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Applying fuel cell experience to sustainable power products

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Abstract

Fuel cell power plants have demonstrated high efficiency, environmental friendliness, excellent transient response, and superior reliability and durability in spacecraft and stationary applications. Broader application of fuel cell technology promises significant contribution to sustainable global economic growth, but requires improvement to size, cost, fuel flexibility and operating flexibility. International Fuel Cells (IFC) is applying lessons learned from delivery of more than 425 fuel cell power plants and 3 million h of operation to the development of product technology which captures that promise. Key findings at the fuel cell power plant level include: (1) ancillary components account for more than 40% of the weight and nearly all unscheduled outages of hydrocarbon-fuelled power plants; a higher level of integration and simplification is required to achieve reasonable characteristics, (2) hydrocarbon fuel cell power plant components are highly interactive; the fuel processing approach and power plant operating pressure are major determinants of overall efficiency, and (3) achieving the durability required for heavy duty vehicles and stationary applications requires simultaneous satisfaction of electrochemical, materials and mechanical considerations in the design of the cell stack and other power plant components. Practical designs must minimize application specific equipment. Related lessons for stationary fuel cell power plants include: (1) within fuel specification limits, natural gas varies widely in heating value, minor constituents such as oxygen and nitrogen content and trace compounds such as the odorant; (2) city water quality varies widely; recovery of product water for process use avoids costly, complicated and site-specific water treatment systems, but water treatment is required to eliminate impurities and (3) the embedded protection functions for reliable operation of fuel cell power conditioners meet or exceed those required for connection to the utility grid, but current standards do not recognize embedded protection functions, and, often, utilities mandate external protective devices. Consequently, current activity to develop such standards under IEEE auspices is important in eliminating the cost of extra protection equipment. Key fuel cell lessons learned from IFC's experience base along with the status of development for future vehicle and stationary power plants at IFC are discussed. These lessons have been applied to the 200 kW stationary fuel cell power plant as the information has become available. They are now being applied to a 50-kW, ambient pressure, polymer electrolyte membrane (PEM) fuel cell power plant that uses gasoline as the fuel. This power plant is intended for experimental bench testing demonstrations associated with vehicle power plant applications. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Fuel cell; Power plant; IFC

1. Experience and demonstrations

International Fuel Cells (IFC), LLC, ONSI and predecessor organizations at United Technologies have delivered power plants for spacecraft, stationary power, vehicle, underwater and portable applications.

The experience-base for fuel cell power plants encompasses ratings from 150 W to 11,000 kW. Fuels range from hydrogen to petroleum distillates. Power plants have been fabricated and tested using high temperature alkaline, low temperature alkaline, phosphoric acid and polymer electrolyte membrane (PEM) fuel cells. The first operation of a fuel cell in space was in 1964; a natural gas fuelled power plant in a home in 1968 was the first application to buildings. Experience in large fleet applications of fuel cell power plants, summarized in Table 1, demonstrates reproducibility of the power plant characteristics and the ability to apply a specific design in a range of application environments.

Fuel cell power plants are distinguished from other power generating technologies by a combination of attractive characteristics including high efficiency, clean and quiet operation, rapid transient response and minimal requirements for maintenance. Demonstrations of these characteristics and their importance in applications and achieving sustainable development are discussed below.

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Table 1
Fleet application of fuel cell power plants

Application	Rating (kW)	Number delivered	Operating time (h)	Comment
Space				
Apollo (1966–1978)	1.4	90	10,750	18 flights including space lab and Apollo-Soyuz
Space shuttle (1981–present)	12	25	70,500	95 flights to date
Stationary				
Field test (1971–1973)	12.5	65	205,000	Concept test, electricity only
Field test (1984–1986)	40	53	365,000	Cogeneration testing
Commercial (1991–present)	200	200 to date	Over 2,700,000 to date	Commercial

