HIGH EFFICIENCY FUEL CELL/GAS TURBINE COMBINATION CYCLE

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ABSTRACT

Combination cycles integrating solid-oxide fuel cells and combustion turbines have the potential to achieve extremely high efficiencies due to the synergy between the cycle components. The challenge is cost-effective realization of that potential; and the latest research results are encouraging. EPRI, with the University of Utah, has developed a solid-oxide fuel cell with power densities at least as high as 1.8W/cm^2—six times previous levels. Working with the University of Utah data for voltage and current as a function of cell temperature, we used computer modeling to vary a wide range of cycle parameters and make a preliminary analysis of cost and efficiency tradeoffs for a combination cycle. Results indicate that such a system could be competitive in many electric power generation markets. At low current densities efficiencies are over 70%, but capital costs are extremely high, while high current densities lead to both lower efficiencies and higher costs. However, for moderate current densities of 2-3 A/cm^2 and fuel cell operating temperatures of 900ºC-1000ºC (1650ºF-1830ºF), capital costs should minimize while efficiencies remain in the 55-65% range. Capital costs for equipment (excluding installation costs) are estimated to be about $400/kW, with an uncertainty range from 300$/kW to 600$/kW.

INTRODUCTION

Although fuel cell/gas turbine combination cycles have the potential to achieve efficiencies over 70%, (with intercooling and exhaust heat recovery 80% efficiencies are possible), non-optimum arrangement of the various components can dissipate much of that potential. In addition, operating over 70% efficiency may be prohibitively expensive. As modeling indicates, such efficiency requires a fuel cell operating with low power density. The low power density means the cycle will demand more fuel cells to produce a given amount of electric power and adequate heat to run the CT, driving up the cost. The additional fuel cells also shift more of the overall system power output to the more expensive fuel cell, which adds to higher costs. A major thrust of this paper is to begin to define and narrow the ranges where cost and efficiency trade-offs are likely to be optimal.

Previous studies of this cycle have tended to treat the fuel cell as an inflexible unit in terms of both power efficiency and heat/electric power ratio.[1] In reality, a designer can—within limits—vary these factors. Similarly, fuel and oxygen utilization are design variables that can affect overall heat efficiency and plant cost. By varying these parameters, researchers can better understand the interaction between fuel cell design and whole system design—the place where the optimal trade-off between efficiency and cost will be realized.

NEW FUEL CELL CHARACTERISTICS

Current SOFCs tend to attain power levels just above 0.3 W/cm^2[2] but EPRI researchers at the University of Utah have created a SOFC (Figure 1) with power densities of 1.8 W/cm^2 at 800ºC (1470ºF). Tests underway indicate that the maximum power will increase to over 3W at 1000ºC (1830ºF). That's a tenfold power increase over current SOFCs and reduces the cost of these cells to the point of making them economically competitive.

The new cell is characterized by open circuit voltage that drops only slightly with increasing temperatures—between 650ºC (1200ºF) and 800ºC (1470ºF)—but whose internal polarization and resistance drop strongly with increasing temperatures. The efficiency of the cell, however, is proportional to the cell voltage, which drops with increasing current and power output.

Figure 2 summarizes the relationship between current density, power density, and voltage in the University of Utah SOFC. It's worth noting that these test results are based on low fuel utilization and high oxygen density. In a practical cost range, a cell running in combination with a gas turbine will see higher fuel and oxygen depletion, which will lower its efficiency and specific power output. In analyzing the FC/CT combination cycle, we varied FC operating temperature by interpolating and extrapolating data for the University of Utah SOFC operating at 800ºC (1470ºF). We used the Nernst equation for the effects of fuel and oxygen.

COMBINATION CYCLE MODEL

Figure 3 is a diagram of the basic combination cycle, which includes a recuperator. The cycle is designed to take advantage of the synergistic relationship between the fuel cell and the gas turbine and achieve a balance between low cost and high efficiency.

