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Environmental, Health, and Safety Issues of Fuel Cells in Transportation

Volume 1: Phosphoric Acid Fuel-Cell Buses

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National Renewable Energy Laboratory
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Preface

This report evaluates the environmental, health, and safety (EH&S) issues that may affect the commercialization of the phosphoric acid fuel-cell (PAFC) bus. The study focuses on safety because it is a critical factor for consumer acceptance of transportation technologies.

The Analytic Studies Division of the National Renewable Energy Laboratory (NREL) prepared this report for the U.S. Department of Energy (DOE), Office of Transportation Technologies, Electric and Hybrid Propulsion Division.

I am grateful to the many people who helped me obtain information and who reviewed this report. Special thanks to Jeffrey Fisher of H Power Corporation and Theodore Woods of Booz, Allen & Hamilton, Inc. for providing me with the documents that furnished the foundation of this report and for their contributions of time during the peer review process. Several people, besides Mr. Fisher and Mr. Woods, reviewed this report. I would especially like to thank Robert Wimmer of Georgetown University, Jim Miller of Argonne National Laboratory, and Kevin Baldwin of the Denver Regional Transportation District. I am indebted to James Ohi and David Corbus of NREL who reviewed this report and provided valuable insight and information. I would also like to thank Jason Mark, Carol Hammel, and Steve Adelman for their diligent efforts to find information that I requested. Finally, I thank Robert Kost and Donna Lee at DOE for contributing information and reviewing this report. Any errors that may be in this report can be solely attributed to the author.

Approved for the
NATIONAL RENEWABLE ENERGY LABORATORY

Thomas D. Bath

Thomas D. Bath, Director
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Executive Summary

The U. S. Department of Energy (DOE) chartered the Phosphoric Acid Fuel-Cell (PAFC) Bus Program to demonstrate the feasibility of fuel cells in heavy-duty transportation systems. As part of this program, PAFC-powered buses are being built to meet transit industry design and performance standards. Test-bed bus-1 (TBB-1) was designed in 1993 and integrated in March 1994. TBB-2 and TBB-3 are under construction and should be integrated in early 1995.

In 1987 Phase I of the program began with the development and testing of two conceptual system designs—liquid- and air-cooled systems. The liquid-cooled PAFC system was chosen to continue, through a competitive award, into Phase II, beginning in 1991. Three hybrid buses, which combine fuel-cell and battery technologies, were designed during Phase II. After completing Phase II, DOE plans a comprehensive performance testing program (Phase III) to verify that the buses meet stringent transit industry requirements. The Phase III study will evaluate the PAFC bus and compare it to a conventional diesel bus.

This NREL study assesses the environmental, health, and safety (EH&S) issues that may affect the commercialization of the PAFC bus. Because safety is a critical factor for consumer acceptance of new transportation-based technologies the study focuses on these issues. The study examines health and safety together because they are integrally related. In addition, this report briefly discusses two environmental issues that are of concern to the Environmental Protection Agency (EPA). The first issue involves a surge battery used by the PAFC bus that contains hazardous constituents. The second issue concerns the regulated air emissions produced during operation of the PAFC bus.

Hazards

The hazards[1] of subsystems unique to the PAFC on a bus originate from the following: phosphoric acid, mineral oil, hydrogen gas, methanol, lithium/potassium hydroxide, cadmium, nickel, high-power batteries, and high-temperature exhaust from the steam reformer. The batteries contain cadmium and nickel, but there is a very low risk of exposure to these constituents during the in-use life of the bus. However, there is a higher potential risk of exposure to cadmium and nickel during battery manufacturing or reclamation. As for the temperature of the PAFC bus exhaust, it is equivalent to the temperature of conventional diesel bus exhaust, and the PAFC exhaust exits from the top of the bus. Therefore, under most circumstances, the exhaust from the PAFC bus is not a threat to passenger safety.

Exposure to phosphoric acid, mineral oil, and lithium/potassium hydroxide may primarily occur in a collision. Hydrogen gas and methanol may affect employee safety during maintenance. The high-power batteries may be hazardous during maintenance or in a collision. The risk of exposure to these hazards was minimized through design features incorporated into the PAFC bus per U.S. Department of Transportation (DOT) Baseline Advanced Transit Coach Specifications (i.e., White Book) recommendations, Federal Motor Vehicle Safety Standards (FMVSS), military specifications, and vehicle system design checklists.

Fire and explosion, electrical, chemical/thermal, and collision are the general categories of hazards. These categories form the structure of the limited qualitative safety analysis summarized in Tables 3 through 6. Booz, Allen & Hamilton, Inc., (BAH) developed lists of potential component and system failure modes (BAH

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[1] A hazard is a substance or action that can cause harm. Risk is the possibility of suffering harm from a hazard (Ohi 1992).

1993). BAH used a fault tree, developed by H Power Corporation (HPC) and included in Appendix B, to identify which constituents or components belonged in each hazard category.

Emissions

Using the PAFC technology in urban buses may result in a substantial reduction in tailpipe emissions compared to using diesel bus technology. Table E-1 compares emissions from the reformer burner used on the PAFC bus with emissions from a diesel bus. The reformer burner component in the fuel-cell subsystem emits the majority of the air emissions. Table E-1 also lists EPA exhaust emission standards. EPA emissions standards for heavy-duty diesel engines for 1998 and later are 15.5 g/bhph of carbon monoxide (CO), 4 g/bhph of nitrous oxide (No_x), and 1.3 g/bhph of hydrocarbons (HC).

Diesel engine manufacturers must certify that their engines will meet the appropriate standards for the year in which they are manufactured. Manufacturers are also responsible for ensuring that engines meet these standards throughout their useful life (EPA 1994). However, manufacturers are not responsible for diesel engines that have not been properly maintained or have been damaged in an accident (Carlson 1994).

Table E-1. A Comparison of Reformer Burner and Diesel Engine Emissions (g/bhph)

Emissions	PAFC* (burner)	Diesel**		EPA Standard
		Low Altitude	High Altitude	
CO	0.07 to 0.35	9.5	16.7	15.5
NO_x	<0.0015	8.0	8.0	4.0
HC	~0	2.1	4.8	1.3

* Kaufman 1994.
** EPA 1991.

Noise

Noise-level measurements taken during the fuel-cell subsystem acceptance test indicate that the PAFC subsystem is quieter than a diesel engine. A maximum sound level of 78 dB(A)[2] (1 m from the start-up burner) was recorded during start-up. During operation, a maximum sound level of 75 dB(A) (1 m from the start-up burner) was recorded at 75% and 100% rated loads (HPC 1993). In contrast, the range of noise measured for diesel engines (1 m away from the engine) was 90 dB(A) to 110 dB(A) (Kirk-Othmer 1981). The difference in sound levels between the fuel-cell subsystem and the diesel engine is significant because the sound level is logarithmic. For example, a 12-dB increase in sound level is equivalent to increasing the

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[2] The sound-pressure level is the magnitude of noise expressed in decibels (dB) (Kirk-Othmer 1981). The A-weighing function (method of measuring broadband sounds) is used in most standard sound-level meters.

acoustic pressure on the ear by a factor of 4. Furthermore, energy will increase by a factor of 16, i.e., pressure squared is the energy.[3]

The motor controller and fuel-cell subsystem air blowers and pumps contributed the most to the noise level measured during the subsystem test. However, noise from the PAFC bus system is caused mainly by the air compressor used for the brakes and suspension system, and by the air conditioner's refrigerant compressor. Another main noise contribution may come from the traction motor blower assembly. This assembly includes the blower and the motor that runs the blower. None of these units were included in the subsystem test. However, BAH plans to measure the noise from the bus as it is being driven. BAH will take measurements from the roadside as the bus goes by, as well as from inside the bus (Woods 1994).

End of Life

End-of-life (EoL) environmental issues are important because they may have a significant impact on the deployment of a fuel-cell-based transportation system. Some issues that need to be considered are the use of recyclable materials in vehicle manufacture and the acceptable disposal of materials that are not recycled.

Currently, of the major subsystems unique to the PAFC bus, only the nickel-cadmium (NiCd) batteries are subject to reclamation processes. NiCd batteries will be reclaimed because nickel is a valuable commodity and EPA regulations prohibit disposal of these batteries in a landfill. Reclamation of NiCd batteries requires a Resource Conservation and Recovery Act permit because of stringent EPA toxicity standards. Constituents of other subsystems that may be considered in a future EoL analysis include the phosphoric acid electrolyte, materials used in the construction of the fuel-cell stack (e.g., plastics), methanol or premix tanks, the reformer catalyst, and other reformer elements.

Future Work

Future work may focus on beginning-of-life and EoL environmental issues in more detail. Manufacturing processes may generate solid waste along with air and water pollutants. When a product reaches the EoL stage, it becomes a solid waste or is recycled. An environmental analysis should also consider land use impacts during the product manufacturing and disposal processes.

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[3] Loudness is proportional to the energy for up to 1-second durations. Loudness stays at the same subjective level when durations are longer than 1 second. However, the noisiness of continuing unwanted sounds increases. The longer the noise lasts, the more unwanted it becomes. This growth of noisiness is approximately proportional to the total energy in the noise (Kryter 1985).

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Acronym List

BAH	Booz, Allen & Hamilton, Inc.
BMI	Bus Manufacturing U.S.A., Inc.
BOS	Balance of system
CEC	California Energy Commission
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EoL	End of life
EPA	U.S. Environmental Protection Agency
ESD	Emergency shutdown
FCIC	Fuel-cell internal controller
FEMA	Failure effect mode analysis
FMVSS	Federal Motor Vehicle Safety Standards
HC	Hydrocarbons
HPC	H Power Corporation
ICEV	Internal combustion engine vehicle
MC	Motor controller
NAVSEA	Naval Sea Systems Command
NiCd	Nickel cadmium
NREL	National Renewable Energy Laboratory
NTP	National Toxicology Program
OSHA	Occupational Safety and Health Administration
PAFC	Phosphoric acid fuel cell
PEL	Permissible exposure limit
RCRA	Resource Conservation and Recovery Act
SAE	Society of Automotive Engineers
SCS	System controller subsystem
SOC	State of charge
STEL	Short-term exposure limit
TBB-1	Test-bed bus-1
TLV	Threshold limit valve
TMC	Transportation Manufacturing Corporation
TWA	Time-weighted average

Introduction

The commercial potential of alternatively powered vehicles is currently being determined. Public support is a key factor in the commercialization of any new technology, and verifying the safety of a product is a requirement in gaining public approval. The environmental, health, and safety, (EH&S) issues that may affect the commercialization of the phosphoric acid fuel-cell (PAFC) bus are assessed in this report, with the main focus on safety issues. Because safety and health are integrally related, a review of relevant health concerns comprises the first part of this report and serves as the framework for the safety analysis. A brief overview of key in-use and end-of-life environmental issues is also presented.

Background

The PAFC Bus Program was chartered to demonstrate the feasibility of fuel cells in heavy-duty transportation systems. PAFC-powered buses are being built to meet transit industry design and performance standards as part of U.S. Department of Energy (DOE) contract DE-AC02-87NV10649. Test-bed bus-1 (TBB-1) was designed in 1993 and integrated in March 1994. TBB-2 and TBB-3 are under construction and should be integrated in early 1995.

Phase I of the program began in 1987 when two conceptual system designs, liquid- and air-cooled systems, were developed and tested. The liquid-cooled PAFC system was chosen to continue, through a competitive award, into Phase II beginning in 1991. The Phase I prime contractors were the Energy Research Corporation and Booz, Allen & Hamilton, Inc. (BAH). Phase I subcontractors were Engelhard Corporation, Fuji Electric Company, Chrysler Pentastar Electronics, Inc., and Eagle-Picher Industries.

Three hybrid buses, which combine fuel-cell and battery technologies, were designed during Phase II and are being built by H Power Corporation (HPC), Bus Manufacturing U.S.A., Inc. (BMI), Fuji Electric Company, Soleq Corporation, and Transportation Manufacturing Corporation. After completing Phase II, a comprehensive performance testing program (Phase III) is planned to verify that the buses meet stringent transit industry requirements. The objective of the Phase III program is to evaluate the PAFC bus and compare it to a conventional diesel bus.

The PAFC system currently under development consists of three principal subsystems: fuel cell, battery, and electrical propulsion. The major components in the fuel-cell subsystem are the fuel-cell stack, methanol steam reformer, fuel-cell auxiliaries, fuel-cell internal controller, and up-chopper. The battery subsystem includes the surge battery modules, battery tray, and battery support. The DC motor, motor controller, line filter, and regenerative brake controls are the main constituents considered in the electric propulsion subsystem. Balance of system (BOS) components, such as the methanol tank, will also be evaluated in the context of EH&S concerns. Refer to Appendix A for an overview of the PAFC system.

Intrinsic Hazards for the PAFC Bus System

The PAFC bus has three components that are unique in current automotive technology: the fuel-cell stack, steam reformer, and high-voltage battery. These three components were reviewed for chemical/thermal, explosive/flammable, and electrical hazards.

Fuel-Cell Stack

Three constituents of the fuel-cell stack assembly were identified as potential intrinsically hazardous substances. Phosphoric acid (used as an electrolyte in the stack) and mineral oil (used as the heat-transfer medium in the cooling loop described in Appendix A) are hazardous through skin contact or ingestion, and hydrogen gas may be explosive in some circumstances. Hydrogen gas may potentially flow through the plastic fuel-cell components that may have been used in the stack. These three constituents are briefly reviewed in the following paragraphs.

Phosphoric Acid

Phosphoric acid (H_3PO_4) may be in the form of a colorless liquid or crystalline solid and is infinitely miscible with water. It does not have any specific toxic effects. However, analogous to weak acids, it can irritate the eyes, respiratory tract, and mucous membranes (Ullman et al. 1985). The threshold limit value (TLV)[1] of phosphoric acid for a time-weighted average (TWA)[2] is 1 mg/m^3. The short-term exposure limit (STEL)[3] is 3 mg/m^3. Although there is no immediate danger to life or health associated with this acid, a solution with a concentration of 75% by weight will cause severe skin burns (OSHA 1990), and the acid emits toxic fumes when heated to decomposition (Lewis 1992).

Mineral Oil

Mineral oil is an odorless, colorless, viscous liquid that can cause aspiration pneumonia when inhaled. It is also a human teratogen[4] when inhaled. When exposed to heat or flame, mineral oil is a combustible liquid with a flash-point[5] temperature of 229°C (444°F). A dry chemical foam should be used to put out a mineral oil fire (Lewis 1992).

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[1] TLVs were established by the American Conference of Governmental Industrial Hygienists. Many of the TLVs were adopted as federal Occupational Safety and Health Administration (OSHA) standards or permissible exposure limits (PELs).

[2] The TLV-TWA is the time-weighted average concentration to which a person may be exposed without adverse effects during an 8-hour workday or 40-hour workweek.

[3] STEL is the maximum allowable concentration not to be exceeded at any time during a 15-minute time frame, separated by 60 or more minutes between exposures, and not more than four exposures within 24 hours.

[4] Teratology is the study of monstrosities or abnormal formations in animals and plants.

[5] Minimum temperature required for an ignitable mixture of product vapor and air to form.

Hydrogen Gas

Hydrogen gas is not toxic, although it can cause asphyxiation if the oxygen content in an area falls below 18% by volume under normal atmospheric pressure. When exposed to heat, flame, or oxidizers, hydrogen gas is a fire and explosion hazard (Lewis 1992). Buildup in an enclosed area must be prevented.

Steam Reformer

The steam-reforming process converts methanol to hydrogen, which is used to power the PAFC bus. Methanol and heat (in the form of high-temperature exhaust) represent potential intrinsically hazardous elements in this process. Details regarding these two elements are provided below. Appendix A contains greater details about the steam-reforming process.

Methanol

Health issues related to methanol include acute and chronic toxicity through ingestion, inhalation, or skin contact. Acute toxicity (poisoning), which can develop from methanol ingestion, may lead to nausea, blindness, liver and kidney damage, and respiratory failure. Methanol poisoning can be effectively treated if diagnosed early (no more than 10 or 15 hours after consumption). Inhalation of methanol vapor or skin contact for long periods of time and at high doses may mimic the symptoms of acute exposure in cumulative stages (NIOSH 1976a). The TLVs of methanol are 260.0 mg/m^3 TWA and 310.0 mg/m^3 STEL. These limits apply to skin exposure (OSHA 1990).

The autoignition[6] temperature of methanol is higher than that of gasoline, as shown in Table 1. Therefore, a much higher temperature is required for methanol to self-combust as compared to gasoline[7]. Additionally, the heat of combustion for burning methanol is less than 50% of that generated by gasoline, so the heat intensity of a methanol fire is lower than that of a gasoline fire. The radiant heat output from a methanol fire is also less than that generated from a comparable gasoline fire (Zebe and Gazda 1985).

Table 1. Flammability and Combustion Properties of Methanol and Gasoline

Property	Methanol	Gasoline
Flash point (°F)	52	-45
Autoignition temperature (°F)	867	495
Flammability or explosion limits (% volume)		
Lower	6.7	1.4
Upper	36.0	7.6
Saturation volume (%)		
68°F (20°C)	13	25 to 50
100°F (38°C)	31	68
Heat of combustion (Btu/gal at 68°F [20°C])	56 560	115 400

Source: U.S. Department of Transportation, (April 1985). "The Transport of Methanol by Pipeline," Materials Transportation Bureau, Research and Special Programs Administration, pp. 4–10.

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[6] Minimum temperature for temperature-generated, self-sustaining combustion to begin.

[7] Methanol and gasoline (instead of diesel) are compared because gasoline use is more widespread than diesel use, and represents a higher degree of danger.

In an open area, the potential for a methanol explosion is relatively low compared to that for a gasoline explosion. Airflow can readily dilute methanol fumes below their minimum flammability/explosion limit (see Table 1) (i.e, methanol-air mixture becomes too lean to ignite). Gasoline has a greater potential of exploding under these circumstances because an infusion of air can easily bring the gasoline-air mixture into the flammability/explosion range (Zebe and Gazda 1985).

The situation is reversed in enclosed areas, where methanol can be more dangerous than gasoline. Under normal ambient conditions, the saturation volume[8] of methanol (13% to 31%) is within its explosion limits (i.e., methanol can ignite when the vapor concentration is between 6.7% and 36% by volume). By contrast, gasoline's saturation volume is higher than its upper explosion limit (see Table 1) (i.e., gasoline-air mixture is too rich to ignite under these circumstances) (Zebe and Gazda 1985).

The flame produced by burning methanol is essentially invisible in daylight. Low flame luminosity is an undesirable trait in a highly flammable substance, as the flames are difficult to detect or extinguish (California Energy Commission [CEC] 1989).

Methanol is a better conductor of electricity than gasoline. Thus, static discharge is not as likely to start a fire with methanol (Zebe and Gazda 1985).

The most important health and safety concerns associated with methanol are summarized in Table 2 (CEC 1989).

Table 2. Summary of Methanol Health and Safety Concerns

Health Concerns	Safety Concerns
Ingestion Accidental Intentional Inhalation Refueling exposure Ambient air Production and distribution Skin Contact Refueling Vehicle maintenance Production and distribution	Heavy duty vehicles • Effectiveness of flame arresters • Flame luminosity • Experience with methanol fires • Effective fire extinguishers Storage • Effectiveness of flame arresters and vapor control equipment • Procedures for fighting fires • Procedures for transferring fuel

Source: CEC 1989.

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[8] The saturation volume is the ratio of the vapor pressure of methanol (in this case) and atmospheric pressure.

Heat

High temperatures are required to steam-reform methanol. Waste heat from this process is vented at 345°C (653°F) from the burner exhaust (BAH 1990). In comparison, the temperature of the exhaust gas from a diesel engine ranges from 200° to 500°C (392° to 932°F) (Heywood 1988).

Battery

The battery provides the surge power required by the bus and stores the energy produced by regenerative braking. A description of the batteries and regenerative brakes is provided in Appendix A. Five battery constituents are identified as intrinsic hazards that may be potential sources of harm: hydrogen gas (fire/explosion hazard); electrolyte, cadmium, and nickel (chemical hazards); and the battery voltage and discharge current (electrical hazard). These five intrinsic hazards are described below.

Hydrogen Gas

Nickel-cadmium (NiCd) batteries are either sealed or nonsealed (vented). Sealed batteries can vent hydrogen gas during failure modes, but nonsealed batteries can vent at any time.

Extremely high internal cell pressures can also build up in the batteries. Pressure-release vents (safety valves) are usually designed into the cells to prevent excessive gas accumulation; an explosion can occur if there is no safety valve (Corbus et al. 1993).

Electrolyte

The NiCd battery's alkaline electrolyte (a solution containing potassium hydroxide) is extremely corrosive. Serious chemical burns can occur if the electrolyte contacts the skin (NAVSEA 1992). Potassium hydroxide solution is a clear liquid that is very corrosive to the eyes, skin, and mucous membranes. When decomposed by heat, it emits toxic fumes (Lewis 1992). The TLV-Ceiling[9] of potassium hydroxide is 2 mg/m^3 (Alliance of American Insurers [AAI] 1983).

Cadmium

The National Toxicology Program (NTP) has identified cadmium as a human carcinogen. Cadmium's TLV-TWA is 0.05 mg/m^3 (OSHA 1990). Various biological effects (other than carcinogenesis) are attributed to cadmium exposure, including pulmonary, renal, olfactory, hematopoietic[10] system, cardiovascular, skeletal, liver, gonadal, and teratological effects. The recorded effects usually resulted from ingestion or inhalation of cadmium oxide fumes or dust. Cadmium oxide fumes are formed when cadmium vapor is ignited, which may occur during some metallurgical or extraction processes. Dust and mist may also be produced during these processes (NIOSH 1976). Although cadmium exposure can occur during the manufacturing and reclaiming processes, there is a very low risk of exposure while the bus is in use.

