DOE/NV/10650-71

**RESEARCH, DEVELOPMENT AND
DEMONSTRATION OF A FUEL CELL/
BATTERY-POWERED BUS SYSTEM
PHASE I**

Contract DOE-AC08-87NV10650

February 28, 1990

Prepared by

**BOOZ, ALLEN & HAMILTON, INC.
Transportation Consulting Division
4430 East West Highway
Bethesda, Maryland 20814**

Prepared for

**Manager, Electric and Hybrid Vehicle R&D
Electric and Hybrid Propulsion Division
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585**

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MASTER

**RESEARCH, DEVELOPMENT AND DEMONSTRATION
OF A FUEL CELL/BATTERY POWERED BUS SYSTEM**

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FINAL REPORT

February 28, 1990

Prepared by:

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I. INTRODUCTION

1. OBJECTIVES

This report describes the findings of the first phase of a program for research, development and demonstration of a fuel cell/battery-powered bus system. The work was performed by Booz, Allen & Hamilton, Inc. and its subcontractors: Engelhard Corporation, Fuji Electric Company, Pentastar Electronics, Inc., and Eagle-Picher Corporation.

The purpose of the Phase I effort was to demonstrate the feasibility of the fuel cell/battery system for powering a small bus (under 30 ft or 9 m) on an urban bus route. A brassboard powerplant was specified, designed, fabricated, and tested to demonstrate feasibility in the laboratory. The proof-of-concept bus, with a powerplant scaled-up from the brassboard, will be demonstrated under Phase II.

The objectives of the Phase I project were:

- (1) Assess the power and energy requirements for the standard DOT/UMTA Transit Bus Cycle and the Georgetown University Transportation Society (GUTS) Arlington Loop, and the power and energy requirements for the standard bus accessories including air conditioning,
- (2) Determine the trade-offs necessary to develop a powerplant based on current technology liquid-cooled phosphoric acid fuel cells (PAFCs) and currently available batteries,
- (3) Develop specifications for the powerplant, its support subsystems, the powertrain, and the bus,
- (4) Perform an economic analysis to determine its cost competitiveness with diesel and methanol-ICE powered buses,
- (5) Assemble and test a brassboard powerplant in the laboratory, and
- (6) Develop recommendations for a fuel cell/battery powered bus system for a small bus for Phase II.

All of the objectives were achieved.

2. APPROACH

Phase I project activities were divided into four tasks and subdivided into subtasks and work elements as shown in Exhibit I-1. The activities within each task are described next.

EXHIBIT I-1

Work Breakdown Structure

<u>Task No.</u>	<u>Subtask/Reporting Element</u>
1.0 PROJECT MANAGEMENT	1.1 Project Management Plan 1.2 Monthly Reporting 1.3 Project Reviews
2.0 SYSTEMS CONCEPTUAL DEFINITIONS	2.1 Assess Bus Performance Requirements 2.2 Develop Subsystem Specifications Fuel Cell/Battery Powerplant Specifications Powertrain Specifications Accessory Specifications 2.3 Develop Preliminary Bus Layout/Concept 2.4 Assess Economic Feasibility 2.5 Conceptual Design Report
3.0 TRADE-OFF ANALYSIS AND PERFORMANCE SPECIFICATIONS	3.1 Review Performance of Available Subsystems Fuel Cell Battery Powertrain Components Auxiliary Support Components 3.2 Develop Fuel Cell/Batter Bus System Model Performance Simulation Model Trade-off Model 3.3 Trade-off Analysis Bus Performance Trade-offs Brassboard Size Trade-offs 3.4 Develop Brassboard Component Specifications Fuel Cell Battery Powertrain Control Subsystem Powertrain Power Absorption Unit 3.5 Trade-off Analysis Report
4.0 FUEL CELL/BATTERY BRASS-BOARD DEVELOPMENT AND TESTING	4.1 System Integration 4.2 Procure and Verify Brassboard Components Fuel Cell Battery Powertrain Controls Powertrain 4.3 Prepare Brassboard Test Plan Safety Plan Simulate Tests Submit Test Plan 4.4 Prepare Brassboard Test Facility 4.5 Assemble Brassboard Assemble Subsystems and Components Conduct Pretest Safety Checks 4.6 Conduct Brassboard Tests Brassboard Initial Performance Tests Analysis Performance Refine Simulation Model Refine Test Parameters Conduct Proof-of-Feasibility Tests Analyze Test Results 4.7 Phase I Proof-of-Feasibility Report 4.8 Deliver Brassboard System to DOE

Task 1.0: Project Management

This task involves overall control of project activities, budget and schedules. Upon award of the contract, a Project Management Plan was prepared to define the project management structure, each task activity, and the budgetary estimates. The report was submitted to DOE on January 8, 1988. Upon approval by the Project Management Team (Argonne National Laboratory and Georgetown University), this plan became the guiding document for conducting all activities related to the contract. The Plan was revised and reapproved at the beginning of the second year of the contract.

Informal technical progress reviews were held at periodic intervals, generally quarterly, with the Project Management Team at Argonne National Laboratory. In addition, formal project reviews were held at each contractor and subcontractor sites; an Annual Review was held at Georgetown University in August 1988, and a special presentation was made to the Technical Advisory (ad hoc) Panel in July 1989.

Task 2.0: Systems Conceptual Definitions

This task laid the foundation for the selection and design of the components for the bus, which in turn led to the specification, design, and fabrication of the brassboard components. The end product of this task was the Conceptual Design Report, which gave preliminary specifications for a baseline bus prior to trade-offs for optimization. The Conceptual Design Report was submitted in November 1988.

Task 3.0 Trade-Off Analysis and Performance Specifications:

This task reviewed the state-of-the-art fuel cell technology, batteries and powertrain components for their availability, performance and suitability for the bus application. An EV simulation model was modified for the hybrid fuel cell/battery powerplant and the INDY and GUTS drive cycles. This model was used to conduct performance and weight trade-offs to develop the specifications for all the bus components. The results of the analysis and the recommended specifications were submitted to DOE in a "Trade- Off Analysis Report" in May 1989.

Using the bus specifications and projected costs and performance in the 1995-2000 timeframe, life cycle costs for fuel cell/battery-powered buses were compared with those of diesel and methanol-ICE buses. The findings were submitted to DOE/UMTA in a report: "Economic Analysis Report" in July 1989.

Task 4.0: Fuel Cell/Battery Brassboard Development and Testing

This task included the procurement and verification of the major brassboard subsystems: fuel cell, battery and power train, and their assembly in a test facility at PEI. Booz, Allen & Hamilton, as the system integration contractor, developed the specifications for the brassboard components, coordinated the preparation of the test plans and schedules, and analyzed the test results. The final report is the culmination of the analysis and findings of the proof-of-feasibility tests performed under this task.

3. SCHEDULE

Exhibit I-2 shows the project schedule. Inevitably, there were unexpected problems which did result in delays. However, in retrospect, the original schedule for completion of the Phase I by September 29, 1989 was very optimistic. The original time allotted for testing was found to be inadequate. Most of the delays occurred during the testing program.

The fuel cell subsystem tests encountered delays due to the conservative design of the automatic emergency shutdown software, which was designed to shut off the subsystem in case of any abnormal temperatures or pressures. Each time the emergency shutdown occurred, the cause of the shutdown was carefully analyzed and corrected.

The lead-acid SLI battery modules supplied by the manufacturer did not meet the manufacturer's specifications. Hence time was lost in remeasuring the capacities, power densities and voltage-current relationships for several modules. The good power characteristics of the battery permitted high currents to be drawn from the battery with small voltage losses; however, its extremely stiff voltage-current characteristics presented problems in calibration of state-of-charge measurement software.

Once these problems were overcome, the testing proceeded flawlessly, and the brassboard performed as projected. The results show conformance with simulation results, thereby confirming proof-of-feasibility.

RESEARCH, DEVELOPMENT & DEMONSTRATION OF A FUEL CELL/BATTERY POWERED BUS SYSTEM
 PHASE I- PROOF-OF-FEASIBILITY OF FUEL CELL/BATTERY SUBSYSTEM

EXHIBIT I-2
 Project Schedule

		1989												1990											
Task/Subt	Reporting Element	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
1.0	PROJECT MANAGEMENT							1a	1b			1a		1a											
1.1	Project Management Plan	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1.2	Monthly Reporting	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1.3	Project Reviews	3		4					3		4			4			3			4	4	3		x	x
		x		x					x		x			x			*	x		x	x	x			
2.0	SYSTEMS CONCEPTUAL DEFINITIONS																								
2.1	Assess Bus Performance Requirements				6	6																			
2.2	Develop Subsystem Specifications	====	====	====	==*	==x																			
2.3	Develop Prelimnry Bus Layout/Concept		====	====	====	==x																			
2.4	Assess Economic Feasibility			====	==*	==	----	----	====	----	====	8a	====	8n	====	====	8b	8b							
2.5	Conceptual Design Report		====	==x	====	====	==x					==x	====	==x	====	====	==*	=x							
3.0	TRADE-OFF ANALYSIS AND PERFORMANCE SPECIFICATIONS		10																						
3.1	Review Available Subsystems	====	==x																						
3.2	Develop FC/Battery Bus System Model	====	====	==*	==x																				
3.3	Conduct Trade-off Analysis			====	==*	====	====	====	==x																
3.5	Trade-off Analysis Report						----	====	==*	==*	==x	----	----	14b	14n	====	==*	=x							

EXHIBIT I-2 (Continued) Project Schedule

RESEARCH, DEVELOPMENT & DEMONSTRATION OF A FUEL CELL/BATTERY POWERED BUS SYSTEM
PHASE I- PROOF-OF-FEASIBILITY OF FUEL CELL/BATTERY SUBSYSTEM

		1988												1989												1990											
Task/Subt	Reporting Element	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb												
4.0	FUEL CELL/BATTERY BRASSBOARD DEVELOPMENT & TESTING			15	16				13							18n		19			19n		25		25n												
4.1	System Integration	====	==x=	==x=	====	==*	====	==x=	====	====	====	====	====	====	==x=	==*	==x=	====	==x=	====	==x=	====	====	====	====												
	Brassboard Component Specs		--	====	====	====	====	====	----	----	----	----	----	====x	==*	=x																					
4.2	Procure, Verify Brassboard Components												17	17a																							
	a. Fuel Cell																																				
	- Rough Layout			====	====																																
	- Detail Design				==	====	====	====	====	====	=																										
	- Order Materials/Parts/Components						--	----	====	====x			20																								
	- Fabrication									====	====	====	====x																								
	- Pretest												====	==																							
	- Final Assembly													==	====	18n																					
	- Verification Tests														----	==*	====x		----	=x																	
	- Shipment to Chrysler																																				
	b. Battery																																				
	- Procurement																21																				
	- Installation and Pretest																----	==*	====	==x																	
																		----	==*	====	==x																
	c. Powertrain (incl Absorption Unit)																																				
	- Specification and Design												====	----	==																						
	- Parts Orders/Assembly														==	----	----				21b																
	- Powertrain Performance Checkout																----	==*			====x		21c														
																					----	==*															
4.3	Prepare Brassboard Test Plan																																				
	- Safety Considerations												====				22a	22b					==x														
	- Test Planning															----	====	=x=	==x=	====	----	==*	==x	22c													
4.4	Prepare Brassboard Test Facility																																				
4.5	Assemble Brassboard																																				
	- Assemble Subsystems, Components																																				
4.6	Conduct Brassboard Tests																																				
	Acceptance Tests (Ph 1)																																				
	Performance Tests (Ph 2)																==	==x				19n															
	Proof-of Feasibility Tests (Ph 3)																				====	====	==*	24													
	Analysis of Test Results																				====	====	----	==*	==x												
																						====	====	====	====	==x											
4.7	Phase I- Proof-of-Feasibility Report																					----	==*	====	====	25n											
4.8	Brassboard System Delivery																									26	*										

EXHIBIT I-2 Project Schedule

RESEARCH, DEVELOPMENT & DEMONSTRATION OF A FUEL CELL/BATTERY POWERED BUS SYSTEM
PHASE I- PROOF-OF-FEASIBILITY OF FUEL CELL/BATTERY SUBSYSTEM
Project Schedule

Symbols

- * Milestone (Planned)
- x Milestone (Completed)
- Timeline (Planned)
- ===== Timeline (Accomplished)

Key to milestones

- 1a. Submit draft Project Management Plan (PMP)
- 1b. DOE approval of PMP
2. Monthly report (technical and management)
3. Formal project review
4. Informal project review
5. Complete assessment of bus power requirements
6. Complete initial performance specifications
7. Finalize bus layout
8. Complete economic feasibility assessment
- 8a. Submit Economic Feasibility Summary
- 8n. Submit Draft Economic Analysis Report (new date)
- 8b. Submit Revised Economic Analysis Report
- 9a. Submit draft Conceptual Design Report
- 9b. DOE approval of Conceptual Design Report
10. Complete review of available subsystems
11. Complete development of simulation model
12. Complete trade-off analysis
13. Specify all brassboard components
- 14a. Submit draft Trade-off Analysis Report
- 14b. DOE comments on Trade-off Analysis Report
- 14n. Submit revised final Trade-off Anal Report
15. Freeze fuel cell/battery interface chopper design
16. Freeze brassboard fuel cell power rating
17. Freeze brassboard battery type and rating
- 17a. Submit Brassboard Component Specifications
- 18n. Fuel Cell Subsystem Acceptance Tests
19. Complete Fuel Cell subsystem Acceptance
- 19n. Complete brassboard integration (new date)
20. Complete fabrication of fuel cell
21. Complete battery procurement
- 21a. Complete pretest of battery at Pentastar
- 21b. Complete controller assembly
- 21c. Complete powertrain checkout at Pentastar (Cancelled)
- 22a. Present Preliminary Test Plan
- 22b. Submit Final Test Plan
- 22c. Complete Proof-of-Feasibility Test Procedure
- 23a. Complete fuel cell/battery assembly
24. Complete Test Ph 3
25. Submit Phase I--Proof of Feasibility Report (Draft)
- 25n. Submit Phase I--Proof of Feasibility Report (Final)
26. Deliver Brassboard (Date Undetermined)

II. BUS SPECIFICATION DEVELOPMENT

1. BASELINE BUS DESIGN

Initial conceptualization for sizing, layout, and performance provided the starting point for performance and design trade-offs for the fuel cell/battery-powered bus system. The major constraints on the bus design are:

- o Bus size limitations
- o Powerplant size and weight
- o Bus operational requirements.

(1) Bus Size Limitations

The size of the bus body is limited to a maximum of 30 feet in length and 8 feet in width to provide the needed maneuverability over the Georgetown University Transportation Society (GUTS) Arlington Loop. The floor of the bus is to be a maximum of 34 inches above the road. Also, the bus should accommodate 20 seated passengers. In order to maintain the weight balance on the axles as close to that for a diesel bus, the fuel cell should be located just behind the rear axle; and the battery should be located just rear to or over the front axle.

(2) Bus Powerplant Size and Weight

The fuel cell and battery together constitute the bus powerplant. The fuel cell provides the average power and a majority of the energy requirements. The rechargeable battery supplies the peak power demands for accelerating the vehicle. The battery also supplies the total energy and power requirements during the fuel cell start-up period. The combined volume of the fuel cell and the battery would be expected to exceed the volume of the diesel engine that they replace. The volume and weight of the powerplant cannot be estimated without knowledge of the bus power and energy requirements. The energy and power requirements imposed by the cycles are impacted by the weight of the powerplant. The size of the powerplant is limited by the available space in the bus. Regenerative braking would be employed to recharge the battery and thereby minimize the energy requirements from, and the weight of, the fuel cell.

(3) Bus Operational Requirements

The major bus operational requirement is operation over the DOT/UMTA Transit Coach Operating Duty Cycle (TCDC) as defined in the UMTA White Book. In addition, bus operation was verified over an urban route known as the Indianapolis (INDY) cycle, and over the GUTS Arlington Loop. The latter route includes significant upgrades and downgrades. The three route missions are summarized in Exhibit II-1. Bus power and energy requirements were estimated through a simulation model and verified by means of the brassboard tests. The cycles are defined in Appendix A.

EXHIBIT II-1
Route Missions for Fuel Cell/Battery Bus

Route	TCDC	INDY	GUTS
Route Length, mi (km)	14.0 (22.4)	14.0 (22.4)	8.2 (13.1)
Stops/Mile /mi (/km)	2.0 (1.3)	4.0 (2.5)	4.0 (2.5)
Max. Speed, mi/h (km/h)	55.0 (88.0)	40.0 (64.0)	35.0 (56.0)
Loops/Day	11	11	17
Approx. Time/Loop (s)	2830	3157	3600
Range/Day, mi (km)	154.0 (246.4)	154.0 (246.4)	139.4 (223.0)

(4) Baseline Bus Configuration

The above requirements resulted in the conceptualization of a 26.7-foot (8.14 m) long baseline bus powered by a 60 kW rated fuel cell operating in conjunction with a 170 Ah NIF-170 nickel/iron battery. Liquid-cooled phosphoric acid fuel cell technology developed by Engelhard Corporation of Edison, New Jersey was selected as the appropriate fuel cell technology for several reasons:

- o Liquid cooling of the stack provides more uniform temperatures, resulting in improved stack life and performance, compared to air-cooled stacks,
- o The high coolant temperature can be used for preheating and vaporizing the methanol prior to reforming, thus increasing the efficiency of the fuel cell,
- o Parasitic losses from auxiliary pumps, etc. used in liquid-cooled systems would be lower than for air-handling equipment required for air-cooled systems,
- o Bus passenger heating would be simplified because standard transit bus liquid-to-air heat exchangers can be utilized, and

- o The high quality waste heat (at about 350° F) can be utilized for energy-efficient absorption air-conditioning systems in the future.

The requirement for utilizing existing drive train technology was met by assuming the use of two two Chrysler TEVan motor/ controllers. The specifications for the Baseline Fuel Cell/Battery Bus are shown in Exhibit II-2.

