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Engineering a 70-Percent Efficient, Indirect-Fired Fuel-Cell Bottomed Turbine Cycle

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Engineering a 70-Percent Efficient, Indirect-Fired Fuel-Cell Bottomed Turbine Cycle

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ABSTRACT

We introduce the natural gas, indirect-fired fuel-cell bottomed turbine cycle (NG-IFFC) as a novel power plant system for the distributed power and on-site markets in the 20 to 200 megawatt (MW) size range. The NG-IFFC system is a new METC-patented system. This power-plant system links the ambient pressure, carbonate fuel cell in tandem with a gas turbine, air compressor, combustor, and ceramic heat exchanger. Performance calculations based on Advanced System for Process Engineering (ASPEN) simulations show material and energy balances with expected power output. Early results indicated efficiencies and heat rates for the NG-IFFC are comparable to conventionally bottomed, carbonate fuel-cell steam-bottomed cycles. More recent calculations extended the in-tandem concept to produce near-stoichiometric usage of the oxygen. This is made possible by reforming the anode stream to completion and using all hydrogen fuel in what will need to be a special combustor. The performance increases dramatically to 70 percent.

BACKGROUND

Because of the abundance and relatively low cost of natural gas, gas turbine systems are gaining unprecedented acceptance in the power generation community. There are many advantages to using gas turbine systems. Nominally clean fuels are required to protect the turbine machinery, so the systems tend to also produce low levels of pollutants. When bottomed with a steam turbine, the energy from the exhaust stream inexpensively produces electric or cogeneration power. In addition, gas turbines require low maintenance and provide rapid start up.

There is, however, a limit to their use imposed by material properties — namely, the temperatures needed to achieve high efficiency exceed what materials can reasonably provide. Over the next 10 years, the Department of Energy's (DOE's) Morgantown Energy Technology Center (METC) will co-sponsor research on its Advanced Turbine System (ATS) Program to develop large, utility-scale units that are expected to achieve gas/steam cycle systems at 60-percent efficiency. These improvements will be possible if new high-temperature materials are indeed developed as planned. Such thermal systems can achieve higher efficiencies if turbine inlet temperatures are increased by approximately 150 to 200 °C. As temperatures are increased, it will become harder to meet the environmental standards, because nitrogen oxides (NO_X) production tends to increase non-linearly with increases in temperature.

The DOE has identified both fuel cells and advanced gas turbines as preferred sources of future electric power. DOE/METC is investigating the possibility of bringing both these two technologies together for the first time. Systems that do this are the subject of this paper.

FUEL CELL TECHNOLOGY

The fuel cell is a device that oxidizes fuel directly into electrical power without the enthalpy of combustion raising the temperature (Appleby and Foulkes 1989). Fuel passes through a semi-permeable membrane in the fuel cell where it electrochemically reacts with the oxidizer (air) compartment or cathode — as in proton-conducting fuel cells. The oxidizer passes through a semi-permeable membrane to the fuel compartment or anode in a molten-carbonate fuel cell (MCFC) or a solid-oxide fuel cell (SOFC).

In MCFCs, the reaction of hydrogen and carbonate ions releases electrons at the anode/electrolyte interface. Water, carbon dioxide, and heat are released by the anode reaction. The electrochemical reaction of oxygen, carbon dioxide, plus two electrons creates carbonate ions at the cathode/electrolyte interface. MCFC stack designs incorporate either internal or external manifolding. Internal and external reforming are being considered in several commercialization concepts. All MCFC concepts employ flat cell components in the cell package (i.e., anode, matrix to hold carbonate, cathode, current collector, and separator plate).

Fuel cells have many advantages that make them the ideal power system of the future, including environmental friendliness because the nitrogen oxide, sulfur oxide, carbon monoxide, and other pollutant exhaust products are insignificant. As attempts are made to improve the efficiency of future gas turbines, ever higher temperatures will be necessary to compete with fuel cell efficiency. Fuel cells produce high efficiency through chemical rather than thermal conversion and are controlled by Gibbs' Free Energy rather than high temperature operation. Thus, ultimately, if we are ever to achieve 70-percent power efficiency, we must integrate the fuel cell and gas turbine systems.