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[9] TLV-Ceiling is the concentration not to be exceeded for any amount of time.

[10] Hematopoietic refers to blood formation.

Nickel

The NTP has identified nickel as a probable carcinogen (Corbus, Hammel, and Mark 1993). According to epidemiological studies, workers in nickel refineries have an increased risk of developing cancer of the nasal cavity and lungs. The TLV-TWA of nickel is 1 mg/m^3 (AAI 1983). Although worker exposure to nickel may occur during the manufacturing and reclaiming processes, bus passenger exposure is not expected during the in-use life of the bus.

Voltage and Discharge Current

High voltage levels coupled with a high discharge current introduce a hazard from batteries that is not present in conventional internal combustion engine vehicles (ICEVs). The nominal voltage of 216-V for the NiCd battery far exceeds the voltage typical of the 12-V battery used in ICEVs. A discharge rate of 300 A is possible. Consequently, a lethal shock could be delivered during recharge, maintenance, or in a collision (NAVSEA 1992).

In-Vehicle Safety Considerations for PAFC Buses

In-vehicle safety concerns of the PAFC bus are highlighted in this section. Minimizing the risk of exposure to hazards can occur only after the hazards have been identified. First, the limited qualitative safety analysis of the PAFC bus is discussed briefly. Key hazards are then identified and some possible pathways leading to hazardous situations are highlighted. Mitigation measures for specific potential hazard categories also are discussed. Finally, a summary of the crashworthiness analysis performed by HPC is presented. This summary includes the mitigation measures that have been taken to reduce the risk of passenger exposure to hazards during a collision.

Once hazards and potential failure modes are identified and the subsequent mitigation features are addressed, the overall safety of the PAFC bus can be assessed. A limited qualitative analysis of the hazards of the PAFC bus was performed. This analysis was limited because only the subsystems or components judged to be unique, as compared to conventional buses, were examined. A qualitative, rather than quantitative, analysis was performed because a Failure Effect Mode Analysis (FEMA)[11] was not performed.

Lists developed by BAH of potential component and system failure modes (BAH 1993) are summarized in Tables 3 through 6. A fault tree, developed by HPC and included in Appendix B, was used by BAH to identify which constituents or components belonged in each hazard category. The next two subsections (Potential Hazards and Safety Features and Crashworthiness Analysis) and the maintenance section include general discussions of safety analysis and mitigation measures. The critical potential failures with a medium probability of occurrence are discussed under the appropriate topic subsections (Fire/Explosion Hazards, Electrical Hazards, Chemical/Thermal Hazards, and Collision Hazards).

Potential Hazards and Safety Features

There are four general categories of hazards that may cause personal injury while the bus is in use: fire/explosion, electrical, chemical/thermal, and collision hazards. A variety of mitigation measures are available to minimize the risks or consequences of possible failure modes in the system, subsystem, or components. This section provides a summary of each hazard category, along with the design features incorporated into the bus to minimize risk.

Fire/Explosion Hazards

Fuel in the proximity of an ignition source, along with a failure in the fire suppression/alarm subsystem, are precursors to fires or explosions. In the case of the PAFC bus, the fuel is either methanol or hydrogen gas.

Leaking methanol or premix can create a fire hazard. Leaks can develop at a faulty connection point, in a distribution line, or in a fuel tank. As discussed previously, methanol presents less of a fire hazard in open areas than does gasoline.

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[11] FEMA basic methodology requires: (1) identification of all critical failure modes of the system; (2) evaluation of the probability of occurrence of these failure modes during critical periods; and (3) determination of an overall figure of merit for reliability (Jordan and Buchanan 1967).

Table 3. Potential Fire and Explosion Hazards

Subsystem	Component	Component Function	Potential Failure	Estimated Severity	Estimated Probability of Occurrence	Comment
Battery	Battery Cells	Load Leveling	Overheating	Critical	Medium	Battery rupture
Battery	Battery Box	House Battery Cells	Hydrogen Leak	Critical	Low	
Battery	Battery Cells	Load Leveling	Short Circuit	Critical	Low	Battery rupture
Bus Body/Chassis	Fire Suppression Equipment	Extinguish Fire Automatically	Fire Suppression Not Activated	Catastrophic	Low	
Bus Body/Chassis	Fuel Tanks & Lines	Provide Fuel	Fuel Leak	Critical	Low	
Driver's Control	Emergency Shutdown Control	Manual Shutdown	Shutdown Not Achieved When Activated	Catastrophic	Low	
Driver's Control	Indicator Lights	Fault/Status Annunciation	Fault Not Indicated	Minimal	Low	
Electric Propulsion	Auxiliary Power Supplies	Enable Auxiliaries	Loss of Auxiliary Power	Critical	Low	Battery-hydrogen leak
Electric Propulsion	Traction Motor	Tractive Effort	Overheating or Flashover	Minimal	Low	Temperature rise or electric arcing
Fuel Cell	CO_2 Purge	CO_2 Purge	Nonoperational	Critical	Low	Major damage to FC stack
Fuel Cell	Hydrogen Plumbing	Distribute Hydrogen	Leak	Critical	Low	
Fuel Cell	Reformer	Hydrogen Production	Leak	Critical	Low	
Fuel Cell	Reformer	Hydrogen Production	Fuel Starvation	Critical	Low	Potential damage to reformer or stack
Fuel Cell	Reformer	Hydrogen Production	Loss of Control	Minimal	Medium	FC stack damage
Fuel Cell	Auxiliaries	Control & Regulate	Nonperformance of Intended Function	Negligible	High	Combined w/ other failures may be hazardous
System Controller	State-of-Charge Calculation	Battery Current Control	Erroneous SOC Signal	Critical	Medium	Potential battery overcharge

Table 4. Potential Electrical Hazards

Subsystem	Component	Component Function	Potential Failure	Estimated Severity	Estimated Probability of Occurrence	Comment
Battery	Battery Cells	Load Leveling	Electrolyte Spill/Leak	Critical	Low	Short possible if electrolyte contacts circuit
Battery	Battery Cells	Load Leveling	Short Circuit	Critical	Low	
Electric Propulsion	Traction Power Circuit	Provide High Voltage	Short or Ground Fault	Critical	Medium	
Fuel Cell	Stack Heater	Stack Heating	Electric Shock	Minimal	Low	

Table 5. Potential Chemical/Thermal Hazards

Subsystem	Component	Component Function	Potential Failure	Estimated Severity	Estimated Probability of Occurrence	Comment
Battery	Battery Cells	Load Leveling	Overheating	Critical	Medium	Battery rupture
Battery	Battery Cells	Load Leveling	Electrolyte Spill or Leak	Critical	Low	
Battery	Battery Cells	Load Leveling	Short Circuit	Critical	Low	Battery rupture
Fuel Cell	CO_2 Purge	CO_2 Purge	Nonoperational When Commanded	Critical	Low	Major damage to FC stack
Fuel Cell	Primary Coolant Loop	Stack Cooling & Heating	Coolant Leak	Critical	Low	
Fuel Cell	Reformer	Hydrogen Production	Fuel Starvation	Critical	Low	Potential damage to reformer or FC Stack
Fuel Cell	Stack	Power Production	Acid Leak	Catastrophic	Low	
Fuel Cell	Start-up Burner	Heat FC Coolant Loop	Fuel Starvation	Critical	Low	Major FC stack damage
HVAC	Secondary Coolant Loop	Interior Heating	Leak	Minimal	Low	

Table 6. Potential Collision Hazards

Subsystem	Component	Component Function	Potential Failure	Estimated Severity	Estimated Probability of Occurrence	Comment
Bus Accessories	Steering Pump	Assist Steering	Rotation Stops	Minimal	Medium	
Bus Accessories	Air Compressor Motor	Drive Air Compressor	Motor Stops	Negligible	Medium	Potential loss of power steering or brakes
Driver's Control	Emergency Shutdown Control	Manual Shutdown	Shutdown not Achieved When Activated	Catastrophic	Low	
Driver's Control	Windshield Defogger	Defog Window	Windshield Fogged up	Critical	Medium	
Driver's Control	System Fault Indicator	Warn of System Fault	Inactive Signal	Minimal	Low	
Electric Propulsion	Traction Power Circuit	Dissipate Excess Power	Open Circuit	Critical	Medium	Potential braking discontinuity
Electric Propulsion	Auxiliary Power Supplies	Enable Auxiliaries	Loss of Auxiliary Power	Critical	Low	Failure in windshield defogging unit or loss of motor
Electric Propulsion	Motor Controller	Control Motor Current	Fail to Respond Correctly	Critical	Low	Potential loss of system control or tractive effort
Electric Propulsion	Traction Motor	Tractive Effort	Electric Braking Failure	Minimal	Medium	
Electric Propulsion	Traction Motor	Tractive Effort	Flash-over	Minimal	Low	Traction power
Electric Propulsion	Traction Motor	Tractive Effort	Overheating	Minimal	Low	Motor may seize
Electric Propulsion	Traction Power Bus	Provide High Voltage	Open Circuit	Minimal	Low	Traction power loss
System Controller	System Controller	System Supervision	Loss of Signals or Erroneous Signals	Minimal	Low	May affect electric brake capability

Methanol can cause some materials to deteriorate. Once the methanol container is breached, leaking methanol becomes a potential fire hazard. Carbon steel, aluminum, and fiberglass are among the materials that should not be used to store or transport methanol (Zebe and Gazda 1985). The components used to contain methanol on the PACF bus are made from stainless steel, which is a compatible material (HPC 1993).

Emergency fire-fighting procedures must take into account the differences between methanol and gasoline or diesel fuel fires. Methanol is hydrophilic (water soluble), and a 25% methanol-water mixture (by weight) has a flash point of 38°C (100°F), which is within the definition of a flammable liquid. Alcohol foams, and not water, should be used to suppress a methanol fire (Zebe and Gazda 1985).

The PAFC bus includes a halon (FM100)[12]/dry chemical-based fire suppression unit equipped with infrared sensors that will automatically activate the unit to extinguish a fire. A separate carbon dioxide (CO_2) fire extinguisher is installed next to the driver for additional protection. The driver can deactivate the fuel-cell subsystem at any time by triggering the emergency shutdown (ESD) switch.[13] When the ESD switch is activated, the Fuel-Cell Internal Controller (FCIC) (see Appendix A) will initiate an ESD with a full CO_2 purge of the fuel-cell subsystem (HPC 1993).

In an enclosed area such as a fuel tank, methanol fumes are an explosion hazard. Reducing vapor buildup and ignition sources in enclosed areas is paramount for safe operation of the PAFC bus. To prevent external sources from igniting the vapors inside the tank, the bus fuel tank vent does include flame arresters. The tank also has a grounded metallic grid at the filler nozzle opening to prevent a charge from developing (HPC 1993).

The unsealed batteries may be sources of hydrogen gas. This situation increases the risk that an explosion may occur, given an unventilated enclosed area and an ignition source (e.g., a short circuit or static discharge). Unsealed batteries may vent hydrogen at any time (Corbus, Hammel, and Mark 1993). A battery may rupture if it has overheated or short circuited. Once ruptured, its contents (e.g., hydrogen gas) may be released. Thus, adequate ventilation must be provided and ignition sources must be eliminated around battery subsystems.

Another source of hydrogen gas is the fuel-cell stack. The fuel-cell stack may vent hydrogen gas through any permeable materials that may have been used in its construction or through faulty seals (Appleby and Foulks 1989). Therefore, adequate ventilation must be provided and ignition sources must be eliminated around the fuel-cell stack. Faults in construction of the fuel-cell stack are checked for during the manufacturing process.

Many design features were included in the PAFC bus to prevent an explosion. The bus incorporates ventilation ducting on the chassis to vent hydrogen gas from the battery trays. Fans are kept running continuously during bus operation to provide the batteries and fuel-cell stack with adequate ventilation. Flame arresters are included as part of the single-point, hook-up battery-watering interface for each tray. (The battery-watering system is discussed in the maintenance section.) The battery chargers and interfaces are grouped in one interconnection and all the chargers are independently grounded to decrease the possibility of creating a spark.

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[12] Halon FM100 will no longer be manufactured by the end of 1995 or 1996. Halon FM200 will be available, but will require a larger container (Elliot 1994).

[13] The motor controller (MC), system controller subsystem (SCS), and FCIC are notified to shut down the appropriate controlled elements when the ESD switch is activated. See Appendix A for a description of the MC, SCS, and FCIC.

Excessive charging of the traction battery could occur if the state-of-charge (SOC) signal is lost or erroneous. Losing the SOC signal can cause the battery to overheat and explode. This risk is mitigated by the MC and SCS, which monitor the battery voltage to prevent the possibility of an erroneous or lost SOC signal (HPC 1993).

The fuel-cell subsystem is enclosed in a shell that is kept at a negative pressure, thus ensuring continuous ventilation to prevent hydrogen gas buildup that may occur during a failure. The fuel-cell subsystem also comes with an emergency shutdown feature that can be activated manually. Hydrogen sensors are installed as a safety precaution to alert the driver to any leakage from either the batteries or the fuel-cell stack (HPC 1993).

Electrical Hazards

Electric shocks and burns can occur if direct contact is made with the exposed wires of high-powered components. These circuits are generally inaccessible under normal circumstances. However, loose cables and incorrectly grounded wires may increase the risk of an injury occurring even under normal circumstances. Under unusual circumstances (such as an accident), high-power wires may be exposed, thus increasing the risk of a potentially lethal shock being delivered.

The PAFC bus design includes features to minimize the risk of an injury from electrical hazards. All subsystems are equipped with shock and circuit protection. The batteries, control signal transducers, fuel cell, accessories, and DC motor have separate wiring harnesses. A floating ground is used on the fuel-cell DC/DC converter, fuel-cell air compressor, DC motor, motor controller, and batteries. The system controller; heating, ventilating, and air conditioning (HVAC) unit; and circuit breaker box are grounded to the chassis. Ground faults are detected by the SCS (see Appendix A), which alerts the driver. Throughout the design phase, military and vehicle system design checklists and specifications were used to ensure that the best currently available design and safety protocols were incorporated (HPC 1993).

Chemical/Thermal Hazards

Inhalation of a toxic gas and physical contact with or ingestion of a toxic or corrosive substance can result in chemical poisoning or burns. Exposure to most chemical hazards may occur in a collision. The crashworthiness analysis section describes the mitigation factors used in the design of the PAFC bus to reduce this risk in the event of a collision.

The batteries can rupture if the cells overheat, increasing the risk of injury from the battery electrolyte. Active mitigation measures are necessary to prevent this from occurring or to minimize the consequences. Current practice on the PAFC bus is to monitor the ambient temperature and place ventilation fans in the battery compartment. Along with these measures, BAH also recommends including overtemperature protection and a fire sensing/suppression unit in the battery compartment (BAH 1993).

Accidental or intentional ingestion of methanol could result in poisoning. Zebe and Gazda (1985) recommend storing methanol in labeled containers identifying the contents as an automobile fuel to help prevent accidental ingestion. They further recommend that the term "alcohol" should not be used to describe methanol, as this may lead some to mistake it for a beverage. In addition, all personnel should be made aware of the toxic effects of drinking methanol. Accidental ingestion of methanol also may occur during siphoning. According to the California Energy Commission, antisiphoning devices on methanol-fueled vehicles may prevent such accidents (CEC 1989). The PAFC bus includes a positive locking fueling system, which prevents siphoning.

Long-term exposure to methanol through inhalation and skin contact must be avoided, because doses are cumulative and may become toxic in the human body. The greatest potential for long-term methanol exposure occurs during refueling. Measures taken to minimize the chemical hazards of exposure to methanol are discussed in the section on safety aspects of maintenance.

Collision Hazards

Potential collision hazards resulting from the unique subsystems on the PAFC bus are discussed here. The aftermath of a collision is discussed in the crashworthiness analysis section.

Failure of various components may cause a collision. In general, these failures cause a reduction in visibility, braking, or steerability.

Under normal conditions, the driver's heater/windshield defogger unit uses heat from the secondary coolant loop to defog the windshield. A failure in the defogger unit may reduce visibility and result in a collision. The failure may be attributed to insufficient heat from the fuel cell, a pump failure of the secondary coolant loop, a heater fan failure, or an obstruction in the secondary coolant loop. If a failure occurs, the driver can divert the heat intended for the passenger compartment to defog the windshield. Additional on-demand heat from the fuel cell (a feature built into the fuel cell stack) also may be delivered to the defogger unit.

Failure of the traction motor, which is used for electric braking on the PAFC bus, may increase stopping distance. The bus, however, has fully functional standard brakes that can stop the bus without electric braking capability. The driver is also trained to identify when electric braking capability has been lost and how to respond.

Total weight and weight distribution can have a direct bearing on the driver's ability to control the bus under all circumstances (HPC 1993). The PAFC bus was designed with a center of gravity forward of the rear axle such that the weight supported by the rear axle should be approximately 65% of the gross bus weight as recommended in the White Book.

The bus may be operated in reverse by reversing the direction of the motor. A preset safe maximum reverse speed limit was built into the MC to prevent the bus from being driven backward at high velocities. In addition, the bus can be put into reverse only when it is at a full stop (HPC 1993).

Crashworthiness Analysis

The system integrity of the PAFC bus can be breached in a collision. By analyzing the potential outcome of each type of accident, mitigation factors can be identified to minimize the damaging consequences of a collision. The crashworthiness analysis performed by HPC examines various collision scenarios to assess the risk of triggering hazards in a collision and identify mitigation strategies. A front-end collision was not considered because an impact in this area would not significantly affect the unique components of the PAFC bus, as these components are not located in the front of the bus. The crashworthiness analysis includes three appendices: the structural design report of the Test Bed Bus (TBB), the TBB assembly drawing (not shown), and calculation of the rollover speed as a function of the curve radius. This section summarizes the analysis; it is included in its entirety as Appendix C.

The crashworthiness analysis assumes the bus will meet all applicable standards contained in the Federal Motor Vehicle Safety Standards (FMVSS) and the White Book, based on the expected certification from

BMI. Proposed standards, such as new side-impact and crash standards, were not considered in this analysis. Three collision scenarios were considered to assess the performance of the bus and various components in an accident: rear-end collision, broadside collision, and rollover (see Appendix C).

The hazardous constituents (e.g., hot phosphoric acid from the fuel-cell stack, methanol from the reformer, or mineral oil from the coolant loop) in the fuel-cell subsystem may decrease passenger safety in a rear-end collision because the subsystem is located in the rear of the bus. The fuel-cell stack, reformer, and coolant loop were designed to meet the shock and vibration requirements of a road vehicle, so containment of their contents can be maintained under most circumstances. The fuel-cell frame and bus structure surrounding the fuel-cell subsystem would provide a protective barrier in the event of a collision. Furthermore, a fireproof wall was placed between the fuel-cell subsystem compartment and the passenger compartment to protect passengers in a collision (see Appendix C).

Because the traction motor is close to the rear bumper, it may be sheared off at the mounting points during a rear-end collision, presenting an electrical hazard. Circuit protection devices such as breakers, fuses, and ground-fault detectors are used to prevent a high-voltage direct current from developing if the traction motor is damaged in a collision (see Appendix C).

The propulsion subsystem and other high-voltage equipment are concentrated in the rear of the bus. In a rear-end collision, the main potential risk to emergency responders or bystanders is receiving an electric shock from ruptured conductors. Circuit protection devices similar to those for the traction motor were incorporated to mitigate this hazard (see Appendix C). Moreover, the system can be shut down quickly either manually or automatically by activating the ESD switch.

When the ESD switch is activated, the following occurs:

The motor is automatically isolated from all power sources.

- The base amount of regeneration provided by the motor controller is inhibited.

- Emergency shutdown with a full CO_2 purge of the fuel-cell subsystem is initiated.

- The fuel-cell stack is automatically disconnected from the subsystem by the up-chopper surge protector, and the fuel-cell power output is diverted to the dummy load.

Exposure to the electrolyte in the batteries may occur in a broadside collision or during a rollover. The batteries on the PAFC bus are placed below the passenger compartment so the electrolyte will flow away from the passengers in the event there is a rupture during a broadside collision. The structure around the battery compartment was designed to withstand penetration, and its structural strength is more than adequate according to White Book specifications. According to these specifications, the body of the bus was designed to withstand a 25-mph (40-km/h) broadside impact by a 4000-lb (1814-kg) vehicle. The risk of dangerous battery constituents migrating beyond the battery compartment was further reduced by using unitized battery compartment structures with internal stiffening members (see Appendix C).

The passenger heating fluid routing has been modified since the crashworthiness analysis was submitted. The new route allows easier maintenance. Previously, the loop was not at risk in a broadside collision because it was in the roof of the bus. The loop now runs along the passenger compartment through the sidewalls and could be compromised in a broadside collision. The temperature of the mineral oil is kept at 82°C (180°F) or lower to help minimize the seriousness of potential burns in the event of skin contact. Also, the coolant loop system is not pressurized, which minimizes the possibility of spraying mineral oil if the system is ruptured (Woods 1994).

Safety Aspects for Maintenance of the PAFC Bus

The PAFC bus will require routine maintenance. Refueling with methanol and recharging the batteries are the most potentially hazardous activities during maintenance. Both of these operations should occur in open or well-ventilated areas to decrease the danger of hydrogen or methanol vapor accumulation, and sources of ignition should be eliminated near stations where either activity takes place. Mitigation measures to decrease the risk of an explosion were described in the previous section.

