POSITIONING THE **STATE OF MICHIGAN** AS A LEADING CANDIDATE FOR **FUEL CELL** AND **ALTERNATIVE POWERTRAIN MANUFACTURING**

A REPORT CONDUCTED FOR THE
MICHIGAN ECONOMIC DEVELOPMENT CORPORATION
AND THE
MICHIGAN AUTOMOTIVE PARTNERSHIP

AUGUST 2001

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MICHIGAN ECONOMIC DEVELOPMENT CORPORATION

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map Michigan Automotive Partnership

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INTRODUCTION

The automotive industry enters the 21st century on the verge of a new powertrain paradigm. Recent technological developments suggest the internal combustion engine (ICE), which has been the driving force over the first 100 years, may have a major competitor within the coming decades. Many industry participants believe that fuel cell technology has the potential to replace the ICE as the primary source of propulsion for automotive applications. Although there are significant hurdles yet to be overcome in the development of a cost-effective automotive fuel cell and a viable infrastructure, the implications for the automotive industry and the State of Michigan could be truly profound. There are 10 engine plants and 5 transmission plants in Michigan and nearly 27,000 people are employed in these facilities. The development of a cost-competitive automotive fuel cell would likely make many of those powertrain facilities obsolete. As these plants close, they would likely be replaced by facilities specially built for the new fuel cell technology. This report begins to identify key market trends in new powertrain technologies (including fuel cell) and hybrid electric vehicles—a critical enabler for automotive fuel cell application—and assists the State in identifying critical actions to position itself as a strong candidate for potential automotive fuel cell manufacturing facility investment

POTENTIAL MARKETS FOR FUEL CELLS

The fuel cell market can be divided into at least three segments: the specialty or premium market, stationary applications, and high volume transportation applications. These three markets have vastly different volume levels and are largely driven by the cost of manufacture per kilowatt. Due to the high value placed on uninterrupted power delivery, this market could justify costs in the $1,000 per kilowatt price range. To achieve cost effectiveness, stationary fuel cells will likely have to be delivered to the consumer on the $400 to $600 per kilowatt range. The volumes required for this cost reduction could be in the range of 10,000 to 100,000 units. The final volume challenge will be delivering fuel cells for transportation applications with a target cost at or below $100 per kilowatt and volumes in the hundreds of thousands to millions.

The hybrid electric vehicle (HEV) has preceded the fuel cell electric vehicle (FCEV) to market. These two types of powertrains share key components, yet also have important differences. Hybrid electric vehicles use an internal combustion engine (usually gasoline or diesel) combined with an electric drivetrain to power the vehicle. The fuel cell electric vehicle uses hydrogen to create electricity, which is used to power the electric drivetrain. Both HEV and FCEV architectures use power electronics to both convert the electricity from DC to AC and manage the high voltage requirements.

FUEL CELL POWERTRAIN DEVELOPMENT

Most automotive fuel cell technology development has been focused on proton exchange membrane (PEM) fuel cell technology. PEM technology offers high power density, low internal operating temperature, and potential low cost mass production vis-à-vis most other fuel cell technologies. This makes PEM the most likely candidate for automotive applications. PEM fuel cell stack is comprised of four basic elements: membrane electrode assembly (MEA), the bipolar plates, and the end plates. Up to 50 MEAs may be required back-to-back (separated by bipolar plates) to make a PEM fuel stack capable of delivering the power requirements for transportation applications. In addition to the fuel cell stack, there are several external components, including the heat, water and air management components commonly referred to as the balance of plant (BoP) that completes the fuel cell system. There remain significant cost reduction challenges. According to the Partnership for a New Generation of Vehicles (PNGV), using current techniques, mass-produced fuel cells would cost over $200/kW, while conventional powertrain costs are under $30/kW.

The hydrogen required to operate PEM fuel cells could be derived from off-board reformulators—most likely using natural gas as the fuel—and located at central locations, or an on-board reformer using gasoline, methane, or other hydrocarbon fuel. Both strategies present significant challenges. Michigan must take a leading role in the development of a hydrogen infrastructure.

The emergence of the fuel cell as a power source provides the opportunity for the automotive industry to develop an entirely new powertrain production-manufacturing paradigm. However, similar to many of the technological barriers for successful fuel cell implementation, future strategies for high volume production remain unclear. It is apparent that manufacturers are struggling to determine if the fuel cell will provide a competitive advantage—and thus be the domain of the OEM (like the current ICE) or conversely be viewed as a component that can best be provided by suppliers. Each automotive manufacturer is currently relying on strategic partners to develop the three modules (reformer, fuel cell and electric drivetrain). Yet each manufacturer also has committed significant resources to develop internal fuel cell capabilities.

FUEL CELL POWERTAIN BUILD ISSUES

Michigan has historically been home to a substantial amount of engine and transmission manufacturing facilities. Currently, there are approximately 27,000 people employed at engine and transmission plants in Michigan, and thousands more throughout the state employed by suppliers who manufacture parts and components for these powertrain facilities. Michigan has 34.5 percent of engine manufacturing and 39.1 percent of automatic transmission manufacturing in North America. These workers have experience in high-volume, high-precision, machining and assembly. Yet these skills do not necessarily cross over into fuel cell manufacturing—a highly automated process.

The PEM electrolyte membrane will most likely be manufactured by chemical companies. Facilities designed for the manufacture of electrolyte membranes will be extremely automated and high volume. The process will likely incorporate the cathode and anode to manufacture a complete MEA. Bipolar plates can be made from metals, graphite and graphite composites. The manufacturing process for these plates will also be highly automated. Volumes for bipolar plate manufacturing facilities may well be approximately a million per day to meet automaker demand.

The heat, water and air management subsystems will require high-pressure fittings and have a substantial amount of stainless steel tubing. Significant manufacturing and performance challenges remain in the development of the BoP components. These systems may be viable candidates for development by automotive suppliers currently manufacturing similar components for internal combustion engines.

The reformer may be the subsystem that is in need of the most refinement. Most current strategies incorporate technology (often in the form of a series of heat exchangers and catalysts) into a canister where air, water and fuel combine to reformulate the fuel. A key aspect of the development of fuel reformers is the need to be manufactured at the high volumes required by the automotive industry. Therefore, much consideration is being given to developing components for fuel reformers which will match the automotive industry's manufacturing skills. The catalyst (an important part of the reformer) and the heat exchangers are examples of components that the industry currently manufactures.

Finally, power electronics will be a critical element of fuel cell electric (and hybrid electric) vehicles. The State does not have significant expertise in the development nor manufacturing of power electronics, and must work to strengthen its position in this area.

Recommendations

Although the initial intention of this report was to define the steps that Michigan should take to become a prime location for fuel cell manufacturing investment, interview respondents quickly reshaped the conclusions to include a more all-encompassing strategy. The fuel cell has the potential to reshape the automotive industry, yet the fuel cell itself is only a portion of the new powertrain paradigm. Based on discussions with Michigan-based manufacturers and suppliers, the Center for Automotive Research (CAR) recommends five key areas that the State must address to better position itself as a leader in alternative powered vehicle technology, and concomitantly, a viable candidate for fuel cell manufacturing.

These recommendations include:

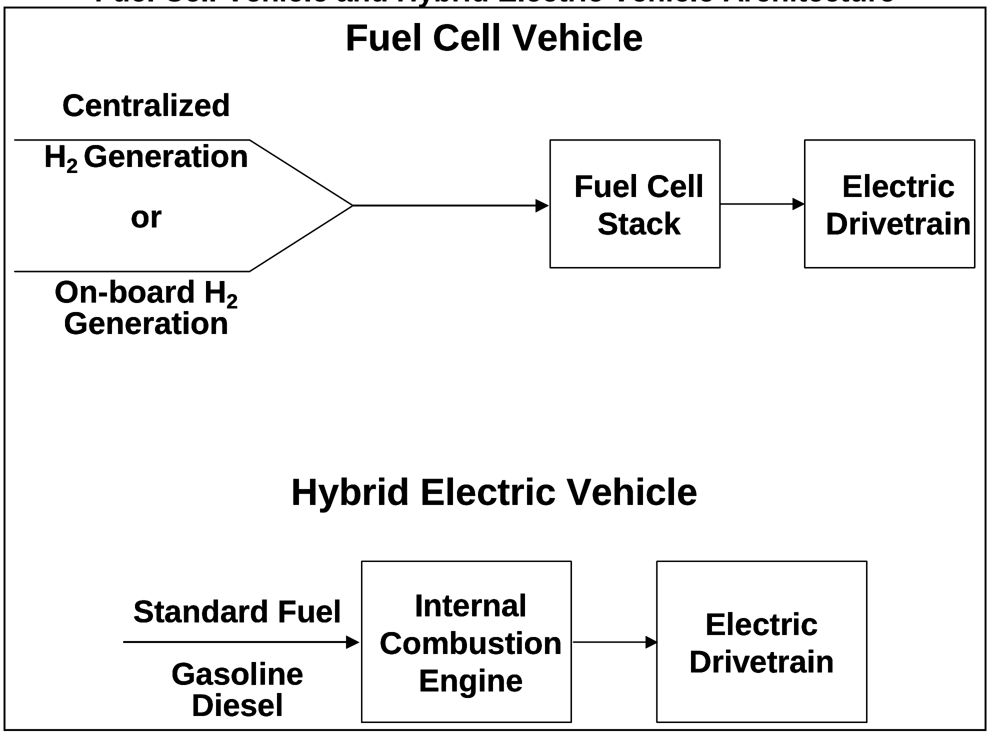
- Creating a Michigan Advanced Automotive Powertrain Technology Alliance;
- Investigating the feasibility of creating a power electronics "Center of Excellence;"
- Establishing a Michigan Hydrogen Infrastructure Working Group;
- Promoting the demonstration and testing of prototype fuel cell vehicles and supporting the commercialization of fuel cells for advanced vehicles and stationary applications; and
- Conducting an economic study to determine the most appropriate financial incentives for the development and commercialization of fuel cell and other advanced technology vehicles.

I. INTRODUCTION

The automotive industry enters the 21st century on the verge of a new powertrain paradigm. Recent technological developments suggest the internal combustion engine (ICE), which has been the driving force over the first 100 years, may have a major competitor within the coming decades. Many industry participants believe that fuel cell technology has the potential to replace the ICE as the primary source of propulsion for automotive applications. Although there are significant hurdles yet to be overcome in the development of a cost-effective automotive fuel cell and a viable infrastructure, the implications for the automotive industry and the State of Michigan could be truly profound. Currently there are 33 engine plants and 14 transmission plants in North America. Importantly, there are 10 engine plants and 5 transmission plants in Michigan and nearly 27,000 people are employed in these facilities (Harbour 2000). The development of a cost-competitive automotive fuel cell would likely make many of those powertrain facilities obsolete. As these plants close, they could be replaced by out-of-state facilities specially built for the new fuel cell technology. This report begins to identify key market trends in new powertrain technologies (including fuel cell) and hybrid electric vehicles—a critical enabler for automotive fuel cell application—and assists the State in identifying critical actions to position itself as a strong candidate for potential automotive fuel cell manufacturing investment.

The hybrid electric vehicle (HEV) has preceeded the fuel cell electric vehicle (FCEV) to market. These two types of powertrains share key components, yet also have important differences. Figure A shows the basic elements of the two powertrains. Hybrid electric vehicles use an internal combustion engine (usually gasoline or diesel) combined in either a parallel, series or integrated motor assist configuration with an electric drivetrain to power the vehicle. The fuel cell electric vehicle uses hydrogen, either stored onboard or generated onboard via a reformer (likely using gasoline or methanol) to create electricity, which is used to power the electric drivetrain. Both HEV and FCEV architectures use power electronics to both convert the electricity from DC to AC and manage the high voltage requirements.

