# Fuel Cells for Cogeneration

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## ABSTRACT

For years, fuel cell technology has been touted as the power technology of the future. Robust progress has been made in the past two years. Low emissions, high efficiencies, cogeneration, and reliability have been met in each type of fuel cell. However, in this article we will discuss three fuel cell types that have significant opportunities to provide true cogeneration capabilities. Cogeneration can be defined as the sequential production of thermal and electrical energy from one fuel source. This heat is used to produce the second form of energy, for cooling or heat such as hot water or steam. With cogeneration, heat would be recovered within the components, the stack, or from the hot exhaust. The three fuel cell types to be discussed include phosphoric acid, molten carbonate and solid oxide. We will discuss the basic operating principals of fuel cells and address some of the significant differences in the technologies.

## WHAT IS A FUEL CELL?

A fuel cell is a device that produces electricity through an electrochemical process within the fuel cell itself. This is very similar to the way a battery produces electricity. However, unlike a battery, a fuel cell only produces electricity while fuel is supplied to it. As a result, the fuel cell behaves much like an electrical generator driven by an internal combustion engine that uses conventional fossil fuel. You may have heard of the fuel cells that power the Space Shuttle electrical systems. A chemical reaction occurs at relatively low temperatures inside the fuel cell, and no combustion takes place. The primary fuel used in fuel cells is hydrogen. When hydrogen is supplied, the chemical reaction, between hydrogen and air, produces electricity, pure water and some heat. Again, similar to an engine-generator, the electrical power output is proportional to the rate of fuel flowing into the fuel cell, and is limited by the physical size of the fuel cell. There are five primary types of fuel cells, each distinguished by the type of the electrolyte that is used to carry electrical charge between the fuel and the oxygen in the air.

Because fuel cells produce power without combustion, they are considerably more efficient than their internal combustion engine counterparts. Gasoline engines in automobiles are approximately 13 to 25 percent efficient. A fuel cell attached to an electric motor can be in excess of 40 percent efficient, and fuel cells that can be used in automobiles and other vehicles are being produced with efficiencies of 45 to 58 percent. Fuel cells that can be used for co-generation can achieve efficiencies of 85 to 90 percent.

## What Fuel Cells Can Do

Fuel cells produce electricity directly from hydrogen fuel. They can be used with anything that requires power in the form of electricity, rotary power or heat. A very important trait exhibited by fuel cell technologies is that they can be made small enough to power a cellular phone or large enough to power a village or skyscraper without significantly changing the design. The markets for fuel cells are virtually unlimited. Examples of major applications include all ground or surface vehicles, such as cars, utility vehicles, trains and motorcycles. There are also applications in power production, such as commercial utility power, premium power, backup power, remote power and portable power production. In fact, by their nature, fuel cells permit us to move towards a more distributed method of electrical power generation, with less need for expensive power transmission infrastructure.

Invented in 1839, fuel cells have only recently gained attention by being employed to produce electricity and water in all our Gemini, Apollo and Space Shuttle missions. What once was exotic technology is becoming commonplace.

## Why Fuel Cells are Important

From 1990 to 2000, the interest in fuel cells has increased dramatically. Once almost unknown ten years ago, today every major automobile company in the United States, Europe and Asia has a serious fuel cell program. In January 2000, General Motors debuted its hydrogen, fuel-cell-powered concept car called the Precept. It is expected to have a hydrogen refueling range of 500 miles and accelerate 0 to 60 mph in about 9 seconds. Additionally, more than 200 fuel cells large enough to power small buildings or neighborhoods have been commercially produced and deployed throughout the world. It is reasonable to expect that fuel cell systems could replace most power-producing devices in the world over the next 40 to 80 years. Clearly, the market potential for such an endeavor is in the trillions of dollars. The fuel cell has recently been termed the "micro-chip of the energy industry," in relation to its economic potential. Two important advantages of fuel cells are that they do not produce polluting emissions or greenhouse gases, and do not require supplies of foreign oil.

We envision a world where the geopolitical distribution of the world's fossil energy sources no longer causes the economic instability that creates turmoil within and among nations on a regular basis. The commercialization of fuel cell power systems is beginning to bring about that eventuality.

Wide scale marketing and use of fuel cells enables the global-scale implementation of renewable energy technologies and hydrogen as a fuel. Early on, fuel cells can be fueled from hydrogen made from conventional sources like fossil fuels. Today, almost all our hydrogen is made from natural gas. The hydrogen used in the Space Shuttle for its main rocket engines and for its electrical power is made from natural gas in Mississippi.

## PHOSPHORIC ACID FUEL CELL

As the name implies, these fuel cells use liquid phosphoric acid as the electrolyte, positively charged hydrogen ions migrate through the electrolyte from the anode to the cathode. Electrons generated at the anode travel through and external circuit, providing electric power along the way, and return to the cathode. There the electrons, hydrogen ions and oxygen form water, which is expelled from the cell.

Operating at a temperature between 300 to 400°F, the expelled water, as well as the water to keep the cell at operating temperature, can be used for space and water heating. In this combined heat and power application, overall efficiencies can approach 80 percent. More than 200 of these “first generation” systems are working around the world in stationary applications with almost all using co-generation modes, heating or absorption cooling. The following charts provided by UTC Fuel Cells provide the performance data for thermal energy recovery.

### Experience

UTC Fuel Cells, a division of United Technologies Corporation, is a world leader in development and production of fuel cells. Their fuel cells can be found in space, commercial, and transportation applications. UTC Fuel Cells has been the sole supplier of fuel cells to the U.S. manned space missions, starting with the Apollo program and continues with today’s Space Shuttle program.

The PC25 model “A” fuel cell was introduced in 1991. Subsequent changes to model “B” and the latest model “C” have provided hundreds of systems and have been delivered to customers around the world.