Synergy occurs in three places: The gas turbine provides pressurized hot air to the fuel cell, boosting its efficiency. The fuel cell provides heat (enthalpy) and fuel to the gas turbine, thereby meeting its turbine inlet temperature requirements. Finally, turbine exhaust gas provides enthalpy to the recuperator, typically at 650ºC (1200ºF). Although steam bottoming is not considered here, it could work since recuperator exhaust temperatures are usually greater than 370ºC (700ºF). Future work will investigate such an option, as well as compressor intercooling. A number of interrelated engineering concerns emerge from this model. The total fuel cell electrode area must be sized to provide the necessary heat output from the fuel cell. The physical configuration must accommodate the heat transfer requirements. The heat output must combine with combusted excess fuel to bring the air up to the turbine inlet temperature. (This study allowed turbine inlet temperature to float.)

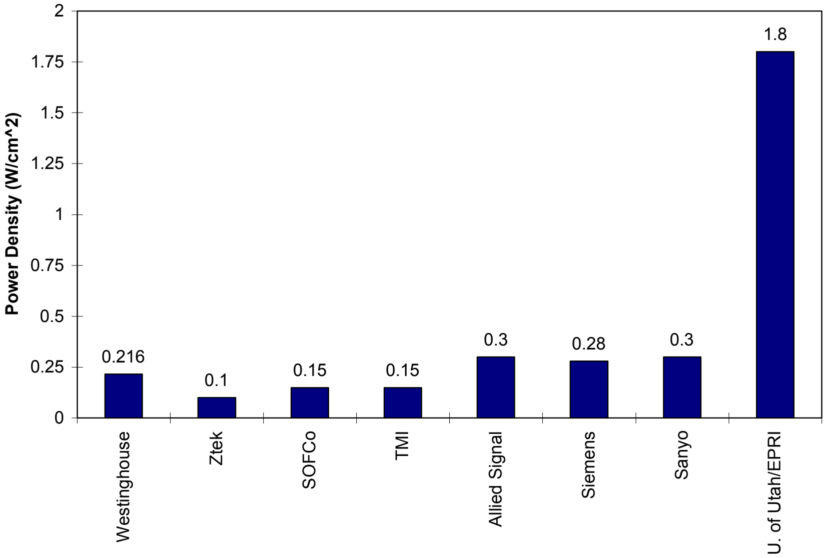

Figure 1. SOFC Status

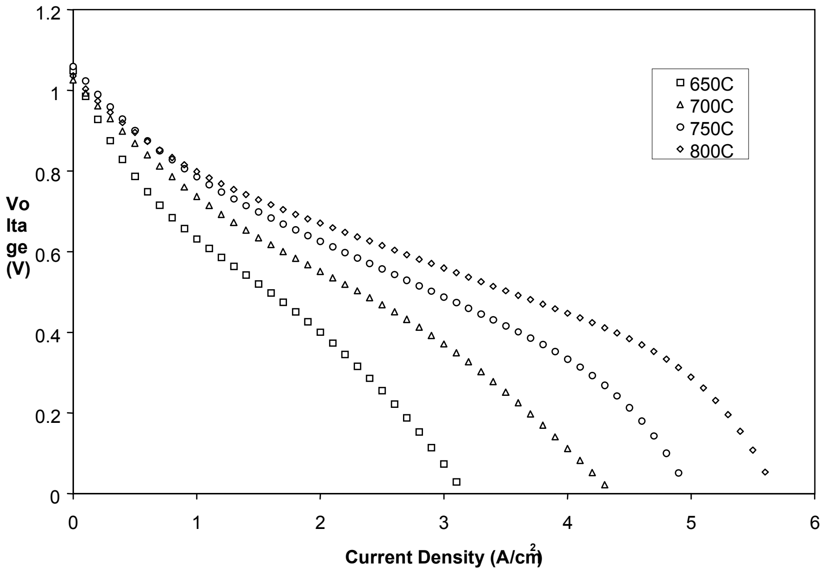

Figure 2a. University of Utah Fuel Cell Data

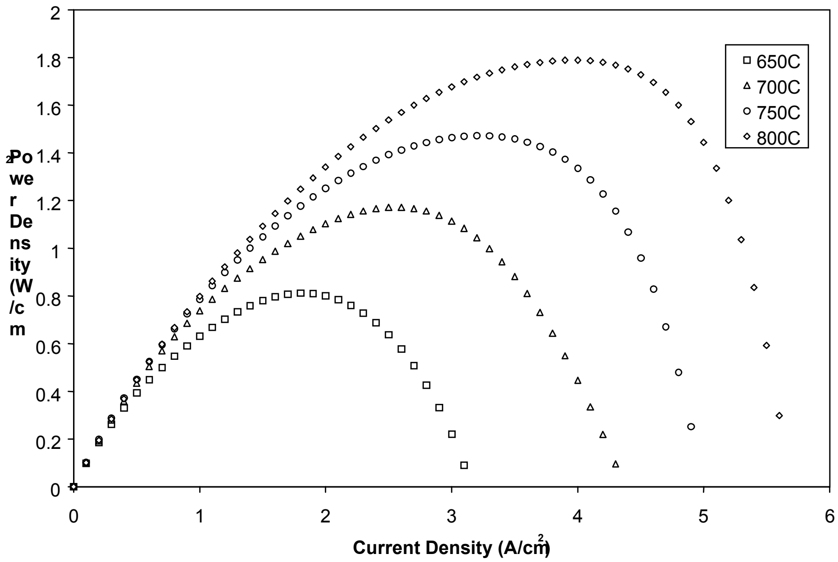

Figure 2b. University of Utah Fuel Cell Data

In addition, recuperator inlet temperature should be equal to the recuperator air exit temperature, plus the approach temperature. This analysis assumed that the temperature of recuperator inlet air was 56ºC (100ºF) above that of recuperator exit air. Finally, the compressor pressure ratio equals the turbine expansion ratio corrected for the pressure drop through the cycle between the compressor exit and the turbine inlet. (This analysis used the GateCycle™ program for turbine system analysis, which includes the bleed of additional air from the compressor for turbine cooling as the turbine inlet temperature rises.)

