A Study of Fuel Cell Systems

December, 2002

A Report By

The Connecticut Academy of Science and Engineering

For

The Connecticut Department of Economic and Community Development and the Connecticut Economic Resource Center

Connecticut Academy of Science and Engineering

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A STUDY OF FUEL CELL SYSTEMS

A REPORT BY

THE CONNECTICUT ACADEMY OF SCIENCE AND ENGINEERING

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The content of this report lies within the province of the Academy's Technical Board on Energy Production Use and Conservation, and has been reviewed by Dr. Arthur Kesten, Chairman, Energy Technical Board and Dr. John Cagnetta, President of the Academy. The report was edited by Dr. Michael J. Werle, Vice President/President Elect of the Academy and Ms. Martha Sherman, the Academy's Managing Editor. The report is hereby released with the approval of the Academy Council.

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EXECUTIVE SUMMARY

STUDY OBJECTIVES

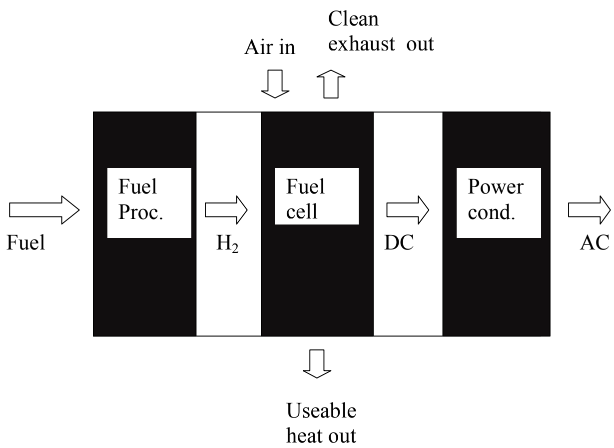
This study had four major objectives:

1. To provide an up-to-date description of fuel cell technology.
2. To provide a description of current applications for fuel cells.
3. To provide a listing of potential future applications for fuel cells.
4. To provide an assessment of the leading fuel cell technologies and their development status and application time horizons, with particular focus on the Connecticut producers of fuel cells.

SUMMARY OF FINDINGS

FUEL CELL SYSTEMS

Fuel cells are the critical core elements of a fuel cell power generation system. The complete power generation system will usually include three major sub-systems:



- a fuel processing sub-system, often needed to remove unwanted impurities and/or convert the incoming hydrocarbon fuel into hydrogen,
- a fuel cell stack sub-system, composed of multiple individual fuel cells ganged in a fuel cell stack, the size of which establishes the power delivered, and
- an output power conditioning unit containing the electronics and control sub-system needed to convert the fuel cell stack DC power into the required voltages and to control the overall system.

The key reasons/advantages that are cited for using a fuel cell system in an application include:

- very low levels of unwanted emissions and low noise levels,
- very clean and reliable power,
- reduced needs for electrical transmission facilities and distribution facility support because the fuel cell's smaller physical size, low emissions and low noise allows it to be located near the electrical load, and
- combined heat and power yields with high overall efficiency.

Of these advantages, the very low levels of unwanted emissions and low noise were the overwhelming ones cited for every application area.

CURRENT FUEL CELL TECHNOLOGIES

Five fuel cell technologies have been developed to meet various application areas. These are:

1. **Alkaline Fuel Cells (AFC),** which can be quite small, are used on the space shuttle and in other applications where pure gases can be used as fuel. They have been the mainstay of NASA's aerospace program since the very early days of manned space flight.

2. **Molten Carbonate Fuel Cells (MCFC),** a leading contender for relatively large (> 100 kW) stationary systems.

3. **Phosphoric Acid Fuel Cells (PAFC) ,** the only fuel cell systems that have been deployed widely to date in commercial use for relatively large (> 100 kW) stationary systems.

Application	Fuel Cell Type				
	AFC	MCFC	PAFC	PEMFC	SOFC
Small electronic devices				✔	
Portable power/APU				✔	✔
Transportation – automotive				✔	
Transportation – bus and truck				✔	
Military and space applications	✔			✔	
Residential power and heat				✔	✔
Off-grid				✔	✔
Commercial building power and heat		✔	✔	✔	✔
Assured power		✔	✔	✔	✔
Distributed stationary power		✔		✔	✔
Hydrogen generation				✔	

4. **Polymer Electrolyte Membrane Fuel Cells (PEMFC),** seen as the system of choice for vehicular power applications, but also being developed for stationary power.

5. **Solid Oxide Fuel Cells (SOFC),** a leading contender for relatively large (> 100 kW) stationary systems.

Of these, only the MCFC, PEMFC, and SOFC are being actively developed for potential large production volume, commercial applications.

The key challenges to the deployment of fuel cell power systems are:

- system and life cycle cost,
- lack of demonstrated reliability, for most fuel cell types,
- lack of infrastructure, for some applications, and
- identification and development of markets in cost-justified applications.

Surmounting these challenges offers possibilities for rewarding investment in the technology and infrastructure. These possibilities include the following:

- For **all fuel cell** types, investments aimed at:
  - lowering the manufacturing cost of the fuel cell stack,
  - improving the long term reliability and thus the operating lifetime of the fuel cell stack,
  - lowering the costs of power conditioning and control portion of the fuel cell system, and
  - increasing the market penetration of the fuel cell system for their respective applications.

- For **PEMFC systems, additional** investments aimed at:
  - lowering the costs and improving the performance of the fuel processing portion of the system, and
  - increasing the operating temperature of the fuel cell to improve the cell tolerance to carbon monoxide in the fuel.

- For **SOFC systems, additional** investments aimed at reducing the operating temperature of the fuel cell.

CONNECTICUT'S LEAD IN THE TECHNOLOGY

Connecticut is currently a world leader in the application of fuel cell systems for stationary power applications, with over 250 United Technologies Corporation phosphoric acid (PAFC) based units installed worldwide, and with substantial demonstration of molten carbonate (MCFC) units. Connecticut is the only state that can claim substantial system experience in any fuel cell power application. However, other states are actively engaged in developing fuel cell-based industries within their borders. These states include:

- Michigan, with a three-year funding level of $50M, and a 700 acre site planned near the University of Michigan,
- Ohio, with a three-year funding level of $100M,
- California, with a commitment to applications and infrastructure, and
- Texas, with a commitment to applications.

These initiatives could pose substantial challenges to the present Connecticut lead for stationary power applications, and will certainly pose challenges to efforts to compete in transportation applications. The Michigan and Ohio efforts are substantially aimed at transportation applications.

COMMERCIALIZATION ISSUES:

- **Fuel Cell Uses and Commercialization Timing**
  Per the following table and discussion, fuel cells' major attractions are the wide range of applications and the relative near term for market penetration.

Fuel Cell Systems Commercialization

Use/Application	Power Levels (kW)	CT Companies	Estimated Year for Commercial Volume
Small electronic devices	0.001- 0.01	Proton Energy, GE	
Portable power and Auxiliary power units	0.5 to 10	Proton Energy	Current
Transportation – auto	50 to 100	UTC Fuel Cells	2012
Transportation - bus	100 to 200	UTC Fuel Cells	2009
Military and space	Wide range	UTC Fuel Cells, Fuel Cell Energy	
Residential heat and power	1 to 5		2007
Off-grid power	Wide range		
Commercial building heat and power	100 and up	UTC Fuel Cells, Fuel Cell Energy	2003
Assured power	100 and up	UTC Fuel Cells, Fuel Cell Energy, Sure Power	2003
Distributed stationary power	100 and up	UTC Fuel Cells, Fuel Cell Energy	2003
Hydrogen generation	Produces hydrogen gas	Proton Energy	Current

- **First Major Commercial Market: "Large Capacity Stationary Power"**
  There was general agreement within the Study Committee that Large Capacity Stationary Power would likely be the first significant commercial market. For this study, Large Capacity is defined as a system with an output power capability greater than 100 kW. The major elements of this market are the following:

  - Stationary Reliable Power: Defined variously as having power available from 99.99% to 99.9999% of the time operative required, depending on the need, typically for applications in which reliability is vital, such as rapid response financial systems, on-line commerce, hospitals, and the like.

  - Commercial Building Power: Used for such applications as a small commercial building, a small strip mall, etc. In these cases, the heat generated by the fuel cell system is also often used, resulting in a combined usage called "Combined heat and power" (CHP).

- Distributed Power: Here the power levels start at about 200 kW in applications that serve several customers or a small sub-station, usually as part of the overall power grid. Larger industrial applications would also be included here, with the likelihood of CHP systems.

For these markets, both UTC and FCE are at par and nationally competitive. UTC is projecting costs in the $1500-$2000/kW range for its introductory 100 kW+ unit in this time frame. FCE talks about costs becoming lower as production volumes increase, with a reasonable chance that volumes will be sufficient to meet these price targets. Also, it is anticipated that as the production volumes increase, the prices will drop to below $1000/kW, allowing further market penetration.

- **Transportation Markets**

  - This market will be much more difficult to enter, due to the relatively low cost of present piston-engine power plants, which are ~$50/kW and less for automobiles and ~$100/kW for buses as compared with many times these values for fuel cells.

  - In spite of this difficulty, there will likely be a small commercial market developed for transit buses, and perhaps other fleet-type commercial vehicles, in the 2005 to 2010 time range.

  - UTC is conducting demonstrations in an SUV, has participated in a previous bus demo, and has several on-going bus demo projects. They seem to have as good a chance as any of their competitors. However, the price goals for this market remain daunting.

  - There is a very wide range of opinion concerning the economic competitiveness of fuel cells for the automobile market, ranging from guarded optimism to substantial pessimism. The current study is unable to resolve that issue. However, the market opportunity is very large, so long as costs can be reduced sufficiently. Investments continue in this regard. Most of the world's car makers, including BMW, Daimler-Chrysler, Ford, GM, Honda, Hyundai, Nissan, Opel, Renault, Suzuki , Toyota and Volkswagen, have fuel-cell powered car programs. One should expect to see test fleets in operation throughout the world in the 2 to 5 year time frame. In that regard, it is also worthy of note that Toyota has recently announced the availability of a fuel cell based hybrid electric powered SUV for leasing by technology-related companies, institutional organizations, and research facilities that have access to hydrogen fueling.

