ABSTRACT
The advancement of efficient hybrid fuel cell systems requires the evolution of analysis strategies for evaluating and developing cycle design. This paper addresses the performance of a recently developed simulation tool for the analysis of tubular SOFC power systems as compared to observed hybrid operation data. Descriptions of the Advanced Power Systems Analyses Tools (APSAT) modeling package and of the world's first hybrid SOFC gas turbine system are presented. Through simulation of the Siemens Westinghouse 220 kW hybrid the analysis program is evaluated to verify the simulation capability and accuracy of the tool. Results show that the APSAT program predicts electrical power generation and efficiency (net AC/LHV) that are in line with observed performance data. In addition, the tool accurately predicts key process temperatures throughout the system. Finally, sensitivity analyses of several major system parameters were accomplished to identifying key development needs and improvement potential for hybrid SOFC gas turbine cycles.

INTRODUCTION
The pursuit of higher generation efficiency has led to the integration of high temperature fuel cells and gas turbines into hybrid cycles. While still in their infancy, system analyses and initial results indicate that hybrid cycles can achieve significant gains in electric generation efficiency and lower pollutant emissions. Hybrid cycle development and system design is being carried forth by both prototyping and computer simulation. At the National Fuel Cell Research Center (NFCRC), the host site for the Southern California Edison and Siemens Westinghouse 220 kW hybrid system, there is a unique opportunity to work on both aspects of development. It is this opportunity that has facilitated the comparisons of advanced power system analysis tool (APSAT) simulation results with operational data obtained with the 220 kW system.

Recently, operation of SOFC systems has been simulated by many groups (e.g. Gemmen et al; Haynes and Wepfer; and Costamagna, et al.) with various assumptions to simplify the underlying physical, electrical, thermal and chemical performance (1,2,3). The current study focuses on tubular SOFC technology, which is most closely related to the
work of Haynes and Wepfer, and Costamagna et al. (2,3). None of these studies presented a comparison of simulation results to experimental data as presented herein.

In order to enhance the development of future hybrid cycles, both model development and application, as accomplished in the above studies, as well as validation of the simulation tools against operating conditions and experimental data is essential. In this paper, the APSAT modeling package, developed at the NFCRC for steady state analysis, is used to simulate the 220 kW hybrid as demonstrated at the Center. Comparisons of significant operating conditions are used to develop a model that produces reasonable simulation of the actual system. System parameters of particular interest are system efficiency, electrical output, and process air states, which are used to validate and refine the APSAT package.

**APSAT DESCRIPTION**

Existing commercially available simulation programs do not have the capability to model complex, highly integrated hybrid power systems that incorporate an advanced fuel cell such as an SOFC (4). APSAT was developed to handle such complex configurations of advanced energy systems, especially those combining electrochemical and thermomechanical components in various thermodynamic cycles.

The capabilities of this tool include an analytical model for the tubular SOFC derived from first principles as well as modules for simulation of secondary equipment required to analyze hybrid power plants. Such secondary equipment includes gas turbines, reformers, partial oxidation reactors, shift reactors, humidifiers, steam turbines, compressors, gas expanders, heat exchangers, pumps, combustors, pipes and so on. A “controller” and a “recycler” are also developed and can be used in the modeling systems to automatically iterate in order to meet the desired process or system design criteria. Another important capability included in the tool is that of arranging the various components or modules as defined by the user in order to configure various hybrid systems.

An integral model was developed for tubular SOFC module, which accounts for the heat and mass transfer process occurring in the various sections of the cell as well as the electrochemistry. The integral model minimizes the computational time required by the computer to solve the entire hybrid plant. The differential equations governing the various processes for a single cell are formulated and assumptions are made in order to solve these equations analytically. All of the major chemical, electrochemical, and physical (e.g. heat transfer) processes that govern SOFC operation are rigorously simulated. Details regarding the assumptions can be found in Rao and Samuelsen (5). The equations that govern these processes are coded into the module with an iterative scheme used to determine the solution for SOFC simulation. The net AC power output from the stack is estimated by applying an estimated inverter efficiency of 95% to the product of the DC power generated by a single cell and the total number of cells.

More details about the analytical and computational strategies about APSAT can be found in the work of Rao and Samuelsen (4,5,6).
A joint sponsorship by Southern California Edison (SCE), California Energy Commission (CEC), the U.S. Department of Energy (DOE), and Siemens Westinghouse Power Corporation and others has produced the proof-of-concept 220 kW hybrid cycle power system (7). The system is the first to integrate a fuel cell stack with a microturbine generator. The microturbine acts as the air mover for the fuel cell stack while the high temperature exhaust from the tubular solid oxide stack replaces the combustor of the gas turbine cycle. More importantly, the microturbine functions as a turbocharger in that it pressurizes the fuel cell to produce elevated performance in the stack’s power density and efficiency. Subsequently, the quality heat gained by the process air in cooling the stack is expanded through turbines to drive the compressor and an AC generator without the need for traditional fuel combustion. Efficiency gains over traditional power generation systems are achieved by utilizing the thermal energy produced from the fuel cell’s exothermic electrochemical reactions to supply the thermal input required by the turbines and fuel reforming.