Caution should be exercised when refueling with methanol to avoid skin contact or inhalation. Although at outdoor refueling stations methanol fumes would not become concentrated enough to be considered an inhalation risk, a vapor recovery system was installed in the fuel tank of the bus to further reduce the risk. Furthermore, when the refueling nozzle is placed into the tank opening, it seals the tank and prevents vapor from escaping (Woods 1994).

DuPont has a great deal of experience handling methanol (Zebe and Gazda 1985). Their recommendations are reproduced in Appendix D. Some of their key recommendations are as follows:

- Personnel must wear proper personal protective equipment if contact cannot be avoided.
- Storage tanks should be electrically grounded.
- Tank vents must be equipped with suitable flame arresters.
- Vents and pressure relief devices must be able to handle pressures and volumes of vapor that could occur during fire.
- Protection against excessive heat should be provided.

Spills or leaks must be collected for disposal or recovery.

To minimize the risk of an electrical hazard, logic was built into the SCS (see Appendix A) that prevents the driver from operating the bus while the charger is still connected. Also, the connector was placed on the door side, in clear view of the driver (HPC 1993).

Routine maintenance for vented batteries includes watering the cells, which may result in a release of hydrogen gas. The NiCd batteries used in the PAFC bus, however, are designed with a single-point watering system from which each cell is automatically filled and gases produced during overcharging are collected (HPC 1993). Therefore, risks are minimized. Refer to Appendix A for a description of the vented NiCd batteries used on the PAFC bus.

Various safety hazards could be avoided by regularly inspecting the fuel-cell subsystem during routine maintenance. The fuel-cell subsystem acceptance test procedure, which includes the following steps (HPC 1993), could be used as a model for the bus inspection process:

- Visual Check - check all mechanical connections.
- Isolation Check - verify that fuel-cell subsystem main circuit and earth ground are electrically isolated.
- Leak Check - check for leaks from fuel-cell subsystem under load conditions; visually examine all components for methanol, water, or oil leaks; and inspect fuel-cell stack and reformer with gas detector.

In-Use Environmental Issues for the PAFC Bus Program

While environmental concerns need to be addressed for each phase in the life of a product, this section reviews only the in-use environmental issues of the PAFC bus. End-of-life (EoL) environmental concerns are discussed briefly in the following section.

Air Emissions

Fuel cells generate clean power. The operation of a methanol reformer fuel-cell subsystem produces very small amounts of NO_x (NO and NO_2), CO_2, CO, and ozone. NO_x is emitted when methanol is burned at start-up. The CO is generated in the reforming process, and CO_2 occurs during shifting. The motor produces a trace amount of ozone[14] (Appleby and Foulkes 1989).

Use of the PAFC technology in urban buses may result in a substantial reduction in tailpipe emissions compared to diesel bus technology. The following table summarizes the emissions from the reformer burner used on the PAFC bus versus those from a diesel bus. The reformer burner is the component in the fuel-cell subsystem that emits the majority of the air emissions.

Table 7. A Comparison of Reformer Burner and Diesel Engine Emissions (g/bhph)

Emissions	PAFC* (burner)	Diesel**		EPA Standard
		Low Altitude	High Altitude	
CO	0.07 to .35	9.5	16.7	15.5
NO_x	<.0015	8.0	8.0	4.0
HC	~0	2.1	4.8	1.3

* Kaufman 1994.
** EPA 1991.

EPA exhaust emission standards for heavy-duty diesel engines for 1998 and later are 15.5 g/bhph of CO, 4 g/bhph of NO_x, and 1.3 g/bhph of HC. The manufacturer of the diesel engine must certify that the engine will meet the appropriate standards for the year in which they are manufactured. The manufacturer is also responsible for ensuring that the engine meets these standards throughout its useful life (EPA 1994). However, the manufacturer is not responsible for diesel engines that have not been properly maintained, nor are they responsible for an engine damaged in an accident (Carlson 1994).

Noise-level measurements were taken during the fuel-cell subsystem acceptance test. A maximum sound level of 78 dB(A) was recorded during start-up. (Measurements were taken 1 m from the start-up burner.) During operation, a maximum sound level of 75 dB(A) was recorded at 75% and 100% rated loads (measured 1 m from the start-up burner) (HPC 1993). The range of noise measured for diesel engines was 90 dB(A) to 110 dB(A). (Measurements were taken 1 m away from the engine.) (Kirk-Othmer 1981). The

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[14] Ozone emissions are generated as a result of sparking between the commutators and brushes of the motor.

noise level is logarithmic (i.e., a 12-dB increase in noise level is equivalent to increasing the acoustic pressure on the ear by a factor of 4). Energy will increase by a factor of 16 (i.e., pressure squared is the energy).

The motor controller and fuel-cell subsystem air blowers and pumps contribute the most to the noise level measured during the subsystem test. However, noise from the PAFC bus system is due mainly to the air compressor used for the brakes and suspension system, and the air-conditioner refrigerant compressor. Another principal noise contribution may be from the traction motor blower assembly. This assembly includes the blower and the motor that runs the blower. None of these units were included in the subsystem test. However, BAH is planning to measure the noise from the bus as it is being driven. Measurements will be taken from the roadside as the bus goes by, as well as from inside the bus. As standard procedure, the bus industry uses Society of Automotive Engineers (SAE) J366 and SAE J1477 to measure exterior and interior sound levels, respectively. Sound-level measurements on the PAFC bus will be taken as recommended by these procedures, along with additional test steps included because of the unique features of the PAFC bus.

End-of-Life Environmental Issues

This section is not intended as an in-depth analysis of EoL environmental issues, although such an analysis may eventually be necessary. EoL environmental issues are important to consider, as they will have a significant impact on the deployment of a fuel-cell-based transportation system. Some issues that need to be considered are the use of recyclable materials in vehicle manufacture and acceptable disposal of materials that are not recycled.

At present, of the major subsystems unique to the PAFC bus, only the NiCd batteries have reclamation processes. NiCd batteries will be reclaimed because nickel is a valuable commodity and disposal of these batteries in a landfill is prohibited by EPA regulations. Reclamation of NiCd batteries requires a RCRA permit because of stringent EPA toxicity standards (Corbus, Hammel, and Mark 1993). Constituents of other subsystems that may be considered in a future EoL analysis include the phosphoric acid electrolyte, materials used in the construction of the fuel-cell stack (e.g., plastics), methanol or premix tanks, the reformer catalyst, and other reformer elements.

Conclusions and Recommendations—Health and Safety

The PAFC bus appears to be as safe as a typical diesel-powered city bus because of its safety features. This report has identified the health and safety issues for the subsystems unique to the PAFC bus. The intrinsic hazards that may put the health and safety of the passengers or bus employees at risk include phosphoric acid, mineral oil, hydrogen gas, methanol, lithium/potassium hydroxide, cadmium, nickel, high-power batteries, and high-temperature exhaust from the steam reformer. Cadmium and nickel are contained within the batteries, so they represent a very low risk to human health during the in-use life of the bus. However, there may be a higher risk to human health from cadmium or nickel exposure at the BoL or EoL. The temperature of the PAFC bus exhaust is equivalent to conventional diesel bus exhaust and the exhaust exits from the top of the bus. Therefore, the high temperature of the exhaust will not be dangerous under most circumstances while the bus is in use.

Exposure to phosphoric acid, mineral oil, and lithium/potassium hydroxide may primarily occur in a collision. Safety and health risks to bus employees from hydrogen gas and methanol are higher during maintenance (compared to while the bus is in use). The high-power batteries may be a hazard during maintenance or a collision. The risk from these constituents was minimized through design features incorporated into the PAFC bus per White Book recommendations, FMVSS standards, military specifications, and vehicle system design checklists.

The following is a summary of the features included in the design to minimize the risks:

- Fire/Explosion Hazards

    - Methanol-containment units and transport lines made from stainless steel
    - Automatic fire-suppression subsystem and a CO_2 fire extinguisher
    - Flame arresters with a grounded metallic grid at the filler nozzle opening on the fuel tank
    - Ventilation ducting on the chassis, to vent hydrogen gas from the battery trays
    - Single-point battery watering system with flame arresters
    - Battery charger power and control connectors are grouped in one interconnection
      Independent grounding of all battery chargers
    - Fuel-cell subsystem enclosed in a shell at a negative pressure
    - Hydrogen sensors
    - Fuel-cell compartment ventilation fan runs continuously, and the fan in the battery compartment is controlled by the battery temperature (i.e., turns on at 35° C and off at 25° C).

- Electrical Hazards

    - Subsystems equipped with shock and circuit protection
    - Electrical system grounded to chassis, or uses floating grounds
    - Ground fault detection with driver warning indicators
    - Circuit protection devices
    - System shutdown quickly accomplished either manually or automatically
    - Shop door open interlock
    - Shop power connector located on the door side
    - 600-Amp fuses.

- Chemical Hazards
  - Fuel-cell subsystem components designed to meet shock and vibration requirements of a road vehicle
  - Fireproof wall placed between the passenger compartment and fuel-cell compartment
  - Fuel-cell frame
  - Unitized battery compartment structures with internal stiffening members
  - Chassis designed to withstand a 25-mph (40-km/h) broadside impact of a 4000-lb (1814-kg) vehicle
  - Vapor-recovery system installed outside the fuel tanks.

- Other Hazards
  - Weight supported by the rear axle is approximately 65% of the gross bus weight
  - Mineral oil temperature is maintained at or below 82°C
  - Coolant loop assembly is nonpressurized.

The following are recommended to enhance the in-use safety of the bus for passengers and employees:

- Establish formal employee training program
- Set up routine inspection process (refer to steps in maintenance section) and include in maintenance procedure
- Install indicators to signal engaged methanol refueling hose.

The training program should include the following:

- Fire alarm response
- Hydrogen gas alarm response
- Response to any activated warning indicator
- Response to loss in electric braking capability
- Safe handling and storage practice for methanol
- Safe recharging practices for batteries.

The coolant loop has been changed since the crashworthiness analysis (see Appendix C) was initially submitted. The loop is currently routed through the bus sidewalls down the length of the bus; it was previously located inside the roof of the bus. Therefore, a follow-up study on how this change may impact the safety of the bus is recommended.

Conclusions and Recommendations—Environment

The in-use environmental impacts of the PAFC bus are insignificant compared to those of the diesel bus. Minor amounts of air pollutants are produced during the steam-reforming process. Current measurements of NO_x and CO are on a fuel-cell subsystem level only. Based on the component-level tests, the PAFC bus emissions are well below the standards set by the Clean Air Act Amendments of 1990 and much lower than air emissions from a diesel bus; nevertheless, measurement of the NO_x, CO, HC, and PM-10 emissions in a chassis (i.e., system) dynamometer test, simulating the Georgetown Driving Cycle and the Transit Coach Duty Cycle, is planned. A comparison between a diesel bus and the PAFC bus will then be done to quantitatively determine the environmental benefits that may be derived from a PAFC bus.

The high noise level caused by vehicular traffic contributes considerably to urban stress. Urban buses are a major source of noise in cities where people and vehicles are in close proximity. Based on currently available test results, the PAFC bus is projected to be quieter than a diesel bus. System-level tests are planned to develop comparisons between diesel and PAFC buses.

Future work may focus on BoL or EoL environmental issues in more detail. Manufacturing processes may generate solid waste along with air and water pollutants. When a product reaches the end of its life, it becomes a solid waste or is recycled. An environmental analysis should also consider land use impacts during the product manufacturing and disposal processes.

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Appendix A
Overview of the PAFC System for Bus Applications

PAFC System

The configuration of the PAFC bus fuel-cell subsystem includes a power section, fuel processor, and power conditioner. The power section is a phosphoric acid fuel-cell stack (as the primary energy source) connected through an up-chopper to an NiCd battery. The battery provides the necessary instant response to heavy load demands. In the fuel processor, methanol is converted to H_2 and CO_2 in the steam-reforming and shifting process. Power conditioning is required for the fuel cell and battery because of their different nominal voltages. The voltages also vary at different rates under load or during charging and regenerative braking. The up-chopper supports the necessary voltage-matching capability between the fuel cell and the battery to avoid an undercharged or overcharged state. Blowers, fans, and solenoid drivers also require power conditioning because they use both AC and DC power (HPC 1993). Figure A-1 is an illustration of the bus.

A diagram of the fuel-cell operation for the PAFC bus is shown in Figure A-2. During start-up, the mineral oil, which is used as the temperature-control medium in the cooling system, is heated by the start-up burner to raise the temperature of the fuel-cell stack to its operating temperature. When the temperature of the oil

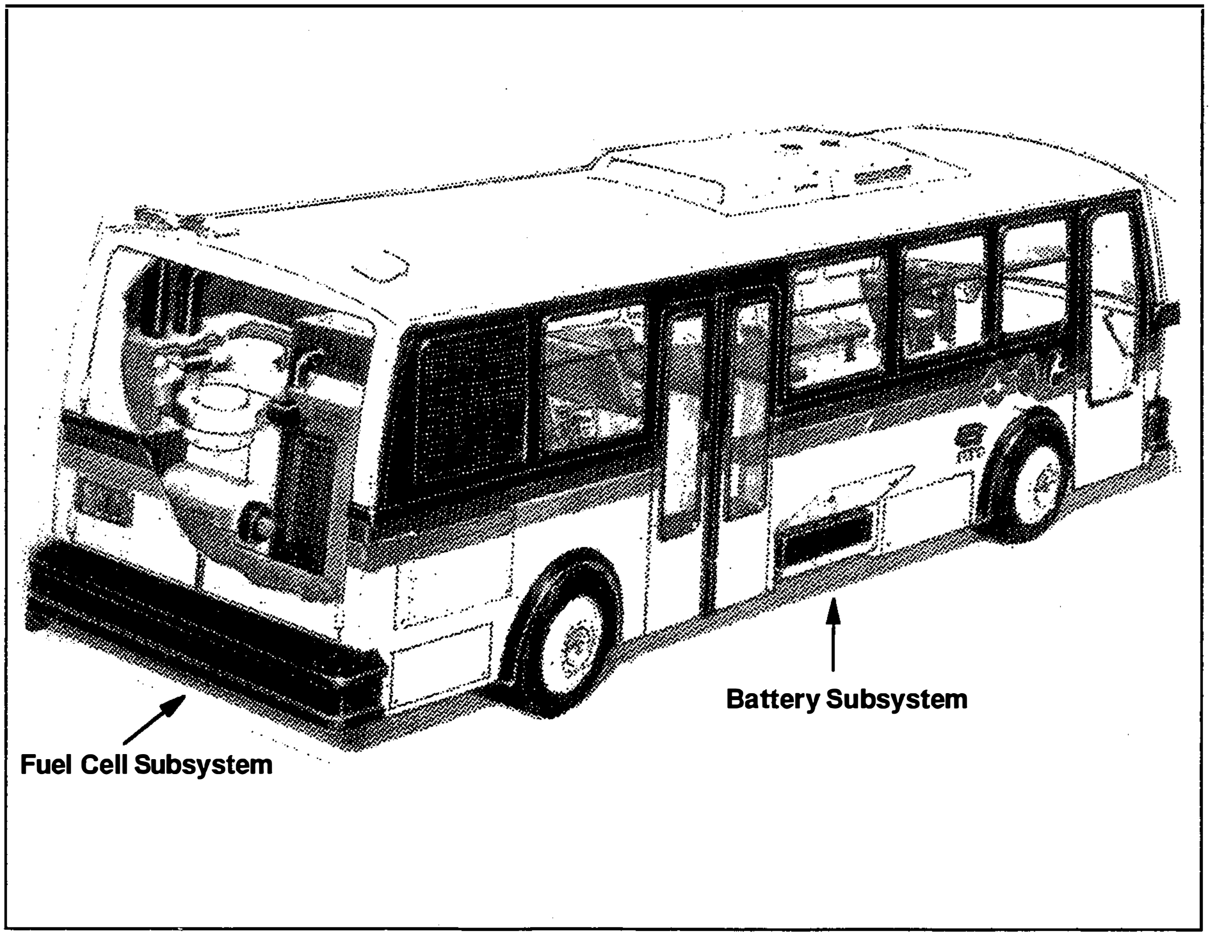

Figure A-1. PAFC bus illustration

has reached the stack's operating temperature, the reformer burner is ignited. The premix proceeds to the methanol reformer through the vaporizer. The vaporized premix is heated by the superheater coils and delivered to the catalyst beds in the reformer, where it is reformed and shifted to H_2 and CO_2. The hydrogen flows to the anode of the stack and reacts with the oxygen in the air, supplied to the cathode in the catalytic matrix, to produce electrical energy (BAH 1990).

The internal composition of the fuel-cell stack is proprietary. Analysis of the stack is therefore general, and information contained in this report may not pertain exactly to the actual stack used in the PAFC bus.

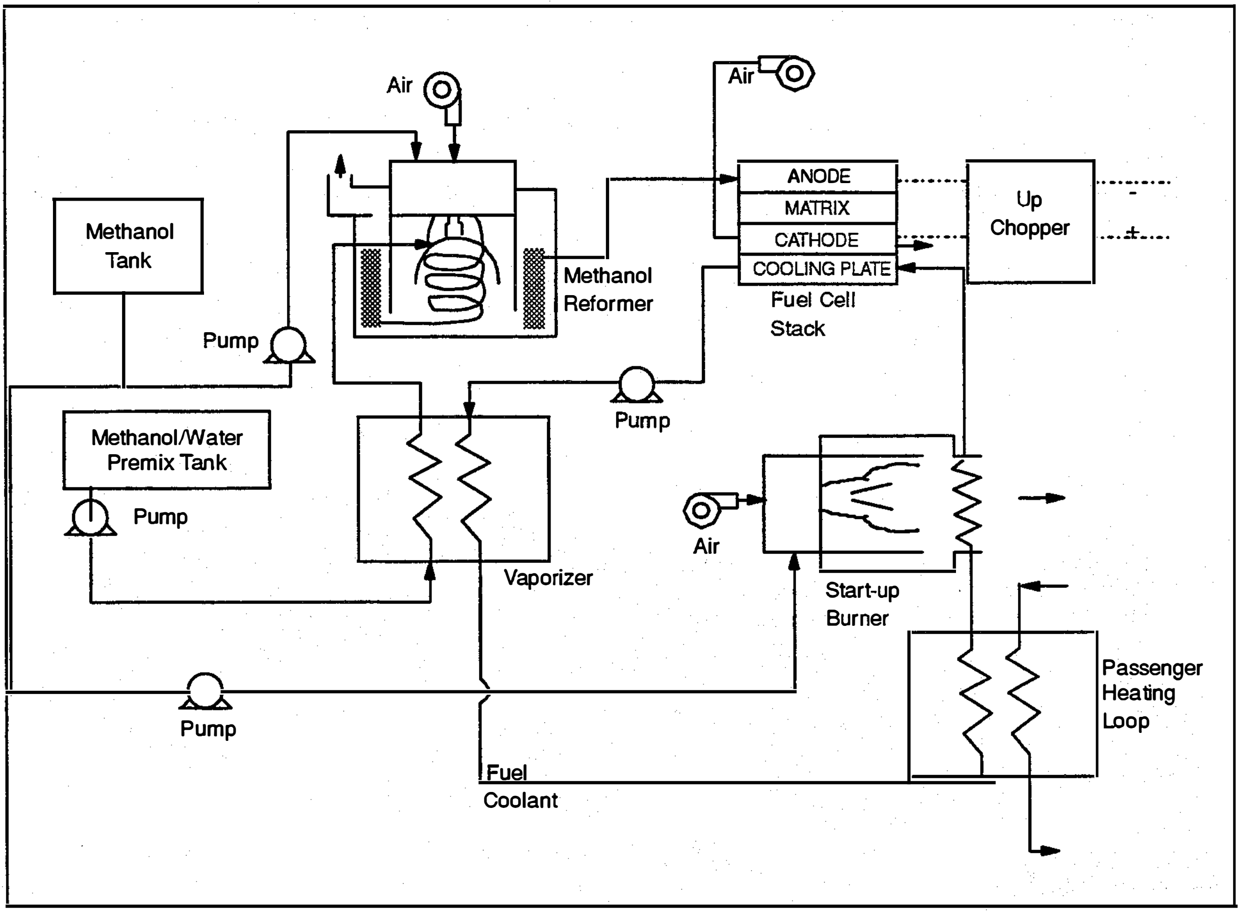

Figure A-2. Diagram of fuel-cell operation

Fuel-Cell Stack

A fuel cell is an electrochemical device in which the chemical energy of a fuel is converted to low-voltage DC electrical energy. Many energy-conversion designs use high-temperature combustion and ensuing processes. However, the fuel cell makes it possible to bypass the conversion-to-heat process and related mechanical-to-electrical processes (Angrist 1976).

The conversion of chemical energy to electricity occurs in a fuel cell, as illustrated in Figure A-3. Incoming gaseous hydrogen dissociates to produce hydrogen ions and electrons at the anode. The electrons flow from the anode through a metallic external circuit while the hydrogen ions migrate through the electrolyte. The electrons and hydrogen ions react with the oxygen at the cathode (Appleby and Foulkes 1989).

Fuel cells are commonly joined by a bipolar electrical arrangement. In bipolar stacks, the plane of the cell cathode is in contact with the anode of the adjoining cell through an electronically conducting plate. Enough electrolyte must be available to prevent gas leaks between electrodes and to maintain proper cell operation. A reservoir capacity to compensate for electrolyte evaporative losses over the life of the fuel cell is usually incorporated within the stack or at the anode and cathode (Appleby and Foulkes 1989).