- **Very Low Power Market**
  - The market for very low power fuel cells, ~1-5 W for electronic applications could be promising, in view of the relatively high cost of the batteries that would be replaced (~$10,000/kW).

  - To our knowledge, there is no Connecticut company targeting this market. This could perhaps be an opportunity for the state.

- **A New Opportunity**
  - The use of fuel-cell-like devices to make pressurized hydrogen gas is expected to be a modest but growing niche market. The competition is pressurized bottled gas, a delivery system with a great deal of overhead cost. Also, a product now exists that couples a hydrogen generating system with a conventional fuel cell system. This combination could lead to the development of reliable power generation systems that are in turn compatible with other methods of generating hydrogen, including renewable techniques.

  - Proton Energy Systems of Connecticut is a leader in these markets.

- **Cost and Demonstrated Reliability Issues**
  - There are still major obstacles to large-scale fuel cell commercialization. Costs are expected to drop, and reliability is expected to improve if investments continue at or above today's levels. Prices low enough to break through to some market segments are expected within one to two years. In the Study Committee's judgment, Fuel Cell Energy (FCE) and UTC Fuel Cells of CT are at least at par, and may be leaders of the USA pack, at least for stationary applications.

  - In more detail, for investment Fuel Cell Energy has been very successful in securing government funding to further technologies and is the only major producer of Molten Carbonate Fuel Cells (MCFC). The government investment has allowed FCE to tackle substantial development efforts without incurring debt. For UTC, the investment is coming from corporate funds, and UTC seems to be committed to its continuation.
    Both FCE and UTC note that costs are substantially dependent on production volume. FCE has just moved into a new production facility, with substantial extra production capacity, and UTC greatly enlarged their facilities in South Windsor.

  - Relative to fuel cell manufacturing technology, the Connecticut Light and Power Conservation Load Management Fund sponsored several projects and programs aimed at improving the manufacturing technology for all of the fuel cell types currently under development. Several of these projects and programs are directed toward fuel cell designs that may make possible the use of structural components that can be used in all of the current fuel cell types (MCFC, PEMFC, and SOFC) while at the same time improving the reliability of these fuel cells.

- For demonstrated reliability, no product has been in field operation long enough with sufficient units to resolve all long-term related issues. However, it appears UTC's product, a Polymer Electrolyte Membrane Fuel Cell and FCE's product, a Molten Carbonate Fuel Cell, are at par and promising, but significantly more data are needed to assure that judgment. The third technology is the Solid Oxide Fuel Cell, which while viewed favorably by some, is in an earlier stage of development than Polymer Electrolyte Membrane or Molten Carbonate Fuel Cells, and thus has more unknowns relative to demonstrated reliability.

I. INTRODUCTION

Topics discussed in this chapter include the basic operation of fuel cells and of fuel cell systems, a comprehensive listing of the types of fuel cells, the uses of fuel cells, the advantages and disadvantages of fuel cells, and a listing of current fuel cell companies in Connecticut.

Fuel Cells and Fuel Cell Systems

An **individual fuel cell element** produces electricity by means of an electrochemical reaction. As depicted in Figure 1, each fuel cell element consists of an anode layer, an electrolyte matrix layer, and a cathode layer.

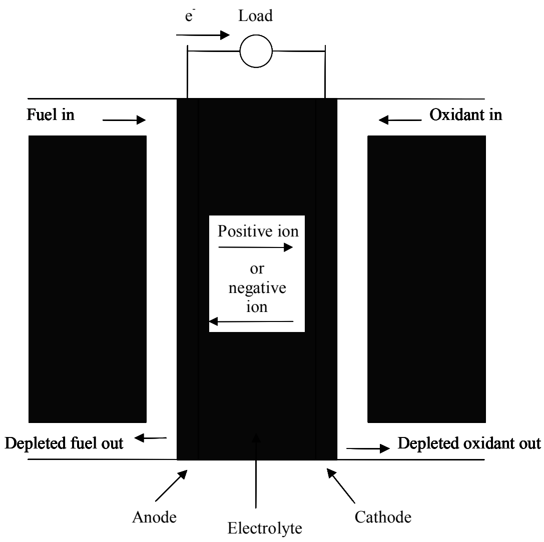


FIGURE 1. BASIC ELEMENTS OF A SINGLE FUEL CELL ELEMENT

In many cases (notably the low-temperature fuel cells), pure hydrogen is fed into the anode, where electrons are stripped from the hydrogen atoms, forming protons. The protons proceed through the electrolyte matrix layer to the cathode. The "borrowed" electrons are sent out to perform work, and are then returned to the cathode, where they combine with oxygen atoms to form ionized oxygen. The ionized oxygen then combines with the protons to form water.

The exhausts from this type of fuel cell are water, nitrogen and heat. Some fuel cells (notably the high-temperature types) can also handle direct feed of methane, coal gas, natural gas, or other hydrocarbon fuels. Here, the exhaust consists of carbon dioxide, water, nitrogen, and heat. In all cases, catalytic materials are applied to the anode and cathode electrodes, to enhance the speed of the various reactions.

For all of the fuel cell types included in this report, the fuel is either hydrogen or a hydrogen-containing energy-rich fuel. The oxidant is oxygen in all cases, usually brought in as air. The ions that traverse the electrolyte matrix will vary with fuel cell type.

Also, all of the fuel cell systems included in this report operating on a hydrocarbon fuel (natural gas, propane, methanol, ethanol, gasoline, etc) require the conversion of that fuel into hydrogen, a process called reformation. The various reformation processes produce the desired hydrogen, the inevitable carbon dioxide that results from utilizing the energy content of the carbon part of the fuel, and very small amounts of emissions of concern, such as the oxides of nitrogen and carbon monoxide. With proper control, these undesired emissions can be held to very low levels.

A **complete fuel cell power generation** system as depicted in Figure 2, will usually include three major sub-systems:

- the fuel processing sub-system, often needed to convert the incoming hydrocarbon fuel into hydrogen, and also to remove unwanted impurities from the incoming fuel,
- the fuel cell stack sub-system, including all those elements needed to convert the hydrogen into DC electrical power and which will often consist of 10 to 1000's of fuel cells, depending on how much power is required by the user, and

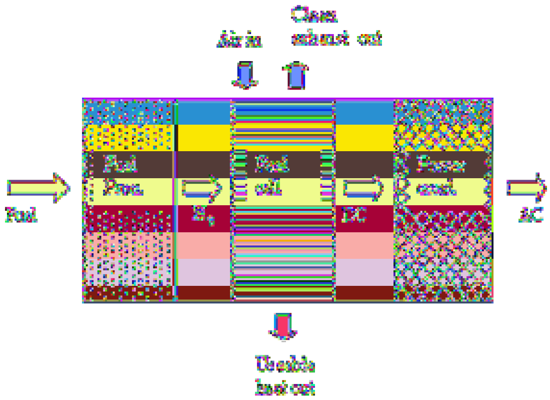


FIGURE 2 - ELEMENTS OF A FUEL CELL SYSTEM

- the electronics and control sub-system needed to convert the fuel cell stack DC power into the required voltages and AC powers required for the applications and also to control the overall system.

For systems that use hydrogen as a fuel, the fuel processor is not needed. Also, some systems incorporate the fuel processor into the fuel cell. Finally, for those systems that can use DC electrical power, some elements of the Power Conditioner are not needed.

Types and Uses of Fuel Cells

As shown in Table 1 below, there are five different types of fuel cells that either have been developed for specific applications or are being developed for large-scale commercial applications. These are presented in Table 1 in alphabetical order. However, in terms of rank by level of current development activity, the order is:
1) PEMFC, 2) MCFC, 3) SOFC, 4.)PAFC, 5)AFC

TABLE 1 - KEY CHARACTERISTICS OF FUEL CELL TYPES

Fuel Cell Type	Electrolyte	Operating Temp. (^{o}C)	CO Tolerance	Comments
Alkaline (AFC)	Liquid alkalis	~100		Very successful use in the US Space Program
Molten Carbonate (MCFC)	Alkali carbonates	~650	Very tolerant	Substantial development for stationary power applications
Phosphoric Acid (PAFC)	Phosphoric acid	~200	~2%	Only commercially deployed fuel cell type
Polymer Electrolyte (PEMFC)	Sulfonic acid in polymer	~80	<100 ppm	Being developed for a very wide range of applications
Solid Oxide (SOFC)	Stabilized zirconia	~700-1000	Very tolerant	Substantial development for stationary power applications

- **Alkaline Fuel Cells (AFC)** – Alkaline Fuel Cells have been deployed in the United States Space Program for over thirty years. During that time, they have proven to be very well suited to that application, operating reliably and dependably. However, issues of cost of manufacture and of fuel requirements have limited further interest in this type.

- **Molten Carbonate Fuel Cells (MCFC)** – Molten Carbonate Fuel Cells are in active development for stationary power applications, including commercial building heat and power, assured power, and distributed stationary power. Demonstration systems are being deployed as this report is being written. The basic building block for this type is ~250 kW, with total system power levels of 1-3 MW in development and demonstration.

- **Phosphoric Acid Fuel Cells (PAFC)** – Phosphoric Acid Fuel Cells are the only type that has seen substantial commercial application, with about 250 systems of 200 kW each deployed. These systems have accumulated an excellent record of reliability. However, cost-of-manufacture issues have limited further interest in this type.

- **Polymer Electrolyte Membrane Fuel Cells (PEMFC)** – This fuel cell type has received interest for all of the applications discussed in this report.

- **Solid Oxide Fuel Cells (SOFC)** – Solid Oxide Fuel Cells are in an earlier stage of development than MCFC and PEMFC, the other types of continuing interest.

Appendix A contains a more detailed discussion of each of these fuel cell types.

