. However, limited performance data from laboratory and pre-bus mount tests are currently being generated by IFC, Ballard, and George Washington University as part of their respective fuel cell-powered bus demonstration projects.

Hydrogen gas offers some unique properties which make it attractive and economical to use on a bus. The most important property is that the by-product of energy conversion in the vehicle's power plant is water. That is, there is no tailpipe emission of pollutants. Hydrogen has very high heating value (per unit mass) and hydrogen fuel cells have significantly higher thermal efficiencies compared to those of internal combustion engines. This high mass-based heating value results in a greater miles-traveled-per-unit mass of hydrogen used. These two beneficial property attributes provide a significant advantage to hydrogen use as a vehicular fuel compared to the use of conventional hydrocarbon fuels.

The wide flammability range, the ease of ignition of a hydrogen-air cloud and the high explosivity of hydrogen are often quoted as being the impediments to its use on a vehicle. However, a rational comparison of beneficial aspects of hydrogen in mitigating the potential hazards has to be made against its adverse properties to determine the relative safety of hydrogen. Mitigating characteristics include its extremely high buoyancy in air which promotes its rapid rise, mixing, and dispersion in the air, high diffusion coefficient which enhances rapid dilution, and nonluminescent flame which reduces thermal radiation emission.

Comparison with other bus fuels (such as methane and gasoline) has been made in this report on the basis of an equivalent amount of thermal energy storage in the bus fuel tanks. A comparative risk assessment of the hazard potential from each of the three fuels has been performed. While hydrogen is flammable and even explosive, it presents an overall risk at best comparable to that posed by an energy equivalent quantity of methane and only about one-half the risk posed by an energy equivalent quantity of gasoline. Even though it appears to contradict popular perceptions, that gasoline is safer than other gaseous alternative fuels, the higher risk from gasoline is due to the heavier than air nature of gasoline vapors and that the comparatively slow consumption rate of gasoline liquid in a fire thereby posing a fire hazard for an extended duration. Also because the LFL of gasoline is 1% whereas that of the hydrogen is 4%, the gasoline vapors in a cloud remain flammable for longer duration. Therefore, on an energy-equivalent storage basis, gasoline presents a higher level of risk compared to hydrogen or methane.

The calculations of the overall energy balance in the production of hydrogen from natural gas and its subsequent use in a bus powered by a fuel cell have been made. The thermal efficiency of the hydrogen-fuel cell system is compared with the thermal efficiency of a system in which natural gas form a pipeline is compressed and this compressed gas is burned in a conventional IC engine. The results indicate that even though there is an energy penalty in producing hydrogen from natural gas, this inefficiency is more than made up by the higher heat content of hydrogen and the significantly higher efficiency of a fuel cell. The overall system thermal efficiency of a hydrogen system is about 3-5% higher than that of an IC engine-based system burning natural gas.

The hydrogen requirement for operating an ATTB, with a pure hydrogen fuel cell in the EPA designated Central Business District (CBD) duty cycle has been calculated. The bus is assumed to follow this duty cycle for the entire operating day. In addition, it is assumed that the total distance traveled in one day is 120 km (75 miles). The total length of a 4% grade that a bus encounters (within this 120 km operating distance) is assumed to be 6 km. Based on these assumptions, together with known efficiency of solid polymer fuel cells and the motor efficiency, the total daily hydrogen requirement is calculated to be 15.2 kg. This amount of hydrogen can easily be carried as a compressed gas at 25 MPa (3,600 psig) in three tanks of the type already in use in CNG service on an ATTB. If, however, the largest CNG tanks[5] available are used (and the total ATTB roof space

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[5]Largest CNG tanks available from Lincoln Composites, Inc. are 46.75 cm (18.4 inch) in diameter and 3.05 m (10 ft) in length.

available for tankage is taken into consideration) about 28 kg of hydrogen can be stored in four large tanks, extending the total range to about 210 km on the CBD cycle. Discussions with transit personnel indicate that the average daily range of currently operating bus service in a typical city is about 230 km (145 miles)/day.[6] Our assumptions on a demonstration bus **operating on a CBD cycle throughout the day** are extremely conservative. That is, buses operate on the average over a less stringent cycle (for acceleration). If a more realistic operational cycle is assumed, the range possible with either 15.2 kg or 28 kg hydrogen storage on the bus will be significantly higher, respectively, than the 120 km and 210 km, calculated earlier.