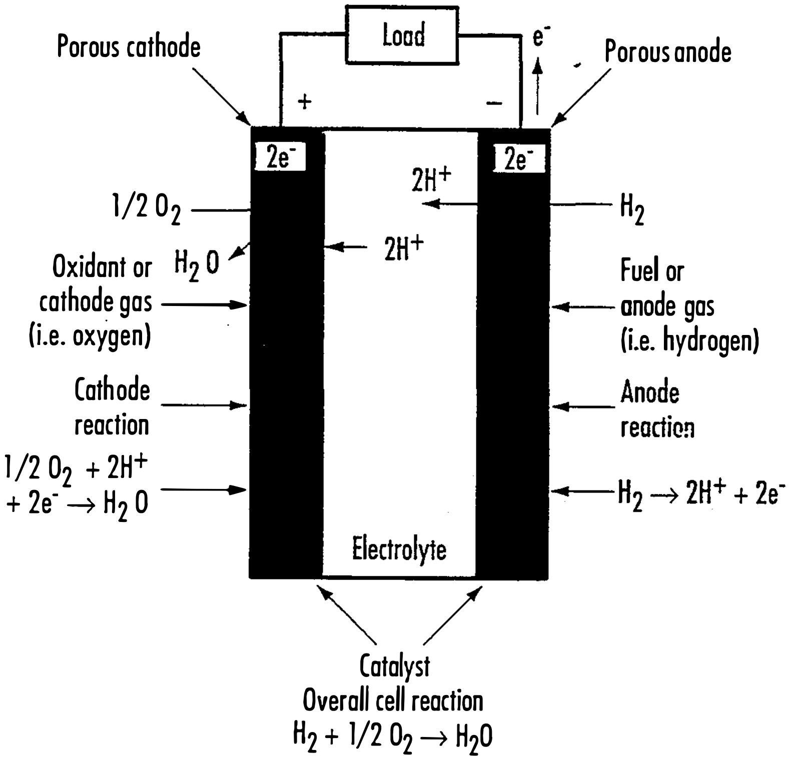

Figure A-3. Principle of operation of typical fuel cell

Hydrophilic, thin-laminated electrolyte matrix structures of low voltage drop expedite routine stack electrolyte replacement. The electrolyte is automatically replenished based on demand from the fuel cell, and is transported to the matrix by wicking along a carbon paper material (Appleby and Foulkes 1989).

The fuel-cell stack for the PAFC bus was designed with a nonpressurized, liquid-cooled, bipolar stack configuration. The stack power density is 95 W/kg; the subsystem power density is 32 W/kg. The stack will be connected to 220-V AC shop power while the bus is in the garage to keep the fuel-cell stack warm (45°C or 113°F). This will prevent possible damage to the stack from thermal shock and will reduce start-up time (HPC 1993). The detailed stack specifications are shown in Table A-1.

Table A-1. Stack Configuration of Fuel Cell

Power (to chopper)	DC 50 kW
Design current density	240 mA/cm^2
Rated current	480 A
Cell design voltage	0.66 V DC
Rated voltage	115 V DC
Number of cells	175
Size	70 cm (W) x 70 cm (D) x 145 cm (H)
Weight	583 kg (1285 lbs)
Hot standby temperature	130° C (266°F)
Operating temperature range	160° to 190° C (320° to 374°F)
Electrical efficiency	52.8%
Stack efficiency	41%
Voltage degradation	1.5% over 10,000-hr rated life
Thermal management	Liquid cooling
Operation pressure	Atmospheric
Active electrode area	2000 cm^2

Source: HPC 1993.

Methanol Reformer

The steam-reforming process is appropriate where size and weight are less of a constraint (e.g., a transit bus). Hydrocarbon fuels can be externally processed to provide a hydrogen-rich mixture. There are three processes available to produce hydrogen from hydrocarbon fuels: steam reforming, partial oxidation, and pyrolysis. The PAFC bus uses the steam-reforming process, which is the reaction of the fuel with steam (water vapor) (Appleby and Foulkes 1989).

The steam-reforming process for the PAFC bus takes place after a premix of methanol and deionized water has been vaporized:

$$CH_3OH(l) + H_2O(l) \rightarrow CH_3OH(g) + H_2O(g) \qquad \Delta H^\circ_{298} = +81.51\ kJ \qquad (1)$$

Steam reforming the pre-vaporized methanol and water requires two steps. First, the methanol is dissociated:

$$CH_3OH(g) \rightarrow CO(g) + 2H_2(g) \qquad \Delta H^\circ_{298} = +90.64\ kJ \qquad (2)$$

A higher percentage of the methanol can be converted when the temperature is above 200°C (392°F). An appropriate catalyst will also increase the reaction rates.

Following the dissociation, the CO is oxidized by steam (shift reaction):

$$CO(g) + H_2O(g) \rightarrow H_2(g) + CO_2(g) \qquad \Delta H^\circ_{298} = -41.16\ kJ \qquad (3)$$

A more complete reaction is achieved as the ratio of water to carbon monoxide increases.

The overall reaction is then:

$$CH_3OH(g) + H_2O(g) \rightarrow 3H_2(g) + CO_2(g) \quad \Delta H^{\circ}_{298} = +49.48 \text{ kJ} \qquad (4)$$

The reforming and shifting of methanol can be combined within the same unit. Each operation occurs at a different optimal temperature. Methanol dissociation occurs at or above 400°C (752°F); the oxidation of CO by steam occurs at about 200°C (392°F), depending on the catalyst. A design can be developed with separate zones to provide the temperatures required for each stage (Kumar et al. 1992).

Heat transfer to the reaction zone of the reformer is a major design element. The overall reaction in steam reforming is endothermic and requires external heat input. Consequently, most reformer configurations incorporate heat exchanger design elements. Reformer size and dynamic performance are mostly determined by heat transfer parameters (Kumar et al. 1992).

The bus's packed-bed reformer is built around an annular catalyst bed and a concentric down-flow burner (Kumar et al. 1992). A premix of methanol and water is passed through the catalyst beds after being vaporized in a separate process and superheated by the reformer burner. A catalyst is used to increase the reforming reaction rates. The copper/zinc oxide catalyst used in the bus reformer is effective for methanol reforming at 250° to 300°C (482° to 572°F) (HPC 1993). Table A-2 provides the details of the reformer configuration.

Table A-2. Reformer Configuration

Type	Catalytic steam reformer
Catalyst	Copper oxide/zinc oxide
Methanol conversion	>99%
Steam: carbon ratio	3:2 (molar)
Reformed gas-H_2	>65%
CO	<2%
Hydrogen flow rate	47 m^3/hour
Hot standby temperature	250°C (482°F)
Reformed gas temperature	260°C (500°F)
Size	700 mm (D) x 1,000 mm (H)
Weight	220 kg (485 lbs)

Source: HPC 1993.

System Controller Subsystem

The SCS provides real-time control and data logging capabilities necessary for effective energy management, fault logging, and emergency shutdown. Energy management functions are implemented by the SCS, FCIC, and MC. The FCIC and MC control their own components with input to and from the SCS. The energy management functions include battery SOC measurement, regeneration current management, accessory power monitoring and management, and emergency shutdown protocols (HPC 1993).

Fuel-Cell Auxiliaries

The blowers, pumps, fans, and solenoid drivers require both AC and DC power to achieve the operating characteristics specified by Fuji Electric Company. The auxiliaries provide the required power conditioning, and include DC/DC converters[1], variable voltage/variable frequency inverters, driver units, and valve drivers with economizers. The estimated power requirement for the auxiliaries is 5.2 kW (HPC 1993).

The fuel-cell stack can be damaged if allowed to run under no-load conditions. An internal dummy load is included in the coolant loop to provide a load during emergencies when the stack is isolated from the rest of the bus (HPC 1993).

Fuel-Cell Internal Controller (FCIC)

The FCIC controls the fuel-cell subsystem start-up, operation, and shutdown. When the system controller, fire suppression subsystem, or FCIC detects a fault, the FCIC automatically shuts down the fuel-cell subsystem. The FCIC also acts as an interface for the SCS signals that are sent to modulate the fuel-cell stack output and up-chopper voltage (HPC 1993).

Up-Chopper

The up-chopper matches the battery and fuel-cell voltage. The FCIC controls the step-up ratio of the up-chopper. The step-up ratio can be constantly adjusted depending on the load demand of the power train and accessories, the battery condition, and the fuel-cell condition. A surge protector inside the up-chopper prevents an excessive amount of current from passing through the fuel-cell stack. The stack will automatically be disconnected from the system and the power output will be diverted to the dummy load when the stack power needs to be isolated. The up-chopper can isolate the fuel-cell stack through a series of DC/AC and AC/DC converters and transformers which prevent stack current reversal (HPC 1993). The configuration is summarized in Table A-3.

Table A-3. Up-Chopper Configuration

Type	Isolated step-up PWM chopper
Chopper operating frequency	20 kHz
Control	Microprocessor-based
Communications	Serial to battery tray
Maximum output current	294 A
Nominal voltage	115 V in, 189–280 V out
Efficiency	> 95%
Output power	47.5 kW (64 hp)
Dimensions	48 cm x 60 cm x 143 cm
Weight	68 kg (150 lbs)

Source: H Power Corporation 1993.

Traction Motor

A DC shunt motor supplies traction for the PAFC bus. The motor features improved high-current brush assemblies with a three-brush cage design and a modified armature design. The improved cage design provides the current rating and increases the durability of the motor. The modified armature was selected

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[1] DC/DC converters change the voltage level instead of the current type.

to permit operating at levels up to 3800 revolutions per minute (rpm) (HPC 1993). Refer to Table A-4 for the motor configuration and Figure A-4 for the torque-versus-speed curves of the motor.

Table A-4. Motor Configuration

Manufacturer	General Electric
Model	CD-407
Armature circuit resistance	0.029Ω
Shunt field	4x4.45Ω = 17.8Ω (cold)
Maximum torque	1057 N-m at 600A, 200A, 975 RPM
Maximum continuous power rating	74 kW
Base speed	1000 RPM at 216 V
Maximum speed	3800 RPM
Cooling	Forced air (830 cfm) 0.5-hp external fan on 24–28 V DC
Volume	0.13 m^3, 0.52 m OD
Weight	622 kg (1371 lbs)
Efficiency	85% to 90%, average
Output spline shaft	30° involute 2.5 in. pitch diameter, 20 teeth

Source: H Power Corporation 1993.

The maximum continuous power rating of the motor is 74 kW at 216 V; therefore, about 345 A may be applied to the motor armature indefinitely. The motor can sustain higher currents over shorter time periods: 100% (74 kW) continuous indefinitely; 118% (86 kW) continuous for 1 hour; 135% (98 kW) for 0.5 hour; 150% (109 kW) continuous for 0.75 hour; and 200% (146 kW) continuous for 1 minute (HPC 1993). Table A-5 shows the estimated efficiency of the motor at various rpms.

Table A-5. Motor Efficiency

RPM	100 A	200 A	300 A	400 A	500 A	600 A
150	83.4	77	68	61	51	44
250	86.5	82.5	77	72	67	60.5
450	89.9	88.2	85	82	79	75.5
650	91	90.5	88.7	86.5	84	82
850	91.8	92	90.6	89	87.4	85.5
1000	92	92.4	91.5	90.3	88.7	87.2
1150	91.6	92.3	91.5	90.1	88.7	87.1
1750	90.9	92	81.2	89.9	88.6	87
2500	89.4	91.2	90.8	89.5	88.2	86.7
3500	86.6	89.7	89.7	88.7	87.6	86.2

Source: HPC 1993.

Motor Controller

The MC supplies a peak power of 120 kW to the motor. A maximum traction power requirement of 100 kW was estimated. This design provides a sufficient safety margin. The motor runs in reverse with a preset safe maximum speed built into the MC reversing logic. At forward speeds exceeding zero, the MC prevents the bus from switching into reverse. Regeneration logic is also provided by the MC: the MC receives signals from the SCS to supply a given amount of regenerative energy to the battery at specific times (HPC 1993). Table A-6 summarizes the MC configuration.

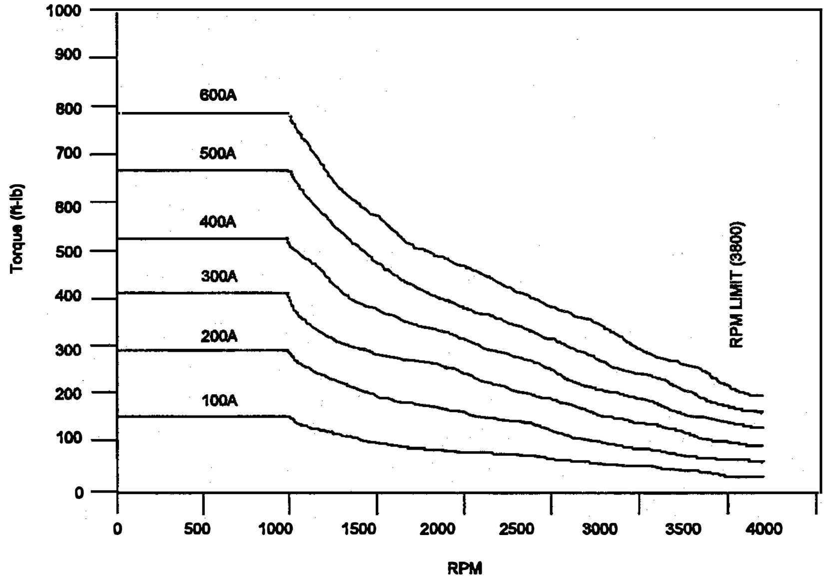


Figure A-4. Estimated performance for peak 120-kW motor

Table A-6. Motor Controller Configuration

Voltage	216 V DC nominal
Current	600 A DC
Efficiency	98% average
Communications	Analog
Chopper frequency	800 Hz
Volume	0.1 m^3
Weight	193 kg (426 lbs)

Source: HPC 1993.

Capacitance Line Filter

The filter reduces power (I^2R) losses within the battery during run mode and integrates the pulsed power signal returning from the motor or generator during regeneration mode. Power losses are reduced by filtering out the higher harmonics of the chopper current drain signal (HPC 1993).

Regenerative Brakes

The operating efficiency of the bus increases when energy that is usually lost is recovered through regenerative braking. Also, standard mechanical brakes suffer less wear when regenerative braking is used along with friction braking. Regenerative braking is used during deceleration, whereas friction braking provides the smooth deceleration and normal feel to the driver at all speeds (HPC 1993).

Battery Module

NiCd batteries provide the required surge power for the bus. A battery comparison test was performed at Argonne National Laboratory based on selection criteria, including battery weight, bus performance, and battery life. Computer simulations on the HYBRID model showed that the bus should be able to perform the Georgetown University Transport Society (GUTS) Arlington Loop route at the BoL and near the EoL of the battery (HPC 1993). Table A-7 lists the battery subsystem configuration.

Table A-7. Battery Subsystem Configuration

Type	Nickel-Cadmium
Manufacturer	SAFT
Battery model number	STM 5-200
Number of cells	180
Nominal battery subsystem voltage	210 V DC
Ambient operating temperature	-12°–40°C (10°–104°F)
Battery cooling	Forced-air cooling provided by thermostatically controlled fans, ambient air to 40°C (104°F)
Minimum life	2 years
Weight	1007 kg (2220 lb)

Source: HPC 1993.

The unsealed NiCd batteries are installed in three self-contained modules. Each module has cooling, watering, and topping charge systems. A topping charge once a week will be required to equalize the cells and reestablish the reference level (100% SOC) required for accurate battery management by the SCS (HPC 1993).

A battery module is constructed with five cells at 200 Ah nominal capacity electrically connected in series. The positive electrode is a sintered nickel that is chemically impregnated with a hydroxide mixture. The negative electrode consists of plastic-bonded cadmium. A solution made from potassium and lithium hydroxide is used for the electrolyte. The total weight of the battery module is a maximum of 23.5 kg (51.8 lb) (Cadmium Association 1990).

Battery Tray and Support

The battery modules fit in three trays located between the structural beams spanning the length and width of the bus. The trays can easily be removed from the side of the bus because they are not part of the load-bearing superstructure. Each tray was designed to support and accommodate the cooling needs of the battery modules. Sufficient spacing between the batteries and tray sides provides the required circulation around the battery for proper ventilation and cooling (HPC 1993).

Cooling Plate

The PAFC stack temperature is actively controlled by a liquid cooling system. Mineral oil is used as the working fluid (HPC 1993). Smaller heat exchangers and minimal pumping power (compared to gas cooled systems) are necessary due to the efficient heat recovery at high heat-transfer temperatures of a dielectric liquid such as mineral oil. The oil is circulated through cooling plates, which are inserted between the cells in the stack. The system is nonpressurized. Controlling temperature gradients axially through the stack and across the surface of each cell is necessary to maintain cell performance, increase stack life, limit corrosion, and prevent electrolyte loss (Appleby and Foulkes 1989).

Fuel and Premix Tanks

The PAFC bus has two stainless-steel tanks for the premix of methanol and water. A separate water tank was not included because this would have required a temperature-control system to ensure that the water remained a liquid under all weather conditions. The premix tanks have a total capacity of 140 gallons (130 gallons usable). There is also a separate 15-gallon stainless steel tank containing pure methanol which is used for the reformer burner and start-up burner (HPC 1993).

Interior Heating

A heat exchanger in the fuel-cell coolant loop pathway provides for interior heating and windshield defrosting. The fuel-cell subsystem generates about 40 kW of waste heat during the premix vaporization process. Because the maximum estimated passenger heating load requirement is 17.6 kW, the waste heat can be recycled to meet this requirement (HPC 1993).

Fire Protection and Alarm Subsystem

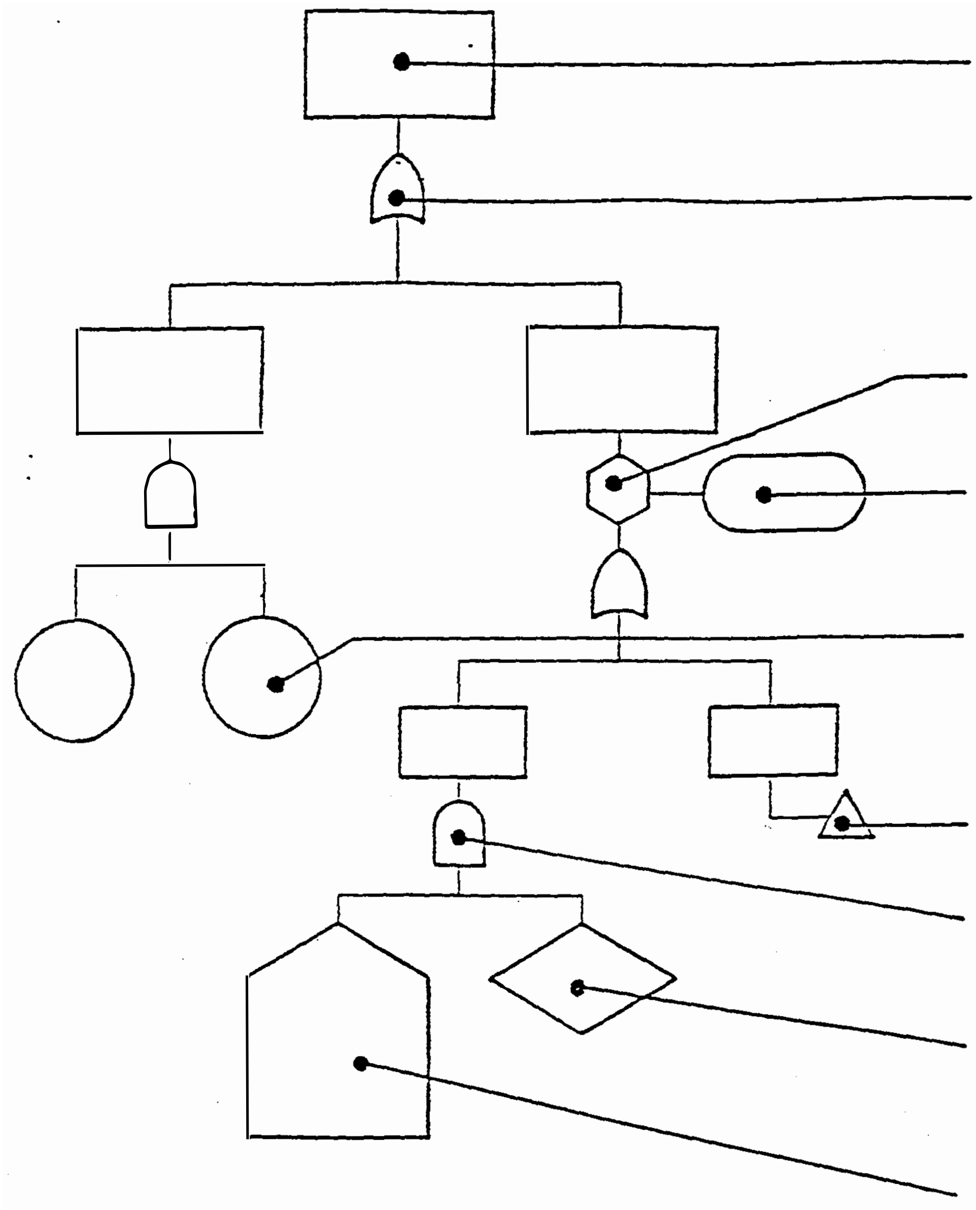
A fireproof wall isolates the fuel-cell subsystem from the rest of the bus. The fuel-cell and fuel-tank areas are protected from fire by a halon/dry chemical-based fire suppression unit equipped with infrared sensors. The unit is independent of the SCS and has multiple redundant circuits. An alarm alerts the driver and fire suppressors are automatically activated when a fire is sensed. The driver is provided with a CO_2 fire extinguisher for additional protection (HPC 1993).