As listed in Table 2, fuel cells are potentially useful for a wide variety of applications, with more discussion and definition of these applications given in Chapter II.

TABLE 2 – SUMMARY OF FUEL CELL SYSTEMS USES/APPLICATIONS.

Use/Application	Power Levels (kW)
Small electronic devices	0.001 to 0.01
Portable power and Auxiliary power units	0.5 to 10
Transportation – automotive	50 to 100
Transportation - bus	100 to 200
Military and space	A wide range
Residential heat and power	1 to 5
Off-grid power	A wide range
Commercial building heat and power	100 and up
Assured power	100 and up
Distributed stationary power	100 and up
Hydrogen generation	Hydrogen gas is the product

Advantages and Disadvantages of Fuel Cell Systems

Table 3 lists the key advantages and disadvantages of today's fuel cell systems. Each of these advantages and disadvantages impacts the use of fuel cells and fuel cell systems in different ways, depending on the intended application. Chapter II discusses this topic in more detail.

TABLE 3 – KEY ADVANTAGES AND DISADVANTAGES OF CURRENT FUEL CELL SYSTEMS

Advantages	Disadvantages
Very low levels of unwanted emissions	System and life cycle cost
High energy density (as compared to batteries)	Lack of demonstrated reliability for several fuel cell types
Clean power	Lack of infrastructure for support
Reliable power	
Stealth power	
Reduced electrical transmission needs	
Combined heat and power generation	

Connecticut's Fuel Cell Companies and Support Organizations

Listed below are those fuel cell companies currently resident in Connecticut

- FuelCell Energy, Inc., 3 Great Pasture Rd., Danbury, CT 06813-1305 (www.fce.com), NASDAQ: FCEL
  Fuel Cell Energy is the only US manufacturer of Molten Carbonate Fuel Cells. Their major facilities are a manufacturing facility in Torrington and a home office and testing facility in Danbury.

- GenCell Corporation (previously Allen Engineering Company), 1432 Old Waterbury Road, Unit 3, Southbury, CT 06488 www.gencellcorp.com.
  GenCell is a small, Connecticut-based company focused on the manufacture of fuel cell elements.

- Proton Energy Systems, Inc., 10 Technology Drive, Wallingford, CT 06492 (www.protonenergy.com), NYSE: PRTN
  Proton Energy Systems is a major player in the development of fuel cell based systems for producing hydrogen. They are also developing systems for use in back-up power applications. Their facility includes the home office, testing, and manufacturing. They publish a quarterly newsletter: *The Hydrogen Wire*.

- Sure Power Corporation, 30 Main Street, Suite 405, Danbury, CT 06810 (www.hi-availability.com)
  Sure Power concentrates on the development and production of systems that are designed to produce electrical power with very high degrees of reliability.

- UTC Fuel Cells (formerly known as International Fuel Cells (IFC), until Dec. 5, 2001); 195 Governors Highway and 90/100 Bidwell Road, South Windsor, CT , 06074 (www.utcfuelcells.com) , NYSE: UTX
  UTC Fuel Cells is the only US manufacturer of Phosphoric Acid Fuel Cells, the only supplier of Alkaline Fuel Cells for the US space program, and is currently making major investments in Polymer Electrolyte Membrane Fuel Cells and in hydrogen generation. Major facilities include a home office, testing, and manufacturing facilities at two sites in South Windsor.

Additionally, the University of Connecticut has established a substantial fuel cell center, the Connecticut Global Fuel Cell Center. This center is currently funded for six endowed chairs, and is actively filling those chairs.

II. CURRENT APPLICATIONS OF FUEL CELLS

Fuel Cell Applications and Power Ranges

Figure 3 provides the anticipated power ranges for several fuel cell applications, showing that the potential range is very large, from about one Watt for small electronic devices up to perhaps 50,000 kW (50 MW) for large distributed power stations.

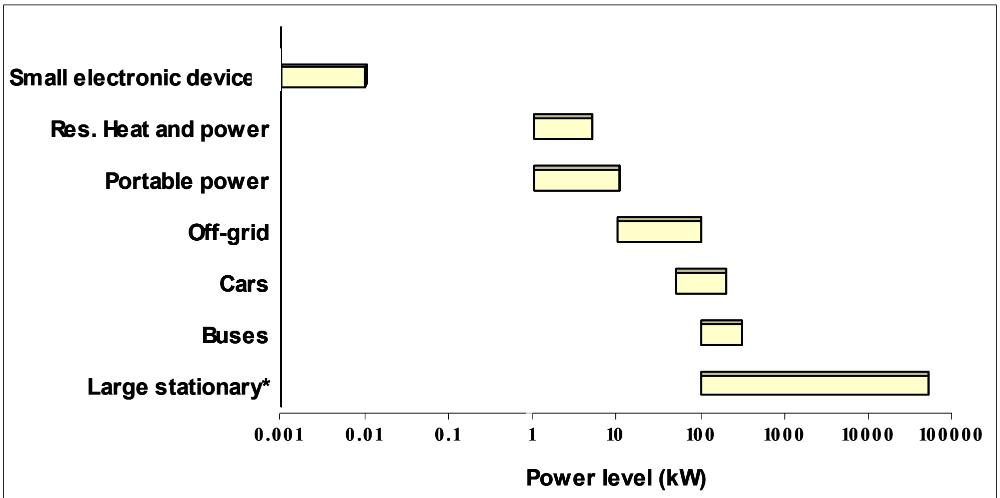


FIGURE 3 – ANTICIPATED POWER RANGES FOR SEVERAL FUEL CELL APPLICATIONS.

For purposes of this report, the following definitions will apply throughout.

- **Small electronic devices** – This application includes fuel cells in the 1 to 10 Watt range, for use in a wide variety of portable electronic devices such as laptop computers, cellular phones and the like.

- **Residential heat and power** (also known as combined heat and power or CHP)– This application includes fuel cells in the 1 kW to 5 kW range, for use in providing both power and heat to the home. Included are those situations in which the residential power system is connected to the grid, as well as those cases in which it is not.

  There is also some discussion today in New York, Michigan and California concerning the possible use of fuel cell powered automobiles for residential power generation when not on the road. This concept has gained attention because of the importance of distributed power generation to the future of the power grid. An article by GM staff concludes…"if only one out of every 25 vehicles in California today were a fuel-cell vehicle, their combined generating capacity would exceed that of the state's utility grid." This is a long term proposition worthy of consideration only if and when systems costs reduce.

- **Portable power and auxiliary power units (APUs)** – This application includes fuel cells in the 500 Watt to 10 kW range for use in hand-portable units and in various vehicles.

- **Off-grid power** – This application includes those for which the user would prefer to be independent of the grid and/or those for which providing grid power is too expensive.

- **Cars** – This application includes fuel cells in the 50 kW to 100 kW range, for use as the primary power source in automobiles.

- **Buses** - This application includes fuel cells in the 100 kW to 200 kW range, for use as the primary power source in buses. Included are those buses in which the fuel cell is the only significant power source, as well as those buses that have a secondary power source in a hybrid arrangement. Such hybrid arrangements are receiving increasing attention in diesel/electric or gasoline engine/electric configurations, offering advantages in fuel economy, emissions, smoothness of acceleration, brake life, and noise.

- **Military and space** – This application includes a variety of military and space needs. The principal use to date has been in the US Space Program, where fuel cells provide a key and essential power source for several vehicles.

- **Large stationary power, comprising:**

  - *Commercial building heat and power* (known as combined heat and power or CHP) – This application includes fuel cells in the 100 kW and up range, for use in providing both power and heat to commercial buildings. As with residential use, both grid connected systems and non-grid connected systems are included.

  - *Assured power* – This application includes fuel cells in the 100 kW and up range, for use in providing power very reliably, well beyond the current 99.9% availability that is quoted for the current power grid system. This application shares many characteristics of the commercial building heat and power application, including an overlap in power range, and often the interest in providing heat (i.e., CHP).

  - *Distributed stationary power* - This application includes fuel cells in the 100 kW and up range, for use in providing power to several/many users. Of the anticipated applications, the most common one is to co-locate the fuel cells with an electric utility grid substation, as a supplemental back-up for grid provided power. For some applications it is anticipated that heat will also be provided.

Benefits, Applications and Characteristics of Fuel Cell Systems

Table 4 below shows the benefits cited for various fuel cell applications, with note taken that low emissions is cited for all applications. Appendix B provides a more detailed discussion of each of these benefits.

TABLE 4 – BENEFITS CITED FOR EACH OF THE APPLICATION AREAS

Application	Benefit						
	Low Emissions	High Energy Storage Density	Clean Power	Reliable Power	Stealth Power	Reduced Transmission Needs	Combined Heat and Power
Small electronic devices	✔	✔		✔	✔		
Portable power/APU	✔		✔	✔	✔		
Transportation – automotive	✔		✔				
Transportation – bus and truck	✔		✔				
Military and space applications	✔		✔	✔	✔		
Residential heat and power	✔		✔	✔		✔	✔
Off-grid*	✔		✔	✔		✔	✔
Commercial building heat and power	✔		✔	✔		✔	✔
Assured power	✔		✔	✔			
Distributed stationary power**	✔		✔	✔		✔	✔
Hydrogen generation	✔		✔	✔		✔	

*Includes cellular phone towers and internal building communication systems.
**Includes larger industrial applications.

Table 5 presents application areas and Table 6 key characteristics of five fuel cell types.