Fuel cells have other operational benefits. They operate efficiently at small size and even at partial loads. Because of this, fuel cells are ideal for distributed power generation. Fuel cell systems produce power with smaller footprints and hence lower land and power costs. These benefits in turn result in the potential to completely eliminate high voltage lines, reducing health concerns. In turn, a society can be created with fuel cells where the industrial complexes are cleaner and where even residential power services are available.

There is another special advantage to fuel cells, namely, low water utilization. This makes fuel cells especially attractive power systems in water-scarce locations. In fact, when natural gas is consumed, it produces relatively pure water, and so could provide a source of water for arid environments.

The many types of fuel cells use different kinds of electrolyte as the principal component by which power is converted, and the types are named after the electrolytes. The MCFC was selected for this analytical evaluation because the temperature required for its operation is nominally about the same as that of the exhaust of a gas turbine. MCFCs operate at about 550 °C (1,050 °F). SOFCs can operate at as much as 1,000 °C (1,800 °F).

Recognizing MCFC operating temperature match with gas-turbine exhaust, we examined the possibility that the clean air exhaust from the turbine could drive the fuel cell. This would all but eliminate a need for yet another heat exchanger to couple the two units.

STATUS OF FUEL CELL COMMERCIALIZATION

Fuel cell technology has evolved from small, curious, laboratory cell tests to fuel cell stack testing and investigations devoted to demonstration testing of complete systems (Energy Research Corporation 1987; Williams 1995; and Williams and George 1990, 1991). Systems testing is the precursor to commercialization. Small units in the 100-kilowatt (kW) range are commercially available. Thus, the fuel cell is no longer a technology of the distant future. Stack life for the MCFC has been extended from 100 hours in the early 1980s to some 5,000 hours for small stacks. Testing is underway to warrant MCFC units for 25,000 hours, and within several years, vendors expect to warrant their units for 40,000-hour operation. The largest MCFC now being manufactured and tested is a 2-MW size.

The SOFC uses solid oxides as electrolyte. Tubular and planar SOFC testing is still behind the MCFC in terms of stack size. However, tubular SOFCs have been tested for 40,000 hours.

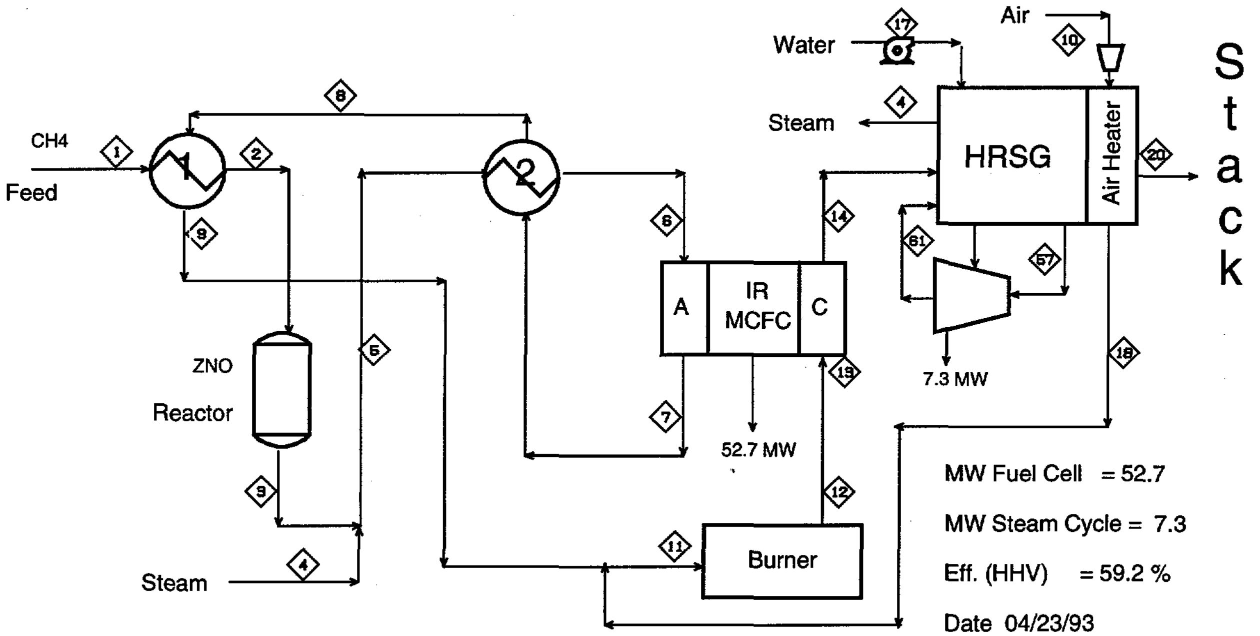
FUEL CELL POWER CONVERSION CONFIGURATIONS

While a fuel cell is extremely efficient, not all of the fuel's energy is electrochemically converted to electric power. Fuel conversion always yields moderate to high temperature product streams and other exhaust streams. These energy streams must be thermally converted to electric power.