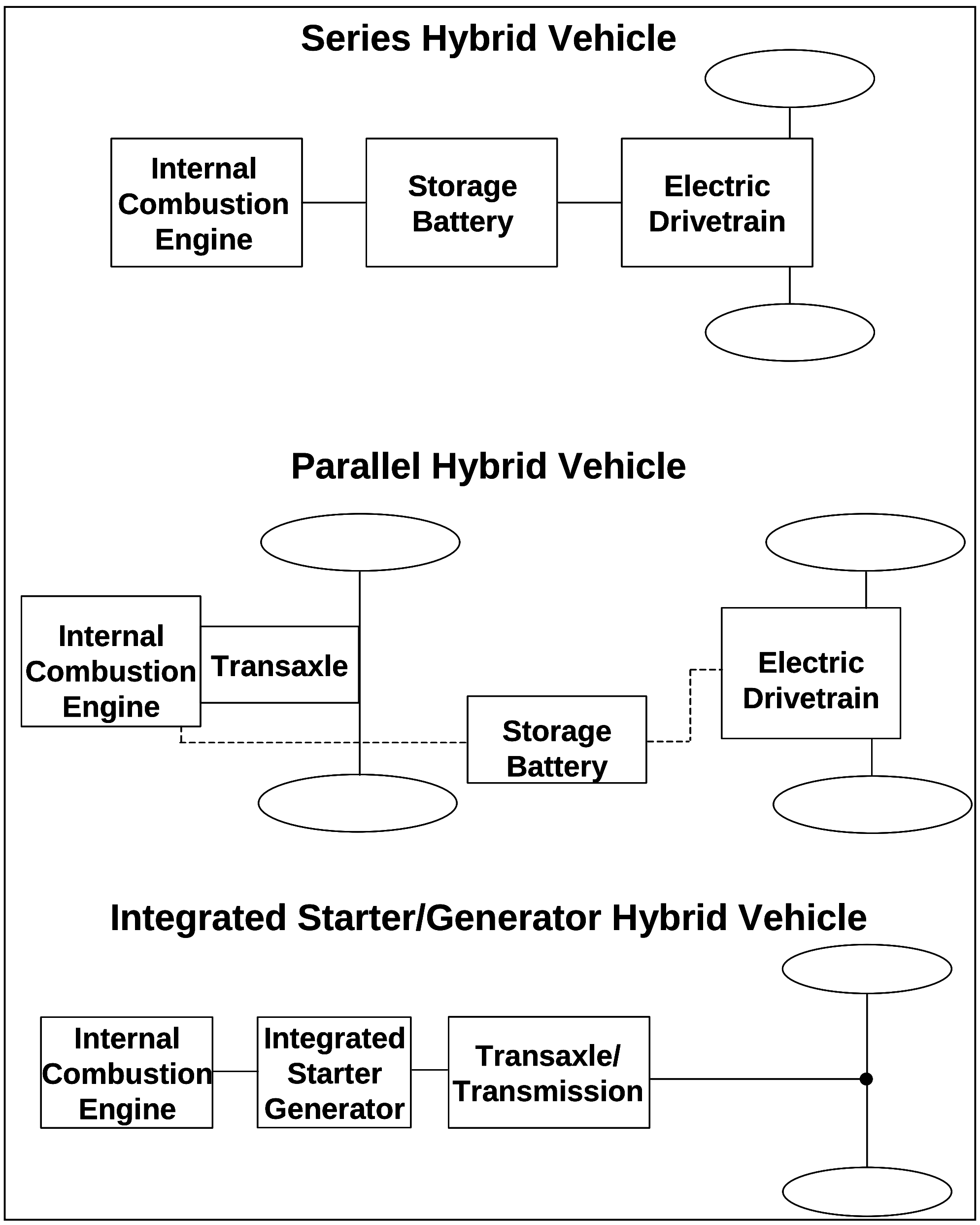
Figure A
Fuel Cell Vehicle and Hybrid Electric Vehicle Architecture



The fuel cell-powered vehicle includes three basic powertrain components—the fuel storage/reformer, the fuel cell engine (which creates electricity), and the electric drivetrain. The fuel storage/reformer will be either on-board hydrogen storage (liquid, compressed or metal hydride or other form) or fuel-stock storage and reformer that converts the fuel-stock into hydrogen. The fuel cell engine is comprised of the fuel cell stack and the balance of plant. The balance of plant includes the fuel delivery system, and the water and heat management systems. The electric drivetrain for fuel cell electric vehicles is similar to that used for series hybrid electric vehicles.

The HEV uses gasoline/diesel storage and an internal combustion engine similar to current ICE vehicles, but adds an electric drivetrain. Figure B shows the three general architectures for hybrid electric vehicles. The series hybrid electric vehicle uses the internal combustion engine to power a generator, which in turn creates the electricity which is used to power the electric drivetrain. In the series HEV, the ICE does not directly power the wheels. The parallel hybrid uses both the internal combustion engine (via a transaxle or transmission) and the electric drivetrain to deliver power to the wheels. The third architecture uses an integrated motor assist, usually in the form of an integrated starter-generator (ISG). This system is commonly referred to as the mild-hybrid electric vehicle because it relies mostly on the ICE but uses the electric starter/generator for ICE engine idle shutdown and power boost. The ISG may share some characteristics with the parallel system. However, parallel hybrid vehicles are designed to operate using the internal combustion engine or the electric drive train or both, whereas an ISG system serves as a booster for the ICE and auxiliary power source.

Figure B
Hybrid Electric Vehicle Architectures



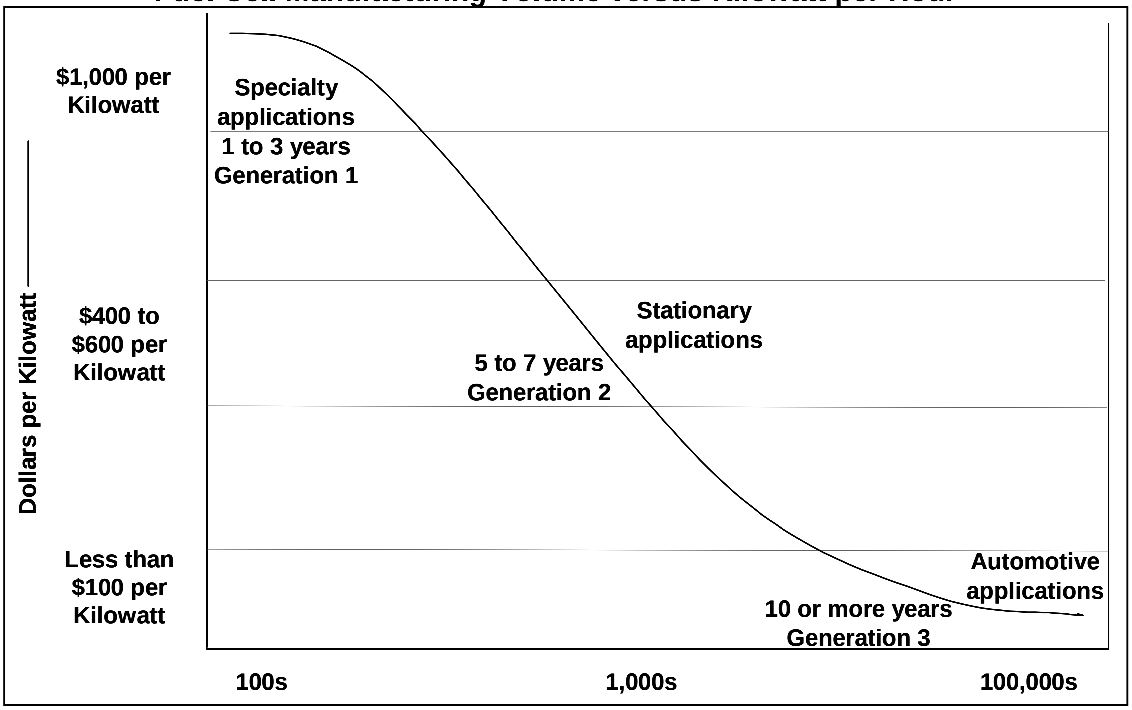
STUDY OVERVIEW

This study will: 1) Investigate initial markets for fuel cell technology and specifically the market for fuel cell electric vehicles (FCEV); 2) Identify the critical barriers that exist in the development of FCHEV for automotive applications; 3) Describe potential build processes for fuel cells, electric drivetrains and fuel reformulators; 4) Describe current competitors, including those companies that are considered leaders in the development of automotive fuel cell technology and alternative power-source applications, as well as stationary (non-automotive applications) and automotive accessory drive applications; and 5) Recommend actions the State can take to position itself as a leading candidate for future of fuel cell, and other advanced powertrain manufacturing investment.

FUEL CELL MARKET ISSUES

The fuel cell market can be divided into at least three segments: the specialty or premium market, stationary applications, and high volume transportation applications. These three markets have vastly different volume levels and they are driven by the cost of manufacture per kilowatt. The introduction of these products will likely follow a cost curve similar to that represented in figure C. The cost of kilowatts is illustrated by a downward sloping cost curve as manufacturing costs are decreased with successive generations of production technology. As production systems are developed that combine the volume requirements at the needed costs per unit, the market opportunity for automotive applications will greatly increase. It is also important to note that these manufacturing issues will only be relevant if the technological development challenges of the fuel cell are overcome.

Figure C
Fuel Cell Manufacturing Volume versus Kilowatt per Hour



Standby power is the primary application of premium or specialty fuel cells for use in hospitals or other businesses highly sensitive to power disruptions. Due to the high value placed on uninterrupted power delivery, this market could justify costs in the $1,000 per kilowatt price range. This stage of manufacturing can be referred to as Generation 1 technology. There are Generation 1 manufacturing facilities currently in the start-up phase, and the products are undergoing proof-of-concept testing. These units will likely be cost effectively manufactured for consumer markets by 2003. Generation 1 volumes will likely be less than 1,000 units per year.

To cost effectively meet the volume requirements for the next stage—the stationary market—the fuel cell industry will likely have to advance to what could be called Generation 2 manufacturing. To achieve cost effectiveness, stationary fuel cells will likely have to be delivered to the consumer in the $400 to $600 per kilowatt range. The volumes required for this cost reduction could be upwards of 100,000 units. Although it is clearly difficult to forecast timing, it is possible that such manufacturing advances may not be fully implemented for five to seven years.

The final volume challenge will be delivering fuel cells for transportation applications with a target cost of at or below $100 per kilowatt. This Generation 3 manufacturing technology could cost effectively deliver fuel cells in volumes above 100,000 units. However, it is possible that such manufacturing capability may be ten or more years away. These manufacturing efficiencies will also likely lower the cost points for specialty and stationary applications, thus increasing the volumes in these markets.

The capital investment strategy for companies is a critical element of fuel cell manufacturing. To advance from Generation 1 to Generation 2, and from Generation 2 to Generation 3, will require significant advancements in the manufacturing processes. Such fuel cell manufacturing technology is rapidly developing (Appendix C contains developmental manufacturing activities funded by the Department of Energy). Therefore, if a company invests in current technology, it may quickly be left with dated—possibly even useless—equipment within a few short years. Yet, if it fails to make investments in the early stages, it risks failing to gain initial market penetration and thus faces even greater barriers upon entry. Consequently, one of the most critical, and perplexing decisions a company must make is the timing for investment in manufacturing facilities. Certainly this is an important factor for the State, because the success of any company in initiating fuel cell manufacturing is highly dependent upon the technology ready at the time of implementation. But success may be even more dependent on the rate of technological change following the investment. Rapid asset depreciation for such technologies may not only be appropriate, but required.

Most interview respondents believe it is possible that there will be at least three generations of manufacturing technology needed to reach the kilowatt per dollar constraints of transportation applications. For a company—or the State—to miss Generation 1 or 2 will likely inhibit its opportunity to gain status as a Generation 3 manufacturer. Conversely, some interview respondents suggested that it was not necessarily important for the State of Michigan companies to gain "experience" in the manufacturing of fuel cells by participating in Generation 1 or 2 manufacturing. These respondents suggest that the introduction of recent automotive facilities in locations that were considered nontraditional automotive regions illustrates that other location criteria, such as training or tax incentives, are as valuable as having a "tradition" in manufacturing.

II. Barriers to the Development of fuel cells for automotive applications

Background

Internal combustion engines change chemical energy (gasoline, diesel, natural gas or LPG) into thermal energy during a combustion process ignited by a spark plug or heat combustion (diesel). The fraction of chemical energy actually used to drive a vehicle is relatively low, generally in the area of 15 to 20 percent. Diesel engines are more efficient than spark ignited engines, but maximum efficiency is still typically less than 40 percent

The fuel stack converts chemical energy directly to electrical energy, without the use of heat. The conversion process is significantly more efficient than the internal combustion engine. Internal combustion engines are about 20 percent efficient compared to about 45 percent for fuel cells, but they offer cost performance of about $30 per kW versus $300 per kW for current fuel cell technology. Fuel cells require hydrogen which, when combined with oxygen from air, produces electricity in an electrochemical reaction. Hydrogen can be stored on-board the vehicle in a compressed, liquefied or metal-hydride form. Conversely, the hydrogen can be derived from gasoline, methanol, methane, ethane or other bio-derived fuels via the use of a reformulator to chemically extract the hydrogen from the fuel stock (SAE 2000-01-0003, p. 16). Although there are several types of fuel cells, all include two electrodes separated by an electrolyte.

Most automotive fuel cell technology development has been focused on proton exchange membrane (PEM) fuel cell technology. PEM technology offers high power density, low internal operating temperature, and potential low cost mass production vis-à-vis most other fuel cell technologies. This makes PEM the most likely candidate for automotive applications.

The powertrain configuration for fuel cell powered vehicles is comprised of three basic subsystems: the fuel storage/reformulator module, the fuel cell, and the electric drivetrain. The system also may require a battery to provide supplemental energy during acceleration and for cold starts. An example of this type of fuel cell hybrid is the DaimlerChrysler NeCar 5 concept vehicle.

In addition to these three systems, an electronic control network is also required. This electronic control system may be similar to a local area network, with separate control modules for each of the systems linked together to a centralized vehicle control module.

It is noteworthy that significant "invention"—in technology development and manufacturing process—may be necessary within each subsystem to achieve cost and performance characteristics equal to that provided by the current internal combustion engine. It is very realistic to say there are many cost issues that remain for all three elements of the fuel cell powered vehicles powertrain.

FUEL STORAGE/REFORMULATOR BARRIERS

HYDROGEN STORAGE

Polymer electrolyte membrane (PEM) fuel cells require hydrogen to operate. This hydrogen will either be derived through off-board reformulators—most likely using natural gas as the fuel—and located at central locations, or via an on-board reformer using gasoline, methane, or other hydrocarbon fuel (SAE 2000-01-0001, p. 1). However, due to the low energy density of hydrogen, it is very expensive to transport and store. Onboard storage of uncompressed hydrogen gas occupies about 3,000 times more space than gasoline under ambient conditions and must, therefore, be pressurized or liquefied.

Furthermore, the infrastructure investments required to use hydrogen in volumes large enough to meet the demands of a high volume vehicle fleet are severe. One estimate to develop the infrastructure required for hydrogen production and distribution would likely be in excess of $100 billion (SAE 2000-01-0003, p. 16). However, a Ford Motor Company and U.S. Department of Energy (DOE) sponsored analysis indicates the total cost of the infrastructure could be significantly lower.