TABLE 5 - APPLICATIONS FOR EACH FUEL CELL TYPE IN DEVELOPMENT

Application	Fuel Cell Type				
	Alkaline Fuel Cell (AFC)	Molten Carbonate Fuel Cell (MCFC)	Phosphoric Acid Fuel Cell (PAFC)	Polymer Electrolyte Membrane Fuel Cell (PEMFC)	Solid Oxide Fuel Cell (SOFC)
Small electronic devices				✔	
Portable power/APU				✔	
Transportation – automotive				✔	
Transportation – bus and truck				✔	
Military and space applications	✔			✔	
Residential power and heat				✔	✔
Off-grid				✔	✔
Commercial building power and heat		✔	✔	✔	✔
Assured power		✔	✔	✔	✔
Distributed stationary power		✔		✔	✔
Hydrogen generation				✔	

TABLE 6 - KEY CHARACTERISTICS OF FUEL CELL TYPES

Fuel Cell Type	Electrolyte	Operating Temp (°C)	Fuel CO Tolerance	Comments
Alkaline Fuel Cell (AFC)	Liquid alkalis	~100		Very successful use in the US space program
Molten Carbonate Fuel Cell (MCFC)	Alkali carbonates	~650	Very tolerant	Substantial development for distributed stationary power applications
Phosphoric Acid Fuel Cell (PAFC)	Phosphoric acid	~200	~2%	Only commercially deployed fuel cell type
Polymer Electrolyte Fuel Cell (PEMFC)	Sulfonic acid in polymer	~80	<100 ppm	Being developed for a very wide range of applications
Solid Oxide Fuel Cell (SOFC)	Stabilized zirconia	~700-1000	Very tolerant	Substantial development for stationary power applications

Current Economics of Fuel Cell Systems

Fuel cells are an evolving technology, and the current costs are relatively high compared to other currently available distributed energy products. Table 7 presents a summary of the current capital costs of fuel cells, sorted by application, along with an estimate of the power level of interest for each application. In order to become a competitor for most of the applications noted in this report, it is essential that costs be reduced. These cost reductions can be achieved by either increasing the scale of manufacture or by improving the level of technology, or both. The Study Committee had differing views on this topic, with some favoring the position that increasing the scale of manufacture was the key element, while others felt that both scale of manufacture and improvements in technology were essential. The various ways in which costs can be reduced are discussed in more detail in the following section entitled, "Opportunities for Improvements."

This issue of the size dependence of the current economics has proven to be difficult for the Study Committee. There was general agreement that, for a given application, the per system costs (i.e. $/kW of installed capacity) decrease as the power levels increase and as

TABLE 7 - CURRENT ECONOMICS OF FUEL CELLS SYSTEMS, ESTIMATES FOR 2003 DELIVERY

Application	Economic Category			
	Capital Costs ($/installed kW)	Power Level for installed costs (kW)	Fuel/ Power	Comments on the size dependence of the various costs
Small electronic devices	10,000	<0.01	H_2/AC	Cost per installed kW, or per kWhr decreases for all fuel cell systems as the installed power level increases.
Portable power	5,000	~1 - 5	H_2/AC	
Transportation – automotive	2,000	~ 50 to 100	H_2/DC	
Transportation – bus and truck	3,000	~ 100 to 200	H_2/DC	
Military applications	3,000	Various	HC/AC-DC	
Residential heat and power	5,000	~1-5	HC/AC	
Off-grid	3,000	~10 - 100	HC/AC HC/DC	
Commercial building heat and power (CHP)	3,000	>100	HC/AC	
Assured power	3,000	>100	HC/AC	
Distributed stationary power	3,000	>200	HC/AC	

H_2 – Hydrogen fuel HC – Hydrocarbon fuel AC/DC – Alternating current/Direct Current the number of systems produced increases. However, a more detailed analysis is difficult, since it is often related to business strategies and plans.

With regard to costs relative to other electric power generation systems, it is noted that fuel cells are a young and evolving technology. Nevertheless, they compete with other, often very well developed technologies, for market share. Table 8 shows the current capital costs for fuel cells as compared to several other methods of generating electrical power.

TABLE 8 - CURRENT CAPITAL COSTS FOR SEVERAL METHODS OF GENERATING POWER

Application	Power Generation Method (costs in $/installed kW)				
	Piston Engine	Steam Turbine	Gas Turbine	Combined Cycle	Fuel Cell
Small electronic devices	-	-	-	-	10,000
Portable power	100 - 200	-	-	-	5,000
Transportation- automobile	<50	-	-	-	2,000
Transportation – bus and truck	<100	-		-	3,000
Military and space	<100	-	500 and up	-	3,000
Residential power and heat	-	-	-	-	5,000
Off-grid					3,000
Commercial building heat and power	200 - 300	800 - 2000	500 - 900	600 - 1000	3,000
Assured power	200 - 300	800 - 2000	500 - 900	600 - 1000	3,000
Distributed stationary power	-	800 - 2000	500 - 900	600 - 1000	3,000
Hydrogen generation	-	-	-	-	

As indicated, competing systems are in widespread use. They are substantially less expensive than today's fuel cell systems, use fuels that are generally available, and are well understood.

- **Piston Engines** – Piston engines have been in development and production for over 100 years. The current products represent a very advanced state of development. These products are applicable to a wide range of the applications included in this report, as noted in the above table.

- **Steam Turbines** – Steam turbines have also been in development and production for over 100 years. The current products are suitable for very large central station power applications.

- **Gas Turbines** – Gas turbines are familiar as the engines on most commercial airliners. For stationary power applications, there are derivatives of the engines used on airliners, as well as units specifically developed for stationary applications.

- **Combined Cycle** – Combined cycle systems combine a gas turbine and a steam turbine. In these systems, the gas turbine combusts the fuel, generating electrical power from the gas turbine and substantial, high temperature, exhaust. The thermal energy in this exhaust is recovered in a heat recovery steam generator, which is, in turn, used to drive a steam turbine and thereby generate additional electrical power.

Except for the small electronic device application, all of the other power generation methods that compete with fuel cells are heat engines. As such, a basic element of the operation of such systems is the combustion of fuel, often at elevated pressures. The inevitable consequences are the generation of unwanted air pollutants and the generation of noise. The air pollutants usually include particulates, the oxides of nitrogen (NOx), carbon monoxide, and unburned hydrocarbons. The noise levels generated vary with the size of the installation and with the power level. For all these systems, their overall efficiency is limited by thermodynamics, with the upper limit of efficiency being the Carnot cycle. For the single power source systems (piston engines, steam turbines, and gas turbines), the resulting efficiencies are usually less than about 40%, often ranging to efficiencies as low as 20%.

Note however, that fuel cells are electrochemical in nature, and do not have this limitation of the heat engines. This difference is an important reason for the intrinsic advantage in efficiency of fuel cell systems.

Also, the gaseous pollutants generated by heat engine based systems can be processed in various remediation devices to reduce their levels before being discharged into the atmosphere. These remediation devices include filters for particulates, and catalytic converters for the oxides of nitrogen, carbon monoxide, and unburned hydrocarbons. Additionally, it is possible to reduce the levels of pollutants through modifications to the combustion process. These modifications include water injection, staged combustion, and exhaust gas recirculation. These devices and/or modifications generally add to the system costs, so there is the inevitable trade-off between remediation effectiveness and cost.

Noise is also an inevitable consequence of generating power with these systems. In all cases, the thermal energy generated by combusting the fuel is converted to the mechanical energy of one or more moving parts of the system. It is always possible to reduce the levels of noise emitted to the outside world with treatments such as exhaust mufflers, noise insulation, and distance.

Market Penetration & Operating Experience for Fuel Cell Systems

As of the time of this report, fuel cells had a negligible penetration into any of the application markets studied here. Table 9 below compares the present installed fuel cell capacity with estimates of several of the total potential markets for the year 2010. With regard to the systems' operating life, the only systems that have been deployed in relatively widespread commercial use are Phosphoric Acid Fuel Cell systems (PAFC). Several such systems have achieved over 40,000 hours of operation and at least one has reached over 60,000 hours. However, as noted earlier, it is not expected that the market for these systems will grow substantially, due primarily to cost issues.

TABLE 9 - PRESENT AND 2010 FUEL CELL MARKET PENETRATION

Application	Present Installed Fuel Cell Capacity (MW)	Estimates of Total Potential Market in 2010 (MW per year)
Small electronic devices	Demo only	
Portable power	Demo only	
Transportation – automotive	Demo only	~15,000 which equates to 150,000 cars per year (assumes 1% of cars have fuel cells). At $50 per kW, this would amount to $750M per year. If the percentage increases to 10%, the market would be $7.5B per year
Transportation – bus and truck	Demo only	~100 which equates 500 buses (assumes 10% of buses have fuel cells)
Military and space applications	~1	
Residential power and heat	Demo only	
Off-grid	Demo only	
Commercial building power and heat	~5 (PAFC)	See Distributed Power below
Assured power	Demo only	See Distributed Power below
Distributed stationary power		180 (assumes 1% of 18,000 MW/year of added capacity estimated by the DOE EIA for all stationary sources) – However, please note, 10% of the market would be 1,800 MW/year, a very substantial market. At $1,000 per installed kW, this would amount to $1.8 B per year.
Hydrogen generation		

Molten Carbonate Fuel Cell systems (MCFC) and Solid Oxide Fuel Cell systems (SOFC) have achieved continuous operating times of over 10,000 hours in demonstration systems. A challenge for both technologies will be to lengthen these operating times in demonstration systems, and to reproduce those lifetimes in commercial service.

Polymer Electrolyte Membrane Fuel Cell systems (PEMFC) have been demonstrated in a variety of applications, including buses, cars, residential power and portable power. A challenge here will be to achieve long operating times, and reproduce those lifetimes in commercial service.

Opportunities for Improvement

As noted earlier in this report, the major challenges that face the commercial applications for fuel cell systems are cost and demonstrated reliability. These challenges vary somewhat for the different applications, and vary considerably for the different fuel cell technologies. Also, because most of the Connecticut-based activities are focused on stationary power, automotive power and bus power, the comments in this section will focus on these applications.

For all of the fuel cell technologies that are expected to be viable in the future market (PEMFC, MCFC, and SOFC), the challenges fall into two categories, those related to the fuel cell stack, and those related to the balance of plant (BOP). Further, for PEMFCs, which require an external reformer when the input fuel is a hydrocarbon (see page 2), there are challenges and opportunities in this area. For all systems, costs are directly related to the scale of manufacture, with increasing manufacturing volumes resulting in lower costs per kW of capacity.