### PC25 Power Plant

The PC25 power plant has a proven track record. This includes sensitive computer equipment being powered without interruption, near zero emissions, highly efficient, low noise profile, operates using city-pressure natural gas, and low-grade and high-grade heat recovery systems.

### Thermal Energy Recovery Performance Data

The PC25 typically produces more than 900,000 Btu/hr of useful heat at rated power conditions. The estimated availability of heat at rated load is primarily a function of customer’s water return temperature to the power plant as shown below. Useful heat at temperatures of up to 140°F is provided to a customer hot water system from an ancillary water or propylene glycol–water loop through a heat exchanger located in the power module. For domestic hot water applications, some local codes require special protection to prevent potential coolant contact with domestic water. In this event, a double–walled heat recovery heat exchanger can be provided as optional equipment. For a higher temperature system, a high–grade heat option is also available.

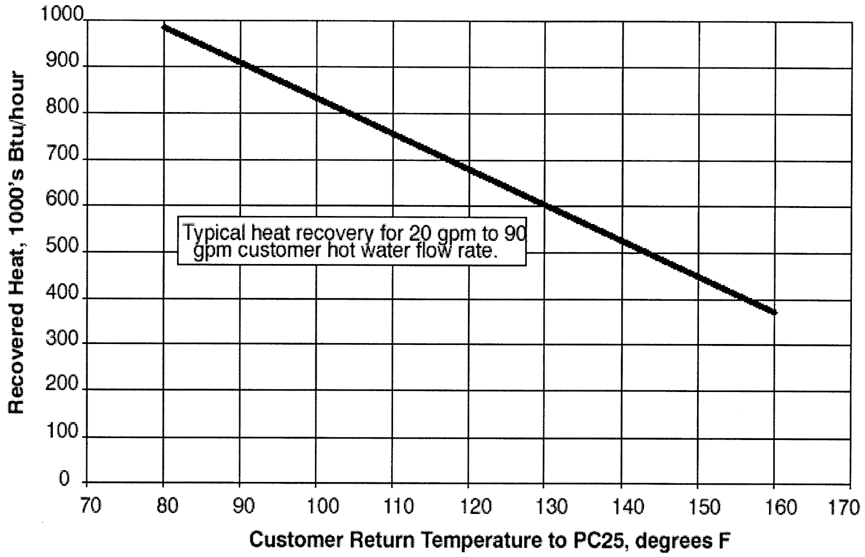

**Figure 1. Low Grade Only Heat Recovery—200 kW Rated Power**

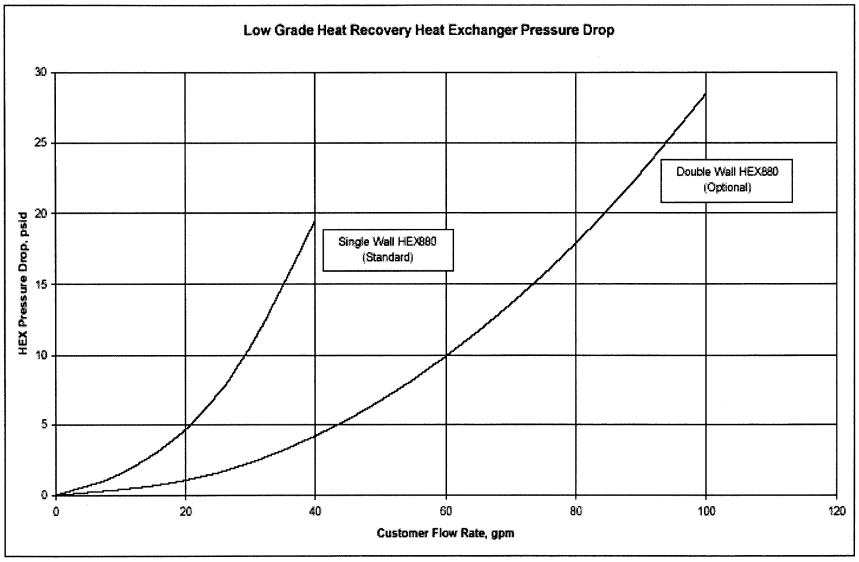

**Figure 2. Low Grade Heat Recovery Heat Exchanger Pressure Drop—200 kW Rated Power**

### High Grade Heat Recovery Option

A PC25 with the high-grade heat option comes with a second customer interface heat exchanger with heat recovery as pressurized hot water at higher temperatures (i.e., up to 250°F) than are possible with the standard heat exchanger. The high-grade heat exchanger is a single wall heat exchanger.

At rated power, approximately 450,000 Btu/hr are available from the high-grade heat exchanger. Recoverable heat not available to the high-grade interface (secondary heat) will still be available from the standard heat exchanger. The total amount of heat available remains 900,000 Btu/hr. The available high-grade heat decreases to zero at approximately half rated power.

The air-cooling module permits electrical operation independent of customer heat recovery. In any combination of heat recovery from the high and low grade heat exchangers, heat not utilized will be dissipated by the air-cooling module.