About 50 percent of the fuel that comes into an MCFC is converted to electric power. The degree of conversion depends on the amount of carbon dioxide in the fuel cell. Carbon dioxide is increased by recycling some of the product stream from the anode, which contains water and carbon dioxide, to the cathode. Recycling increases the conversion from 50 to approximately 60 or 70 percent of the fuel. The excess fuel is then consumed in a secondary combustor. Three possible configurations that compare ways of using the exhaust stream energy are shown in Figures 1 to 3.

The arrangement shown in Figure 1 is one that has been studied in greatest depth: the exhaust energy is used in a steam cycle that acts as a bottomer part of a power system. The combustor raises the temperature using a heat recovery steam generator (HRSG). In Figure 1, a coal gasifier produces fuel for the fuel cell, but natural gas (NG) is equally viable. As an alternative, a gas turbine could be used to provide a high temperature, pressurized air stream which then passes into a pressurized fuel cell. This configuration is shown in Figure 2: the fuel cell is a topper for the low-pressure gas turbine. One still has the exhaust stream from the fuel cell to deal with. This is probably best utilized by heating the compressor discharge air. Finally, we have the indirect-fired configuration, shown in Figure 3, in which the air used by the fuel cell passes through the heat exchanger, and a combustor raises the temperature of the air to the gas turbine inlet temperature.

Figure 3 illustrates the basic features of a NG-IFCFC power plant. The compressed air for the gas turbine is heated by combustion products from an off-base combustor. While there are



STREAM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	17
FLOW (LBMOLE/HR)	872.95	872.95	872.92	1761.9	2634.9	2634.9	7179.6	7179.4	7179.4	11847	19027	19027	19027	14491	1761.9
TEMPERATURE (F)	60.01	775.00	775.00	740.00	754.40	1100.00	1250.00	1121.03	1030.15	57.00	611.47	1099.84	1100.00	1250.00	60.00
PRESSURE (PSIA)	45.00	30.00	25.20	35.00	25.00	16.00	16.00	15.90	15.70	14.70	15.50	15.50	15.50	15.50	42.00
H (MM BTU/HR)	-28.4	-21.5	-21.5	-173.6	-195.0	-185.0	-824.5	-834.6	-841.6	-15.9	-841.4	-841.4	-841.4	-393.3	-218.5

STREAM	18	20	57	61											
FLOW (LBMOLE/HR)	11847	14491	2697.73	2697.73											
TEMPERATURE (F)	250.00	200.26	1050.00	107.83											
PRESSURE (PSIA)	15.70	14.70	1465.00	1510.00											
H (MM BTU/HR)	0.2	-514.4	-260.4	-331.9											

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Figure 1. Baseline MCFC Steam Turbine System

many advantages to this configuration, there are also some problems that need to be resolved (Micheli, Williams, and Parsons 1993).

The NG-IFFC configuration in Figure 3 shows only hot air passing through the turbine. This all but eliminates corrosion of the turbine blades, thereby extending turbine life. The hot air source then supplies the fuel cell. The problem of contamination focuses on the heat exchanger rather than the turbine, which turns out to be a less challenging environment in which to handle both the corrosion and the erosion that commonly damage a turbine.

CYCLE EFFICIENCY CALCULATIONS

Calculations were carried out by DOE using a modified ASPEN code to calculate the conversion of chemical and thermal energy to electric power. The baseline case of the fuel cell plus steam turbine provides a way of comparing the efficiency of using the residual energy. Although higher efficiency is expected to be available by the turn of the century, we conducted the study assuming current steam turbine technology. Hence, the calculations reflect a conservative viewpoint.