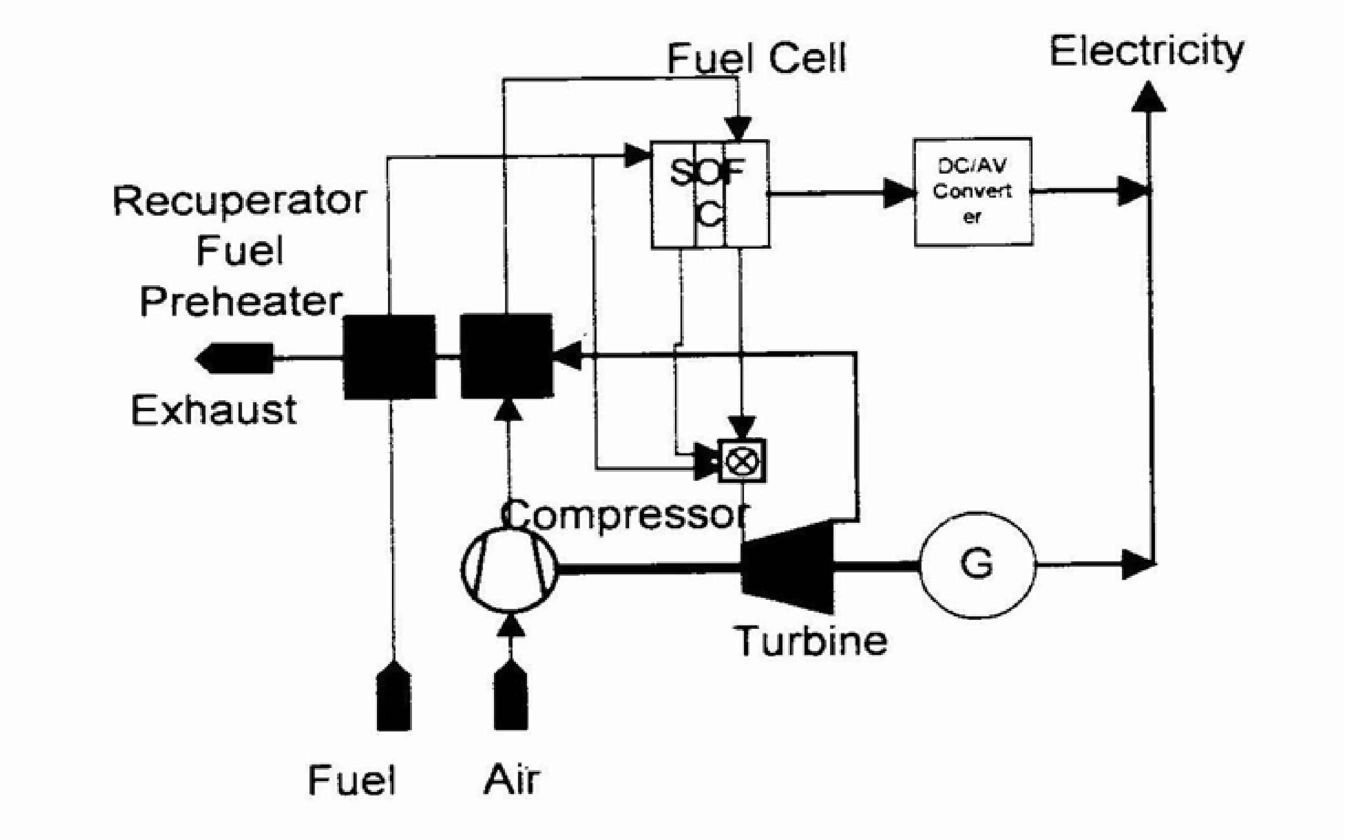

Figure 3. Fuel Cell/Combustion Turbine Combination Cycle

PERFORMANCE AND COST

For the cycle examined here we extrapolated the data from the University of Utah (Figure 4) to determine the effects of cell temperature and current density, and the Nernst equation for the effects of fuel utilization and oxygen depletion. Computer models calculated combination cycle performance and cost while varying five parameters: current density, FC operating temperature, FC air exit temperature, recuperator air exit temperature, and fuel utilization. The ranges were:

