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DIRECT-HYDROGEN-FUELED PROTON-EXCHANGE-MEMBRANE FUEL CELL SYSTEM FOR TRANSPORTATION APPLICATIONS

CONCEPTUAL VEHICLE DESIGN REPORT PURE FUEL CELL POWERTRAIN VEHICLE

CONTRACT NO. DE-AC02-94CE50389

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FOREWORD

This report documents a portion of the results of the project entitled "Direct-Hydrogen-Fueled Proton-Exchange-Membrane Fuel Cell System for Transportation Applications" performed by Ford Motor Company, under contract DE-AC02-94CE50389. The project objective was to design, fabricate, and test a 50-kW direct hydrogen fueled proton exchange membrane (PEM) fuel cell system including onboard hydrogen storage, efficient lightweight fuel cell, gas management system, and complete system controls that can be economically mass produced and comply with all safety, environmental, and consumer requirements for vehicle applications for the 21st century. Specifically, this report presents conceptual designs for a pure (no power augmentation) fuel cell-powered vehicle based on three different vehicle classes, namely, small car, mid-size car, and full-size van.

Dr. Djong-Gie Oei, project manager at Ford, prepared the report with contributions from Ford staff, namely, Alan Kinnelly, Ron Sims, Mark Sulek, and David Wernette. Brian James, Franklin Lomax, George Baum, C. E. (Sandy) Thomas, and Ira Kuhn, all from Directed Technologies, Inc., also contributed to the report.

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ABSTRACT

In partial fulfillment of the Department of Energy (DOE) Contract No. DE-AC02-94CE50389, "Direct-Hydrogen-Fueled Proton-Exchange-Membrane (PEM) Fuel Cell for Transportation Applications", this preliminary report addresses the conceptual design and packaging of a fuel cell-only powered vehicle. Three classes of vehicles are considered in this design and packaging exercise, the Aspire representing the small vehicle class, the Taurus or Aluminum Intensive Vehicle (AIV) Sable representing the mid-size vehicle and the E-150 Econoline representing the van-size class.

A fuel cell system spreadsheet model and Ford's Corporate Vehicle Simulation Program (CVSP) were utilized to determine the size and the weight of the fuel cell required to power a particular size vehicle. The fuel cell power system must meet the required performance criteria for each vehicle.

In this vehicle design and packaging exercise, the following assumptions were made: fuel cell power system density of 0.33 kW/kg and 0.33 kg/liter, platinum catalyst loading less than or equal to 0.25 mg/cm^2 total and hydrogen tanks containing gaseous hydrogen under 340 atm (5000 psia) pressure. The fuel cell power system includes gas conditioning, thermal management, humidity control, and blowers or compressors, where appropriate.

This conceptual design of a fuel cell-only powered vehicle will help in the determination of the propulsion system requirements for a vehicle powered by a PEMFC engine in lieu of the internal combustion (IC) engine. Only basic performance level requirements are considered for the three classes of vehicles in this report. Each vehicle will contain one or more hydrogen storage tanks and hydrogen fuel for 560 km (350 mi) driving range. Under these circumstances, the packaging of a fuel cell-only powered vehicle is increasingly difficult as the vehicle size diminishes.

1.0 Executive Summary

1.1 Introduction

On July 1, 1994 the Department of Energy (DOE) awarded the Ford Motor Company a contract, identification number DE-AC02-94CE50389, for the research and development of a "Direct-Hydrogen-Fueled Proton-Exchange-Membrane (PEM) Fuel Cell for Transportation Applications". The subcontractors under this program received their subcontracts at different times and the last subcontract was placed on May 23, 1995. Due to the staggered awarding of the subcontracts, Phase I of the overall program ends May 31, 1996, Phase II ends May 31, 1997, and Phase III ends September 30, 1997.

For several decades, Ford Motor Company has been diligently working towards the production of vehicles that are both consumer-oriented and environmentally benign. With increasingly stringent emission regulations and demand towards higher vehicle fuel economy, Ford has been conducting research and development in alternative power sources and alternative fuels for automotive applications to meet these new challenges. In the early 1960's, Ford began research and development of high energy density batteries, which culminated in the invention of the sodium-sulfur battery [1]. This effort was part of Ford's research and development in providing a high power and high energy density battery for a vehicular electric propulsion system.

Recent emission regulations proposed by the State of California, requiring Zero Emission Vehicle (ZEV) standards for automobiles, have focused the efforts of car manufacturers on the electric car. Using currently available batteries, the electric car has a very limited driving range depending on weather and road conditions. A fuel cell is an electrochemical power source that can supply the electricity for electric propulsion, and if fueled by hydrogen, is a true ZEV engine. Driving range for the fuel cell vehicle is only limited by the amount of stored fuel onboard. Both theoretical and practical fuel efficiencies of the fuel cell are much higher than for thermal combustion engines. Hence, for these reasons, a fuel cell engine is an attractive alternative to replace the internal combustion engine.

1.2 Fuel Cell Attributes

A fuel cell is an electrochemical energy conversion engine which converts a fuel and oxidant directly into electricity. This electrochemical conversion has a very high thermodynamic efficiency compared to thermal energy conversion in the internal combustion (IC) engine. The practical energy conversion efficiency in a fuel cell can be as high as 65% compared to 30% to 35% for the IC engine. Moreover the fuel cell is a clean engine and if hydrogen is used as the fuel, then the products of the electrochemical reaction are water and electrical energy.

The proton exchange, or polymer electrolyte membrane fuel cell (PEMFC), uses a proton conducting polymer membrane as the electrolyte and operates in a lower temperature range, between 20 ^{0}C and 120 ^{0}C. PEMFC technology is considered to be most suitable for automotive application. To be a viable replacement of the IC engine, the fuel cell power system must achieve parity in terms of cost, weight and volume density with the IC engine. For a variety of reasons, such as temperature of operation, carbon dioxide tolerance and other factors, the PEMFC is the best candidate for automotive application. PEMFC technology has advanced considerably since their early application as an electricity generator for space vehicles, and recently platinum catalyst loading on the electrodes have been reduced drastically. At the same time, the fuel cell power volume and weight density have improved.

1.3 Conceptual Vehicle Designs

In the DOE/Ford fuel cell contract, the intention is to put the fuel cell power system and ancillary equipment on a test bed and exercise the fuel cell system through various drive cycles. In this report, consideration is given to the pure fuel cell powered vehicle, to be followed by the final report on the battery augmented fuel cell powered system.

Three basic vehicle sizes are examined in this conceptual vehicle design. The small vehicle is represented by Ford's Aspire model, the intermediate size vehicle by the Taurus or AIV (Aluminum Intensive Vehicle) Sable, and the E-150 Econoline series represents the van-size vehicle. Based on Ford's experience in manufacturing automobiles, customer expectations of vehicle performance (acceleration, throttle response, speed, range, gradeability, and start-up time) are the basic important parameters to be considered in the conceptual propulsion system design. From these expectations, power and drivetrain performance requirements were calculated. Practical, feasible conceptual vehicle designs were then proposed for the three vehicle sizes, and a power system analysis carried out to establish vehicle architecture and performance trade-offs for the powertrain and hydrogen storage systems. Although three vehicle sizes are studied in this conceptual design, the mid-size vehicle, the AIV Sable, was more extensively studied and comprehensively examined as the most probable vehicle size for implementing both the pure fuel cell and battery augmented fuel cell vehicle configurations. This effort will also contribute to the PNGV (Partnership for a New Generation of Vehicles) goal of advancing new, more fuel-efficient powertrains.

1.4 Remaining Technical and Commercial Issues

To be a viable candidate for replacing the conventional gasoline engine, the PEMFC power system must achieve technical and economic parity with the IC engine. Currently the most advanced PEMFC power system achieves a power system density of 0.33 kW/kg [2]. The fuel cell power system consists of the fuel cell stack, humidity control, gas conditioning, thermal management, and air blower or compressor units. Estimates of the power density of an IC engine vary from 1.2 to 1 kW/kg. Fuel (hydrogen) storage is another major technical challenge when compared to gasoline, especially when a 560 km (350 mi) driving range is required of the vehicle.

At present, the cost of an IC engine, on a power basis, is estimated to be between $25 and $35 per kW. For the PEMFC engine, cost figures are not readily available. However, when the trend of diminishing cost of the maturing stationary phosphoric acid fuel cell power system is considered, and the advances in material application of the PEMFC system are taken into account, it is possible to make a credible estimate of the cost of the PEMFC. Various sources report the cost as greater than $500 per kW [3]. However, other projections of the cost using advanced manufacturing methods and future material costs reduce the fuel cell system cost to less than $50/kW [4].

For the direct hydrogen-fueled PEMFC, the onboard storage of hydrogen presents several choices and challenges. Various methods of hydrogen storage, such as in the form of chemical hydride, rechargeable metal hydride, liquid, and compressed gas, were considered. Advantages and disadvantages of each method have been analyzed as noted in Reference 5. Compressed hydrogen gas was chosen after considering the present state of hydrogen storage technology as well as weight and volume considerations. In the proposed conceptual design, the hydrogen is stored in the compressed gaseous form using an advanced composite hydrogen storage tank. Typically, natural gas is stored at a pressure of 245 atm (3600 psia), but hydrogen requires a higher pressure, at least 340 atm (5000 psia), in order to provide adequate energy. At this pressure, the volume of the hydrogen tank is about three times that of a 22 gallon gasoline tank providing the same vehicle driving range. If the compressed hydrogen gas pressure is increased to 510 atm (7500 psia) then the volume of the compressed hydrogen gas tank will be twice that of the gasoline tank for an equivalent driving range. This is considered to be the maximum size allowed for realizable packaging of the PEMFC system in a vehicle. The cost of manufacturing a safe and reliable compressed gaseous hydrogen tank is also considerably higher than the cost of a gasoline tank. Gasoline tanks can be made from different materials, such as metals or polymers and can be manufactured in large quantities resulting in lower prices. Current gasoline tanks cost less than $100, compared to a 340 atm (5000 psia) hydrogen gas storage system costing an estimated $430 to $1,400 based on high volume production and carbon fiber wrapped aluminum tank technology. The storage system might consist of one or two tanks with connecting hardware and valves. Thus it can be appreciated that onboard hydrogen storage presents formidable packaging and cost challenges.

There are no inherently expensive materials in the fuel cell system except for the platinum (Pt) catalyst at the electrodes. Technological advances in the application of this noble metal catalyst for fuel cell electrodes have diminished the amount required for practical electrode reactions in the fuel cell and have reduced the cost of Pt catalyst electrodes to a reasonable value. Based on the contract goal of 0.25 mg/cm^2 total platinum loading the amount of the catalyst in the fuel cell is 0.38 g/kW. It is also anticipated that the cost of the membrane will be lower when ordered in large quantities. Encouraging results have also been reported with a PEM other than the DuPont NAFION™. The membrane electrode assembly (MEA) manufacturing process is currently also in a primitive state when compared to mass assembly in the automotive or electronic industry. New MEA manufacturing methods are needed before fuel cell stack mass production can achieve cost competitiveness with the IC engine, especially when the total life-cycle costs are taken into account.

1.5 Recommendations for Further Design Study

This preliminary report shows that packaging of the pure fuel cell system powered vehicle is extremely challenging, increasing in difficulty as the size of the vehicle decreases. Carrying onboard hydrogen, at 340 atm (5000 psia), enables the fuel cell power system and hydrogen tanks to be accommodated in the E-150 Econoline van. For the intermediate size AIV Sable, cargo space may have to be sacrificed to accommodate the total fuel cell and hydrogen storage system, but for the small size Aspire, rear passenger seats must be relinquished. Future packaging efforts must be based on the intermediate size fuel cell powered vehicle without being encumbered by the restrictions of available space and weight of current model vehicles - in other words, a ground-up vehicle packaging design.

The design study in this report is based on a fuel cell engine system having a power density of 0.33 kW/kg (as reported as being viable in the 1994 Ballard Annual Report [2]). Our contract objective is the delivery of a 50 kW fuel cell system with 0.37 kW/kg gravimetric power density. Improvements in power density will further facilitate development of viable packaging options. The path towards improvement of the power density of the fuel cell power system includes the development of better fuel cell stacks, smaller and high efficiency air compressors and blowers, and smaller and more efficient heat exchange components.

Powertrain (P/T) matching involves sizing the powertrain components to meet performance targets, and when possible, maximizing fuel efficiency and/or range. As the fuel cell size increases, packaging issues in these passenger vehicles become increasingly more difficult. Thus, it is assumed that the fuel cell size would be dictated by the minimum power necessary to meet performance targets. However, the effect of sizes greater than minimum on fuel efficiency and range should be investigated in future vehicle application studies. The P/T matching in this study was done in 5 kW increments of fuel cell system peak power output.

As technology advances, vehicle design studies must be continued. Such studies must also address the trade-offs for the battery-augmented fuel cell powered vehicles following improvements in both fuel cell and battery power densities.

2.0 Introduction

2.1 Goals and Objectives of Report

The objectives of this preliminary report are to present the results of the pure fuel cell powered vehicle design efforts and to indicate the barriers that might be encountered on the road to the commercialization of hydrogen-fueled fuel cell vehicles. These barriers are perceived as being technological, economical and psychological. Technological advances, such as Pt catalyst loading reduction and MEA manufacturing processes, can be helpful in overcoming the economic barriers [4]. The psychological perception that hydrogen is a dangerous fuel, as evidenced by the "Hindenburg syndrome" is addressed in this contract in the "Preliminary Hydrogen Vehicle Safety Report" and is not a detailed aspect of this report.

Another goal of this preliminary report is the dissemination of the knowledge and experience gained, and to use them in developing refinements of the modeling and conceptual designs of pure or augmented fuel cell powered vehicles.

2.2 Direct-Hydrogen-Fueled PEMFC for Transportation Program Background

Ford was awarded a Department of Energy (DOE) contract "Direct Hydrogen-Fueled Proton-Exchange-Membrane (PEM) Fuel Cell for Transportation Applications", No. DE-AC02-94CE50389 on July 1, 1994. Under this contract, Ford proposed to conduct the "Fuel Cell Systems Development" program to advance PEMFC technology for automotive applications. At the end of the contract, a fully functional fuel cell power system will be integrated and tested on a test bed and exercised through various automotive drive cycles. During the first phase of the contract, Ford agreed to work with several fuel cell suppliers to develop fuel cell stacks producing 10 - 12 kW using 3 atm (44 psia) air supply and having a power density goal of at least 0.27 kW/kg (8 lb/kW) and Pt catalyst loading of ≤ 0.25 mg/cm^2. One or two of the fuel cell stacks meeting those goals would then be developed further in the second phase of the contract. At the end of Phase II, the ultimate program goal for the fuel cell system is a 50 kW net power supply with a system voltage of 250 V minimum and a system power density of ≥ 0.37 kW/kg (6 lb/kW), including air compression, thermal management, humidity and power control. Within this contract, Ford would also make comprehensive studies of the safety aspects of hydrogen as a vehicle fuel and the hydrogen production supply infrastructure.

2.3 Ford Team and Tasks

Directed Technologies, Inc. (DTI) was subcontracted to be chief coordinator of the hydrogen fuel-related infrastructure assessment and safety studies and also to be technical consultants to Ford in fuel cell related areas. The subcontractors to Ford for the hydrogen infrastructure and safety studies were:

Praxair, Inc.; Air Products & Chemicals, Inc.; The Electrolyser Corporation, Ltd.; and BOC Gases.

For the development and delivery of compressed gaseous hydrogen tanks, the subcontractors were:

EDO Fiber Science and AeroTec Laboratories, Inc.

Lawrence Livermore National Laboratory received a direct DOE subcontract for their work and contribution to the previous task.

The fuel cell developers who were subcontractors in Phase I include:

H Power Corporation; Energy Partners; International Fuel Cells Corporation (IFC); Mechanical Technology, Inc. (MTI), and Tecogen, A Division of Thermo Power Corporation.