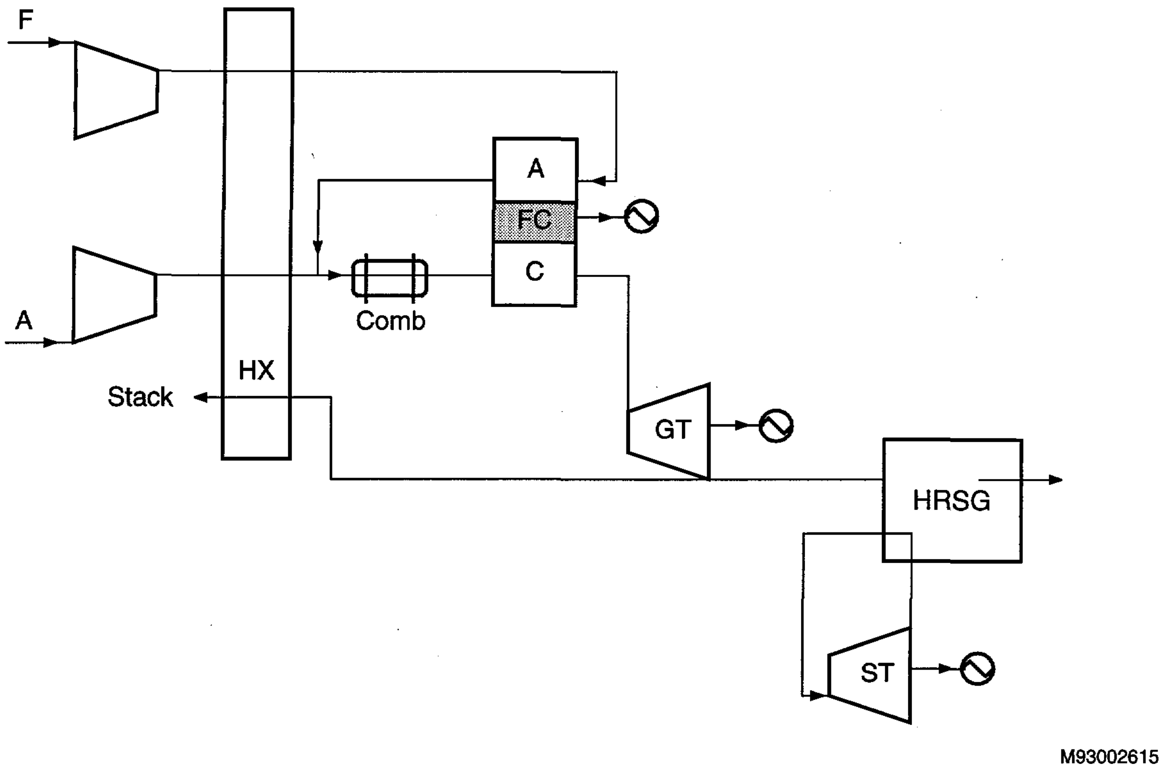


Figure 2. Pressurized Fuel Cell Topper Cycle

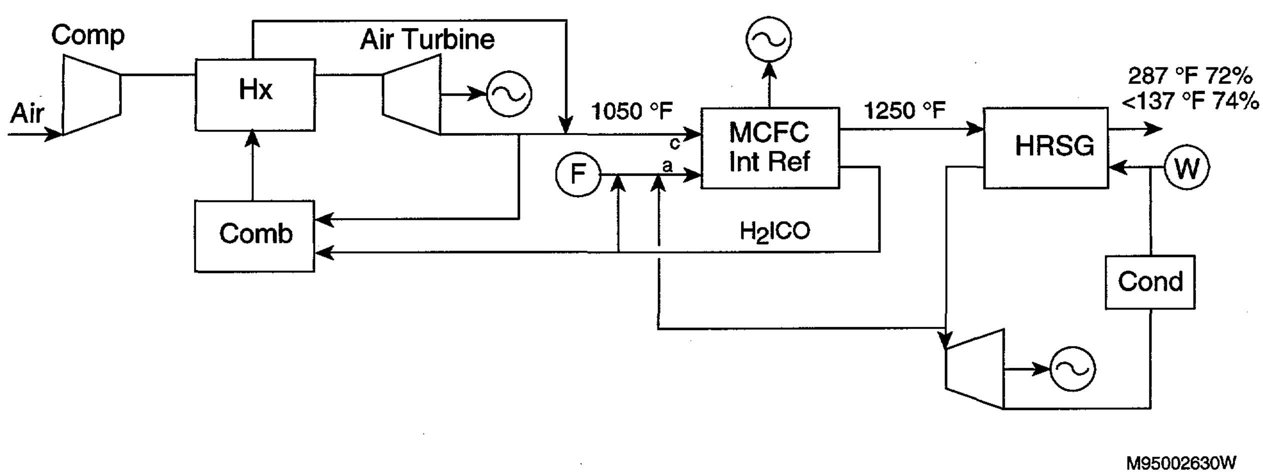


Figure 3. METC ASPEN, ASPENPlus, ERC ChemCAD

Performance calculations using ASPEN simulations present material and energy balances with expected power output. Figure 3 is the schematic used for the ASPEN simulation of the system. The results indicate that efficiencies and heat rates of the NG-IFFC are superior to the conventionally bottomed, carbonate fuel-cell, steam-bottomed cycles. The NG-IFFC also has smaller and less expensive components (Micheli, Williams, and Parsons 1993).

More recent calculations extended the in-tandem concept to produce near-stoichiometric usage of the oxygen. This is made possible by reforming the anode stream to completion and using the all-hydrogen fuel in what will need to be a special combustor. The performance increases