Driver Controls Subsystem

The Driver Controls subsystem is composed of the control components and hardware, driver switches, and driver gauges and indicators. All Baseline Advanced Transit Coach Specifications in the White Book were adhered to in designing the driver interface (HPC 1993).

Appendix B`
Fault Tree

FAULT TREE SYMBOLS



An event, usually a fault, resulting from the combination of more basic faults.

OR GATE – The output event occurs when one or more of the input events are present.

INHIBIT GATE – Used to indicate application of a conditional event which may be a fault in itself or an event normal to system operation.

A CONDITION EVENT – One which must occur in order for an input fault (cause) to result in an output fault (effect).

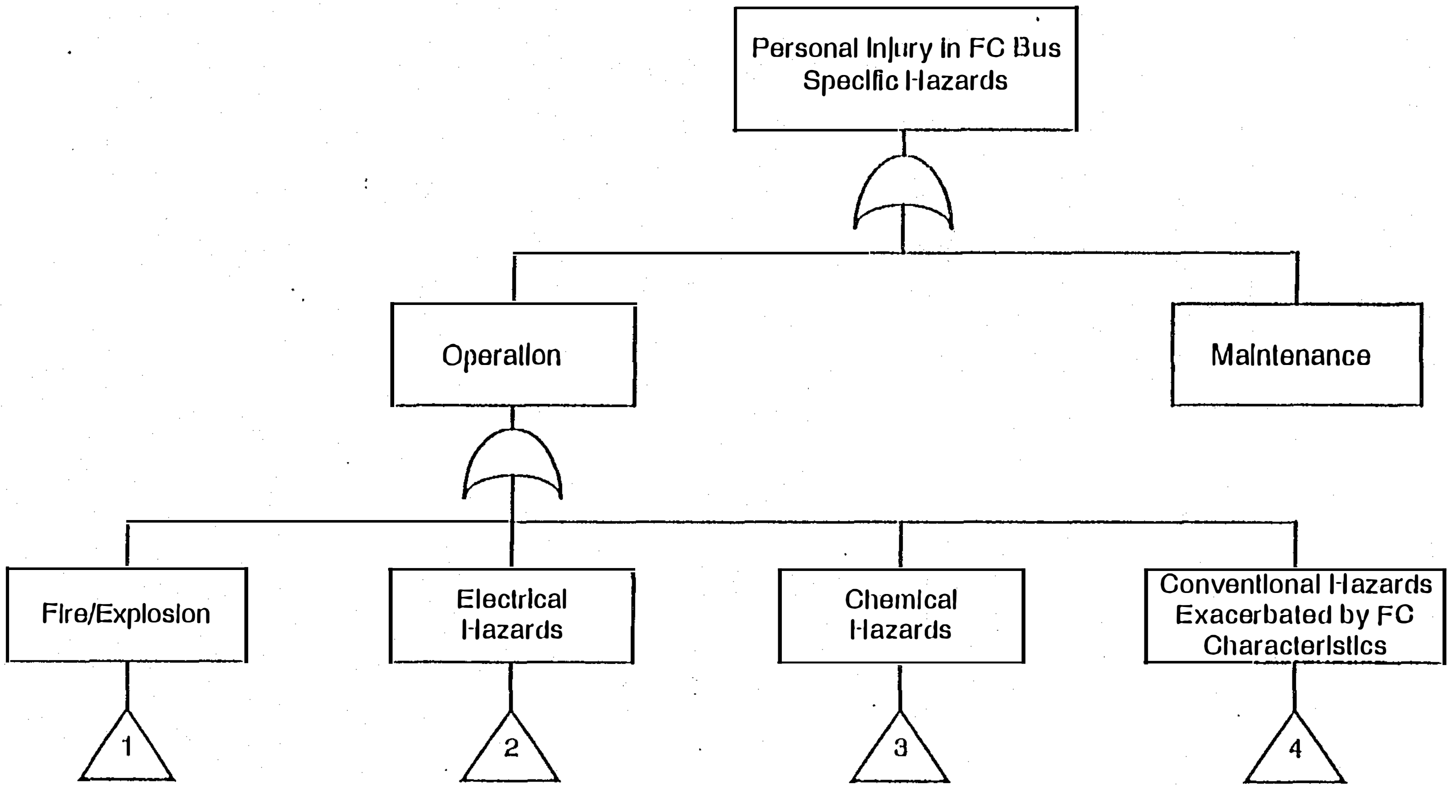
A basic component fault which can be assigned a probability of occurrence based on test results or physics of failure analysis.

TRANSFER SYMBOL – Used to show continuity between two parts of the tree.

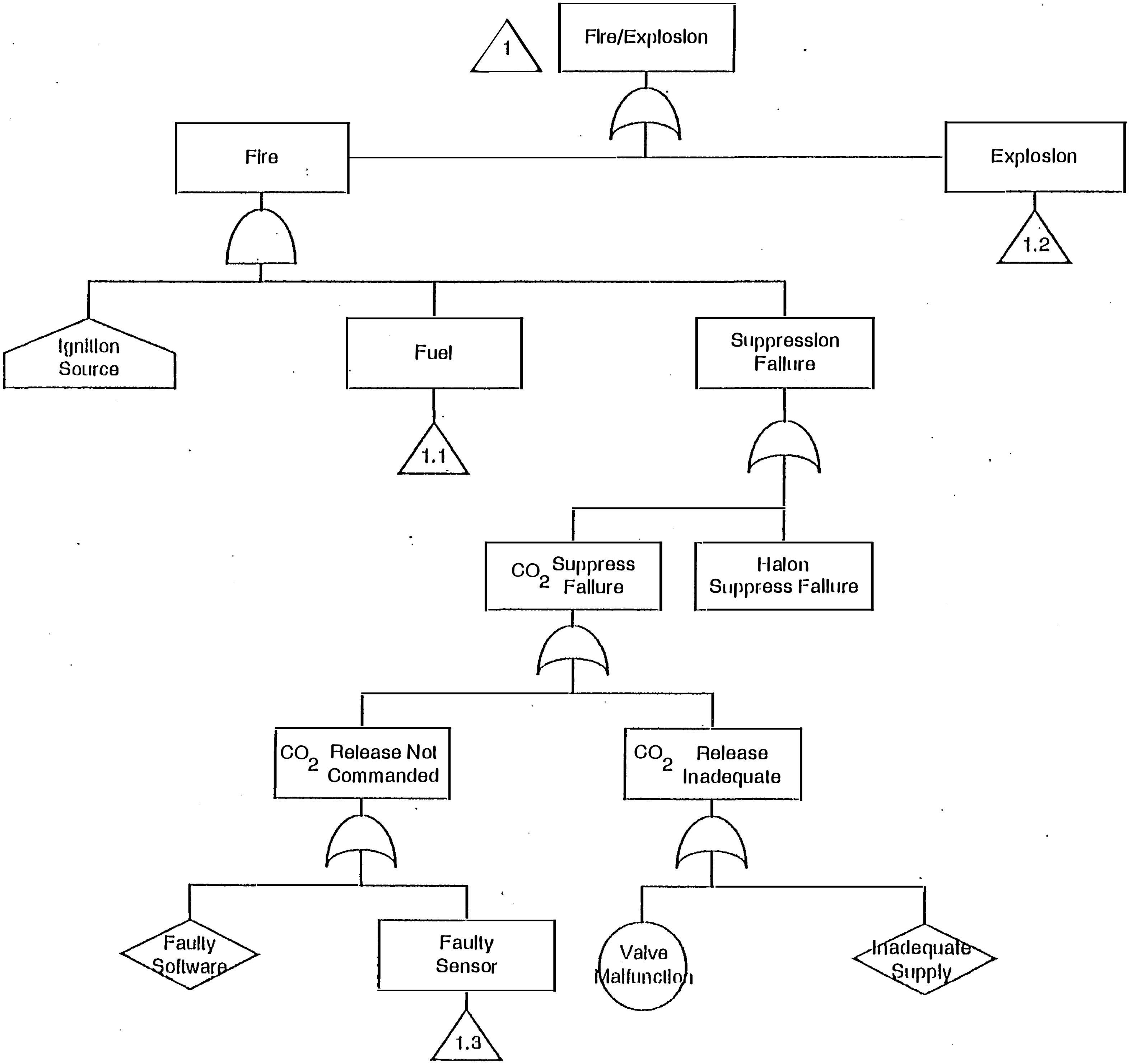
AND GATE – The output event occurs only when all of the input events are present.

A fault not developed further as to its causes because of lack of information, time or value in doing so.

An event expected to occur in normal operation.

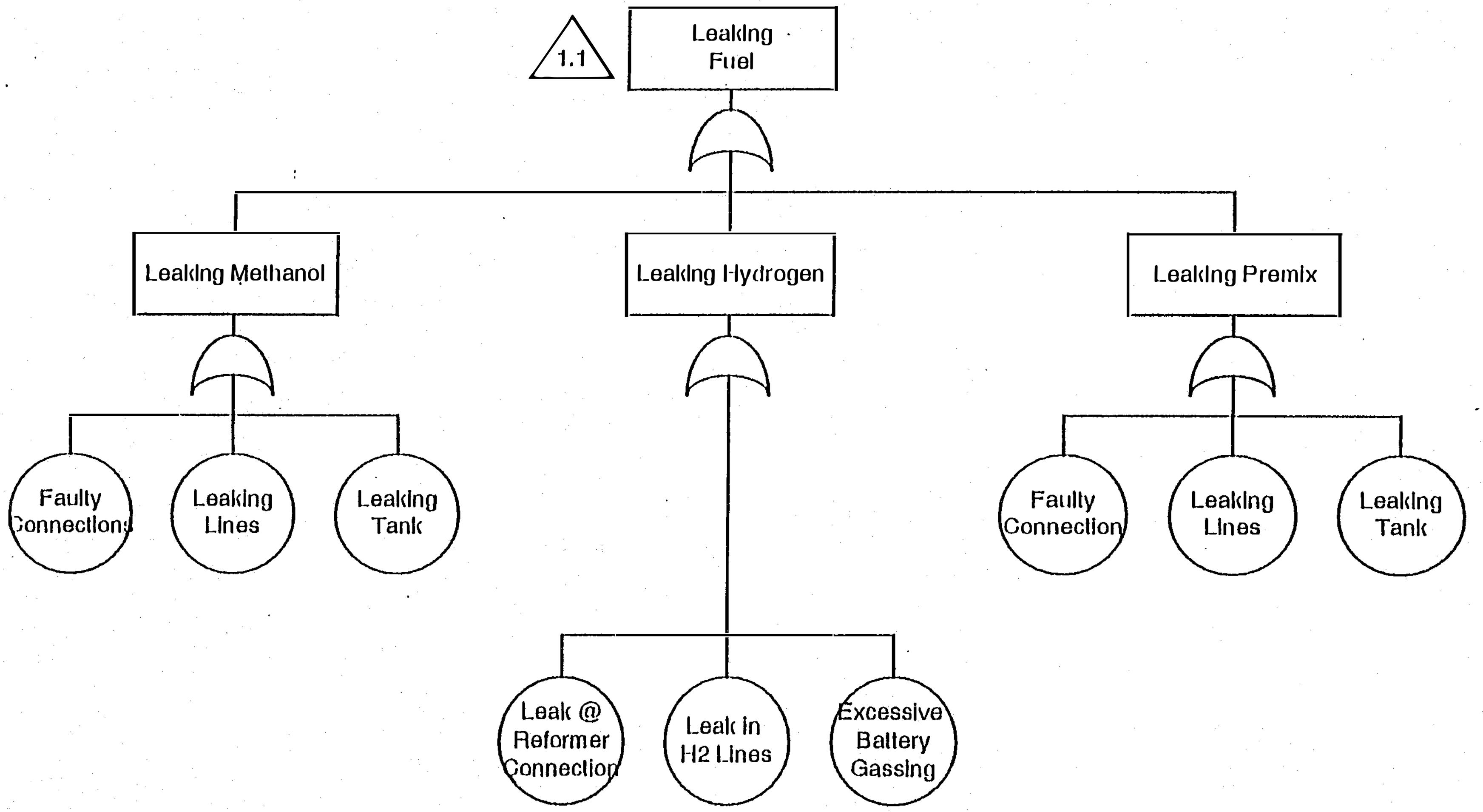

Personal Injury in FC Bus Specific Hazards
Operation
Maintenance
Fire/Explosion
Electrical Hazards
Chemical Hazards
Conventional Hazards Exacerbated by FC Characteristics
1
2
3
4

1/15/93


1
Fire/Explosion
Fire
Explosion
1.2
Ignition Source
Fuel
1.1
Suppression Failure
CO_2 Suppress Failure
Halon Suppress Failure
CO_2 Release Not Commanded
CO_2 Release Inadequate
Faulty Software
Faulty Sensor
1.3
Valve Malfunction
Inadequate Supply

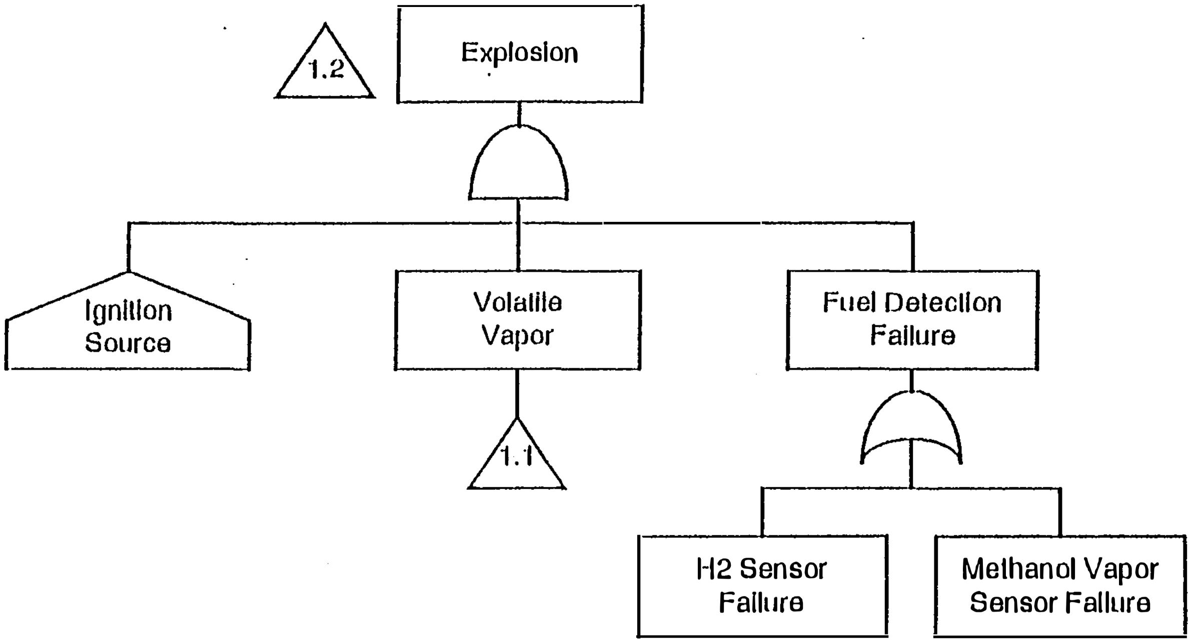
1/15/93

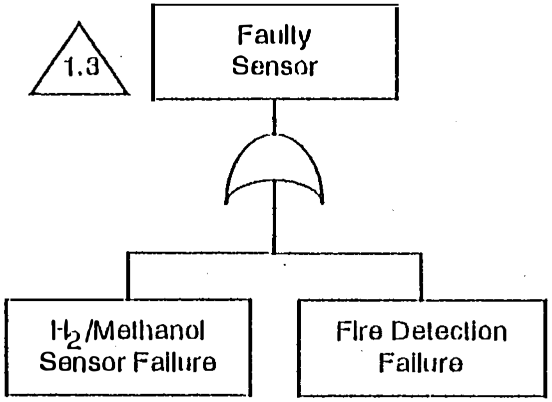
3


1.1
Leaking Fuel
Leaking Methanol
Leaking Hydrogen
Leaking Premix
Faulty Connections
Leaking Lines
Leaking Tank
Leak @ Reformer Connection
Leak in H2 Lines
Excessive Battery Gassing
Faulty Connection
Leaking Lines
Leaking Tank