EXHIBIT II-2 Baseline Bus Specification

Type	Transit, forward control with powerplant in rear
Length	26.7 ft (8.14m)
Width	90 in (2,286 mm)
Height	78 in (1,981 mm) interior 114 in (2,896 mm) overall
Floor Height	34 in (610 mm), allowing component placement underneath
Seating	20 passengers
Weight(gross)	26,000 lb (11.8 Tonnes metric)
Powerplant	60 kW liquid-cooled PAFC - 3,753 lb (1,700 kg) 175 AH (C/2) Ni/Fe Battery - 1,950 lb (884 kg)
Powertrain	DC Motors(2): 70 peak HP (52.4 kW) 100 ft lb (74 N.m) peak torque 8000 rpm max shaft speed Transmission: 2-speed automatic, 2:1 reduction Rear Axle: 3.44 : 1

In arriving at the specifications shown in Exhibit II-2, it was assumed that the bus would have power steering and air-conditioning. The total accessory power requirements were estimated at 15.5 kW average, as shown in Exhibit II-3.

EXHIBIT II-3. Accessory Load Inputs to Baseline Specifications

ACCESSORY	AVG. POWER (WATTS)	PEAK POWER (WATTS)
Electrical, continuous	300	300
exterior lights	245	245
intermittent	119	700
Climate Control, less a/c	277	339
Air conditioning	8,213	12,423
Compressed air	5,396	6,237
Power Steering	991	6,237
TOTAL	15,500	26,500

(4) Baseline Bus Performance

Exhibit II-4 shows the acceleration performance on level grade for the baseline fuel cell/battery-powered bus, and compares it with standard and low power diesel transit bus acceleration specifications. The baseline fuel cell/battery-powered bus performance thus exceeded standard and low diesel powerplant diesel bus acceleration performance. Preliminary simulation results, shown in Exhibit II-5, revealed that an average fuel cell power of 55 kW, together with the NIF-170 battery, was acceptable in meeting both the GUTS Arlington Loop and INDY transit cycle mission requirements. A smaller fuel cell than the 60 kW fuel cell can therefore be used to provide additional economies in power plant and bus weight and cost.

EXHIBIT II-4
Baseline Bus Acceleration Performance

EXHIBIT II-5
Baseline Bus Route Performance

	INDY CYCLE	GUTS ROUTE
<u>BUS TRACTION</u>		
Energy, kWh/mi (kWh/km)	1.8 (1.12)	2.0 (1.25)
Peak Power, kW	108.3	108.3
Average Power, kW	34.0	33.0
<u>60 KW FUEL CELL</u>		
Energy, kW	46.1	34.0
Average Power, kW	53.4	55.1
<u>170 Ah NI/FE BATTERY</u>		
Energy in, kWh	21.7	17.9
Energy out, kWh	12.8	10.4
Peak Power, kW	66.9	67.9

2. BUS DESIGN TRADE-OFFS

The baseline bus simulated performance exceeds standard diesel bus performance. However, the weight and volume of the baseline fuel cell/battery powerplant exceeds the weight and volume of the standard diesel powerplant. Thus, it would be logical to consider the smallest fuel cell and battery powerplant that would still deliver the required traction and accessory power for acceptable performance. This section presents the trade-offs and analysis leading up to the specification of the fuel cell, battery and drivetrain for the Phase I bus system.

(1) Bus System Design Considerations

The major considerations in bus system design are:

- o Availability of components-- maturity of technology, availability of reliable test data, models, etc. The Phase I bus is required to use only current technology, readily available components.
- o Performance-- acceleration, deceleration, maximum speed, gradability, dynamic handling, and range should equal standard diesel bus performance for INDY and GUTS routes. Further, the bus should meet all applicable future emissions standards.

- o Cost-- component, subsystem and system cost; operating costs; and maintenance costs for projected market size in the 1995-2000 time frame should be reasonably close to the costs for comparable alternative fuel buses.
- o Packaging-- volume and weight constraints and ease of installation, removal, and maintenance should be considered for the small 26.7 ft (8.14 m) bus, preferably with a low floor to enable the use of a ramp for handicapped passenger access.
- o Operational factors-- safety, reliability, aging, drivability, and industry acceptance should be considered at a very early stage of the design.

For the Phase I bus, the major consideration is the availability of the components in the 1990-1992 timeframe. It is clear that performance and cost are major considerations. Component cost, weight and volume need to be minimized; while performance needs to be adequate. Packaging and safety issues need to be addressed in conjunction with the above trade-offs.

(2) Initial Selection of Components

Fuel Cell Subsystem

The liquid-cooled Phosphoric Acid Fuel Cell (PAFC) is in general more compact and allows better flexibility in ducting and layout than the air-cooled PAFC. Engelhard Corporation and Fuji Electric have jointly developed a liquid-cooled PAFC/ surge battery system for a forklift truck. After completing the trade-offs, Engelhard Corporation made a decision to withdraw from further development of the technology for fork lift and bus applications. Fuji Electric then undertook the development of the liquid-cooled fuel cell subsystem for Phase I.

The fuel cell subsystem includes the stack, the reformer, an internal controller, and a step-up chopper. Auxiliary components such as air blowers and fluid pumps for proper operation of the fuel cell subsystem can be powered from the fuel cell. (For the Brassboard system, the auxiliaries will be powered from the mains supply to enable accurate monitoring of their operation). A flow schematic of the Brassboard fuel cell subsystem is shown in Exhibit II-6.

EXHIBIT II-6
Schematic of Liquid-Cooled Fuel Cell Subsystem

To further ensure the suitability of the fuel cell for bus application in the near term, the stack size (active area) and power density were carefully analyzed. A short stack height has obvious advantages in transportation applications where vibration is an important consideration. A tall stack or multiple stacks also have problems related to uneven distribution of the hydrogen gas to each cell. The fork lift truck fuel cell stack had an active area of only 650 cm², which would have resulted in a 2.3 m stack height with two 30kW stacks placed side by side. The standard stationary power fuel cell stack had an active area of 3825 cm². Even at a lower cell performance level, this stack would be only 84 cm high, but would weigh considerably more than the fork lift stack. Finally, an intermediate area stack (2000 cm² active area) that provided the advantage of a reasonably short height and very low weight penalty was selected. The major parameters of the three stack designs are shown in Exhibit II-7.

Further advances in stack technology appear feasible. Fuji Electric projects that in the time frame of Phase II, cell performance of 0.66V @ 240 mA/cm² will be feasible. When commercialization takes place, cell performance of 0.66V @ 300 mA/cm² may be achieved. However, for the present analysis, the conservative performance of 0.60V @ 240 mA/cm² is assumed.

EXHIBIT II-7
Stack Size Selection Trade-offs
60 kW Rated Output

STACK DESIGN	Fork Lift	Stationary Power	Bus
CELL PERFORMANCE	**	*	**
ACTIVE AREA (cm ²)	650	3825	2000
NUMBER OF STACKS	2	2	2
RATED VOLTAGE (V)	384.6	97.2	124.8
RATED CURRENT (A)	156	612	480
WEIGHT (kg)	920	2350	954
HEIGHT (m)	2.3	0.84	0.9

* 0.6V - 160 mA/cm²
 ** 0.6V - 240 mA/cm²

Battery Subsystem

For hybrid applications where the battery is required mainly to supply the power surges for acceleration and occasional grade climbing, the battery must exhibit high power-to-weight ratio. In order to provide the high power pulses without unacceptable losses, the internal impedance of the battery should be very low. The energy density of the battery is not critical, but it should provide sufficient storage capability to maintain its state-of-charge at an appropriate level by the end of the route.

Several near-term batteries can be used for the present application. Nickel/iron, sodium/sulphur and zinc/bromine batteries and state-of-the-art lead-acid batteries were considered. Sodium/sulphur and zinc/bromine batteries are in a relatively early stage of development and their availability is very uncertain. For the sodium/sulphur battery, the sulphur electrode has to be maintained at a temperatures of 350° C because it is susceptible to damage under freeze-thaw conditions. The zinc/bromine battery cannot provide the required surge power due to its high internal impedance. Thus only nickel/iron and lead-acid batteries were considered further.

The nickel/iron battery was selected for the baseline bus because it offers high peak power capabilities, exhibits long life under deep discharge conditions, and can accept high recharge currents available from regenerative brakes. However, its cost is high and its availability in the time frame of Phase I testing was unlikely.

Engelhard Corporation had successfully used a standard lead-acid SLI battery as the surge battery for their fork lift truck application. This type of battery is available commercially and offers high peak power capabilities at only 10 percent of the present cost of nickel/iron batteries. If the battery is kept in a charged condition, its life may be adequate for the bus application. A tubular plate lead-acid battery with deep discharge capabilities was also selected for detailed analysis. The specifications for the three batteries selected for further trade-offs are shown in Exhibit II-8.

Powertrain

The powertrain for the bus consists of an electric motor, its controller, and a transmission. The DC shunt motor was selected because of the proven controller technology for these motors for traction applications. AC motors and controllers are under development and they offer superior power capabilities per unit weight, better control over regeneration, as well as lower cost for motors. They should be considered for future bus systems.

EXHIBIT II-8
Initial Battery Selection Parameters

TYPE	Nickel/iron	Lead-acid	
MANUFACTURER	Eagle-Picher	Exide	Chloride
MODEL No.	NIF-170	HP31E	3ET205
NOMINAL VOLTAGE	180	204	204
SYSTEM WT, lb(kg)	1,950(884)	1,250(567)	2,500(1,134)
CAPACITY, Ah	175 (C/2)	76 (C/2)	186 (C/3)

Two options were evaluated. One option was an air-cooled GE traction motor and controller package developed by Soleq. The other option was a compact, high-speed, oil cooled GE motor and high frequency controller developed by Pentastar Electronics Inc (PEI) for the TEVan application. A third option, to develop a new high-speed motor specifically for the bus, was also considered but discarded due to the high developmental costs for a completely new motor and controller.

A comparison of the physical and operating characteristics and costs of the two powertrains is shown in Exhibit II-9. The advantage of the TEVan powertrain is its lighter weight and projected lower cost in high volume production. The controller utilizes a high frequency (20 kHz) converter that operates above the audible range. The advantage of the Soleq system is that it will have fewer

EXHIBIT II-9
Comparison of Available Powertrains

	Soleq	TEVan
<u>Motor</u>		
Efficiency	85%	90%
Number Required	1	2
Weight (lb)	1,050	322 (total)
Base Speed (rpm)	900	3,500
Maximum Motor Speed (rpm)	3,500	8,000
Volume (cu. ft.)	5.8	1.47 (total)
Cooling	Air	Oil/Air
Total Cost (1989 \$) High Volume	6,000	3,000
<u>Controller</u>		
Number Required	1	2
Voltage (DC)	128	200
Current	1200 ADC	600 ADC total
Efficiency	98%	97%
Communications	None	In Place
Chopper Frequency (Hz)	1200	20,000
Weight (lb)	600	180 (total)
Volume (cu. ft.)	7.7	6.4 (total)
Total Cost (1989 \$) High Volume	15,000	6,000
<u>Transmission</u>		
Reduction Type	Ratio Change Only	Chain Reduction & Ratio Change
Efficiency Hi/Lo	99/97	97/95
Weight (lb)	120	300
Volume (cu. ft.)	1	2.5
Total Cost (1989 \$) High Volume	2,000 *	2,500

* This cost would be included in the rear axle if a two-speed axle is employed.

parts and will not need a speed reducer chain unit for coupling to a standard transmission. It is a road-proven system and it is readily available. The disadvantage is its bulk and weight.

The TEVan powertrain would constitute a higher risk since the powertrain has not been road proven. Transit authorities are not familiar with and have not had good experience with chain drive arrangements. Thus, since the Soleq powertrain is road-proven and simpler in design it was selected for the Phase II bus system.

(3) Key Performance Trade-Off Parameters

The objective of the performance trade-offs is to develop the fuel cell/battery powerplant specifications. The Phase I bus specifications were developed by an iterative procedure of practical bus design parameters and powerplant size using computer simulation.

The initial evaluation of the baseline bus performance was useful for selecting the key design parameters that influence bus performance. For each design parameter, several realistic values around the baseline design were selected for simulation and trade-offs. The range of trade-off parameters evaluated is shown in Exhibit II-10. In the case of the TEVan powertrain, two motors, each operating at half the peak power indicated, were assumed. The motor power output is varied from 120 kW to 80 kW by setting the limit of the armature current for the TEVan motors between 300 Amps and 200 amps.

EXHIBIT II-10
Performance Trade-off Parameters

FUEL CELL	55, 50, 45 kW
BATTERY TYPE	NIF-170 (Nickel/iron) HP31D (Lead-acid SLI) 3ET205 (Lead-acid deep discharge)
MOTOR POWER OUTPUT	120kW peak 100kW peak 80kW peak
TRANSMISSION	Two-speed : 2:1 low 1:1 high Direct Drive
REGEN CURRENT LIMIT	250, 150, 50, 0 Amps/motor

3. PERFORMANCE PROJECTIONS

The size (net power output) of the fuel cell/ battery subsystem along with key design parameters were evaluated based on peak power requirements, range of battery state-of-charge (SOC), traction energy consumed, and level and grade acceleration performance.

The following sections give an overview of the results of the parametric analyses for optimizing the fuel cell/battery powerplant bus for the GUTS Arlington Loop with verification on the DOT/UMTA INDY driving cycle.

(1) Fuel Cell/Battery Bus Performance Trade-Offs

When the average power available from the fuel cell is reduced, the battery provides the supplemental power, since the peak traction power requirement for a route is relatively fixed. Based on the peak power capabilities of each of the three batteries and the demands of the GUTS Arlington Loop route, a minimum 45 kW rated fuel cell is required. Trade-offs for the bus with a 45 kW fuel cell indicate the following:

Level Grade Performance

With a two-speed transmission the fuel cell bus acceleration performance exceeds the low power as well as standard diesel bus performance on level grade. Whereas, the fuel cell bus with a direct-drive transmission meets the low diesel powerplant performance.

Maximum Grade Performance on GUTS Arlington Loop

For acceptable grade performance on the GUTS Arlington Loop, a two-speed transmission and 120 kW peak traction power (300 amps/motor for the TEVan motor) are required for all three surge batteries, as shown in Exhibit II-11.

To reach a given speed on the 7 percent grade, the fuel cell bus will take about twice as long when the peak power is reduced from 120 to 80 kW.

Maximum Speed Performance on GUTS Arlington Loop

The type of transmission, direct-drive or two-speed, or the traction power available, do not play a major role in the fuel cell bus acceleration performance on the maximum speed segment.

EXHIBIT II-11
Effect of Transmission Type on Acceleration
Up a 7 Percent Grade GUTS Arlington Loop Segment

(2) INDY Cycle Performance

A summary of the simulation results for the INDY cycle is shown in Exhibit II-12. A 50 kW fuel cell bus would require 13 minutes rest time to fully recharge the batteries. A two-speed transmission is not essential for the INDY route.

EXHIBIT II-12
INDY Cycle Performance Summary

Fuel Cell/ Battery Type	Transmission	Armature amps/motor	Fuel Cell		Battery Peak Power, kW	Min SOC	Time (sec)	
			Energy, kWh	Power, kW			Trip	Rest*
60/NIF 170	Two-speed	300	46.1	53.4	66.9	71%	2718	360
60/NIF 170	Two-speed	200	41.7	47.7	35.4	75%	2854	240
50/NIF 170	Two-speed	300	47.1	46.7	76.4	55%	2714	900
50/NIF 170	Direct-drive	300	46.9	46.3	76.4	60%	2855	780
50/HP31E	Direct-drive	300	43.0	46.0	91.4	66%	2835	780
50/3ET205	Direct-drive	300	47.2	46.9	79.7	68%	2899	720

* Time required to return battery to maximum state-of-charge

(3) Battery Power and State-of-Charge Considerations

The influence of the fuel cell rated power on battery minimum and end-of-loop SOC for the three batteries is shown in Exhibit II-13. The lowest SOC reached for the NIF-170 and 3ET205 batteries is 53 and 65 percent with a 45 kW fuel cell. Both are within the acceptable range of these batteries. However, a 50 kW fuel cell is required for the HP-31D battery in order to maintain a maximum 20% variance from 90 percent to 70 percent SOC.

When the motor armature current limit is lowered, the power demands on the battery are lowered. Thus the variance in the SOC can be reduced by lowering the armature current below the maximum limit for the selected motor. This would result in increasing battery life. However, with this lower armature current, the fuel cell bus grade performance would be substantially degraded. Based on these considerations, a 50 kW fuel cell rating and utilization of the full armature current capability of the motor are recommended for the TBB.

EXHIBIT II-13
Fuel Cell Rated Power versus Battery State-of-Charge
(2-speed Transmission)

4. LAYOUT AND WEIGHT BALANCE

This section presents the proposed layout configuration and the overall bus system weight balance for the Test Bed Bus (TBB) to be developed under Phase II. This configuration is based on the performance and size trade-offs described earlier. The brassboard tests discussed in Sections II and III of this report do not alter the basic configuration of the bus, but some revisions in component sizes and weights may be needed as specifications are finalized and component designs get under way.

The bus packaging and weight analysis covers the major components of the fuel cell/battery-powered bus system including the 50 kW fuel cell subsystem, HP-31E surge battery, the drivetrain subsystem, and the standard bus accessory components.

(1) Bus Layout

As a result of the performance trade-off analysis, the size of the fuel cell subsystem for the Test Bed Bus (TBB) was reduced from 60 kW to 50 kW. A single Soleq motor and controller and a two-speed axle are utilized in the drivetrain. The TBB system layout, shown in Exhibits II-14 and II-15, reveals the packaging arrangement of the fuel cell/battery powerplant system in a low floor bus. Placement of the major components in the bus was performed by addressing the following packaging criteria:

- o The components should be placed in such a manner as to minimize or eliminate any modifications to the bus structural members
- o The bus seating capacity should be maximized while retaining the required spacing for proper passenger leg room
- o Components should be placed in an easily accessible location in order to minimize repair and maintenance costs. The bus system layout must result in a favorable weight distribution which meets the axle load rating specification.

