1.1 Fuel Cell and Batteries Description

Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. The basic physical structure or building block of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side. A schematic representation of a fuel cell with the reactant/product gases and the ion conduction flow directions through the cell is shown in Figure 1-1.

![Figure 1-1 Schematic of an Individual Fuel Cell](image)

In a typical fuel cell, gaseous fuels are fed continuously to the anode (negative electrode) compartment and an oxidant (i.e., oxygen from air) is fed continuously to the cathode (positive electrode) compartment; the electrochemical reactions take place at the electrodes to produce an electric current. A fuel cell, although having components and characteristics similar to those of a typical battery, differs in several respects. The battery is an energy storage device. The maximum energy available is determined by the amount of chemical reactant stored within the battery itself. The battery will cease to produce electrical energy when the chemical reactants are consumed (i.e., discharged). In a secondary battery, the reactants are regenerated by recharging, which involves putting energy into the battery from an external source. The fuel cell, on the other hand, is an energy conversion device that theoretically has the capability of producing electrical energy for as long as the fuel and oxidant are supplied to the electrodes. Figure 1-2 is a simplified diagram that demonstrates how the fuel cell works. In reality, degradation, primarily corrosion, or malfunction of components limits the practical operating life of fuel cells.

Note that the ion specie and its transport direction can differ, influencing the site of water production and removal, a system impact. The ion can be either a positive or a negative ion,
meaning that the ion carries either a positive or negative charge (surplus or deficit of electrons). The fuel or oxidant gases flow past the surface of the anode or cathode opposite the electrolyte and generate electrical energy by the electrochemical oxidation of fuel, usually hydrogen, and the electrochemical reduction of the oxidant, usually oxygen. Appleby and Foulkes (1) have noted that in theory, any substance capable of chemical oxidation that can be supplied continuously (as a fluid) can be burned galvanically as the fuel at the anode of a fuel cell. Similarly, the oxidant can be any fluid that can be reduced at a sufficient rate. Gaseous hydrogen has become the fuel of choice for most applications, because of its high reactivity when suitable catalysts are used, its ability to be produced from hydrocarbons for terrestrial applications, and its high energy density when stored cryogenically for closed environment applications, such as in space. Similarly, the most common oxidant is gaseous oxygen, which is readily and economically available from air for terrestrial applications, and again easily stored in a closed environment. A three-phase interface is established among the reactants, electrolyte, and catalyst in the region of the porous electrode. The nature of this interface plays a critical role in the electrochemical performance of a fuel cell, particularly in those fuel cells with liquid electrolytes. In such fuel cells, the reactant gases diffuse through a thin electrolyte film that wets portions of the porous electrode and react electrochemically on their respective electrode surface. If the porous electrode contains an excessive amount of electrolyte, the electrode may "flood" and restrict the transport of gaseous species in the electrolyte phase to the reaction sites. The consequence is a reduction in the electrochemical performance of the porous electrode. Thus, a delicate balance must be maintained among the electrode, electrolyte, and gaseous phases in the porous electrode structure. Much of the recent effort in the development of fuel cell technology has been devoted to reducing the thickness of cell components while refining and improving the electrode structure and the electrolyte phase, with the aim of obtaining a higher and more stable electrochemical performance while lowering cost.

The electrolyte not only transports dissolved reactants to the electrode, but also conducts ionic charge between the electrodes and thereby completes the cell electric circuit, as illustrated in

Figure 1-2 Simplified Fuel Cell Schematic
The functions of porous electrodes in fuel cells are: 1) to provide a surface site where gas/liquid ionization or de-ionization reactions can take place, 2) to conduct ions away from or into the three-phase interface once they are formed (so an electrode must be made of materials that have good electrical conductance), and 3) to provide a physical barrier that separates the bulk gas phase and the electrolyte. A corollary of Item 1 is that, in order to increase the rates of reactions, the electrode material should be catalytic as well as conductive, porous rather than solid. The catalytic function of electrodes is more important in lower temperature fuel cells and less so in high-temperature fuel cells because ionization reaction rates increase with temperature. It is also a corollary that the porous electrodes must be permeable to both electrolyte and gases, but not such that the media can be easily "flooded" by the electrolyte or "dried" by the gases in a one-sided manner (see latter part of next section).

A variety of fuel cells are in different stages of development. They can be classified by use of diverse categories, depending on the combination of type of fuel and oxidant, whether the fuel is processed outside (external reforming) or inside (internal reforming) the fuel cell, the type of electrolyte, the temperature of operation, whether the reactants are fed to the cell by internal or external manifolds, etc. The most common classification of fuel cells is by the type of electrolyte used in the cells and includes 1) polymer electrolyte fuel cell (PEFC), 2) alkaline fuel cell (AFC), 3) phosphoric acid fuel cell (PAFC), 4) molten carbonate fuel cell (MCFC), 5) intermediate temperature solid oxide fuel cell (ITSOFC), and 6) tubular solid oxide fuel cell (TSOFC). These fuel cells are listed in the order of approximate operating temperature, ranging from ~800°C for PEFC, ~1000°C for AFC, ~2000°C for PAFC, ~6500°C for MCFC, ~8000°C for ITSOFC, and 10000°C for TSOFC. The operating temperature and useful life of a fuel cell dictate the physicochemical and thermomechanical properties of materials used in the cell components (i.e., electrodes, electrolyte, interconnect, current collector, etc.). Aqueous electrolytes are limited to temperatures of about 200°C or lower because of their high water vapor pressure and/or rapid degradation at higher temperatures. The operating temperature also plays an important role in dictating the type of fuel that can be used in a fuel cell. The low-temperature fuel cells with aqueous electrolytes are, in most practical applications, restricted to hydrogen as a fuel. In high-temperature fuel cells, CO and even CH₄ can be used because of the inherently rapid electrode kinetics and the lesser need for high catalytic activity at high temperature. However, descriptions later in this section note that the higher temperature cells can favor the conversion of CO and CH₄ to hydrogen, then use the equivalent hydrogen as the actual fuel.