1.1. Efficiency

Fig. 1 illustrates the efficiency of a number of fuel cell power plants of different cell technologies as a function of operating point. Spacecraft applications require high efficiency over a broad operating range to accommodate multiple redundancy while minimizing reactant weight. The space shuttle efficiency meets this requirement. Vehicle power plants expend most of their energy at low power settings and the efficiency profile for a 50-kW PEM system with hydrogen fuel peaks at around 20% of rated power to provide optimum performance. Stationary fuel cell power plants must meet a broad range of load profiles with a standard power plant and take advantage of cogeneration to increase energy efficiency. This is the case with the curve for a 200-kW, natural gas fuelled power plant illustrated in Fig. 1. The relationship of these curves also illustrates the effect of fuels, oxidants, applications and fuel cell technology on efficiency level. Pure hydrogen and oxygen are the reactants of choice for space and permit use of high efficiency alkaline cells. Transportation applications require compact PEM cell stacks and could benefit from development of a hydrogen fuel infrastructure. Stationary applications require hydrocarbon fuels and benefit from heat recovery to reduce greenhouse gas production. Initial stationary applications have been with phosphoric acid fuel cells; future development of PEM stationary power plants will achieve similar efficiency levels and broaden application to lower ratings and buildings requiring cycling operation.

1.2. Environmental characteristics

Fuel cell power plants operate quietly, a feature which permits location of stationary power plants adjacent to occupied buildings. Quiet operation is also valuable for

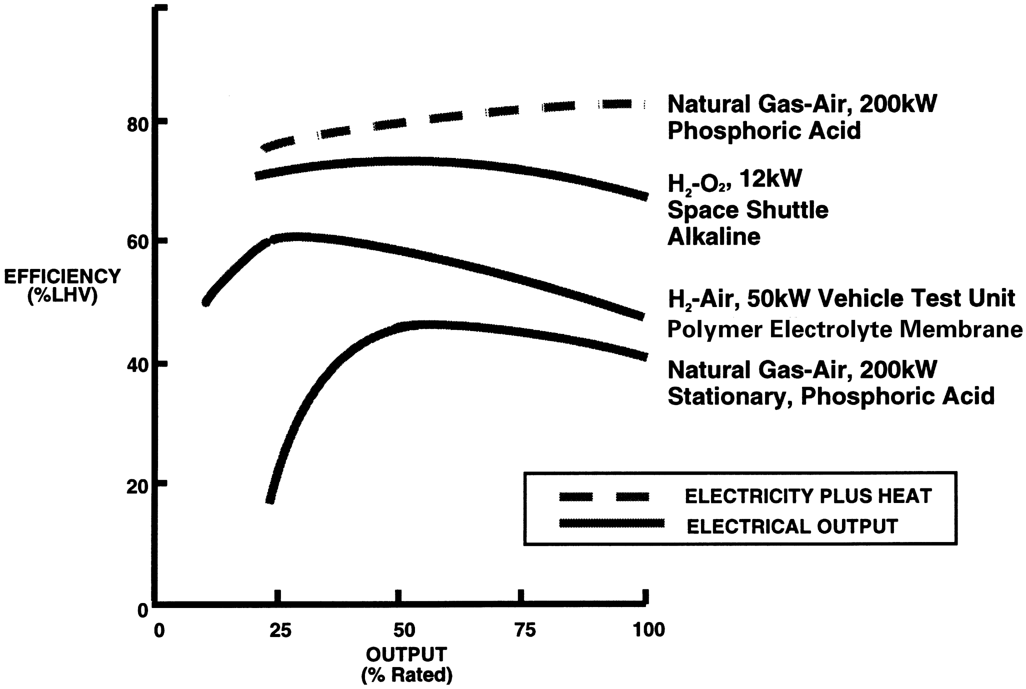

Fig. 1. Efficiency vs. percent rating.