dramatically to greater than 70 percent. Figure 4 graphs the capacity and demand of the tandem technology cycle by season, showing the effect of pre-chilling to match capacity and demand requirements. Figures 5 and 6 graph the idealized efficiency of IFFC cycles with the fuel cell operating at 50 and 70 percent of maximum capacity.

DISCUSSION

The NG-IFFC system has a 72 to 74 percent efficiency and could have significant use in new specialized (niche) markets, e.g., the distributed power and on-site markets in the 20 to 200 MW size range.

The NG-IFFC has significantly higher cycle efficiency than the gas-turbine combined cycle (GT/CC) alone. A 200-MW utility-size NG-IFFC system will average 72 to 74 percent efficiency compared to 60 percent for a GT/CC

Courtesy of Southern California Gas Co.

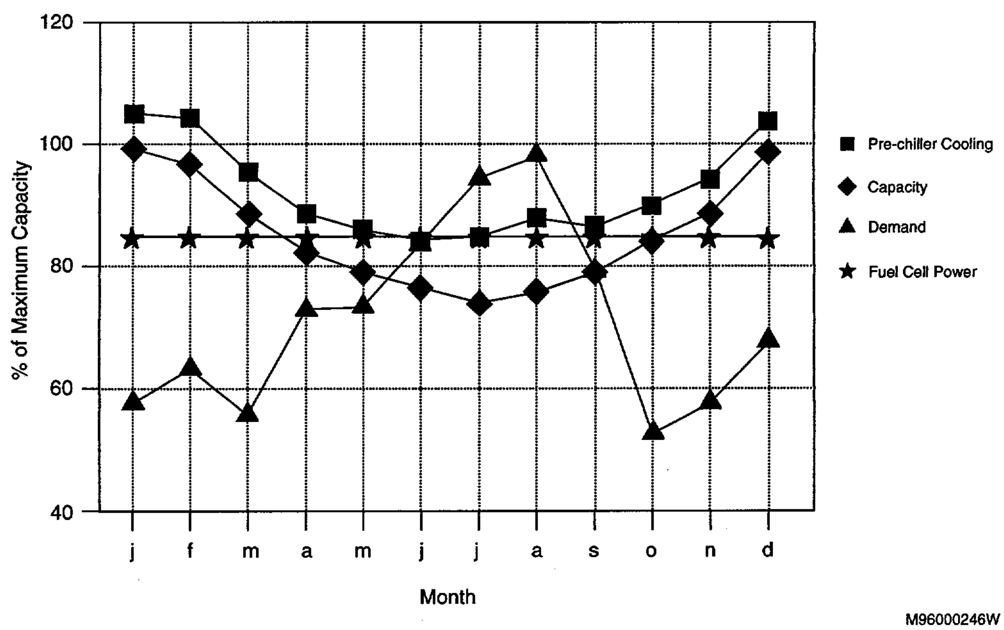
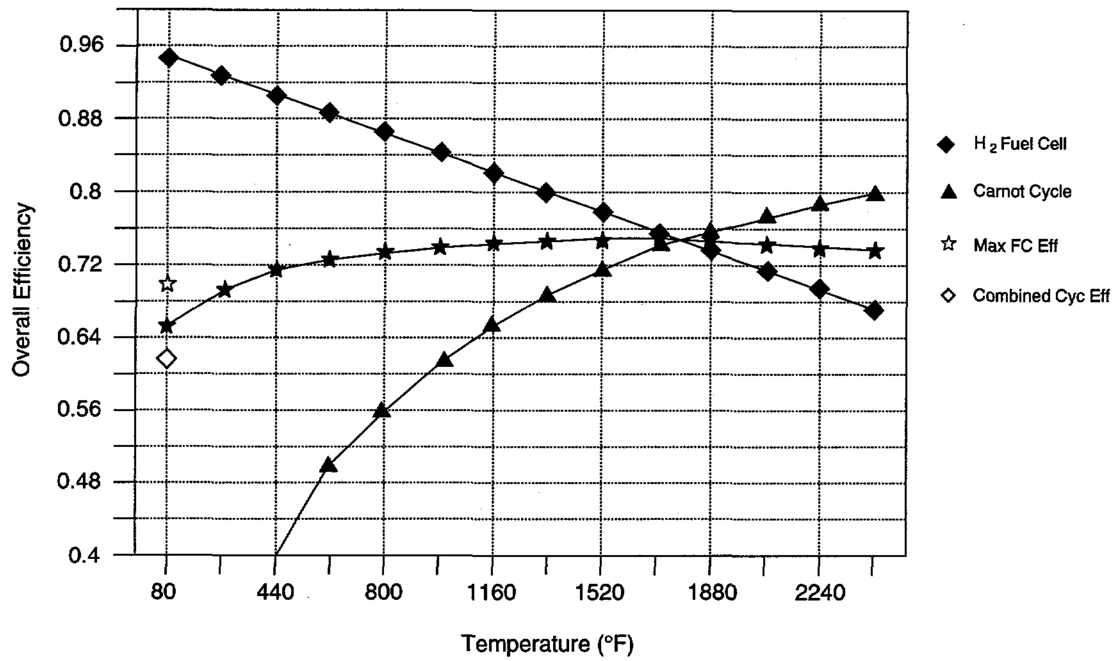