Current research efforts for hydrogen storage have focused on three main methods. Possible storage options include high pressure, liquefying at extremely low temperatures, and the use of metal hydride storage powders.

Many proof-of-concept fuel cell vehicles use hydrogen stored on-board in compressed form. However, to store an amount of hydrogen on board that would provide equivalent range to current ICEs, hydrogen storage requires pressures of 5,000 psi. For comparison, natural gas is commonly stored at 3,600 psi. At such a high pressure, the electricity required for compression will alter the overall efficiency of the total fuel. High compression hydrogen also presents safety concerns (SAE 2000-01-0001, p. 1).

Liquefied hydrogen is also under consideration for automotive fuel cell application. DaimlerChrysler's NeCar 4 incorporates a cryogenic liquefied hydrogen storage system. However, the energy required for the liquefaction process greatly decreases the overall fuel efficiency of the technology. And, as with compressed hydrogen, many safety and distribution barriers remain.

Another option under consideration is the storage of hydrogen in solid form by using metal hydrides. These metal alloys are in a loose, dry powder form. Hydrogen gas enters the storage unit and is absorbed into the powder. Relative to alternative hydrogen solutions, metal hydrides are more easily and possibly more safely stored. Energy Conversion Devices, a Michigan-based company, has made strides in developing this technology; yet there are many significant barriers—both cost and technical—to overcome. One of those barriers is weight: metal hydride storage of hydrogen may be six to ten times that of liquid hydrogen storage.

It is important to note that although the in-vehicle storage and delivery infrastructure for hydrogen presents challenging problems, the use of large-scale stationary chemical plants to produce hydrogen is a well-established process. The ability to reduce the complexity and cost of the reformulating process on the vehicle is an important driver of such a distribution system (SAE 2000-01-0001, p. 1).

FUEL REFORMERS

An alternative to processed hydrogen is the onboard extraction of hydrogen from gasoline, methanol, or other similar hydrogen-rich fuels. However, the development of reformers required to convert these fuels to hydrogen has proven difficult and costly. There are three basic reformulator designs currently under consideration: partial oxidation (POX), steam and autothermal (ATR). These reformers currently share somewhat similar design features. They are comprised of a primary reformer, followed by processors to convert CO to CO_2 via the use of water or oxygen. It is possible that each of the three different reformers may be capable of forming hydrogen from each of the fuel stocks under consideration. However, early developmental advances may suggest that steam reformers are more advantageous for use with methanol, while POX and ATR reformers are more adaptable to gasoline, methane and ethane (SAE 2000-01-0003, p. 17).

The advantage of using gasoline to power fuel cells is the ability to rely on the current fuel delivery infrastructure. Methanol could also rely on the current fuel infrastructure; however, modification to the system would be required. One estimate places the cost for upgrading 10 percent of the current gasoline stations to be compatible with methanol at about $1 billion (SAE 2000-01-0005, p. 36).

The presence of sulfur in gasoline presents significant durability challenges for the PEM catalyst. Also, the management of water is more critical for gasoline reformulation than for other fuels (SAE 2000-01-0007, p. 38). Another important drawback of gasoline is that it is not a renewable resource.

As compared to an ICE, the emissions from a gasoline-fed PEM fuel cell are likely to be greatly reduced. Table 1 compares the levels of three important pollutants common to the use of gasoline. It is important to note that these measures are based on laboratory testing, and not on the EPA driving cycle. Therefore they are not necessarily comparable to real world applications. However, it does give an indication that the gasoline-fed fuel cell may offer significant environmental improvements (SAE 2000-01-0375, p. 120).

Table 1
Comparison of Internal Combustion Engine and Gasoline-fed PEM Fuel Cell Emissions

Type of emissions	Internal combustion engine	POX-based PEM fuel cell
NOx	10-200 p.p.m.	Less than 1 p.p.m.
CO (carbon monoxide)	200-5000 p.p.m.	Less than 1 p.p.m.
C1 (hydrocarbons)	100-600 p.p.m.	15 p.p.m.

Source: (SAE 2000-01-0375, p. 120).

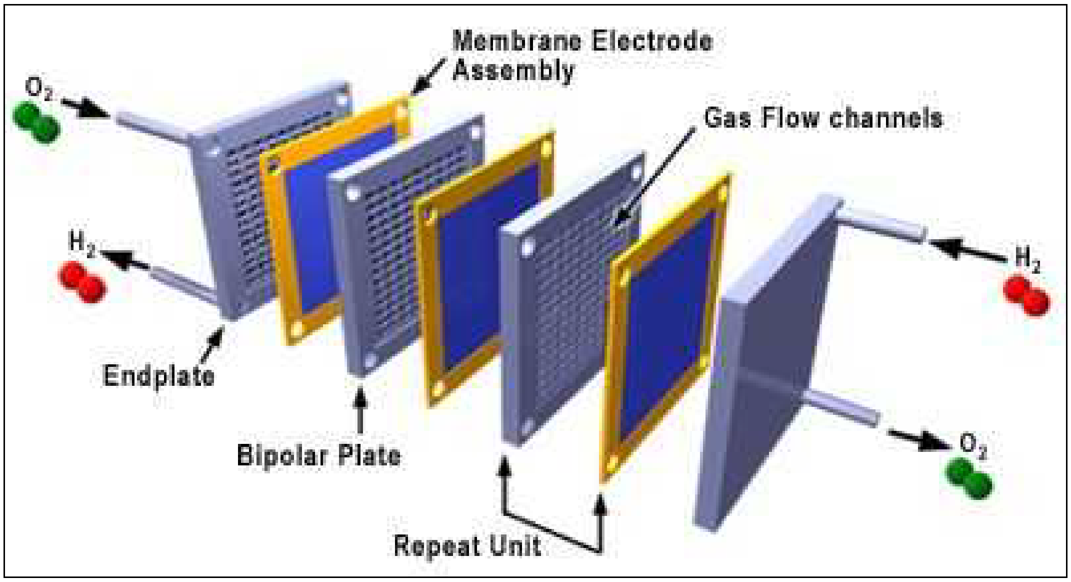
Methanol has two distinct advantages when compared to gasoline. Due to the less complex molecular nature of methanol, the energy required to reformulate methanol is lower than that required for gasoline. Reformulator technology for methanol is also more advanced than that for gasoline.

Methanol can be derived from natural gas, crude oil, or coal. It can also be derived from renewable resources such as biomass and wood. However, since it is most commonly derived from natural gas, it too can be considered a nonrenewable form of energy (SAE 2000-01-0003, p. 20). Methanol also presents safety concerns that differ from gasoline. For example, methanol is extremely poisonous and tasteless. The ingestion of very small amounts can cause blindness or death. Methanol also burns with an invisible flame, and is readily absorbed through the skin.

FUEL CELL TECHNOLOGY AND DEVELOPMENT

The proton exchange membrane (PEM) fuel cell stack is comprised of four basic elements: membrane electrode assembly (MEA), the bipolar plates, and the end plates. Up to 50 MEAs may be required back-to-back (separated by bipolar plates) to make a PEM fuel stack capable of delivering the power requirements for transportation applications. Figure D shows a diagram of a fuel cell stack.

Figure D
Expanded view of PEM Fuel Cell Stack



Source www.3m.com, 3M Corporation

The MEA consists of an electrolyte membrane, the anode and cathode, the catalyst and the gas diffusion/current collector. Dupont, and 3M are two of the relatively few companies that have established capability to provide complete MEAs.

The electrolyte is a substance that dissociates into positively and negatively charged ions in the presence of water—thereby making it electrically conducting. The PEM electrolyte is a polymer (plastic). The most common of these is Nafion, manufactured by DuPont. This membrane is about the thickness of approximately 175 microns—or about the thickness of 4 pages of paper—and is similar in look to clear cellophane wrapping paper. Nafion, when highly humidified, conducts positive ions while providing a barrier for the negative ions to pass through. The negative ions follow an external path to the other side of the membrane to complete the circuit.

The anode is the negative electrode that splits the hydrogen and sends the electrons through the external field and the positive ions through the electrolyte, where they are rejoined with the negative ions by the cathode. The cathode is the positive electrode that accepts the electrons from the external path and the electrolyte, combining them to make water and oxygen.

A catalyst is needed to speed up the oxidization process by lowering the activation energy required for oxidization. However, existing fuel cell technology relies on an extremely expensive material—platinum. Although there has been progress made in reducing the amount of platinum needed for the catalyst, the development of a more cost-effective catalyst will be a critical step in meeting cost requirements.

The gas diffusion/current collector or backing layer is made of a porous cloth, such as carbon paper. The flow fields—or current collectors—are pressed against the outer surface of each backing layer and serve to provide a flow path for the gases allowing the electrons to exit the anode side and re-enter the cathode plate. These flow fields are likely to be made from graphite, metals or possibly composites. A single fuel cell is capped by bipolar plates on both sides. To meet the needed power requirements, single fuel cells are placed end to end to form a fuel cell stack with metal endplates.

Historically the size of these fuel cell stacks has presented packaging issues. However, today, size no longer appears to be a major concern since fuel cell power density has increased seven-fold since 1991 to more than 1 kW per liter. The modular flexibility of fuel cells might enable a 50 kW fuel cell stack to be placed down the floor tunnel of an existing mid-sized sedan (PNGV Website). There remain significant cost reduction challenges. According to the Partnership for a New Generation of Vehicles (PNGV), using current techniques, mass-produced fuel cells would cost over \$200/kW, while conventional powertrain costs are under \$30/kW.

In addition to the fuel cell stack, there are several external components, known as the balance of plant (BoP), that complete the fuel cell system. Included in this group of external components are the thermal loop to remove heat from the fuels cell and an air compressor to increase airflow into the cell. Interestingly, these components have some similarities to components currently being manufactured for internal combustion engines such as radiators, heater cores, air compressors, and solenoids. Another critical area to the ancillary components is that of stainless steel tubing and high-pressure seals—not necessarily the domain of current automotive manufacturers.

Electric drivetrain development

Although there are several variations of the electric drivetrain, it will likely be comprised of at least four main components: a DC/DC converter, an inverter, an AC motor and transmission system, and a battery or ultracapacitor for power storage (most fuel cell powered vehicles would likely have a battery to facilitate cold start and as an assist in acceleration). (SAE 2000-01-3969)

The power electronics system (comprised of the DC/DC converter, the power inverter, and the control electronics for electric drivetrain, fuel cell and fuel system) is a critical element. Appendix B presents the parts and components that comprise the electric drivetrain. The power electronics system is the controlling part of any alternative powered vehicle, and therefore may be viewed as similar to modern ICE management software. The inverter is necessary to convert the power from DC to AC for application in the electric motors.

The rapid development of power electronics and associated components is critical for the effective development of electric drivetrain technology. Power electronics development is not traditionally an automotive industry strength. Defense and aerospace research has lead to the creation of centers of expertise for power electronics far from the traditional automotive industry. Interview respondents believe that these power electronics knowledge centers will likely remain outside of Michigan for the foreseeable future.

The DC/DC converter is necessary to boost the fuel cell voltage to the required voltages. The inverter is used to convert DC power to AC power for use in the electric induction motors. Currently the induction motor is most commonly used in HEV and FCHEV programs. The reliability, size and performance make them a likely choice for near-term vehicle programs.

III. Manufacturing strategies

The emergence of the fuel cell as a power source provides the opportunity for the automotive industry to develop an entirely new powertrain production-manufacturing paradigm. However, similar to many of the technological barriers for successful fuel cell implementation, future strategies for high volume production also remain unclear. It is apparent that manufacturers are struggling to determine if the fuel cell will provide a competitive advantage—and thus be the domain of the OEM (like the current ICE) or conversely be viewed as a component that can best be provided by suppliers. Each automotive manufacturer is currently relying on strategic partners to develop the three modules (reformer, fuel cell and electric drivetrain). Yet each manufacturer also has committed significant resources to develop internal fuel cell capabilities.

There are to be at least three distinct strategies for fuel cell manufacturing, although there could be many variations of each strategy. It is likely that manufacturing models will largely be driven by volume requirements.

The low-volume model is likely to mirror the model used in manufacturing electric vehicle products in the late 1990s. One example of an existing low-volume product is the Silver Volt, a SUV-based alkaline fuel-cell-powered vehicle with a 350-mile range, capable of a five-minute fill-up using either liquid ammonia or methanol. Electric Auto Corporation of Ft. Lauderdale, Florida expects to start production of the vehicle within two years. The vehicle will be assembled in Santa Anita, California. The fuel cells will be produced at a former textile factory in Valley, Alabama. The company expects a capacity of 24,000 vehicles per year. According to the company, the SUV is to be provided as a "glider" (i.e., fully assembled, without powertrain, from a major automotive manufacturer). It is highly unlikely that this type of low-volume producer can meet the quality and warranty requirements. Often these early boutique builders have difficulty reaching production.

The medium volume model may rely heavily on the partnerships that have been so critical in the development of fuel cell technology. In North America, DaimlerChrylser and Ford have invested in Ballard Power Systems, a leader in the development of fuel cells. These three companies have, in turn, invested in EXCELLIS (a fuel reformer and storage company) and Ecostar (an electric drivetrain company). EXCELLIS, Ballard and Ecostar jointly own Ballard Automotive whose mission is to deliver complete fuel cell powertrains. In this case, Ford and DaimlerChrysler have leveraged their resources and joined with suppliers to establish a partnership for the development of fuel cell technology. In addition, General Motors has an agreement with Toyota to share advanced powertrain research and technologies, and it has an agreement with ExxonMobil to research gasoline reformers. These partnerships are indicative of the increasing willingness of OEMs to leverage their assets with those of partners and suppliers.