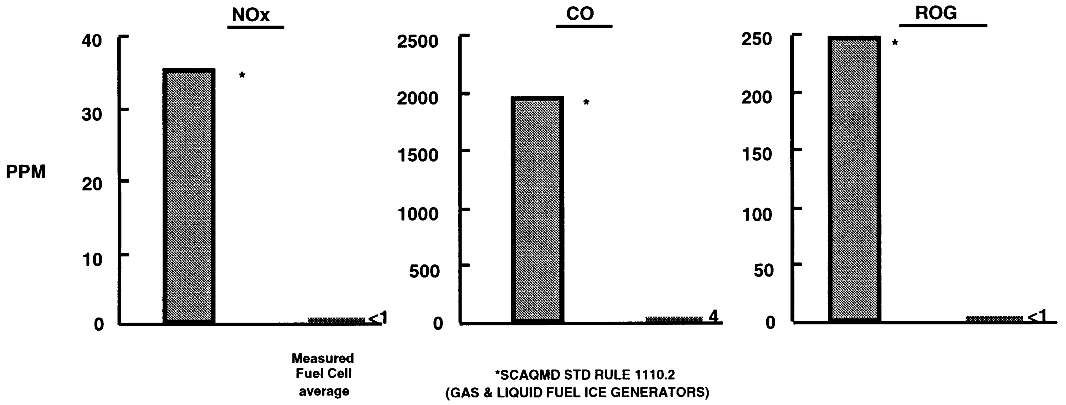

Fig. 2. Measured air emissions vs. requirements.

reducing noise in congested urban transport applications. Fig. 2 shows measured air emissions from the 200-kW power plant are orders of magnitude below the requirements of the South Coast Air Quality District; this characteristic resulted in an exemption from air emissions permitted in this District and in other air pollution control districts in the United States for the 200 kW power plant.

1.3. Transient response

Fuel cell reactions involve movement of ions, electrons and gas molecules. Power conditioners involve only the movement of electrons. Power plant subsystems operate at constant pressure and temperature; consequently, response is limited only by the inherent inventory of reactants within the cell stack and the time required to increase reactant flow. The result is that any properly designed fuel cell power plant will have excellent transient response. Fig. 3 shows the response characteristics of three power plants. Fig. 3A, for the 50 kW hydrogen-air power plant, shows the power delivery profile associated with the Federal Urban Driving Schedule. The power plant in Fig. 3A is an ambient pressure power plant using a PEM cell stack. Fig. 3B shows the response of a 100-kW methanol fuelled power plant in changing load between 20% and 100% of rated power. This power plant is designed for a load change rate of 20 kW per second meeting performance requirements for transit bus application. Faster response is possible, but passenger comfort dictates limitations on transit bus acceleration rate. The power plant in Fig. 3B is an ambient pressure power plant with catalytic steam reforming of methanol and a phosphoric acid cell stack.

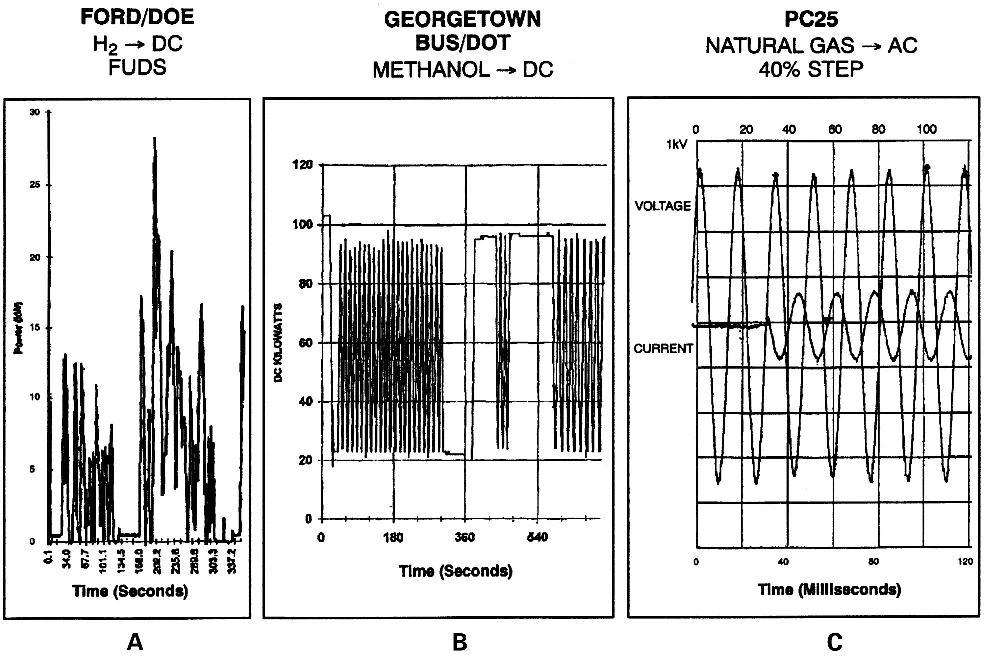

Fig. 3. Transient response.