(2) Bus Weight Balance

A bus weight distribution analysis was performed to obtain the front and rear weight balance of the fuel cell/battery bus system and to locate the bus center of gravity. The location of the bus center of gravity is an indication of how the loads are distributed between the two axles. Once the center of gravity is located and the rear axle loading is calculated, both axles can be appropriately sized.

II-17

EXHIBIT II-14
Bus Layout, Side View

DIMENSIONS ARE IN INCHES

LEGEND

1. FUEL CELL STACK	8. MOTOR CONTROLLER
2. METHANOL REFORMER	9. DC/DC CONVERTER
3. START-UP BURNER	10. WATER TANK
4. STEP-UP CHOPPER	11. METHANOL TANK
5. VAPORIZER	12. WHEEL CHAIR LIFT
6. BATTERY SUBSYSTEM	13. POWER STEERING ASSEMBLY
7. DC MOTOR	14. AIR CONDITIONING
MOTOR & PUMP ASSEMBLY

II-18

1. FUEL CELL STACK
2. METHANOL REFORMER
3. START-UP BURNER
4. STEP-UP CHOPPER
5. VAPORIZER
6. BATTERY SUBSYSTEM
7. DC MOTOR
8. MOTOR CONTROLLER
9. DC/DC CONVERTER
10. WATER TANK
11. METHANOL TANK
12. WHEEL CHAIR LIFT
13. POWER STEERING ASSEMBLY
14. AIR CONDITIONING
15. MOTOR & PUMP ASSEMBLY

The fuel cell stack and reformer components were placed in close proximity to the rear axle in order to reduce the stresses on the bus body structural members. The major powerplant and accessory component dimensions and weights are listed in Exhibit II-16.

Results of the bus weight balance analysis locate the bus center of gravity 5.6 feet forward of the rear axle and about 1 inch from the bus centerline. The weight on the rear axle was reduced from 70 percent (18,000 pounds) for the baseline bus configuration to 61.7 percent (14,000 pounds), a reduction of 4,000 pounds. This reduced weight is within the load rating specification of the rear axle.

EXHIBIT II-16
Powerplant and Accessory Dimensions and Estimated Weights

	Weight (pounds)	Dimensions L x W x H (inches)
Fuel Cell Stack (includes auxiliaries and piping)	1,685	49.1 x 27.5 x 33.6
Methanol Reformer	441	27.6 DIA x 39.4 H
Start-Up Burner	82	17.8 x 27.2 x 21.5
Step-Up Chopper	265	23.5 x 15.8 x 22.1
Vaporizer	20	22.8 x 5.7 x 8
Start-Up Burner Blower	35	15.5 DIA x 6 W
Reformer Blower	35	15.5 DIA x 6 W
Stack Blower	35	15.5 DIA x 6 W
Fuel Cell Subsystem	2,598	
Battery Tray (LHS)	588	29.2 x 26.8 x 9.5
Battery Tray (RHS)	662	34.4 x 26.2 x 9.5
Battery Subsystem	1,250	
DC Motor	1,050	20 DIA x 40.0 L
Motor Controller	275	37 x 8.2 x 12
DC/DC Converter	100	26 x 7 x 10
Water Tank (1/2 capacity)	225	76.8 x 12 x 12
Methanol Tank (1/2 capacity)	182	76.8 x 12 x 12
Air Tanks (4 total)	100	9.5 DIA x 26.4 L
Power Steering Assembly	100	20 x 6.5 x 12.4
Air Compressor Assembly	150	13.8 x 21.5 x 14
Air Conditioning Motor and Pump Assembly	150	13.8 x 19.3 x 14
Bus Body (approximately)	13,000	
Total Bus Weight (Curb)	19,180	
Passengers (22 @ 150 lbs)	3,300	
Total Bus Weight (GVW)	22,480	

III. FUEL CELL/ BATTERY POWERTRAIN FOR THE TEST-BED BUS

This section presents the development of the specifications for the powertrain components of the fuel cell/battery-powered bus system: the fuel cell subsystem, the surge battery, and the drivetrain subsystem. Major steps in the development of specifications for the powertrain include:

- o Development of a powertrain system concept
- o Development of operating concepts for the major powertrain components
- o Development of specifications for the major powertrain components based on the results of the trade-off analysis.

1. POWERTRAIN SYSTEM CONCEPT

The fuel cell/battery bus powertrain is a hybrid system utilizing the best characteristics of power devices: the fuel cell, and the storage battery. The fuel cell can generate electricity so long as a hydrogen-rich fuel such as methanol is supplied to it. Thus the fuel cell can efficiently convert the electrochemical energy from methanol into electrical energy at a steady rate depending on the rate of supply of methanol. The battery can store a limited amount of electrical energy, either generated by the fuel cell or by an external electrical generator, and discharge the stored energy at a high rate when needed.

In the case of the bus system, the fuel cell should provide the energy for the operating cycle at a constant power level determined by the average power needs for the entire cycle, including the energy needs for passenger comfort and for operating the bus accessories such as power steering, brakes, and lighting. The battery should be designed to provide any additional power needed for short periods above the average power supplied by the fuel cell. For the bus system, this additional power includes the power needed for acceleration and for climbing grades. In addition, the battery should store sufficient energy to power the bus while the fuel cell is inoperative for any reason, including the start-up period.

To meet these requirements, a parallel hybrid powerplant system concept was developed. This concept is illustrated in Exhibit III-1. The major components of the powerplant are:

- o The fuel cell subsystem,
- o The surge battery, and
- o The drivetrain.

EXHIBIT III-1
Bus Powerplant System Concept

2. FUEL CELL SUBSYSTEM

The fuel cell subsystem for the bus is composed of a phosphoric acid fuel cell stack, a methanol steam reformer, a step-up chopper, auxiliary equipment (such as heat exchangers, start-up burner, tanks, pumps, blowers, valves, etc.), and an internal controller that operates these components under suitable predetermined conditions.

(1) Fuel Cell Operation

A flow schematic of the 50 kW subsystem showing its components and operating conditions at full load is shown in Exhibit III-2. As stated in Section II, the liquid-cooled phosphoric acid fuel cell was specified on the basis of initial considerations pertaining to its higher operating efficiencies, compactness of cooling system and heat exchanger components, and its ready adaptability to standard automotive passenger climate control systems. The liquid-cooled fuel cell/battery hybrid system is a proven technology with the demonstration of the forklift truck by Engelhard and Fuji Electric, shown in Exhibit III-3.

Referring to Exhibit III-2, during start-up, methanol is supplied to the start-up burner [B-02] to heat the liquid coolant through the heat exchanger [HX-03]. The liquid coolant is a highly conductive synthetic fluid with a boiling point of 391°C. During the start-up mode, the coolant is actually used to raise the temperature of the stack. The coolant is also circulated through another heat exchanger [HX-01], which is used to preheat and vaporize the methanol-water mixture prior to entering the reformer. Since the fuel cell operates at about 160°C, the coolant loop does not need pressurization.

Once the coolant reaches operating temperature, the reformer burner [B-01] is ignited. A mixture of methanol and water is supplied to the reformer through the mixer [X-01] and the vaporizer [HX-01]. In the reformer, the mixture is heated through the superheater coils [HX-02], and passes over the catalyst bed which reforms it to hydrogen and carbon dioxide through the shift reaction:

The reformer begins supplying hydrogen to the anode of the stack. The oxygen from the air supplied to the cathode reacts with the hydrogen in the catalytic matrix to produce an electrical potential. Typically for the liquid-cooled system, 85 percent of the reformed fuel is oxidized electrochemically in the fuel cell stack; the remaining energy is used at the reformer by recirculating the

EXHIBIT III-2
50 kW Liquid-Cooled Phosphoric Acid Fuel Cell
Flow Schematic and Operating Conditions

01 123 01

EXHIBIT III-3
Prototype Fuel Cell/Battery Hybrid Forklift Truck
(Developed by Engelhard Corporation and Fuji Electric)

off-gases to the reformer burner [B-01]. The supply of methanol to the reformer can thus be shut off once the fuel cell reaches operating temperature. (In the air-cooled PAFC, only about 70 percent of the hydrogen is allowed to oxidize in the stack because a larger amount of fuel is needed in the endothermic reform reaction, without the benefit of the highly efficient vaporizer feasible with the liquid-cooled system.)

During normal operation, the temperatures and heat flow rates shown in Exhibit III-2 are achieved. The specifications of the TBB fuel cell subsystem are shown in Exhibit III-4.

EXHIBIT III-4
Specifications for 50 kW Fuel Cell Subsystem

1	Fuel Cell	
	Liquid Cooled Phosphoric Acid Fuel Cell	
2.	Rated Output Power	
	Fuel Cell Stack:	50kW (DC 105V x 480 A)
	Chopper:	47.5 kW
	Reformer:	H ₂ 42.4Nm ³ /hour
3.	Fuel/Water	
	Fuel:	Commercial Grade Methanol
	Water:	Deionized Water
	Methanol Consumption:	20.5 kg/hour (45.2 lb/hour)
	Water Consumption:	17.3 kg/hour (38.1 lb/hour)
4.	Efficiency	
	System:	42% (LHV) at the Chopper Output Terminal
	Step-up Chopper:	95%
5.	Total Weight of Subsystem	
		1,178 kg (2,598 lb)

(2) Fuel Cell Stack Design Considerations

The design of the liquid-cooled phosphoric acid fuel cell for transit bus application was further assessed by considering the size, cost and performance trade-offs in stack design as discussed earlier in this section.

The final stack design has an active cell electrode area of $2,000 \text{ cm}^2$, based on packaging, weight and cost objectives for a $0.66 \text{ V @ } 240 \text{ mA/cm}^2$ single cell performance. This power density is achievable by the year 1990, when the TBB fuel cell will be designed. Even higher power densities, with cell outputs of $0.66 \text{ V @ } 300 \text{ mA/cm}^2$ are forecast for 1995. However, for the brassboard system, current stack technology of $0.60 \text{ V @ } 240 \text{ mA/cm}^2$ would be employed. The main benefit of the higher cell output levels is in reducing the physical size and weight of the stack for a given rated power level.

The 50 kW fuel cell stack specifications and a conceptual drawing of the stack for the TBB are shown in Exhibit III-5.

(3) Reformer Design Considerations

The specifications and a conceptual drawing of the methanol reformer are shown in Exhibit III-6. The reformer uses an inexpensive copper oxide/zinc oxide catalyst and is designed for high conversion efficiencies. These efficiencies and improved stability of the catalyst bed require temperature uniformity to be maintained under all operating conditions. Typical reformer construction is shown in Exhibit III-7.

(4) Step-Up Chopper Design Considerations

The need for the chopper arises because of the different optimum voltages for the fuel cell stack and the battery under operating conditions. The battery voltage is governed by the voltage and current limits of the motor/controller subsystem. The battery voltage is also a function of the state-of-charge (SOC) and the current output of the battery. The use of the chopper to interconnect the fuel cell with the battery simplifies the control of the system power output in response to the power demands for the operation of the bus.

For the fuel cell/battery bus system, a high frequency (10 kHz) chopper will be used to step up the voltage output of the stack to the proper voltage to allow battery charging when needed and to supply power to the motor/controller when necessary. The specifications for the step-up chopper are shown in Exhibit III-8.

EXHIBIT III-5
Specifications for 50 kW Liquid-Cooled Fuel Cell Stack

1. Rated Power:	DC 50kW
2. Rated Current:	480 A
3. Rated Voltage:	105V (52.8V x 2)
4. Performance of Single Cell:	0.66V/Cell-240mA/cm2
5. Pressure of Operation:	Atmospheric Pressure
6. Temperature of Operation:	190°C
7. Number of Cells	80 x 2
8. Active Area of Electrode	2,000 cm2 (2.15 ft2)
9. Cooling Method	Liquid Cooling
10. Size	1,250 (W) x 700 (D) x 850 (H) mm (4.1 ft) (2.3 ft) (2.8 ft)
11. Weight	620 kg (1,366 lb)

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EXHIBIT III-6
Specifications for Reformer for the 50 kW Fuel Cell System

1. Output	for 50 kW Fuel Cell Stack
2. Process	Steam Reforming
3. Methanol Conversion	>99%
4. Reforming Fuel	Methanol
5. Steam Carbon Ratio	1.5
6. Reformed Gas Composition	H ₂ >65% (Wet Base) CO<2% (at Steady State)
7. Catalyst	CuO + ZnO Type
8. Hydrogen Flow Rate	11.6 ~ 46.6 Nm ³ /hour (410 ft ³ ~ 1,645 ft ³ /hour)
9. Size	70 ø x 1,000 (mm) (2.3 ft ø x 3.3 ft)
10. Weight	Ca 200 kg (440 lb)

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III-9

EXHIBIT III-7
Cross-section of a Typical Methanol Reformer

Reformer Cross Section

EXHIBIT III-8
Specifications for Step-up Chopper

Type: Step-up PWM Chopper
 Operational Frequency: 10 KHz
 Output Power: 47.5 kW
 Voltage: 200 volts (nominal)
 Current: 238 amps
 Efficiency: 95%
 Control: Microprocessor based
 Communications: Serial to battery tray

	Height H (mm)	Size Width W (mm)	Length L (mm)	Weight (kg)
Chopper Stack	250	180	300	(Approx. 120 kg 265 lb)
Direct Current Reactor	450	330	230	
Controller	50	250	300	
Overall	550 (1.8 ft)	600 (2 ft)	400 (1.3 ft)	

M12.19-04

3. SURGE BATTERY

The nickel/iron and lead-acid SLI batteries were determined to be suitable for use in the fuel cell/battery bus system, based on initial trade-offs of cost and availability within the timeframe of the study. The NIF-170 nickel/iron battery is a flat-plate design with deep discharge capability, developed by Eagle-Picher Industries for electric vehicle applications. This battery will be used for the Eaton Dual Shaft Propulsion System program funded by the U.S. Department of Energy. The Exide HP-31E SLI lead-acid battery is also of flat-plate design and is used as a truck cranking battery. The HP-31E is a 12-Volt module battery offering higher peak power capability than the NIF-170 battery.

Of these two, the Exide battery was utilized for initial proof-of-feasibility brassboard tests due to its lower cost, immediate availability off-the-shelf, and higher performance. Battery sizing for the TBB will be reassessed after the completion of the analyses of the brassboard test findings. At this time, it appears that a higher ampere-hour capacity battery than the HP31E will be required to ensure a longer life for the battery under the charge-discharge conditions of the DOT TCDS and GUTS routes.

4. DRIVETRAIN SUBSYSTEM

The drivetrain subsystem that was initially selected for the conceptual (baseline) bus consisted of a dual-drive motor/transmission arrangement controlled by two motor/system controllers. The dual-drive system links the motors to a common transmission through two HI-VO chains. This arrangement allows the chain drive and the transmission to be integrated into the same structure, resulting in higher efficiency and quieter operation. However, the use of two motors in parallel requires a higher number of parts, including a HI-VO chain drive coupler.

Subsequent analysis and comments from the Technical Advisory Panel suggested that the dual-drive system arrangement constitutes a higher risk to transit authorities since the powertrain has not been road proven in a transit bus application, and the chain drive may not be reliable under the stop and go conditions prevalent in transit operations.

As noted previously, the Soleq powertrain is road-proven and simpler in design, and is recommended for the Phase II bus system. The Soleq powertrain has somewhat different operating conditions and design voltage. This is likely to change the specification for the battery and the step-up chopper from the specifications developed earlier for the dual motor arrangement. Revised specifications will be developed in conjunction with Soleq Corporation if the liquid/cooled fuel cell/battery bus system is selected for Phase II.

IV. BRASSBOARD DESIGN

The brassboard system consists of all the major components required for the propulsion of the fuel cell/battery powered bus system, appropriately scaled down to allow laboratory testing at reasonable cost. The overall objective of the brassboard laboratory testing is to prove the feasibility of the fuel cell/battery subsystem to power a 30 ft bus over selected segments of the INDY and GUTS bus operating cycles.

The major components of the brassboard are the fuel cell subsystem, a surge battery, traction motor, and controller. The brassboard system is a one-half scale representation of the bus powerplant. The half-scale brassboard system power, fuel economy and response time will be measured and compared to the bus simulation model performance to determine the projected full-size bus operating performance.

1. BRASSBOARD SYSTEM DESCRIPTION

A block diagram of the brassboard system is shown in Exhibit IV-1. The fuel cell and battery subsystems are connected in parallel and operate at a nominal 204 Volts providing one-half the bus total power and energy requirements. The battery support system monitors module voltage, temperature, full pack voltage and current. The battery support system includes a logic nest with a computer/auxiliary board and an internal power supply.

System control is maintained through a control panel. This panel provides the simulated accelerator and brake input. Start-up/shut-down switch, thermal protection override and other support functions are also provided.

A single DC drive motor was scheduled to be used to simulate the brassboard drivetrain. The motor would be loaded by an identical DC motor operating in generation mode; the generated energy dumped into a suitable resistive load bank. Prior to the testing phase, however, it became apparent that the selected TEVan motor and controller units would be unsuitable for the full size bus. Hence installation of the TEVan motor/controller would not be meaningful for the brassboard tests. To save time and costs, the motor/controller for the brassboard were replaced by a resistive load bank.

EXHIBIT IV-1
Brassboard System Block Diagram

IV-2

2. BRASSBOARD/TBB RELATIONSHIP

The brassboard system power is half of the full size TBB. Thus, only one 25 kW (gross) fuel cell stack is used. The fuel cell subsystem net power output yields about 23.2 kW vs 47.5 kW for the TBB, thus a scaling factor of 2.05 will be used to properly extrapolate the performance for the TBB.