- Current density: 0.5 A/cm^2-7 A/cm^2
- Fuel cell operating temperature:
- 800°C (1470ºF)-1000°C (1830ºF)
- Fuel cell air exit temperature:
- 750°C (1380ºF) -1000°C (1830ºF).
- Recuperator air exit temperature:
- 540ºC (1000°F) -590ºC (1100°F).
- Fuel utilization: 70%-90%.

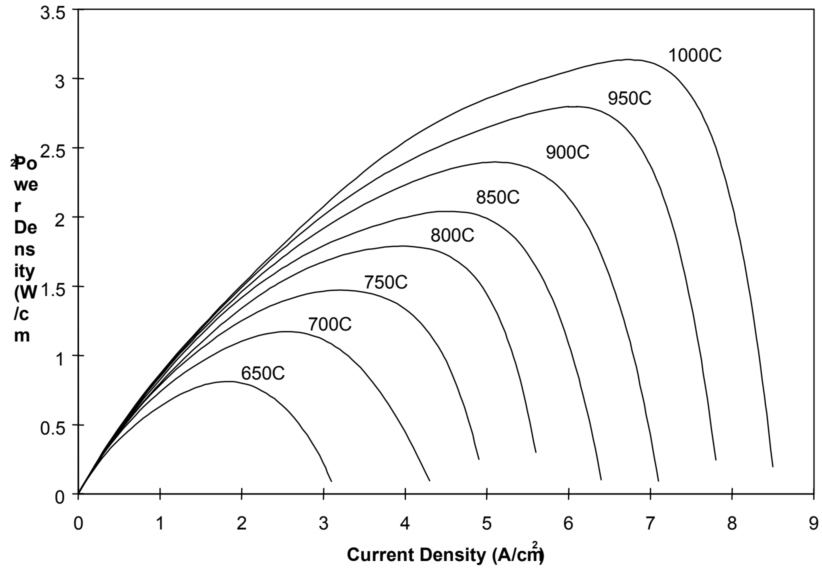

Figure 4. University of Utah Data Extrapolated to 1000°F

Strikingly, the variations for the final three parameters have little impact on overall system efficiency. Rather, the strongest influences on system efficiency and cost are current density and fuel cell operating temperature.