A brief description of various electrolyte cells of interest follows. A detailed description of these fuel cells may be found in References (1) and (2).

**Polymer Electrolyte Fuel Cell (PEFC):** The electrolyte in this fuel cell is an ion exchange membrane (fluorinated sulfonic acid polymer or other similar polymer) that is an excellent proton conductor. The only liquid in this fuel cell is water; thus, corrosion problems are minimal. Water management in the membrane is critical for efficient performance; the fuel cell must operate under conditions where the byproduct water does not evaporate faster than it is produced because the membrane must be hydrated. Because of the limitation on the operating...
temperature imposed by the polymer, usually less than 1200°C, and because of problems with water balance, a H₂-rich gas with minimal or no CO (a poison at low temperature) is used. Higher catalyst loading (Pt in most cases) than that used in PAFCs is required for both the anode and cathode.

**Alkaline Fuel Cell (AFC)**: The electrolyte in this fuel cell is concentrated (85 wt%) KOH in fuel cells operated at high temperature (~2500°C), or less concentrated (35-50 wt%) KOH for lower temperature (<1200°C) operation. The electrolyte is retained in a matrix (usually asbestos), and a wide range of electrocatalysts can be used (e.g., Ni, Ag, metal oxides, spinels, and noble metals). The fuel supply is limited to non-reactive constituents except for hydrogen. CO is a poison, and CO₂ will react with the KOH to form K₂CO₃, thus altering the electrolyte. Even the small amount of CO₂ in air must be considered with the alkaline cell.

**Phosphoric Acid Fuel Cell (PAFC)**: Phosphoric acid concentrated to 100% is used for the electrolyte in this fuel cell, which operates at 150 to 2200°C. At lower temperatures, phosphoric acid is a poor ionic conductor, and CO poisoning of the Pt electrocatalyst in the anode becomes severe. The relative stability of concentrated phosphoric acid is high compared to other common acids; consequently the PAFC is capable of operating at the high end of the acid temperature range (100 to 2200°C). In addition, the use of concentrated acid (100%) minimizes the water vapor pressure so water management in the cell is not difficult. The matrix universally used to retain the acid is silicon carbide (1), and the electrocatalyst in both the anode and cathode is Pt.

**Molten Carbonate Fuel Cell (MCFC)**: The electrolyte in this fuel cell is usually a combination of alkali carbonates, which is retained in a ceramic matrix of LiAlO₂. The fuel cell operates at 600 to 7000°C where the alkali carbonates form a highly conductive molten salt, with carbonate ions providing ionic conduction. At the high operating temperatures in MCFCs, Ni (anode) and nickel oxide (cathode) are adequate to promote reaction. Noble metals are not required.

**Intermediate Temperature Solid Oxide Fuel Cell (ITSOFC)**: The electrolyte and electrode materials in this fuel cell are basically the same as used in the TSOFC. The ITSOFC operates at a lower temperature, however, typically between 600 to 8000°C. For this reason, thin film technology is being developed to promote ionic conduction; alternative electrolyte materials are also being developed.

**Tubular Solid Oxide Fuel Cell (TOSOFC)**: The electrolyte in this fuel cell is a solid, nonporous metal oxide, usually Y₂O₃-stabilized ZrO₂. The cell operates at 10000°C where ionic conduction by oxygen ions takes place. Typically, the anode is Co-ZrO₂ or Ni-ZrO₂ cermet, and the cathode is Sr-doped LaMnO₃.

In low-temperature fuel cells (PEFC, AFC, PAFC), protons or hydroxyl ions are the major charge carriers in the electrolyte, whereas in the high-temperature fuel cells, MCFC, ITSOFC, and TSOFC, carbonate ions and oxygen ions are the charge carriers, respectively. A detailed discussion of these different types of fuel cells is presented in Sections 3 through 8. Major differences between the various cells are shown in Table 1-1.
Table 1-1 Summary of Major Differences of the Fuel Cell Types

<table>
<thead>
<tr>
<th></th>
<th>PEFC</th>
<th>AFC</th>
<th>PAFC</th>
<th>MCFC</th>
<th>ITSOFC</th>
<th>TSOFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyte</td>
<td>Ion Exchange Membranes</td>
<td>Mobilized or Immobilized Potassium Hydroxide</td>
<td>Immobilized Liquid Phosphoric Acid</td>
<td>Immobilized Liquid Molten Carbonate</td>
<td>Ceramic</td>
<td>Ceramic</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>80°C</td>
<td>65°C - 220°C</td>
<td>205°C</td>
<td>650°C</td>
<td>600-800°C</td>
<td>800-1000°C</td>
</tr>
<tr>
<td>Charge Carrier</td>
<td>H⁺</td>
<td>OH⁻</td>
<td>H⁺</td>
<td>CO₃⁻</td>
<td>O⁻</td>
<td>O⁻</td>
</tr>
<tr>
<td>External Reformer for CH₄ (below)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Prime Cell Components</td>
<td>Carbon-based</td>
<td>Carbon-based</td>
<td>Graphite-based</td>
<td>Stainless-based</td>
<td>Ceramic</td>
<td>Ceramic</td>
</tr>
<tr>
<td>Catalyst</td>
<td>Platinum</td>
<td>Platinum</td>
<td>Platinum</td>
<td>Nickel</td>
<td>Perovskites</td>
<td>Perovskites</td>
</tr>
<tr>
<td>Product Water Management</td>
<td>Evaporative</td>
<td>Evaporative</td>
<td>Evaporative</td>
<td>Gaseous Product</td>
<td>Gaseous Product</td>
<td>Gaseous Product</td>
</tr>
</tbody>
</table>