These partnerships are also an indication of the high cost and difficulty to develop this drivetrain. It is also possible that some Michigan-based manufacturing capacity might be used for production. DaimlerChrysler, Ford and General Motors have labor contracts that guarantee hourly employees job security. Thus, there may be considerable incentive to develop production facilities in reasonable proximity to the existing production sites.

The high-volume strategy appears to be the most difficult to predict at this time. Each manufacturer has significant research and development invested in fuel cell technology, yet they are heavily leveraging their technology partners. This is in keeping with the current trend of asset reduction, including some outsourcing of powertrains. But, there are indications that some manufacturers view fuel cell technology as a critical strategic strength and plan to control it internally, while others view partnerships as an opportunity to reduce capital assets. The emergence of a dominant player in fuel cell technology development is impossible to predict at this time. Therefore, much like the companies involved in fuel cell development, the State should take great care to not place all its resources behind one technology or company—especially in the early developmental stages of fuel cells

IV. CURRENT INTERNAL COMBUSTION ENGINE STRUCTURE

Michigan has historically been home to a substantial amount of engine and transmission manufacturing facilities. Currently, there are approximately 27,000 people employed at engine and transmission plants in Michigan, and thousands more throughout the state employed by suppliers who manufacture parts and components for these powertrain facilities. Michigan has 34.5 percent of engine manufacturing (table 2) and 39.1 percent of automatic transmission manufacturing (table 3) in North America. These workers have experience in high-volume, high-precision, machining and assembly. Yet these skills do not necessarily cross over into fuel cell manufacturing—a highly automated process.

Based on current engine capacities, it can be assumed that scale economies are most commonly reached at between 300,000 to 400,000 engines per year for head and block machining lines. However, the manufacturing volumes of a typical engine module vary greatly. There are certainly efficient computer numerically controlled (CNC) lines that can operate well below the average, and highly dedicated lines that operate at twice the average. To reach these volumes, engines are used for several vehicle platforms or models.

A critical question for future manufacturers of fuel cells and HEV powertrains is what will be the scale economies for manufacturing. Will manufacturing volumes be similar to the current paradigm, or will scale economies required for the new technologies be vastly different than current powertrain strategies? It will be important to monitor the fuel cell manufactures as they determine the answer to this and other important questions.

Although fuel cell vehicles might someday supplant the ICE, hybrid electric vehicles may present a more near-term threat to Michigan's ICE engine production facilities. Table 2 shows that Michigan has a high concentration of 8-cylinder engine production and a comparably small percentage of 4-cylinder engine production. The State's engine-manufacturing imbalance will be further exacerbated by the closing of the Lansing Delta engine plant, which produced nearly 300,000 4-cylinder engines in 1999. If, as many believe, HEVs are manufactured in significantly higher volumes in the coming decade, there will be an increased need for three-cylinder, four-cylinder and six-cylinder engines and a decrease in the use of eight-cylinder engines. Such a scenario would be troublesome for a state that relies heavily on eight-cylinder engine production. However, data presented do not include two new 6-cylinder Michigan facilities (General Motors' Flint plant and DaimlerChrysler's Mack Avenue Detroit plant) that are scheduled to begin production in 2001.

Table 2
Michigan Engine Production as a Percent of North American Engine Production
(1999 Calendar Year)

	Total engine production	Michigan engine production	Michigan percent of total production
4-Cylinder	5,811,469	938,120	17.7%
6-Cylinder	6,138,995	1,996,410	32.5
8-Cylinder	4,518,609	2,595,680	57.4
10-Cylinder	115,454	17,785	15.3
All Engines	16,054,618	5,547,995	34.5

Source: Harbour Report 2000

Table 3
Michigan Automatic Transmission (AT) Production as a
Percent of North American AT Capacity
(1999 Calendar Year)

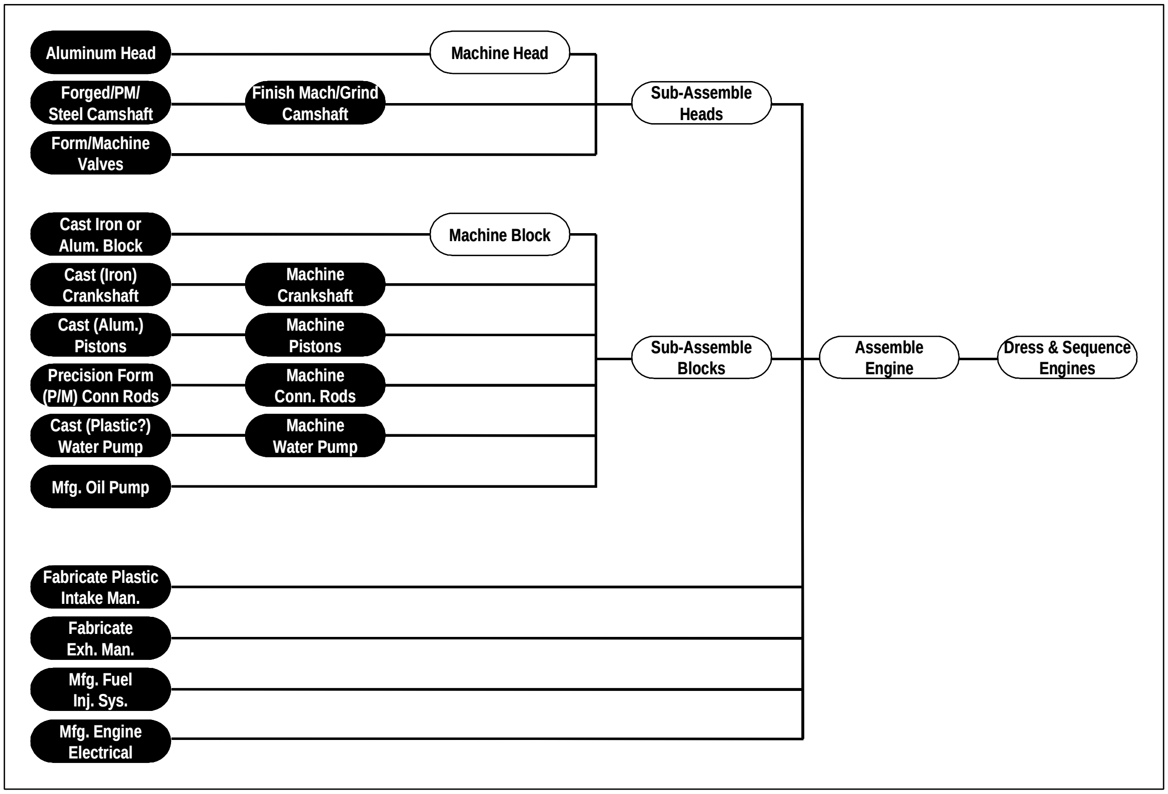
	Percent of Total
Automatic Transmissions	39.1

Source: Harbour Report 2000

A STYLIZED BUILD MODEL FOR THE INTERNAL COMBUSTION ENGINE

A logical place to develop a fuel cell build scenario is to first review a simplified schematic of the internal combustion engine build. Figure E taken from an *Auto In Michigan Project Newsletter (AIM June 1986)* presents the main components and processes in the manufacture and assembly of the ICE. The activities in the black ovals are those most commonly performed by suppliers, while those in white ovals are more likely to be done by the vehicle manufacturer. The dominant skills involved in the manufacture of an engine (and transmissions) are machining, casting, assembly and more recently, fabricating of plastic external engine components.

Figure E
ICE Engine Build Diagram



A STYLIZED BUILD MODEL FOR THE FUEL CELL HYBRID ELECTRIC POWERTRAIN

A build model for a FCHEV vehicle will vary greatly from that of the current ICE model. There are three main subsystems that must be investigated to gain understanding of the potential “cross-walking” of current manufacturing skills available within the state of Michigan and those required for FCHEV manufacturing. Appendix D present a list of some Michigan manufacturers with fuel cell engine compatible products or processes. The following diagrams illustrate the components for each subsystem of the FCHEV powertrain, and a likely build schematic. It is important to note that since fuel cell technology is in the developmental stages, any build model must be considered preliminary, and will most likely be modified in the future.

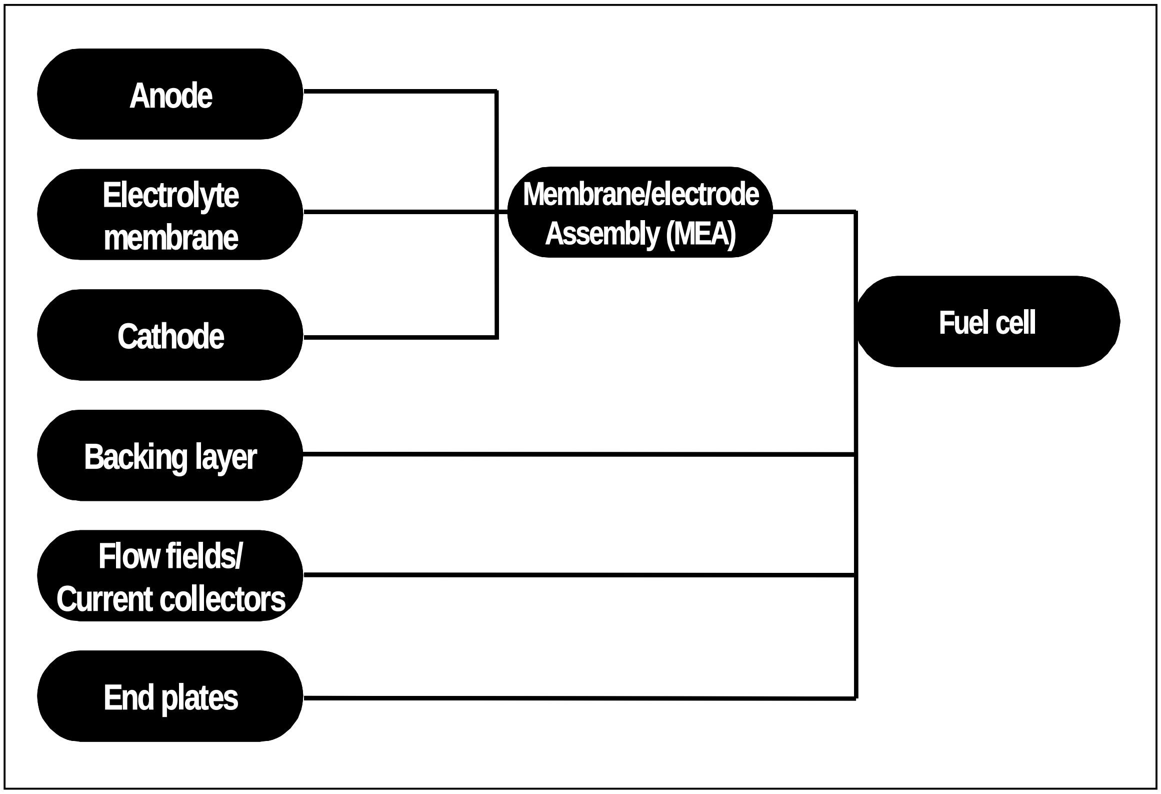
FUEL CELL STACK

The fuel stack is comprised of the MEA, bipolar plates and end plates (figure F). The electrolyte membrane will most likely be manufactured by chemical companies, (e.g., Nafion by DuPont). Facilities designed for the manufacture of electrolyte membranes will be extremely automated and high volume. Southwest Research Institute has had initial success with a vacuum disposition process for anode and cathode production. This process, similar to that used for the manufacture of thin film capacitors for over 15 years, may provide high volume, low cost electrode production.

Bipolar plates can be made from metals, graphite and graphite composites. These plates must be low cost, impermeable, highly conductive, chemically inert, and lightweight. Compression molded graphite has been used for developmental programs, but due to its long processing times, will not be a viable high-volume material. Many companies are now focusing on the development of injection-molding processes capable of manufacturing acceptable bipolar plates. Graphite, combined with thermoplastics has shown potential. The manufacturing process for these plates will also be need to be highly automated. Volumes for bipolar plate manufacturing facilities will likely need to be approximately a million per day to meet automaker demand.

A brief description of the FuelCell Energy fuel cell manufacturing technology presents insight into the processes that may become integral elements of fuel cell manufacturing. The Torrington, Connecticut facility includes rolling mill continuous casting to laminate the fuel cell components, a fully automated cathode production line, electrode sintering in a continuous furnace, a continuous extrusion line, and fully automated stacking equipment. Although this facility manufactures a carbonate fuel cell—not proton exchange membrane fuel cells—it does illustrate the high degree of automation required for fuel cell stack manufacturing.