The fuel cell stack is the heart of any fuel cell system. As such, it is key to both the cost and reliability of the system. For each of the technologies, the challenges are different. Some of these are noted below:

- **Polymer Electrolyte Membrane Fuel Cells (PEMFC)** – PEMFCs operate at relatively lower temperatures, compared to MCFCs and SOFCs. This lower temperature operation, and related features, make PEMFCs the system of choice for applications in which a quick start-up is needed and an ability to respond rapidly to changing load is essential. Also, the lower temperature operation allows the use of relatively inexpensive materials in the construction of the stack. However, the lower temperature operation results in a significantly greater sensitivity to impurities in the feed material, particularly carbon monoxide. *Opportunities exist for increasing the operating temperature from the present 80°C to perhaps 150°C. This increase in operating temperature is expected to result in substantially improved tolerance to carbon monoxide in the feed material, without compromising the quick start-up and response to changing load characteristics.*

- **Molten Carbonate Fuel Cells (MCFC)** – MCFCs operate at relatively higher temperatures than PEMFCs, and somewhat lower temperatures than SOFCs. This higher temperature operation allows these systems to combine the fuel reformer into the fuel cell, and results in higher overall efficiency. However, the higher temperatures require a controlled heat-up and cool-down process to minimize thermal stresses in the stack. Also, the molten carbonate electrolyte is a naturally aggressive material, and care must be taken to minimize the effects of that aggression. *Opportunities exist for improved stack design, to minimize the limitations of heat-up/cool-down and electrolyte properties.*

- **Solid Oxide Fuel Cells (SOFC)** – SOFCs operate at the highest temperature of the current fuel cell systems of interest. As with MCFCs, this higher temperature operation allows these systems to combine the fuel reformer into the fuel cell, and results in higher overall efficiency. However, these high temperatures can result in the need for special materials to cope with the temperatures, and issues with heat-up/cool-down. *Opportunities exist in fundamental areas, to achieve satisfactory operation at somewhat lower temperatures, and in stack design, to minimize the effects of heat-up/cool-down.*

- **Providing hydrogen for PEMFCs** - PEMFCs require hydrogen as a fuel. This hydrogen can be provided by an on-board hydrogen storage system, such as compressed hydrogen in strong tanks, or by a hydrocarbon reforming system. Because of the widespread potential applications of PEMFCs, progress in this area would have similar widespread impact.

With regard to Balance of Plant (BOP), as noted in Chapter I, a complete fuel cell based power system is usually partitioned into the fuel cell stack, the fuel reformer (if needed), and the remaining elements. The latter largely consist of: (a) the electronics needed to provide conversion of the fuel cell output power (DC at a voltage level that varies somewhat with power demands and with cell age) to a relatively constant voltage level, often in AC form, (b) the control electronics needed to control the overall system, and (c) whatever sensors are needed to provide the inputs to the control system. Because the BOP is almost always a substantial part of the system cost, opportunities for cost reduction exist for all technology types and applications.

Appendix C provides more detail of specific opportunities for improvement.

III. APPLICATION TIMELINES & RELATED ISSUES

Following are a series of tables and figures providing an assessment of critical developmental issues for several leading fuel cell technologies.

Timelines

The developmental status of five fuel cell technologies is presented in Table 10.

TABLE 10 - FUEL CELL TECHNOLOGIES

Technology;	Development Status	Application Time Horizon	Comments
Alkaline (AFC)	Production - space	Current	Almost exclusively military and space applications
Molten Carbonate MCFC)	Field testing	2003	Several MW scale demonstrations in progress
Phosphoric Acid (PAFC)	Production	Current	High cost of manufacture, as much as $4500/kW
Polymer Electrolyte Membrane (PEMFC)	Field testing	2003	Many demonstrations in progress, for a wide variety of applications
Solid Oxide (SOFC)	Limited field tests	2006	

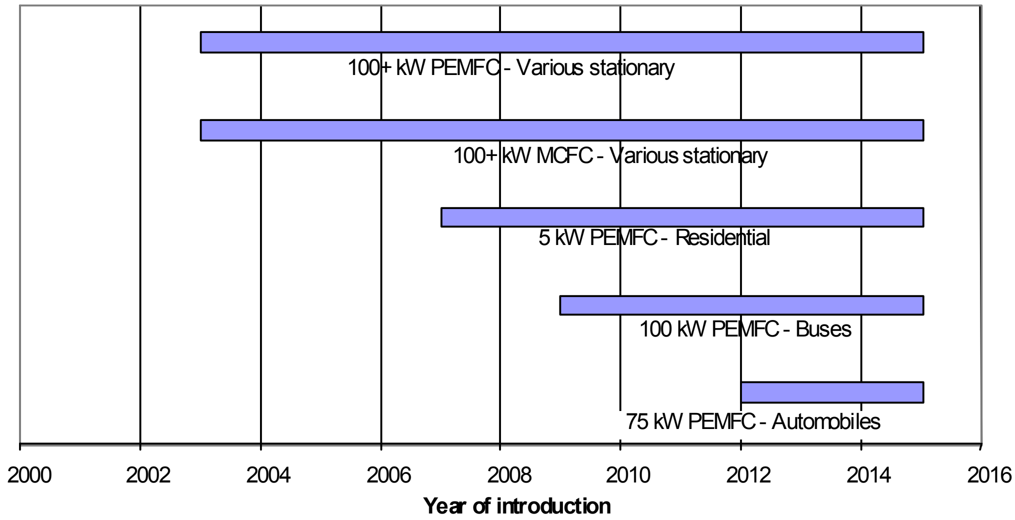
The development status and application timelines for the Connecticut producers of fuel cells is presented in Table 11.

TABLE 11 - CONNECTICUT FUEL CELL PRODUCERS

Connecticut Company	Development Status	Application Time Horizon	Comments
Fuel Cell Energy (MCFC)	Field testing	2003	Currently making products with > 250 kW installed capacity
Proton Energy Systems – hydrogen generation	Production hydrogen generators	Current	A part of the hydrogen production market is well suited to the Proton Energy Systems approach
Proton Energy Systems – back-up power	In development		
Sure Power	Production	Current	A wide variety of electrical power generation technologies are used
UTC Fuel Cells – Alkaline (AFC)	Production	Current	High cost of production, almost exclusively military and space applications
UTC Fuel Cells – Phosphoric Acid (PAFC)	Production	Current	High cost of production and limited continued investment
UTC Fuel Cells – Polymer Electrolyte Membrane (PEMFC)	Field testing	2003	Introductory products > 100 kW of installed capacity

Figure 4 provides an overview of the application timelines.

FIGURE 4 – ESTIMATES OF THE TIMELINES FOR COMMERCIAL VOLUME



- **Fuel Cell Uses and Commercialization Timing**
  Table 12 and the following discussion further expand on the timelines above showing fuel cells' two major attractions to be the wide range of applications and the relative near term for market penetration.

Table 12 - Fuel Cell Systems Commercialization

Use/application	Power levels (kW)	CT Companies	Estimated Year for Commercial Volume
Small electronic devices	0.001- 0.01	Proton Energy, GE	
Portable power and Auxiliary power units	0.5 to 10	Proton Energy	Current
Transportation – auto	50 to 100	UTC Fuel Cells	2012
Transportation - bus	100 to 200	UTC Fuel Cells	2009
Military and space	Wide range	UTC Fuel Cells, Fuel Cell Energy	
Residential heat & power	1 to 5		2007
Off-grid power	Wide range		
Commercial building heat and power	100 and up	UTC Fuel Cells, Fuel Cell Energy	2003
Assured power	100 and up	UTC Fuel Cells, Fuel Cell Energy, Sure Power	2003
Distributed stationary power	200 and up	UTC Fuel Cells, Fuel Cell Energy	2003
Hydrogen generation	Produces hydrogen gas	Proton Energy	Current

- **First Major Commercial Market: "Large Capacity Stationary Power"**
  There was general agreement within the Study Committee that Large Capacity Stationary Power would likely be the first significant commercial market. For this study, Large Capacity is defined as a system with an output power capability greater than 100 kW. The major elements of this market are the following:

  - Stationary Reliable Power: Defined variously as having power available from 99.99% to 99.9999% of the time operative, depending on the need, typically for applications in which reliability is vital, such as rapid response financial systems, on-line commerce, hospitals, and the like.

  - Commercial Building Power: Used for such applications as a small commercial building, a small strip mall, etc. In these cases, the heat generated by the fuel cell system is also often used, resulting in a combined usage called "Combined heat and power" (CHP).

  - Distributed Power: Here the power levels start at about 200 kW in applications that serve several customers or a small sub-station, usually as part of the overall power grid. Larger industrial applications would also be included here, with the likelihood of CHP systems.

  For these markets, both UTC and FCE are at par and nationally competitive. UTC is projecting costs in the $1500-$2000/kW range for its introductory 100 kW+ unit in this time frame. FCE talks about costs becoming lower as production volumes increase, with a reasonable chance that volumes will be sufficient to meet these price targets. Also, it is anticipated that as the production volumes increase, the prices will drop to below $1000/kW, allowing further market penetration.

- **Transportation Markets**

  - This market will be much more difficult to enter, due to the relatively low costs of present piston-engine power plants, which are ~$50/kW and less for automobiles and ~$100/kW for buses as compared with many times these values for fuel cells.

  - In spite of this difficulty, there will likely be a small commercial market developed for transit buses, and perhaps other fleet-type commercial vehicles, in the 2005 to 2010 time range.

  - UTC is conducting demonstrations in an SUV, has participated in a previous bus demo, and has several on-going bus demo projects. They seem to have as good a chance as any of their competitors. However, the price goals for this market remain daunting.