Figures 5 and 6 chart efficiency and cost as a function of current density and FC operating temperature. The efficiency trend decreases noticeably with increased current density. The highest efficiencies—above 70%—are only reached for current densities below 1.0 A/cm^2. However, in this range the calculated system cost rises dramatically because, again, high efficiency implies a lower density fuel cell contributing less heat to the combustion turbine (CT). To generate sufficient heat, more cells would be required, shifting the balance of energy produced to the fuel cell, which in turn is more costly than the CT. Further, less electric power is generated per cell so the overall power per cell drops as well. This makes the highest efficiency fuel cells impractical for commercial use in a combination cycle.

Another look at the data indicates that for any given fuel cell temperature, cycle efficiency is always highest for low current density and lowest at high current density. Further, the match between low current density and low temperature can produce the highest efficiencies, but as current density rises at low temperatures there is a very sharp efficiency drop-off. (Again, to keep costs competitive, current density must rise at least to moderate levels.) Cost begins to dip when fuel cell temperature is above 800°C (1470ºF), and current density is above 1.5 A/cm^2, although it is certainly not competitive at those levels. Cycle cost minimizes at 1000°C (1830ºF) and 3-4 A/cm^2, yet this lowest-cost scenario only achieves efficiencies in the 55-60% range. It might seem then, that the optimal trade-off occurs at temperatures between 900°C (1650ºF) and 1000°C (1830ºF) and current densities between 2-3 A/cm^2. At that intersection, efficiencies can be retained at over 60%. The first rough cut at a capital cost estimate was arrived at by adding fuel cell cost, turbine cost, and recuperator cost. These figures are for equipment costs only, and do not include installation costs, which add another 50% for typical combustion turbine power plants. Figure 7 illustrates the range for costs contrasted with efficiency for 1000°C (1830ºF).

Models used a fixed cost per unit area for the fuel cell and recuperator, with nominal values set at US\$0.60/cm^2 and US\$64/m^2 respectively. The fuel cell cost ranged from US\$0.40-0.90/cm^2, while the recuperator cost varied from US\$48-85/cm^2. (The recuperator cost should be factored in as a function of surface area, mass flows, and pressure level, but in this initial cut, we only used surface area.) For the gas turbine, researchers assumed the projected cost to be US\$400/kW for a 5-MW plant, and scaled to the -0.25 power for other power levels.

The test cases assumed 75% fuel use and recuperator air exhaust temperature of 590ºC (1100°F). Cost ranged from US\$380/kW (at 4.0 A/cm^2 current density and 1000ºC [1830°F]) to over US\$2000/kW (at a current density below 0.5 A/cm^2 and 900ºC [1650°F]).