In order to maintain the system voltage at 204 volts, the step-up chopper ratio is about 3.9:1 in the brassboard, about twice the TBB chopper ratio. A current design low frequency 1 kHz chopper (93% efficiency) is used as opposed to a high frequency 10 kHz chopper (95% efficiency) to be used in the TBB. Since the overall efficiencies are nearly the same, the brassboard fuel cell subsystem will correctly produce half of the power output as compared to the TBB.

The selected surge battery for the brassboard has one-half of the capacity as the TBB, thus producing half of the peak power to ensure proper scaling. Since the brassboard system voltage is 204 volts (identical to the TBB) the battery is correctly stressed in order to properly assess the battery performance.

The peak power requirements of the TBB for the INDY and GUTS routes is 120 kW. The brassboard fuel cell and battery together should therefore be capable of delivering 60 kW for short periods of time.

3. FUEL CELL SUBSYSTEM

The fuel cell subsystem consists of the following major components:

- o Liquid-Cooled Fuel Cell Stack
- o Methanol Steam Reformer
- o DC/DC Step-Up Chopper
- o Auxiliary Equipment (starting, cooling, air supply blowers, and other support systems)
- o Internal Controller.

The brassboard fuel cell subsystem specifications are shown in Exhibit IV-2. The fuel cell stack has a 25 kW rated power output, delivering 480 amps at 52.8 volts. A schematic of the Brassboard fuel cell is shown in Exhibit IV-3.

The auxiliary components are supplied by a DC power source operating from line voltage. This would allow accurate measurement of the auxiliary power requirements. The auxiliary power load is expected to be 1.6 kW maximum at fuel cell rated power.

EXHIBIT IV-2
Specifications for Brassboard Fuel Cell Subsystem

1. Fuel Cell: Liquid Cooled Phosphoric Acid Fuel Cell
2. Rated Output Power
 - Fuel Cell Stack : 25kW (DC 52.8V × 480A)
 - Subsystem (Step-up Chopper) : 22.5kW
3. Fuel/Water
 - Fuel : Commercial Grade Methanol
 - Water : Deionized Water
 - Methanol Consumption : 11.3kg/hour (as pure methanol at rated power)
 - Water Consumption : 9.5kg/hour
 - Tank Capacity of Methanol : ca 100 ℓ
 - Tank Capacity of Water : ca 60 ℓ
4. Efficiency
 - Subsystem : 36% (LHV) at the Point of Step-up Chopper Output
 - Step-up Chopper : 90%
5. Startup Time : Within 45 Minutes
6. Operation
 - Operation : Automatic Operation by Personal Computer as Internal Controller for Subsystem
 - Output Power : Controlled by Signal sent from System Controller
 - Operation Conditions : Displayed on CRT
 - Alarm : Displayed on CRT and Buzzer
7. Environmental Conditions
 - Ambient Temperature : 5 to 40 °C
 - Humidity : 0 to 90%RH
8. Configuration of Subsystem : Brass Board
9. Protection of Electrolyte Freezing in Fuel Cell : Heating by Electric Heaters
10. Inert Gas to purge Fuel in Subsystem : CO₂ or N₂ in Cylinder
11. Installation : Indoor

EXHIBIT IV-3 Brassboard Fuel Cell Schematic

IV-5

4. BATTERY

Brassboard battery should be able to supply the difference between the peak traction power and the net fuel cell power output. For the brassboard, this would be approximately 36 kW. The Exide HP31D battery selected for the TBB is a truck starting battery. Manufacturer specifications for the HP31D and two other batteries of similar design that were considered suitable for the brassboard are shown in Exhibit IV-4. Based on these data, it appeared that the BCI-27 battery, with half the number of plates per module, may be the right battery for the brassboard. However, the D-31D battery had a plate design identical with the HP31D, and also represented a viable choice.

Capacity measurements were performed at several representative discharge rates to help make the final selection. A summary of the test data is shown in Exhibit IV-5. The HP31D module performance was significantly below expectations. Upon further examination, it was found that the module that was shipped was of a low maintenance design, and not the one that was used in the simulations. The D31D module was found to be most representative of the half-size unit for the brassboard. The BCI-27 module capacity was found to be lower than the D31D and hence testing of the BCI-27 module was not pursued further. Based on these findings, the D31D battery was selected for the brassboard tests.

EXHIBIT IV-4
Published Data for Exide Battery Modules

	HP31D	D31D	BCI27
Module Voltage	12	12	12
Cold Cranking Amps	950	525	500
Res. Capacity at 25A (minutes)	190	130	90
C/20 Capacity, Ah	106	72	50
Plates per Module	132	72	66
Weight, lbs	56	47	40

EXHIBIT IV-5
Battery Module Test Results

	HP31D	D31D	BCI27
CAPACITY (Ah)			
C/5	56	41	35
C/2	44	34	34
C/1	36	25	-
CAPACITY (Wh)			
C/5	743	529	455
C/2	565	435	428
C/1	462	319	-
IMPEDANCE, (Ohms@ 80%SoC)			
2400 W Pulse	0.0065	0.0073	-
1200 W Pulse	0.0085	0.0092	-
PEAK POWER			
@ 50 % SOC (kW)	>3.6	>3.6	>3.0

5. POWER TRAIN

Brassboard powertrain selection is straightforward for the TEVan motor and controller, since two motors and two controllers would be needed for the full size TBB. However, since the Soleq system was ultimately selected for the TBB, development of a half-power motor and controller would be necessary. To conserve costs and time, it was decided, with the concurrence of the Project Management Team, that testing of a motor/controller would not be conducted in the Phase I work. For the brassboard, the actual loads represented by the controller current would be simulated by means of resistive loads.

6. SUMMARY

A summary of the final specifications for the brassboard is shown in Exhibit IV-6.

EXHIBIT IV-6
Summary of Brassboard Component Specifications

FUEL CELL:

Type	Liquid-cooled PAFC
Rated Power	22.5 kW at Chopper Output
Cell Performance	240 mA/cm ² @ 0.6 V
Active Plate Area	2000 cm ²
Number of Cells	88

BATTERY:

Type	Exide D31D Flat Plate SLI
Nominal Voltage	12 V per Module
Number of Modules	17
Peak Power	>36 kW @ 60% DoD
Capacity (C/5)	41 Ah

MOTOR CONTROLLER:	To be represented by a load bank capable of handling 60 kW at 200V.
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V. TEST SET-UP AND PLANNING

1. TEST FACILITY

The brassboard tests were conducted at a newly constructed facility at PEI, in Huntsville, Alabama. PEI provided the facility as a part of its cost-share for the project. The fuel cell system test area adjoins the PEI TEVan development laboratory. The layout of the test facility is shown in Exhibit V-1.

EXHIBIT V-1
Brassboard Test Facility at PEI

2. BRASSBOARD SETUP

The brassboard setup includes the fuel cell subsystem, the battery, the load unit, and the instrumentation for recording the results. The fuel cell subsystem consists of the fuel cell, its internal controller, a step-up chopper unit, and regulated power supplies for the auxiliary components. The fuel cell (stack, reformer, coolant loop, heat exchangers and burners for starting and maintaining the stack temperature, a carbon dioxide purge system, and methanol and water tanks) was assembled on a 8.2 ft (2.5 m) x 4.9 ft (1.5 m) platform with a steel frame 4.6 ft (1.4 m) high.

Front and rear views of the brassboard fuel cell are shown in Exhibit V-2, and a layout drawing is shown in Exhibit V-3. The configuration of the complete brassboard fuel cell subsystem is shown in Exhibit V-4.

3. TEST CONFIGURATION AND INSTRUMENTATION

The brassboard test configuration is shown in Exhibit V-5. The output of the fuel cell/battery system was connected to two adjustable resistive load banks, which allowed simulation of the bus powertrain. A data acquisition system monitored and recorded the important test parameters.

(1) Load Bank

The resistive load bank was capable of handling the peak traction and accessory power required for bus operation over the TCDS, INDY and GUTS routes. The variable load power requirements for different bus operating segment profiles were regulated manually.

Two load banks were employed in parallel as shown in Exhibit V-5 to give complete control of the load over a voltage range of 140 to 210 V. The peak power absorption capacity of the load bank exceeded the projected peak power output of the brassboard of 60 kW. Manual controllers provided power variation in steps of 4 kW at the low voltage end and 9.2 kW at the maximum voltage.

EXHIBIT V-2
Photographs of Brassboard Fuel Cell

EXHIBIT V-3
Fuel Cell Layout

EXHIBIT V-4 Brassboard Fuel Cell Configuration

EXHIBIT V-5
Brassboard Test Configuration

LOAD SETTINGS			
BATTERY VOLTAGE	LOAD STEPS	POWER STEP	MAX. LOAD POWER
240	44 A	2848 V	350 A
140	29 A	4060 V	350 A
			72,500 V

(2) Data Acquisition Instrumentation

A data acquisition system was used to monitor all pertinent system data for later data reduction and analysis. The brassboard test equipment included:

- . Hewlett Packard Series 9000/300 System Controller
- . Fluke 2280B Data Logger
- . Two Fluke Model 8840A Digital Multimeters
- . Two Clarke Hess Digital Volt/Amp/Watt Meters
- . Two Lebow Torque Sensors and Electronic Packages
- . Two Hewlett Packard 3457A Scanning Digital Multimeters.

This instrumentation monitored key brassboard system performance parameters including:

- . Fuel Cell Subsystem -- start-up, shut-down times, temperatures, voltages, currents, time response to load changes, methanol/water consumption, etc.
- . Battery Subsystem -- voltage, current, state-of-charge (SoC), temperatures, amp-hours (in/out).

Data measured and calculated during each test were down-loaded into an ASCII file for plotting load power, fuel cell power, battery power and SOC versus time. The plots provided a means for direct comparison of the test results with projected simulation results.

The measured parameters and their expected ranges during the brassboard testing program are shown in Exhibit V-6. To keep a log of the tests and activities, and to maintain a visual record of major data points for backup, the test operator maintained appropriate data sheets designed for each test sequence.

EXHIBIT V-6
Ranges of Test Parameters

Parameter	Range
Battery Current	-300 to +300 amps
Battery Voltage	0 to 300 volts
Battery Temperature	0 to 200 C
Power Demand	0 to 10 volts
Fuel Cell Temperatures	0 to 1100 C
Load Current	0 to 400 amps
Methanol Pump (P-01)	40 to 300 ml/min
Water Pump (P-02)	40 to 200 ml/min
Methanol Pump (P-03)	10 to 40 ml/min
Methanol Pump (P-04)	0 to 128 ml/min
Methanol Pump (P-05)	0 to 113 ml/min

4. TEST PLANS

The complete brassboard test program covered three test phases:

PHASE 1- Fuel Cell Subsystem Acceptance Tests
PHASE 2- Fuel Cell/Battery Subsystem Performance Tests
PHASE 3- Fuel/Battery Brassboard Proof-Of-Feasibility Tests.

A Test Plan was prepared in August 1989. It defined the criteria and measures for the three test phases.

(1) Fuel Cell Subsystem Acceptance Tests

The objective of these tests is to operate the fuel cell subsystem automatically by internal controller and verifying the subsystem performance with the specified design goals. The equipment and test set-up is shown in Exhibit V-7. The acceptance tests were performed at Fuji Electric facilities.

The following items were checked during the tests:

- o Automatic start-ups and emergency shut-down
- o Leak check all fluid systems under full power
- o Operation at steady load power levels ranging from minimum to maximum rated power
- o Stepwise power tests to determine response for specific load profiles
- o Overall system efficiency and fuel/water consumption
- o Temperature uniformity
- o Stack and reformer emission levels (CO and NOx).

The test plan defined the test schedule for start-up, steady load power, steady-load reduced power levels, followed by stepwise power response testing and emergency and normal shutdowns. A list of test parameters and their expected ranges during the tests is shown in Exhibit V-8.

EXHIBIT V-7
Test Equipment and Set-Up

EXHIBIT V-8
Test Parameters and Measured Ranges
For Acceptance Tests

		TEMPERATURE					POWER				
CHOPPER	FC STACK	REFORMER	No	MEASURING POINT	RANGE	SENSOR OUTPUT	SENSOR				
			1	FURNACE	0~ 1,100℃	DC 0~ 45.1 mV	K-TYPE TC *1				
			2	CATALYST	0~ 500℃	DC 0~ 20.6 mV	K-TYPE TC				
			3	FUEL INLET	0~ 200℃	DC 0~ 8.1 mV	K-TYPE TC				
			4	CENTER OF STACK	0~ 250℃	DC 0~ 10.2	K-TYPE TC				
		5	FUEL INLET	0~ 300℃	0~ 12.2	K-TYPE TC					
		6	FUEL OUTLET	0~ 250℃	0~ 10.2	K-TYPE TC					
		7	AIR INLET	0~ 100℃	0~ 4.1	K-TYPE TC					
		8	AIR OUTLET	0~ 250℃	0~ 10.2	K-TYPE TC					
		9	COOLANT INLET	0~ 200℃	0~ 8.1	K-TYPE TC					
	10	COOLANT OUTLET	0~ 200℃	0~ 8.1	K-TYPE TC						
	HX-3	11	COOLANT INLET	0~ 200℃	0~ 8.1	K-TYPE TC					
		12	COOLANT OUTLET	0~ 200℃	0~ 8.1	K-TYPE TC					
		FC	13	OUTPUT VOLTAGE	DC 0~ 100 V	DC 0~ 10 V	TRANSDUCER				
			14	OUTPUT CURRENT	DC 0~ 550 A	DC 0~ 10 V	TRANSDUCER				
			15	OUTPUT VOLTAGE	DC 0~ 260 V	DC 0~ 260 V					
16			OUTPUT CURRENT	DC 0~ 200 A	DC 0~ 8 V	HOLE CT					

*1 TC: THERMOCOUPLE

(2) Fuel Cell/Battery Subsystem Performance Characterization Tests

The objective of this phase of brassboard testing is to verify the fuel cell and battery subsystem operation and performance independently and as a system. These tests characterized the bus powerplant and verified its capability to provide the needed power and energy levels as projected by the computer simulation program. These tests were performed by PEI at their brassboard test facility.

The fuel cell subsystem testing was first conducted to verify consistency with the findings of the Acceptance Tests. Three lead-acid SLI battery modules (HP31D, D31D and BCI-27) were tested to determine their capacities and V-I characteristics. The test configuration used for capacity and peak power tests is shown in Exhibit V-9. The results of these tests were used to first select the correct battery module for the brassboard and then to calibrate the Amp-hr measuring instrumentation in the battery support system. Next, a full pack of 17 D31D modules was assembled and tested along with the instrumentation and support systems.

The final sequence of testing should first verify the fuel cell-battery interface system operation and then test the fuel cell/battery system under stepwise loadings. System response to sudden changes in load should also be tested.

(3) Proof-of-Feasibility Tests

The objective of the proof-of-feasibility tests is to verify the capability of the fuel cell/battery system to power the bus over the DOT/UMTA TCDC, INDY and specified segments of the GUTS driving cycles. Proof-of-feasibility would be demonstrated by comparing the measured fuel cell and battery parameters with the parameter values projected from the simulation program. Measurements of fuel consumption and battery state-of-charge during the tests will be made to verify the predicted fuel consumptions and battery conditions.

The DOT TCDC and INDY cycles should be tested in their entirety on the brassboard. For the GUTS Arlington Loop, two segments that offer the severest test of performance are the 45 mph constant speed segment and the 8 % upgrade section. The brassboard tests should be designed to first verify performance over these two segments, and later extended to show operation over the entire GUTS Arlington Loop route.

EXHIBIT V-9
Test Configuration for Battery Module
Capacity and Peak Power Tests

Run Schedule for Proof-of-Feasibility - The Proof-of-Feasibility tests were the most involved tests of the brassboard system. The number of tests, test sequences, and system settings were carefully planned to avoid last-minute difficulties in conducting the tests or in interpreting the voluminous data that would be generated.

The test run schedule is shown in Exhibit V-10. Initial tests were designed to confirm operation over the CBD, Arterial and Commuter segments of the INDY and DOT TCDC route. These tests were followed by entire TCDC runs at several settings of the initial state-of-charge (SoC) of the battery. For the GUTS Arlington Loop, two segments that offer the severest test of system performance: the 7% upgrade segment and 45 mph cruise segment, were selected for initial tests. These tests, if successful, would be followed by two runs of the entire GUTS route.

Test Procedures - The brassboard test procedures used are briefly described below. In all tests, LOAD1 (Exhibit V-5) was set between 4.6 and 7.8 kW to simulate the bus auxiliary loads including air-conditioning under varying system voltage conditions.

EXHIBIT V-10
Proof-of-Feasibility Tests
Test Run Schedule

Run No.	Objective	Starting Conditions	
		Fuel Cell Power	Battery SoC
3A1-14	14 CBD start-stops, 300 s idle	25%	85%
3A15-18	4 ART start-stops	100%	85%
3A19	1 Commuter profile	100%	85%
3A20	TCDC	100%	75%
3A21	TCDC	100%	70%
3A22	TCDC	100%	75%
3A23	TCDC	100%	70%
3A24	TCDC	100%	90%
3A25	TCDC	100%	85%
3B1	GUTS 7% upgrade	100%	76%
3B2	GUTS 45 mph accel & cruise	100%	73%
3B3	GUTS 7% upgrade	100%	76%
3B4	GUTS 45 mph accel & cruise	100%	73%
3B5	GUTS Arlington Loop	0%	90%
3B6	GUTS Arlington Loop	25%	90%

CBD Profile - The CBD profile, as shown in Exhibit V-11, requires LOAD2 to increase from 0 to 60 kW in 4 seconds and maintained at 60 kW for another 6 seconds in order to approximate the power requirements of accelerating the TBB from 0 to 20 mph. After acceleration to 20 mph, the load is decreased and maintained at 9.2 kW to approximate the 20 mph cruise condition, to be maintained for 20 seconds. Each CBD profile is followed by a 10 second idle period during which no load is applied to the system. The expected brassboard fuel cell and battery power profiles and the battery SOC variation are also shown in Exhibit V-11.