The task of the fuel cell subcontractors was to deliver, within 12 months of the contract, a 10 - 12 kW fuel cell stack or system, having a stack power density goal of $\geq$ 0.27 kW/kg (8 lb/kW) and Pt catalyst loading of $\leq$ 0.25 mg/cm^2. One or two of these stack suppliers would then be chosen to participate in the development of a 50 kW net fuel cell system for further extensive testing on a test bed. The goals for this 50 kW fuel cell system included a fuel cell system power density $\geq$ 0.37 kW/kg (6 lb/kW) and Pt catalyst loading $\leq$ 0.25 mg/cm^2 on both electrodes.

Ford Motor Company is the major contractor and assumes responsibility for the overall program. The testing of the 10 kW and 50 kW fuel cell systems will be carried out both at the fuel cell subcontractors' premises as well as at a fuel cell testing laboratory, either at the Ford Research Laboratory or at a site designated by Ford, for verification of the test results. The Los Alamos National Laboratory was chosen for testing of the fuel cell stacks delivered in Phase I. Ford will also conduct the conceptual vehicle design and packaging study. System integration of the fuel cell, simulation and test bed evaluation will be conducted at the Ford research center. A final report will be issued at the end of the program.

3.0 Vehicle Requirements

3.1 Selection of Vehicle Types

Three sizes of vehicles, representative of a broad spectrum of light duty transportation, were selected for this study. The small vehicle size is represented by the Aspire, the intermediate vehicle size is represented by the AIV Sable and the van-size vehicle is represented by the E-150 Econoline. These Ford vehicles represent the range of passenger vehicles sold in the United States and are production or "baseline" vehicles.

Preliminary powertrain sizing for the production Taurus resulted in unsuccessful packaging of the fuel cell and hydrogen tanks for this vehicle. The AIV SABLE is mechanically identical to the Taurus, but about 285 kg (625 lb) lighter due to aluminum substitution in the body structure. With the lower weight and thus reduced fuel cell power requirement, the AIV Sable is a more viable platform for packaging. From a manufacturing standpoint the AIV Sable is production feasible, and in fact, a small fleet has already been produced.

3.2 Vehicle Performance Specifications

Performance requirements for various classes of vehicles and for various performance levels were discussed extensively in "Technology Development Goals for Automotive Fuel Cell Power Systems" prepared by Directed Technologies, Inc. for the Argonne National Laboratory [5]. In this report, the vehicle performance specifications were defined for the basic performance level, but other performance levels were analyzed as well. Table 1 shows the Baseline IC Vehicle Parameters for the selected vehicles, and Table 2 shows the Baseline IC Vehicle Performance Capabilities. The vehicle propulsion requirements determine the minimum acceptable gear/motor torque, the average and maximum power for the selected vehicles. Additional automotive propulsion requirements for customer-acceptable automobiles are sustainable speeds of 137 km/h (85 mph), 105 km/h (65 mph), and 80.5 km/h (50 mph) on a level road or 0% grade, a long 3% grade and a 5 km (3 mi) long 7% grade, respectively. These performance capabilities and the vehicle parameters determined the size of the fuel cell power systems required for each selected vehicle.

Table 1 - Baseline IC Vehicle Parameters

Vehicle	Aspire	AIV Sable	Econoline
Drive Configuration	**FWD**	**FWD**	**RWD**
Frontal Area, m^2 (ft^2)	1.88 (20.2)	2.13 (22.9)	3.67 (39.5)
Aero Drag Coefficient	0.37	0.33	0.39
Tire Rolling Resistance (lb_f)	17.9	22.6	47.2
Curb Weight, kg (lb)	941 (2075)	1168 (2575)	2245 (4950)
Test Weight, kg (lb)	1094 (2412)	1321 (2912)	2698 (5950)
Engine:			
Displacement/Configuration	1.3 l / V4	3.0 l / V6	4.9 l / V6
Power, kW	48	103	121
Transmission			
Type	AUTO	AUTO	AUTO
Number of Gears	3	4	4

Table 2 - Baseline IC Vehicle Performance Capabilities

Vehicle/Acceleration, seconds	Aspire	AIV Sable	Econoline
0-> 96.5 km/h (0->60 mph)	18.9	12.0	15.1
8->32 km/h (5->20 mph)	3.2	2.0	2.2
32->64 km/h (20->40 mph)	5.4	3.5	4.5
64->96.5km/h (40->60 mph)	9.3	5.6	7.4
88.5->105km/h(55->65 mph)	6.1	3.3	4.6
Maximum speed, km/h (mph)	153 (95)	187 (116)	166 (103)
Maximum Gradeability, %			
From Standing Start	30.2	37.0	30.2
At 88.5 km/h (55 mph)	10.6	16.0	11.9

3.3 Fuel Cell Power Requirements

Minimum road-load engine power requirements were calculated for the Aspire, AIV Sable, and E-150 Econoline size vehicles. In this regard, the engine power for each selected vehicle must be able to maintain speeds of 137 km/h (85 mph) at 0% grade, 105 km/h (65 mph) on a long 3% grade road, and 80.5 km/h (50 mph) for a 5 km (3 mi) long road at 7% grade. The results of these calculations are tabulated in Table 3 and pictorially depicted in Figures 1, 2, and 3.

Table 3 - Roadload Engine Power Requirements

Vehicle / Grade & Speed	0%	3%	7%
km/h (mph)	137 (85)	105 (65)	80.5 (50)
Aspire	32.2 kW	26 kW	24.6 kW
AIV Sable	36.4	33.6	36.9
Econoline	66	57.8	63.8

As can be seen, the minimum fuel cell size to meet these power requirements for each vehicle is 32.2 kW for the Aspire, 36.9 kW for the AIV Sable, and 66 kW for the Econoline. Heating, air conditioning and other auxiliary power requirements are included in the calculations, although generally they represent only 2.5% of the total power. Using the Ford CVSP (Corporate Vehicle Simulation Program) and various drive cycle schedules, the matching fuel cell system size can be determined for each vehicle. This is further discussed in Section 4.0.