1/15/93

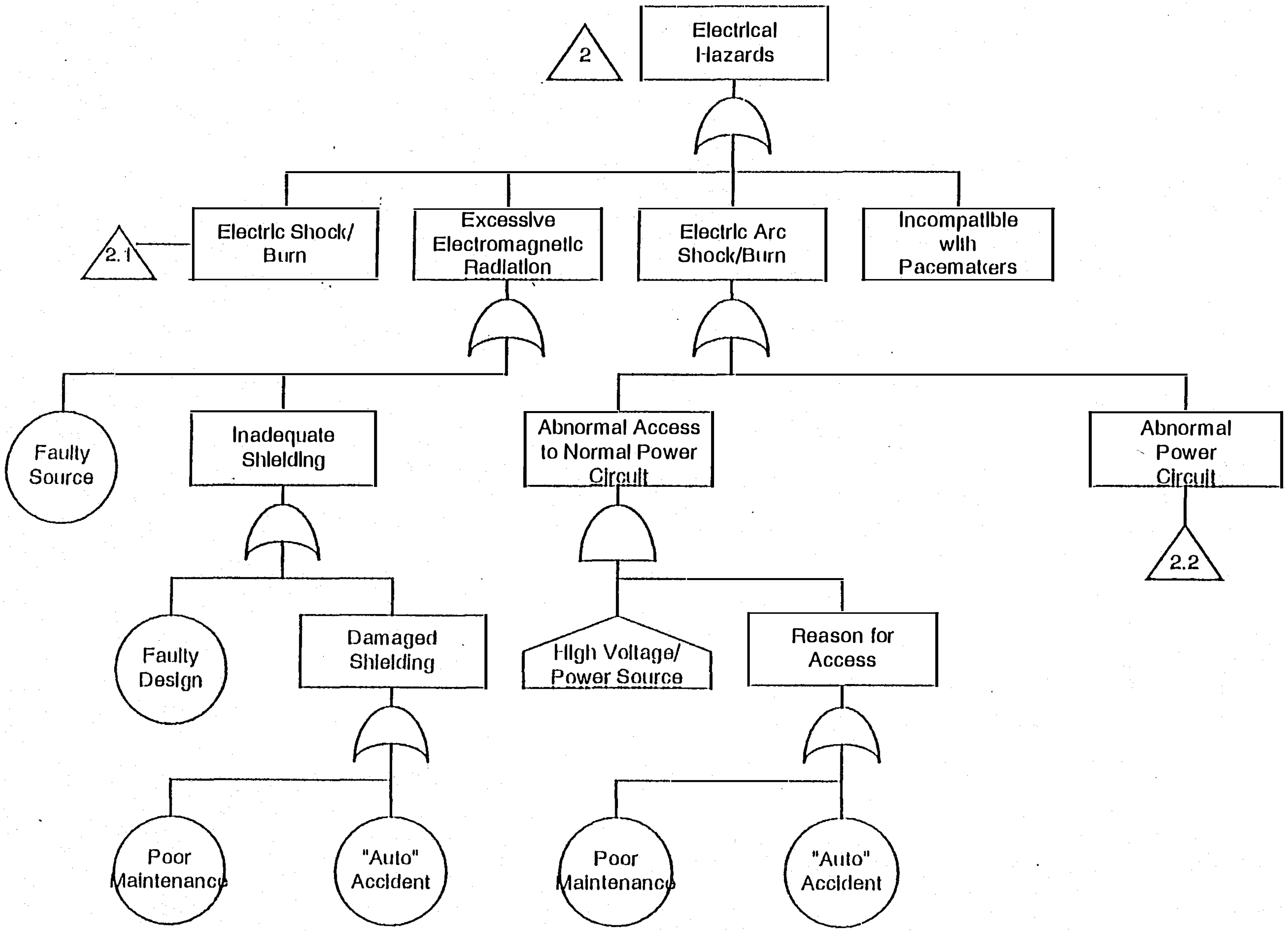
4


1.2
Explosion
Ignition Source
Volatile Vapor
1.1
Fuel Detection Failure
H2 Sensor Failure
Methanol Vapor Sensor Failure

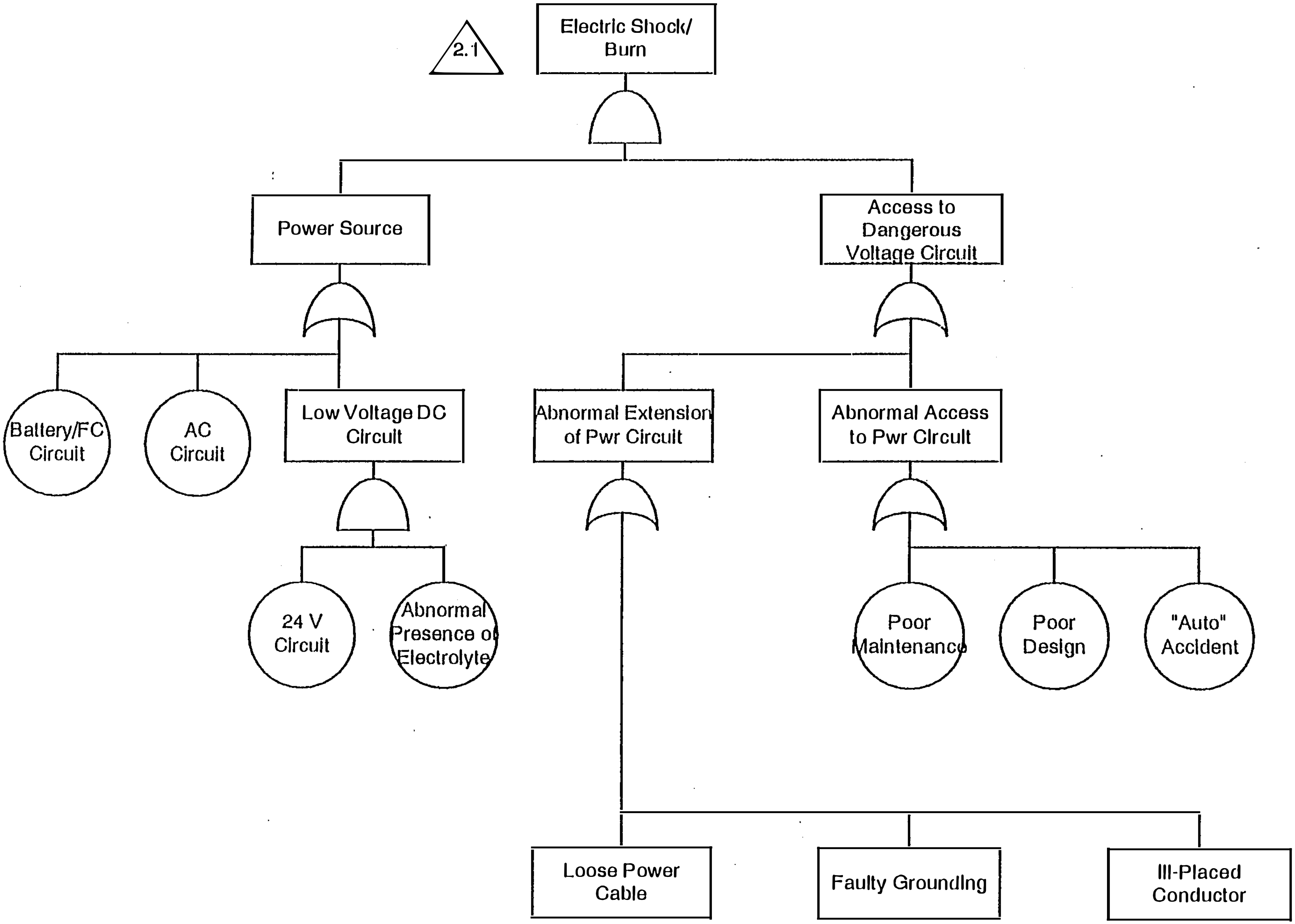

1.3
Faulty Sensor
H2/Methanol Sensor Failure
Fire Detection Failure

1/15/93

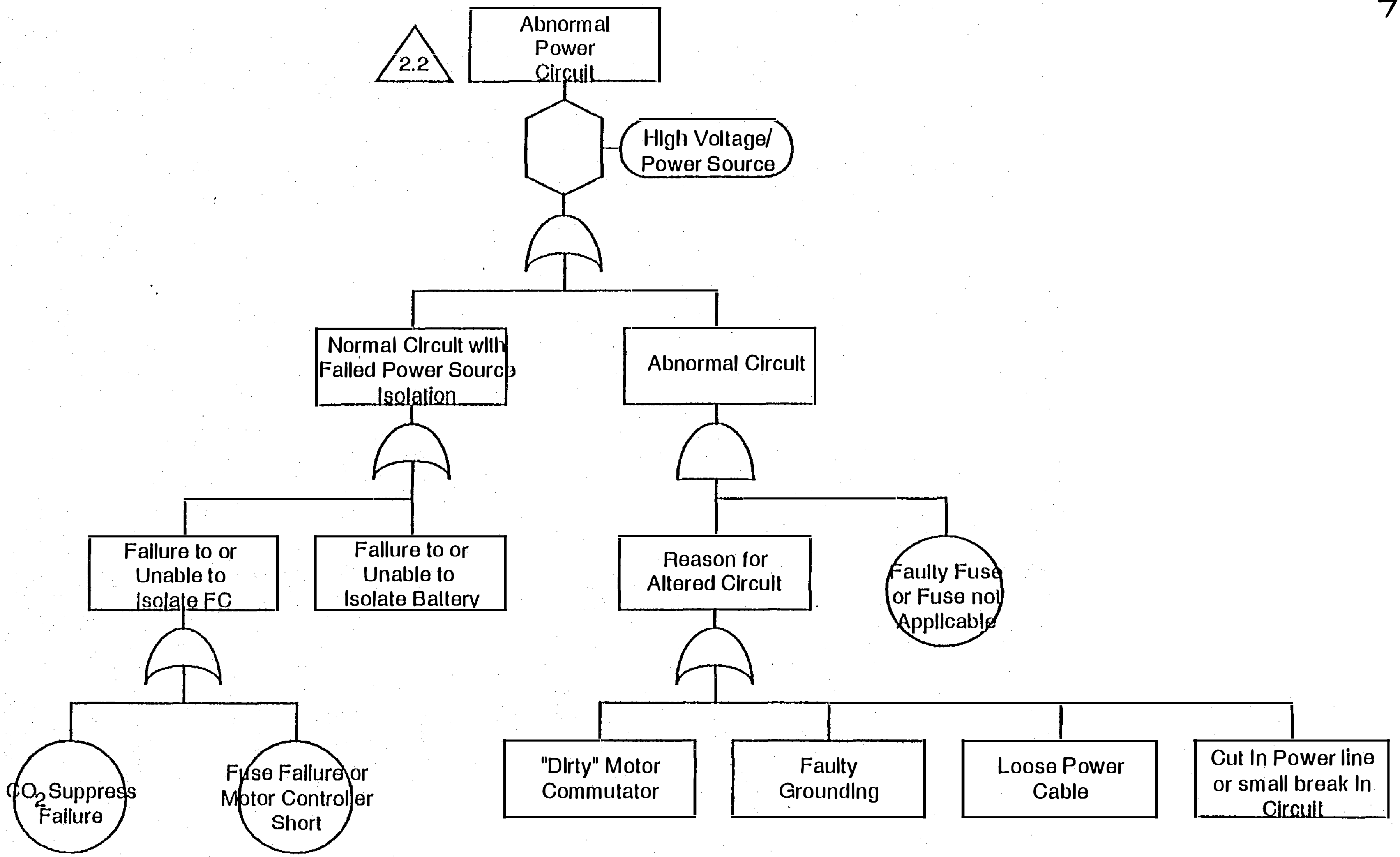
5.


2
Electrical Hazards
2.1
Electric Shock/ Burn
Excessive Electromagnetic Radiation
Electric Arc Shock/Burn
Incompatible with Pacemakers
Faulty Source
Inadequate Shielding
Abnormal Access to Normal Power Circuit
Abnormal Power Circuit
2.2
Faulty Design
Damaged Shielding
High Voltage/ Power Source
Reason for Access
Poor Maintenance
"Auto" Accident
Poor Maintenance
"Auto" Accident

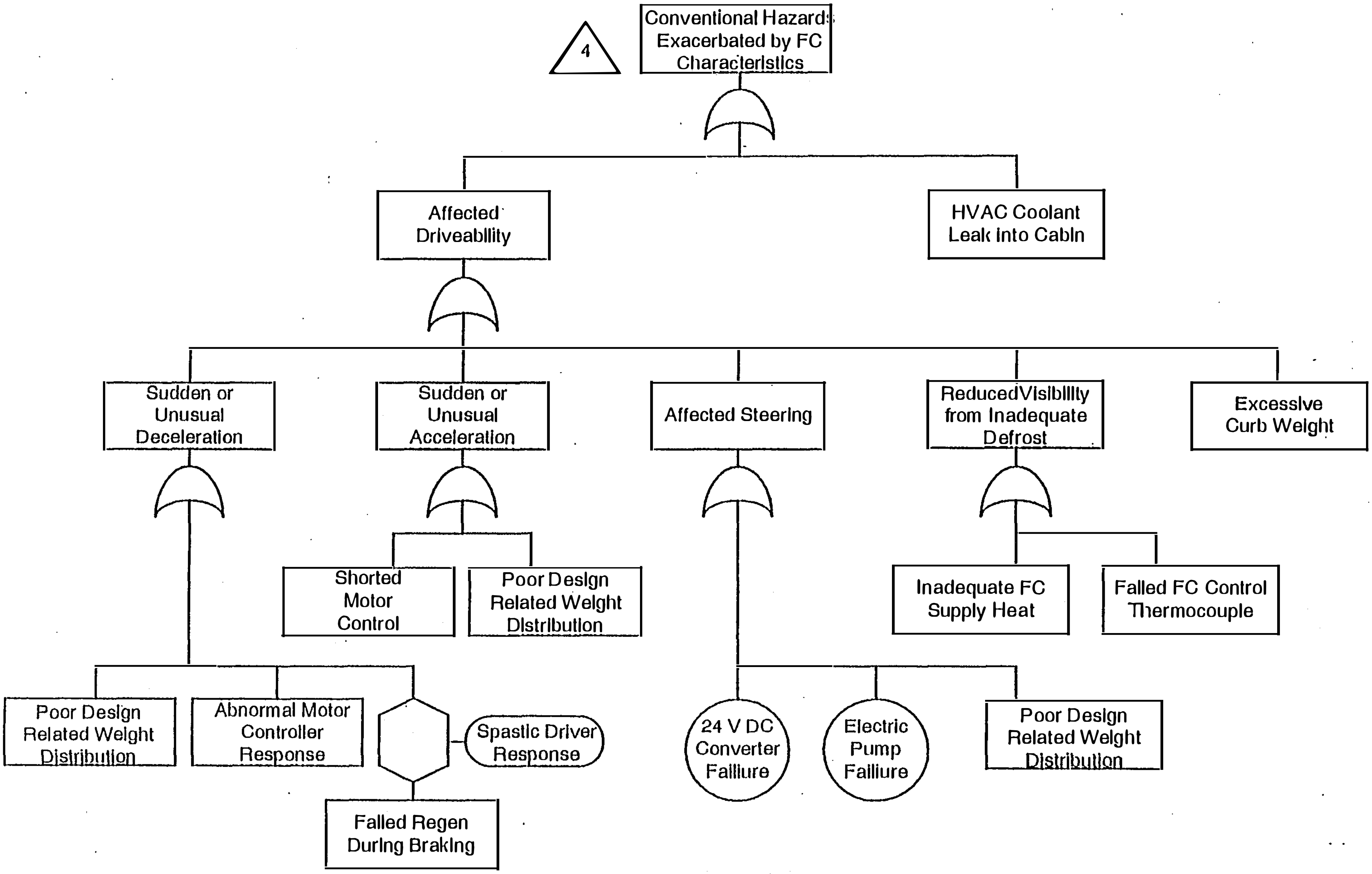
1/15/93


2.1
Electric Shock/ Burn
Power Source
Access to Dangerous Voltage Circuit
Battery/FC Circuit
AC Circuit
Low Voltage DC Circuit
Abnormal Extension of Pwr Circuit
Abnormal Access to Pwr Circuit
24 V Circuit
Abnormal Presence of Electrolyte
Poor Maintenance
Poor Design
"Auto" Accident
Loose Power Cable
Faulty Grounding
Ill-Placed Conductor

1/15/93

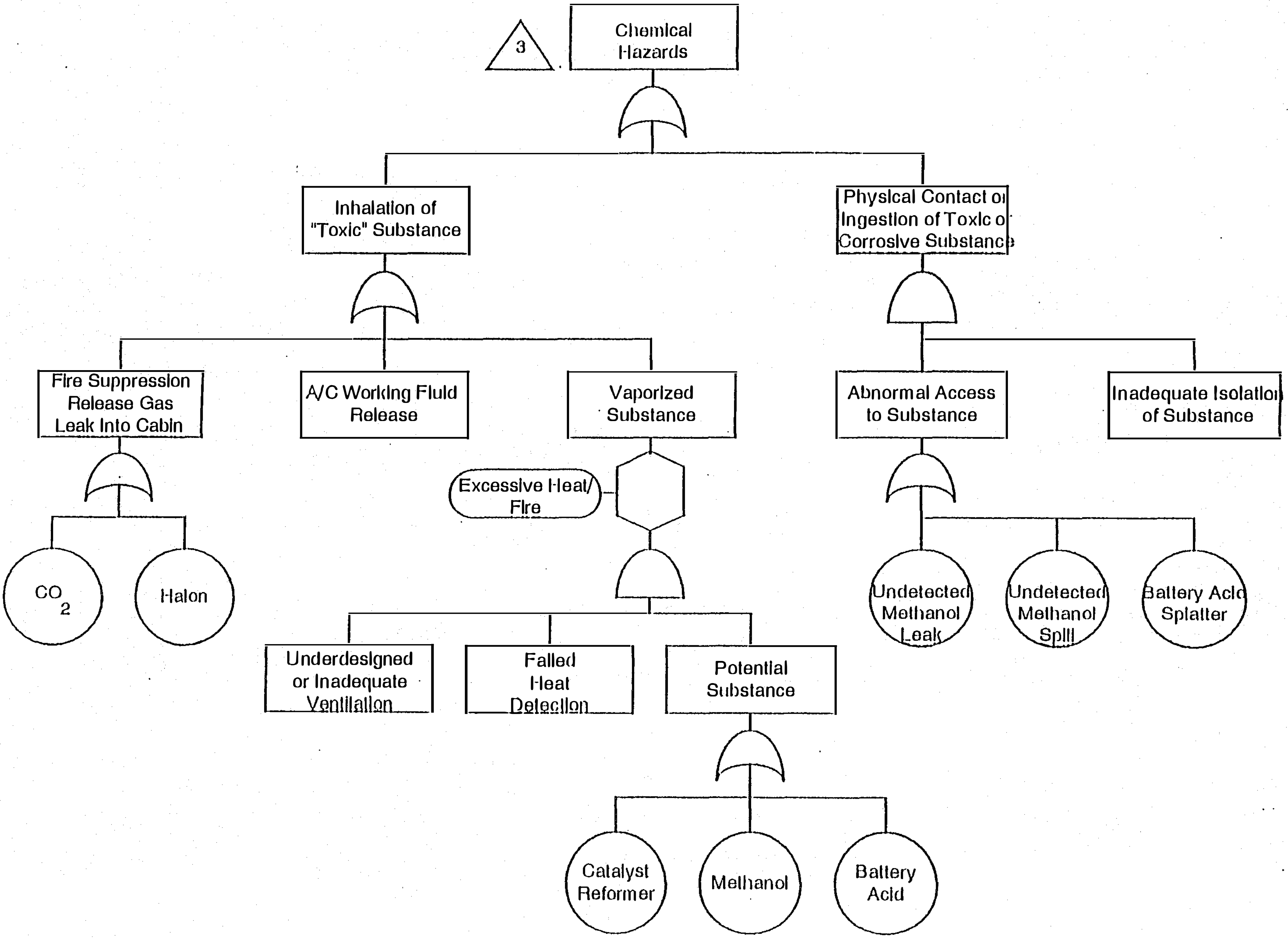

2.2
Abnormal Power Circuit
High Voltage/ Power Source
Normal Circuit with Failed Power Source Isolation
Abnormal Circuit
Failure to or Unable to Isolate FC
Failure to or Unable to Isolate Battery
Reason for Altered Circuit
Faulty Fuse or Fuse not Applicable
CO_2 Suppress Failure
Fuse Failure or Motor Controller Short
"Dirty" Motor Commutator
Faulty Grounding
Loose Power Cable
Cut In Power line or small break In Circuit

1/15/92


4
Conventional Hazards Exacerbated by FC Characteristics
Affected Driveability
HVAC Coolant Leak into Cabin
Sudden or Unusual Deceleration
Sudden or Unusual Acceleration
Affected Steering
Reduced Visibility from Inadequate Defrost
Excessive Curb Weight
Shorted Motor Control
Poor Design Related Weight Distribution
Inadequate FC Supply Heat
Failed FC Control Thermocouple
Poor Design Related Weight Distribution
Abnormal Motor Controller Response
Spastic Driver Response
Failed Regen During Braking
24 V DC Converter Failiure
Electric Pump Failiure
Poor Design Related Weight Distribution

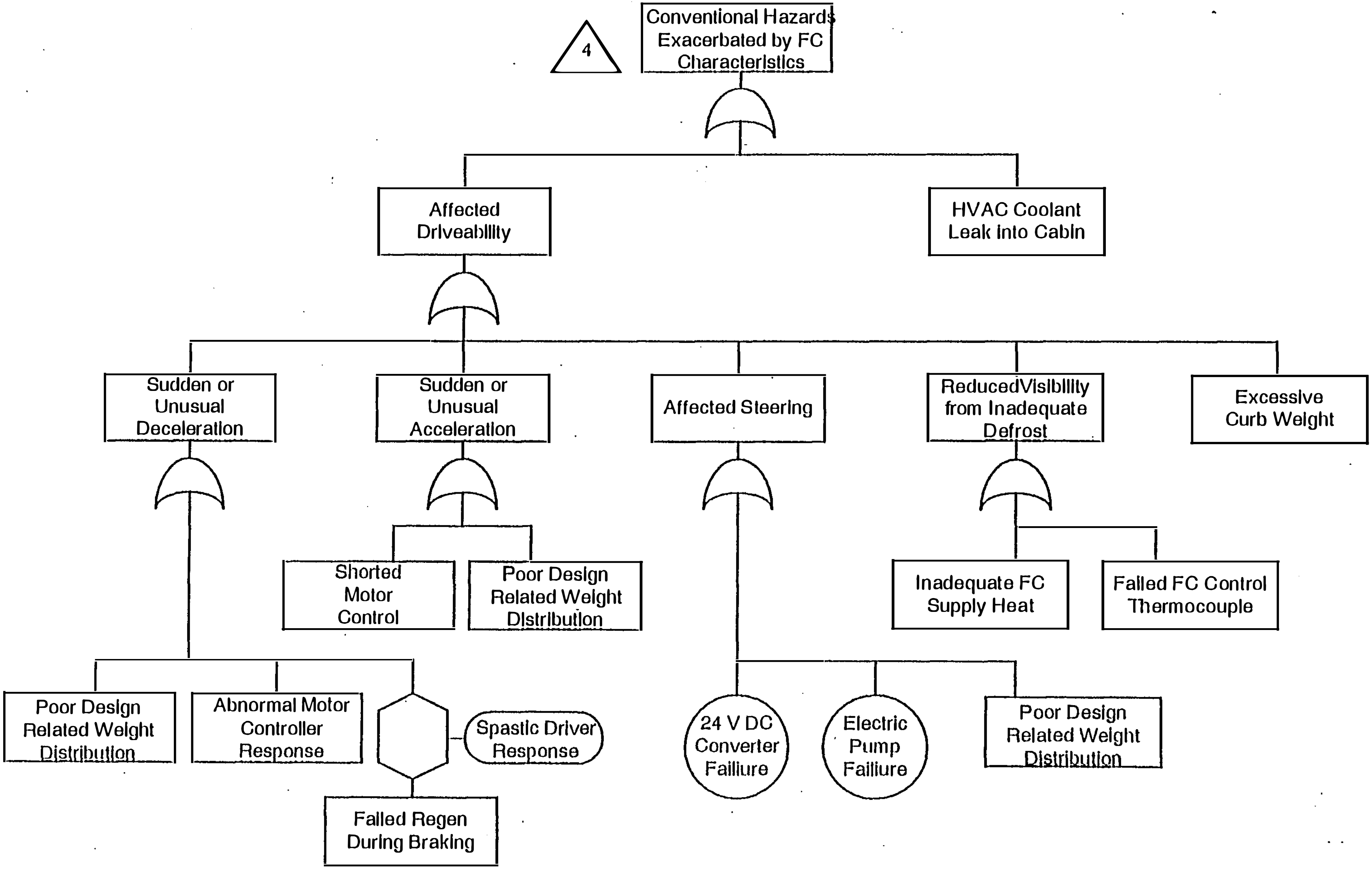
1/15/93

8


3
Chemical Hazards
Inhalation of "Toxic" Substance
Physical Contact or Ingestion of Toxic or Corrosive Substance
Fire Suppression Release Gas Leak Into Cabin
A/C Working Fluid Release
Vaporized Substance
Abnormal Access to Substance
Inadequate Isolation of Substance
Excessive Heat/ Fire
CO2
Halon
Undetected Methanol Leak
Undetected Methanol Spill
Battery Acid Splatter
Underdesigned or Inadequate Ventilation
Failed Heat Detection
Potential Substance
Catalyst Reformer
Methanol
Battery Acid

1/15/93

9


4
Conventional Hazards Exacerbated by FC Characteristics
Affected Driveability
HVAC Coolant Leak into Cabin
Sudden or Unusual Deceleration
Sudden or Unusual Acceleration
Affected Steering
Reduced Visibility from Inadequate Defrost
Excessive Curb Weight
Shorted Motor Control
Poor Design Related Weight Distribution
Inadequate FC Supply Heat
Failed FC Control Thermocouple
Poor Design Related Weight Distribution
Abnormal Motor Controller Response
Spastic Driver Response
Failed Regen During Braking
24 V DC Converter Failiure
Electric Pump Failiure
Poor Design Related Weight Distribution

1/15/93

Appendix C
Crashworthiness Analysis

RESEARCH AND DEVELOPMENT OF A PHOSPHORIC ACID FUEL CELL/BATTERY POWER SOURCE INTEGRATED IN A TEST-BED BUS

CONTRACT NO. DE-AC02-91CH10447

CRASHWORTHINESS ANALYSIS

December 13, 1993

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TABLE OF CONTENTS

1. SCOPE

The purpose of this analysis is to document the safety and major equipment damage implications of a collision involving the Test Bed Bus (TBB) that were identified during the design process. The analysis is based upon available information from TBB equipment suppliers, and to the extent possible analyzes the final configuration of the TBB (see referenced design documents in Section 2 below). The analysis considers only equipment and hazards which would not be standard for a prototype diesel or methanol transit coach.