Arterial Profile - The Arterial profile, shown in Exhibit V-12, requires LOAD2 to increase from 0 to 60 kW in 4 seconds and maintained at 60 kW for an additional 21 seconds to approximate the power requirements for accelerating the TBB from 0 to 40 mph. The load is then decreased to 18.4 kW to approximate the 40 mph cruise condition, to be maintained for 35 seconds, followed by no load for 10 seconds. The expected brassboard fuel cell and battery power profiles and battery SoC variation are also shown in Exhibit V-12.

Commuter Profile - The Commuter profile, shown in Exhibit V-13, requires LOAD2 to increase from 0 to 60 kW in 4 seconds and maintained at 60 kW for an additional 56 seconds to approximate the power requirements for accelerating the TBB from 0 to 55 mph. The load is then decreased and maintained at 27.7 kW for 240 seconds, followed by no load for 20 seconds. The expected brassboard fuel cell and battery power profiles and battery SoC variation are also shown in Exhibit V-13.

TCDC and INDY Profiles - These profiles are obtained by combining the CBD, Arterial and Commuter profiles with suitable idle periods as shown in Exhibit V-14.

GUTS 7% Upgrade and 45 mph accel/cruise - The load settings and expected brassboard fuel cell and battery power profiles and battery SoC variations are shown in Exhibit V-15.

GUTS Arlington Loop Profile - The load settings for the entire GUTS route were derived in similar manner to those for the TCDC profile by combining various GUTS segments. The results of the GUTS profile testing should be considered as approximate because of the difficulty in manually varying the load settings.

EXHIBIT V-11
 CBD Profile Test Procedure

4.6 KW < LOAD1 < 7.8 KW

TIME [SEC]

1/25/90

EXHIBIT V-12 Arterial Profile Test Procedure

4.6 KW < LOAD1 < 7.8 KW

1/25/90

EXHIBIT V-13
Commuter Profile Test Procedure

EXHIBIT V-14
Summary of TCDC and INDY Profiles

	TCDC		INDY	
	Time (seconds)	Distance (miles)	Time (seconds)	Distance (miles)
CBD	560	2	560	2
Idle	300	0	10	0
Arterial	270	2	270	2
CBD	560	2	560	2
Arterial	270	2	270	2
CBD	560	2	560	2
Arterial	0	0	540	4
Commuter	310	4	0	0
Idle	0	0	300	0
TOTAL	2,830	14	3,070	14

EXHIBIT V-15
GUTS Arlington Loop Segment Test Procedures

VI. BRASSBOARD TEST FINDINGS

The brassboard test program covered three test phases:

TEST PHASE 1- Fuel Cell Subsystem Acceptance
TEST PHASE 2- Performance Characterization
TEST PHASE 3- Proof-Of-Feasibility.

The test objectives and set-up for the three phases were described in Section V. In this section, the major findings of the brassboard tests are described. Details of the test plans, methodology, and results are provided in separate reports.

1. TEST PHASE 1 - FUEL CELL ACCEPTANCE

Test Phase 1 was conducted at Fuji Electric facilities.

(1) Summary of Tests

The fuel cell subsystem was assessed to verify design performance goals as specified for the 25 kW brassboard fuel cell subsystem (see Section IV). The tests included:

- o Visual Check - Confirm component sizes and weights. Visually inspect each component to ensure proper connections.
- o Isolation Check - Ensure adequate electrical isolation between the main circuit of the fuel cell subsystem and earth ground.
- o Leak Check - Ensure no leakage from subsystem under load. Visually check all components for methanol, water or oil leaks. Also, inspect fuel cell stack and reformer for possible reformat leakage using gas detector.
- o Start-Up and Shut-Down Tests - Measure response times for 0- 25%, 25- 100% and 100- 0% rated load under full automatic operation. Measure warm start-up response time for 0-25% and emergency shut-down response from 50-0% and 100- 0% rated load. Record fuel cell stack temperatures.
- o Steady-Load Operation - Characterize the fuel cell subsystem at 100%, 75%, 50% and 25% rated load. Record the fuel cell subsystem V-I curve, methanol/water consumption, chopper efficiency, auxiliary loads and component temperatures for verification.

- o Noise and Emission Levels - Measure noise and exhaust emissions at start-up (0- 25%), 25%, 50%, 75% and 100% rated load. Record noise levels at six locations around the fuel cell subsystem. Measure emission levels for CO, NO+NO2 and hydrocarbons from the fuel cell stack, reformer and start-up burner.
- o Step-wise Power Operation - confirm fuel cell subsystem operation at stepped power increases from 0%, 25%, 50%, 75% and 100% rated load. Confirm that battery voltage changes do not affect the performance of the fuel cell subsystem.

(2) Test Results

The fuel cell subsystem acceptance tests verified the full automatic start-up, shut-down and normal operation of the half-scale brassboard system. Also, key performance parameters were measured and subsystem operation was observed to verify the specified design goals. Important findings are summarized below.

Visual Check - Visual checks revealed no leaks, incorrect assembly, or wiring. The weights and sizes were measured and recorded for the major components of the brassboard fuel cell subsystem. A weight comparison between the 25 kW brassboard and 50 kW TBB specification for the three major components, is shown in Exhibit V-1. It is seen that the 50 kW stack and reformer are expected to be only 69 and 50 percent heavier than the brassboard components. The 1 kHz step-up chopper used in the brassboard system is larger and heavier than the 10 kHz chopper proposed for the TBB. Since both chopper designs have nearly the same efficiencies, 93% at 1 kHz and 95% at 10kHz; the lower frequency chopper was selected for the brassboard since it was readily available.

Start-Up and Shut-Down Operation - The test results for normal start-up and shut-down operation, summarized in Exhibit VI-2, show that the fuel cell subsystem start-up times for 0-25% and response times for 25-100% rated power are within specifications. However, it takes 5 minutes longer during normal shut-down than specified. The shut-down time will be shortened by improving the internal controller logic routine for the TBB bus design in Phase II.

Steady-Load Power Operation - The steady-load operation of the fuel cell subsystem at various rated power levels from 25% to 100% were measured and the results are shown in Exhibit VI-3. The test results reveal that the components and brassboard subsystem exceed the design specifications at 100% rated power. The output power from the fuel cell

EXHIBIT VI-1
Brassboard Vs TBB Powerplant Weight Comparison

Component	BRASSBOARD Weight (kg)	TBB Weight (kg)	RATIO
Fuel cell stack	368	620	1.69
Methanol reformer	133	200	1.50
Step-up chopper	290 (1 kHz)	120 (10 kHz)	0.41
TOTAL WEIGHT (kg)	791	940	1.19

EXHIBIT VI-2
Normal Start-up/Shut-down Response Times

	SPECIFICATION	RESULT
Start-up from 0- 25%	within 45 min	33 min (-12 min)
Normal shut-down from 100- 0%	30 min	35 min (+5 min)
Power increase from 25- 100%	7 min	7 min (0 min)

subsystem is 3.2% greater than the design goal. This is due to an improvement in the 1 kHz step-up chopper design yielding 3.3% greater efficiency.

The fuel cell voltage-current characteristic performance curve is shown in Exhibit VI-4. The fuel cell stack cell performance at the design point is 0.62V @ 240mA/cm² compared to a design goal of 0.60V @ 240mA/cm².

Noise and Emission Levels - The results of the noise level test, shown in Exhibit VI-5, show a maximum noise level of 78 dBA during start-up operation about 1 meter from the start-up burner. The maximum noise level during operation was measured at 75 dBA.

EXHIBIT VI-3
Steady-Load Power Characteristics

	SPECIFICATION	RESULT			
	100%	100%	75%	50%	25%
Output					
Power: (kW)					
FC stack	25.0	24.97 (-0.1%)	18.7	12.0	6.2
Chopper	22.5	23.23 (+3.2%)	17.5	11.3	5.4
Auxiliaries	1.40	1.39 (-0.7%)	1.19	1.14	1.10
Consumption:					
(kg/hr)					
Methanol	11.30	10.79 (-4.5%)	8.33	5.55	3.46
Water	9.50	9.23 (-2.8%)	7.09	4.10	2.79
Efficiency:					
Chopper	90.0%	93.0% (+3.3%)	93.5%	94.1%	87.0%
Subsystem					
w/ aux	36.0%	36.5% (+1.4%)	35.3%	33.1%	22.5%
w/o aux	--	38.8% --	37.9%	36.8%	28.2%

NOTE: The test results at 100% rated power were averaged for three test data points.

EXHIBIT VI-4 Fuel Cell Voltage-Current Characteristics

Cell Number 88
Cell Temp. 190 °C
H₂ Utilization 75 %
(Reformed Gas)
O₂ Utilization 40 %
(Air)

EXHIBIT VI-5
Measured Noise and Emission Levels

-33mA - 7min -

Rated Power		Start-up to 25%	25%	50%	75%	100%
NOISE: (dBA) Maximum Level		78	72	74	75	75
EMISSIONS: (ppm)						
Fuel cell	CO	ND	--	--	--	ND
stack	NO+NO ₂	ND	--	--	--	ND
	HC	ND	--	--	--	ND
Reformer	CO	ND	140	150	20	30
	NO+NO ₂	ND	1	0.6	0.9	0.5
	HC	ND	3	5	ND	ND
Start-up burner	CO	ND	10	40	--	ND
	NO+NO ₂	ND	0.8	1	--	ND
	HC	ND	5	3	--	ND

NOTE: ND= Not Detectable

The emission levels recorded from the exhaust gases of the fuel cell stack, reformer and start-up burner reveal the greatest concentration of CO, NO+NO₂ and HC from the reformer and start-up burner, with no detectable traces from the fuel cell stack. At 50% rated load the reformer produces the highest concentration of CO and HC, whereas, the start-up burner has the highest NOx emission level of 1 ppm. However, the maximum emission levels recorded from the fuel cell subsystem are well below the levels exhausted from internal combustion engines.

2. TEST PHASE 2 - PERFORMANCE CHARACTERIZATION

The purpose of Test Phase 2- Fuel Cell/Battery Subsystem Performance Tests is to fully characterize and demonstrate the operation of the fuel cell/battery powerplant system. The tests consisted of the following three test sequences:

Test Sequence A: Fuel Cell Subsystem Tests

Test Sequence B: Battery Characterization Tests

- Battery Module Characterization
- Battery Subsystem Characterization

Test Sequence C: Fuel Cell/Battery Characterization Tests

- Fuel Cell/Battery System Control Test
- Fuel Cell/Battery System Operation

The brassboard testing results for each of the test sequences are discussed in the following sections.

(1) Fuel Cell Subsystem Tests

Fuel Cell Subsystem Tests conducted at Pentastar Electronics Inc. (PEI) facilities were a repeat of the tests conducted in Test Phase 1 at Fuji Electric facilities. The purpose of these tests was to verify the consistent performance and operation of the fuel cell subsystem. The start-up and shut-down times measured were within two minutes of the times measured under the Acceptance Tests.

The steady-load operation of the fuel cell subsystem was measured at two rated power levels 50% and 100%. The results are shown in Exhibit VI-6. The test data results are in good agreement with the Acceptance Test results.

The fuel cell voltage-current characteristic performance curve is shown in Exhibit VI-7. The characteristic curves measured during Test Phase 2 is in close agreement with that measured during Test Phase 1. The fuel cell performance is compared to a design goal of 52.8V @ 480A.

Based on the brassboard test results conducted at PEI facilities, the fuel cell subsystem was determined to be in compliance with the projected design performance goals.

(2) Battery Characterization Tests

The purpose these tests was to determine the correct half-power battery to be used in the brassboard system and characterize its operation. Also, the battery subsystem (17 modules) was calibrated and its operational characteristics determined.

Based on the results of the battery module characterization tests, the Exide D-31D battery was selected for the half-power brassboard (see Exhibit IV-5). The battery system was next tested for proper operation prior to integration with the fuel cell.

EXHIBIT VI-6
Steady-Load Power Test Results

	SPECIFICATION	RESULTS			
		TEST PHASE 1		TEST PHASE 2	
	100%	100%	50%	100%	50%
Output Power: (kW)					
FC stack	25.0	24.97	12.0	25.2	12.2
Chopper	22.5	23.23	11.3	23.2	11.8
Auxiliaries	1.40	1.39	1.14	1.38	1.11
Consumption: (kg/hr)					
Methanol	11.30	10.79	5.55	10.8	5.5
Water	9.50	9.23	4.10	9.2	4.8
Efficiency:					
Chopper Subsystem	90.0%	93.0%	94.1	92.1%	96.7
w/ aux	36.0%	36.5%	33.1	36.5%	35.1%
w/o aux	--	38.8%	36.8	38.8%	38.7%

NOTE: The test results at 100% rated power for Test Phase 1 were averaged for three test data points.

EXHIBIT VI-7
Fuel Cell Voltage-Current Characteristic
Comparison of Test Data

Number of Cells= 88
Cell Temperature= 190 C
H2/O2 Utilization= 75%/40%

Problems were encountered with the Hall effect current sensors, which tended to drift and were susceptible to drift magnetic effects. The sensors were replaced with a coaxial shunt and isolated amplifiers, which remedied the drift problem. The state-of-charge (SoC) algorithm also needed software changes to account for the very flat impedance curve of the SLI battery in its operating range.

For the D-31D battery, the rise in polarization voltage during long duration charging at high rates resulted in automatic shut-down of the fuel cell. For short durations (under 2 minutes), the voltage rise did not shut down the system, but gasing was observed. This should not pose a problem under route operation if the battery tray is properly designed to keep even temperatures and vent the gases. System operation with a larger capacity battery should be evaluated.

(3) Fuel Cell/Battery Characterization Tests

The purpose of these tests is to fully characterize the fuel cell/battery powerplant system and to ensure proper signal communication between the battery subsystem controller and the fuel cell internal controller.

Once the system control logic was verified for proper system power response to specific load demand profiles, the fuel cell/battery subsystem constant load profile tests were conducted. The plots of the demand load profile and the resulting fuel cell and battery power outputs under bus idle conditions (5.4 kW for TBB, 2.7 kW for brassboard) are shown in Exhibit VI-8. Battery SoC is maintained at 90% by automatically cycling the fuel cell power output. Operation at maximum traction power (120 kW for the TBB, 60 kW for brassboard) is shown in Exhibit VI-9. In this case, the battery SoC continually drops while the fuel cell is powered up from 25% to full power. This type of sustained power demand is not a normal operating condition for the bus.

The fuel cell/battery powerplant performance, starting from fuel cell stand-by power as the load power is increased to the maximum load level (60 kW), is shown in Exhibit VI-10. The battery supplies the initial peak power demands as the fuel cell power ramps up to full power. The load was reduced to 18 kW after the battery SoC dropped below 70 percent. The results clearly show that the fuel cell continues to charge the battery at this load level, until the battery SoC reaches 90 percent. The next run shows the fuel cell/battery system starting from fuel cell power level of 25% of maximum power. Once the battery reaches 90% SoC, the fuel cell power output decreases automatically to prevent overcharging of the battery.

EXHIBIT VI-8
Fuel Cell/Battery Powerplant Operation
Bus Idling Condition

EXHIBIT VI-9
Fuel Cell/Battery Powerplant Operation
Maximum Power Condition

EXHIBIT VI-10
Fuel Cell/Battery Powerplant Operation
Varying Load Condition

3. TEST PHASE 3 - PROOF-OF-FEASIBILITY

The objective of the final test phase - Fuel Cell/ Battery Brassboard Proof-of-Feasibility Tests - was to verify the capability of the brassboard, after proper scaling corrections, to power the TBB over the DOT/UMTA TCDC, INDY and GUTS Arlington Loop routes. Proof-of-feasibility for the fuel cell/battery powerplant was demonstrated by the safe operation of the brassboard during the tests, and by verifying the predicted fuel consumptions and battery SoC conditions for the specified routes. The test procedures and run schedules described in Section V were used.

(1) Transit Coach Operating Duty Cycle (TCDC) Tests

Objective - The objective of this test sequence (Runs 3A1 through 3A19) was to determine the capability of the brassboard system to supply the power and energy requirements for operating the bus over the standard DOT TCDC route, and to determine if the fuel cell/battery powerplant design was adequate to fulfill the mission requirements. Fuel (methanol) consumption, fuel cell operating temperatures, and the battery state-of-charge (SoC) during the cycle were recorded to confirm the assumptions of the trade-off analysis and the brassboard design. The results of the tests were compared with projected simulation results to verify the accuracy of the simulation program.

Results - Exhibit VI-11 shows the load applied, the resultant battery and fuel cell chopper outputs, and battery SoC for the 14 CBD cycles (Runs 3A1 through 3A14). The power requirements were met by the battery and fuel cell (through the chopper), as the battery SoC declined from 85% to 80.3%.

Exhibit VI-12 shows the load applied, the resultant battery and fuel cell chopper outputs, and the battery SoC for the 4 Arterial cycles (Runs 3A15 through 3A18), and the Commuter cycle (Run 3A19). During the first Arterial cycle, the fuel cell chopper output continued to rise from 20 kW to the maximum, 22.5 kW, in response to the power demand for the cycle. The battery SoC at the end of the Commuter cycle (not shown in Exhibit VI-12) was 68%.

Exhibit VI-13 shows the results of for the entire TCDC route (Run 3A20), starting at a battery SoC of 75%. As shown in Exhibit V-10, a total of 6 TCDC runs were made at various starting battery conditions. The fuel consumption during various segments of the cycle for these runs is summarized in Exhibit VI-14. The data should be scaled appropriately to obtain the fuel consumption for the TBB.