Table 2
Stationary power plant maintenance requirements and performance

Maintenance parameter	Required for units > 100 kW	Required for remote application and smaller units	200 kW fleet experience	Comments
Scheduled maintenance interval (h)	2200 (3 months)	8760 (1 year)	3000 (4 months)	Maintenance performed while unit is running except once per year
Overhaul period (h)	40,000 (5 years)	40,000 (5 years)	Several units have achieved 40,000 h	80,000 preferred
Mean time between forced outages (h)	2000	8760 (1 year)	1500	Several runs greater than a year

Fig. 3C shows the voltage stability of the 200-kW inverter in a load change of 40% of rated load. This excellent voltage stability is important when considering application to loads requiring tight voltage control such as data centers or critical industrial processes. The power plant in Fig. 3C is a natural gas fuelled power plant using a catalytic steam reformer, a phosphoric acid cell stack and an inverter based on Insulated Gate Bipolar Transistors (IGBTs).

In transport applications, which are represented in Fig. 3A and B, the load increases gradually in response to a change in the position of the accelerator pedal. The pedal position change provides advance indication of the load increase which results as the vehicle accelerates. In grid-independent stationary applications, there is no advance warning of a load change and the power plant must respond instantaneously to the load change where the definition of instantaneous is that the output voltage of the inverter remains nearly constant. Fig. 3C is for a stationary power plant and it shows this requirement is met — a very slight drop in voltage occurs and only for two or three cycles (50 ms).

1.4. Minimum maintenance

Long scheduled maintenance intervals and high reliability are required for economic application to distributed generation applications particularly for applications in developing rural areas and for installations with low power demand. Table 2 shows the fuel cell is well on its way to meeting these requirements. The experience with the first commercial fuel cell power plant fleet already exceeds maintenance interval experience with mature reciprocating engine technology. Unscheduled maintenance outages are still too frequent, but a large number of long continuous runs provides confidence that improvement to the levels required for all distributed generation applications can be realized with further development of ancillary components and preventative maintenance actions.

Experience with spacecraft application of fuel cell power plants is another illustration of the reliability of basic fuel cell components. There has been only one failure over 80,000 h of fuel cell operation in space. That failure occurred on the second space shuttle flight and there have been no failures in 70,000 h of operation since that design was corrected. The failure was caused by foreign particle contamination that blocked an aspirator nozzle in the hydrogen pump/water separator thereby restricting the removal of fuel cell water. The pump assembly was subsequently redesigned with filters and alternative aspiration features.

Both the stationary fleet experience and the spacecraft experience have involved continuous duty operation of the power plants. Vehicle application, particularly for light duty applications, requires frequent cycling of the power plant and reliability demonstration in cycling applications will be required prior to commercial deployment.

2. Lessons learned — power plant

2.1. Importance of ancillary components

Much attention has been focused on the fuel cell stack. However, fuel cell power plants also include fuel processing components, a power conditioner if AC power is required and ancillary components and subsystems associated with air supply, thermal management, water recovery

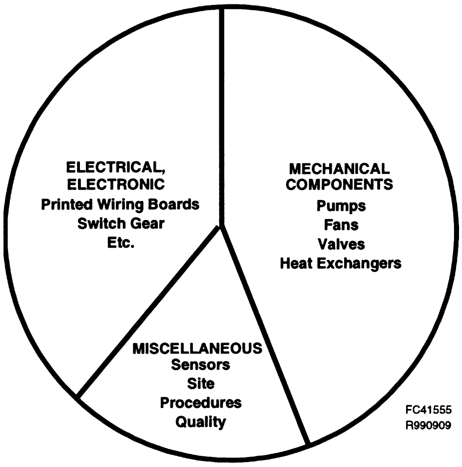

Fig. 4. Distribution of forced outage causes in 200 kW fuel cell fleet (recent experience).

and treatment, cabinet ventilation and system control and diagnostics. Ancillary components typically account for 40% of power plant weight for hydrocarbon-fuelled fuel cell power plants.