Figure 4. Tandem Technology Cycle, Effect of Pre-Chilling to Match Capacity and Demand Requirements



Fuel Cell @ 70% of maximum
Combined Cycle @ 62% of Carnot

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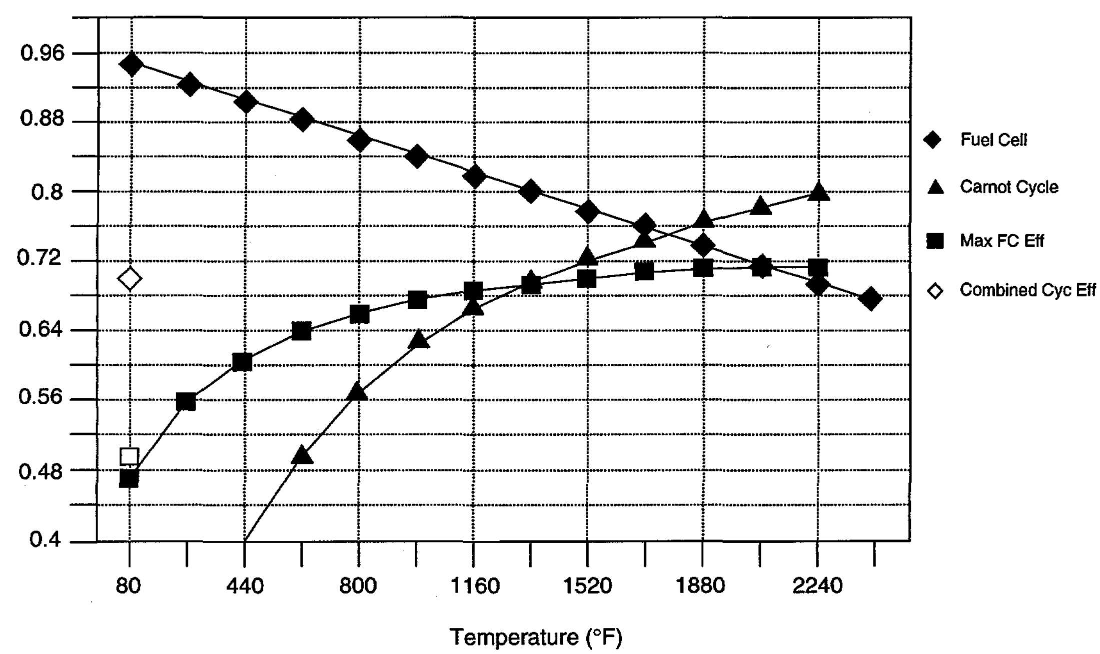
Figure 5. Idealized Efficiency of IF-FCB Cycles, Fuel Cell at 70 Percent of Maximum