Figure F
Fuel Cell Stack Build



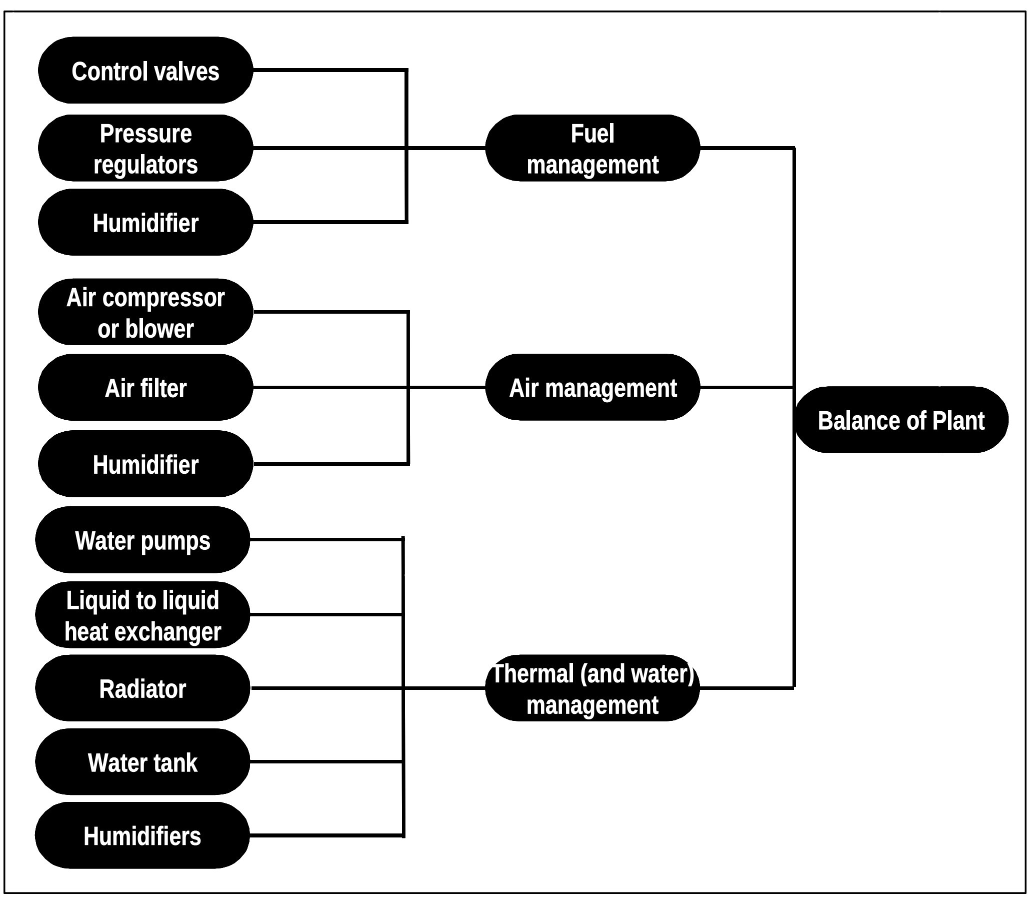
BALANCE OF PLANT (BOP)

The fuel cell is comprised of two major components: the fuel cell stack, and the heat, water and air management components, commonly referred to as the balance of plant (BoP). The heat, water and air management subsystems will require high-pressure fittings and have a substantial amount of stainless steel tubing, leading more than one interviewee to refer to the fuel cell as a "plumbers nightmare." Significant manufacturing and performance challenges remain in the development the BoP components. These systems may be viable candidates for development by automotive suppliers currently manufacturing similar components for ICE engines.

The critical component for the air handling system is comprised of a compressor, an expander and a drive motor assembly. Turbo compressors, scroll compressors and variable delivery compressors are among the technologies being investigated to provide high compression rates with extremely low energy consumption. However, as stack efficiency is increased in coming years, there may be a less of a need for higher compression or an acceptance of lower efficiency compressors. This relaxing of requirements would likely lead to the application of current automotive industry technology for these components.

Although the PEM fuel cell operates at a much lower temperature than does the internal combustion engine, heat management will be an important challenge. A rule of thumb for ICE's heat dissipation is that the heat is removed equally by mechanical work, coolant, and exhaust. The fuel cell will only have a small portion of the heat carried away by exhaust (10 percent). Approximately 50 percent of the heat loss will be via the coolant system. Another interesting challenge is that heat management for lower temperatures is more difficult due to the initial temperature differential between the coolant at ambient temperatures (SAE2000-02-0373). The fuel cell heat management system will be largely comprised of a radiator—likely larger than current models. Therefore, the cooling system for a fuel cell system may prove to be a significant packaging issue. The heat management system will (also) be largely comprised of a radiator—likely larger than current models. Some form of humidifier will also be needed for the air delivery system. This humidifier will likely be integrated into the cooling system.

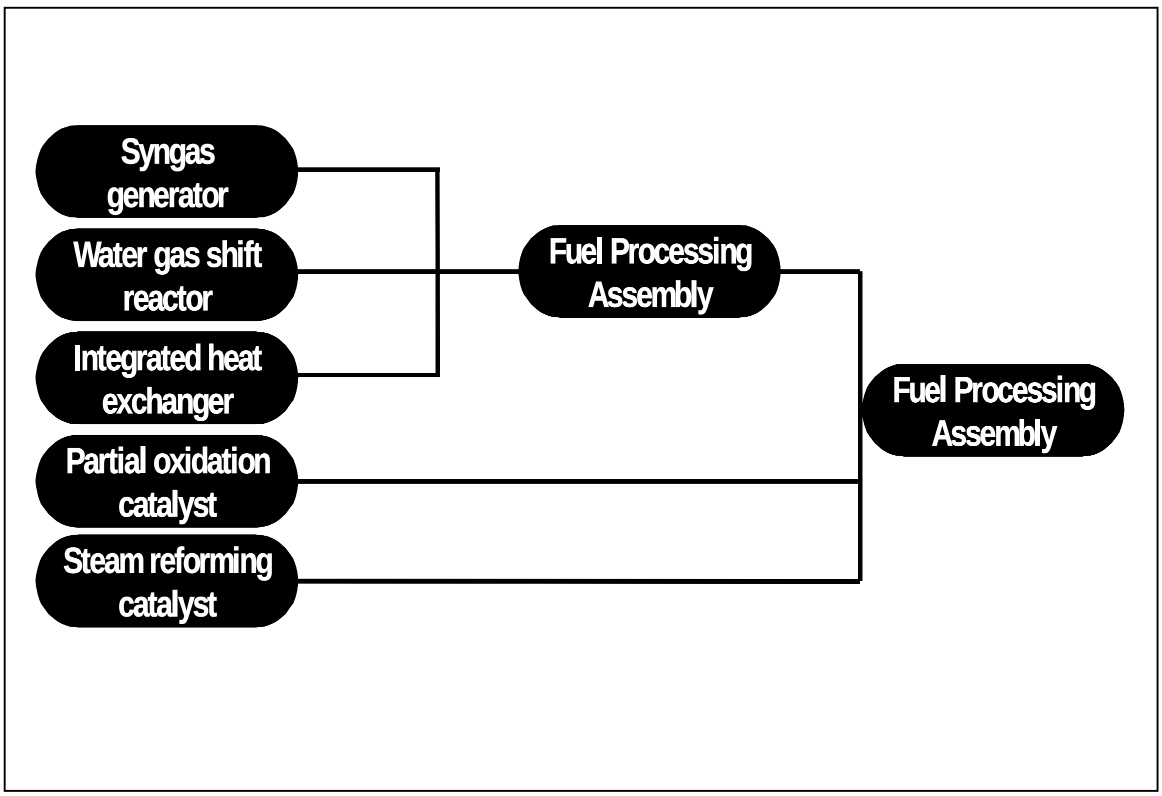
Figure G
Balance of Plant



REFORMULATOR

The reformer may be the component that is in need of the most refinement. Thus, the final design is most uncertain. Most current strategies incorporate technology (often in the form of a series of heat exchangers and catalysts) into a canister where air, water and fuel combine to reformulate the fuel. These reformers will likely have a partial oxidation, steam reforming and water gas shift. A key aspect of the development of fuel reformers is the need to be manufactured at the high volumes required by the automotive industry. Therefore, much consideration is being given to developing components for fuel reformers which will match the automotive industry's manufacturing skills. The catalyst (an important part of the reformer) and the heat exchangers are examples of components that the industry currently manufactures.

Figure H
Reformulator Build Diagram

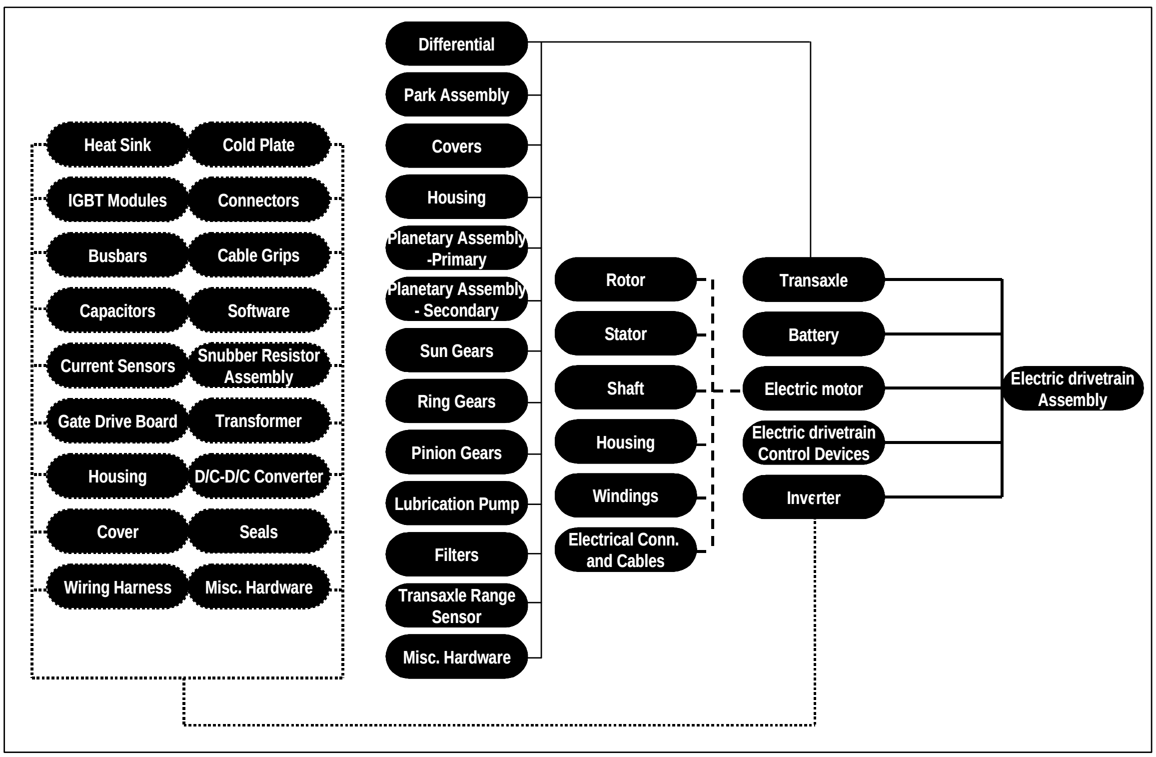


ELECTRIC DRIVETRAIN

The transaxle and electric motor are well suited for traditional automotive suppliers, requiring technical skills and manufacturing knowledge common to the industry. The inverter however, requires engineering skills that are not necessarily traditional automotive—or Michigan—

strengths. Southern California and Boston companies have the majority of power electronics engineering skills. Milwaukee also is an important location—due mainly to Allen-Bradley and the University of Wisconsin. The main competitors in the packaging of power electronics are Infineon (Siemens), Mitsubishi, Toshiba, Fuji, and Hitachi. U.S. firms are less competitive in this field. Several interview respondents suggested that these traditional power electronics manufacturers were not accustomed to high volume requirements found in automotive applications—leaving an opportunity for partnerships with traditional automotive suppliers.

Figure I
Electric Drivetrain Build



(Source: Ecostar)

V. CURRENT FUEL CELL MANUFACTURERS/DEVELOPERS

The development and manufacture of fuel cell technology is done by both independent fuel cell companies as well as internal research and development groups at the major vehicle manufacturers. Table 4 presents a matrix of independent North American fuel cell developers, their products and their customers.

Table 4
Fuel Cell Developers

Company	Location	Mfrg. Facilities	Technology (type of fuel cell)	Applications (stationary, transportation, portable)	Power (kilowatts)	Known Customers	Partners (equity or other)
Anuvu, Inc.	Sacramento, CA	Sacramento, CA (2001)	Proton Exchange Membrane (PEM)	Residential, Transportation, Stand-by	N/A	N/A	Small start-up using some state incentives
Avista Corp.	Spokane, WA	Logan Industries	PEM	Commercial, Residential	50-300	N/A	Logan Industries
Ballard	Burnby, B.C. Canada	Opened in 4Q 20001	PEM	Stationary, Transportation	250	Ford, DCX, GM, Nissan, Honda, VW	Ford, DCX
Ceramic Fuel Cells Limited (CFCL)	Australia, Asia	Australia	Solid Oxide	Residential	40	N/A	N/A
Delphi	Troy, MI		Solid Oxide	Auxiliary	5	BMW, Renault	Global Thermoelectric (Fuel Cell Developer)
Fuel Cell Energy	Danbury, CT	Torrington in spring 2001	Carbonate Fuel Cell	Stationary	225 250	DCX, U.S. Navy, U.S. Coast Guard	MTU/DCX
Hpower	Clifton, NJ		PEM	Stationary, Mobile, Portable	Up to 1,000	N/A	ECO Fuel Cells
International Fuel Cells	South Windsor, Connecticut	South Windsor, Connecticut	PEM	Residential, Transportation, Commercial	500-11,000	N/A	A Div. Of United Technology
Nuvera Fuel Cells	Cambridge, MA		PEM	Residential, Transportation	N/A	Several automotive customers	DeNora Fuel Cells (Italy), Epyx Corp. (A.D. Little), Amerada Hess
Plug Power	Latham, NY	Netherlands	PEM	Residential	7-15	N/A	DTE
Texaco Ovonic Fuel Cell LLC	Rochester Hills, MI	Troy and Rochester Hills, MI	Ovonic Proprietary	Residential, Stationary, UPS, Transport	1-1,000	N/A	Energy Conversion Devices, Texaco

Ballard Power Systems, based in Burnaby, B.C., Canada is considered the dominant independent PEM fuel cell developer. The company, founded in 1979, includes major investment from DaimlerChrysler and Ford. Ballard also supplies fuel cells to Nissan, Honda, Volkswagen, and General Motors. The company opened a manufacturing facility in British Columbia in late 2000. They anticipate manufacturing volumes at the new facilities in the scale in the hundreds per year by 2004, to coincide with the commercial delivery commitments to DaimlerChrysler and Ford.