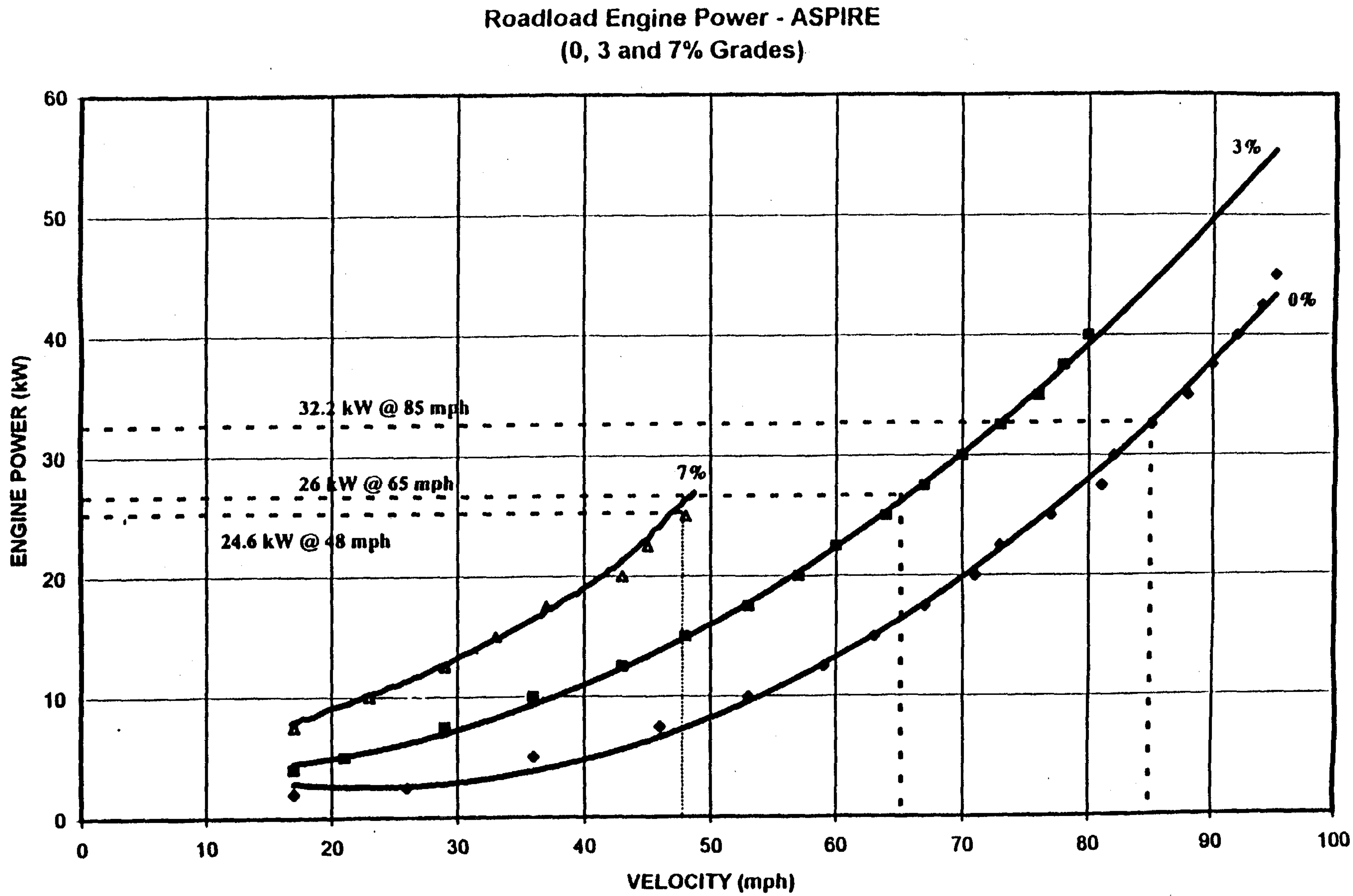


Figure 1 - Roadload Engine Power Requirements

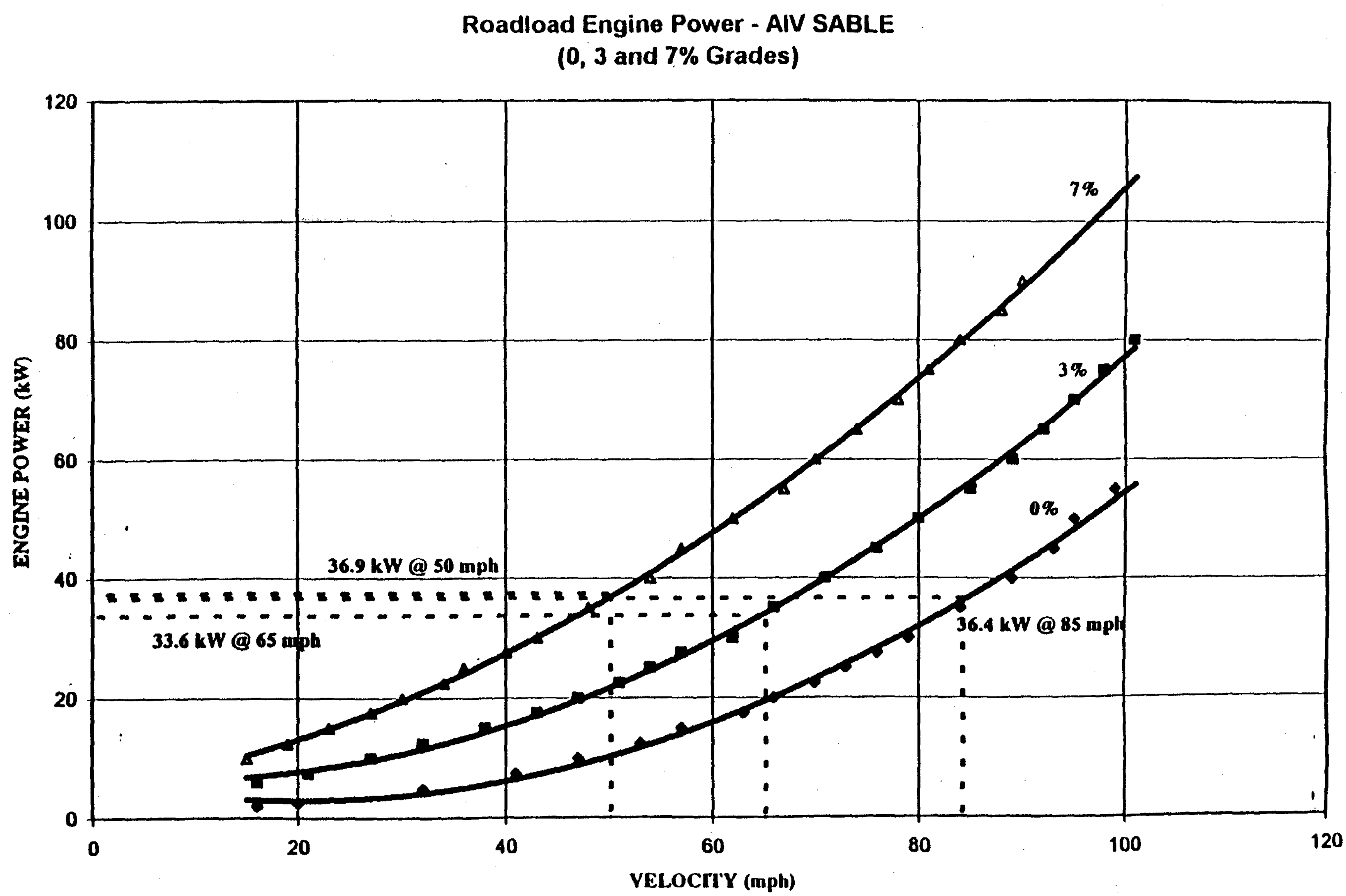


Figure 2 - Roadload Engine Power Requirements

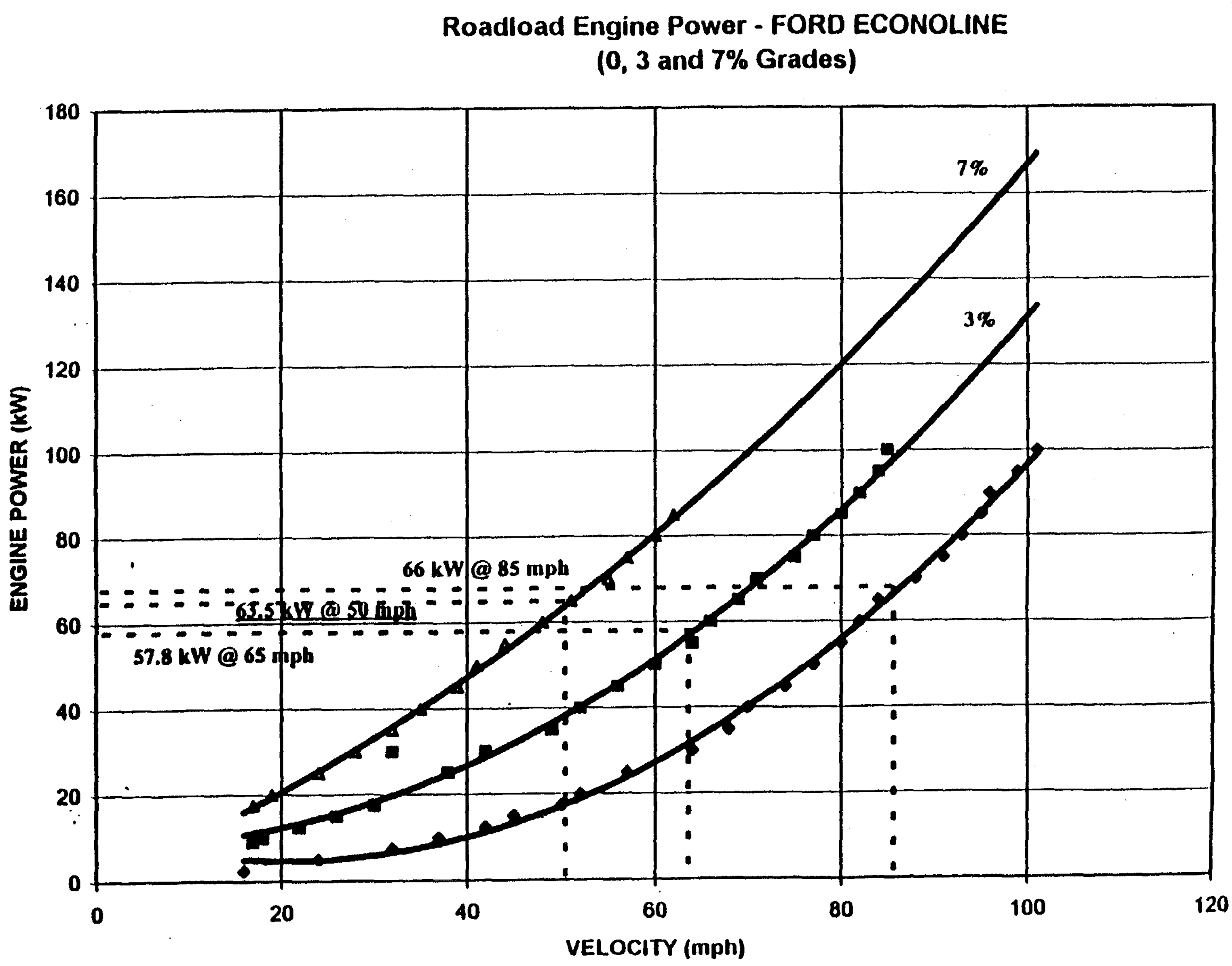


Figure 3 - Roadload Engine Power Requirements

3.4 Power System Architecture

For this report, the only primary power source considered is the fuel cell. However, the power demand from the automobile can be categorized into peak power for acceleration and passing, and sustained power for maintaining the minimum speed requirements when ascending various grades. The sustainable power category is that most suited to the highly efficient hydrogen/air fuel cell since this equates to continuous delivery of constant power at low partial load. The peak power demand for acceleration, which generally lasts for about 10 seconds, could be supplied by the fuel cell using high pressure air supply or oxygen enrichment. During this short period of peak power demand, the fuel cell is operating close to its maximum rated power and therefore has a somewhat lower efficiency. In meeting these peak power demands, the pure fuel cell power system will be much simpler in design and have fewer components than if the power system was augmented by an additional power source such as a battery, ultracapacitor, or flywheel.

A generic pure fuel cell vehicle architecture consists of a fuel storage tank, an appropriately sized fuel cell system, a power controller, an electric motor inverter/ controller, an electric drive motor with step-down gearing and differential, and thermal control unit. Such an architecture is illustrated in Figure 4.

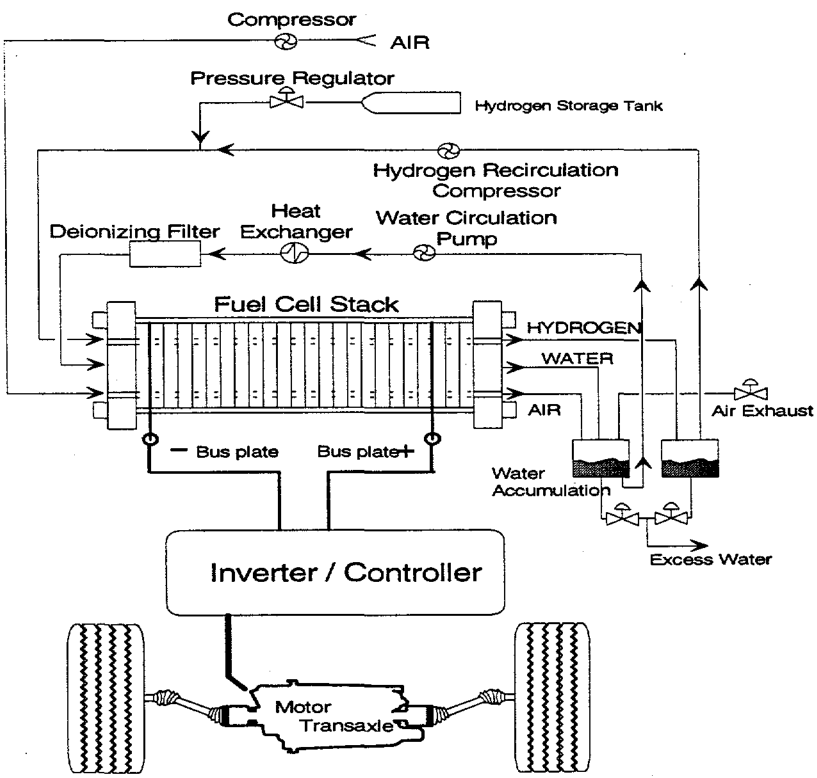


Figure 4 - Pure Fuel Cell Vehicle Architecture

Based on the fuel cell spreadsheet model calculations generated by DTI, the Ford CVSP, and available vehicle information on the weight of the three base vehicle sizes, the powertrain matching exercise resulted in the following minimum pure fuel cell system power requirements: for the Aspire, 50 kW (67 hp); for the AIV Sable, 80 kW (107 hp);

and for the E-150 Econoline van, 125 kW (168 hp). Thus, the power requirements for acceleration for the three vehicles are higher than for the roadload requirements, and meeting these requirements will meet the roadload power requirements shown in Table 3. For transportation applications, the use of pressurized air to boost fuel cell power is a preferred solution; the practical challenge being to obtain a high efficiency, small compressor. The direct hydrogen-fueled PEMFC power system faces another challenge regarding the availability of a fuel tank carrying compressed hydrogen gas for the required range of 560 km (350 mi). In this contract, an advanced composite hydrogen storage tank to store hydrogen gas at 340 atm (5000 psia) , with a projected leak rate of less than 1%/yr, is under development. The amount of hydrogen needed for the three vehicle sizes are: 5 kg (12 lb) for the Aspire, 6 kg (13 lb) for the AIV Sable, and 11 kg (25 lb) for the E-150 Econoline van. These results and the associated calculations and methodology applied to arrive at the vehicle fuel cell power, size and the necessary ancillary equipment, are described in the next section.

4.0 Conceptual Vehicle Design

4.1 Fuel Cell System Modeling Methodology

PEM fuel cell system performance, weight and dimensions are based on the output derived from the Fuel Cell Power System (FCPS) spreadsheet model. The FCPS model was developed by Directed Technologies, Inc. (DTI under subcontract to Ford Motor Company as part of the Midwest Research Institute (MRI)/Department of Energy contract entitled "U. S. Hybrid Propulsion System Development"). This is an interlinking set of spreadsheets and macro programs written in Excel 5.0 for Windows, suitable for IBM compatible personal computers. FCPS models the entire fuel cell power system and not merely the PEM fuel cell stack, and consequently encompasses the following five main subsystems:

1. fuel cell stacks,
2. reactant gas temperature and humidity control system,
3. reactant gas pressure control system,
4. stack cooling subsystem,
5. miscellaneous components (tubing, clamps, sensors, fuel cell product water storage, etc.)

The FCPS model has two operating modes. The first, Configuration Mode, utilizes user-entered sizing and efficiency data to determine the component weight, dimensions, and cost for a given level of system net power production. This mode was used to size the system components for the fuel cell vehicle conceptual design presented in this report. The second mode, Operating Mode, determines the hydrogen and air flow rates, temperatures, humidities, and the power losses and efficiencies of all system components when operating at system power levels below the design point. This mode was used to determine the fuel cell vehicle hydrogen consumption for 560 km (350 mi) on the Federal Urban Driving Schedule (FUDS).

Figure 5 presents a preliminary power system schematic of the onboard fuel cell power system. All components shown in the schematic are modeled by FCPS. The schematic of the complete fuel cell propulsion system is illustrated in Figure 4. Each major subsystem component is described further below.

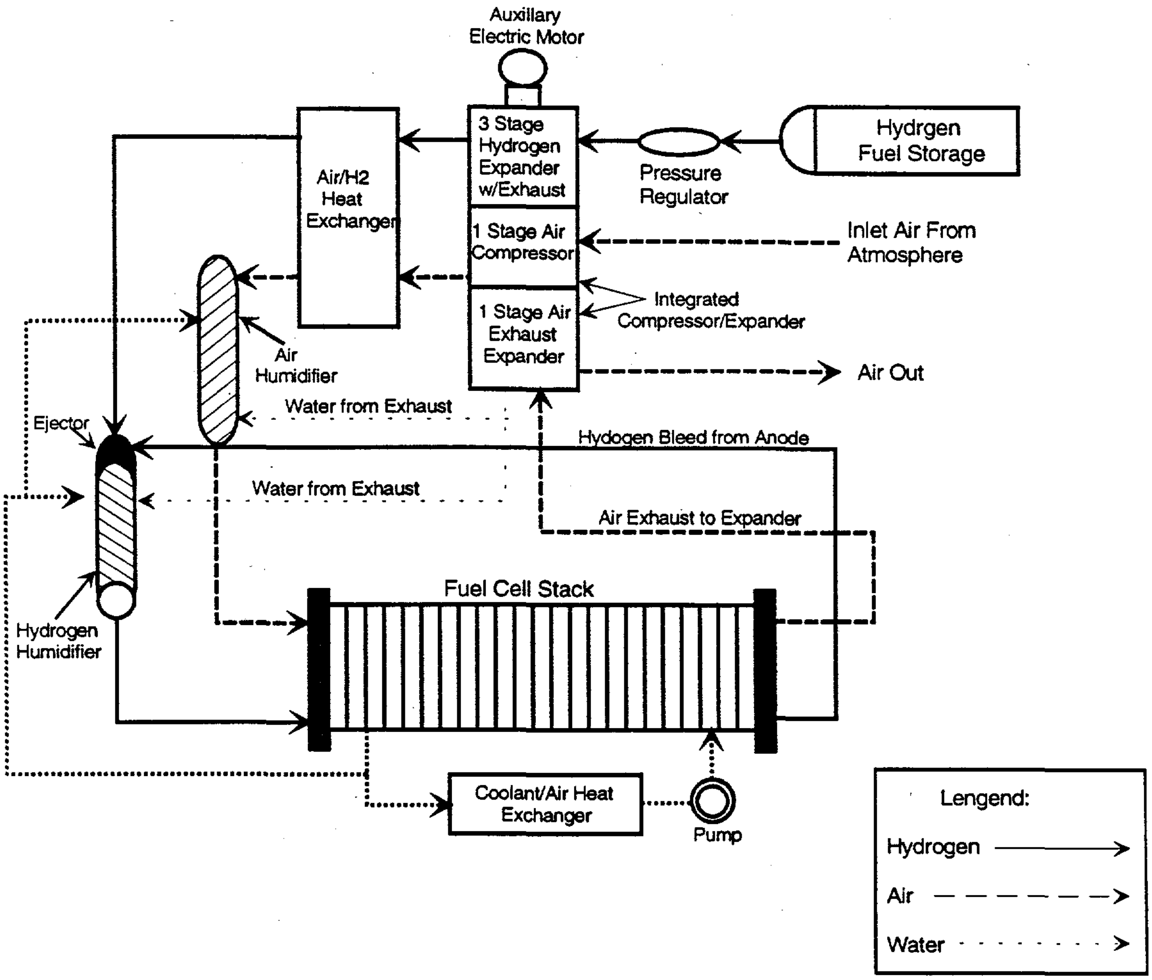


Figure 5 - Fuel Cell Power Schematic

Fuel Cell Stacks:

Fuel cell stack performance is determined by user-entered lookup tables indexed to cell voltage, cell current density, and stack operating temperature. The same polarization data and operating conditions were used for all fuel cell stack designs and can be best summarized by conditions at the system rated operating point: 0.6 V/cell, 1.076 A/cm^2, operating under 3 atm at 90 ^{0}C. Stack weight and dimensions are based on user-entered dimensions and densities of reference active cells, cooling cell, endplates, tie-rods, and manifolds, all scaled appropriately to match system power and voltage requirements.

Air Delivery System:

The air delivery system consists of three components: an air filter, an air compressor, and an air humidifier. The air filter is modeled as currently used IC engine automobile air filters appropriately sized for the fuel cell system air flow requirement. The air compressor is modeled as a single stage centrifugal compressor. The compressor operates at high rpm and is compact due to relatively low air flow rate and low air compression ratio. Compressor shaft power is generated by three sources: (1) by hydrogen expansion turbines connected to the compressor via magnetic coupling, (2) by an exhaust air turbine connected to the compressor shaft which expands the oxygen depleted fuel cell stack exhaust gas from the approximate 3 atm stack operating pressure to ambient pressure, and (3) by an auxiliary electric motor. The hot, newly compressed air is used to heat each of the three hydrogen expansion turbine exhaust streams. The hydrogen/air heat exchanger is of plate fin construction. The air humidifier is external to the fuel cell stack and is approximately one-eighth the size of the fuel cell stack.

Hydrogen Delivery System:

The hydrogen delivery system consists of three components: a pressure regulator, turbine expander, and hydrogen humidifier. The pressure regulator reduces gas pressure from its storage pressure (up to 340 atm = 5000 psia) to approximately 68 atm (1000 psia) in order to provide consistent conditions to the expander. The hydrogen turbine expander is modeled as a 3-stage centrifugal expander with reheating. The expanded gas from each turbine stage is fed into the hydrogen/air heat exchanger where the air is cooled and the hydrogen is heated. As described above, the single shaft of the turbine expander is linked to the air compressor through a magnetic coupling at one end and is linked to the auxiliary electric motor at the other. Like the air humidifier, the hydrogen humidifier is external to the fuel cell stack.

High Pressure Hydrogen Storage Vessels:

The baseline onboard hydrogen storage system is 340 atm (5000 psia) pressurized hydrogen gas. The pressure vessels are modeled as T-1000G carbon wrapped, thin metallized mylar lined cylindrical tanks with ellipsoidal endcaps. The performance factor (PF) of the tanks is set at 4.953 X 10^6 cm (1.95 X 10^6 inch). PF is defined as the operating pressure X safety factor X internal volume/tank weight. The higher the performance factor for a constant safety factor, the lighter the empty tank weight for an equivalent weight of hydrogen at operating pressure. Available hydrogen gas tanks have a PF of 3.3 X 10^6 cm (1.3 X 10^6 inch) and a PF of 5.72 X 10^6 cm (2.25 X 10^6 inch) is the theoretical limit for carbon fiber wrapped containers. All tank designs use a safety factor of 2.25.

4.2 Vehicle Descriptions

The Ford vehicles selected for investigation were chosen to span the range of passenger vehicles sold in North America today. As mentioned previously, these production or "baseline" vehicles are the Aspire, representing the small vehicle segment, the Taurus, representing the mid-size vehicle segment, and the E-150 Econoline van. The AIV Sable which is identical in size, but 285 kg (625 lb) lighter than the production Taurus, was used in this conceptual design when preliminary calculations showed that the larger size fuel cell and hydrogen tanks for the heavier Taurus led to unsuccessful packaging. The lower weight of the AIV Sable and thus its reduced power requirement renders this vehicle as a more suitable platform for a fuel cell power system. The AIV Sable is also production feasible and a small fleet has been produced for demonstration. Vehicle parameters for these baseline vehicles are shown in Table 1.

4.3 Vehicle Simulation Methodology

The vehicle simulations were performed using Ford's Corporate Vehicle Simulation Program or CVSP. CVSP is Ford's production tool for projecting/modeling vehicle performance, range and fuel economy. Its use plays a key role in assuring future products meet customer performance expectations as well as EPA fuel economy and emission standards. The input to CVSP can be broken down into four broad categories:

(1) components, their sizes, characteristic parameters and/or efficiencies (see Figure 6)
(2) operating strategies such as transmission shifting, accessories, regenerative braking, and power switching (when the use of more than one power source is possible)
(3) drive cycle schedules
(4) test location and environmental conditions.