## SOLID OXIDE FUEL CELLS

The Siemens Westinghouse Power Corporation plans to market a combined heat and power (CHP) system that is based upon the

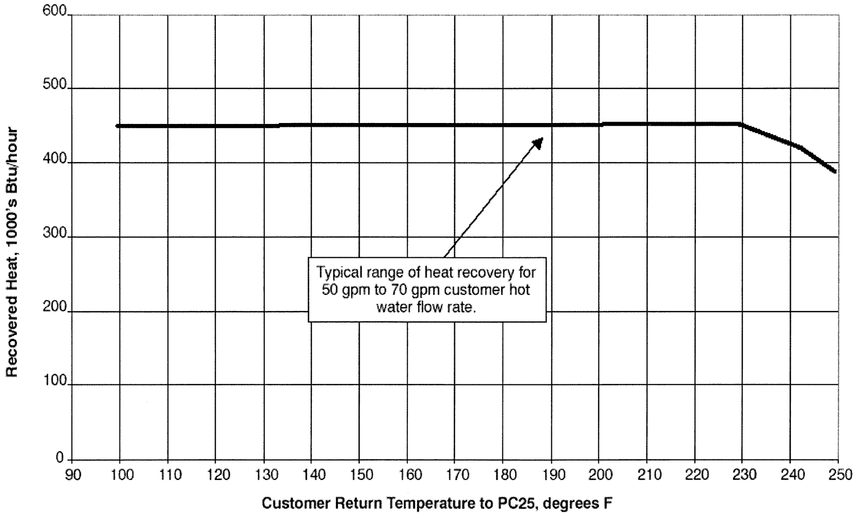

**Figure 3. High Grade Heat Recovery—200 kW Rated Power**

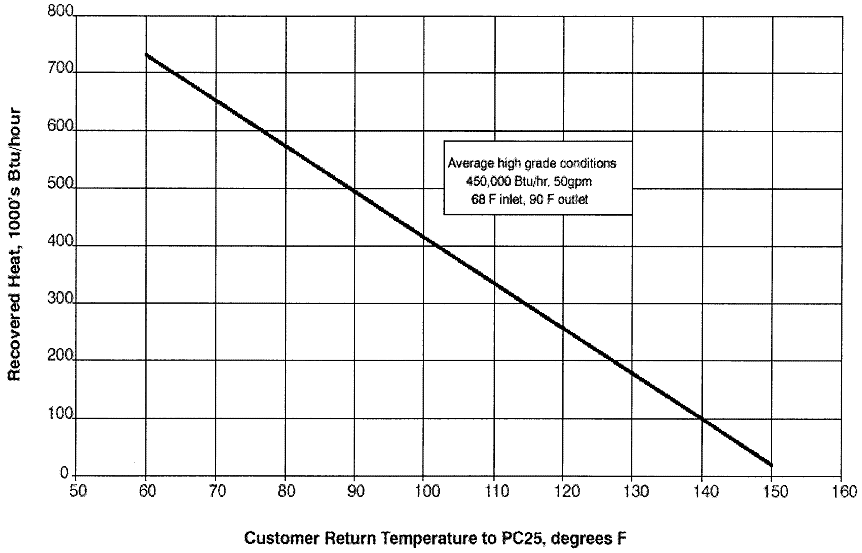

**Figure 4. Secondary Low Grade Heat Recovery—200 kW Rated Power**

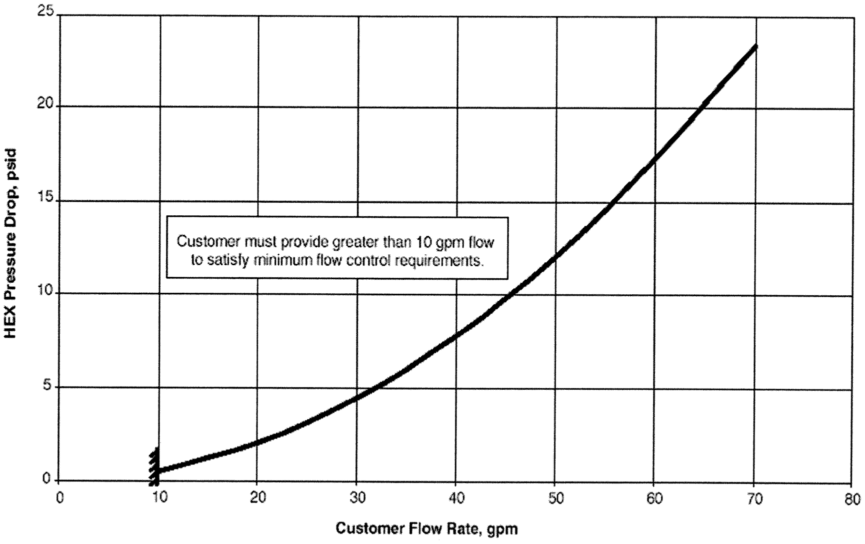

**Figure 5. High Grade Heat Recovery Heat Exchanger Pressure Drop—200 kW Rated Power**

Siemens Westinghouse atmospheric-pressure tubular solid-oxide fuel cell (SOFC) technology. The system, termed the CHP250, will be rated at 250 kWe electric power output (maximum net AC power), and the standard product will be equipped for the production of hot water using recovered SOFC exhaust heat.

A proof-of-concept demonstration of a Siemens Westinghouse SOFC CHP system rated at 100 kWe was recently completed in Europe. The system operated first in the Netherlands at a site provided by NUON, one of the Dutch utilities participating in the project. Operations at the Dutch test site were concluded successfully in November 2000, and the unit was then moved to an RWE Energie site in Essen, Germany, where additional operating hours were logged. A larger proof-of-concept SOFC CHP system, with 250 kWe capacity, is being installed at the Kinectrics, Inc. facility in Toronto, Ontario, and will begin operation in 2003. In the material that follows, and in addition to some tubular SOFC background information, the proof-of-concept and CHP250 systems are discussed. For the CHP250, the design being developed, the system and its cycle are described, and system performance estimates are provided.

### 100 kWe SOFC CHP Proof-of-Concept System

The cycle for the 100 kWe proof-of-concept system is shown in Figure 6. Basic components for any SOFC CHP system are the SOFC module, a fuel supply system, an air supply system, plus recuperator hardware, and a heat export system (HES). Auxiliary components and subsystems that are active only during system startup and shutdown operations are not shown in Figure 6.