EXHIBIT VI-11
CBD Tests

EXHIBIT VI-12
Arterial and Commuter Cycle Tests

EXHIBIT VI-13
Typical TCDC Run

Analysis - Based on the fuel consumption measurements shown in Exhibit VI-14, the measured and projected average fuel consumption for the TBB over various segments, the INDY cycle, and the TCDC are shown in Exhibit VI-15. The fuel economies for the CBD, INDY and Commuter cycles projected by the PC simulation program are in excellent agreement with the measured fuel economy. The PEI simulation program projected somewhat higher fuel economy. The main difference between the PC and PEI simulation programs was in the efficiency and gear ratios of the drivetrain.

EXHIBIT VI-14
TCDC Fuel Consumption Measurements.

Run	Fuel Consumption (kg)					
	3A20	3A21	3A22	3A23	3A24	3A25
CBD	1.67	1.65	1.72	1.52	1.78	1.67
5-min Idle	.88	.87	.92	.87	.84	.88
Arterial	.85	.87	.81	.81	.72	.80
CBD	1.41	1.67	1.71	1.67	1.70	1.68
Arterial	1.14	.83	.87	.86	.89	.87
CBD	1.67	1.69	1.67	1.66	1.71	1.68
Commuter	.92	.87	.96	.96	. 3	.97
<hr/>						
TOTAL TCDC	8.54	8.45	8.66	8.49	8.52	8.55

EXHIBIT VI-15
Comparison of Measured and Projected
Fuel Consumption for TBB.

Cycle	Measured Fuel Consumption (mpg)	Projected Fuel Consumption (mpg)	
		PC	PEI
CBD	1.87	1.87	4.2
Arterial	3.63	2.53	3.86
Commuter	.93	1.00	
5-minute Idle	.88 kWh	.87 kWh	
INDY	2.37	2.38	2.66
TCDC	2.59	2.40	

(2) GUTS Segment Tests

Objective - The objective of this test sequence (Runs 3B1 through 3B4), was to determine the capability of the brassboard fuel cell/battery subsystem to supply the power and energy requirements for selected segments of the GUTS Arlington Loop. The maximum grade and maximum speed segments were used for comparison between simulated and measured performance.

Results - Exhibit VI-16 shows the load applied, the resultant battery and fuel cell power outputs, and battery SoC for the GUTS 7% upgrade segment and the GUTS maximum speed (45 mph) segment. The load variation observed between the two segments was required to bring the battery SoC at the start of the maximum speed segment to the projected SoC at that point in the GUTS route. The fuel cell and corresponding battery voltage and current variations are shown in Exhibit VI-17.

Analysis - The measured and projected fuel cell and battery conditions for the two segments are summarized in Exhibit VI-18. The agreement between the measured and projected power and energy requirements for the two segments appears to be quite good, considering that due to the short duration of these segments (about 17 seconds each), manual control of power demand was difficult.

Referring to Exhibits VI-16 and VI-17, it is seen that the fuel cell peak power excursions were significant during the initial acceleration portion of the maximum speed segment. The peak power recorded at that point was 25.1kW, about 8% above the rated power output of 23.2 kW for the brassboard, and over 11% above the design power of 22.5 kW.

(3) GUTS Arlington Loop Runs

Objective - The objective of these runs was to verify overall fuel consumption projections for the GUTS Arlington Loop and to demonstrate the capability of the brassboard system to provide the power and energy requirements for the runs. The power demand for the route was controlled manually. Hence repeatability and accuracy were not major considerations in verifying the capabilities of the brassboard system.

Results - Exhibit VI-19 shows the load applied, the resultant battery and fuel cell chopper outputs, and the battery SoC for the GUTS Arlington Loop run (Run 3B5). The run was started with the fuel cell at idle and the battery at 90 % SoC. As soon as the load is applied, the fuel cell chopper output power rises to 25 % of rated power and then

EXHIBIT VI-16
GUTS Segment Tests

EXHIBIT VI-17
GUTS Segment Tests
Battery and Fuel Cell Voltage-Current Relationships.

EXHIBIT VI-18
Comparison of GUTS Segment Test Results with Projections

	Measured	Projected (PEI)
<u>7% Upgrade Segment</u>		
Peak Traction Power (kW)	116.8	119.0
Battery Initial SoC (%)	76.0	76.0
Minimum SoC (%)	74.4	74.0
<u>Maximum Speed Segment</u>		
Peak Traction Power (kW)	115.9	118.0
Battery Initial SoC (%)	73.0	73.0
Minimum SoC (%)	71.2	70.0

ramps up to full power in about 7.3 minutes. During this period, the battery SoC drops from 90.0 to 82.0 %. At the end of the route, the SoC reaches 64.6 %. The battery is then recharged from fuel cell power to 90.0 % SoC in 10 minutes.

Analysis - Exhibit VI-20 shows the GUTS route parameters for the two tests performed, and for the PC and PEI simulation projections. The test results appear to fall near the values projected by the two simulation programs.

Measured and projected fuel consumptions for the GUTS Arlington Route are shown in Exhibit VI-21. It was not possible to include regenerative braking in the brassboard tests, which results in a higher fuel consumption measurement for the brassboard.

The discrepancy between the simulation projections and the measured fuel consumption is also due to the different start up condition during the tests and that assumed for the simulation. The brassboard tests started the GUTS profile while the fuel cell was on standby power, while the simulations assumed that the fuel cell was on full power at the start of the run. During brassboard tests, energy was extracted from the battery during the fuel cell ramp up period of 7.3 minutes during which the battery SoC dropped from 90 to 82 %. Preliminary analysis has shown that this puts a significant burden on the fuel cell output throughout the cycle, resulting in higher fuel consumption. Since the fuel cell ramp up time is estimated to be only 4 minutes for the TBB, the brassboard ramp up time of over 7 minutes is not indicative of the actual conditions. The results need to be analyzed in greater detail before definite conclusions may be reached.

EXHIBIT VI-19
GUTS Arlington Loop Tests

EXHIBIT VI-20
GUTS Route Test Parameters

Run No.	Battery SoC				Run Duration	Time to Recharge to 90 % SoC
	BoC	100%FC	Min.	EoC		
3B5	90%	82%	64%	65%	1704 sec	608 sec
3B6	90	79	59	59	1680 sec	791 sec
PEI Simuln	90	70	69	71	1817 sec	480 sec
PC Simuln	75	75	37	37	1787 sec	-

EXHIBIT VI-21
GUTS ROUTE Fuel Consumption Analysis

Run No	Methanol	Brassboard	TBB
	kg	mpg	mpg
3B5	9.83	2.49	1.32
3B6	9.5	2.58	1.36
PEI Simuln			1.95
PC Simuln			2.08

VII. ECONOMIC ANALYSIS

1. INTRODUCTION

The economic cost-competitiveness of equivalent PAFC/battery, diesel, and methanol-ICE powered buses is assessed. The analysis does not attempt to quantify any indirect or societal costs or benefits related to environmental impacts, infrastructure changes, noise reduction, performance differences, or petroleum replacement.

The cost comparisons are made on a life cycle cost (LCC) basis. The LCC method is the best approach for comparing the cost to own and operate vehicles with differing initial and operating costs and salvage values.

The uncertainties in projecting the technology levels, market sizes, fuel prices and component costs at a future time, especially when petroleum and competitive fuel usage are involved, are very great. Wherever possible, two or more alternative scenarios are assumed to bracket the probable range of variation of the parameters in question. In the case of fuel prices, projections of current pricing structures as well as energy-content pricing are used. A sensitivity analysis was conducted to provide a range of possibilities related to cost and bus operational usage scenarios.

It is expected that the cost estimates will get more narrowly defined as the program develops more definitive information on fuel cell capabilities and other technological advances. At the present time, the findings should be used only as a basis for assessing if the fuel cell/battery powered bus system can be an economically viable alternative to diesel or methanol-ICE powered transit bus systems.

2. STUDY TIME FRAME

The DOE/UMTA PAFC/battery-powered bus development program is divided into four phases:

I. Proof-of-Feasibility	FY 1988-89
II. Proof-of Concept	FY 1990-91
III. Test-Bed Bus Evaluation	FY 1992-93
IV. Field Testing	FY 1994-95

The first fuel cell/battery-powered buses are likely to be available for route service after 1995. Hence the economic analysis addresses competing fuel cell, diesel and methanol ICE buses in the 1995-2000 time frame.

3. ENVIRONMENTAL CONSIDERATIONS

In 1981, the Environmental Protection Agency (EPA) amended the Clean Air Act of 1977, establishing emission standards for buses and trucks with diesel engines. Almost all transit buses in the U.S.A. are diesel-powered. After 1991, they will be required to limit their particulate emissions to 0.1 grams/brake horsepower-hour. To meet this standard, diesel engines will have to be fitted with particulate traps (trap oxidizers) or utilize some other technology yet to be developed. Alternatively, transit buses will have to be powered by methanol-ICEs which can meet the emission standards. Either alternative is likely to increase transit bus capital and operating costs. When fuel cell/battery buses become available in 1995, they will provide a third alternative to the bus operators if the costs of these buses are competitive.

The fuel cell produces electricity by catalytically reacting hydrogen and oxygen to form water and electricity. Hydrogen is supplied to the anode and oxygen in the form of air is supplied to the cathode. The anode and the cathode are immersed in a conducting electrolyte that completes the circuit. When an acid electrolyte such as phosphoric acid is used, oxygen, hydrogen ions, and electrons from the external circuit combine to form water at the cathode. No other emission products are produced.

The phosphoric acid fuel cell is tolerant of the presence of carbon oxides, and allows the use of hydrogen obtained by reforming methanol and steam in the presence of a catalyst such as zinc oxide. The by-products of methanol reforming are nitrogen, carbon-dioxide and carbon-monoxide, and water. Oxides of nitrogen emissions are negligible at the reforming burner temperatures (800° to 850° C). There are no aldehyde or particulate emissions.

Diesel engines produce substantial particulate and nitrogen oxides emissions. The technology for reducing diesel bus exhaust emissions to the EPA 1991 particulate standard is not yet commercially available. For the present analysis, it is assumed that particle trap oxidizers will be utilized to meet the 0.1 gram/brake hp-hour standard.

The primary engine emissions with methanol fuel are aldehydes. The EPA will require the control of aldehydes to a level equivalent to emissions from gasoline and diesel engines. Aldehyde emissions in methanol-ICE powered buses will be removed with catalytic converters. Based on current estimates, the methanol engine can meet the 1991 EPA emission standards with minimal use of control devices. The methanol-ICE powered bus is expected to be about 80 percent lower in nitrogen oxides emissions and 90 percent lower in particulate emissions than current diesel-powered buses.

Finally, diesel engines produce high noise levels at the engine exhaust and air inlet, particularly during acceleration. Bus noise is a typical urban problem. Pedestrians are exposed to it at close range. Methanol-ICE noise levels are expected to be similar to diesel engine noise levels. The main sources of noise from fuel cells are the air blowers and liquid pumps, which are amenable to effective noise control. In the case of liquid-cooled fuel cells, the air blowers are required only for air supplies to the stack and reformer, and not for cooling. Liquid-cooled fuel cell noise levels, therefore, are expected to be lower than air-cooled fuel cells.

4. STUDY ASSUMPTIONS

(1) Market Size

The economics of bus production are tied to the market size. Recently, U.S. bus sales have been fluctuating between 2,000 and 4,000 buses per year (Exhibit VII-1). It is difficult to project bus sales for the 1995-2000 period, but due to the expected increase in highway congestion, bus ridership is expected to increase. Bus sales of 5,000 units/year appear feasible during this period. It seems certain that there will be a window of opportunity for any 'clean' bus powerplant technology during that period. For the present analysis, therefore, a reasonable target for fuel cell/ battery-powered buses has been assumed at 2,000 units/year.

EXHIBIT VII-1
U.S. Bus Sales

(2) Bus Technology and Prices for 1995

It is assumed that if Federal or local subsidies are available, all bus technologies will receive equal subsidies. Hence the comparisons are made without consideration to any subsidies.

Diesel Buses. In 1988, the average price of a fully equipped 40 ft diesel transit bus was \$162,000, based on sales of 2,800 buses. Market improvement is expected to continue through 1990 in anticipation of the EPA diesel bus particulate emission standards. In 1991, diesel bus sales may slump due to the uncertainties of the reliability of particulate emission controls. By 1995, when demand begins to increase, prices may again rise.

Based on the above considerations, a fully equipped 40 ft bus is expected to cost \$165,000 in 1989. The 1995 diesel bus is expected to use a particulate trap for emission control, which would cost an additional \$5,000. Exhibit VII-2 shows the cost breakdown for 1995 technology 30 ft and 40 ft diesel transit buses.

EXHIBIT VII-2
1995 Technology Diesel Transit Bus Cost Breakdown

	<u>30 ft</u> <u>Bus</u>	<u>40 ft</u> <u>Bus</u>
Diesel Engine	\$ 7,000	\$ 15,000
Intake, Exhaust System	400	500
Engine Cooling, soundproofing	1,600	2,000
Transmission w/ Torque Conv.	5,000	13,500
Air-Conditioner	7,500	7,500
Emission Controls	5,000	5,000
Remaining Components	108,500	126,500

Fully Equipped Bus Cost	\$135,000	\$170,000

The "Remaining Components" in Exhibit VII-2 include the bus body, suspension system, accessories, air compressor, and the brake system. These costs are common between the diesel bus and equivalent fuel cell/battery buses, and will be used later to build up the projected initial cost for fuel cell/battery buses.

Fuel Cell/Battery Buses. For the fuel cell/battery bus, the bus price is derived by removing cost of the ICE powertrain components from the diesel transit bus and replacing them with the estimated costs for a fuel cell, battery, DC motor and control system.

The fuel cell power plant cost is estimated to be \$750 per kW output, based on a worldwide combined market of 8,000 to 10,000 50 kW units per year for buses and other applications. PAFC technology for 1995 is assumed to be at a level that has already been tested in the laboratory: 300 mA/cm² at 0.66 V/cell.

Platinum catalyst for the stack will be leased for the duration of the bus life. The cost of leasing, about 3 percent on the open market, is treated as operating cost along with insurance and taxes. About 70 to 75% of the platinum is recoverable. The cost of unrecovered platinum is treated as part of the bus maintenance cost, occurring every 5 years during stack replacement. Exhibit VII-3 shows the cost build-up for the 30 ft and 40 ft fuel cell/battery bus.

EXHIBIT VII-3
Cost Build-up for Fuel Cell/Battery bus

		<u>30 ft</u>	<u>40 ft</u>
		<u>Bus</u>	<u>Bus</u>
Fuel Cell	Liquid-cooled PAFC	\$ 37,500	46,875
Chopper		500	600
Battery	Lead-acid SLI type	1,360	1,500
Motor	DC traction type	2,000	2,500
Motor/system Controls		3,500	4,200
Transmission		3,000	3,000
Electric Drives		700	800
Air Conditioner		6,000	7,000
Remaining Components (Exhibit VI-2)		108,500	126,500
Fully Equipped Bus Cost		\$163,060	\$192,875
Ratio: Fuel Cell/Diesel Cost		1.21	1.13

Methanol-ICE Buses. The methanol-ICE bus power plant is assumed to be a modified diesel engine. The methanol fuel will contain additives to provide the lubricity to the fuel to reduce engine wear and luminosity to the methanol flame for safety. In addition, advanced electronic engine controls will be needed. Some hardware changes will also be needed to avoid problems related to corrosion. The methanol-ICE bus will meet the 1991 bus particulate emission standards without any additional control devices. However, an inexpensive catalytic muffler will be needed to reduce aldehyde emissions to diesel engine emission levels.

For the present analysis, the added hardware and electronics costs have been assumed at 10 percent of the diesel bus prices. Exhibit VII-4 shows the cost build-up for the 30 ft and 40 ft methanol ICE bus.

EXHIBIT VII-4
Cost Build-up for Methanol-ICE Bus

	<u>30 ft</u> <u>Bus</u>	<u>40 ft</u> <u>Bus</u>
1989 Diesel Bus Cost	\$130,000	\$165,000
Additional Hardware and Electronics	13,000	16,500
Formaldehyde Controls	500	500
Fully Equipped Bus Cost	<u>\$143,500</u>	<u>\$182,000</u>
Ratio: Methanol-ICE/Diesel Cost	1.06	1.07

(3) Fuel Prices

The cost of No. 2 diesel fuel for all end users, which includes a \$ 0.10/gallon surcharge for transportation costs, is \$ 0.57/gallon. The cost of commercial grade methanol on the U.S. Gulf Coast spot market is \$ 0.58/gallon, including the cost of transportation. These prices for diesel and methanol fuel do not include federal road taxes. Taxes are assumed to be equal for diesel and methanol fuels on a per gallon basis.

In the long term, it appears possible that petroleum prices will rise and methanol prices will come down until an energy-based price parity is achieved. When this occurs, methanol-based technologies will become attractive, especially for the more efficient fuel cell powered systems.

For the present analysis, therefore, two 1995 price scenarios are considered to provide a range of possible outcomes of fuel price changes. Exhibit VII-5 gives the fuel prices assumed, in 1989 dollars. Scenario A is the current price scenario. For Scenario B, it is assumed that diesel fuel prices will reach the levels reached during the 1979 oil crisis, \$1.00 per gallon plus taxes, while methanol price will be exactly one half of that price.

EXHIBIT VII-5
Fuel Price Scenarios

<u>Price Scenario</u>	<u>Diesel</u>	<u>Methanol</u>
A: Current Prices cents/gal	57	58
B: Energy-Based Prices cents/gal	100	50

5. RESULTS

The results of the life cycle cost analysis are presented in this section.

(1) Relative Costs of Owning and Operating Buses

The results of the analysis clearly show the fractions of the total life cycle costs that can be attributed to the initial, maintenance, and operating costs of the three bus types. Exhibit VII-6 presents the capital, maintenance, and operating costs for standard 40 ft buses in cents/mile at current and energy-based fuel prices.