The Fuel Cell Power System (FCPS) program was used to project the characteristics and performance of the fuel cell system. In addition to providing system dimensions for use in vehicle packaging, it provides the system weight and hydrogen consumption as a function of maximum rated power. It was used to generate a table of the hydrogen consumption versus power performance curves at every 5 kW interval from 5 to 175 kW peak output power. These system performance curves and weights were used to characterize the fuel cell in CVSP. The resultant power densities ranged from about 0.17 kW/kg at 175 kW peak power to approximately 0.1 kW/kg at 5 kW. For all three vehicles, the initial pure fuel cell powered designs with these calculated fuel cell power densities, resulted in vehicle packaging with unacceptable incursions into the passenger compartments. In September 1995, Ballard reported it had demonstrated power densities of 0.33 kW/kg for their fuel cell system [2] and subsequently, the weight and volumes based on the Ballard results replaced the earlier FCPS results. The approach used in setting the performance targets was the same as would be employed in a typical (i.e. internal combustion engine powered) vehicle program at Ford. Previous experience with electrical vehicle performance showed that extra attention is required to ensure acceptable highway performance feel. This is particularly important when a single speed transmission is used, as is the case here. Therefore, 88.5 - 105 km/h (55 - 65 mph) acceleration time was added to the traditional performance parameters:

acceleration time: 0 - 96.5 km/h (0 - 60 mph), 8 - 32 km/h (5 - 20 mph), 32 - 64 km/h (20 - 40 mph), and 64 - 96.5 km/h (40 - 60 mph)

maximum gradeability: from standing start and at 88.5 km/h (55 mph), and: maximum speed.

These baseline vehicle performance capabilities are shown in Table 2.

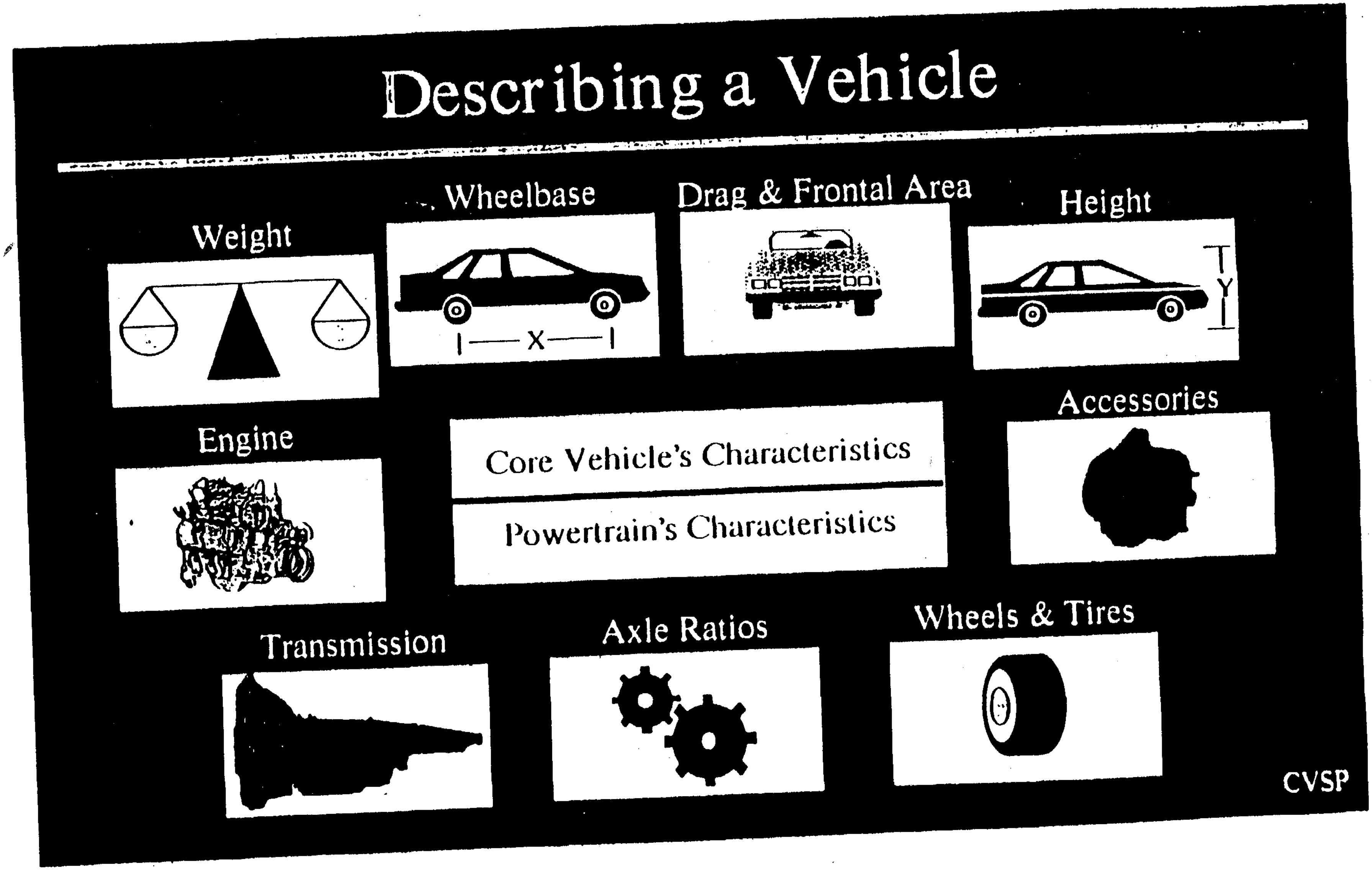

Describing a Vehicle
Weight
Wheelbase
X
Drag & Frontal Area
Height
Y
Engine
Core Vehicle's Characteristics
Powertrain's Characteristics
Accessories
Transmission
Axle Ratios
Wheels & Tires
CVSP

Figure 6

Previous studies at Ford have shown that the best single indicator of overall performance feel is 0 - 96.5 km/h (0 - 60 mph) acceleration time. Acceleration time from 8 - 32 km/h (5 - 20 mph) and standing start gradeability address launch performance feel, while 88.5 km/h (55 mph) gradeability, and 64 - 96.5 km/h (40 - 60 mph) and 88.5 - 105 km/h (55 - 65 mph) acceleration time are used for highway performance feel. Of all the performance parameters, only standing start gradeability has a fixed corporate requirement of 30%.

The CVSP projected performance of the respective production versions is used as the target for the proposed fuel cell powered vehicles. Just as would be done for a "traditional" vehicle program, the maximum speed criterion is not directly used in the performance matching process. Only if there were a substantial degradation from target would it be addressed. (Note that this would not be the case for a European vehicle.)

In balancing increasing fuel cell size and weight against the need to meet performance targets, it was decided to compromise slightly and allow one of the parameters to be as much as 10% deficient to target. The high performance feel, e.g. the 88.5 - 105 km/h (55 - 65 mph) acceleration time was consistently the hardest to meet and turned out to be the one deficiency for all three vehicles.

In order to provide insight into actual customer performance, all projections simulated vehicles "on the road" at performance test weight (PTW), as opposed to a typical program where the fuel economy/range type simulations would be on a dynamometer at an EPA emissions test weight (ETW) class. The difference is that actual weight and aerodynamics of the vehicle are simulated by the dynamometer. For example, a 3000 ETW class would be used to test a car whose curb weight + 300 lb falls between 3000 $\pm$ 62.5 lb. PTW is defined as ETW + 16.8 kg (37 lb) for cars and ETW + 318 kg (700 lb) for trucks (van). It is used to reflect typical customer usage.

Baseline vehicle representations were used in the CVSP projections and were taken from the official Ford database. These are the best available representations of those vehicles. The vehicle parameters which characterize these baseline vehicles are shown in Table 1. Table 2 shows the results of three CVSP simulations which become the performance targets for the fuel cell powered vehicles.

Starting with the production vehicle CVSP representations, the pure fuel cell powered vehicle representations were constructed by deleting:

- the internal combustion engine and its accessories,
- the radiator/coolant system,
- the driveshaft and rear axle, if so equipped,
- the fuel tank and exhaust system,

and then adding

- the fuel cell system (including thermal management, humidity control, etc.)
- scaled Ford Ecostar electric drive unit which includes a DC-AC inverter, AC electric motor and a single speed transaxle,
- powertrain electronic controller, and
- electric heat and air conditioning.

A new curb weight was determined. Using EPA methodology for fuel economy and emission testing, an ETW class was determined. Finally, as in a typical Ford vehicle program, the performance test weight (PTW) was set.

Figure 7 shows the power curve of the electric motor (EM) in its nominal 75 kW (100 hp) peak output power version. The sizing of the electric motor requires some explanation. There are inefficiencies associated with delivering the fuel cell output power to the EM. These are typical electrical and mechanical losses of an inverter and electric motor combination. If the output power of the EM were constant or relatively constant, the peak power of the EM would only need to be somewhat less than the fuel cell power in order to fully utilize the power of the fuel cell at all speeds. However, as Figure 7 shows, the power curve of the electric motor is not constant with speed, whereas the maximum fuel cell power is constant. Scaling the EM to increasingly higher power will always result in utilizing more of the fuel cell's power and thus result in better performance. This oversizing of the EM must be balanced against the weight, size, and cost penalties associated with it. Based on a brief analysis of the increasingly smaller performance gains with increasing EM size, it was decided to limit the EM peak output power to 110% of peak fuel cell output power. It should be noted however, that launch related performance is still improving at 50% oversizing. A future, more exhaustive study could optimize the size, weight, and cost trade-offs for the EM versus the fuel cell.

Once a fuel cell size sufficient to meet the performance targets is found, the last parameter varied to complete the P/T matching of a vehicle is the overall drive ratio (ODR). The overall drive ratio is the product of the gear ratios within the transmission. Note that in these calculations, there is only one ODR, since there is a single-speed transmission.

Table 4 contains the results of the final P/T match for the 1494 kg (3287 lb) PTW AIV Sable with an 80 kW fuel cell. Figures 8 - 10 illustrate the powertrain matching process for the AIV Sable. The results for the other two vehicles follow a similar pattern in their P/T matching. The final selection of overall drive ratio (ODR) comes down to balancing launch gradeability, which favors a higher ODR, against 88.5 - 105 km/h (55 - 65 mph) acceleration time, which favors a lower ODR. The 88.5 - 105 km/h (55 - 65 mph) acceleration time, to within 1% of target, and launch gradeability are satisfied with an ODR in the 5.5 - 6.4 range. Once those two criteria are reconciled, all others are found to be satisfied too. The selection of 6.4 provides the best 0 - 96.5 km/h (0 - 60 mph) time. Tables 5 and 6 show the results for the Aspire and the E-150 Econoline, respectively.

Table 7 summarizes the final vehicle descriptions that result from the P/T matching. Note that the curb weight of the fuel cell vehicle is 168 kg (370 lb) and 180 kg (396 lb) greater than the baseline versions of the Aspire and AIV Sable. The Econoline is only about 90.9 kg (200 lb) heavier because it alone had the additional weight advantage of deleting the rear wheel drive axle and the driveshaft components.