This is not an exhaustive safety analysis; it deals only with identifiable hazards and damage resulting from TBB collisions in the scenarios considered. Collision avoidance issues are not considered in this analysis. Similar limitations in scope to those of the Hazards List and Data Sheets (see Section 2 below) also apply to this document. This document does not necessarily identify all potential hazards or equipment damage. Furthermore, the analysis assumes that all applicable crashworthiness standards will be met by the TBB, based upon the expected certification from BMI. The analysis and conclusions are primarily qualitative, although some quantitative data may be used. None of the information contained herein has been verified by test.

It should be noted that this analysis was originally conceived to address the unique characteristics of the low-floor bus design that was under consideration. This is no longer an issue because the project team has decided against the low-floor design for TBB-1 through TBB-3.

2. REFERENCE DOCUMENTS

The analysis is based upon the following documents, which are the most current available at the time of writing:

1. Federal Motor Vehicle Safety Standards (FMVSS), as amended through September 27, 1991
2. DOT Baseline Advanced Transit Coach Specifications ("White Book")
3. BMI Structural Analysis, dated 11 December 1993 (Appendix A)
4. TBB Assembly Drawing, Dwg. No. BBC-1-ASM-1-1, dated 22 January 1993 (Appendix B) [not shown]

5. Test Bed Bus #1 Critical Design Review Report, letter number HPC-0067, dated 22 February 1993

6. Hazard List and Data Sheets, letter number BAH-0098, dated 19 March 1993.

3. REVIEW OF APPLICABLE CRASHWORTHINESS STANDARDS

Applicable crashworthiness standards are listed below. Applicable standards are contained in the FMVSS and the White Book. In this analysis, it is assumed that the TBB will meet all applicable standards, based upon the expected certification from BMI. It is expected that upon completion of fabrication, BMI will supply this written certification. This analysis does not consider proposed standards, such as new side impact and crash standards.

3.1 Glazing Materials

Glazing materials requirements are contained in FMVSS 205. This standard specifies the chemicals and strength test characteristics for glass and other glazed material on vehicles. It deals primarily with what testing requirements apply to specific materials and vehicle locations/applications.

3.2 Seating Systems

Seating systems requirements are contained in FMVSS 207. This standard specifies strength and testing requirements for seats, their attachment assemblies, and their installation. Many of the requirements, such as seat belts, do not apply to bus passenger seats.

3.3 Occupant Crash Protection

Occupant crash protection requirements are contained in FMVSS 208. This standard specifies which seats are required to have seat belts, which on a bus (over 10,000 lbs. GVWR) only applies to the operator seat. The standard also contains requirements for crash-dummy testing and acceptable damage levels. Miscellaneous items such as seat belt latching and pressure vessels are covered.

3.4 Seat Belt Assemblies

Seat belt assemblies requirements are contained in FMVSS 209 and 210. These standards specify requirements for seat belt hardware, mechanical characteristics, webbing requirements, wear resistance, and the like. Detailed drawings and other requirements for seat belt mechanism configuration and testing are given. FMVSS 210 deals specifically with seat belt assembly anchorages. For the TBB, these standards apply only to the operator's chair.

3.5 Bus Window Retention and Release

Bus window retention and release requirements are contained in FMVSS 217. This standard specifies the force and testing requirements a bus window must withstand to deter against occupants being thrown from the bus. It also contains emergency exit provisions, such as exit minimum area per passenger, location, and release requirements.

3.6 Fuel System Integrity

Fuel system integrity requirements are contained in FMVSS 301. This standard specifies the allowable fuel spillage for various barrier crash and rollover conditions. Test conditions and other requirements are given. This standard is not a requirement for buses (other than school buses) with GVWR above 10,000 lbs. However, there is no other definitive standard which applies to the TBB in this area either. Therefore, FMVSS 301 can serve as a guideline, but not an absolute requirement, for the TBB.

3.7 Body and Roof Structural Strength

White Book Section 2.1.2.10 states that,

> "The coach body and roof structure shall withstand a static load equal to 150 percent of the curb weight evenly distributed on the roof with no more than a six-inch reduction in any interior dimension. Windows shall remain in place and not open under such a load."

3.8 Penetration Into the Passenger Compartment

White Book Section 2.1.2.10 states that,

> "The coach shall withstand a 25-mph impact by a 4,000 pound, post-1973, American automobile at any point, excluding doorways, along either side of the coach with no more than three inches of permanent structural deformation at seated passenger hip height. This impact shall not result in sharp edges or protrusions in the coach interior."

3.9 Structural Members Below Rubrail

White Book Section 2.1.2.10 states that,

"Exterior panels below the rubrail and their supporting structural members shall withstand a static load of 2,000 pounds applied to the coach anywhere below the rubrail by a pad no larger than five inches square. This load shall not result in deformation that prevents installation of new exterior panels to restore the original appearance of the coach."

3.10 Five-mph Front Bumper Impact

White Book Section 3.6.3.2 states that,

"No part of the coach, including the bumper, shall be damaged as a result of a 5-mph impact of the coach at curb weight with a fixed, flat barrier perpendicular to the coach's longitudinal centerline. The bumper shall protect the coach and a stationary 4,000-pound, post 1973, American automobile from damage as a result of impacting at 6.5 mph into the rear bumper of the automobile parallel to the longitudinal centerline of the coach and at 5.5 mph into the rear bumper of the automobile at a 30° angle to the longitudinal centerline of the coach. The energy absorption system of the bumper shall be independent of every power system of the coach and shall not require service or maintenance in normal operation during the service life of the coach. The flexible portion of the bumper may increase the overall coach length specified in Section 1.5.1.1 by no more than six inches."

3.11 Five-mph Rear Bumper Impact

White Book Section 3.6.3.3 states that,

"The rear bumper and its mounting shall provide impact protection to the coach at curb weight from a two-mph impact with a fixed, flat barrier perpendicular to the longitudinal centerline of the coach. The rear bumper shall protect the coach, when impacted by the striker defined in FMVSS #215 loaded to 4,000 pounds, at four mph parallel to, or up to a 30° angle to, the longitudinal centerline of the coach. The rear bumper of bumper extensions shall be shaped to preclude unauthorized riders standing on the bumper and shall wrap around the coach to protect the engine compartment doors and radiator. The bumper extensions shall not hinder service and shall be faired into the coach body with no protrusion or sharp edges. The bumper shall be independent of all power systems of the coach and shall not require service or maintenance in normal operation during the service life of the coach."

4. COLLISION SCENARIOS CONSIDERED

Below is a listing of the collision scenarios considered. Each of these scenarios is used to assess the collision performance of the TBB and various components. Collisions with both light-duty automobiles (low weight, low bumper height) and heavy-duty trucks (high weight, high bumper height) are considered. Note that a front-end collision is not considered because it is unlikely that impact in this area would have significant effects on major TBB-unique components. Collisions with objects other than vehicles are not considered, because it is very unlikely that a serious collision of this type would occur in the scenarios considered. Shock levels due to each collision scenario are not quantified in this analysis.

4.1 Broadside Collision

Collision on either side of the TBB. The major components in question would be the batteries and the fuel tanks.

4.2 Rear-End Collision

Collision in the rear of the TBB. The major components in question would be the traction motor, fuel cell subsystem, and electric propulsion equipment.

4.3 Rollover

Roll of the TBB over 90 degrees onto either side or 180 degrees over onto the roof. This is a highly unlikely scenario. In a turning situation under most conditions, a sideways slide will occur before a rollover. It can be shown that for rollover to occur rather than a slide, the wheel/road static coefficient of friction must be greater than x / h. Here x is the distance from the vehicle centerline to the wheel centerline and h is the height of the vehicle center of mass. For the TBB, the static coefficient of friction must be greater than 0.86 for rollover to occur, whereas this value typically does not exceed 0.85 (corresponding to new tires, dry pavement, and low speed) in nearly all driving conditions. Nonetheless, rollover speed versus curve radius has been calculated (see Appendix C) for the unlikely situation where rollover is possible, where a sideways slide is prevented by excessive friction or some side constraint in the roadway (i.e., grooves, a pothole, etc.).

The minimum curve radius of the TBB is 33.5 feet, which corresponds to a rollover speed of 20.8 mph on flat ground with excessive static friction conditions. This is a very conservative calculation, and rollover will likely occur at higher speeds than indicated. Rollover could also occur by a sudden maneuver to avoid a collision or a broadside collision with an unusually high center of effort.

5. ASSESSMENT OF TBB PERFORMANCE IN COLLISIONS

In this section, various major components of the TBB are assessed in each of the scenarios described above in Section 4. Particular consideration is given to the placement of components.

5.1 Bus Body/Chassis

BMI has considered crashworthiness in the TBB structural design, although this is not specifically addressed in the TBB Structural Design Report. The design does not appear to employ a sacrificial, energy-absorbing approach. The primary mechanism for withstanding collisions is through the rigidity of the underframe, which has two continuous longitudinal trusses. Therefore, loads generated by a collision in one location of the TBB could be transmitted to other locations. While this may cause some structural deformation in locations remote from the collision location, it is not expected that major component damage would occur in remote locations.

5.2 Batteries

The main scenario of concern for the batteries is the broadside collision. The TBB battery arrangement employs many of the safety features found in the G-Van, which has undergone significant safety analysis and testing. The batteries are located below the passenger compartment, so that if ruptured, electrolyte would tend to flow downward away from passengers. Based on the passenger compartment penetration and below-rubrail requirements of White Book Section 2.1.2.10, there is significant structural strength outboard of the battery compartments. Also, battery compartment structures are unitized and have internal stiffening members. Therefore, the danger of passenger exposure to battery electrolyte in a broadside collision has been minimized in the design.

Batteries are also of concern in a rollover. There would be a greater likelihood of electrolyte reaching passengers in this situation. The major protection here is the floor structural integrity, which is less likely to be compromised in a rollover. Also, the battery watering system will tend to limit the widespread release of electrolyte.

It should be noted that nickel-cadmium electrolyte, used in the current TBB design, is generally considered to be much less caustic and toxic than lead-acid electrolyte.

5.3 Fuel Cell Subsystem

The main scenario of concern for the fuel cell subsystem is the rear-end collision. Personal injury and equipment damage could be caused mainly by the stack phosphoric acid, contents of the reformer, and fuel cell coolant loop fluid. Each of these components is built very robustly, plus protected by the substantial fuel cell frame and bus structure. Passengers are protected by the fire wall, and the hazard would probably be greater for the occupant(s) of the colliding vehicle. Some hazard may exist if control of the fuel cell subsystem is lost, fuel is suddenly deprived, or the CO_2 purge cannot be accomplished. At worst, an explosion or major damage to the fuel cell reformer or stack could occur.

Rollover is also of concern for the fuel cell subsystem. Major equipment damage to fuel cell components is the major hazard here, and the probability of personal exposure to hazardous materials is relatively less than in a rear-end collision.

Individual fuel cell subsystem components will be shock and vibration tested, but the assembled subsystem will not be.

5.4 Traction Motor

The main scenario of concern for the traction motor in the rear-end collision. Due to its proximity to the rear bumper, the motor has a high probability of being sheared off of its mountings in a rear-end collision. This would cause major hardware damage, including fracture of the drive shaft and traction power connections. The major threat to personal safety in this situation is possible exposure to high-voltage DC current. This is mitigated primarily through circuit protection devices such as breakers, fuses, and ground fault detection.

5.5 Propulsion and Other High Voltage Equipment

High voltage equipment is concentrated in the rear of the bus. Some high voltage wire runs also exist under the floor to the batteries, refrigerant compressor, and air compressor/power steering pump motor. The major hazard here is the danger of electric shock from ruptured conductors in a collision scenario. This danger is mitigated by circuit protection devices such as breakers, fuses, and ground fault detection. There is some degree of redundancy in these devices, and they are generally designed for quick response. Also, system shut down including disabling high voltage circuitry can be accomplished quickly, either manually or automatically. Even if energized high voltage conductors are exposed, the probability that a person would actually complete a circuit is fairly low. The entire chassis is common and there will generally not be a path to earth ground.

5.6 Passenger Heating Loop

The passenger heating loop is routed from the fuel cell compartment to the roof and front end, but is generally not within the passenger compartment. The working fluid is mineral oil, which could be more dangerous than the standard ethylene-glycol-water mixture due to its higher specific heat. However, the temperature will be regulated to 180°F or less at nearly all times. A collision or rollover situation will increase the likelihood of a mineral oil leak, which is covered in hazard data sheet number HZD-HVC-001. The major mitigation measure to this hazard in a collision or rollover is the physical separation of the passenger heating loop from the passenger compartment. Also, the passenger heating loop plumbing and insulation will undergo regular inspection in service.

6. CONCLUSIONS AND RECOMMENDATIONS

Based upon the preceding analysis, the following conclusions can be made, subject to the limiting assumptions and information availability of the analysis.

1. The projected crashworthiness of the TBB is acceptable for the stated mission and is comparable to other prototype buses and electric vehicles.

2. Where possible, information and assumptions in this analysis should be verified by test. In particular, some non-destructive static load testing of the bus frame should be performed to verify BMI structural analyses.

3. Some areas could be investigated further when hardware is available to increase the confidence level in the crashworthiness of the TBB. These include

   The possible effects of a rear-end collision on the fuel cell subsystem and the vehicle that collides with the TBB

   The possible effects of a broad-side collision on the battery subsystem and the vehicle that collides with the TBB.

4. Periodic inspection of the TBB will be important in maintaining the crashworthiness of the TBB, and these inspections should be incorporated into standard maintenance practices. These structural inspections, inspections of the battery installation, and inspections of the passenger heating loop plumbing and insulation.

APPENDIX A

BMI TBB STRUCTURAL DESIGN REPORT

UNITED STATES DEPARTMENT OF ENERGY
OFFICE OF TRANSPORTATION TECHNOLOGY

RESEARCH AND DEVELOPMENT OF A PHOSPHORIC ACID FUEL CELL/BATTERY POWER SOURCE INTEGRATED IN A TEST-BED BUS

CONTRACT NO. DE-AC02-91CH10447

11 DECEMBER 1992

TBB STRUCTURAL DESIGN REPORT

Prepared By

BUS Manufacturing USA Inc.
325-F Rutherford Avenue
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Prepared For

H Power Corporation
60 Montgomery Street
Belleville, New Jersey 07109

TBB STRUCTURAL DESIGN REPORT

Introduction

The purpose of this report is to document the structural design of the Fuel Cell/Battery Test Bed Bus, constructed for the United States Department of Energy under a subcontract to H Power Corp, as part of DOE contract number DE-AC02-91CH10447. The bus is intended to demonstrate fuel cell technology in a 25-30 foot heavy-duty bus capable of operating in a typical transit environment. This report is limited to the structural design of the bus body and chassis. The bus structure is shown in figure 1.

The Design of the Fuel Cell/Battery Test Bed Bus

The fuel cell bus frame and integral body are a unitized assembly consisting of cold drawn low carbon structural steel tubing and elctrogalvanized carbon sheet steel. The tubing specification is in conformance with ASTM A-500, grade C (50,000 psi minimum yield strength). All steel joining is done by inert gas metal arc welding.

The principal load carrying members of the frame are two longitudinal trusses which run the length of the chassis. The upper and lower tubes of each truss are constructed of one continuous piece and contain no splices. Numerous diagonal tubes are used to reinforce the truss. Welding is not permitted across main truss tension members.

Cross trusses are used to support the body and also support the battery trays. The body structure is essentially that part of the bus above the floor line. The body adds strength and rigidity to the frame and helps to transfer battery and passenger loads to the suspension. The side and roof structural members are also reinforced with diagonal braces. Sheet steel skins are welded to the body and act as shear panels.

All tubes are protected from corrosion both inside and out. The interior of each tube is coated with a corrosion preventative compound and drain holes are provided to prevent the entrapment of any water or condensation. All exterior surfaces are sprayed with specially formulated epoxy primers containing corrosion inhibitors. Wheel houses are constructed of heavy gauge corrosion resistant steel.

The resulting structure is designed to withstand the rigors of heavy duty transit service for a minimum of 12 years. Conservative design factors were used in the selection of materials and the specifications for tube dimensions and wall thickness. Over ??? buses have been constructed over the past 30 years using the above approach, and there have been no reported failures of the frame or body.

The roof and roof support structure is designed to withstand a static load of 150 % of the TBB curb weight with minimum deformation, per the FTA guidelines.

Design Methodology

The design methodology of the unitized body/frame assembly includes a comprehensive load analysis using proprietary values for member strengths, deflections and allowable material stresses. This methodology is the result of over 30 years of bus body construction and includes the results of numerous load tests on similar structures. The detailed methodology is the essence of the design of lightweight and efficient vehicle structures and is proprietary, and thus will not be published.

Analysis

For this report a simplified beam analysis of the frame is presented to demonstrate that the expected loads will not cause any permanent deformation or fatigue damage to the frame over the life of the vehicle. The simplified analysis is conservative in the respect that it assumes that the bus body does not contribute any stiffness or strength to the frame. In actual practice the body will reduce the frame stresses by 25-50%, thus this analysis is conservative by this amount.

A simple beam strength analysis of the frame indicates that the 2 main longitudinal frame rails are capable of withstanding a combined vertical bending moment of 1,313,000 in-lbs at their yield point of 50,000 psi.

An analysis of the distributed and point loads to the bus structure indicate that the maximum static (1 G) vertical bending moment is 260,000 in-lbs at 27,500 lbs gross vehicle weight. The loading condition assumed a 2400 lb battery load, 26 seated passengers, driver and 13 standees. The static loading and bending moment diagrams are shown in figures 2 and 3. The location of this maximum moment is approximately midway between the axles. The dynamic loads transmitted through the suspension are not expected to exceed 3 G, which would result a maximum bending moment of 780,000 in-lbs. Thus, the minimum frame factor of safety (assuming the body contributes no strength) is 1.68 with respect to the yield point in the vertical bending mode, relative to a 3 G input.

Our estimate is that the bus body reduces the bending load on the frame by 25-50%. This figure has been calculated by assuming that the loads directly carried by the body are:

1. 100 % of the body
2. 50% of the battery load
3. 50% of the seated passengers

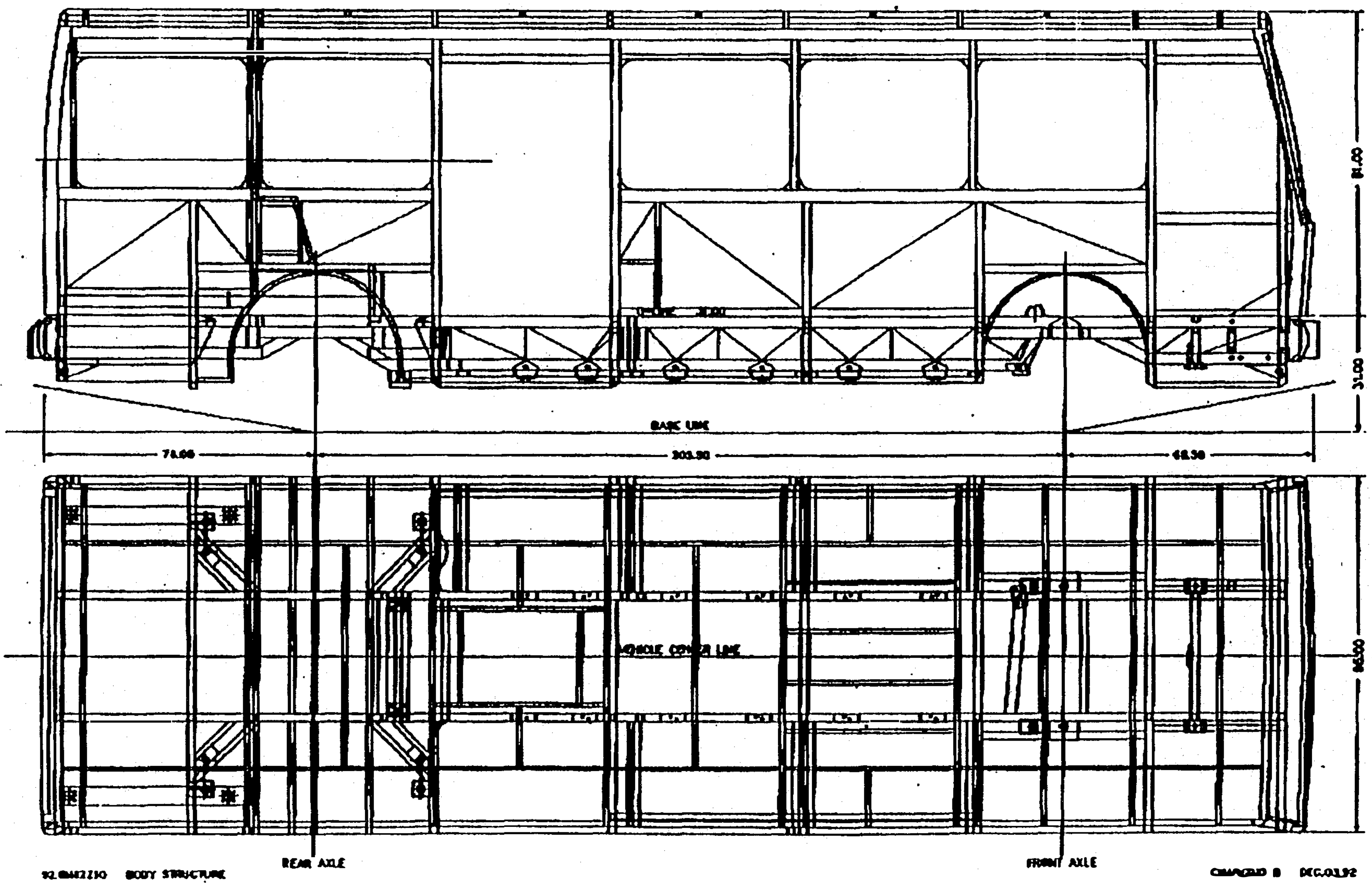
This assumption reduces the maximum bending moment of the frame by apporoximately 50%, thus the saftey factor will increase to approximately 3.