Fuel Cell @ 50% of maximum
Combined Cycle @ 70% of Carnot

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Figure 6. Idealized Efficiency of IF-FCB Cycles, Fuel Cell at 50 Percent of Maximum

system; at the 20-MW industrial-size, the NG-IFFC system averages 68 percent and the GT/CC system averages 52 percent efficiency.

The heat engine and the fuel cell complement each other. They must be linked in tandem: the gas turbine bottomed by an MCFC is an excellent choice, and the gas turbine topper to an SOFC is also an excellent choice.

The maximum temperature of the gas turbine in the NG-IFFC system reaches about 2,200 °F. Higher temperatures could be wasteful. Table 1 shows the advantages of the fuel cell/heat engine in a tandem approach and the applicable domestic and foreign niche markets. Cost estimates of the NG-IFFC are shown in Table 2.

SUMMARY

We introduce the NG-IFFC as a novel power plant system for the distributed power and on-site markets. The system has a 72 to 74 percent efficiency and could conceivably attain 80-percent cycle efficiency. The system has significant potential use in new specialized (niche) markets, e.g., the distributed power and on-site markets in the 20 to 200 MW size range. The NG-IFFC has significantly higher cycle efficiency than the gas-turbine combined cycle (GT/CC) alone. A 200-MW utility-size NG-IFFC system will average 72 to 74 percent efficiency compared to 60 percent for a GT/CC system; at 20-MW industrial-size, the NG-IFFC system averages 68 percent and the GT/CC system averages 52 percent efficiency.

Table 1. Indirect-Fired, Fuel-Cell Bottomed System

Advantages Fuel Cell and Heat Engine	Applicable Niche Markets (Domestic and Foreign)
Constant efficiency over a wide temperature range.	FC/CC overcomes mismatches between annual baseload demand and capacity. - 25 percent smaller power rating.
Low NO_X and SO_X (remove S from fuels).	Sales in non-attainment areas.
	Low NOx implies very low exhaust temperature < 137 °F; provide H_2O for arid climate by condensing water.
Quiet operation.	Siting and permitting simplified; distributed power markets and APPA with no overhead power line.
Air turbine operations.	Better RAM, higher profits.

Table 2. Indirect-Fired, Fuel-Cell Bottomed System Cost Estimates

Addition of Combined-Cycle Power Units (GT + ST) Reduces Costs by:	**Estimate Capital Savings (%)**
- Decreasing balance of plant size and cost at higher efficiencies.	5%
- Lowering at-risk cost while FC is still a maturing technology.	10%
- Lowering financing charges since plant is faster on line.	5%
- Lowering capital cost.	10%
Profit margins significantly higher in niche markets.	**25%**

REFERENCES

Appleby, A.J., and F.R. Foulkes, 1989, *Fuel Cell Handbook*, van Nostrand Reinhold, 762 p.

Energy Research Corporation, 1987, *Molten Carbonate Fuel Cell Development*, Final Report to U.S. DOE, under Contract No. DE-AC21-76ET11304.

Micheli, P., M. Williams, and E. Parsons, 1993, Configuration and Performance of the IFCFC, presented at AIChE Annual Meeting, St. Louis, MO, November 1993, in *AIChE Extended Abstracts*, p. 105.

Williams, M.C., and T.J. George, 1990, The Developmental Status of Coal-Fueled Molten Carbonate Fuel Cell Power Plants, *Proceedings of the 25th IECEC* 3: 185-192.

Williams, M.C., and T.J. George, 1991, Cathode Corrosion in MCFCs, *Proceedings of the 26th IECEC* 3: 577-582.

Williams, M.C., 1995, The Status of Fuel Cell Development in the U.S., in *Materials Technology* 10(5/6): 104-112.