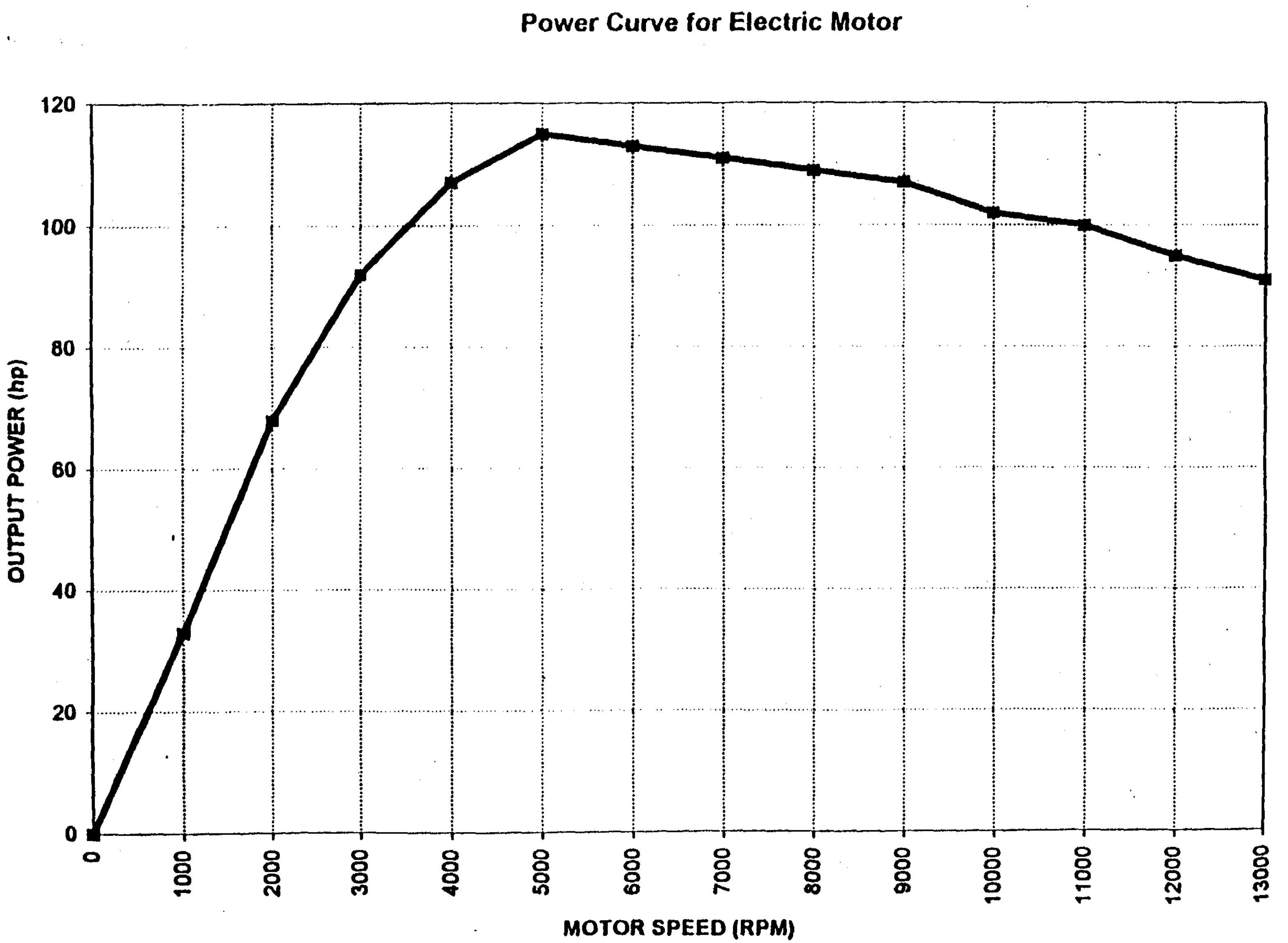


Figure 7 - Power Curve for 100 HP Electric Motor

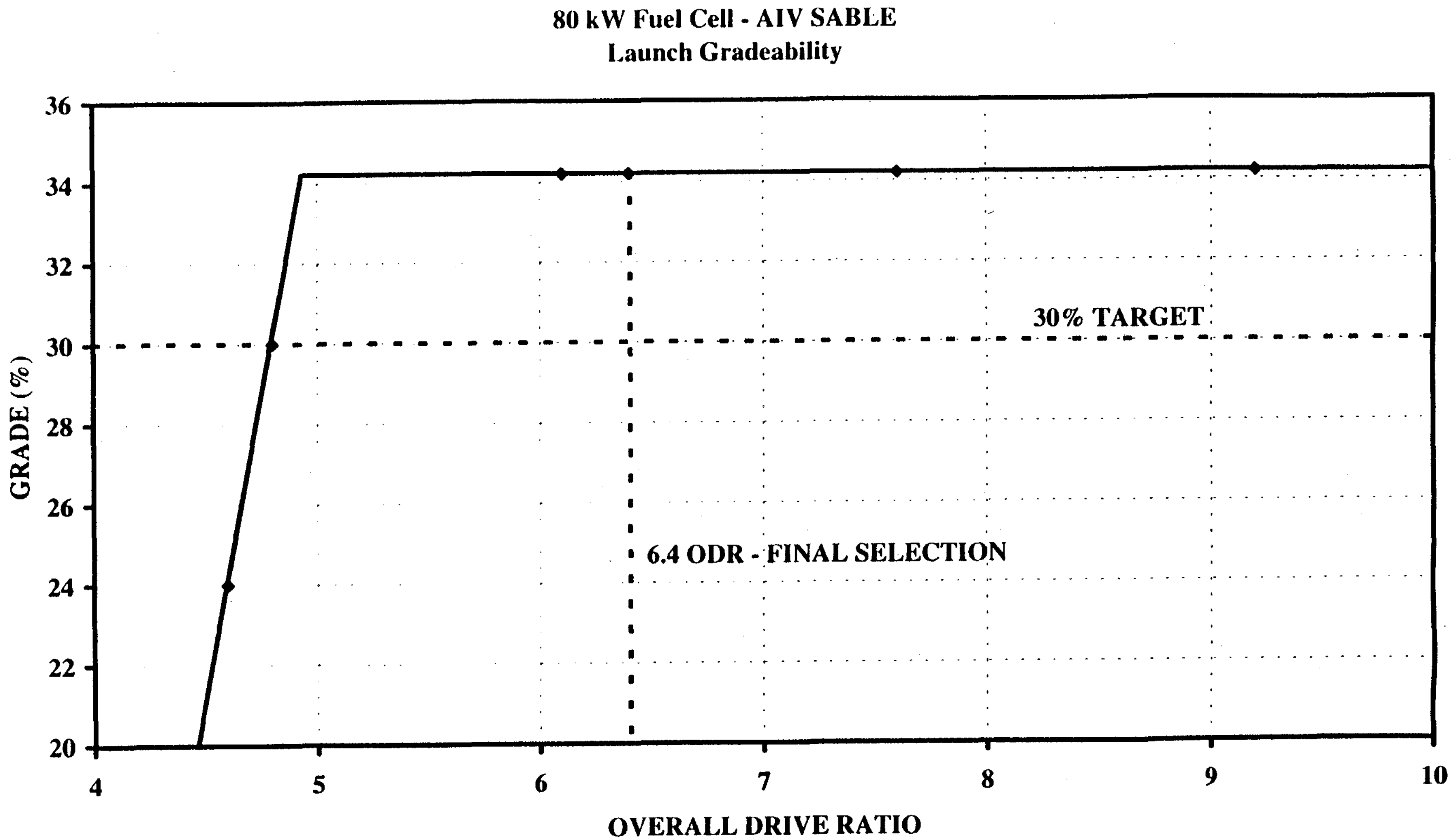


Figure 8 - Launch Gradeability of 80 kW Fuel Cell Powered AIV SABLE

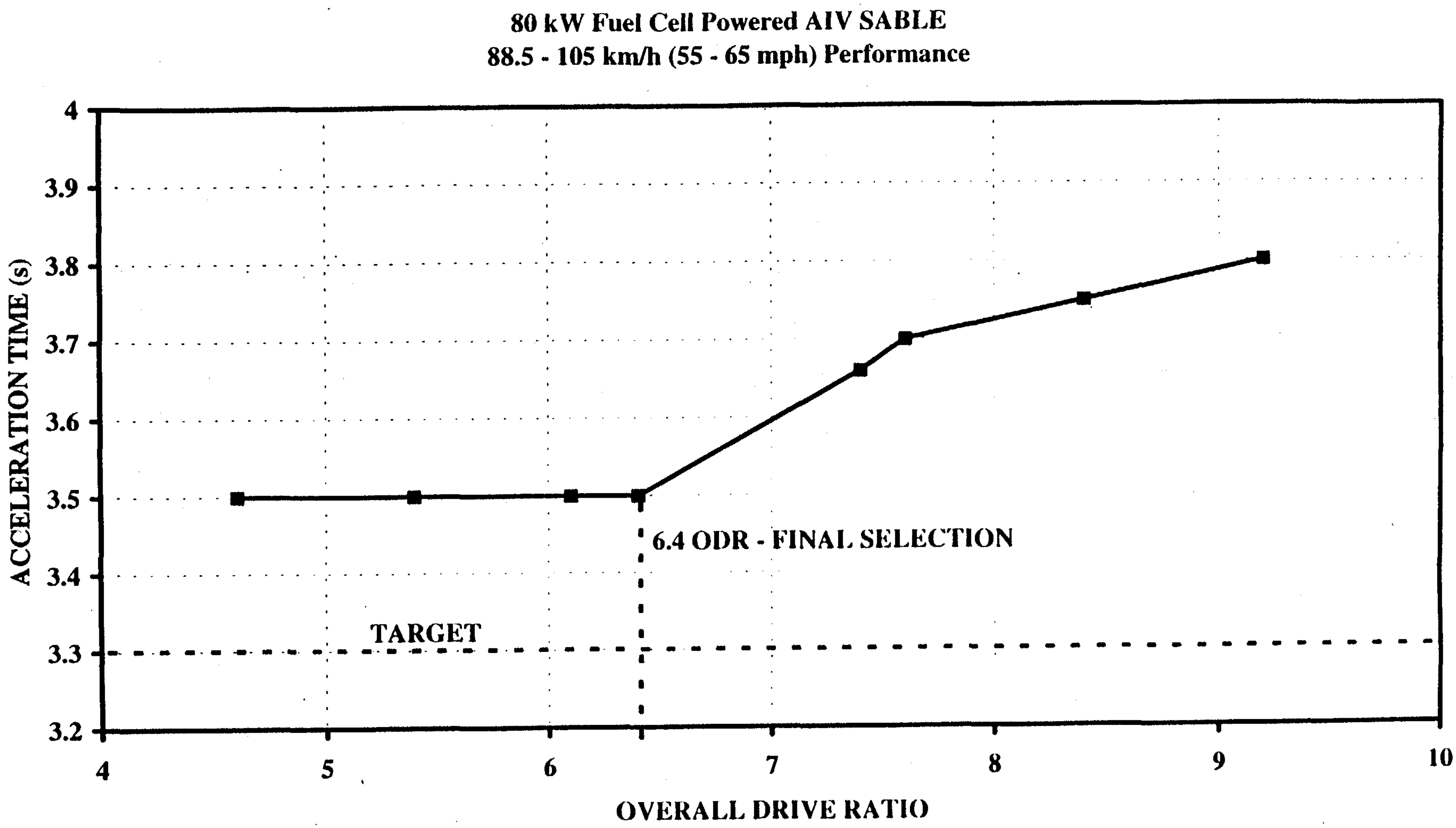


Figure 9 - Performance of 80 kW Fuel Cell Powered AIV SABLE
(88.5 - 105 km/h Acceleration)

80 kW Fuel Cell Powered AIV SABLE
0 - 96.5 km/h (0 - 60 mph) Performance

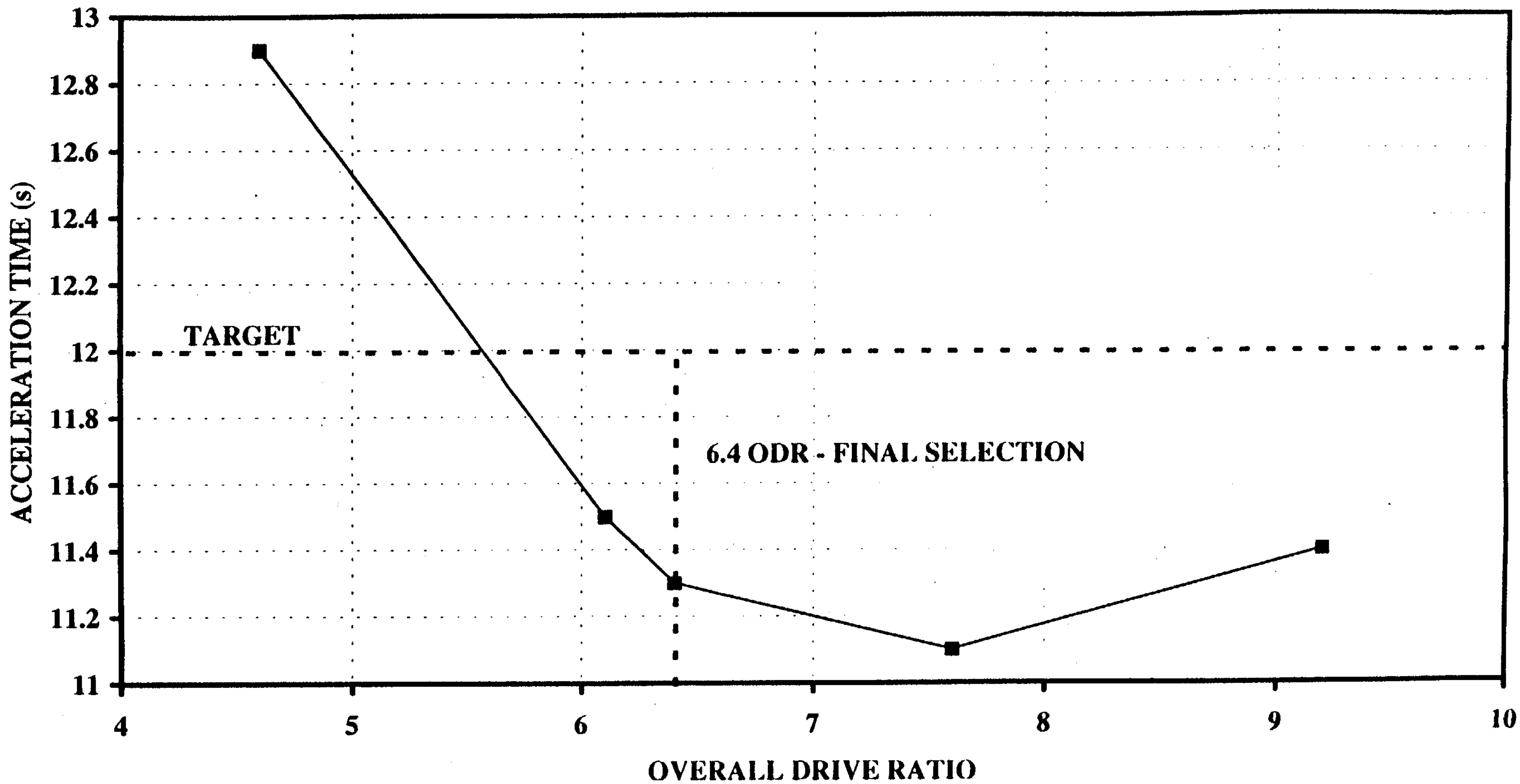


Figure 10 - Performance of 80 kW Fuel Cell Powered AIV SABLE
(0 - 96.5 km/h Acceleration)

Table 4 - AIV Sable Powertrain Matching Results

(80 kW Fuel Cell - 1494 kg (3287 lb) PTW)

Acceleration (sec) km/h (mph)	Production Target	ODR 4.6	ODR 6.1	**ODR 6.4**	ODR 7.6	ODR 9.2
0 - 96.5 (0 - 60)	12.0	12.9	11.5	**11.3**	11.1	11.4
8 - 32 (5 - 20)	2.0	2.6	2.0	**1.9**	1.7	1.8
32 - 64 (20 - 40)	3.5	3.8	3.3	**3.3**	3.2	3.2
64 - 96.5 (40 - 60)	5.6	5.6	5.5	**5.5**	5.6	5.9
88.5 - 105 (55 - 65)	3.3	3.5	3.5	**3.5**	3.7	3.8
Max.Speed km/h(mph)	186 (116)	183 (114)	182 (113)	**182 (113)**	180 (112)	166 (103)
Max.Gradeability(%)						
From Standing Start	30	24	34	**34**	34	34
At 88.5 km/h(55 mph)	16.0	15.5	15.9	**15.9**	15.6	15.4

ODR = Overall Drive Ratio

PTW = Performance Test Weight

Table 5 - Ford Aspire Powertrain Matching Results

(50 kW Fuel Cell - 1267 kg (2787 lb) PTW

Acceleration (sec) km/h (mph)	Production Targets	ODR 6.1	**ODR 6.4**	ODR 7.6	ODR 9.2
0 - 96.5 (0 - 60)	18.9	16.2	**16.2**	16.3	16.8
8 - 32 (5 - 20)	3.2	2.4	**2.3**	2.0	1.9
32 - 64 (20 - 40)	5.4	4.6	**4.6**	4.6	4.7
64 - 96.5 (40 - 60)	9.3	8.5	**8.6**	9.0	9.8
88.5 - 105 (55 - 65)	6.1	5.9	**6.0**	6.3	6.8
Max.Speed km/h (mph)	153 (95)	153 (95)	**151 (94)**	150 (93)	138 (86)
Max.Gradeability (%)					
From Standing Start	30	29	**31**	33	33
At 88.5 km/h (55 mph)	10.6	10.1	**10.1**	9.8	9.4

ODR = Overall Drive Ratio

PTW = Performance Test Weight

Table 6 - Ford Econoline Powertrain Matching Results

(125 kW Fuel Cell - 2818 kg (6200 lb) PTW)

Acceleration (sec) km/h (mph)	Production Target	ODR 6.1	ODR 7.6	**ODR 8.2**	ODR 9.2
0 - 96.5 (0 - 60)	15.1	15.3	14.2	**14.0**	13.8
8 - 32 (5 - 20)	2.2	2.8	2.3	**2.1**	2.0
32 - 64 (20 - 40)	4.5	4.4	4.1	**4.0**	4.0
64 - 96.5 (40 - 60)	7.4	7.1	7.1	**7.1**	7.2
88.5 - 105 (55 - 65)	4.6	4.6	4.7	**4.7**	4.8
Max.Speed km/h (mph)	166 (103)	166 (103)	166 (103)	**164 (102)**	164 (102)
Max.Gradeability (%)					
From Standing Start	30	22	29	**32**	37
At 88.5 km/h (55 mph)	11.9	12.0	12.1	**12.0**	12.0

ODR = Overall Drive Ratio

PTW = Performance Test Weight

Table 7 - Powertrain Matching Results

Powertrain Parameters	Ford Aspire	AIV Sable	Ford Econoline
Fuel Cell Power, kW (hp)	50 (67)	80 (107)	125 (168)
Electric Motor Power, kW (hp)	56 (75)	90 (120)	138 (185)
Overall Drive Ratio	6.4	6.4	8.2
Weights, kg (lb)			
Fuel Cell	150 (331)	235 (518)	360 (794)
Electric Motor	72 (159)	115 (254)	180 (396)
Hydrogen Tanks w/o Hydrogen	39 (85)	42 (92)	78 (173)
Hydrogen*	5 (12)	6 (13)	11 (25)
Curb	1109 (2446)	1348 (2972)	2338 (5155)
Performance Test	1264 (2787)	1491 (3287)	2812 (6200)
Ref: Production Curb #	941 (2075)	1168 (2575)	2245 (4950)

Notes: * = Weight of Hydrogen required for 565 km (350 miles) Federal Urban Drive Schedule (FUDS) range

 # = for AIV Sable, base ICE-powered AIV

4.4 Fuel Cell Vehicle Drive Cycle Simulation

A variety of drive cycles/schedules were selected to provide insight into the range and energy efficiency of the fuel cell powered vehicles in different customer applications. The various drive cycles are:

- Federal Urban or FUDS - EPA fuel economy and emissions testing
- Federal Highway - EPA fuel economy and emissions testing
- Ford customer - Ford cycle representing typical U. S. customer actual usage patterns
- Steady 65 mph - Interstate highway type cruising
- SCE Commuter - Derived from Southern California Edison (SCE) "in-use" monitoring data.