Even though the electrolyte has become the predominant means of characterizing a cell, another important distinction is the method used to produce hydrogen for the cell reaction. Hydrogen can be reformed from natural gas and steam in the presence of a catalyst starting at a temperature of ~760°C. The reaction is endothermic. MCFC, ITSOFC, and TSOFC operating temperatures are high enough that reforming reactions can occur within the cell, a process referred to as internal reforming. Figure 1-3 shows a comparison of internal reforming and external reforming MCFCs. The reforming reaction is driven by the decrease in hydrogen as the cell produces power. This internal reforming can be beneficial to system efficiency because there is an effective transfer of heat from the exothermic cell reaction to satisfy the endothermic reforming reaction. A reforming catalyst is needed adjacent to the anode gas chamber for the reaction to occur. The cost of an external reformer is eliminated and system efficiency is improved, but at the expense of a more complex cell configuration and increased maintenance issues. This provides developers of high-temperature cells a choice of an external reforming or internal reforming approach. Section 6 will show that the present internal reforming MCFC is limited to ambient pressure operation, whereas external reforming MCFC can operate at pressures up to 3 atmospheres. The slow rate of the reforming reaction makes internal reforming impractical in the lower temperature cells. Instead, a separate external reformer is used.
Figure 1-3  External Reforming and Internal Reforming MCFC System Comparison
Porous electrodes, mentioned several times above, are key to good electrode performance. The reason for this is that the current densities obtained from smooth electrodes are usually in the range of a single digit mA/cm² or less because of rate-limiting issues such as the available area of the reaction sites. Porous electrodes, used in fuel cells, achieve much higher current densities. These high current densities are possible because the electrode has a high surface area, relative to the geometric plate area that significantly increases the number of reaction sites, and the optimized electrode structure has favorable mass transport properties. In an idealized porous gas fuel cell electrode, high current densities at reasonable polarization are obtained when the liquid (electrolyte) layer on the electrode surface is sufficiently thin so that it does not significantly impede the transport of reactants to the electroactive sites, and a stable three-phase (gas/electrolyte/electrode surface) interface is established. When an excessive amount of electrolyte is present in the porous electrode structure, the electrode is considered to be "flooded" and the concentration polarization increases to a large value.
The porous electrodes used in low-temperature fuel cells consist of a composite structure that contains platinum (Pt) electrocatalyst on a high surface area carbon black and a PTFE (polytetrafluoroethylene) binder. Such electrodes for acid and alkaline fuel cells are described by Kordesch et al. (3). In these porous electrodes, PTFE is hydrophobic (acts as a wet proofing agent) and serves as the gas permeable phase, and carbon black is an electron conductor that provides a high surface area to support the electrocatalyst. Platinum serves as the electrocatalyst, which promotes the rate of electrochemical reactions (oxidation/reduction) for a given surface area. The carbon black is also somewhat hydrophobic, depending on the surface properties of the material. The composite structure of PTFE and carbon establishes an extensive three-phase interface in the porous electrode, which is the benchmark of PTFE bonded electrodes. Some interesting results have been reported by Japanese workers on higher performance gas diffusion electrodes for phosphoric acid fuel cells (see Section 5.1.2).

In MCFCs, which operate at relatively high temperature, no materials are known that wet-proof a porous structure against ingress by molten carbonates. Consequently, the technology used to obtain a stable three-phase interface in MCFC porous electrodes is different from that used in PAFCs. In the MCFC, the stable interface is achieved in the electrodes by carefully tailoring the pore structures of the electrodes and the electrolyte matrix (LiAlO2) so that the capillary forces establish a dynamic equilibrium in the different porous structures. Pigeaud et al. (4) provide a discussion of porous electrodes for MCFCs.

In a SOFC, there is no liquid electrolyte present that is susceptible to movement in the porous electrode structure, and electrode flooding is not a problem. Consequently, the three-phase interface that is necessary for efficient electrochemical reaction involves two solid phases (solid electrolyte/electrode) and a gas phase. A critical requirement of porous electrodes for SOFC is that they are sufficiently thin and porous to provide an extensive electrode/electrolyte interfacial region for electrochemical reaction.

1.2 Cell Stacking

Additional components of a cell are best described by using a typical cell schematic, Figure 1-4. This figure depicts a PAFC. As with batteries, individual fuel cells must be combined to produce appreciable voltage levels and so are joined by interconnects. Because of the configuration of a flat plate cell, Figure 1-4, the interconnect becomes a separator plate with two functions: 1) to provide an electrical series connection between adjacent cells, specifically for flat plate cells, and 2) to provide a gas barrier that separates the fuel and oxidant of adjacent cells. The interconnect of a tubular solid oxide fuel cell is a special case, and the reader is referred to Section 8 for its slightly altered function. All interconnects must be an electrical conductor and impermeable to gases. Other important parts of the cell are 1) the structure for distributing the reactant gases across the electrode surface and which serves as mechanical support, shown as ribs in Figure 1-4, 2) electrolyte reservoirs for liquid electrolyte cells to replenish electrolyte lost over life, and 3) current collectors (not shown) that provide a path for the current between the electrodes and the separator of flat plate cells. Other arrangements of gas flow and current flow are used in fuel cell stack designs, and are mentioned in Sections 3 through 8 for the various type cells.
1.3 Fuel Cell Plant Description

As shown in Figure 1-1, the fuel cell combines hydrogen produced from the fuel and oxygen from the air to produce dc power, water, and heat. In cases where CO and CH₄ are reacted in the cell to produce hydrogen, CO₂ is also a product. These reactions must be carried out at a suitable temperature and pressure for fuel cell operation. A system must be built around the fuel cells to supply air and clean fuel, convert the power to a more usable form such as grid quality ac power, and remove the depleted reactants and heat that are produced by the reactions in the cells.