The HES for the 100 kWe SOFC CHP system is a shell-and-tube heat exchanger that applies SOFC exhaust heat to heating water. For operation in the Netherlands, the HES was designed to produce hot water at 120°C (maximum). The HES gas inlet temperature is typically 300°C.

The design, construction, and operation of the 100 kWe SOFC CHP system was sponsored by EDB/ELSAM, a consortium of Dutch energy companies (EDB), the Danish electric production company (ELSAM), and Novem, a subsidizing agency of the Dutch government. Project financial support was also provided by the U.S. Department of Energy and Siemens Westinghouse. The system was installed initially in Westervoort, the Netherlands, near Arnhem, at a site provided by

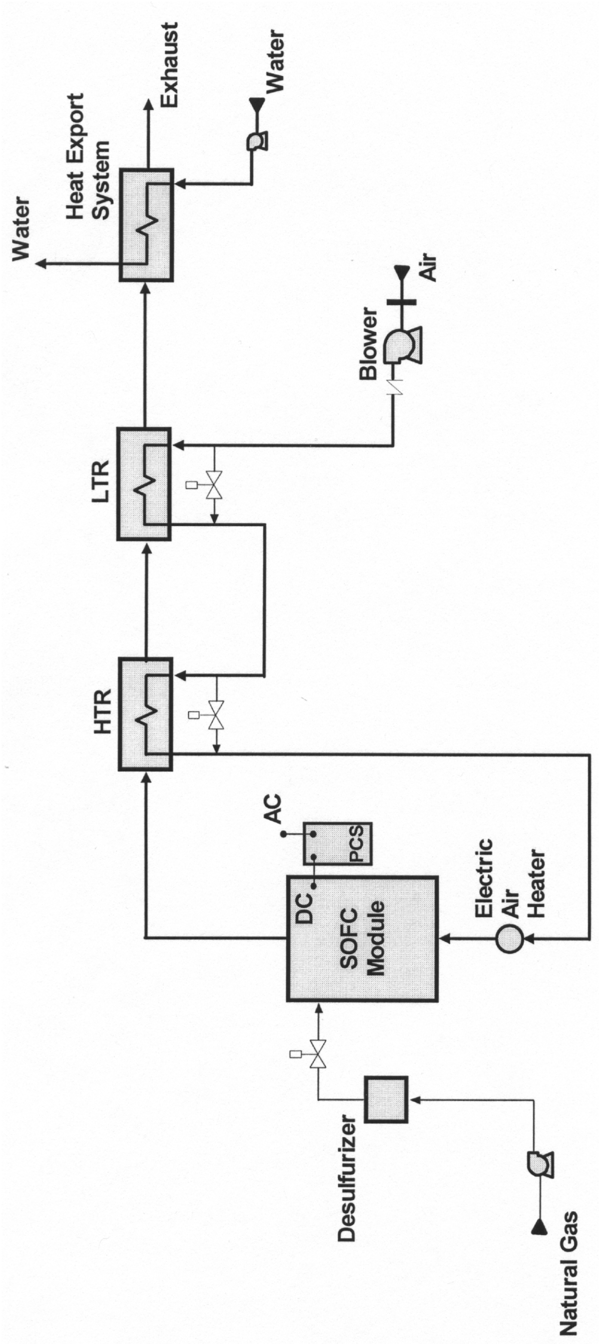

**Figure 6. 100 kWe SOFC CHP system cycle.**

NUON, one of the participating Dutch energy companies. System operations were begun in January 1998, and were completed successfully in November 2000. During that period, the system logged approximately 16,000 operating hours, making it the longest-running SOFC power system of >100 kWe capacity, and virtually no degradation in cell voltage performance was experienced. Further, the system was interfaced with both the NUON electric power grid and the local district heating system, the first SOFC CHP system to be so connected. Typically, approximately 110 kWe of net AC power were generated, at a net AC efficiency of 46%, the highest efficiency achieved by any natural-gas-fueled atmospheric-pressure fuel cell system, and the typical hot-water heat recovery rate was 65 kWt. Thus, the system heat recovery efficiency was 27%, and the system overall energy efficiency was 73%. Measured concentrations of $NO_x$ and $SO_x$ in the system exhaust were < 1 ppmv, and measured noise levels at 0.3 m from the operating equipment were < 67 dB(A).

Upon the completion of testing in the Netherlands, the 100 kWe system was moved to an RWE site in Essen, Germany, where operations were continued. The system logged an additional 4,000 operating hours, with performance similar to that experienced in the Netherlands, before testing was concluded in 2002. A picture of the system as installed at the RWE site is provided in Figure 7.

The cycle for the 250 kWe SOFC CHP proof-of-concept system is shown in Figure 8. The configuration is very similar to the 100 kWe cycle, Figure 6, with the exceptions that a single recuperator section is used and the air heater is gas fired.

The system is pictured in Figure 9, as installed at the Kinectrics facility in Toronto. As noted above, operation of this system began in 2003. It is expected that approximately 230 kWe of net AC power will be generated at the nominal operating point, and distributed to the grid at a target efficiency of approximately 47%. At that point, 140 kWt will be recovered from the SOFC exhaust for hot water production, and an overall system energy efficiency of approximately 75% is projected. The system capacity is estimated at approximately 250 kWe.

### CHP250 – The 250 kWe Standard-Product SOFC CHP System

The CHP250 is the system to be marketed. The standard-product system cycle is depicted in Figure 10, showing the components that function during normal steady-state operations.