The target range was selected to be 565 km (350 mi) on the FUDS. The final step in setting vehicle configurations shown in Table 7 was the sizing of the hydrogen tanks (to the nearest kg (lb)) so that at least 565 km (350 mi) range is achieved. Table 8 shows the final range results. The production Econoline with its 132.5 liter (35 gallon) fuel tanks has a range of 867 km (539 mi). To match the 867 km (539 mi) would require 17.4 kg (38 lb) of hydrogen with its attendant severe packaging problem. It was decided not to match it, but to simply note the deficiency to current production capability.

Table 8 shows the average fuel cell output power on each of the drive cycles. The average energy efficiency of the fuel cell and total vehicle over the FUDS are also shown in Table 8. Fuel cells are approximately twice as efficient as internal combustion engines. This can be seen in the almost doubling of the Aspire's fuel economy (93%). Because of the Econoline's reduced driveline weight advantage, its fuel economy is more than double the production version (108%). The AIV Sable with its 284 kg (625 lb) weight advantage is 156% better than production.

4.5 Fuel Cell Vehicle Packaging

Three vehicle platforms were used to determine available volumes for the packaging of fuel cell-related components. The first vehicle was the Ford Aspire, a four passenger sub-compact. The second vehicle was the AIV Sable, a six-passenger mid-sized vehicle. The third vehicle was the Ford Econoline, an eight passenger personal use van. The results of this investigation are presented separately for the three car-sizes.

Table 8 - Range, Power & Efficiency Results

	Ford Aspire	AIV Sable	Ford Econoline
Drive Schedules	Range, km (mi)	Range, km (mi)	Range, km (mi)
Federal Urban (FUDS)	595 (370)	575 (357)	576 (358)
Federal Highway	655 (407)	663 (412)	650 (404)
Ford Customer	456 (277)	457 (284)	452 (281)
Steady 105 km/h(65 mph)	518 (322)	529 (329)	536 (333)
Commuter (Southern Cal. Edison)	428 (266)	449 (279)	439 (273)
Ref: FUDS - Production	575 (357)	621 (386)	867 (539)
Average Fuel Cell Output Power, kW			
Federal Urban FUDS)	5.3	6.1	11.8
Federal Highway	11.8	13.1	25.3
Ford Customer	10.5	11.8	22.4
Steady 105 km/h (65 mph)	19.7	21.6	40.6
Commuter (Southern Cal. Edison)	19.4	21.2	40.9
Average Energy Efficiency[1] on FUDS Cycle			
Fuel Cell (%)	54.8	56.9	57.0
Vehicle - kWh/km (kWh/mile)	0.30 (0.49)	0.34 (0.55)	0.66 (1.06)
Vehicle - km/liter (mpg)	29.3 (68.9)	26.1 (61.3)	13.6 (32.0)
Ref: Production km/liter (mpg)	15.2 (35.7)	10.2 (24.1)[2]	6.55 (15.4)
Improvement in fuel economy (%)	93	156	108

1 - Assuming 115,000 Btu per gallon of gasoline (LHV) and 51,532 Btu per pound of hydrogen(LHV)

2 -Since there is no AIV Sable production vehicle, the results for a production Sable are presented.

Aspire Volume Calculations and Packaging

The first area of the vehicle considered for the packaging of fuel cell-related components was the engine compartment. Drawings were assembled to establish what internal combustion engine components could be removed and what components would be required regardless of the powertrain configuration. For example, components like the power brake booster, radiator and A/C condenser, and steering gear assembly, would be required for the fuel cell vehicle as well as for the IC engine vehicle. Note that the vacuum power brake booster in the IC vehicle would be replaced by an electric power brake booster in the fuel cell vehicle. Items such as the air cleaner and engine/transmission assembly could be eliminated from the front end package and the available volume calculated. The result of this calculation of the available volume under the hood structure and the space in front of the dashpanel and rearward of the radiator support was 305 liters. These calculations are in compliance with Ford's corporate guidelines for ground clearance.

The next area measured is the space under the front floor pan or the area known as the tunnel, which is between the driver and passenger seats at the center of the vehicle. This tunnel area measures 41 liters. The next area under the floor, but above the Ford corporate ground clearance, is that under the rear passenger seat where the production fuel tank is packaged, and the space directly behind the rear seating compartment. This total volume was 107 liters.

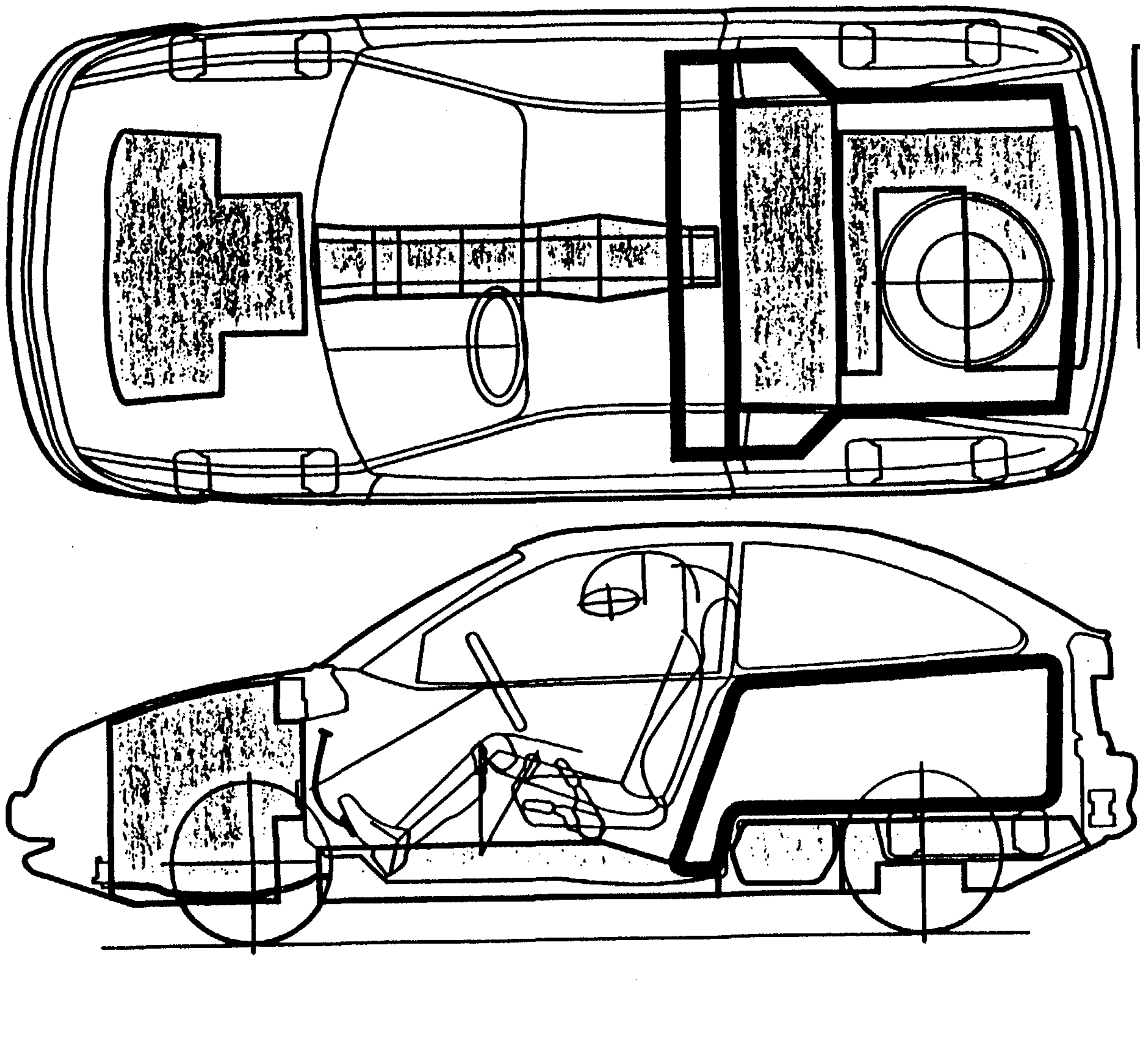
It was determined that the volumes calculated thus far for the Aspire were not large enough to account for all of the fuel cell system components, so additional packaging volume was acquired by removing the two passenger seats and measuring the trunk volume and the remaining rear seating compartment area. This increased the usable volume by 758 liters for a total vehicle volume of 1211 liters, and is shown in Figure 11.

After the initial volume estimates had been completed for the Aspire and the available space identified for the packaging of various fuel cell-related components, actual packaging studies began which utilized component sizing and weight estimates supplied by DTI. Several packaging studies were undertaken and various component combinations investigated. All but one was discarded. Because of the restrictive nature of a vehicle of this size, major considerations such as weight distribution and crashworthiness precluded many of the concepts. The final package for the Aspire sub-compact sized vehicle is shown in Figure 12.

The main study began in the front of the vehicle where the existing powertrain was replaced with a 56 kW (75 hp) electric transaxle. Next, the electrical components that control the motor functions were packaged along with what were described as peripheral components. These are the pieces of equipment that are required to operate the fuel cell power system, i.e. humidifiers, air compressors, and heat exchangers. The fuel cell stacks in this vehicle were placed under the rear floor in the area previously used for the production fuel tank. The last major component packaging task was the hydrogen storage tanks, which were placed in the area behind the front seat on the rear load floor. The exact location was determined by the desire to keep the pressure vessels at least 700 mm (about 28") from the rear bumper to protect the tanks in the event of a rear-end collision.

Several issues to be resolved in this vehicle package are also shown in Figure 12. Fuel cell cooling may be an issue because of the location of the cell stacks under the floor and at the rear of the vehicle and the heat exchanger's location in the front of the vehicle, resulting in undesirable lengthy coolant line routing. Another concern was the loss of the rear seating area and the need to achieve isolation of the hydrogen storage tanks from the interior compartment. This configuration shows the problems encountered in the fuel cell powertrain vehicle packaging for a sub-compact sized vehicle.

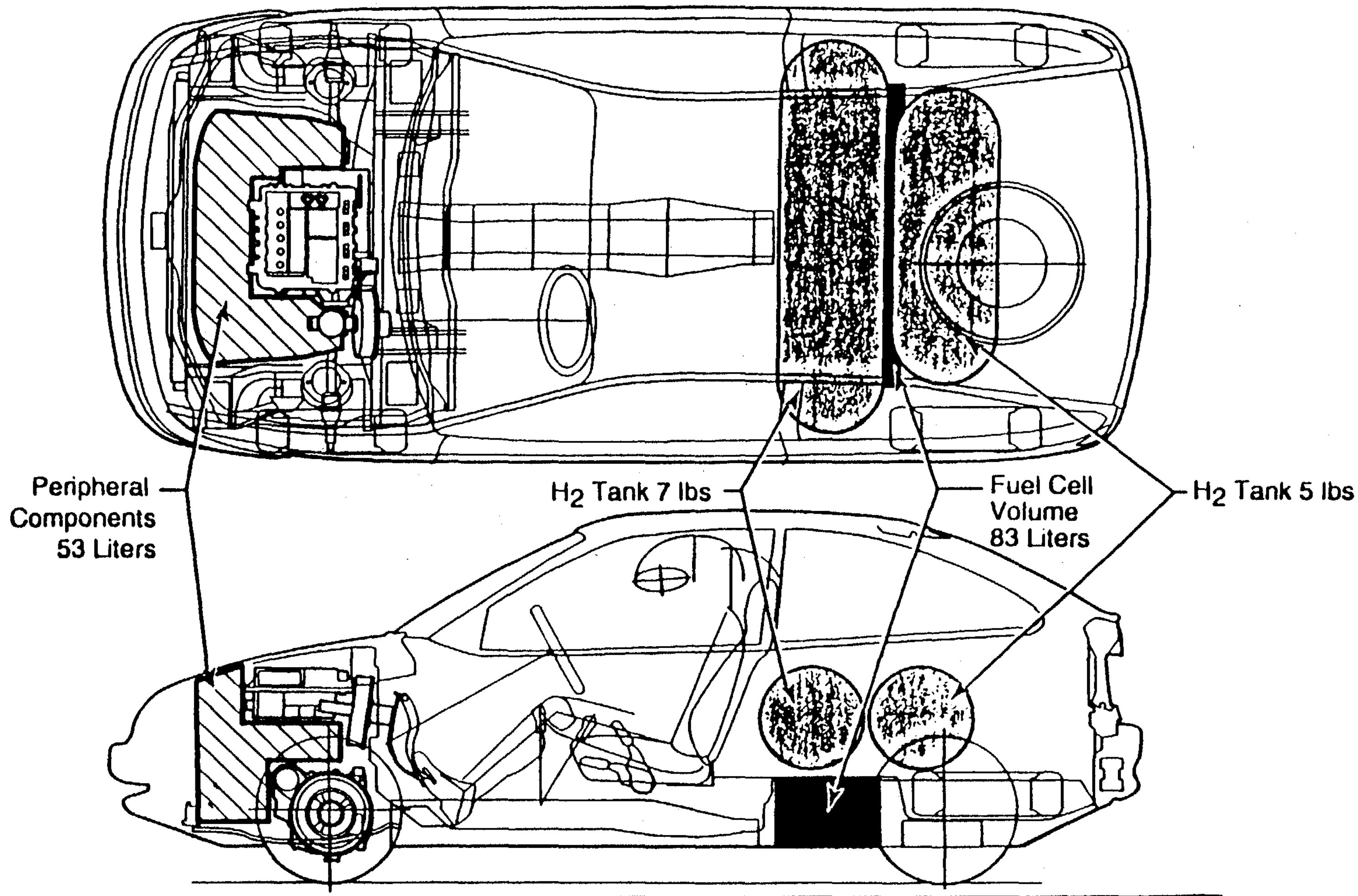
ASPIRE VOLUMES



Available Volume For Packaging	
Front End	305 Liters
Tunnel & Floor	41 Liters
Rear End	107 Liters
Interior Cargo	758 Liters
Total Volume	**1211** Liters

Figure 11

ASPIRE FUEL CELL PACKAGE
Assumed Fuel Cell System Power Density
3 Kilograms Per Kilowatt / 3 Liters Per Kilowatt



ISSUES
Fuel Cell Cooling
Loss of Rear Seating Area
Tanks not Isolated from Interior Compartment

PACKAGE VOLUMES
Fuel Cell Volume: 136 Liters (8299 cu. in.)
Eletric Motor 56 (kW) (75 HP)
H2 Tanks Volume: 264 Liters (5.4 kg)

Figure 12

AIV Sable Volume Calculations and Packaging

As with the Aspire, the vehicle-related drawings were assembled to define exactly what components would be deleted and which were required for vehicle operation. Not surprisingly, it was found that both vehicle architectures were similar. In the engine compartment, the same components were removed and the resulting available volume was calculated to be 478 liters.

Following the method used in the previous vehicle, the volume under the floor pan and under the rear seat area was calculated, and as before, much of this area was of little use in packaging components. The space in the tunnel could be used for wire and coolant line routing and the mounting of numerous sensors and small non-critical components that would not be affected by possible road hazards and high water conditions. Even though a cover could be fashioned to protect items packaged at a low height in the vehicle, the danger of packaging high voltage electrical components in a potentially wet environment needed to be addressed. The total volume calculated under the vehicle floor plan was 222 liters.