Figure 1-5 shows a simple rendition of a fuel cell power plant. Beginning with fuel processing, a conventional fuel (natural gas, other gaseous hydrocarbons, methanol, naphtha, or coal) is cleaned, then converted into a gas containing hydrogen. Energy conversion occurs when dc electricity is generated by means of individual fuel cells combined in stacks or bundles. A varying number of cells or stacks can be matched to a particular power application. Finally, power conditioning converts the electric power from dc into regulated dc or ac for consumer use. Section 9.1 describes the processes of a fuel cell power plant system.
1.4 Characteristics

Fuel cells have many characteristics that make them favorable as energy conversion devices. Two that have been instrumental in driving the interest for terrestrial application of the technology are the combination of relatively high efficiency and very low environmental intrusion (virtually no acid gas or solid emissions). Efficiencies of present fuel cell plants are in the range of 40 to 55% based on the lower heating value (LHV) of the fuel. Hybrid fuel cell/reheat gas turbine cycles that offer efficiencies greater than 70% LHV, using demonstrated cell performance, have been proposed. Figure 1-6 illustrates demonstrated low emissions of installed PAFC units compared to the Los Angeles Basin (South Coast Air Quality Management District) requirements, the strictest requirements in the US. Measured emissions from the PAFC unit are <1 ppm of NOx, 4 ppm of CO, and <1 ppm of reactive organic gases (non-methane) (5). In addition, fuel cells operate at a constant temperature, and the heat from the electrochemical reaction is available for cogeneration applications. Because fuel cells operate at nearly constant efficiency, independent of size, small fuel cell plants operate nearly as efficiently as large ones.1 Thus, fuel cell power plants can be configured in a wide range of electrical output, ranging from watts to megawatts. Fuel cells are quiet and even though fuel flexible, they are sensitive to certain fuel contaminants that must be minimized in the fuel gas. Table 1-2 summarizes the impact of the major constituents within fuel gases on the various fuel cells. The reader is referred to Sections 3 through 8 for detail on trace contaminants. The two major

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1. The fuel processor efficiency is size dependent; therefore, small fuel cell power plants using externally reformed hydrocarbon fuels would have a lower overall system efficiency.
impediments to the widespread use of fuel cells are 1) high initial cost and 2) high-temperature cell endurance operation. These two aspects are the major focus of manufacturers’ technological efforts.

Other characteristics that fuel cells and fuel cell plants offer are

- Direct energy conversion (no combustion).
- No moving parts in the energy converter.
- Quiet.
- Demonstrated high availability of lower temperature units.
- Siteing ability.
- Fuel flexibility.
- Demonstrated endurance/reliability of lower temperature units.
- Good performance at off-design load operation.
- Modular installations to match load and increase reliability.
- Remote/unattended operation.
- Size flexibility.
- Rapid load following capability.

General negative features of fuel cells include

- Market entry cost high; Nth cost goals not demonstrated.
- Unfamiliar technology to the power industry.
- No infrastructure.
1.5 Advantages/Disadvantages

The fuel cell types addressed in this handbook have significantly different operating regimes. As a result, their materials of construction, fabrication techniques, and system requirements differ. These distinctions result in individual advantages and disadvantages that govern the potential of the various cells to be used for different applications.

**PEFC:** The PEFC, like the SOFC, has a solid electrolyte. As a result, this cell exhibits excellent resistance to gas crossover. In contrast to the SOFC, the cell operates at a low 800°C. This results in a capability to bring the cell to its operating temperature quickly, but the rejected heat cannot be used for cogeneration or additional power. Test results have shown that the cell can operate at very high current densities compared to the other cells. However, heat and water management issues may limit the operating power density of a practical system. The PEFC tolerance for CO is in the low ppm level.

**AFC:** The AFC was one of the first modern fuel cells to be developed, beginning in 1960. The application at that time was to provide on-board electric power for the Apollo space vehicle. Desirable attributes of the AFC include its excellent performance on hydrogen (H\textsubscript{2}) and oxygen (O\textsubscript{2}) compared to other candidate fuel cells due to its active O\textsubscript{2} electrode kinetics and its flexibility to use a wide range of electrocatalysts, an attribute that provides development flexibility. Once development was in progress for space application, terrestrial applications began to be investigated. Developers recognized that pure hydrogen would be required in the fuel stream, because CO\textsubscript{2} in any reformed fuel reacts with the KOH electrolyte to form a carbonate, reducing the electrolyte's ion mobility. Pure H\textsubscript{2} could be supplied to the anode by passing a reformed, H\textsubscript{2} rich fuel stream by a precious metal (palladium/silver) membrane. The H\textsubscript{2} molecule is able to pass through the membrane by absorption and mass transfer, and into the fuel cell anode. However, a significant pressure differential is required across the membrane and the membrane is prohibitive in cost. Even the small amount of CO\textsubscript{2} in ambient air, the source of O\textsubscript{2} for the
reaction, would have to be scrubbed. At the time, U.S. investigations determined that scrubbing of the small amount of CO₂ within the air, coupled with purification of the hydrogen, was not cost effective and that terrestrial application of the AFC could be limited to special applications, such as closed environments, at best. Major R&D on AFC is no longer done in the U.S. but recent development in Europe has created renewed interest in this fuel cell type.

**PAFC:** The CO₂ in the reformed fuel gas stream and the air does not react with the electrolyte in a phosphoric acid electrolyte cell, but is a diluent. This attribute and the relatively low temperature of the PAFC made it a prime, early candidate for terrestrial application. Although its cell performance is somewhat lower than the alkaline cell because of the cathode's slow oxygen reaction rate, and although the cell still requires hydrocarbon fuels to be reformed into an H₂-rich gas, the PAFC system efficiency improved because of its higher temperature environment and less complex fuel conversion (no membrane and attendant pressure drop). The need for scrubbing CO₂ from the process air is also eliminated. The rejected heat from the cell is high enough in temperature to heat water or air in a system operating at atmospheric pressure. Some steam is available in PAFCs, a key point in expanding cogeneration applications.