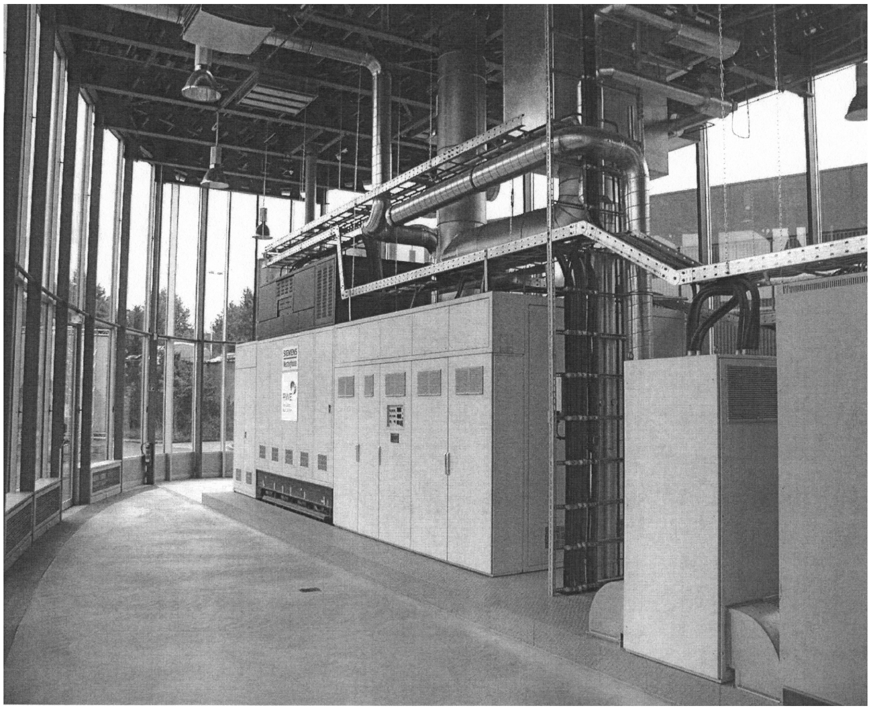

**Figure 7. 100 kWe SOFC CHP system installed at the RWE test site.**

For cost reduction reasons, the SOFC module is designed to house the recuperator as well as the cell stack. In other respects, the basic cycle is similar to the proof-of-concept cycle of Figure 8.

As indicated in Figure 10, the system will use recovered SOFC exhaust heat for the production of hot water. As the figure shows, the heat-delivery part of the system could be configured to serve more than one on-site thermal application. With appropriate valving, hot water could be directed in part (or in total) to the chiller, while the remainder could be sent to another hot-water user. The cooling tower is the sink for rejected chiller heat. The SOFC exhaust temperature at the module exit (~300°C) is sufficiently high for the production of useful hot water. For district heating applications, water temperatures in the 100°C to 120°C range are frequently required, while lower water temperatures could suffice for many process and domestic applications. For use by a single-effect, hot-water-fired chiller, the water temperature required at the chiller inlet will typically be 90°C.

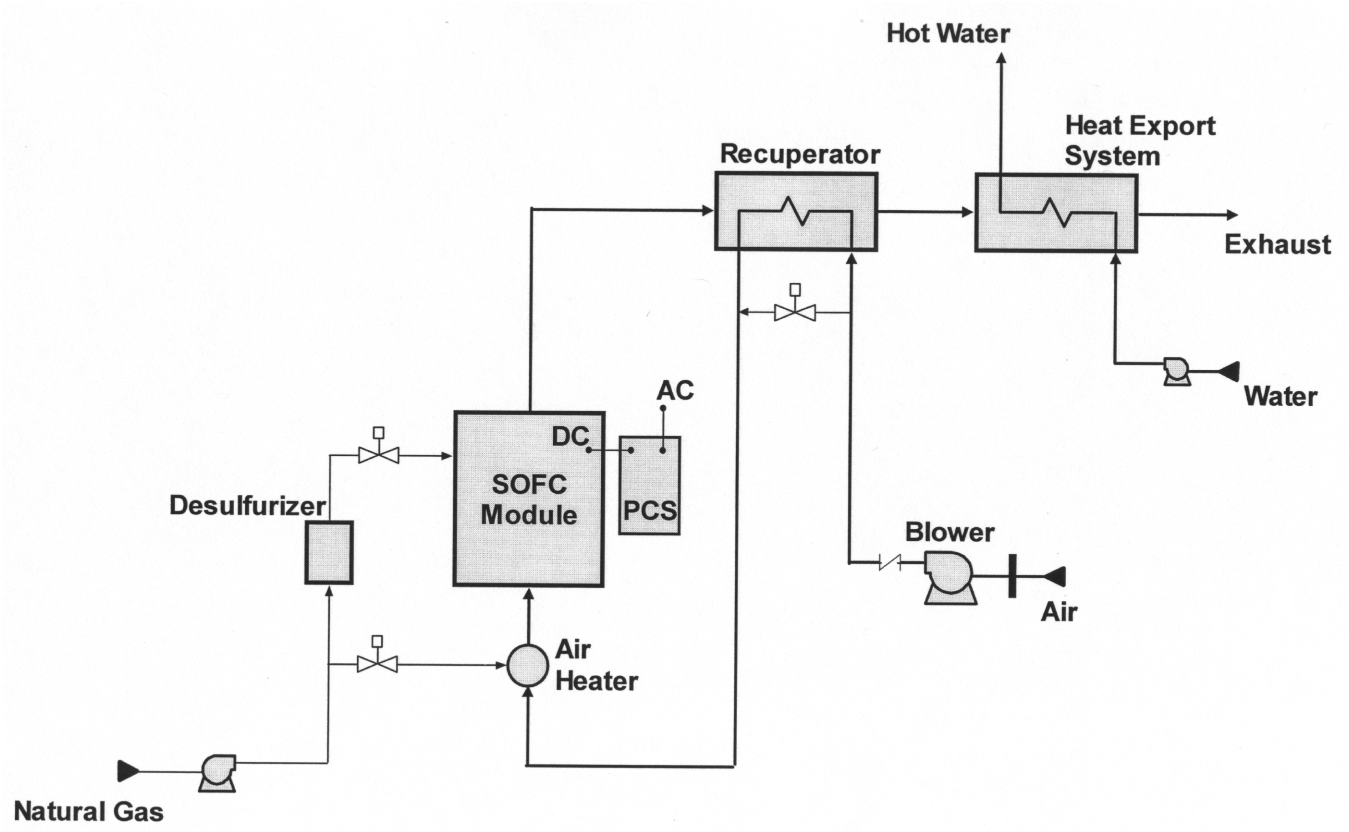

Figure 8. 250 kWe SOFC CHP proof-of-concept system cycle.