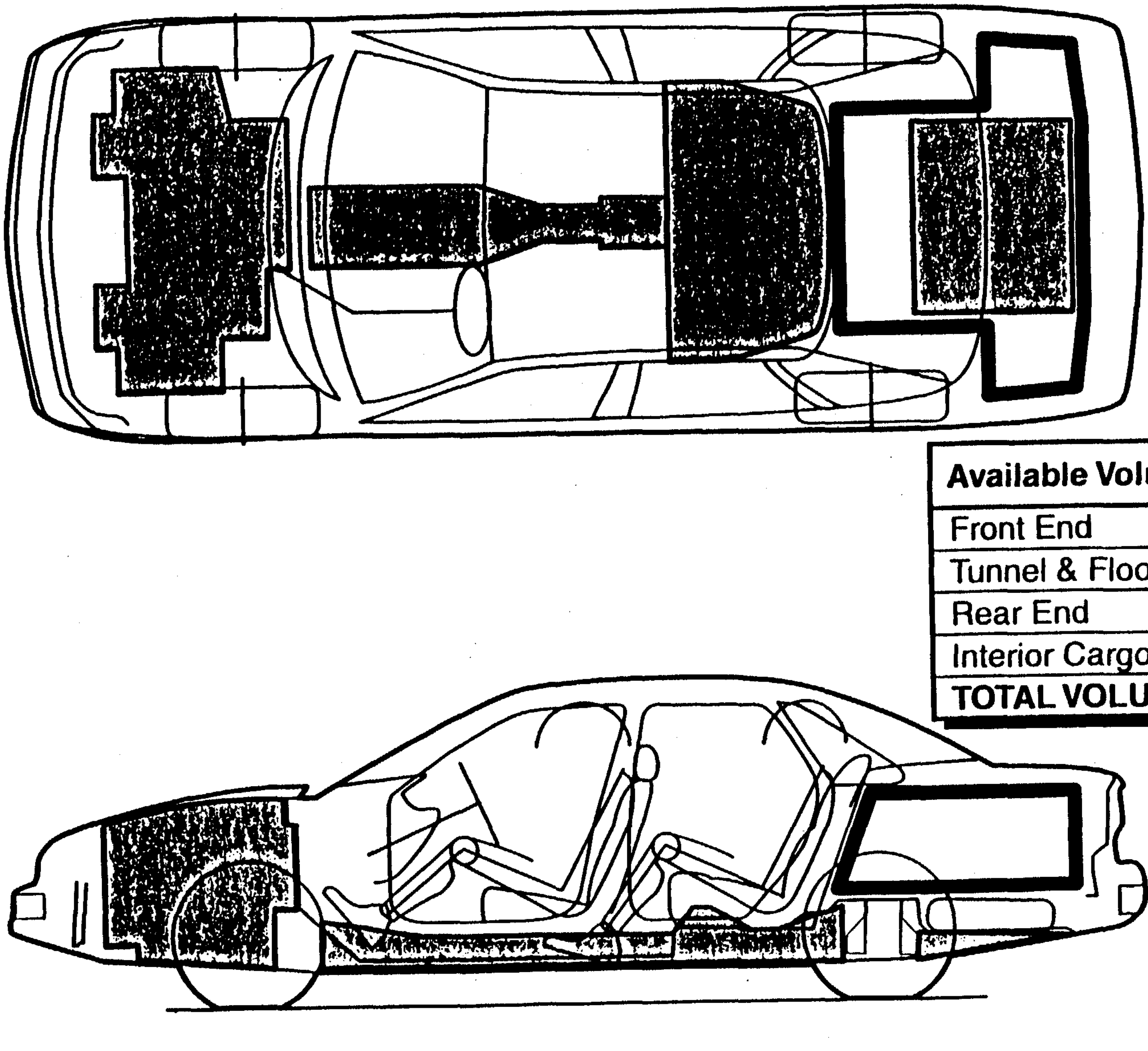
It was again agreed that additional volume would be required, therefore the trunk space was used for additional volume calculations. This added 555 liters to the total volume for this vehicle and yielded a total volume of 1255 liters. (See Figure 13).

In a similar manner to the Aspire, the AIV Sable component packaging studies commenced following the volume studies. The component sizing and weight aspects of the packaging efforts were centered around maintaining as much of the existing vehicle architecture as possible. Many packaging designs were investigated and three were determined to be viable.

The first acceptable design, shown in Figure 14, involves packaging a 90 kW (120 hp) motor in the front engine compartment area. The fuel cell-related components that would fit in the engine compartment were placed there. These include the compressor/expander, the motor controller/inverter and gas management system. Synonymous with the Aspire, these fuel cell peripherals all packaged favorably here along with the electric motor controller and its components. The next set of components to be packaged were the hydrogen storage tanks. For this exercise, 5.9 kg (13 lb) of hydrogen were divided into two storage tanks and placed under the trunk area of the vehicle. Next, the fuel cell stacks were packaged just behind the hydrogen tanks, also in the trunk compartment. Even though this is a viable package, it presented some issues. The issues related to this package, listed in Figure 14, were:

- unfavorable crashworthiness due to the fuel cell's proximity to the rear bumper and quarter panel
- loss of all cargo carrying capacity,
- propulsion system cooling issues and non-optimum weight distribution arising from the location of the fuel cell stacks behind the rear axle.

AIV SABLE VOLUMES



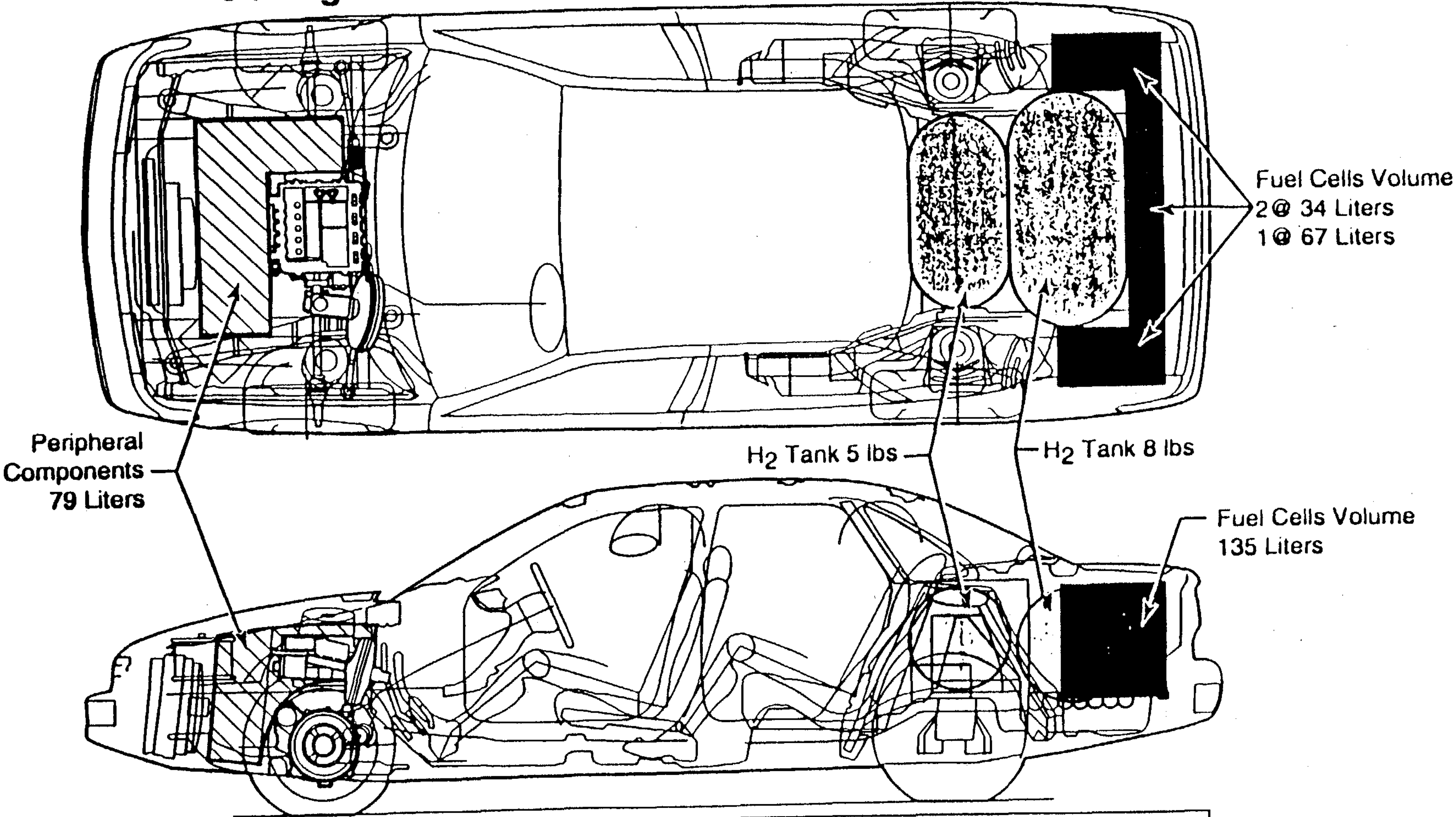
Available Volume For Packaging	
Front End	478 Liters
Tunnel & Floor	189 Liters
Rear End	33 Liters
Interior Cargo	555 Liters
TOTAL VOLUME	**1255** Liters

Figure 13

AIV SABLE FUEL CELL PACKAGE

Assumed Fuel Cell System Power Density

3 Kilograms Per Kilowatt / 3 Liters Per Kilowatt



ISSUES
Crashworthiness
Fuel Cell Cooling
Weight Distribution
Cargo Space

PACKAGE VOLUMES
Fuel Cell/Periphal Volume: 214 Liters (13059 cu. in.)
Eletric Motor 90 (kW) (120 HP)
H2 Tanks Volume: 285 liters (5.9 kg)

Figure 14

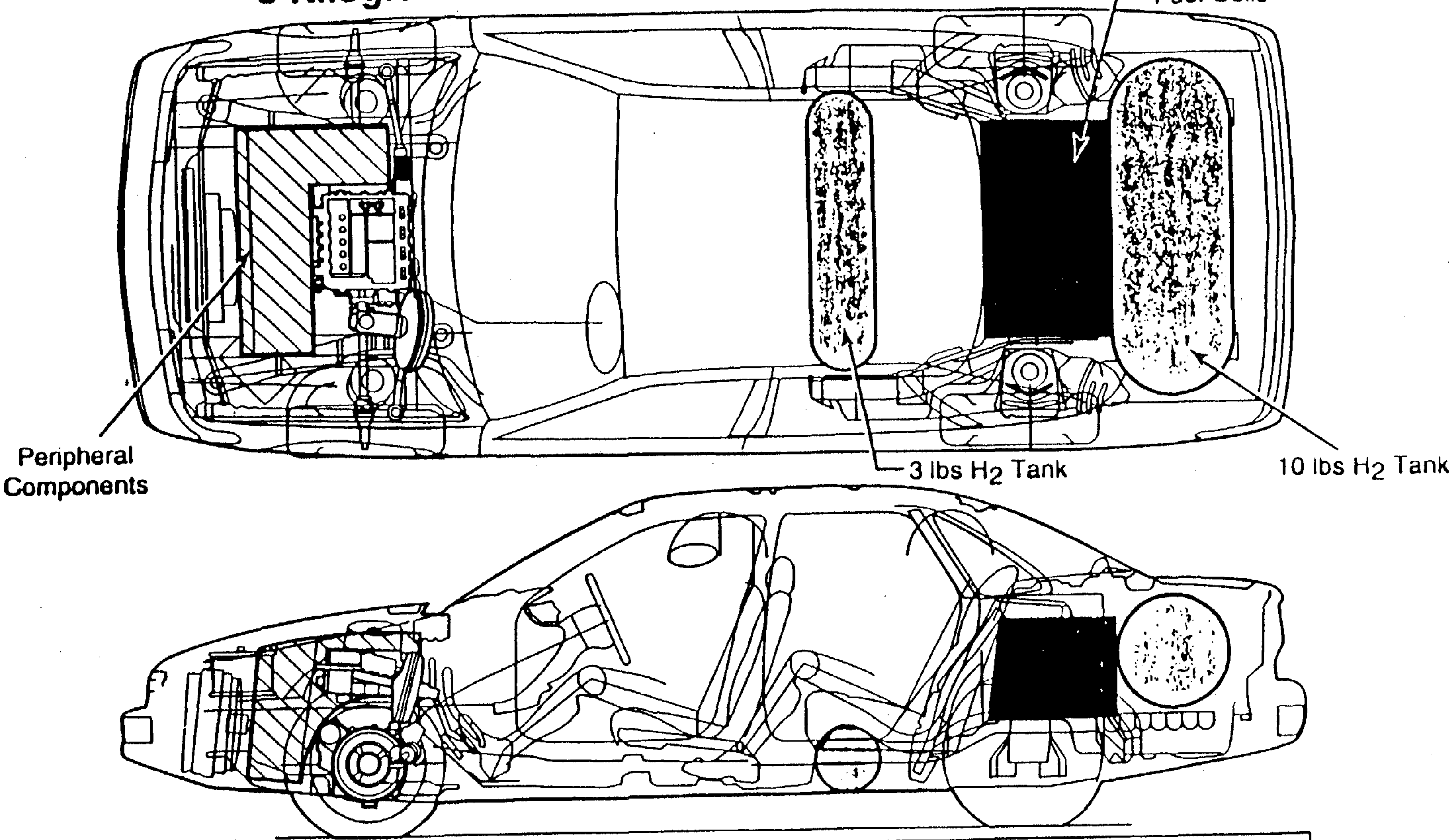
The next design that exhibited some promise is shown in Figure 15. In this arrangement, the overall layout is very similar to the previous design except the fuel cell was moved forward over the rear axle for better weight distribution. The hydrogen tanks were altered in size. One tank, with the appropriate volume to contain 1.4 kg (3 lb) of hydrogen, was located under the rear floor pan area where the production fuel tank was originally located. The other tank was increased in size to accommodate 4.5 kg (10 lb) of hydrogen and packaged behind the fuel cell stacks. Many of the same issues that were identified in the previous package were the same for the package shown in Figure 15.

The final AIV Sable fuel cell package demonstrated much of the same characteristics as the previous two, with the main difference being the location of the fuel cell stacks. For this design, the stacks were located in the tunnel area and that previously occupied by the production fuel tank, under the floor pan as shown in Figure 16. This package achieved the best combination of weight distribution and protection from both side and rear-end impact. An issue related to this design was again the loss of cargo volume. Because of the projected physical sizes and shapes of the stacks themselves, slight floor pan modifications may be required to house the cells below the floor and under the rear seating area. However, overall, this package shows the most promise in both safety and vehicle dynamics.