PAFC systems achieve about 37 to 42% electrical efficiency (based on the LHV of natural gas). This is at the low end of the efficiency goal for fuel cell power plants. PAFCs use high cost precious metal catalysts such as platinum. The fuel has to be reformed external to the cell, and CO has to be shifted by a water gas reaction to below 3 to 5 vol% at the inlet to the fuel cell anode or it will affect the catalyst. These limitations have prompted development of the alternate, higher temperature cells, MCFC, and SOFC.

**MCFC:** Many of the disadvantages of the lower temperature as well as higher temperature cells can be alleviated with the higher operating temperature MCFC (approximately 650°C). This temperature level results in several benefits: the cell can be made of commonly available sheet metals that can be stamped for less costly fabrication, the cell reactions occur with nickel catalysts rather than with expensive precious metal catalysts, reforming can take place within the cell provided a reforming catalyst is added (results in a large efficiency gain), CO is a directly usable fuel, and the rejected heat is of sufficiently high temperature to drive a gas turbine and/or produce a high pressure steam for use in a steam turbine or for cogeneration. Another advantage of the MCFC is that it operates efficiently with CO₂-containing fuels such as bio-fuel derived gases. This benefit is derived from the cathode performance enhancement resulting from CO₂ enrichment.

The MCFC has some disadvantages, however: the electrolyte is very corrosive and mobile, and a source of CO₂ is required at the cathode (usually recycled from anode exhaust) to form the carbonate ion. Sulfur tolerance is controlled by the reforming catalyst and is low, which is the same for the reforming catalyst in all cells. Operation requires use of stainless steel as the cell hardware material. The higher temperatures promote material problems, particularly mechanical stability that impacts life.

**ITSOFC:** The intermediate temperature solid oxide fuel cell combines the best available attributes of fuel cell technology development with intermediate temperature (600-800°C) operation. Ceramic components are used for electrodes and electrolytes: carbon does not
deposit on these ceramic materials; therefore, this fuel cell may accept hydrocarbons and carbon monoxide in the fuel. Internal reforming is practical at temperatures above 650°C. Moreover, use of solid state components avoids design issues, such as corrosion and handling, inherent in liquid electrolyte fuel cells. The reduced temperature from the TSOFC allows stainless steel construction, which represents reduced manufacturing costs over more exotic metals. The disadvantages of ITSOFCs are that electrolyte conductivity and electrode kinetics drop significantly with lowered temperature. Present technology development is addressing these issues through thin-film electrolyte development and also a search for alternate materials.

**TSOFC:** The TSOFC is the fuel cell with the longest continuous development period, starting in the late 1950s, several years before the AFC. The solid ceramic construction of the cell alleviates cell hardware corrosion problems characterized by the liquid electrolyte cells and has the advantage of being impervious to gas cross-over from one electrode to the other. The absence of liquid also eliminates the problem of electrolyte movement or flooding in the electrodes. The kinetics of the cell are fast, and CO is a directly useable fuel as it is in the MCFC and ITSOFC. There is no requirement for CO₂ at the cathode as with the MCFC. At the temperature of presently operating TSOFCs (≈1000°C), fuel can be reformed within the cell. The temperature of a TSOFC is significantly higher than that of the MCFC and ITSOFC. However, some of the rejected heat from a TSOFC is needed to preheat the incoming process air.

The high temperature of the TSOFC has its drawbacks. There are thermal expansion mismatches among materials, and sealing between cells is difficult in the flat plate configurations. The high operating temperature places severe constraints on materials selection and results in difficult fabrication processes. The TSOFC also exhibits a high electrical resistivity in the electrolyte, which results in a lower cell performance than the MCFC by approximately 100 mV.

Developers are assessing the advantages of each type of fuel cell to identify early applications and address research and development issues (see Sections 3 through 8).

### 1.6 Applications, Demonstrations, and Status

The characteristics, advantages, and disadvantages summarized in the previous section form the basis for selection of the candidate fuel cell types to respond to a variety of application needs. The major applications for fuel cells are as stationary electric power plants, including cogeneration units; as motive power for vehicles; and as on-board electric power for space vehicles or other closed environments. Derivative applications will be summarized.

#### 1.6.1 Stationary Electric Power

One of the characteristics of fuel cell systems is that their efficiency is nearly unaffected by size. This means that small, relatively high efficient power plants can be developed, thus avoiding the higher cost exposure associated with large plant development. As a result, initial stationary plant development has been focused on several hundred kW to low MW capacity plants. Smaller plants (several hundred kW to 1 to 2 MW) can be sited at the user’s facility and are suited for cogeneration operation, that is, the plants produce electricity and thermal energy. Larger, dispersed plants (1 to 10 MW) are likely to be used for distributed generation. The plants are fueled primarily with natural gas. Once these plants are commercialized and price improvements materialize, fuel cells will be considered for large base-load plants because of their high efficiency.
The base-load plants could be fueled by natural gas or coal. The fuel product from a coal gasifier, once cleaned, is compatible for use with fuel cells. Systems integration studies show that high temperature fuel cells closely match coal gasifier operation.