The initial cost of the fuel cell bus is the highest of the three. The maintenance cost is the highest for diesel buses, in part due to the high cost of maintaining the particulate traps. At current diesel and methanol fuel prices, the operating costs of the methanol-ICE buses are the highest, due to their relative fuel inefficiency compared to fuel cell buses. The operating costs of fuel cell buses are also higher than diesel buses due to the smaller energy content per gallon of methanol compared to diesel fuel.

EXHIBIT VII-6
Relative Costs for Owning and Operating Buses
(Life Cycle Costs in cents/mile)

<u>Current Fuel Prices</u>			
	Diesel	Fuel Cell	Methanol
Capital	28.3	32.1	30.3
Maintenance	10.3	9.9	8.1
Operating	8.5	13.9	19.2

Total LCC	47.1	55.9	57.7
 <u>Energy-Based Prices</u>			
Capital	28.3	32.1	30.3
Maintenance	10.3	9.9	8.1
Operating	14.9	12.0	16.6

Total LCC	53.5	54.1	55.0

When energy-based fuel prices are considered, the fuel cell bus operating costs are the least and the methanol-ICE bus operating costs are the highest. The fuel cell bus operating costs include the cost of leasing platinum.

(2) Comparison of Overall Bus Life Cycle Costs

Looking at Exhibit VII-6, fuel cell bus LCCs are slightly lower than the methanol-ICE bus at current fuel prices. Interestingly, all three buses exhibit relatively constant LCCs at energy-based fuel prices. A comparison of LCCs for 30 ft and 40 ft buses is shown in Exhibit VII-7. The cost trends are the same for the two bus sizes.

(3) Impact Of Fuel Cell Cost Uncertainties

The assumption of the fuel cell price of \$ 750/kW is based on worldwide combined sales of 8,000 to 10,000 50 kW units for transportation type applications. These applications include fork lift trucks and small buses for specialized applications such as airport buses, campus transport, and in-plant transport vehicles. If these sales do not materialize by 1995, fuel cell cost may be as high as \$ 1,000/kW. This will adversely impact the initial or capital cost of fuel cell/battery powered buses.

EXHIBIT VI-7
Comparison of Life Cycle Costs

(a) Current Fuel Prices

(b) Energy-Based Fuel Prices

A 40 ft bus with a 62.5 kW fuel cell will cost \$15,625 more than the estimated cost of \$192,675, an 8% increase. This will result in increasing the LCC by about 2.6 cents per mile, or about 5%. This is within the current level of uncertainty in the economic analysis, so that the overall conclusions should not be impacted.

6. CONCLUSIONS OF THE ECONOMIC ANALYSIS

The results of the analysis clearly indicate that at current diesel to methanol fuel price differentials, it will be difficult for fuel cell buses to compete with diesels on economics alone.

The fuel cell bus has an economic advantage over methanol-ICE buses due to its higher operating efficiency. The methanol-ICE bus operating costs are almost one-third of the overall LCC, even if energy-based fuel prices are considered. The fuel cell bus operating costs are higher than diesel bus operating costs at current fuel prices, but are substantially lower than diesel and methanol-ICE bus operating costs at energy-based fuel prices.

The fuel cell bus is cost-competitive with all buses in overall LCC at energy-based prices. Its operating and maintenance costs are the lowest of the three, while its capital costs are not unreasonably high in comparison.

Within the level of uncertainties existing in the current analysis, therefore, the fuel cell bus economics are within the competitive range of all buses. In comparison to the methanol-ICE bus, the fuel cell bus offers definite economic advantages.

If the fuel cell bus technology and cost projections are accurate, then, the deciding factors for the selection of the type of bus in the 1995-2000 time frame will be based on other than purely economic considerations. Even if the assumed fuel cell cost is inaccurate by as much as 25 percent, the overall impact on the LCC will only be of the order of 5 percent. This is within the degree of uncertainty of the fuel price, market size, and other assumptions.

At present, the transit bus industry enjoys many tax benefits and subsidies, primarily because of the need to reduce urban and highway congestion. These include:

- o Federal grants for capital purchases,
- o Exemption from taxes on gasoline and diesel fuels,
- o State and local subsidies or special grants for operating expenses,
- o Special rights-of-way and travel lanes on highways.

The bus technology of 1995 and beyond will have to show superior environmental, safety, as well as other socioeconomic benefits to be deserving of these special subsidies and tax exemptions. While it is premature to conduct an exhaustive analysis of these factors for the three types of buses, it is clear that any environmentally benign alternative to the diesel bus would receive favorable consideration, if its economics are not too prohibitive.

Other analyses have already shown that the electrically powered bus will offer performance equal to or superior to the current diesel transit bus. The final outcome will depend on the successful demonstration of the fuel cell/battery bus system, favorable public perceptions of electrically-driven vehicles, and on transit industry acceptance of new technology.

The present analysis has shown that the fuel cell/battery bus, using the liquid-cooled phosphoric acid fuel cell as the major power source, could be economically competitive with the alternative bus technologies if energy-based fuel prices, expected fuel cell technology improvements, and the projected cost reductions can be achieved.

VIII. SUMMARY AND RECOMMENDATIONS

Booz, Allen & Hamilton, Inc. and its subcontractors: Englehard Corporation, Fuji Electric Company, Pentastar Electronics, Inc. (PEI), and Eagle-Picher Industries, have met the objectives of the first phase of a program to demonstrate the feasibility of the fuel cell/battery system for powering a small transit bus over an urban route. Various sections of this report discussed the approach used, the work performed, and the findings that resulted from the analyses and brassboard tests. The team concludes that:

- . The liquid-cooled phosphoric acid fuel cell, when coupled with a suitable surge battery, is capable of providing the total power and energy requirements for a standard urban transit bus.
- . The electric drivetrain provides superior traction capabilities to the bus and offers the added energy saving benefits from regenerative braking, which allows storing and reusing braking energy which is normally wasted by conventional power sources.
- . The fuel cell/battery bus system can be economically viable if the projected fuel cell technology improvements and cost reductions can be achieved, along with energy-based fuel prices in the future.
- . The fuel cell offers an attractive alternative power source for urban transit and similar vehicle systems because it allows more efficient utilization of alternative fuels such as methanol and CNG than achievable with internal combustion engines.
- . The fuel cell bus will meet all present and future environmental standards without any performance or cost penalty.

Based on these conclusions, the team recommends that:

A full size liquid-cooled fuel cell/battery powerplant should be developed and tested in one or more suitable urban transit buses to further demonstrate the viability of the concept.

This section summarizes the major findings of the Phase I program and gives general recommendations for further work to be undertaken for Phase II.

1. SUMMARY AND FINDINGS OF THE REPORT

(1) Bus and Powerplant Specifications (Sections II and III)

A baseline bus with a 60 kW liquid-cooled phosphoric acid fuel cell (L-PAFC) developed by Engelhard Corporation and a 170 Ah nickel/iron battery developed by Eagle-Picher Industries was conceptualized as the starting point for the development of bus specifications. When the performance of this bus was calculated by means of a simulation program, it was found to exceed the requirements for acceleration of a standard transit bus. Trade-offs between fuel cell power rating, battery type and size, and powertrain gear ratios were conducted to develop the final bus design and specifications. Major considerations were:

- . Bus performance equivalent to standard diesel bus acceleration and grade performance,
- . Ability to operate over standard DOT urban bus cycle as well as over specified GUTS Arlington Loop route,
- . Ready availability of components, and
- . Reasonable costs in relation to diesel bus costs.

Exhibit VIII-1 shows the specifications for the bus and its major components developed as a result of the trade-offs and inputs from the Technical Advisory Panel. These specifications resulted in a realistic layout and weight balance for the fuel cell/battery powered bus. Exhibit VIII-2 shows a conceptual drawing of the bus.

Detailed simulations of the bus performance were made for the standard DOT Transit Bus and GUTS Arlington Loop routes. The simulations provided the system performance and energy consumption data that would be used for comparing with test data.

(2) Brassboard Design (Section IV)

The specifications for the fuel cell, battery and power train were used to develop the specifications for a brassboard system suitable for testing in the laboratory. A 25 kW fuel cell was specified, along with a half-size (38 Ah) lead-acid SLI battery.

EXHIBIT VIII-1
Summary of Specifications for the
Fuel Cell/Battery Powered Bus

<u>Fuel Cell Subsystem</u>	Liquid-Cooled Phosphoric Acid
Nominal Power Rating	50 kW
Fuel	Commercial Grade Methanol
Efficiency	42% (LHV) at Chopper Output Terminal
Single Cell Performance	0.66V @ 240 mA/cm ²
Number of Cells	160
Total Weight	2,598 lb (1,178 kg)
<u>Battery</u>	Lead-acid SLI Type
Nominal Voltage	204 V
Capacity (C/2)	76 Ah
Subsystem Weight	1,250 lb (567 kg)
<u>Motor</u>	DC Traction Motor
Base Speed/Maximum Speed	900 rpm/3,500 rpm
Weight	1,050 lb
<u>Controller</u>	Transistorized
Voltage/Current	128 VDC/1200 A
Weight	600 lb
<u>Bus Body</u>	Standard Transit, forward control
Length	26.7 ft (8.14 m)
Width	90 in (2,286 mm)
Floor Height	14 in.
Seating	22 passengers
Weight, including axle	13,000 lb
<u>Accessories</u>	All standard bus accessories, including air conditioning
<u>Total Bus Weight (GVW)</u>	22,480 lb (10,195 kg)

EXHIBIT VIII-2
Artist's Concept for the
Fuel Cell/Battery Powered Bus

VIII-4

The brassboard fuel cell subsystem was designed, built, and tested by Fuji Electric Company. The fuel cell subsystem included the fuel cell stack, a reformer, a fuel cell internal controller, and a step-up chopper. PEI integrated the fuel cell internal controller and the step-up chopper output with the battery management system and the system controller.

The brassboard battery (Exide HP31D) was acquired and tested to verify its operating characteristics and to calibrate the battery state-of-charge measuring algorithms. It was found that the battery did not meet the published manufacturer's specifications. Considerable variation was observed between the battery modules obtained from different suppliers. Finally, a different battery (Exide D31D) was selected for the brassboard tests.

A half-size motor and controller were acquired and checked out, but not assembled and tested on the brassboard system due to lack of time. Instead, a resistive load bank was used to provide the traction power demand.

(3) Brassboard Tests (Sections V and VI)

The brassboard tests were conducted at PEI facilities in Huntsville, Alabama. An automatic data acquisition system was utilized to record the important test parameters.

The complete brassboard test program covered three test phases:

Test Phase 1 - Acceptance
Test Phase 2 - Performance Characterization
Test Phase 3 - Proof-of-Feasibility.

Careful planning of each test phase was essential to meet the tight time schedule and meet all the test objectives.

Acceptance Tests - The purpose of these tests was to verify that the performance of the fuel cell subsystem and the battery modules complied with the specifications.

The brassboard fuel cell subsystem exceeded the power and efficiency specifications. The steady load power output of the fuel cell subsystem was measured to be 23.23 kW, 3.2% above the 22.5 kW specification, while the fuel consumption was 4.5% below the 10.79 kg/hr specification. As a result, the subsystem efficiency at full power was measured to be 38.8% without auxiliaries, and 36.5% with auxiliaries. The auxiliaries (cooling pumps, air and fuel supply pumps, etc.) thus consumed only 2.3% of the gross output of the fuel cell. The efficiencies are higher, and the parasitic losses from the auxiliaries are lower, than those obtainable from air-cooled PAFC systems.

The start-up time (33 minutes) and power-up time (7 minutes for power increase from 25 to 100% rated power) also were within specifications. [The power-up time for the full size fuel cell is expected to be only 4 minutes for power increase from 0 to 100%.]

The Exide HP31D battery did not meet specifications. After testing several different modules, the Exide D31D battery module was accepted and installed in the brassboard.

Performance Characterization - The purpose of these tests was to characterize the performance of the fuel cell and battery subsystems individually and then in the hybrid configuration. Steady-state operation was used for characterization. Varying loads were also applied to test and verify the communication between the fuel cell and the battery subsystems, automatic control of fuel cell power output, and proper operation of the system controller.

Good agreement was obtained between the fuel cell performance measured during these tests and that measured during the earlier acceptance tests.

The battery, which consisted of 17 Exide D31D 12 V modules, performed well, but its still voltage-current characteristic presented some problems in accurately measuring the state-of-charge from the calibrated voltage-current curve. Periodic corrections to the Ampere hour readings and periodic equalization charges were required to ensure proper system control.

The power demand from the fuel cell was controlled by the battery and system controller, based on the battery voltage and traction power requirement. The fuel cell power output was controlled by a 0 to 10V analog signal supplied to the fuel cell internal controller. Some temperature drift problems were encountered by the Hall effect sensors which sensed the load current. The problems were remedied by replacing the sensors by shunts. The control system worked well and excellent correlation was obtained between the load demand (the traction power) and the fuel cell/battery system power output.

The data acquisition system developed by PEI worked flawlessly. It provided the needed data for further analysis, and served as a learning tool for future data acquisition systems. Due to time and cost limitations, the system was limited in the number of channels recorded. For example, much of the on-line fuel cell performance data: temperatures, auxiliary power supply rates, and fluid flow rates, were not recorded. Future systems may selectively record some of these data.

Proof-of-Feasibility - The purpose of this final test phase was to verify the capability of the brassboard, after proper scaling corrections, to power the full size bus over the standard DOT and GUTS routes. The measured fuel consumption and battery state-of-charge data were compared with the corresponding data projected by two independent computer simulation programs. The analysis therefore also provided verification of the assumptions used in developing the simulation programs.

The loads on the fuel cell/battery powerplant were controlled manually. The test procedure was carefully developed to ensure that the loads corresponded with the traction power requirements for the test routes. This procedure worked well, although automatic control through a small microprocessor or personal computer would be the preferred method for future testing.

The fuel consumption measurements for the DOT cycles agreed exceptionally well with the PC simulation program. Highest fuel consumptions were measured for the Commuter segment at 0.93 mpg. The consumption for the Central Business District (CBD) segment was 1.87 mpg and for the Arterial segment, it was 3.63 mpg. The agreement for individual segments was poorer between the PEI simulation and the measured data. A more detailed analysis of the discrepancy is needed.

For the GUTS 7% upgrade and maximum speed segments, agreement between the measured fuel consumption and the PEI simulation results was excellent. The battery states-of-charge at the beginning of the segments were controlled. Agreement between the end of segment measured and estimated states-of-charge was also excellent.

For the complete GUTS Arlington Loop test data, several corrections were needed to match the test conditions with the simulation results. The brassboard tests were commenced with the fuel cell at 25% power, while the simulations had assumed full power at commencement. Also, the brassboard tests did not include regeneration, which could account for as much as 18% improvement in fuel economy for the GUTS route. Additional test and simulations are needed to verify these conclusions.

Based on the limited number of test performed, the brassboard tests verified proof-of-feasibility of the fuel cell/battery powered bus system.

(4) Economic Analysis (Section VII)

The cost-competitiveness of equivalent L-PAFC/battery, diesel, and methanol-ICE powered buses was analyzed and compared on a life cycle cost basis. A sensitivity analysis was conducted to provide a range of possibilities related to cost and bus operational usage. The bus technologies were assumed to comply with the environmental standards for the 1995-2000 time frame, and current as well as energy-based fuel pricing structures were evaluated.

The results indicate that with energy-based fuel prices, the fuel cell bus economics are within the competitive range of all buses.

The fuel cell bus has an economic advantage over methanol-ICE buses due to its higher operating efficiency and lower maintenance costs. At the current diesel and methanol fuel price differential, however, L-PAFC powered buses will not be economically competitive with diesel buses.

The analysis did not quantify the economics of environmental benefits, performance improvement, and petroleum replacement potential of fuel cell powered buses. These benefits would make the fuel cell bus technology more attractive if suitable incentives are available to bus manufacturers and operators.

2. RECOMMENDATIONS

The findings of the Phase I study clearly indicate that L-PAFC/battery powered buses are technologically feasible. However, many uncertainties in the actual performance and design of the hybrid system and in the projected capital and operating costs of such systems still exist. Therefore, further government funded research and development efforts will be needed before the bus industry, which is a highly competitive industry in the U.S., will be able to assume the full costs of further development toward commercialization.

Booz, Allen & Hamilton and its team members recommend that the program should proceed to Phase II, with the development and testing of a full size test-bed bus system utilizing the L-PAFC system as the power source. The experience of the team members in developing and testing the brassboard system should be utilized to ensure continued success and to avoid the cost of relearning by new organizations.

A bus manufacturer should assume a leading role for the next phase. This will ensure that industry inputs are fully factored in at the earliest stage of bus design. It will also ensure that industry will begin to acquire hands-on experience with electric vehicle and fuel cell technologies, thereby reducing the perception of risks inherent in accepting new and unknown technologies. The probability of industry participation will be enhanced if full size (40 ft) transit bus designs are developed along with the small bus during Phase II, and tested soon thereafter.

Ultimately, some government incentives will be needed to encourage bus operators to specify and evaluate the fuel cell powered buses and thereby demonstrate their environmental and energy conservation benefits. These incentives may be in the form of a larger percentage of capital grants for the purchase of environmentally benign buses, or in the form of mandated purchases of a specified percentage of such buses in each fleet.

APPENDIX A
BUS DRIVING CYCLES

APPENDIX A
BUS DRIVING CYCLES

Georgetown University Transportation Society (GUTS) Arlington Loop has been documented by the Advanced Engineering Department of Georgetown University and is tabularly shown in Exhibit A-1. A graphical representation of this route, showing the speed limits and elevation changes, are also shown in Exhibit A-2.

The Indianapolis (INDY) driving cycle, shown in Exhibit A-3, is made up of two distinct phases -- Central Business District (CBD) and Arterial-type service with top speeds of 20 and 40 mph, respectively. The INDY driving cycle is the Indianapolis variant of the Transit Bus Driving Cycle and is used to establish a correlation with diesel buses meaningful to the transit industry.