AIV SABLE FUEL CELL PACKAGE

Assumed Fuel Cell System Power Density

3 Kilograms Per Kilowatt / 3 Liters Per Kilowatt



ISSUES
Crashworthiness
Fuel Cell Cooling
Fuel Cell Stack Isolation from Interior Compartment

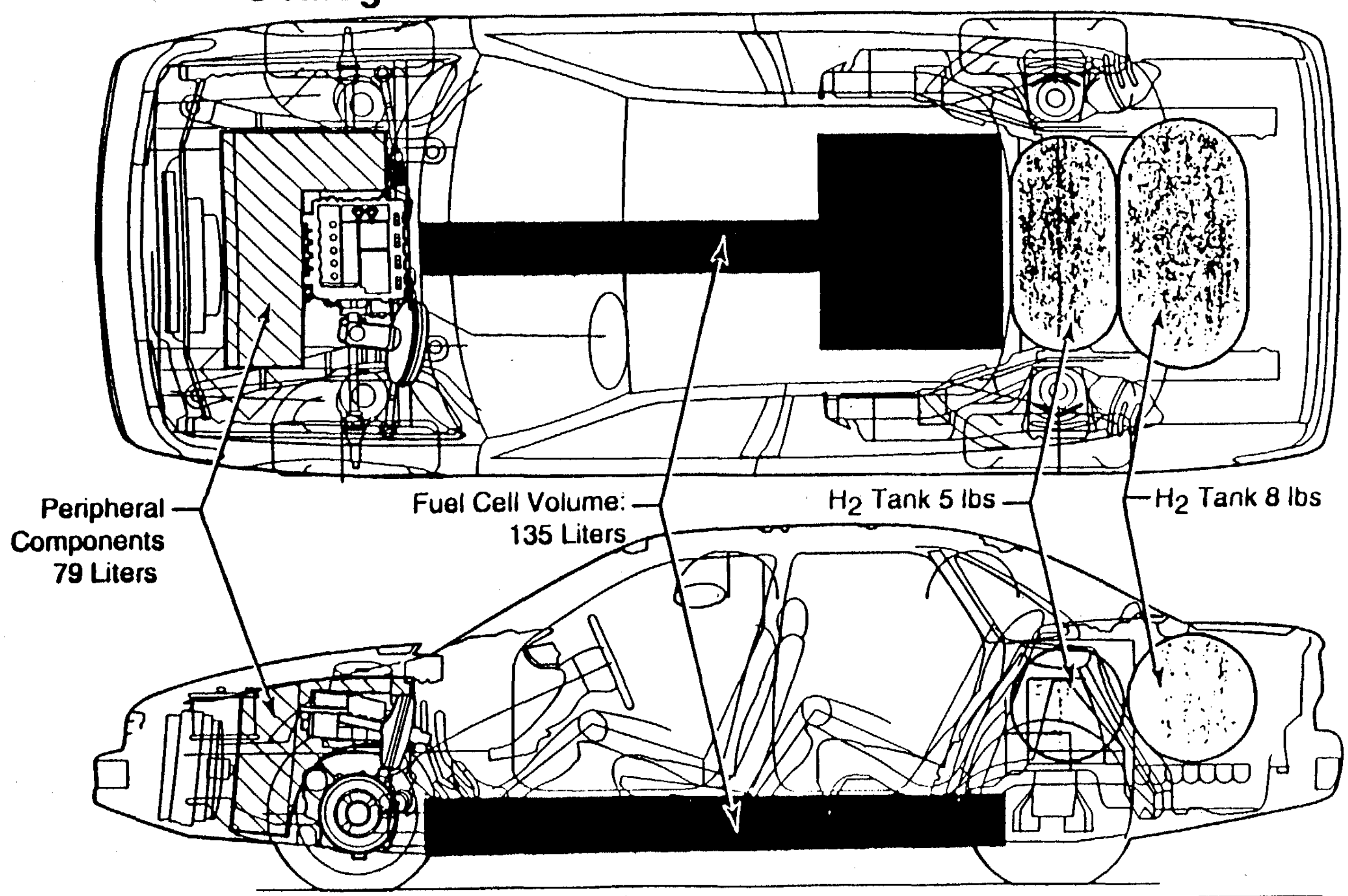
PACKAGE VOLUMES
Fuel Cell Volume: 230 Liters (14035 cu. in.)
Eletric Motor 90 (kW) (120 HP)
H2 Tanks Volume: 285 liters (5.9 kg)

Figure 15

AIV SABLE FUEL CELL PACKAGE

Assumed Fuel Cell System Power Density

3 Kilograms Per Kilowatt / 3 Liters Per Kilowatt



ISSUES
Comprised Rear Seating Package
Fuel Cell Cooling
Tunnel & RR Floorpan Rework
Cargo Space

PACKAGE VOLUMES
Fuel Cell/Periphal Volume: 214 Liters (13059 cu. in.)
Eletric Motor 90 (kW) (120 HP)
H2 Tanks Volume: 285 liters (5.9 kg)

Figure 16

E-150 Econoline Van Volume Calculations and Packaging

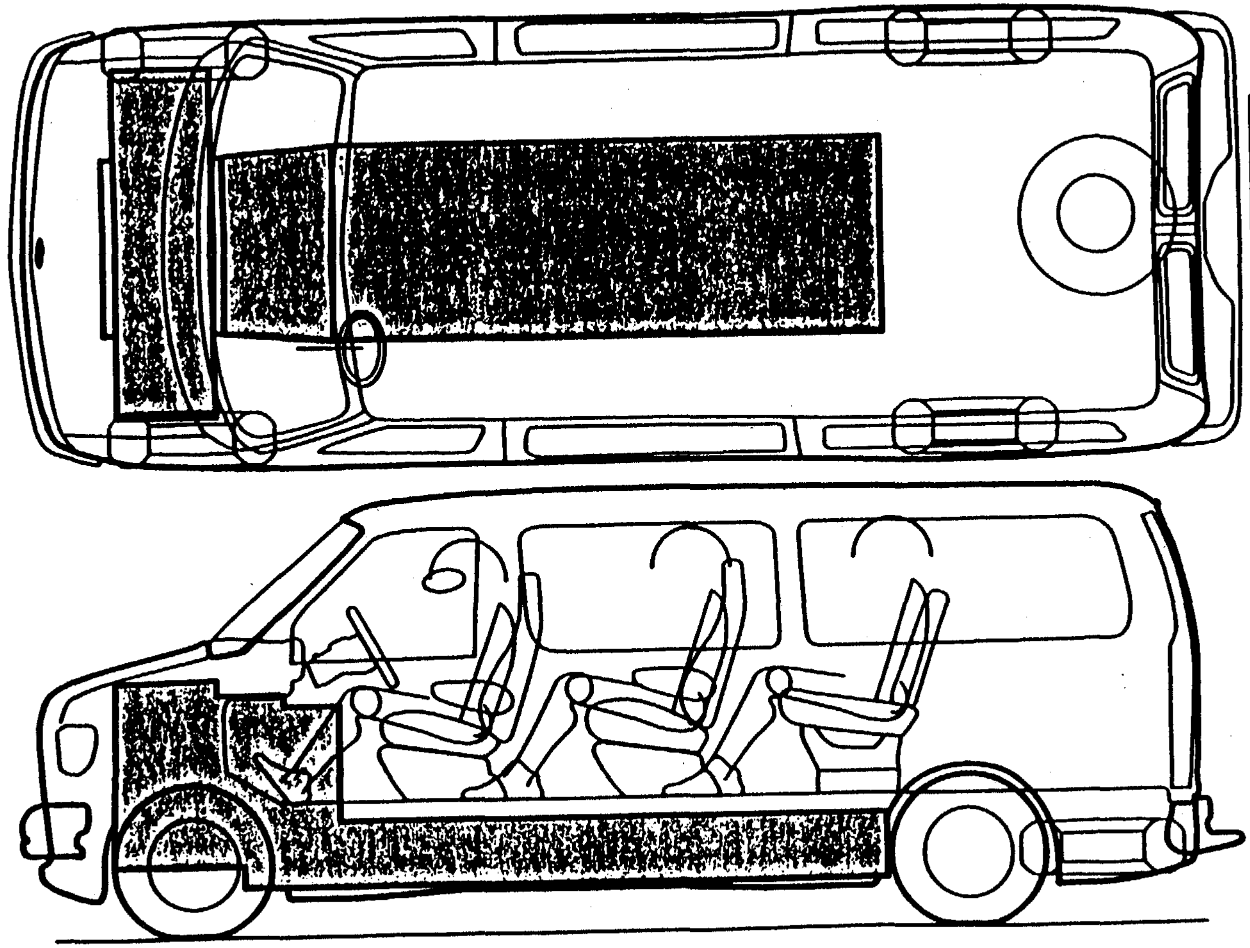
The determination of the volume available in this vehicle began with the elimination of the engine and transmission assemblies, the drive shaft, and the fuel tank. Because of its size and relatively large open areas, this vehicle provided greater volume. As can be seen in Figure 17, the engine compartment area and that between the vehicle's frame rails provide most of the required volume. The total of these two locations measured 1,284 liters and at the time this volume study was carried out, further packaging volumes were not investigated. As the next packaging study showed, however, regions outside the frame rails were required to provide the needed hydrogen storage capacity. Except for the elimination of the powertrain, no significant vehicle modifications were required to achieve this vehicle's packageability.

In a similar manner to the Aspire and AIV Sable, many packaging attempts were executed and all but one were eliminated for reasons of weight distribution, safety, or poor vehicle dynamics. The package that was most efficient, in terms of weight distribution and space utilization, is shown in Figure 18. It shows the fuel cell stacks located up front in the engine compartment. The compartment also housed the fuel cell peripheral components as well as two small hydrogen storage tanks containing 0.9 kg (2 lb) of hydrogen. The remaining hydrogen storage tanks were located between the frame rails and under the floor pan. One tank will hold 2.7 kg (6 lb) of hydrogen and two adjacent tanks held 1.9 kg (4.25 lb) of hydrogen each. The final 3.9 kg (8.5 lb) of hydrogen were packaged on the outboard side of the frame rails, under the floor pan, and just behind the driver and front seat passenger. The rationale for packaging the two tanks outboard on the frame rails stems from the fact that this vehicle provides sufficient body structure between the side of the vehicle and the surface of the tanks to protect them in case of side impact. If required, additional sheet metal protection could be added without compromise to the vehicle package.

The remaining components of this package were the electric motor and its controller. The 125 kW (168 hp) motor was comprised of two 62 kW motors attached to a common transmission, located under the cargo floor just ahead of the rear axle which it drives. In keeping with the Ford corporate ground clearance requirements, the floor pan of the van may require a local modification to clear the motor transmission assembly. The vehicle electric motor controller is located adjacent to the electric motor and just ahead of the rear axle.

As with all of the vehicles studied, compromises had to take place between the vehicle architecture and the fuel cell components because none of the vehicles were designed specifically for electric peripherals and fuel cells. Adapting such equipment would require some trade-offs if existing vehicles were to be used as test beds for fuel cell power systems in light duty transportation.

ECONOLINE (E-150) VOLUMES
BASE 7 PASSENGER



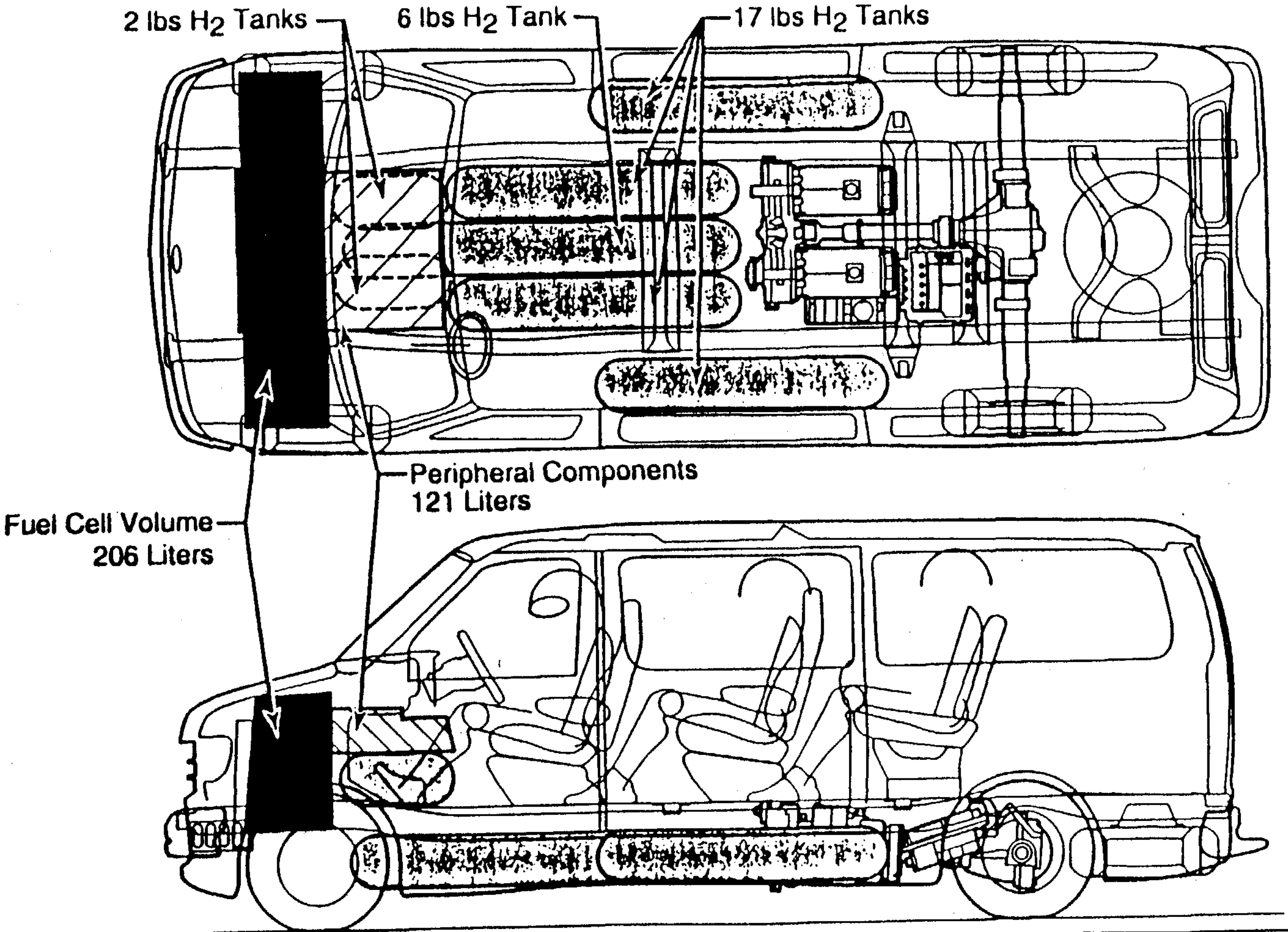
Available Volume for Packaging	
Front End	687 Liters
Tunnel & Floor	597 Liters
Total Volume	**1284** Liters

Figure 17

ECONOLINE (E-150) FUEL CELL PACKAGE

Assumed Fuel Cell System Power Density

3 Kilograms Per Kilowatt / 3 Liters Per Kilowatt



ISSUES
Rework Floor - Motor Interference
Crashworthiness

PACKAGE VOLUMES
Fuel Cell/Peripheral Volume: 327 Liters (19955 cu. in.)
Eletric Motor 125 (kW) (168 HP)
H2 Tanks Volume: 525 liters (11 kg)

Figure 18

5.0 Conclusions

This conceptual design study of the sub-compact, mid-size and van-size vehicles shows that the packaging of the direct hydrogen-fueled PEMFC power system is difficult without compromising vehicle architecture and still adhering to all automotive industry safety standards. The advances that have been made with regard to increasing power density of the fuel cell system are very encouraging indeed, but onboard hydrogen storage, at a pressure of 340 atm (5000 psia), remains the greatest packaging challenge.

The reported packaging study, based on the results from CVSP and the FCPS simulation programs, showed that for the sub-compact size vehicle, i.e. the Ford Aspire, the two rear passenger seats have to be sacrificed in order to house the fuel cell power system, drivetrain, accessories and hydrogen storage tanks. Although this study was based on a fuel cell power density of 0.33 kW/l, this did not significantly alleviate the main challenge of packaging the hydrogen storage tank. Even if the power density of the fuel cell advances to 0.5 kW/l it might not be sufficient to package the fuel cell power system and other peripherals into this sub-compact vehicle without again sacrificing the rear seat area.

Packaging of the mid-size AIV Sable showed this to be a good basis for a fuel cell powered passenger vehicle. The most amenable opportunity to package the fuel cell power system, its accessories and the hydrogen fuel tank, is provided by the Econoline van. In this conceptual vehicle design study, all of the efforts were directed towards integrating the fuel cell power system and the hydrogen storage into existing car products. Future design studies could include automobile frames and chassis that are specifically designed from the ground upwards for a fuel cell system powered vehicle. The success of such endeavors will profoundly depend upon the advances made by both the fuel cell technology and the fuel processing or storage technologies.

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