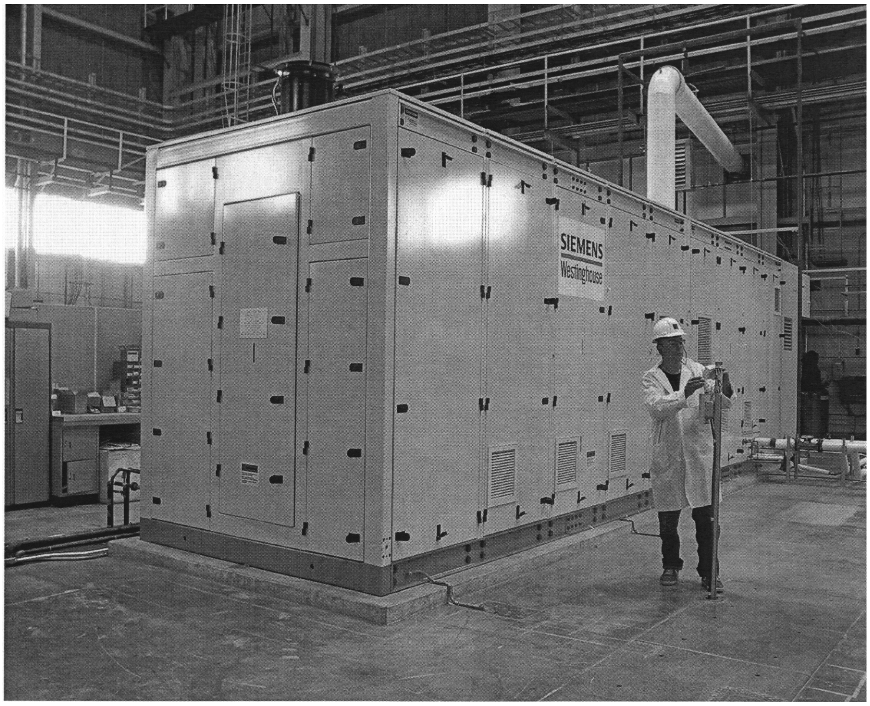

**Figure 9. 250 kWe SOFC CHP proof-of-concept system installed at the Kinectrics facility in Toronto.**

Figure 11 shows the physical arrangement of major CHP250 components. For improved capacity factor, cells are packaged in two vertical cylindrical canister modules. Other system components—air blowers, HES equipment, the PCS, instrumentation and controls (I&C), and the fuel supply system—are housed on the balance-of-plant skid that is positioned between the two SOFC modules. Figure 11 also shows a module cut-away view, identifying certain module interior components.

CHP250 performance estimates are provided in Table 1. The estimates are based upon current-status cell voltage and current characteristics, and are presented for the nominal-power and maximum-power operating points. At maximum power, by definition, the current at the SOFC module terminals is 600 amps. Note that the system net AC power in this analysis is defined as the gross AC power at the PCS output terminals, less a constant auxiliary power allowance for instrumentation, controls, computer, cabinet ventilation fan power, etc; less the power re-