EXHIBIT A-1
Georgetown Route Profile Arlington Loop

ARLINGTON GUTS BUS ROUTE		DIST (FT)	ELEV (FT)	SPEED LIMIT (MPH)	DWELL (SEC)
Podium A (Transportation Center)	(pickup)	0	140	0	0
Parking lot stop sign #1	(stop sign)	404	153	15	2
Parking lot stop sign #2	(stop sign)	236	155	15	2
St. Mary's	(pickup)	165	159	15	20
Enter Reservoir Road	(stop sign)	289	162	15	3
Apartment entrance (36th St)		564	182	25	0
Reservoir Road/35th St.	(traffic light)	464	176	25	10
35th St/Volta	(stop sign)	1061	146	25	2
35th St/P St.	(stop sign)	362	133	25	2
35th St/O St.	(stop sign)	362	117	25	2
35th St/N St.	(stop sign)	363	108	25	2
N St./34th St.	(stop sign)	334	104	25	2
34th St./Prospect St.	(stop sign)	293	103	25	2
34th St./M St.	(traffic light)	283	78	20	50
M St./KEY BRIDGE	(traffic light)	149	68	25	0
middle of KEY BRIDGE		1000	78	30	0
KEY BRIDGE/Parkway ramp	(traffic light)	1000	68	30	30
Fort Myer/Lee Highway	(traffic light)	430	65	30	10
Lee Highway/Nash	(traffic light)	230	78		0
Lee Highway/Oak	(traffic light)	540	84	35	0
Lee Highway/Scott	(pickup, traffic light)	1570	140	35	20
Lee Highway/Veitch	(traffic light)	1840	215	35	5
Lee Highway/Adams	(pickup, traffic light)	590	226	35	5
Lee Highway/Cleveland	(traffic light)	765	228	35	10
Lee Highway/Calvert	(pickup)	100	235	35	0
Lee Highway/Daniel	(traffic light)	495	225	35	0
Lee Highway/Spout Run	(traffic light)	935	175	35	10
Kirkwood Rd pickup	(pickup)	185	173	35	0
Kirkwood Rd/17th St.		2170	198	30	0
Kirkwood Rd/13th St.	(pickup)	1340	224	30	20
Kirkwood Rd/Washington Blvd.	(traffic light)	620	240	30	10
Washington Blvd/Fairfax Dr	(traffic light)	485	262	30	10
Washington Blvd/Wilson Blvd	(traffic light)	366	260	35	0
Washington Blvd/Highland	(traffic light)	729	260	35	0
Washington Blvd/10th St.	(traffic light)	660	260	35	10
10th St./Danville	(pickup)	785	252	35	0
10th St./Barton	(traffic light)	600	225	35	0
Barton/ 9th St.	(pickup)	560	245	35	0
Barton/Pershing Dr	(stop sign)	806	239	25	15
Pershing Dr/Wayne	(pickup)	484	235	25	18
Pershing Dr/Arlington Blvd	(traffic light)	410	231	25	10
Arlington Blvd/10th St		1650	188	25	0
Arlington Blvd/Rolle		1810	128	45	0
Arlington Blvd/BRIDGE	(pickup)	580	146	45	10
BRIDGE/Fairfax Dr	(pickup)	350	140	45	2
Fairfax Dr/Fort Myer	(traffic light)	2318	108	20	12
Fairfax Dr/Lynn St.	(traffic light)	100	94	25	0
Lynn St/River Place	(pickup)	187	90	25	0
Lynn St/Wilson Blvd	(traffic light)	547	86	30	0
Lynn St./METRO STATION	(pickup)	213	81	30	15
Lynn St./18th St.	(traffic light)	580	67	30	0
Lynn St./19th St.	(traffic light)	426	63	30	20
Lynn St./Route 68 ramp	(traffic light)	269	66	30	0
KEY BRIDGE/PKWY ramp	(traffic light)	255	68	30	0
middle of KEY BRIDGE		1000	78	30	0
KEY BRIDGE/M St.	(traffic light)	1000	68	30	10
M St./34th St.	(traffic light)	240	78	30	10
M St./33rd St.	(traffic light)	510	70	25	0
33rd St./Prospect St.		325	85	25	0
33rd St./N St.	(stop sign)	335	85	25	2
N St./34th St.	(stop sign)	494	104	25	2
N St./35th St.	(stop sign)	334	108	25	2
35th St/O St.	(stop sign)	363	117	25	2
35th St/P St.	(stop sign)	362	133	25	2
35th St/Volta	(stop sign)	362	146	25	2
35th St./Reservoir Road	(traffic light)	1066	176	25	20
Apartment entrance		510	182	25	0
Hospital parking lot entrance	(left turn)	928	146	25	4
St. Mary's	(pickup)	272	154	25	4
Parking lot stop #1	(stop sign)	190	154	15	2
Parking lot stop #2	(stop sign)	160	152	15	2
Parking lot stop #3	(stop sign)	290	151	15	2
Podium A (Transportation Center)	hold over.....	185	140	15	1700

MI215-01

EXHIBIT A-2 GUTS Arlington Loop Profile

NOTE: Buses normally operate at about 10 mph below the maximum speeds shown

EXHIBIT A-3
 DOT Indianapolis (INDY) Bus Driving Cycle

M12.15-02

APPENDIX B

FUEL CELL/BATTERY POWERED BUS SIMULATION MODEL

APPENDIX B
FUEL CELL/BATTERY POWERED BUS SIMULATION MODEL

The fuel cell/battery powered bus system performance was projected by means of a computer simulation program. The program was originally developed by Pentastar Electronics for analysis of the Chrysler TEVan system and recently modified, incorporating the fuel cell subsystem for the fuel cell/battery hybrid bus program. The analysis program is written in BASIC language and runs on a Tandem mainframe. The program is written using modular construction, whereby each subsystem is contained in a subroutine allowing for ease of modification.

In analyzing the bus system operation, the total system is evaluated based on given input forcing functions as shown in Exhibit B-1. The Georgetown University Transportation Society (GUTS) Arlington Loop profile is based on measured road data supplied by Georgetown University. The Indianapolis (INDY) cycle route profile was derived from existing transit bus performance data. The INDY cycle closely complies with current transit bus operation in the Indianapolis area.

The functional block diagram of the fuel cell/battery powered bus simulation program is shown in Exhibit B-2. The simulation program uses mathematical models of the major bus subsystems to calculate the total system load required for each incremental time step in the route profile to obtain the total energy used, instantaneous peak power, bus velocity and distance traveled. The traction load is calculated based on the road load the bus encounters due to aerodynamic drag, tire rolling loss, road gradient and in overcoming inertia. The voltage-current characteristics of the Engelhard/Fuji liquid-cooled phosphoric acid fuel cell subsystem used in the simulation program is shown in Exhibit B-3. The fuel cell performance is based on nominal operation at 190°C (375°F).

The fuel cell provides constant power to meet the bus traction and accessory load requirements and to maintain the traction battery state-of-charge at a desirable level. If the traction battery is fully charged the total system load from traction and accessories falls below the fuel cell power, then, the fuel cell is throttled back.

The accessory load is based on a typical transit duty cycle and includes the power and weight of an air conditioning system yielding a nominal electrical load of 15.5 kW. This load is reduced to 5.4 kW during the rest period at the end of the GUTS Arlington Loop and during the 5-minute idle period at the completion of the INDY cycle.

EXHIBIT B-1
System Forcing Function Profiles

• Constant Speed (Cruise)• Maximum Acceleration to Speed• Maximum Speed• Grade Performance• Arterial Bus Route• Commercial Business District Bus Route• Commuter Bus Route	• Diesel Equivalency• SAE J227a Schedule C• SAE J227a Schedule D• Georgetown University Transportation Society (GUTS) Arlington Loop• Indianapolis (INDY) cycle

M12.15-12

EXHIBIT B-2
**Functional Diagram of Fuel Cell/Battery Powered
Bus Simulation Program**

M12.15-13

EXHIBIT B-3
Fuel Cell Voltage-Current Characteristics

M12.15-14

The major bus subsystems modeled are the fuel cell, the traction battery, DC motors, transmission, and controller. These major subsystems are examined during bus acceleration, cruise and deceleration modes to further understand the workings of the fuel cell/battery bus system.

1. FUEL CELL/BATTERY BUS SYSTEM EQUATION

The bus system equation used to compute the required system power and energy requirements from the driving profile is expressed as:

$$DV = \frac{1}{M} \times FBS \times DT \quad (1a)$$

$$V = \frac{1}{M} \times \Sigma (FBS \times DT) + V_0 \quad (1b)$$

where:

V = bus velocity, ft/sec
 DV = velocity increment, ft/sec
 M = bus weight + inertia weight, slugs
 FBS = bus force, lb
 DT = time increment, sec
 V₀ = initial bus velocity, ft/sec

The bus force required for accelerating the bus is the sum of the forces due to road gradient, FG, FA, aerodynamic drag, FR tire rolling friction, braking, FB and FM motor. Each of these forces is expressed as:

$$FBS = -(FG + FA + FB + FR \pm FM) \quad (2)$$

NOTE: The $\pm$ pertains to the fact that during regen the sign changes

$$FG = G \times MB \quad (3)$$

where,

G = road grade, %/100
MB = bus weight

$$FA = C_d \times A \times V^2 \times K \quad (4)$$

where,

$C_d \times A$ = bus drag coefficient frontal area product, ft^2

K = constant of proportionality

$$FR = RT \times MB \quad (5)$$

where,

RT = rolling coefficient of tire, lb/lb

$$FM = (MT \times GTR \times GTE)/SLR \quad (6)$$

where,

MT = motor shaft torque, ft-lbs
GTR = gear torque ratio, ft-lbs
GTE = gear torque efficiency, ft-lbs
SLR = tire static loaded radius, ft

The net shaft torque (NST) of the motor is expressed as:

$$NST = AC \times MTC \times FF \pm WT \quad (7)$$

NOTE: + is during Regen

where,

AC = armature current, amps
MTC = motor torque constant
FF = field flux
WT = windage and friction torque losses

$$WT = FC + WC \times MS$$

(8)

where,

FC = friction constant
 WC = windage constant
 MS = motor speed

The motor field flux is a function of the field current and is derived from the motor saturation curve.

The bus velocity is derived from the following equation:

$$V = MS/GR \times RPM$$

(9)

where,

MS = motor speed, rpm
 GR = overall gear ratio

where,

GR = f (transmission gear ratio)
 RPM = tire revolutions per mile per minute

The bus inertia weight represents the equivalent weight of wheel inertia, which includes the effects of the tires and wheels to accelerate/decelerate the bus. For a 25,000 pound bus the ratio of inertia weight to bus weight is approximately .03.

The simulation program varies the incremental time step during the route profile based on whether the bus is in acceleration, cruise, deceleration or rest mode. The time step varies from 0.01 seconds during the acceleration mode to 1 minute during rest mode.

(1) Acceleration

During bus acceleration it is assumed that the driver will demand the maximum acceleration from the bus, thus, requiring the maximum armature current from the motor. The motor produces constant torque output up to a base speed of 3,500 rpm and constant horsepower up to its rated maximum speed of 8,000 rpm.

The electrical power of the motor, MP, is obtained from the expression:

$$MP = AV \times AC + FR \times FC^2 + MCFP \quad (10)$$

where,

AV = armature volts
 AC = armature current
 FR = field resistance
 FC = field current
 MCFP = motor cooling fan power

Once the electrical motor power is calculated, the sum of accessory power, controller power losses and parasitic battery tray power are combined with the traction motor to obtain the total required system power. The controller model includes switching, free wheel, conduction, and fixed power losses, as defined below.

$$\begin{aligned} \text{Switching Losses (SL)} = & \frac{(100E-9)BV \times AC \times CF}{2} + \\ & (0.5E-6)AC^2 \times \frac{CF}{2} + \\ & (150E-9) \times \frac{CF}{2} + (0.1E-6) \frac{CF}{2} \quad (11) \end{aligned}$$

where,

BV = battery volts
 CF = chopper frequency

$$\text{Free Wheel Losses (FWL)} = 1.5 \times AC (1 - DC) \quad (12)$$

where,

DC = duty cycle (Note: losses occur when DC $\neq$ 1)

$$\text{Conduction Losses (CL)} = CR \times AC^2 \times DC \quad (13)$$

where,

CR = conduction resistance in chopper on mode

$$\text{Fixed Power Losses (FPL)} = CPS + HSF \quad (14)$$

where,

CPS = controller power supply losses
 HSF = heat sink fan losses

The total system power is reduced by the constant fuel cell power to obtain the power available for charging/discharging the battery. A matrix array of battery voltage, current and state-of-charge (SOC) is used to determine the terminal voltage of the traction battery.

The battery equation used to derive the SOC is expressed as:

$$\text{SOC} = \frac{(-\text{BC} \times \text{CE} + \text{FL}) \times \text{DT}}{\text{AH}} \quad (15)$$

where,

BC = battery current
CE = coulombic efficiency
FL = fan loss current
AH = amp hour capacity

NOTE: The CE value is a function of the battery current direction

Once the battery terminal voltage is calculated, the current levels and power of the fuel cell and battery are known, since both are in parallel. This procedure is iterated for each time increment during the acceleration mode.

(2) Cruise

The computer simulation model uses the same procedure as outlined in the acceleration section to calculate the cruise traction and total power requirements. However, in cruise mode, the required armature current is calculated to maintain the constant speed, whereas in acceleration mode the maximum armature current is assumed. The armature current is calculated from the net shaft torque (equation 7) required from the motor, since the motor force is the sum of external forces acting on the bus (equation 2).

The program logic during cruise mode assumes that if available power is remaining from the fuel cell after meeting the bus load requirements, then this remaining power is used to charge the traction battery up to the maximum desirable level. If the battery has reached the maximum SOC level, then, the fuel cell power is reduced.

(3) Deceleration

Two scenarios can occur during the deceleration mode--braking with regeneration only or braking with regeneration and air braking.

The first scenario, braking with regeneration only, when the regenerative braking force is sufficient to slow the bus at 6 fpsps. A new regenerative braking current is calculated and the resulting motor (generator) force equation becomes,

$$FM = (MT \times GTR)/(GTE \times SLR) \quad (16)$$

The second scenario, braking with regeneration and air brakes occurs when the regeneration current limit specified is insufficient to slow the bus at constant 6 fpsps deceleration. Therefore, additional frictional air braking is necessary to slow the bus further.

In both scenarios, braking with regeneration only or braking with regeneration and air braking, the excess power generated from regeneration is always used to charge the traction battery.

2. SUMMARY OF MODELING ASSUMPTIONS

The simulation model contains a number of assumptions that were made for predicting the fuel cell/battery powered bus performance. The following is a list of the assumptions:

1. At the start of each working day, the fuel cell is assumed to be at operating temperature to supply the required current level and the traction battery is charged to operating SOC. The fuel cell and chopper are lumped together and considered as a "black box."
2. The bus weight is constant over the entire driving cycle profile.
3. The bus accelerates to the limits of the capacity of its powerplant or in conformance with the specified driving cycle.
4. Altitude and temperature conditions were based on sea level atmospheric pressure of 29.92 Hg and 60°F.
5. Effective frontal area and aerodynamic drag coefficient is computed as:

$$AF = W \times H - [Hb \times (W - Wt)]$$

$$AF = 84 \times 114 - [25 \times (84 - 20)] = 7976 \text{ in}^2 \\ (55 \text{ ft}^2)$$

$$\text{so, } Cd = 0.85$$

where

W = bus width, inches
H = bus height, inches
Hb = bumper height, inches
Wt = tire width, inches

6. Each passenger weighs 150 pounds.
7. Bus operates on dry concrete with no head/tail wind.
8. No accounting is made for road traffic congestion.
9. Constant deceleration rate of 6 fpsps is used.
10. The tire characteristics are based on 10R22.5 steel/
steel radial tires with 22.5 x 7.5 tubeless wheels.
 - . SLR (Static Loaded Radius) = 18.8 inches
 - . Turns/mile = 517
 - . Rolling force coefficient - 7.5 lb/1,000 lb
 - . Equivalent weight of tire/wheel inertia = 649.4 lb
 - . Front tire capacity = 5,150 lb/tire @ 100 psi
 - . Rear tire capacity = 4,520 lb/tire @ 90 psi
 - . Weight per tire is 200 pounds
11. The overall drivetrain gear ratio is 20.63:1 and is
based on a bus top speed of 45 mph with a maximum
motor rpm of 8,000.
12. The overall drivetrain gear torque efficiency is
constant at 93 percent. The HY-VO chain coupler,
transmission and axle/differential are 98 percent,
97 percent, and 98 percent efficient, respectively.
13. The battery constants and parameters used are:

	No. of Cells	Initial SOC	Circuit Resistance	Open Circuit Voltage	Charging Coulombic Efficiency
NIF-170	150	80%	0.108324	207.09	85%
HP31E	102	90%	0.063	218.07	85%
3ET205	102	90%	0.12597	218.07	85%

14. The DC motor constants and parameters used are:
- . Maximum field strength = 0.89 meglines
 - . Armature circuit DC resistance = 0.0654
 - . Generator constant = 0.05 V/(meglines)x RPM
 - . Torque constant = 0.352 ft-lb/(armature amperes)x (meglines)
 - . Windage constant = 2.0 E-9
 - . Static friction constant = 0.044
15. The water and liquid methanol tanks are filled to one-half capacity (24 gallons) and remain constant during the driving cycle.
16. The rest accessory power consists of 300 watts of continuous electrical load and a partial air conditioning load of 5,123 watts. The air conditioning compressor load during this period is 2 tons. The air compressor and power steering pump will not be in operation during the rest period.
17. All accessory power requirements for pumps, compressors and component motors have been adjusted upwards by 10 percent to account for electric motor losses.

Differences between these modeling assumptions and actual operating environments may account for significant variations in the performance figures. Therefore, the computer simulation performance results should be used only within the context of this report.

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