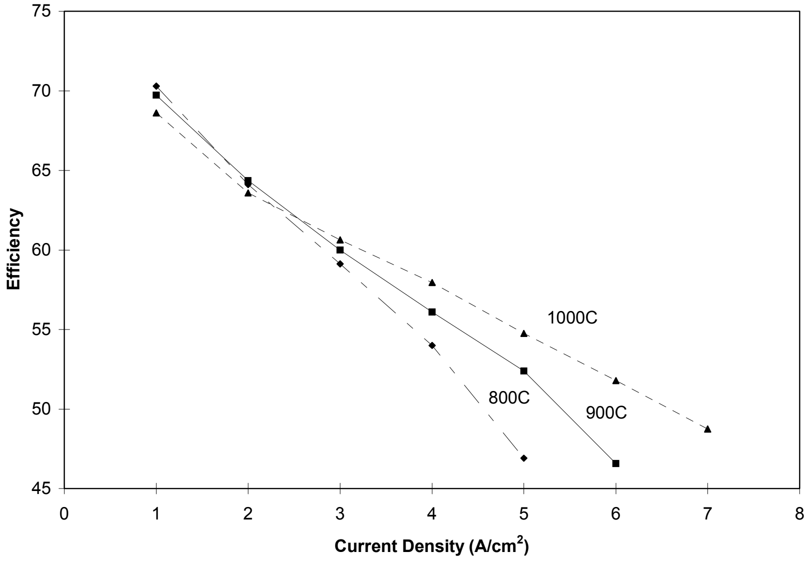

Figure 5. Efficiency Results from Models

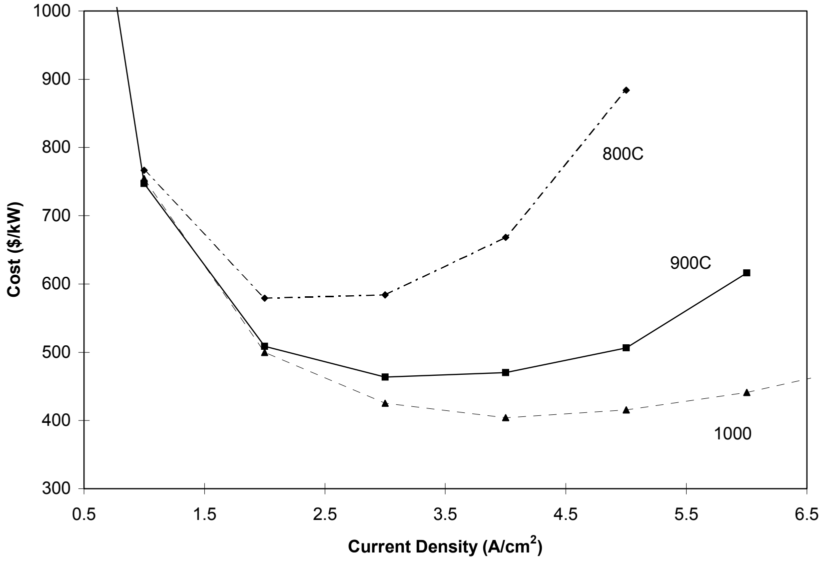

Figure 6. Cost Results from Models

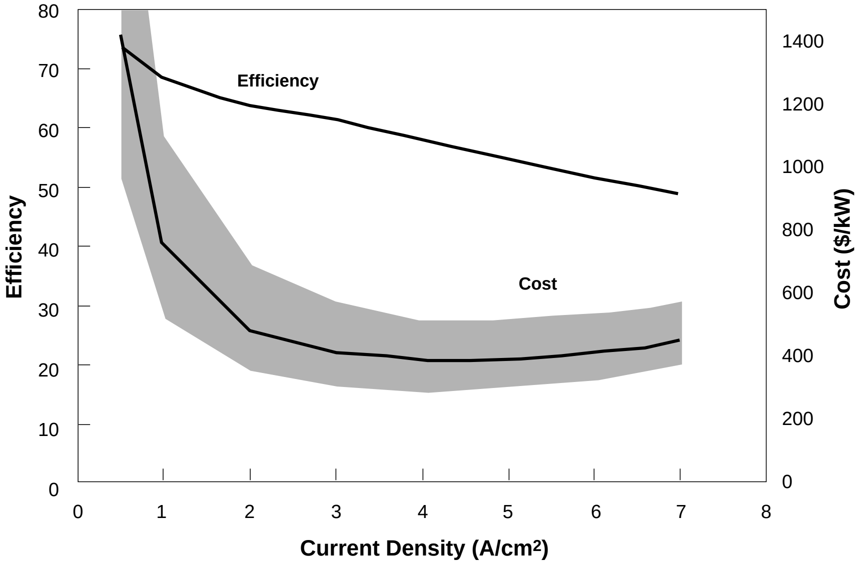

Figure 7. Cost Ranges at 1000 C

SUMMARY

Moderate current density in fuel cell design (about 2-3 A/cm^2) and a fuel cell operating temperature between 900ºC (1650°F) and 1000ºC (1830°F) lead to a very competitive plant cost while retaining efficiencies in the 60-65% range. Capital costs of between US$400-500/kW are feasible and highly competitive. Efficiency might be further boosted with the addition of steam bottoming and compressor intercooling, an area for future investigation. Other significant findings are that low current density levels lead to higher fuel cell efficiency, but at substantially higher capital costs. At high current density not only does efficiency suffer, but costs rise as well.

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