  - There is a very wide range of opinion concerning the economic competitiveness of fuel cells for the automobile market, ranging from guarded optimism to substantial pessimism. The current study is unable to resolve that issue. However, the market opportunity is very large so long as costs can be reduced sufficiently. Investments continue in this regard. Most of the world's car makers, including BMW, Daimler-Chrysler, Ford, GM, Honda, Hyundai, Nissan, Opel, Renault, Suzuki , Toyota and Volkswagen, have fuel-cell powered car programs. One should expect to see test fleets in operation throughout the world in the 2 to 5 year time frame. In that regard, it is also worthy of note that Toyota has recently announced the availability of a fuel cell based hybrid-electric powered SUV for leasing by technology-related companies, institutional organizations, and research facilities that have access to hydrogen fueling.

In related news, Toyota and GM have announced plans to jointly promote fuel cell vehicles, including cooperation in the establishment of hydrogen filling stations. In addition, Toyota and BMW are working with other manufacturers to establish international standards for such stations.

- **Very Low Power Market**
  - The market for very low power fuel cells, ~1-5 W for electronic applications could be promising, in view of the relatively high cost of the batteries that would be replaced (~$10,000/kW).

  - To our knowledge, there is no Connecticut company targeting this market. This could perhaps be an opportunity for the state.

- **A New Opportunity**
  - The use of fuel-cell-like devices to make pressurized hydrogen gas is expected to be a modest but growing niche market. The competition is pressurized bottled gas, a delivery system with a great deal of overhead costs. Also, a product now exists that couples a hydrogen generating system with a conventional fuel cell system. This combination could lead to the development of reliable power generation systems that are in turn compatible with other methods of generating hydrogen, including renewable techniques.

  - Proton Energy Systems of Connecticut is a leader in these markets.

- **Cost and Demonstrated Reliability Issues**
  - There are still major obstacles to large-scale fuel cell commercialization. Costs are expected to drop, and reliability is expected to improve if investments continue at or above today's levels. Prices low enough to break through to some market segments are expected within one to two years. In the Study Committee's judgment, Fuel Cell Energy (FCE) and UTC Fuel Cells of CT are at least at par, and may be leaders of the USA pack, at least for stationary applications.
  - In more detail, for investment Fuel Cell Energy has been very successful in securing government funding to further technologies and is the only major

producer of Molten Carbonate Fuel Cells (MCFC). The government investment has allowed FCE to tackle substantial development efforts without incurring debt. For UTC, the investment is coming from corporate funds, and UTC seems to be committed to its continuation.

- Both FCE and UTC note that costs are substantially dependent on production volume. FCE has just moved into a new production facility, with substantial extra production capacity, and UTC greatly enlarged their facilities in South Windsor.
- Relative to fuel cell manufacturing technology, the Connecticut Light and Power Conservation Load Management Fund sponsored several projects and programs aimed at improving the manufacturing technology for all of the fuel cell types currently under development. Several of these projects and programs are directed toward fuel cell designs that may make possible the use of structural components that can be used in all of the current fuel cell types (MCFC, PEMFC, and SOFC) while at the same time improving the reliability of these fuel cells.
- For demonstrated reliability, no product has been in field operation long enough with sufficient units to resolve all long-term related issues. However, it appears UTC's product, a Polymer Electrolyte Membrane Fuel Cell and FCE's product, a Molten Carbonate Fuel Cell, are at par and promising, but significantly more data are needed to assure that judgment. The third technology is the Solid Oxide Fuel Cell which, while viewed favorably by some, is in an earlier stage of development than Polymer Electrolyte Membrane or Molten Carbonate Fuel Cells, and thus has more unknowns relative to demonstrated reliability.

Sources of Support

As listed in Table 13, several organizations are candidates for providing funds for fuel cell programs and projects in Connecticut.

TABLE 13 – POTENTIAL SOURCES OF FUNDING FOR FUEL CELL PROGRAMS

Organization	Web Address and Other Information
Connecticut Clean Energy Fund	www.ctcleanenergy.com
Connecticut Light and Power Conservation and Load Management Fund	www.cl-p.com,, then click on Research Funding
United States Department of Energy	www.energy.gov, then click on A-Z index, then on fuel cell technology

Other States' Programs

As shown in Table 14 on the following page, several other states have significant fuel cell initiatives in progress or in review.

TABLE 14 - SUMMARY OF SEVERAL STATE INITIATIVES DEVOTED TO FUEL CELLS

State	Funding/Other Resources	Objectives
Michigan	$50M 700 acre site + State and local tax exemption + Small business tax credit	-Become a center for alternate energy technology R&D, education and manufacturing -Establish a federal-level certification center
Ohio	$100M	-Expand state's research capabilities -Participate in demonstration projects -Attract companies and jobs
California		Promote fuel cells for mobile & stationary applications
Texas		Promote fuel cells for mobile & stationary applications

- **Michigan** – The state of Michigan appears to be committed to becoming a significant player in the fuel cell area. The current Michigan initiative includes the creation of a 700-acre site near the University of Michigan at Ann Arbor campus, devoted to the development of alternate energy sources, with fuel cells at the forefront of the presentations and discussions. The initial funding for this effort is $50M. There are plans for state and local tax exemptions, and small business credits.

  The initiative includes elements of education, technology research and development, and manufacturing. One expectation is that the Michigan center will be the focus for attracting small business and start-up companies. The focus of this initiative is clearly transportation applications, with automobiles mentioned frequently during the discussions. However, stationary applications are also mentioned.

- **Ohio** – The state of Ohio also appears to be committed to becoming a significant player in the fuel cell area, with an overall objective "To position Ohio as a national leader in the growing fuel cell industry." The stated objectives of the current $100M, 3-year initiative are to:
  - Expand the state's research capabilities by building on the work at universities such as Case Western Reserve University, Ohio University and Ohio State University and at technology leaders like NASA Glenn and the Air Force Research Lab at Wright-Patterson;
  - Participate in demonstration projects involving hydrogen infrastructure; and
  - Invest in expanding the fuel cell industry in Ohio, to attract companies and jobs.

  The Ohio announcement indicates that "Ohio has a rich supplier network in chemicals, polymers, ceramics, sensors and controls which positions the state to capture a significant portion of the emerging fuel cell market."

- **California** – The state of California has several programs devoted to fuel cells. The current focus of many of these programs is the demonstration of fuel cell systems for both transportation and stationary applications.

For example, the California Fuel Cell Partnership aims to achieve four main goals. These are to:

- Demonstrate vehicle technology by operating and testing the vehicles under real-world conditions in California,
- Demonstrate the viability of alternative fuel infrastructure technology, including hydrogen and methanol stations,
- Explore the path to commercialization, from identifying potential problems to developing solutions, and
- Increase public awareness and enhance opinion about fuel cell electric vehicles, preparing the market for commercialization.

Although the California programs seem to emphasize applications, at least initially, California is the most populous state in the nation, with a tradition of technological innovation and the nurturing of new start-up companies based on new technology. Also, California has been a leader in demanding new ways to provide goods and services with lower levels of emissions. It could become a formidable competitor.

- **Texas** – The state of Texas is at a somewhat earlier stage of decision making in the area of fuel cells. There are proposals in discussion for both transportation and for stationary applications. As is the case for California, the Texas proposals seem to emphasize applications, at least initially. However, Texas is the second most populous state in the nation, with a tradition of innovation, and with a rich tradition in the field of energy. It also could become a formidable competitor.

IV. SUMMARY OF FINDINGS & CONCLUDING REMARKS

Fuel cell power systems are in active development for a wide range of applications: from very low power (~1 to 10W) applications such as portable electronics, through higher power applications such as portable power units and auxiliary power units (~0.5 to 10kW), residential power units (~1 to 5 kW), military and space (a wide range), automobiles (~50 to 100 kW), buses (~100 to 200 kW), off-grid power (a wide range), and a variety of stationary power applications (> 100 kW) aimed at commercial building heat and power, assured power, distributed stationary power, and perhaps even central power stations. Also, a separate application area that uses fuel cell technology--the generation of very pure and pressurized hydrogen--is in active development.

Five fuel cell technologies have been developed to meet these application areas. These are Alkaline Fuel Cells (AFC), Molten Carbonate Fuel Cells (MCFC), Phosphoric Acid Fuel Cells (PAFC), Polymer Electrolyte Membrane Fuel Cells (PEMFC), and Solid Oxide Fuel Cells (SOFC). Of these, only the MCFC , PEMFC, and SOFC are being actively developed for potential large volume and commercial applications.

Among the several application areas, the first (~ CY 2003 to 2004) that are expected to become competitive in the relatively large scale commercial market are those aimed at stationary powers greater than 100 kW: the commercial heat and power, assured power, and distributed stationary power areas. Following after will be the residential power area (~CY 2007 to 2008), buses (~CY 2009 to 2010), and automobiles (~CY 2012 and beyond). However, major investments are being made by the world's automotive firms that may accelerate the process. Application areas for which time scales were not estimated in this study include the portable electronics area, the off-grid power area, and the military and space area.

The key reasons/advantages that are cited for using a fuel cell system in an application include:

- very low levels of unwanted emissions and low noise levels
- very clean and reliable power
- reduced needs for electrical transmission facilities
- combined heat and power
- high efficiency

Of these advantages, the very low levels of unwanted emissions and low noise were the overwhelming ones, cited for every application area.

The key challenges to the deployment of fuel cell power systems are:

- system and life cycle cost
- lack of demonstrated reliability, for several fuel cell types
- lack of infrastructure, for some applications

The surmounting of these challenges offers possibilities for rewarding investment in the technology and infrastructure. These possibilities include the following:

- For **all fuel cell** types, investments aimed at:
  - lowering the manufacturing cost of the fuel cell stack,
  - improving the long term reliability and thus the operating lifetime of the fuel cell stack,
  - lowering the costs of power conditioning and control portion of the fuel cell system and
  - increasing the market penetration of the fuel cell system for their respective applications.

- For **PEMFC systems, additional** investments aimed at:
  - lowering the costs and improving the performance of the fuel processing portion of the system, and
  - increasing the operating temperature of the fuel cell to improve the cell tolerance to carbon monoxide in the fuel.

- For **SOFC systems, additional** investments aimed at reducing the operating temperature of the fuel cell.