Operation of complete, self-contained, stationary plants has been demonstrated using PEFC, AFC, PAFC, MCFC, ITSOFC, and TSOFC technology. Demonstrations of these technologies that occurred before 1998 were addressed in previous editions of the Fuel Cell Handbook and in the literature of the period. Recent U.S. manufacturer experience with these various fuel cell technologies has produced timely information. A case in point is the 200 kW PAFC on-site plant, the PC-25, that is the first to enter the commercial market (see Figure 1-7). The plant was developed by International Fuel Cells Corporation (IFC), a division of United Technologies Corporation (UTC). The plants are built by IFC. The Toshiba Corporation of Japan and Ansaldo SpA of Italy are partners with UTC in IFC. The on-site plant is proving to be an economic and beneficial addition to the operating systems of commercial buildings and industrial facilities because it is superior to conventional technologies in reliability, efficiency, environmental impact, and ease of siting. Because the PC-25 is the first available commercial unit, it serves as a model for fuel cell application. Because of its attributes, the PC-25 is being installed in various applications, such as hospitals, hotels, large office buildings, manufacturing sites, wastewater treatment plants, and institutions, to meet the following requirements:

- On-site energy
- Continuous power – backup
- Uninterrupted power supply
- Premium power quality

Figure 1-7 PC-25 Fuel Cell

1-14
Independent power source

Characteristics of the plant are as follows:

- **Power Capacity**: 0 to 200 kW with natural gas fuel (-30 to 450°C, up to 1500 m)
- **Voltage and Phasing**: 480/277 volts at 60 Hz; 400/230 volts at 50 Hz
- **Thermal Energy** (Cogeneration): 740,000 kJ/hour at 60°C (700,000 Btu/hour heat at 1400°F); module provides 369,000 kJ/hour at 120°C (350,000 Btu/hour at 2500°F) and 369,000 kJ/hour at 60°C
- **Electric Connection**: Grid-connected for on-line service and grid-independent for on-site premium service
- **Power Factor**: Adjustable between 0.85 to 1.0
- **Transient Overload**: None
- **Grid Voltage Unbalance**: 1%
- **Grid Frequency Range**: +/-3%
- **Voltage Harmonic Limits**: <3%
- **Plant Dimensions**: 3 m (10 ft) wide by 3 m (10 ft) high by 5.5 m (18 ft) long, not including a small fan cooling module (5)
- **Plant Weight**: 17,230 kg (38,000 lb)

Results from the operating units as of August, 2000 are as follows: total fleet operation stands at more than 3.5 million hours. The plants achieve 40% LHV electric efficiency, and overall use of the fuel energy approaches 80% for cogeneration applications (8). Operations confirm that rejected heat from the initial PAFC plants can be used for heating water, space heating, and low pressure steam. One plant has completed over 50,000 hours of operation, and a number of plants have operated over 40,000 hours (6). Fourteen additional plants have operated over 35,000 hours. The longest continuous run stands at 9,500 hours for a unit purchased by Tokyo Gas for use in a Japanese office building (9). This plant ended its duration record because it had to be shut down because of mandated maintenance. It is estimated at this time that cell stacks can achieve a life of 5 to 7 years. The fleet has attained an average of over 95% availability. The latest model, the PC-25C, is expected to achieve over 96%. The plants have operated on natural gas, propane, butane, landfill gas (10,11), hydrogen (12), and gas from anaerobic digestors (13). Emissions are so low (see Figure 1-6) that the plant is exempt from air permitting in the South Coast and Bay Area (California) Air Quality Management Districts, which have the most stringent limits in the U.S. The sound pressure level is 62 dBA at 9 meters (30 feet) from the unit. The PC-25 has been subjected to ambient conditions varying from -320°C to +490°C and altitudes from sea level to 1600 meters (~1 mile). Impressive ramp rates result from the solid state electronics. The PC-25 can be ramped at 10 kW/sec up or down in the grid connected mode. The ramp rate for the grid independent mode is idle to full power in ~one cycle or essentially one-step instantaneous from idle to 200 kW. Following the initial ramp to full power, the unit can adjust at an 80 kW/sec ramp up or down in one cycle.

IFC recently (spring, 2000) delivered a 1 megawatt PAFC power plant to a utility in Anchorage, Alaska. The unit consists of 5-200 kilowatt PC-25 units integrated with a supervisory dispatching controller. The system was installed and is being operated by Chugach Electric. Operation began in June, 2000.
Recent customers have obtained a Federal Grant rebate of $1,000/kW as the result of the Climate Change Fuel Cell Program. The PC-25 program also has received the support of the U.S. military, which installed 30 units at government facilities.

The fuel cell stacks are made and assembled into units at an 80,000 ft² facility located in South Windsor, Connecticut, U.S. Low cost/high volume production depends on directly insertable sub-assemblies as complete units and highly automatic processes such as robotic component handling and assembly. The stack assembly is grouped in a modified spoke arrangement to allow for individual manufacturing requirements of each of the cell components while bringing them in a continuous flow to a central stacking elevator (14).

Ballard Generation Systems, a subsidiary of Ballard Power Systems, has produced a PEFC stationary on-site plant. It has these characteristics:

<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
<td>ξ Power Capacity</td>
<td>250 kW with natural gas fuel</td>
</tr>
<tr>
<td>ξ Electric Efficiency</td>
<td>40% LHV</td>
</tr>
<tr>
<td>ξ Thermal Energy</td>
<td>854,600 kJ/hour at 740°C (810,000 Btu/hour at 165°F)</td>
</tr>
<tr>
<td>ξ Plant Dimensions</td>
<td>2.4 m (8 ft) wide by 2.4 m (8 ft) high by 5.7 m (18.5 ft) long</td>
</tr>
<tr>
<td>ξ Plant Weight</td>
<td>12,100 kg (26,700 lb)</td>
</tr>
</tbody>
</table>

One plant demonstration, which began operation in August 1997, has been completed. The plant achieved an electric efficiency of 40% LHV. Ballard is in the process of securing plant orders to field test additional plants. Ballard expects field trials from 1998 to 2001 and commercial production of the plant with the characteristics listed above in 2002. Partners are GPU International, GEC Alsthom, and EBARA Corporation (15).