FuelCell Energy, Inc., the second largest of the independent developers, is focused mainly on stationary fuel cell development in terms of market capitalization. Unlike many automotive-oriented fuel cell developers, FuelCell is developing and marketing a metal carbonate fuel cell that feeds fuel (either natural gas or methane) directly into the fuel cell where it is converted into hydrogen used to run the fuel cell for use in stationary applications. This directly fueled technology does not need the excess cost or complexity of a reformulator. The company has several proofs of concept programs currently underway and several more planned to start in

2001, including one at the DaimlerChrysler manufacturing facility in Vance, Alabama. FuelCell Energy plans to open a 65,000 square foot manufacturing facility in Connecticut in the spring of 2001. Expected volumes for this plant have not been made public.

Nuvera Fuel Cells, Inc. is the result of a recent merger between Epyx, Corporation (a division of A.D. Little, Inc.) and De Nora Fuel Cells (Italy). The company is also partially owned by energy conglomerate Amerada Hess (16 percent). The merger combines Epyx' strong position in fuel processors with De Nora Fuel Cells' stack expertise to offer a "full service" fuel cell system supplier. Nuvera has shipped complete gasoline reformer/fuel cell systems to four major vehicle manufacturers for evaluation purposes.

International Fuel Cell (IFC) has recently announced the development of a 50-kilowatt PEM fuel cell that can operate reliably using gasoline as the fuel source. The fuel cell is the result of a partnership with the Department of Energy. IFC has incorporated the fuel cell stack with a flexible fuel reformer.

Table 5 shows the major North American membrane (MEA) and MEA manufacturers. DuPont has held a market leader position with its membrane by the trade name of Nafion. Yet others have also established market positions. The companies that have established early leadership in the development of membrane technology are predominately chemical manufacturers. However, there are indications that fuel cell developers are attempting to develop membrane technology internally.

Table 5
Electrolyte Membrane and Membrane Electrode Assembly (MEA) Manufacturers

Company	Electrolyte Membrane	Membrane Electrode Assemblies (MEA)	Comments
Ballard	Developmental stages	Yes	Currently purchases membrane, but is considering internal production capability.
DuPont	Yes	Yes	Manufacturer of Nafion. Recently announced plans to move into MEA and fuel cell stack manufacturing. Initial goal is stationary, but interested in long-term automotive applications.
Gore & Associates	Yes	Yes	DOE funding for high-volume electrode manufacturing. Chemical and material manufacturer.
Johnson Matthey	No	Yes	Manufacturer of MEA. Supplies half the 'world demand' including Ballard's for catalysts. R&D facilities in UK, production facilities in UK and Pennsylvania.
3M	Yes	Yes	Began R&D in 1995, but has established itself as a major player. 3M doesn't sell the membrane as a separate component, but delivers it only as part of the MEA. Has manufacturing facilities in Menomonie, Wisconsin, and St. Paul, Minnesota.

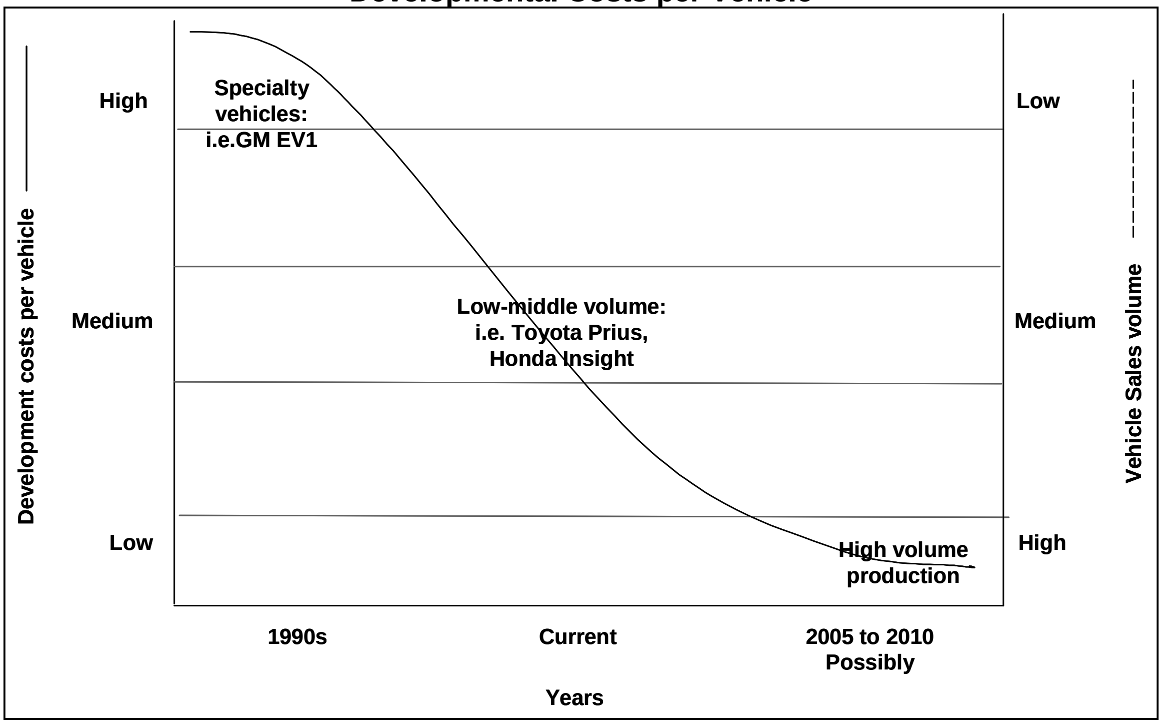
MARKET ACCEPTANCE CONSIDERATIONS FOR ALTERNATIVE POWERED VEHICLES

Market position and price points are critical to the market acceptance of alternative powered vehicles. Appendix A presents the various alternative powertrain vehicle programs at DaimlerChrysler, Ford and General Motors. The price of the vehicle is a direct function of the costs of the powertrains. The initial price of alternative powered vehicles have, and will likely be, heavily subsidized—by manufacturers as well as several State governments. These vehicles are produced in extremely small volumes and with extremely high-cost technology have been costly to manufacture and sell (or lease). However, they have been sold below cost to establish a market position. The General Motors EV1, an electric vehicle, and the Honda Insight and Toyota Prius—both hybrid electric vehicles—are good examples of early entries. The EV1 was the first electric vehicle designed and manufactured as an electric vehicle by a major automobile manufacturer. The extremely advanced EV1 used state-of-the-art technology in electronics, batteries and materials and was manufactured to gain a better understanding of the real-world applications of alternative powertrains. Yet, the vehicle by design was a low volume niche product—a two-seat vehicle with limited driving range. Although the Honda Insight uses an integrated starter and generator with power assist (thus is a so-called mild hybrid) it is similar to the EV1 in that it is a limited niche vehicle. The Toyota Prius, another HEV, is a four-seat sub-compact with potentially more significant market appeal.

Figure J shows a downward sloping curve for developmental cost per vehicle, and an upward sloping curve for vehicle sales volumes. Developmental costs per vehicle are a function of the amount of new technology and materials required—or technological complexity as well as function of the level of maturity of the manufacturing processes for the technologies. As manufacturing processes and new technology become better understood, the developmental cost required by each new program decreases. The EV1, with its advanced technologies and materials applications, was representative of a very low volume, very high per-vehicle development-cost program. The Prius and Insight represent medium-to-high developmental cost per vehicle and low-to-moderate sales per vehicle.

Each of these three vehicles has further defined the viability of alternative powered vehicles, yet to gain the high volumes needed to manufacture HEV—and even FCHEV—at a competitive cost, the vehicles will have to be mass market products. It is possibly a more effective strategy to focus hybrid powertrains on low mileage vehicles that offer potentially more environmental gains. For example, converting an inefficient ICE vehicle (such as a large sport utility vehicle) into a high-efficiency hybrid vehicle saves more fuel than making an already-efficient design into a super-efficient hybrid. A relatively simple calculation can prove the point. Converting a small car that might get 50 mpg to a hybrid at 70 mpg, saves 57 gallons over 10,000 miles of driving experience. But, converting a 25 mpg vehicle into a 35 mpg hybrid, while improving the m.p.g. rating by only half as much, actually saves more fuel—114 gallons over 10,000 miles. (GM Press release NAIAS). To further emphasize the importance of this strategy, several manufacturers have announced plans to bring hybrid electric-powered light trucks to market by 2004.

Figure J
Developmental Costs per Vehicle



VI. FINAL OBSERVATIONS

Although much progress has been made in the development of alternative fueled vehicles, it is important to give some historical perspective. The internal combustion engine has been the automotive power plant for over 100 years. The highly aggressive plans of manufacturers suggest that within the next ten years, the industry could see as many as three powertrain paradigms—advanced ICE, HEV and FCHEV (a fourth, the all electric vehicle, may also have a place in the future). The financial burden that such rapid technology change would have for the industry is staggering. Given this potential burden, it is important to highlight the various technologies and infrastructure options that may be available. Automotive manufacturers will have to develop financial strategies to mitigate the size of these future investments.

Figure K (provided by General Motors Advanced Technology Vehicles group) schematically illustrates the varied options that face the industry. The automotive industry must make decisions regarding infrastructure, propulsion systems, and vehicle architecture and body materials while carefully evaluating the social and environmental effect of their strategies. The automotive industry faces a time of severely constrained resources. Whereas a decade ago, powertrain suppliers and manufacturers focused almost entirely on improving the ICE, they now must also include development of different propulsion systems and powertrain formats in an increasingly resource-constrained environment.

Figure K
How Do We Create Options

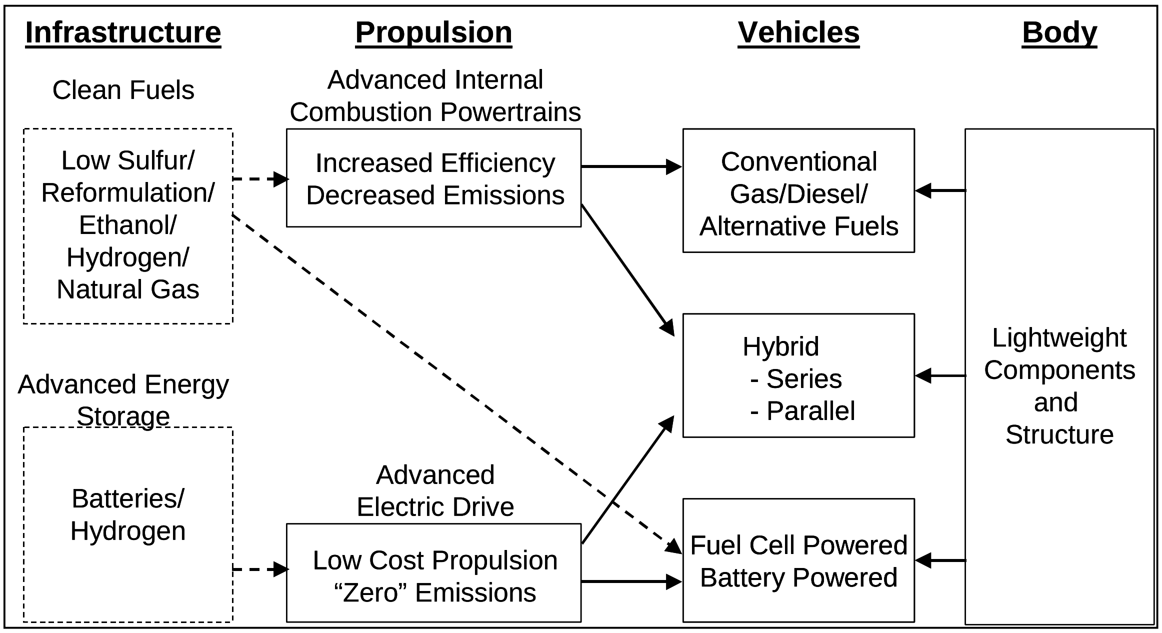
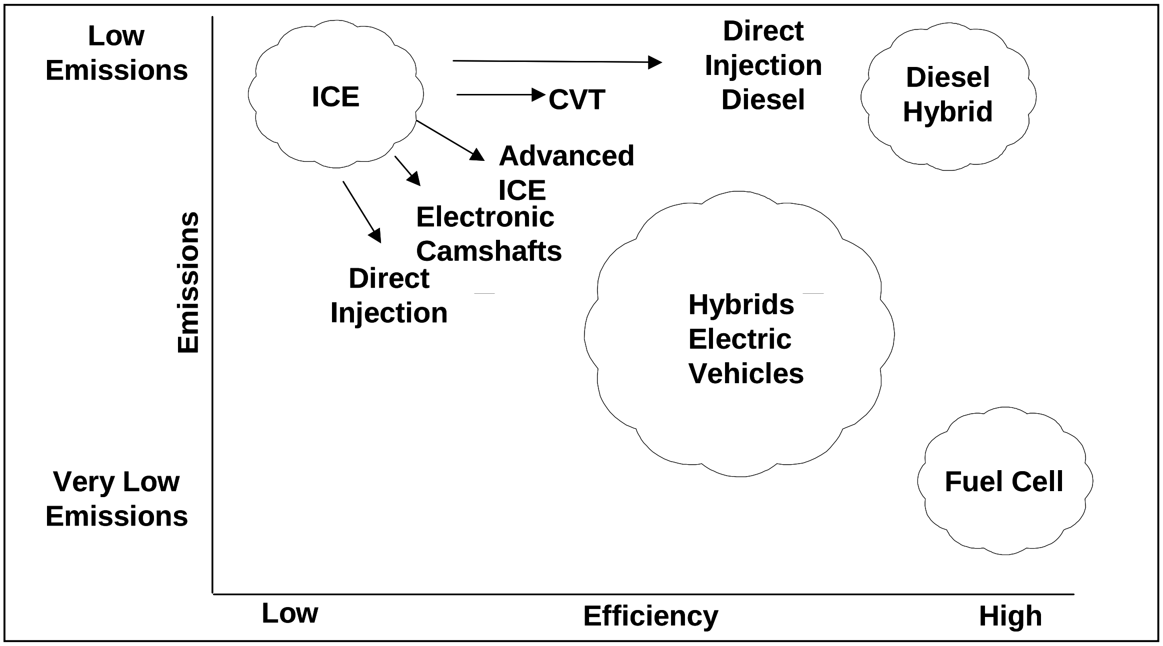