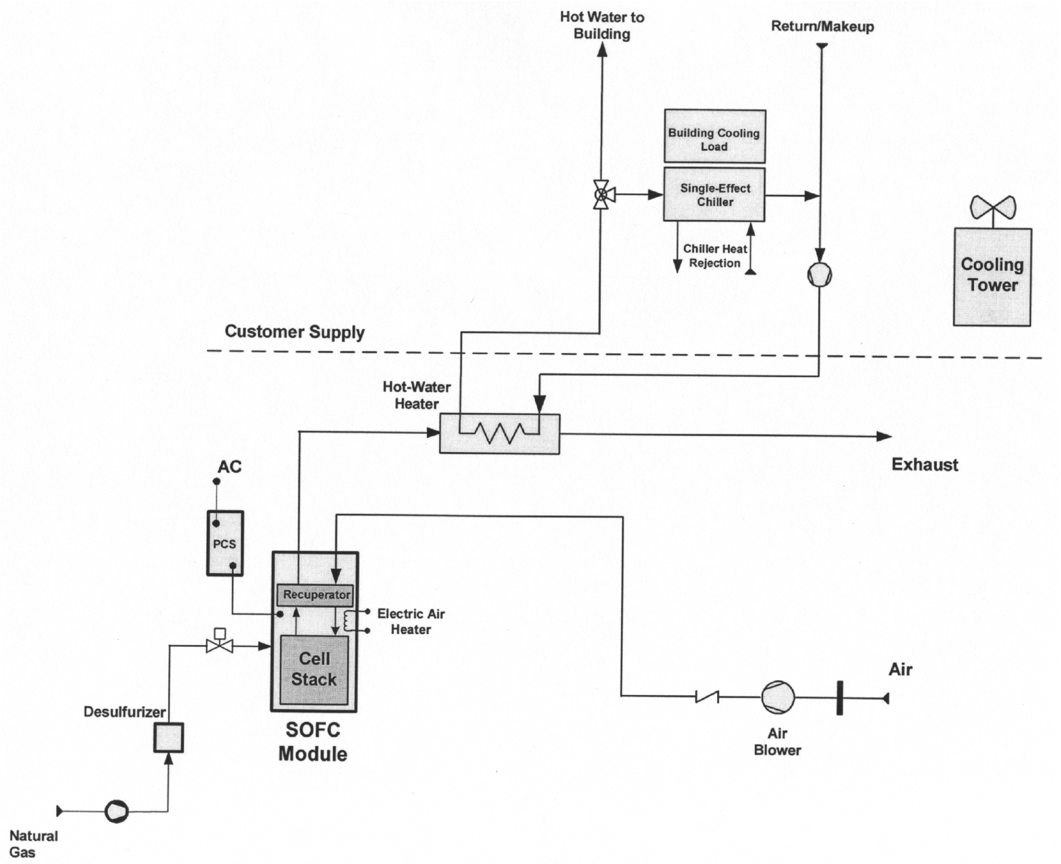

Figure 10. CHP250 cycle configured for hot-water production and application.

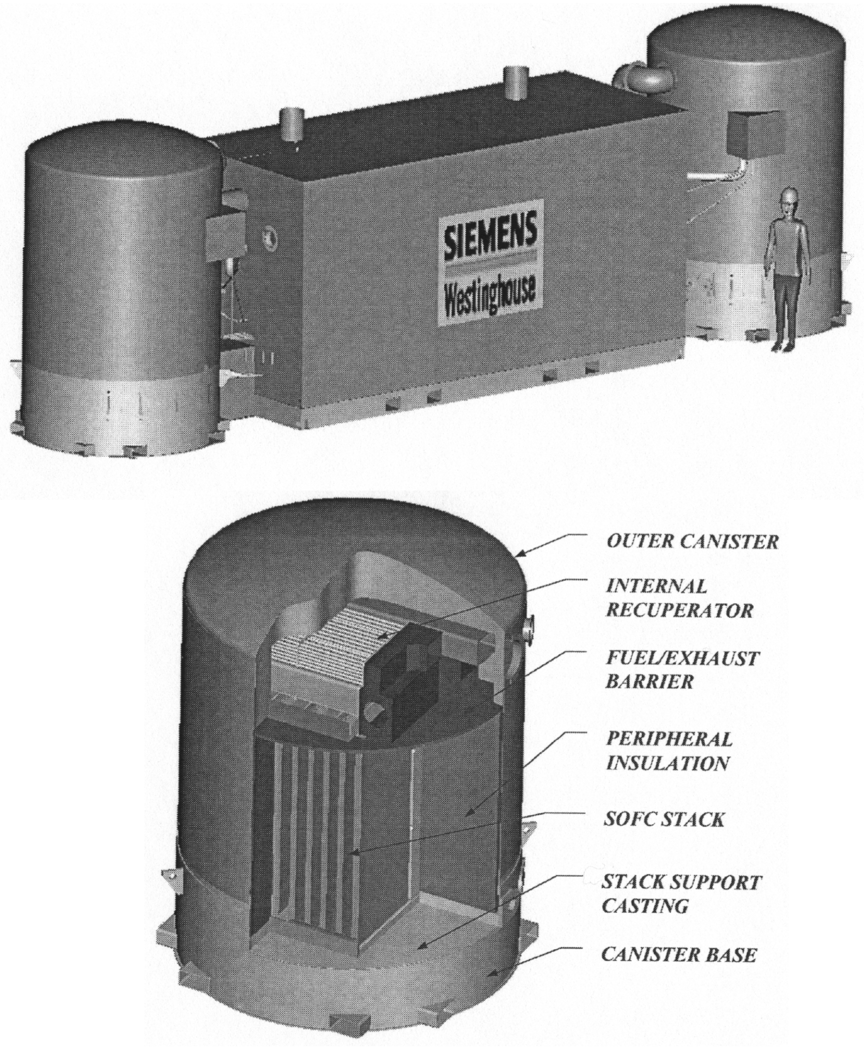

**Figure 11. CHP250 system.**

quired by the main air blower drive; system fuel is assumed to be available at sufficiently high pressure such that no fuel boost compression is needed. Cooling-effect estimates were made assuming all recovered heat was used by the chiller. A coefficient of performance (COP) of 0.7, representing single-effect chiller performance, was assumed. Table 1 indicates that the CHP250 equipped for hot-water production will generate 225 kWe net AC power at 47% net AC/LHV efficiency, while delivering 160 kWt in hot-water form. The estimated system overall energy efficiency at this operating point is 80%. The estimated maximum-power capability of the system is approximately 250 kWe, with an estimated heat recovery rate of near 210 kWt. The maximum cooling capacity of the system, based upon application of a hot-water-fired chiller with COP=0.7, is approximately 35 tons.

- Siemens Westinghouse will market the CHP250, an SOFC CHP system that will generate 225 kWe of net AC power with 47% (net AC/LHV) efficiency. At this operating point, approximately 160 kW will be recovered from the SOFC exhaust in hot-water form, which can be applied to site thermal processes or to driving an absorption chiller. A heat recovery efficiency of 33% is projected, and an overall system energy efficiency of 80%. The estimated cooling capacity of the system at this operating point is 26 tons. At maximum electric power, 250 kWe net AC, the projected electric efficiency is 44%, the estimated hot-water heat recovery rate is 211 kWt, and the cooling capacity estimate is 35 tons.

- The development of the CHP250 design is based upon a successful and continuing proof-of-concept demonstration program. A 100 kWe SOFC CHP proof-of-concept unit performed well in Europe between 1998 and 2000, demonstrating the generation of electric power at high efficiency (46%) and the production of hot water from SOFC exhaust heat. The system was the first SOFC CHP unit to supply power to the utility AC grid and heat to the local district heating system. Approximately 16,000 hours of operating time were logged, with virtually no degradation of cell voltage.