Connecticut is currently a world leader in the application of fuel cell systems for stationary power applications, with over 250 PAFC units installed worldwide, and with substantial demonstration of MCFC units. Connecticut is the only state than can claim substantial system experience in any fuel cell power application. However, other states are actively engaged in developing fuel-cell-based industries within their borders. These states include:

- Michigan, with a three-year funding level of $50M, and a 700 acre site planned near the University of Michigan
- Ohio, with a three-year funding level of $100M
- California, with a commitment to application and infrastructure
- Texas, with a commitment to application

These initiatives could pose substantial challenges to Connecticut's current lead for stationary power applications, and will certainly pose challenges to efforts to compete in transportation applications. The Michigan and Ohio efforts are substantially aimed at transportation applications.

APPENDICIES

Appendix A - Fuel Cell Types and Properties

The following fuel cell types are listed in order of current development activity.

Polymer Electrolyte Membrane Fuel Cell (PEMFC): Polymer Electrolyte Membrane Fuel Cells (PEMFC) deliver high power density, which offers low weight, cost, and volume. The immobilized electrode membrane simplifies sealing in the production process, reduces corrosion, and provides for longer cell and stack life. PEMFCs operate at low temperature (~80°C), allowing for faster startups and immediate response to changes in the demand for power. The PEMFC system is seen as the system of choice for vehicular power applications, but is also being developed for stationary power.

The basic cell consists of a proton-conducting plastic-like membrane sandwiched between two platinum impregnated porous electrodes. In operation, hydrogen at the anode provides a proton, freeing an electron in the process that must pass through an external circuit to reach the cathode. The proton diffuses through the membrane to the cathode to react with oxygen and the returning electron. Water is subsequently produced at the cathode.

Because of the intrinsic nature of the materials used, low-temperature operation of approximately 80°C is possible. The cell also is able to sustain operation at very high current densities. These attributes lead to a fast start capability and the ability to make a compact and lightweight cell. Other beneficial attributes of the cell include no corrosive fluid hazard and lower sensitivity to orientation. As a result, the PEMFC is particularly suited for vehicular power application.

Any initial commercial scale transportation application will likely use on-board hydrogen as a fuel. Many committee members felt that hydrogen stored in the vehicle was likely to be the fuel of choice for the foreseeable future. However, considerable effort is also being devoted to developing systems that could use liquid fuels such as methanol, ethanol, and perhaps gasoline. The cell also is being considered for stationary power application, which will use natural gas or other hydrogen-rich gases.

The lower operating temperature of a PEMFC results in both advantages and disadvantages. Low temperature operation is advantageous because the cell can start from ambient conditions quickly, especially when pure hydrogen fuel is available. It is a disadvantage in that platinum catalysts are required to promote the electrochemical reaction, catalysts that are very sensitive to carbon monoxide at temperatures below about 150°C. Due to this carbon monoxide effect, only a few ppm (parts per million) of carbon monoxide can be tolerated when the platinum catalyst is at 80°C. Because reformed and shifted hydrocarbons contain about one percent of CO, a mechanism to reduce the level of CO in the fuel gas is needed. The low temperature of operation also means that little if any heat is available from the fuel cell for any energy-requiring reforming process.

A significant and potentially important variant of the PEMFC is a type that is designed to use a liquid fuel, such as methanol or ethanol. Miniature fuel cells of this type are actively being developed for use in cell phones, laptop computers, and other portable small appliances.

Molten Carbonate Fuel Cell (MCFC): Molten Carbonate Fuel Cells (MCFC) operate at higher temperatures (~650^0 C) than PEMFCs. This higher temperature operation allows higher overall system efficiency, the elimination of precious metal catalysts, and the possibility of internally reforming a hydrocarbon fuel into the necessary hydrogen. The MCFC system is a leading contender for relatively large (> 100 kW) stationary systems.

The basic cell consists of a molten alkali carbonate membrane sandwiched between two nickel-based porous electrodes. As in the PEMFC cell, hydrogen at the anode is separated into a proton and an electron, with the electron flowing in the external circuit to provide electrical power. However, in contrast to the PEMFC, the ion that moves through the membrane is a carbonate ion (CO_3^{-2}), which moves from the cathode to the anode where it reacts with the proton. Both carbon dioxide and water are produced at the anode.

Because of the higher temperature operation, the overall efficiency of the MCFC tends to be higher than that of the PEMFC. Also, the higher temperature operation results in waste heat that is also at a considerable high temperature. This waste heat is suitable for a number of auxiliary uses, including the operation of a turbine-based secondary power system. Such combined systems should result in still higher overall system efficiency.

Any initial commercial scale application will almost certainly use natural gas as a fuel. Natural gas is widely available, compatible with virtually all of the applications for MCFC's, and is a fuel that can be internally reformed inside the fuel cell, allowing for the elimination of any external fuel reformers.

The higher operating temperature of a MCFC results in both advantages and disadvantages. As noted above, higher operating temperature can result in higher overall system efficiency and in higher quality waste heat generation. Also, the need for precious metal catalysts is eliminated, and the sensitivity to carbon monoxide is also eliminated. However, the higher temperature operation requires more attention to the nature of the heat-up and cool-down of the fuel cell, in order to minimize thermal expansion mismatch effects. In particular, the liquid phase/solid phase transition of the electrolyte membrane requires attention, to minimize the naturally occurring thermal effects of this transition.

Solid Oxide Fuel Cell (SOFC): Solid Oxide Fuel Cells (SOFC) operate at still higher temperatures (700^0 C to 1000^0 C.) This higher temperature operation also allows higher overall system efficiency, the elimination of precious metal catalysts, and the possibility of internally reforming a hydrocarbon fuel into the necessary hydrogen. The SOFC system is a leading contender for relatively large (> 100 kW) stationary systems.

The basic cell consists of a solid rare-earth-oxide membrane sandwiched between two sintered porous electrodes. As in the PEMFC cell, hydrogen at the anode is separated into a proton and an electron, with the electron flowing in the external circuit to provide electrical power. However, in contrast to the PEMFC, the ion that moves through the membrane is an oxygen ion (O^{-2}), which moves from the cathode to the anode. If the fuel is hydrocarbon based, the most likely situation, both carbon dioxide and water are produced at the anode.

Because of the high temperature operation, the overall efficiency of the SOFC tends to be high, comparable to that of the MCFC, and perhaps a little higher. Also, as with the MCFC, the waste heat produced by the cell is suitable for a number of auxiliary uses, including the operation of a turbine-based secondary power system. Such combined systems should result in still higher overall system efficiency.

Any initial commercial scale application will almost certainly use natural gas as a fuel. Natural gas is widely available, compatible with virtually all of the anticipated applications for SOFCs, and is a fuel that can be internally reformed inside the fuel cell, allowing for the elimination of any external fuel reformers.

The higher operating temperature of an SOFC results in both advantages and disadvantages. As noted above, higher operating temperature can result in higher overall system efficiency and in higher quality waste heat generation. Also, the need for precious metal catalysts is eliminated, and the sensitivity to carbon monoxide in also eliminated. However, the very high temperature operation requires fuel cell construction materials that are compatible with these temperatures. Often, these materials, which tend to include precious metal components, tend to be considerably more expensive than those for PEMFCs and somewhat more expensive than those for MCFCs.

Phosphoric Acid Fuel Cell (PAFC): PAFCs are the only fuel cell systems that have been deployed widely in commercial use. There are currently about 250 such systems in operation. For these fuel cell systems, the electrolyte is concentrated phosphoric acid and the operating temperature is about 200 °C.

Alkaline Fuel Cell (AFC): These units use potassium hydroxide for the electrolyte, and operate at about 100°C. These units, which can be quite small, are used on the space shuttle and in other applications where pure gases are used. These units are very sensitive to impurities such as carbon monoxide and carbon dioxide, and so cannot make use of direct fossil fuel gases. These fuel cells have been the mainstay of NASA's aerospace program since the very early days of manned spaceflight.

Appendix B – Benefits of Fuel Cell Systems

Low Emissions – This benefit is cited as important for all of the application areas. It is certainly true that fuel cells that operate with hydrogen as a fuel are capable of very low levels of unwanted emissions, with the only substance of consequence emitted being water, usually in vapor form, and the nitrogen that is part of the air that is supplied to the system. As noted on page 2 of this report, fuel cells operating on a hydrocarbon fuel (natural gas, propane, methanol, ethanol, gasoline, etc) require the conversion of that fuel into hydrogen, a process called reformation. The various reformation processes produce the desired hydrogen, the inevitable carbon dioxide that results from utilizing the energy content of the carbon part of the fuel, and very small amounts of emissions of concern, such as the oxides of nitrogen and carbon monoxide. With proper control, these undesired emissions can be held to very low levels. The following comments discuss the details of the importance of low emissions for each of the application areas listed.

- ***Small electronic devices*** – The fuel cells in these applications will be operating very near to people. Laptop computers are usually directly in front of and usually used within one to two feet of the operator. Cellular phones are even closer, of course, and within a few inches of the operator's nose and mouth.

- ***Portable power and Auxiliary power units(APUs)*** – The benefit in these applications is probably strongest for the APUs. These units will likely be used in vehicles that are stationary for extended periods of time (i.e., diesel engine powered trucks that need electrical power while stopped, school buses that need power while stopped, and recreational vehicles that are parked and using the APU for electrical power).

- ***Transportation – Automobile*** – The ability to achieve very low levels of emissions is a crucial and vital element behind the interest in applying fuel cells to automobiles. In order to compete with the present power plants — gasoline and diesel-powered piston engines — fuel cell-powered systems must overcome their present disadvantages in cost, durability, size, weight, and perhaps some elements of operating characteristics. The goal is to have a car that has very low emission levels, perhaps rivaling the emission performance of all-electric cars, but with a driving range competitive with piston-engine powered cars, something not currently achieved by all-electric cars. Fuel cell-powered cars that use hydrogen as a fuel can achieve that characteristic. However, it is important to remember that today's hydrogen is usually produced from a hydrocarbon feed, and that the process of conversion results in carbon dioxide, as noted above, and also small amounts of the oxides of nitrogen and of carbon monoxide, also as noted above.