Figure L shows the relative position of many powertrain technologies. The gasoline internal combustion engine is a relatively low emission, low efficiency power source. Hybrid electric vehicles are more efficient and emit lower emissions. While fuel cells are the most efficient and produce the lowest emissions, although when hydrocarbons are formulated to produce hydrogen, the remaining carbon is expelled as carbon dioxide, a global warming gas. Yet, there are many methods of increasing efficiency and/or decreasing emissions, in addition to the selection of alternative power sources. For example, direct injection is a technology that could increase efficiency for both gasoline- and diesel-powered engines. The PNGV proof-of-concept vehicles suggests that diesel engines offer significant efficiency advantages. These proof-of-concepts show that a hybrid electric vehicle with a diesel engine offers exceptional efficiency but may deliver unacceptable emissions. If technology is developed that can control diesel emissions, such technology may quickly change strategies. The *2000 Delphi X Forecast and Analysis of the North American Automotive Industry; Volume 1: Technology* forecasts that 3 percent of all cars sold in 2009 will be hybrid electric vehicles, and that 30 percent of those will use diesel engines. It is important to note that the interquartile range for the diesel engine forecast is extremely wide (ranging from 20 percent to 60 percent) indicating significant uncertainty among respondents. Each of the other technologies offers potential for gain but also significant hurdles.

Figure L
Powertrain Technologies



Although the potential of fuel cell technology is enticing, significant hurdles exist there as well. Each of the individuals interviewed strongly indicate that significant invention and refinement still remain before the fuel cell can be considered a viable candidate for mass production vehicles. Such invention may or may not occur. Table 6 shows critical operational characteristics for fuel cell stack system running in hydrogen-rich fuels from a flexible fuel processor, and includes only fuel cell stack and ancillaries for heat water and air management. The table also includes goals for 2004.

Table 6
DOE Technical Targets for a 50kW Peak Power Fuel Cell

Characteristics [a] – Includes fuel cell stack and ancillaries (heat, water and air management). Excludes fuel processing and delivery	Units	Calendar Year		
		1997	2000	2004
Stack system power density [b]	W/L	300	350	500
Stack system specific power	W/kg	300	350	500
Stack system efficiency [c] @ 25% of peak power	%	50	55	60
Stack system efficiency [c] @ peak power	%	40	44	48
Precious metal loading	g/peak kW	2.0	0.9	0.2
Cost [d]	$/kW	200	100	35
Durability (<5% power degradation)	hour	>1000	>2000	>5000
Transient performance (time from 10 to 90% power)	sec	10	3	1
Cold start-up to maximum power at -40ºC	min	15	5	2
Cold start-up to maximum power at 20ºC	min	2	1	0.5
Emissions [e]		<Tier 2	<Tier 2	<Tier2
CO tolerance (steady state)	ppm	10	100	1000
CO tolerance (transient)	ppm	100	500	5000

[a] Technical targets are consistent with those of the PNGV.
[b] Power refers to net power (I.e., stack power minus auxiliary power requirements).
[c] Ratio: (output dc energy) / (lower heating value of hydrogen-rich fuel stream).
[d] High-volume production: 500,000 units per year.
[E] Emission levels will comply with emission regulations projected to be in place when the technology is available for market introduction.

Source: U.S.D.O.E Transportation Fuel Cell Power Systems, 2000 Annual Progress Report, p. 165.

Each of the characteristics represents significant challenges for fuel cell development. According to PNGV, using current (albeit unproven) techniques mass-produced fuel cells would cost over $200/kW well above DOE's stated goal of $150 kW for 2000. Start-up to full power using reformers is also another critical characteristic that presents significant challenges. It is technologically possible to operate the vehicle using battery power during the initial fuel cell start-up phase (for example five minutes). However, this deep draw down cycle dramatically hinders battery life. Another challenge is water management for the fuel cell. The fuel cell stack has an internally moist environment that needs constant water management to maintain operating viability. If this water freezes, it can cause the fuel cell to become inoperable. The repairability of the fuel cell stack itself is another open issue. If an individual cell within the stack freezes and cracks, it is uncertain whether the individual cell could be replaced or if the entire stack would need to be replaced. While many appear to believe such issues will be resolved, failure to resolve any one of the many challenges could greatly reduce the likelihood of successful implementation.

Table 7 further illustrates the cost challenges that remain for the key elements of the fuel cell stack. The table shows theoretical costs of the components for a volume production of 500,000 units per year. The DOE goal for the anode and cathode layers, combined with the electrolyte, is 10 $/kW for 2004. Currently the best theoretical manufacturing practices can achieve no better than 100$/kW. Obviously much progress is needed before the fuel cell can be considered an economically viable alternative.

Table 7
Breakdown of Fuel Cell Stack Cost, 50kw @ 500,000 Units per Year

	Component	Cost			2004
		%	$	$/kW	$/kW
MEA	Anode and Cathode Layers	50%	$3,625	$75	$5
MEA	Electrolyte	20	1,310	25	5
MEA	Gas Diffusion Layers	5	420	5	5
	Bipolar Plates	15	1,035	20	n/a
	Gaskets	5	380	10	5
	Other	5	280	5	n/a
	Total	100	7,050	140	n/a

Source: U.S.D.O.E Transportation Fuel Cell Power Systems, 2000 Annual Progress Report, p. 19.

These hurdles suggest that there are many potential near- and long-term outcomes regarding alternative powered vehicles. The fuel cell may represent significant potential opportunity, and the State should work to develop a strategy that will encourage fuel cell manufacturing within Michigan. Yet, it must also be aware that the success of other powertrain alternatives may make fuel cell application less likely or at least delay their implementation for transportation applications. Clearly, it is important to monitor technical developments closely through an ongoing technology assessment process

VII. Recommended actions for positioning the State as a primary fuel cell manufacturing location

Although the initial intention of this report was to define the steps that Michigan should take to become a prime location for fuel cell manufacturing investment, interview respondents quickly reshaped the conclusions to include a more all-encompassing strategy. The fuel cell has the potential to reshape the automotive industry, yet the fuel cell itself is only a portion of the new powertrain paradigm. Based on discussions with Michigan-based manufacturers and suppliers, the Center for Automotive Research (CAR) recommends four key areas that the State must address to better position itself as a leader in alternative powered vehicle technology, and concomitantly, a viable candidate for fuel cell manufacturing.

1. The Michigan Advanced Automotive Powertrain Technology Alliance

The Michigan Advanced Automotive Powertrain Technology Alliance would serve as an umbrella organization whose mission is to assist the industry in charting the course for widespread commercialization of advanced powertrain vehicles in the new millennium. The Alliance would be comprised of several types of organizations, including technology developers, vehicle manufacturers, component suppliers and fuel suppliers as well as local, state and federal agencies.

We believe there are several critical technologies—life sciences, MEMS and advanced powertrain technology for example—which are advancing at astonishing rates and thus deserve special attention by the State of Michigan. It is vital for the State to develop a strategy to monitor and promote each of these potentially paradigm-shifting technologies. Advanced powertrain technology—whether ultra clean internal combustion engines, continuously variable transmission hybrid electric vehicles, or fuel cell technology—is certainly one of those key technology areas, and as such should be a focal point for the State.

The fuel cell offers opportunity to significantly change the automotive industry landscape. Yet there remains great uncertainty with regard to the future of the technology. While many believe that the fuel cell will be a viable powertrain option in the coming decade, others believe that the fuel cell is best suited for stationary market applications, and might not be a viable short- or mid-term automotive power source. The Michigan Advanced Automotive Powertrain Technology Alliance would allow the State to develop a strong position with all advanced powertrain technologies. Furthermore, such an alliance would allow market conditions to pick the winning technologies, and avoid placing the State in a position to choose winning and losing technologies at this early stage.

Michigan's position as the center of the automotive industry makes it a critical member in any advanced powertrain partnership. The State should approach the major manufacturers to obtain guidance on the development and positioning of a Michigan Advanced Powertrain Technology Alliance. We believe CAR could act as the agent for such a program, leveraging its relationships and the strong technological base of ERIM. The State should also consider supporting university programs such as the Advanced Vehicle programs at University of Michigan Dearborn, and Lawrence Tech, as well as advanced engineering at other Michigan Universities.

Michigan should work with California and other states with active fuel cell and electric vehicle efforts to coordinate efforts. Although California already has the California Fuel Cell Partnership (CFCP), to demonstrate and market fuel cell technology, the State of Michigan should aggressively work to create an Alliance with the mission of working with the CFCP to set a national agenda for all future powertrain options. We believe there would likely be strong support for the Alliance.

The State should aggressively pursue all companies that have the technologies that will be critical in the new powertrain paradigm. One company interviewed estimated that they have 60 critical partners for fuel cell development—slightly more than half are not traditional automotive suppliers. As these partnerships are made public, the State should be ready to immediately establish a relationship with key suppliers, and work to include them in the Alliance. CAR believes that the State should promptly establish an on-going dialogue with vehicle manufacturers with major operations in Michigan, as well as the state's largest suppliers. This dialogue should be focused not only on getting their guidance in developing the Alliance, but also on gaining insight into the new automotive supply base. The State should also work to develop a mechanism that would allow the manufacturers to quickly notify the State of any newly announced partnerships. As the manufacturers make public the names of their suppliers, the State should proactively approach these suppliers with concise, informed location opportunities.

2. Investigate the Feasibility of Creating Power Electronics "Center of Excellence."

   A critical component of fuel cell powered vehicles—and all other hybrid type vehicles will be the development and manufacture of power electronics. The State is not currently a leader in power electronics. This stands as a significant challenge. All respondents indicated that the need for power electronics engineering and manufacturing has led them to find centers of expertise outside of the State. According to many respondents, it is a significant challenge to convince individuals with expertise in power electronics to move away from these centers of expertise. The State must increase the number of power-electronics-proficient people in Michigan. (Michigan's university engineering programs are not considered competitive in power electronics.) Michigan also must develop vocational programs that will produce individuals capable of taking the forefront in high-volume power electronics manufacturing.

   In addition to newly emerging advanced vehicle applications, power electronics are also key enabling technologies for variable speed drive devices used throughout the industrial manufacturing sector. In the 1980s, a power electronics center was established by the EPRI Electric Utility's Research Institute and the utility industry and located in Knoxville, Tennessee. This center was for the express purpose of coalescing power electronics engineering talent in one place for the utility industry. Likewise, the State of Michigan, in cooperation with the automotive industry, could create a Center of Excellence for power electronics to serve the automotive manufacturers, suppliers and others that manufacture variable speed motors

3. Establish a Michigan Hydrogen Infrastructure Working Group.

   The State must be known globally as a thought (and action) leader in the development of the hydrogen economy. Although the term hydrogen economy has been tossed about for decades, all respondents strongly indicated that such a paradigm shift might be possible—even likely—within two decades. Michigan must take a leading role in understanding the implications of hydrogen infrastructure (both for manufacturing and distribution) for use in vehicles. As all of the interviewees pointed out, if Michigan is to establish itself as a center of expertise in fuel cell manufacturing, it must be a hydrogen-friendly state.

The Hydrogen Infrastructure Working Group would be comprised of organizations within and outside Michigan that have a stake in the new hydrogen economy. Included in such a forum would be vehicle manufacturers, major tier-one suppliers, energy companies, fuel processors and government agencies, possibly including the U.S. Department of Energy.

The State must work to become a leader in understanding the infrastructure issues that hydrogen use must address. If hydrogen will be stored aboard the vehicle, special building codes and other considerations may be necessary for garages, tunnels, parking structures, and even ferries. There are programs already established to investigate the challenges of using hydrogen as a vehicle fuel. It would be valuable for the State to use these programs as a starting point, and work to further the knowledge in complementary ways. Partnerships with these programs should be considered

Many of the new technologies will require the use of hydrogen—either in the development, testing or manufacturing stages. The State has experienced some difficulty in gaining local municipality cooperation with the installation of rather benign digital cables. The possibilities of increased controversy regarding a hydrogen infrastructure is very real. It is important for the State to work with local governing agencies to develop standard procedures. Several respondents indicated that their local Michigan governments were not accustomed to dealing with requests for the use of hydrogen in manufacturing, whereas other states had a greater familiarity. As one respondent suggested, it took months of work to get the needed permits in Michigan, compared to hours in some other locations.

Another example is the certification of non-standard equipment. Because much of the manufacturing is unique, none of the machines purchased are certified by independent agencies. Therefore each individual piece of equipment has to be certified by a consultant. Smaller companies cannot afford to pay a consultant to certify each machine. The State could simplify the certification process for manufacturing technologies unique to the alternate powertrain manufacture. There could be an education program available from the State to make the cities aware of the unique needs of an advanced powertrain company.