Fig. 4 shows the recent data on the distribution of fleet outages for the 200-kW power plant fleet. The cell stack and fuel processing components are extremely reliable. Electrical and mechanical ancillary components account for most of the failures. Further system simplification, a higher degree of component integration, development of more reliable components and development of preventive maintenance approaches will be required to improve power plant reliability.

2.2. Power plant design

Power plant design requires consideration of the interaction among all components to achieve required characteristics. Experience with design of a large number of power plants for many different applications shows that achieving high efficiency in fuel processing, power conditioning and ancillary components is required to provide high power plant efficiency while maintaining high power density operation of the cell stack. While higher cell stack efficiency can compensate for lower efficiencies in the rest of the system components, this can be achieved only by reducing current density to achieve higher cell voltage. Selection of fuel processor approaches that provide the highest possible efficiency for the required fuel and minimizing power consumption associated with air and fuel supply are important to achieving high efficiency and compact power plant designs. A high degree of thermal integration is also helpful in meeting efficiency goals; choosing operating conditions that balance design requirements among the power plant components is essential.

2.3. Durability

The fuel cell stack and fuel processor are the major determinants of power plant durability because they are subjected to the most intense electrochemical, oxidizing and thermal environments and because they are subject to degradation associated with small quantities of impurities such as sulfur, conducting ionic species, etc. The durability issues involve details of component design and operating conditions imposed on these components; care is required to ensure that all aspects of the power plant operating requirements have been considered. Durability testing at the complete component and system level is required to verify that these issues have been considered properly.

Some durability issues are introduced within the power plant. For example, water is recovered from the fuel cell exhaust to avoid dependence on local water supplies. Water recovered from the fuel cell exhaust will contain dissolved carbon dioxide and other impurities which could affect the durability of the cell stack or fuel processor; a water treatment system is required to eliminate these effects.

3. Lessons learned-installation

Stationary power plants have been applied worldwide and have experienced a wide range of compositions of natural gas, waste water gas and propane fuels. Generally, a common power plant design can accommodate most of the fuels encountered. The 200-kW power plant design accommodates the range of natural gas odorants encountered in different countries, while the control system accommodates a broad range of heating values. Waste water gas requires additional fuel clean-up prior to the power plant because sulfur levels exceed those in natural gas. Propane derived from natural gas liquids is generally an acceptable fuel; however, propane produced in refineries may require changes to the fuel processor if it contains high levels of unsaturated hydrocarbon compounds. A comparison of expected fuel compositions to the fuel specification is required for each power plant installation.

3.1. Grid connection

Protection of the fuel cell power plant and the electric utility grid from disturbing one another is a key consideration for power plants taking advantage of connection to the electric grid to improve application economics. Both the fuel cell power plant designer and the electric utility have legitimate concerns with a proper interface. Fortunately, proper control of the inverter already requires all the sensors associated with these requirements and protection of the inverter from grid disturbances requires sub-cycle response which is much faster than requirements for protecting the grid. Fuel cell power plants have now been connected to utility grids in over 100 cities throughout the world and the internal protection functions have performed flawlessly. In most cases, the internal protection has been accepted by the local electric utility. Where the protection has not been accepted, the primary reason is lack of a design or test standard for electrical protection embedded within the inverter control. A standard to deal with this issue is being pursued under IEEE Committee SCC 21.

3.2. Installation

Installation design and permitting costs must be minimized for any distributed generation device to succeed since installation costs for the 200-kW power plant have ranged from US$50,000 to over US$200,000. It is important to incorporate all possible ancillary equipment within the power plant to minimize site construction activity. Fig. 5 shows the simplicity of the installation of a 200-kW power plant. The power plant connections are minimal and quiet operation permits location in close proximity to an

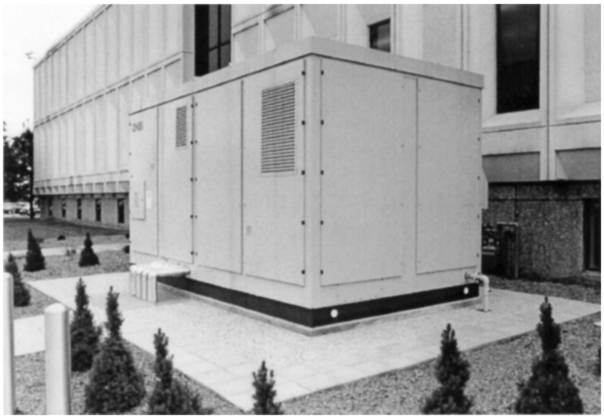

Fig. 5. Typical installation of 200 kW fuel cell power plant.

office building which minimizes the length of plumbing and electrical connections.