Storage of hydrogen as a saturated cryogenic liquid at ambient pressure on-board a bus in a cryogenic tank may not be feasible at present, because, the liquid is very cold, at 20.3 K (-423.5 °F) and, therefore, needs to be carried in vacuum-jacketed, double-walled tanks. In fact, some liquid hydrogen tanks are jacketed with liquid nitrogen. Second, the technology of double wall vacuum jacket tanks with leak proof fuel lines to the tank does not seem to exist, especially for operation in a highly vibrational environment as in a typical bus route. Third, even with the best of insulation, there will be heat leaking into tanks resulting in hydrogen boil off. Equipment and processes must be in place to handle (and, if necessary, to gas) the hydrogen produced. Finally, using a liquid hydrogen storage on a bus requires the provision of an evaporator and the associated equipment complexity. Therefore, for storage of a small quantity[7] of hydrogen, liquefied storage is not recommended.

The requirements for hydrogen storage at the fueling station depend on the bus duty cycle. If a 120 km/day x 4 days/week x 4 weeks/month service is assumed, then the monthly hydrogen requirement is about 250 kg/month (2,900 std m^3 of gas/month or 3.6 m^3 of liquid/month).This can be easily met with a standard (gaseous) tube trailer. Tube trailers are available in 3,568 std m^3 (126,000 cft) and 4,248 std m^3 (150,000 cft) with gas stored at pressures up to 18.3 MPa (2,640 psig). Approximately one smaller tube trailer per month will be sufficient to meet the needs of the assumed 120-km CBD service from an ATTB. The tube trailer pressure has to be increased to the bus storage tank pressure by using an auxiliary compressor in the fueling line.

Hydrogen can be stored on the facility as a cryogenic liquid especially if a six months supply is to be stored. The larger the storage volume the more economical it is to store as a liquid. However, liquid storage requires the provision of an evaporator and a compressor to compress hydrogen from essentially ambient pressure to bus tank pressure (25 MPa). In addition, because a liquid tank represents a more permanent fixture, many local regulations related to long term storage of cryogenic

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[6]The average service distance changes with business day and weekend days.

[7]Storage of 16 kg of hydrogen requires 225 L tank volume for liquid hydrogen storage.

and flammable materials require compliance. Small-scale reformers that can produce hydrogen at say, 3 kg/min (so that the fill time is five minutes) are neither available, nor are economical to develop. It is clear from this discussion that a gaseous, tube trailer-based storage may be preferable if a single bus is operated on a hydrogen fuel cell for a relatively short period of a few months.

5.2 CONCLUSIONS

The following conclusions are based on this study:

1. A demonstration project is feasible using a hydrogen-powered fuel cell on an ATTB. There are no serious technical hurdles to overcome.

2. The daily hydrogen requirement for a single ATTB operating on a Central Business District cycle for 120 km including a 6-km length of 4% grade is 15.2 kg. This amount of hydrogen can easily be stored in composite tanks currently certified for CNG duty at 25 MPa.

3. Four tanks of the type already being used on a CNG-driven ATTB can be used for hydrogen storage. Use of these tanks for hydrogen results in a net decrease in total tank plus fuel weight.

4. Fueling station can be fed by an on-site tube trailer of hydrogen augmented with a booster compressor. One trailer will service about a month's requirement for operating a single ATTB in a CBD environment for 120 km.

5. Hydrogen risk from flammability, fire, and explosion is less than that from gasoline of equivalent energy quantity. Risk values for hydrogen and energy equivalent quantity of methane are close to each other. Therefore, there are no insurmountable safety problems in using hydrogen. Normal precautions taken in CNG systems should be adequate for hydrogen systems also.

6. The key to a successful project involving hydrogen use in buses and storage in fueling stations is educating the public on the benefits of hydrogen and its risks comparable to that of CNG.

Acronyms

ATTB	Advanced Technology Transit Bus
CBD	Central Business District
CFR	Code of Federal Regulations
CNG	Compressed Natural Gas
DARPA	Defense Advanced Research Projects Agency
DDC	Detroit Diesel Company
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
FTA	Federal Transit Administration
ICE	Internal Combustion Engine
IFC	International Fuel Cell Corporation
LACMTA	Los Angeles County Metropolitan Transportation Authority
NREL	National Renewable Energy Laboratory
PAFC	Phosphoric Acid Fuel Cell
PEM	Proton Exchange Membrane
STP	Standard Temperature and Pressure
TMS	Technology & Management Systems, Inc.

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