- A second SOFC CHP proof-of-concept system was scheduled for operation in 2003. This system will be tested in Toronto, Ontario. The system electric power capacity is 250 kWe; at nominal power, approximately 230 kWe of net AC power will be generated at 47% efficiency, and 140 kWt will be recovered from the system exhaust for hot-water heating.

## MOLTEN CARBONATE FUEL CELLS

DOE has been funding Direct Fuel Cell (DFC) development at Fuel Cell Energy, Inc. (FCE) for stationary power plant applications.

**Table 1. CHP250 Performance Estimates**
**(Ambient/Intake Air Temperature –15°F)**

| Parameter | Nominal Electric Power | Maximum Electric Power |
|---|---|---|
| SOFC module terminal current, DC amps | 493 | 600 |
| Fuel energy input rate (LHV), kW | 480 | 581 |
| SOFC DC power, kWe | 258 | 297 |
| System net AC power, kWe | 225 | 258 |
| Electric efficiency (net AC/LHV), % | 47 | 44 |
| Water heater inlet water temperature, C (F) | 100 (212) | 100 (212) |
| Water heater outlet water temperature, C (F) | 55 (131) | 55 (131) |
| Hot water flow rate, kg/s (lb/s) | 0.85 (1.86) | 1.12 (2.47) |
| Heat recovery rate, kWt | 159 | 211 |
| Heat recovery efficiency (kWt/LHV), % | 33 | 36 |
| System overall energy efficiency ([net AC + kWt]/LHV), % | 80 | 81 |
| Potential cooling effect (COP=0.7), tons | 26 | 35 |
| Water heater inlet water temperature in, C (F) | 89 (192) | 89 (192) |
| Water heater outlet water temperature, C (F) | 83 (181) | 83 (181) |
| Hot water flow rate, kg/s (lb/s) | 5.8 (12.9) | 7.9 (17.3) |
| Heat recovery rate, kWt | 145 | 195 |
| Heat recovery efficiency (kWt/LHV), % | 30 | 34 |
| System overall energy efficiency ([net AC + KWt/LHV]), % | 77 | 78 |
| CO2 emission rate, kg/MWh (lb/MWh) | 432 (952) | 459 (1,008) |
| NOx emission rate, kg/MWh (lb/MWh) | 0.009 (0.019) | 0.009 (0.020) |

FCE, Danbury, CT, is a world-recognized leader for the development and commercialization of high efficiency fuel cells that can generate clean electricity at power stations or in distributed locations near the customer, including hospitals, schools, universities, hotels and other commercial industrial applications.

Fuel Cell Energy has designed and is beginning to commercialize three different fuel cell power plant models.

Those power plants offer significant advantages compared to existing power generation technology higher fuel efficiency, significantly lower emissions, quieter operation, flexible siting and permitting requirements, scalability and potentially lower operating costs. Also, the exhaust heat by product can be used for cogeneration applications such as high-pressure steam, district heating, and air conditioning. Because hydrogen is generated directly within the fuel cell module from readily available fuels such as natural gas and waste water treatment gas, DFC power plants are ready today and do not require the creation of a hydrogen infrastructure.

FCE, products are based on its patented direct fuel cell technology. Several DFC sub-megawatt power plants are currently operating in Europe, Japan and the U.S. Accomplishments to date include over 17 million kWh generated to date with an excess of 12 million kWh at customer sites. FCE has also developed manufacturing and testing capabilities to produce 50 MW per year. Additional DFC power plants are scheduled for delivery in Europe, Japan and the U.S. over the next 12 months, including its first DFC 1500 and DVC3000. In parallel, FCE is also developing technology for coal gas, Department of Defense logistic fuels, and other fossil and renewable fuels such as coal mine methane gas and anaerobic digester gas (ADG) from municipal and industrial wastewater treatment facilities.

FCE has also been funded by a DOE contract to develop the ultrahigh efficiency hybrid system, direct fuel cell/turbine (DFCT), a power plant designed to use the heat generated by the fuel cell to drive a unfired gas turbine for additional electricity. During 2002, FCE completed successful proof-of-concept testing of a DFC/T power plant based on a 250-kilowatt DFC integrated with 30-kilowatt modified micro turbine. This proof-of-concept demonstration has proved information for the continued design of a 40 megawatt DFC/T power plant that is expected to approach the 75% efficiency goal as specified by the Vision 21 program, as well as to serve as a platform for high efficiency DFC/T system in smaller sizes. FCE is currently continuing its proof-of-concept testing of the DFC/T power plant with a 60-kilowatt micro turbine.

## THE COMMERCIAL IMPLICATIONS

Just like any new technology, the best early market applications for fuel cells are in the small, high value niche markets. Economies of scale and other drivers will expand the market and drive further development, in turn expanding markets. All this is still subject to traditional "valley of death syndrome" issues in new business and technology development. However, the level of development and international interest to date assures that fuel cells will play a significant role in nations' economies throughout the 21st century.

### References

UTC Fuel Cells Design and Application Guide, UTC Fuel Cells Revision B, November 2001.

Siemens Westinghouse Power Corporation, AEE Fuel Cell CHP document, March 13, 2003.

Dr. Subhash C. Singhal, Grove Abstract for FCE's input, Pacific Northwest National Laboratory, Richland, WA.

Fuel Cells: A Handbook (Revision 4, November 1998), Report Number DOE/FETC 99/1076 (CD), Washington DC.

SECA Workshop Proceedings, Baltimore, Maryland, June 1-2, 2000.

M.C. Williams, "Distributed generation fuel cells and power reliability," #1605, Energy 2001, Baltimore, Maryland, 2001.

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