4. Become a Leader in the Demonstration and Testing of Prototype Fuel Cell Vehicle Development and Commercialization of Fuel Cells for Advanced Vehicles and Stationary Applications.

   Michigan, under the auspices of the Alliance and the Hydrogen Infrastructure Working Group should consider establishing a test and demonstration center to gain early experience with fuel cell and other advanced technology vehicles and provide demonstration vehicles for fleet use. This demonstration program should involve both public and private organizations. The State could further show its leadership by becoming one of the early participants in this program.

   Another important element of such a program is the encouragement of the use of fuel cells for stationary power applications. The State's large manufacturing base offers outstanding opportunity for a leadership role in distributed power. The State, either via financial or other incentive, should assist businesses in adopting stationary fuel cell power sources.

5. Conduct an Economic Study to determine the most Appropriate Financial Incentives for the Development and Commercialization of Fuel Cell and Other Advanced Technology Vehicles.

   All companies are faced with critical financial decisions with respect to various advanced powertrain technology options. These financial constraints suggest that tax incentives and financial grants would be a strong enticement for investment in fuel cell technology. Since many industries have developed in clusters, Michigan should consider a strategy similar to the one for the life sciences corridor and stimulate investment in selected advanced automotive technologies. One suggestion is to offer financial rewards to companies for innovative technologies that appear to have strong potential for application. These technologies should also have a strong tie to the skill base in Michigan. According to one respondent, a competition to "advance the state of the art" in selected technologies tied to investing in Michigan would offer an interesting opportunity.

   Respondents strongly believe that financial incentives, whether for research and development, manufacturing, or consumers, will be important stimulators for growth. Yet incentives must be carefully crafted. There are instances where consumer incentives for alternative-powered vehicles were poorly designed, causing little real incentive for increased alternative-powertrain usage, while incurring the state financial burden. Most respondents recommended consumer incentives for alternative-powered (especially fuel cell) vehicles.

VIII. APPENDICES

APPENDIX A
ADVANCE POWERTRAIN VEHICLES FOR DAIMLERCHRYSLER, FORD AND GENERAL MOTORS

DaimlerChrysler

Product	Type of Drivetrain				Status	Battery	Comments
	G\E	D\E	E	FC			
Dodge ESX-3					Concept	Li	EMAT transmission
Durango					Production Ready	NiHM	
EPIC					In Production	NiHM	PEM Fuel Cell
Jeep Commander					Concept		PEM Fuel Cell
NECAR 4					Concept		PEM Fuel Cell
NECAR 5					Production Ready		PEM Fuel Cell
GEM					In Production	Pb-Acid	
G/E = Gas Electric, D/E = Diesel Electric, E = Electric, FC = Fuel Cell							

APPENDIX A CONTINUED

Ford

Product	Type of Drivetrain				Status	Battery	Comments
	G\E	D\E	E	FC			
Focus FCV				🚗	2000		42/12 volt PEM Fuel Cell
Prodigy		🚗			Concept	NiHM	
Escape	🚗				2003	NiHM	
P2000				🚗	Concept		PEM Fuel Cell
Electric Ranger			🚗		In Production	Pb-Acid	
Think City			🚗		2002	NiCad	
Think Neighbor			🚗		2001	NiHM	
Think FC5				🚗	Concept		PEM Fuel Cell
Think USPS			🚗		In Production	NiHM	
Volvo ISG Hybrid			🚗		Concept	Pb-Acid	
Volvo Power Split Hybrid			🚗		Concept	Pb-Acid	

G/E = Gas Electric, D/E = Diesel Electric, E = Electric, FC = Fuel Cell

General Motors

Product	Type of Drivetrain				Status	Battery	Comments
	G\E	D\E	E	FC			
Chevrolet Triax			🚗		Concept	NiHM	
EV-I			🚗		In Production	NiHM	
Fuel Cell Precept				🚗	Concept	NiHM	PEM Fuel Cell
Hybrid Electric Bus		🚗			In Production	Pb-Acid	
Opel Zafira				🚗	Concept	NiHM	PEM Fuel Cell
Parallel Hybrid		🚗			Concept	NiHM	
Parallel Hybrid Full Pickup	🚗				2004		
Precept		🚗			Concept	NiHM	
Series Hybrid					Concept	NiHM	
S-10 Electric			🚗		In Production	NiHM	

G/E = Gas Electric, D/E = Diesel Electric, E = Electric, FC = Fuel Cell

APPENDIX B
ELECTRIC DRIVE INTEGRATED POWERTRAIN MAJOR COMPONENTS PARTS LIST

- IPT Assembly
  - Electric Traction Motor
    - Rotor
    - Stator
    - Shaft
    - Housing
    - Windings
    - Electrical Connectors & Cables
  - Transaxle
    - Differential
    - Park Assembly
    - Covers
    - Housing
    - Planetary Assemblies-Primary
    - Planetary Assemblies-Secondary
    - Sun Gears
    - Rings Gears
    - Pinion Gears
    - Lubrication Pump
    - Filters
    - Transaxle Range Sensor
    - Miscellaneous Hardware
  - Inverter
    - Heat Sink
    - IGBT Modules
    - Busbars
    - Capacitors
    - Current Sensors
    - Gate Drive Board
    - Housing
    - Cover
    - Wiring Harness
    - Cold Plate
    - Connectors
    - Cable Grips
    - Software
    - Snubber Resistor Assembly
    - Transformer
    - D/C-D/C Converter
    - Seals
    - Miscellaneous Hardware

APPENDIX C
DEPARTMENT OF ENERGY TRANSPORTATION FUEL CELL POWER SYSTEMS: SELECTED FUNDED PROJECTS

I. Fuel Cell Power System Development

Project	**Contractor**
Atmospheric Fuel Cell Power System for Transportation	International Fuel Cells, South Windsor, CT
Cost Analysis of Fuel Cell Stack/System	A.D. Little, Inc., Cambridge, MA, and Nuvera Fuel Cells, Inc., Cambridge, MA
Fuel Cell Systems Analysis	Argonne National Laboratory, Argonne, IL

II. Fuel Processing Subsystem

Project	**Contractor**
Advanced Fuel Processor Development for the Next Millennium Fuel Processor for Transportation Fuel Cell Power Systems	A.D. Little, Inc., Cambridge, MA, and Nuvera Fuel Cells, Inc., Cambridge, MA. Subcontractors: Modine Manufacturing, Energy Partners, Illinois Department of Commerce and Community Affairs, United Catalysts, Corning, and STC Catalysts
Multi-fuel Processor for Fuel Cell Electric-Vehicle Applications	McDermott Technologies, Alliance, OH
Fuel-Flexible UOB (TM) Fuel Processor System Development and Status	Hydrogen Burner Technology, Inc., Long Beach, CA
Integrated Fuel Cell Processor Development	Argonne National Laboratory, Argonne, IL
Microchannel Fuel Processor Components	Pacific Northwest National Laboratory, Richland, WA
Catalysts for Improved Fuel Processing	Los Alamos Laboratory, Los Alamos, NM
R&D on a Novel Breadboard Device suitable for Carbon Monoxide Remediation in an Automotive PEM FC Power Plant	Honeywell Engines & Systems, Torrence, CA Honeywell Des Plaines Technology Center, Des Plaines, IL
CO Clean-up Development	Los Alamos Laboratory, Los Alamos, NM
Evaluation of Partial Oxidation Fuel Cell Reformer Emissions	A.D. Little, Inc.-- Acurex Environmental, Cupertino, CA
Alternative Water-Gas Shift Catalyst Development	Argonne National Laboratory, Argonne, IL

III. FuelCell Stack Subsystem

Project	Contractor
R&D on a 50-kW, High-efficiency, High-power-density, CO-Tolerant PEM Fuel Cell Stack System	Honeywell Engines & Systems, Torrance, CA
Development of Advanced Low-cost PEM Fuel Cell Stack and System Designed for operation on Reformate Used in Vehicle Power Systems	Energy Partners, L.C., West Palm Beach, FL
Cold-Start Dynamics of a PEM Fuel Stack	Los Alamos Laboratory, Los Alamos, NM
Efficient Fuel Cell Systems	Los Alamos Laboratory, Los Alamos, NM
Direct Methanol Fuel Cells	Los Alamos Laboratory, Los Alamos, NM

IV. PEM Stack Component Cost Reduction

Project	Contractor
High-performance Matching Fuel Cell Components and Integrated Manufacturing Processes	3M Company, St. Paul, MN Subcontractor: Energy Partners, Inc., West Palm Beach
Design and Installation of a Pilot Plant for High-Volume Electrode Production	Southwest Research Institute, San Antonio, TX
Low-Cost, High Temperature, Solid-polymer Electrolyte Membrane for Fuel Cells	Foster-Miller, Inc., Waltham, MA
Development and optimization of Porous Carbon Papers Suitable for Gas Diffusion Electrodes	Spectracorp, Ltd., Lawrence, MA
Electrodes for PEM Operation on Reformate/Air	Los Alamos Laboratory, Los Alamos, NM
New Electrocatalysts for Fuel Cells	Lawrence Berkley National Laboratory, U.C. Berkley, CA
Development of a $10/kW Bipolar Plate	Institute or Gas Technology, Des Plaines, IL. Subcontractors: PEM Plates, LLC, Stimson Corporation, Superior Graphite Corporation, Honeywell, Inc.
Layered Stack PEM Stack Development	ElectroChem, Inc., Woburn, MA

V. Air Management Subsystems

Project	Contractor
Turbocompressor for PEM Fuel Cells	Honeywell Engines & Systems, Torrance, CA
Development of a Scroll Compressor/Expander Module for Pressurization of a 50kW Automotive Fuel Cell System	A.D. Little, Inc., Cambridge, MA,
Variable Delivery Compressor/Expander Development	VAIREX Corp., Boulder, CO
Turbocompressor for Vehicular Fuel Cell Service	Meruit, Inc., Santa Monica, CA
High-Efficiency Integrated Compressor/Expandor Based on TIVM Geometry	Mechanology, LLC, Attleboro, MA

VI. Hydrogen Storage

Project	Contractor
High-Pressure Conformable Hydrogen Storage for Fuel Cell Vehicles	Thiokol Propulsion, Brigham City, UT Subcontractors: Aero Tec Laboratories, Inc. Rational Molding of Utah, and Powertech Testing Labs
Advanced Chemical Hydride Hydrogen-Generation/Storage System for PEM Fuel Cell Vehicles	Thermo Technologies, Waltham, MA

Source: 2000 Department of Energy Annual Progress Report

APPENDIX D
MICHIGAN MANUFACTURERS WITH FUEL CELL ENGINE COMPATIBLE PRODUCTS/ PROCESSES

The following table contains manufacturing current operations that either produce components or use processes that may have potential application to hybrid electric or fuel cell electric vehicles powertrains. These companies were identified using the Elm Guide Electronic Database. This list is not inclusive, nor is it intended to indicate that the companies presented are actively working to develop technologies for future powertrains—realistically, these companies will have to invest in new manufacturing or product technology to be competitive in the new paradigm. Instead, it is merely presented to illustrate that Michigan potentially has a strong manufacturing base for many critical technologies and should work to leverage those skills.

WATER PUMPS

Great Lakes Castings Corporation
Uni Boring Co., Inc.
Visteon Automotive Systems

Radiators

Denso Manufacturing Michigan, Inc.
Visteon Automotive Systems

COMPRESSORS

Alma Products Co.
Federal-Mogul Corporation
Michigan Automotive Compressor, Inc.
Newcor Deco Group
Visteon Automotive Systems

HEAT EXCHANGERS

Denso Manufacturing Michigan, Inc.
Visteon Automotive Systems

CONDENSERS

Calsonic North America, Inc.
Denso Manufacturing Michigan, Inc.
Visteon Automotive Systems

EVAPORATORS

Brazeway, Inc.
Calsonic North America, Inc.
Denso Manufacturing Michigan, Inc.
Visteon Automotive Systems
Acutex Inc.
Borgwarner Inc. - Air/Fluid Systems Corporation
LDI, Inc.
Prestolite Electric, Inc.
Saturn Electronics & Engineering, Inc.

ACTUATORS

Android Industries, Inc.
Eaton Corporation - Automotive Controls Division
First Inertia Switch Ltd.
Johnson Electric Automotive Motors, Inc.
LDI, Inc.
Saturn Electronics & Engineering, Inc.

RELAYS

CME Corporation
Lear Electronics And Electrical Division
Nickson-Wade, Inc.
Prestolite Electric, Inc.
Robert Bosch Corporation
Saturn Electronics & Engineering, Inc.
TRW, Inc.

SENSORS

Alps Automotive, Inc.
Autoliv North America Inc.
Donnelly Electronics
Eaton Corporation – Automotive Controls Div.
First Inertia Switch Ltd.
Forsheda North America
Logghe Stamping Co.
Nartron Corporation
Panasonic Automotive Electronics Co.
Pilot Industries, Inc.
Robert Bosch Corporation
Sensor Developments Inc.
Solvay Automotive, Inc.
Takata, Inc.
TRW, Inc.
Valeo Wiper Systems

SWITCHES

Alps Automotive, Inc.
Bytec, Inc.
Federal-Mogul Corporation
Hutchinson Fluid Transfer Systems North American
Mantex Corporation
Mariah Industries, Inc.
Micro Craft
Nartron Corporation
Panasonic Automotive Electronics Co.
Robert Bosch Corporation
Saturn Electronics & Engineering, Inc.

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