Cost containment requires equipment certification to speed the permitting process; a standard for equipment design, manufacture and test is available (ANSI Z21.83/CGA 12.10). Installation design effort and installation cost can be contained by availability of standard design drawings and installation standards such as that being developed under National Fire Protection Association Standard 853. Performance standards are important for objective comparisons of power plant performance; one is being prepared under American Society of Mechanical Engineers Standard PTC 50.

Broadening these North American stationary power plant standards to vehicle applications and to international regulations and requirements has begun. The Society of Automotive Engineers is beginning a consideration of standards for vehicle fuel cell power plants. The International Electrical Commission (IEC) is beginning a study of a fuel cell standard in Technical Committee 105. The International Standards Association (ISO) is also considering standards applicable to fuel cells under ISO/TC22/SC21.

4. Future directions

It has been shown that fuel cell power plants have demonstrated superior environmental and operating performance including reliability and durability while operating on practical fuels in worldwide operating environments. Encouraging progress has been made in improving weight and cost. However, the impact of fuel cells on world energy issues is still severely limited by cost, and by weight, volume and operational limitations which preclude application to vehicles and to the broad stationary market. Considerable additional progress in simplification of the product design, improvement of component performance and development of manufacturing processes is required to achieve fuel cell power plant characteristics required for broad impact on the objective of sustainable development. The business, engineering and operating experience associated with the fuel cell developments described above provide a substantial basis for the efforts of IFC to develop these improvements.

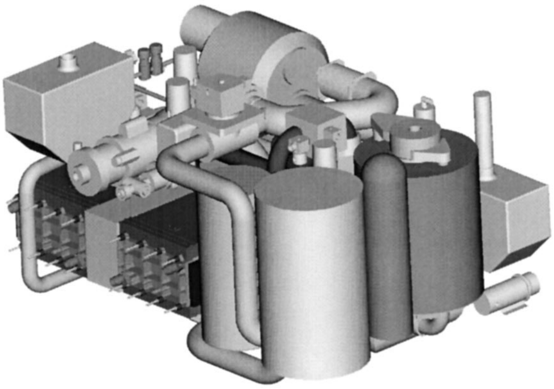

Fig. 6. Conceptual design of 50 kW gasoline power plant.

IFC is applying the lessons learned from this base to advance the characteristics of fuel cell power plants for both stationary and vehicle applications. The first experimental unit in this effort is a 50-kW gasoline fuelled, PEM power plant designed around vehicle applications. It incorporates a fuel processor which utilizes a proprietary sulfur removal approach, an autothermal reformer, a shift converter and a two-stage selective oxidizer to generate a hydrogen-rich, low carbon monoxide fuel stream for use in an ambient pressure, PEM fuel cell stack. The autothermal reformer was selected because it is the most efficient fuel processor available for use with liquid fuels. The power plant operates at ambient pressure to avoid the considerable power loss and efficiency penalties of air compression. The cell stack incorporates passive water management to achieve robust, durable operation. A conceptual drawing of the power plant is shown in Fig. 6. Full scale fuel processor and cell stack components are being tested; the 50-kW cell stack assembly is shown in Fig. 7. This power plant will be followed by subsequent units with reduced size and weight and improved operating features. As the technology requirements for heavy and light duty vehicles, stationary power plants and other applications are demonstrated, specific product development activities will be launched.

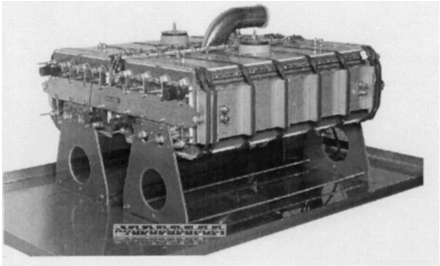

Fig. 7. Cell stack for 50 kW gasoline power plant.

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