- ***Transportation (Bus)*** – As with automobiles, the ability to achieve very low levels of emissions is one of the crucial and vital elements behind the interest in applying fuel cells to buses. Transit buses often operate in densely populated urban areas, where air quality is a concern. As compared to automobiles, the concerns about cost, size, and weight are somewhat reduced, due to the greater flexibility of buses to accommodate these issues.

- ***Military and space*** – This application includes a variety of military and space needs. The principal use to date has been in the US space program, where fuel cells provide a key and essential power source for several vehicles.

- ***Residential heat and power*** – In this application, the fuel cell system will be installed in, or adjacent to the customer's residence. As such, the achievement of very low levels of emission could be a significant selling point. Also, low emission levels would likely make permitting and licensing easier.

- ***Off-grid power*** – In this application, the fuel cell system often will be installed in areas and/or buildings where low emissions are advantageous/essential to licensing, permitting, and acceptance.

- ***Commercial building heat and power (CHP)*** – In this application, the fuel cell system will be installed in, or adjacent to the building.

- ***Assured power*** – In this application, the fuel cell system will often be installed in, or adjacent to areas where people will be working.

- ***Distributed stationary power*** **–** In this application, the fuel cell system will often be installed at electric utility sub-stations which are often located in areas where any significant levels of unwanted emissions would block, or at least greatly hinder, the possibilities of local acceptance. Significant unwanted emissions would also likely hinder licensing and permitting. Additionally, fuel cells could be located at custom sites to efficiently produce combined electricity and heat.

High Energy Storage Density – In this case, the fuel cell system is competing with rechargeable batteries. It is expected that these fuel cell systems will have several times the energy storage density of current batteries. The increased energy storage density would be welcomed by most users of small portable electronic devices such as laptop computers and cellular phones. Also, as discussed in Chapter II, the costs of rechargeable batteries per unit of energy stored/produced (i.e., $/kWhr) are much higher than other systems discussed in this report (e.g., engines, turbines, etc.). These much higher costs should make it easier for fuel cell systems to capture a share of the market. However, it should be noted that there is continued and intense development of battery systems, a development that will likely result in somewhat higher power densities and somewhat lower costs, which may continue to keep these systems competitive.

Clean Power – is defined as electrical power that is relatively more constant in voltage and with relatively less electrical noise than power delivered from the electric grid. Although cited as a significant benefit for a variety of applications, clean power provides the greatest benefit when used to power electronic equipment that is sensitive to voltage levels and noise.

Reliable Power – is defined as electrical power that is more reliable than that currently delivered by the electric grid. Current estimates of grid reliability are about 99.9%. That is, the grid delivers power to the application 99.9% of the time. At this level, the electrical power would be out for about 8 to 9 hours per year.

Stealth Power – is defined as the generation of electrical power with little or no external evidence that the power was being generated. That is, there will be very little external noise, very little thermal plume, and very little identifiable emissions. The term is almost always associated with military applications, and it is expected that the major benefit will be for that application. However, the small electronic device and portable power/APU applications are also included, to reflect the expectation that these applications will demand very unobtrusive systems, with low noise, low external heat, and low emissions.

Reduced Transmission Needs – is defined as a reduced need for electrical transmission lines to deliver power to a customer/user. This benefit is expected to be of most significance to the application of Distributed stationary power. For at least some of these systems, the fuel cell system would be installed at an electric grid sub-station and used to supplement the power delivered to that sub-station by the grid. Such Distributed stationary power systems could be of significance for Connecticut, particularly for such areas as the southwest part of the state, with its ever growing power consumption coupled with difficulties in increasing the ability to deliver power to the region.

Combined Heat and Power (CHP) – is defined as the use of both the heat and electrical power that are generated by the fuel cell system. Such combined use results in increased overall efficiency of the system, and lower overall cost of delivering the power.

Hydrogen Generation – is defined as the use of fuel-cell like technology to produce hydrogen with systems that have water and power as inputs. Often, these systems are capable of producing this hydrogen under substantial pressure (e.g., 2000 psi has been demonstrated). Also, such a hydrogen generation system, coupled with a more conventional hydrogen-fed fuel cell, can serve as an assured power system. In addition, such a system could be coupled and/or fed with other sources of electrical energy, including renewable sources such as wind power, or perhaps even renewable sources of hydrogen. Some committee members feel that such systems could be important contributors to our future energy needs.

Appendix C - Improvement Opportunities for Fuel Cell Systems

TABLE 15 - OPPORTUNITIES FOR IMPROVEMENT – 3 TO 5 YEARS

Application	Improvement Area					
	Learning Curve Issues	**Manufac-turing Methods**	**New Technology**	**Other**	**Scale of Manufac-turing**	**Design Features**
Transportation – automotive	*	*	Higher temperature operation	Hydrogen storage/ generation	*	*
Transportation – bus and truck	*	*	Higher temperature operation	Hydrogen storage/ generation	*	*
Military applications	*	Increase levels of automation – reduce labor content of system	Longer stack life	Better packaging	*	*
Residential power and heat	*	*	*	*	*	*
Off-grid	*	*	*	*	*	*
Commercial building power and heat	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power
Assured power	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power
Distributed stationary power	Optimized cell stack, reduced manufac-turing labor, balance of plant, materials improve-ment, installation issues, permitting issues	Increase levels of automation – reduce labor content of system	Longer stack life	Lower packaging cost and installation costs	Goals for all large stationary systems of 400 MW by 2004	Minimize precious metal content, minimize number of heat exchangers, minimize/ reduce/ eliminate fuel processors, improve system efficiency, implement hybrid systems

*- Insufficient information available for this report

TABLE 16 - OPPORTUNITIES FOR IMPROVEMENT – 5 TO 10 YEARS

Application	Improvement Area					
	Learning Curve Issues	Manufacturing Methods	New Technology	Other	Scale of Manufac-turing	Design Features
Transportation – automotive	*	*	*	*	*	*
Transportation – bus and truck	*	*	*	*	*	*
Military applications	*	*	*	*	*	*
Residential power and heat	*	*	*	*	*	*
Off-grid	*	*	*	*	*	*
Commercial building power and heat	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power		See Distributed stationary power	See Distributed stationary power
Assured power	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power		See Distributed stationary power	See Distributed stationary power
Distributed stationary power	Continued economies of scale and improved manufac-turing methods	Full automation, distributed assembly centers	High efficiency hybrids	Multiple fuel capability – i.e., natural gas, wastewater treatment, landfill gas, diesel, gasoline, coal-gas, methane, methanol, ethanol	Goals of GW production per year	Develop-ment of hybrid fuel cell/ engine systems

* - Insufficient information available for this report

TABLE 17 - OPPORTUNITIES FOR IMPROVEMENT – > 10 YEARS

Application	Improvement Area					
	Learning Curve Issues	**Manufacturing Methods**	**New Technology**	**Other**	**Scale of Manufac-turing**	**Design Features**
Transportation – automotive	*	*	*	*	*	*
Transportation – bus and truck	*	*	*	*	*	*
Military applications	*	*	*	*	*	*
Residential power and heat	*	*	*	*	*	*
Off-grid	*	*	*	*	*	*
Commercial building power and heat	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power		Goals 1 of 2 GW production per year	See Distributed stationary power
Assured power	See Distributed stationary power	See Distributed stationary power	See Distributed stationary power		Goals 1 of 2 GW production per year	See Distributed stationary power
Distributed stationary power	Mature	Full automation, distributed assembly centers	High efficiency hybrids	Multiple fuel capability – i.e., natural gas, wastewater treatment, landfill gas, diesel, gasoline, coal-gas, methane, methanol, ethanol	Full automation distributed assembly centers	Fully mature hybrid systems, with efficiencies of 65 to 70%

*- Insufficient information available for this report

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Major Studies of the Academy

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- Transportation Investment Evaluation Methods and Tools
- An Analysis of Energy Available from Agricultural Byproducts, Phase 1: *Defining the Latent Energy Available*

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- A Study of Bus Propulsion Technologies in Connecticut

2000

- Efficacy of the Connecticut Motor Vehicle Emissions Testing Program
- Indoor Air Quality in Connecticut Schools
- Study of Radiation Exposure from the Connecticut Yankee Nuclear Power Plant

1999

- Evaluation of MTBE as a Gasoline Additive
- Strategic Plan for CASE

1998

- Radon in Drinking Water

1997

- Agricultural Biotechnology
- Connecticut Critical Technologies

1996

- Evaluation of Critical Technology Centers
- Advanced Technology Center Evaluation
- Biotechnology in Connecticut

1994

- Science and Technology Policy: Lessons from Six Amer. States

1992

- A State Science and Technology Policy
- Electromagnetic Field Health Effects

1990

- Biotechnology (Research in Connecticut)
- Economic Impact of AIDS Health Care in Connecticut

1989

- Science and Engineering Doctoral Education in Connecticut

1988

- Indoor Pollution: Household Survey
- Vocational-Technical High School Curriculum Evaluation

1987

- Waste Conversion for State Construction
- High Technology Plan for Connecticut

1986

- Automobile Emissions Testing
- Health Standard (for EDBs)

1985

- Well Treatment (for EDBs)

1984

- VDT Radiation Health Effects
- Chemical Transformations of PCB
- VDT Radiation
- Radiation Technicians
- High Technology List (for CT)

1983

- Atmospheric Sulfur Oxides

1982

- Public Utility Conversion to Coal
- Costs of Deferring Highway Maintenance

1981

- Tidal Wetlands
- New Haven Harbor
- Human Health Effects (of PCBs)
- Health Effects of Eating PCB-Containing Fish
- Toxicity of PCBs

1979

- CT Building Code; Energy Conservation
- Nuclear Plant Capacity
- Thermographic Mapping
- Air Pollution in CT
- SSET Program for CT
- Urea-Formaldehyde Foam

1978

- Oil Spill Containment
- PCB and the Housatonic River
- The Opportunities and Limitations of Our Resource and the State of Our State in 2000 AD

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