Fuel Cell Energy (FCE), formerly Energy Research Corporation (ERC) completed successful testing in June 2000 of a near-commercial molten carbonate fuel cell system at their corporate site in Danbury, Connecticut. The power plant was rated at 250 kilowatts and achieved a maximum of 263 kilowatts. Power was produced by a single stack having 340 cells. The fuel delivered to the stack was internally reformed. Over the 16 month run, the system operated for more than 11,800 hours, providing 1.8 million kilowatt-hours to FCE’s facility and the grid. Electric efficiency was 45% (LHV). For most of this time, it operated unattended. Acid gas emissions during the test were negligible. Post-operation analysis will be performed on the fuel cell module after disassembly.

FCE’s German partner, MTU Friedrichshafen, is operating a 250 kilowatt molten carbonate fuel cell system in Bielefeld, Germany. The power plant is located on the campus of the University of Bielefeld and provides electric power and byproduct heat. The fuel cells were manufactured by FCE. MTU developed a new power plant configuration for this unit termed a “Hot Module” that simplifies the balance of plant. The system began operation in November 1999 and logged over 4,200 hours by August, 2000. Electric efficiency is 45% (LHV).

The focus of the utility demonstrations and FCE’s fuel cell development program is the commercialization of 300 kilowatt, 1.5 megawatt, and 3 megawatt MCFC plants. Characteristics of the FCE 3 megawatt internal reforming commercial MCFC plant are as follows (17):
Field trials employing FCE’s commercial MCFC design are being planned at a number of sites. Some are discussed below.

FCE plans to demonstrate a molten carbonate fuel cell/turbine hybrid system in late 2000. The balance of plant equipment employed in the 250 kilowatt test at ERC’s facility will be modified to accommodate a fuel cell and a gas turbine. The turbine is to be powered by waste heat from the fuel cell. The goal of the test is to demonstrate that the hybrid system will realize high efficiencies. This activity is a part of the U.S. DOE Office of Fossil Energy Vision 21 Program.

A demonstration of a MCFC power plant at an automobile manufacturing plant site in Tuscaloosa, Alabama is planned for the first quarter of 2001. The 250 kilowatt system will feed the production facility power distribution grid. Four companies are teaming up to support the program: Southern Company, Alabama Municipal Electric Authority (AMEA), Fuel Cell Energy, and Mercedes Benz U.S. International, Inc. (MBUSI). The system will employ FCE stack and MTU’s power plant design, called the “Hot Module.”

FCE plans to build a 1 megawatt power plant for a King County site near Renton, Washington. The molten carbonate fuel cell system will be installed as part of a municipal waste water treatment system. The power plant will use fuel produced by a digester in the form of a methane rich gas. The fuel cell system will provide power to the water treatment facility and provide a means to control methane and carbon dioxide emissions. Delivery is expected in 2001. The U.S. Environmental Protection Agency and the King County Washington Department of Natural Resources are supporting this program.

FCE and the Los Angeles Department of Water and Power (LADWP) plan to install a MCFC power plant at their downtown Los Angeles headquarters building. The 250 kilowatt system is expected to be operational in 2001 (16, 17).

Siemens Westinghouse Power Corporation (SWPC) has three TSOFC systems employing tubular cell technology operating on user sites. All were produced in their Pittsburgh, Pennsylvania facility. The capacities of the systems are 220 kilowatts, 100 kilowatts, and 25 kilowatts.

The most recent system is a 220 kilowatt fuel cell/gas turbine power plant operating at the University of California’s National Fuel Cell Research Center located in Irvine, California. The first-of-a-kind hybrid power plant consists of a 200 kilowatt fuel cell generator pressurized at about 3.5 atmospheres in combination with a 20 kilowatt two-shaft gas turbine. The system was first run at the Pittsburgh facility and started operating at Irvine in June, 2000. Total run time until July, 2000 was 264 hours. Electric energy delivered was 42 megawatt-hours. Electric efficiency was 51% (LHV). An electric power feed-through mounted on the pressure vessel devel-

<table>
<thead>
<tr>
<th>Power Capacity</th>
<th>3.0 MW net AC</th>
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<tbody>
<tr>
<td>Electric efficiency</td>
<td>57% (LHV) on natural gas</td>
</tr>
<tr>
<td>Voltage and Phasing</td>
<td>Voltage is site dependent, 3 phase 60 Hz</td>
</tr>
<tr>
<td>Thermal energy</td>
<td>~4.2 million kJ/hour (~4 million Btu/hour)</td>
</tr>
<tr>
<td>Availability</td>
<td>95%</td>
</tr>
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oped a problem. Although the fuel cells were intact, it was necessary that the fuel cell generator be shipped back to Pittsburgh for repair. Operation is expected to resume by October, 2000.

The 25 kilowatt system is back on test at the National Fuel Cell Research Center. The unit typically operates at 21.7 kW DC and 173 amperes. The unit has operated at two facilities on various fuels for a combined time of more than 9,500 hours. Support for this test is provided by Wright Patterson Air Force Base.

The nominal 100 kW 50 Hz unit is presently operating at the NUON District Heating site in Westvoort, The Netherlands. The unit is sponsored by EDB/ELSAM, a consortium of Dutch and Danish Energy distribution companies. Site acceptance was completed by February 6, 1998. Since then, this system has operated unattended, delivering 105 kW ac to the grid for over 14,000 hours. The electric only efficiency is 45%, plus the plant supplies 85 kW of hot water at 110°C to the local district heating system. The plant, which consists of three major systems, measures 8.42 m long by 2.75 m wide by 3.58 m high. The unit is scheduled to operate until autumn 2000.

The Siemens Westinghouse TSOFC commercialization plan is focused on an initial offering of a hybrid fuel cell/gas turbine plant. The fuel cell module replaces the combustion chamber of the gas turbine engine. Figure 1-8 shows the benefit behind this combined plant approach. Additional details are provided in Section 8. As a result of the hybrid approach, the 1 MW early commercial unit is expected to attain ~60% efficiency LHV when operating on natural gas.