A fatigue analysis indicates that the frame will withstand in excess of 12 years of service life. The analysis assumes that the frame variable loads are +1.5G and +0.5G (+/- 0.5G superimposed upon the 1.0G static load). The stress variation is assumed to be sinusoidal and that 12 years the bus will accumulate the equivalent of 5 million cycles. Using stress concentration factors of 2.5 and the material endurance limit of 30,000 psi results in a fatigue factor of safety in excess of 2.

A review of the structure and the analysis indicates that although the fuel cell and traction motor are the heaviest components and concentrate the most weight behind the rear axle, this is not the area of highest frame loading. This is due to the relatively close couple to the rear suspension mounts and resultant low bending moment. The area of highest loading is mid-way between the axles, in the area of the fuel tanks and batteries. The combined weight of the batteries and fuel and their position relative to the axles contribute significantly to the maximum bending moment. Fortunately, the side structure is very effective in sharing the bending loads in this area. On the left side of the vehicle, the side structure carries loads nearly directly the suspension cross members. The right side structure acts similarly in transferring loads to the front suspension, but has a gap for the rear door in the load path to the rear suspension, and is therefore less effective. The door frame area has been reinforced to help carry the loads and reduce deflections.

Body and Frame Warranty

Bus Manufacturing USA, Inc. warrants the bus body and frame to be free from structural defects and/or permanent deformation sufficient to cause a Class 1 or Class 2 failure (as specified in the FTA Baseline Advanced Design Transit Coach Specifications) for the lessor of the 12 year service life or 500,000 miles of the bus, when operated under the conditions of transit service. Should such defects occur, Bus Manufacturing USA, Inc. will repair or replace any defective part. Unauthorized repairs and or modifications to the body and frame assembly or loading in excess of the GVWR will void this warranty.


81.00
31.00
96.00
BASE LINE
78.00
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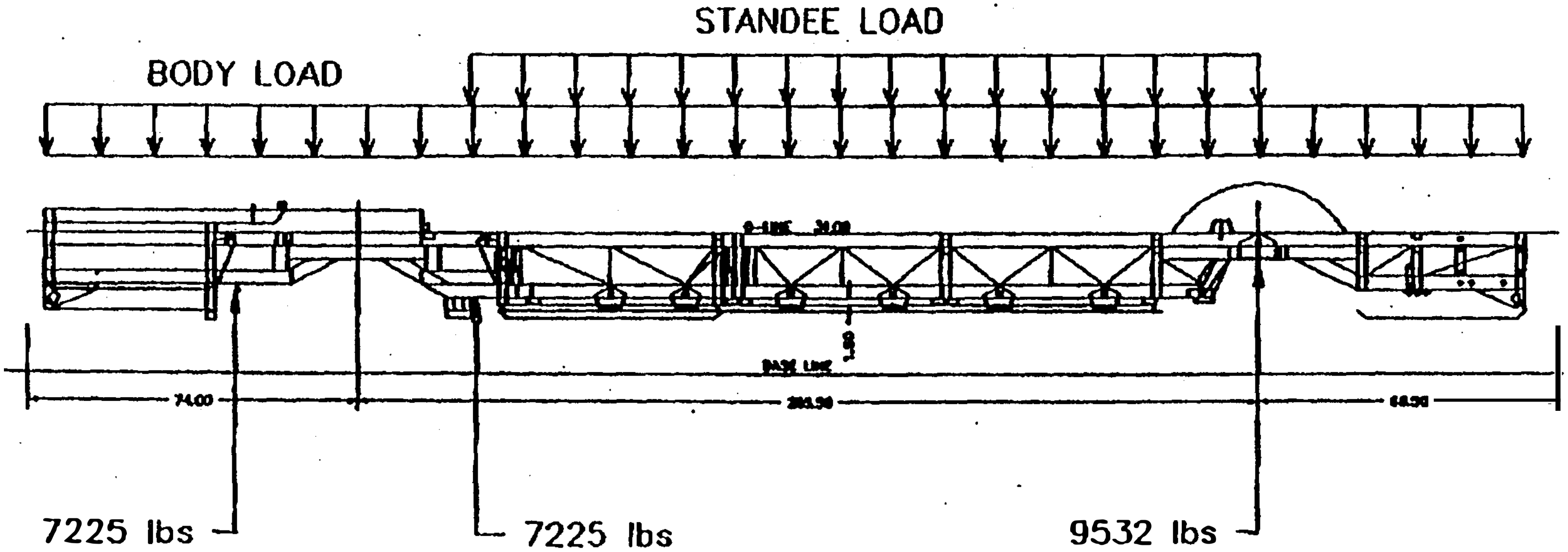
68.30
VEHICLE CENTER LINE
REAR AXLE
FRONT AXLE
92.0M12210 BODY STRUCTURE
CHANGED B DEC.03.92

figure 1.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BODY LOAD
BASE LINE
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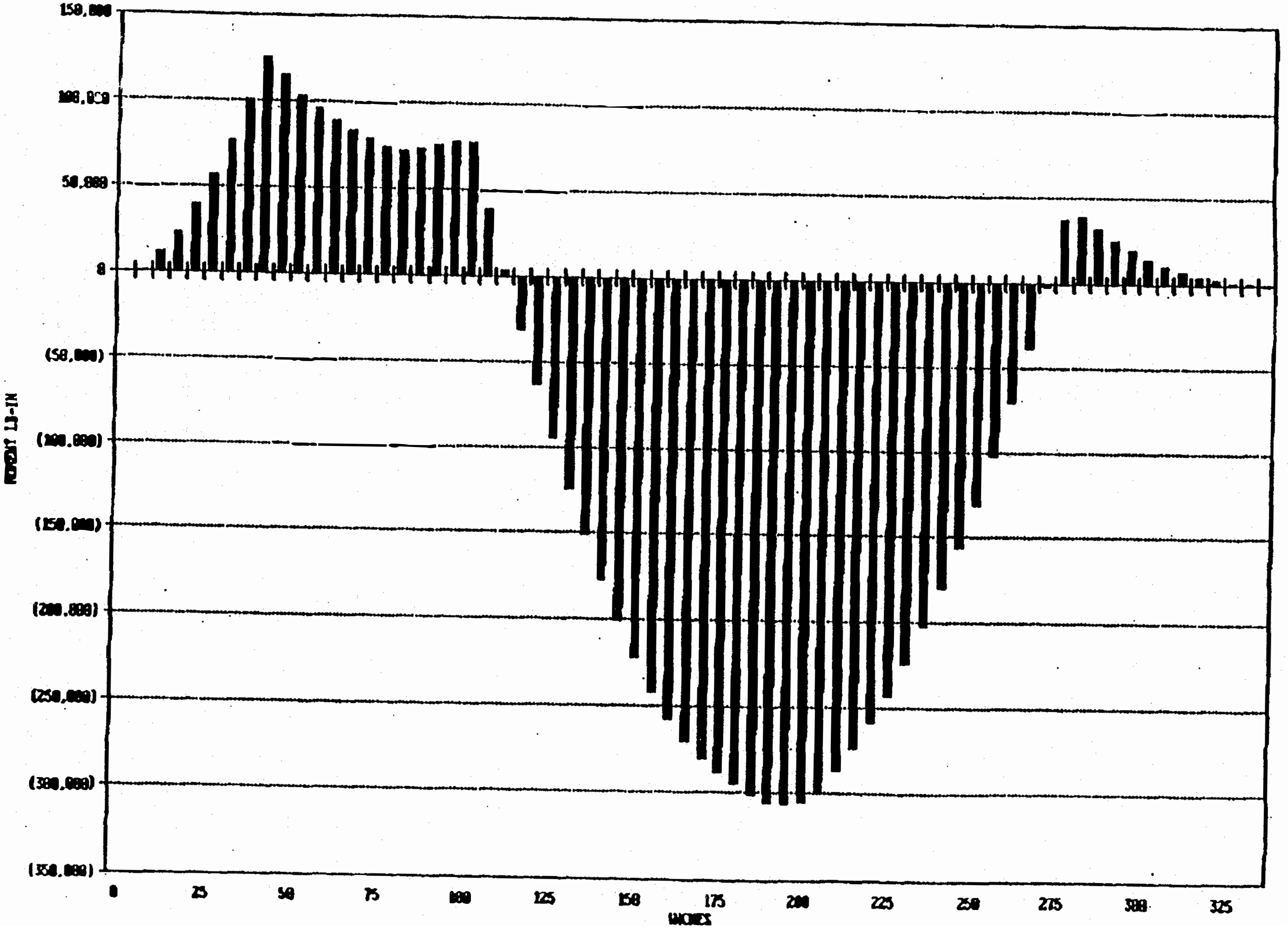
7225 lbs
9532 lbs

TBB CHASSIS BENDING MOMENT DIAGRAM

1 G



APPENDIX C

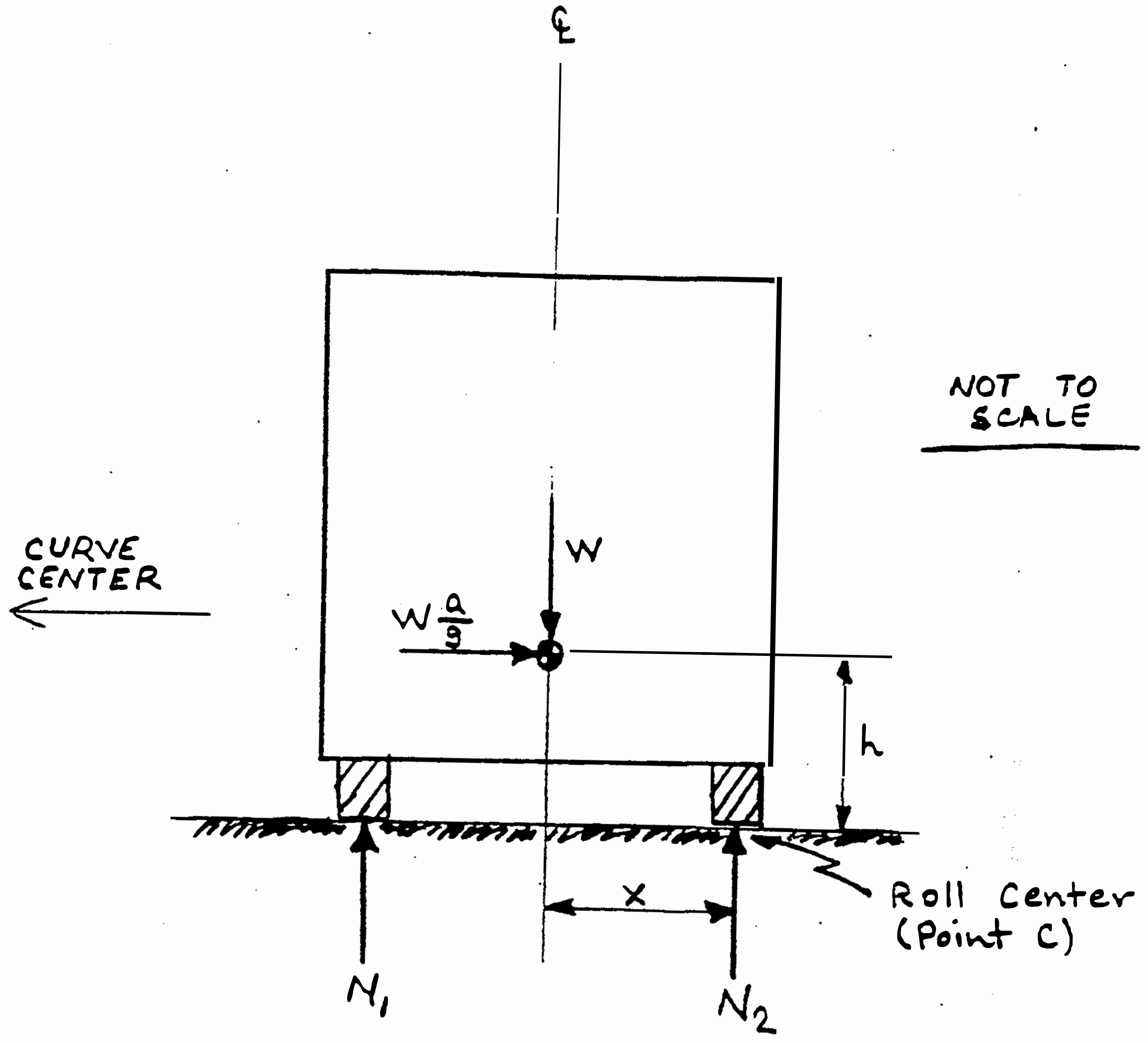
ROLLOVER SPEED CALCULATION

ROLLOVER SPEED CALCULATION

Assumptions

- The assumed TBB weight distribution coresponds to the maximum seated load with no standees. TBB weight (W) is eliminated from the calculation algebraically.
- The height of the center of mass is h = 42.0 inches.
- The center of mass lies on the longitudinal centerline of the TBB at a lateral distance x = 36.3 inches from the centerlines of the rear tire sets on each side of the TBB.
- The center of mass is equivalent to the centroid of rotational inertia about the curve center, and lies at a radius R from the curve center.
- The road is assumed to be level.
- Suspension deflection is not considered.
- Cross wind effects are not considered.
- Rollover occurs when the normal force N_i on the rear tires of one side of the TBB equals zero. The roll center (point C) is assumed to be at ground level on the center line of either rear tire set.
- Rollover speed (in mph) is a function of curve radius (in feet):

  S = 0.682 * SQRT [(32.2*(x/h))*R].



$$\Sigma M_c = 0$$

$$Wx - W\left(\frac{a}{g}\right)h = 0$$

$$a = \frac{s^2}{R}$$

$$x - \left(\frac{s^2}{R}\right)\left(\frac{h}{g}\right) = 0$$

$$s = \sqrt{\frac{1}{h}(Rgx)}$$

WHERE:

s = speed
g = gravity = 32.2 ft/sec^2
a = centrifugal acceleration

FUEL CELL BUS
ROLLOVER SPEED CALCULATION

x= 36.30 in.
h= 42.00 in.

Radius (ft.)	Speed (mph)
25.00	17.99
50.00	25.44
75.00	31.16
100.00	35.98
125.00	40.22
150.00	44.06
175.00	47.59
200.00	50.88
225.00	53.97
250.00	56.89
275.00	59.66
300.00	62.32
325.00	64.86
350.00	67.31
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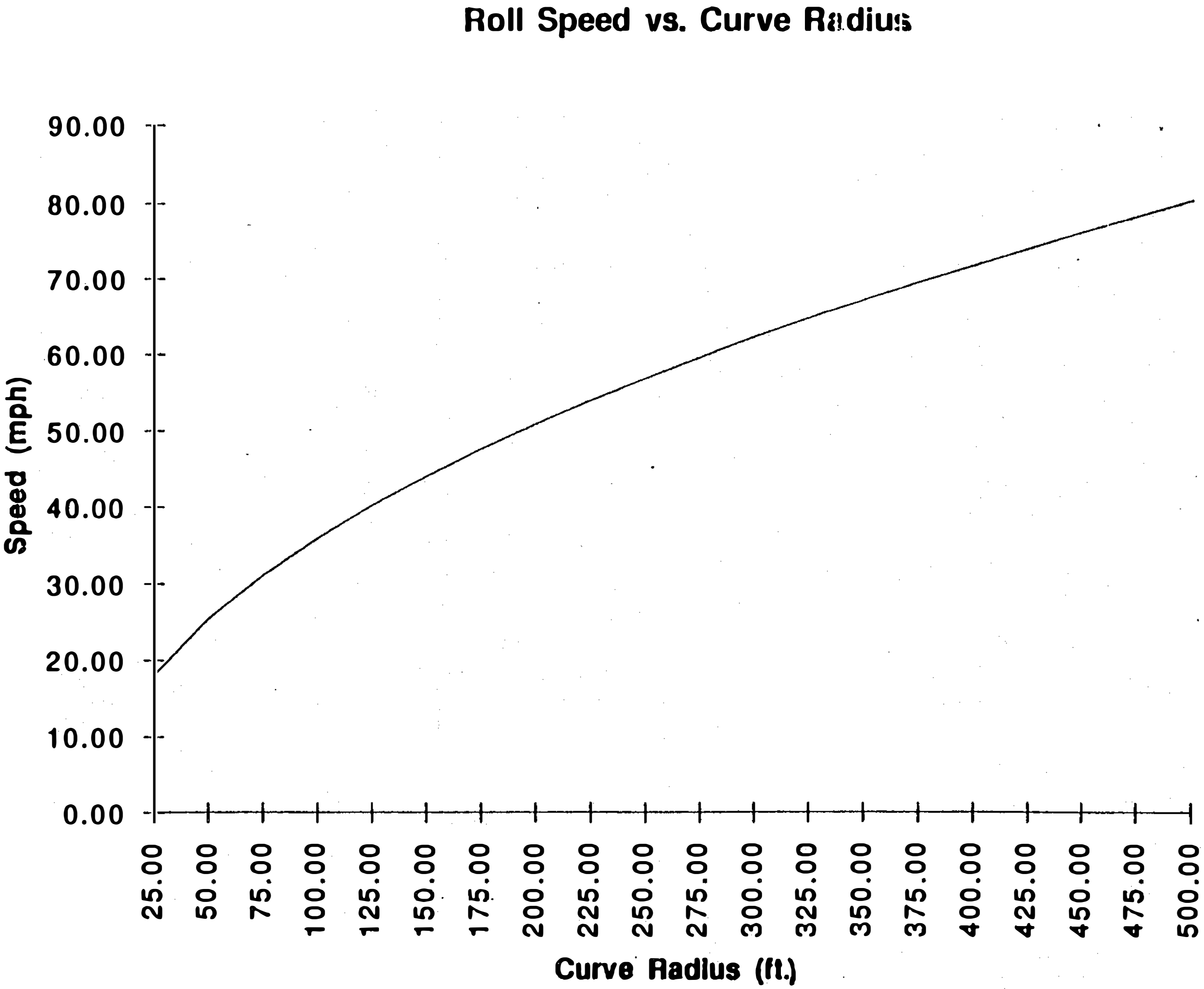
450.00	76.32
475.00	78.41
500.00	80.45



$$S = 0.682\sqrt{[32.2(x/h)]R}$$

Appendix D

Recommendations for Safe Handling and Storage of Methanol

RECOMMENDATIONS FOR THE SAFE HANDLING AND STORAGE OF METHANOL

- Store and handle methanol in totally enclosed equipment where possible, or in systems designed to avoid human contact. If contact cannot be avoided, personnel must wear proper personal protective equipment.

- Methanol is a flammable liquid and should be stored and used in areas protected from flames, sparks and excessive heat.

- Storage tanks and all other equipment should be electrically grounded.

- Tank vents must be equipped with suitable flame arresters. Use of inert gas blankets on tanks should be considered. Fill pipes must extend to within 6 inches (15.2 centimeters) of bottom of the tank.

- Electrical equipment wiring and fixtures must meet the requirements of the National Electrical Code, Article 500. The Hazard Classification for Methanol is Class I, Div. 1 or 2, Group D.

- Vents and pressure relief devices must be designed to handle pressures and volumes of vapor that could be expected in emergency fire conditions.

- The process and storage tank vents should be located so that hazardous vapors given off during fires or emergency conditions will not harm personnel or increase the fire hazard.

- Dikes, waste drains and collection facilities must be provided to contain possible spills or leaks during unloading and other transfers. Methanol spills, leaks and rinsings must be safely collected for later disposal or recovery.

- The storage and process layout must include provisions for more than one escape route in the event of fire, explosion or release of toxic vapors or liquid methanol.

- The following safety facilities should be provided: readily accessible safety showers, fire extinguishers and other fire fighting equipment, water hydrants or hoses with spray nozzles for flushing and other emergency equipment such as chemical-proof suits and respiratory apparatus.

- In addition to engineering controls, thorough operator training, written operating instructions, safety rules, check lists, regular inspection, work permit and flame permit procedures are required to assure safe operation.

Source: DuPont, "Methanol," p. 7.

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13. ABSTRACT *(Maximum 200 words)*

This study assesses the environmental, health, and safety issues that may affect the commercialization of the phosphoric acid fuel cell (PAFC) bus. The study focuses on safety but also reviews relevant health concerns and discusses environmental issues related to the hazardous constituents in the PAFC bus' surge battery and related to regulated air emissions produced during operation. The report identifies some potential health and safety hazards of the PAFC bus subsystem, including phosphoric acid, mineral oil, hydrogen gas, methanol, lithium/potassium hydroxide, cadmium, nickel, high-power batteries, and high-temperature exhaust. It also lists design features that minimize risks from these hazards. Study results indicate that the PAFC bus appears to be at least as safe as a diesel bus and that in-use environmental impacts of a PAFC bus are insignificant compared to those of a diesel bus.

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