![Diagram of Hybrid System](image)

**Figure 1-8 Combining the TSOFC with a Gas Turbine Engine to Improve Efficiency**

Siemens Westinghouse is planning a number of tests on power plants that are prototypes of future products. All systems employ the tubular SOFC concept and most are combined with gas turbines in a hybrid configuration. Capacities of these systems are 250 kilowatts atmospheric, 300 kilowatt class hybrid, and 1 megawatt class hybrid. They are to operate at various sites in the U.S., Canada, and Europe. Some of them are discussed below.

1-18
A 250 kilowatt atmospheric system is planned for a Toronto, Ontario, Canada site. The system will be operated by Ontario Power Technologies (formerly Ontario Hydro). The unit will supply 145 kilowatts of heat to the site heating system. Electric efficiency is expected to be about 47% (LHV). Operation of the combined heat and power system is expected in late 2001.

Operation of a 300 kilowatt class hybrid system is planned for Essen, Germany. The utility RWE will operate the system. Efficiency of the system will be about 57% (LHV). Operation is expected in late 2001 to early 2002.

A 300 kilowatt class hybrid system is planned to operate near Milan, Italy. The power plant will be operated by Edison SpA. Efficiency will be about 57% (LHV). Operation is expected to begin in mid 2002.

Plans are underway for a field test of a megawatt class fuel cell/gas turbine hybrid system on an Environmental Protection Agency site at Ft. Mead, Maryland. This system is expected to exhibit an efficiency of about 60% (LHV) depending on the turbine and the inverter selected. Operation is expected in the second half of 2002.

A 250 kilowatt system is planned for a site in Norway. The system will be operated by Norsk Shell to demonstrate that CO2 can be economically recovered. The CO2 recovery technology is being developed by Shell Hydrogen. The CO2 could be sequestered in underground reservoirs or could be used for special applications such as fish farms or agricultural greenhouses. The test system will be sited at a fish hatchery. The system is expected to begin operation in early 2003.

A megawatt class hybrid system is planned for a site in Stuttgart, Germany. The system will be operated by ENBW. Efficiency of the system will be about 60%. Partial support for the operation will be provided by the European Union. Operation is expected in the second half of 2003.

The military finds certain characteristics of fuel cell power plants desirable for field duty. Foremost, a fuel cell unit is quiet so can be close to the front line. It has a low heat trace, and can be scaled to various sizes, from a few kW backpack to larger mobile power plant. The main drawback for the military is that the existing infrastructure is limited to logistic fuels. Logistic fuels (defined as easily transportable and stored, and compatible with military uses) are difficult to convert to hydrogen for fuel cell use. The burden of changing the fuel infrastructure to accommodate lighter fuels, normally used in fuel cells, is far greater than the benefits fuel cells offer the military. The Advanced Research Projects Agency of DOD funded several projects to investigate adapting logistics fuels to fuel cell use.

IFC conducted testing of a 100 kW mobile electric power plant (MEP) with the logistic fuels of JP-8 and DF-2. An auto-thermal reformer that achieved 98% conversion was used to convert the logistic fuel to a methane rich fuel.

FCE tested a lab-scale carbonate fuel cell stack on a model diesel-like fuel (Exxsol) using an adiabatic pre-reformer to convert the liquid fuel to methane in 1991 to 1993. In 1995 and 1996, FCE verified a 32 kW MCFC stack operation on jet fuel (JP-8) and diesel (DF-2) in system inte-
grated tests using the diesel-to-methane adiabatic pre-reformer approach. Test results showed that there was a 5% power derating compared to natural gas operation.

The 25 kW TSOFC power unit (see Siemens Westinghouse, above) was fitted with a pre-reformer similar to the FCE and operated with JP-8 (766 hours) and DF-2 (1555 hours) while the unit was installed at FCE’s Highgrove Station.

SOFCo, a limited partnership of Babcock and Wilcox (a McDermott International Company) and Ceramatec (an Elkem company), has tested a planar SOFC unit for the MEP program that will operate on logistic fuels. Honeywell tested their MEP unit on logistic fuel.

All demonstrations showed that fuel cell units can be operated with military logistic fuels (18). An eventual market for fuel cells is the large (100 to 300 MW), base-loaded, stationary plants operating on coal or natural gas. Another related, early opportunity may be in repowering older, existing plants with high-temperature fuel cells (19). MCFCs and SOFCs coupled with coal gasifiers have the best attributes to compete for the large, base load market. The rejected heat from the fuel cell system can be used to produce steam for the existing plant's turbines. Studies showing the potential of high-temperature fuel cells for plants of this size have been performed (see Section 9). These plants are expected to attain from 50 to 60% efficiency based on the HHV of the fuel. Coal gasifiers produce a fuel gas product requiring cleaning to the stringent requirements of the fuel cells’ electrochemical environment, a costly process. The trend of environmental regulations has also been towards more stringent cleanup. If this trend continues, coal-fired technologies will be subject to increased cleanup costs that may worsen process economics. This will improve the competitive position of plants based on the fuel cell approach. Fuel cell systems will emit less than target emissions limits. U.S. developers have begun investigating the viability of coal gas fuel to MCFCs and SOFCs (20,21,22). An FCE 20 kW MCFC stack was tested for a total of 4,000 hours, of which 3,900 hours was conducted at the Plaquemine, LA, site on coal gas as well as pipeline gas. The test included 1,500 hours of operation using 9,142 kJ/m³ syngas from a slip stream of a 2,180 tonne/day Destec entrained gasifier. The fuel processing system incorporated cold gas cleanup for bulk removal of H₂S and other contaminants, allowing the 21 kW MCFC stack to demonstrate that the FCE technology can operate on either natural gas or coal gas.