Siemens Westinghouse designed and manufactured the hybrid’s solid oxide stack using their unique tubular cell design. The stack is essentially a 100 kW atmospheric stack, composed of 1152 cells, vertically housed in a pressure vessel. Figure 1 presents a photograph of the complete skid-mounted hybrid system with the pressure vessel housing the stack near the rear in this photograph. While operating, the stack is pressurized to approximately 3 atmospheres allowing maximum fuel cell power production to reach 180 kW DC. The design of the stack arranges sets of three cells in parallel, which leads to stack production of about 750 amps and 240 volts near full load. The fuel used is desulfurized pipeline natural gas that is converted into hydrogen rich gas by internal reformers that are integrated into the stack design. Reformer plate modules are inserted between rows of three parallel cells with recycling of the anode exhaust providing the steam and the stack itself providing the thermal energy required for reformation. In order
to maintain the desired voltage and to protect the anode surface the SOFC fuel utilization is targeted at 82%. The unused fuel, which passes through the stack, is allowed to spontaneously combust as it is mixed with the cathode exhaust. This minimal amount of combustion produces thermal energy used in other portions of the cycle.

The second major component, the microturbine, is supplied by Ingersoll-Rand (formerly Northern Research and Engineering Corporation) and is a modified stand-alone system rated at 75 kW (8). The front cabinet is open in Figure 1 showing several of the microturbine components. The microturbine system is a recuperated two-shaft configuration comprised of a radial compressor shafted with a high-pressure radial turbine, and a low-pressure radial turbine connected to an AC generator. When coupled with the SOFC stack, the turbine will produce 10 to 20% of the total electric power generated by the hybrid system. The dual shaft configuration offers the advantage of eliminating power inversion equipment for the microturbine by allowing the power turbine to be geared directly with the electric generator. However, this feature also makes airflow management challenging since the rotational speed of the gasifier turbine cannot be controlled directly. The turbine recuperator recovers exhaust heat to preheat the pressurized process air before it is sent to the SOFC generator.

As presented in Figure 2, the hybrid cycle diagram shows the presence of several additional key components, specifically duct burners (combustors) and bypass valves. The combustors in the system are used for system start-up and maintaining partial loads when the stack does not produce sufficient waste heat to power the microturbine portion of the cycle. The stack bypass valve provides the means to independently control stack airflow by adjusting the proportion of flow directed around the stack. With this functionality, the microturbine can be started using the combustors alone, and subsequently employed to heat the SOFC generator to operating temperature by closing down the bypass valve to direct airflow through the SOFC. As the SOFC approaches operating temperature natural gas, with reforming steam initially, is introduced to the reformer and anode compartments. Then current is drawn from the generator and slowly stepped up while the stack continues to heat and the steam addition is halted. As steady-

Figure 2. The 220 kW hybrid system cycle diagram.
state operation of the cycle is reached the fuel to the duct burners is shut off and the SOFC generator furnishes the full thermal energy needs of the cycle. A second bypass valve allows for the management of the hot exhaust through the recuperator so that the desired stack inlet air temperature can be maintained.

The current system was initially operated at a factory acceptance test in Pittsburgh, Pennsylvania, in April 2000 and then was moved to the NFCRC for installation. As of October 2002, the unit has operated approximately 1700 hours and is currently undergoing revisions that will allow its continued demonstration. In its initial operation the unit has achieved an efficiency (net AC/LHV) of 53% proving the concept of high efficiency for hybrid systems. Thus far, electrical power by both the SOFC generator and turbine has been dissipated through controlled resistor banks.

SIMULATION USING APSAT

The steps required to simulate the whole fuel cell or fuel cell hybrid systems include:

1. Identify the desired equipment and components for the system of interest,
2. Configure the model to connect the component modules in the appropriate system configuration and appropriate connection components (e.g. pipes with pressure drop and/or heat loss),
3. Assign numbers to each component and each stream entering or leaving the components.
4. Define the streams entering the system by specifying composition, flow rate, temperature, and pressure,
5. Add “controller” or “recycler” modules into the system to define cycle design and controlled parameters/targets within the system, and
6. Run the program to obtain the results.

These steps were taken for the current hybrid system of interest to produce the system simulation schematic presented in Figure 3. In the current effort we are only simulating continuous operation of the hybrid system when the combustors are not operating. Therefore, the two duct burners shown in Figure 2 are not included in the system model. One controller, one recycler and three pipe modules are added into the simulation cycle in order to adjust and control the performance of the system. The controller is used to control the bypass valve in order to provide the required airflow for SOFC, determined by the fuel flow to and stoichiometric ratio of the SOFC, as is done in the experiment. The recycler is used to set the effectiveness of the heat exchangers at a reasonable and constant value and to adjust this to accomplish the sensitivity analyses. The three pipe modules are applied to simulate the heat losses in the actual system by specifying the temperature drops in the pipes.

The APSAT tool can predict intermediate stream compositions and properties within the system, stream features leaving the system, power consumption (of pumps, compressors), power generation (of SOFC, gas turbine, turbo-expander, etc.), and heat transferred in
each of the heat exchangers. The model also predicts the size of the SOFC (number of tubes for a specified tube diameter and length) and dimensions of the humidifier column (diameter and packed height) required for the cycle. In addition, the model performs exergy analyses that are useful in identifying the system design features and components that most significantly impact system performance and efficiency.

![System schematic for simulation of the 220 kW hybrid system.](image)

**Figure 3.** System schematic for simulation of the 220 kW hybrid system.

### COMPARISON OF SIMULATION RESULTS WITH OBSERVED DATA

Table 1 shows the design conditions for the simulation, which are kept identical to the actual parameter values of the experiment. The lower heating value of the site natural gas was determined by analysis to be 49810 kJ/kg. Heat losses in the system are considered to varying degrees in the sensitivity analyses. The total heat loss relative to total fuel heating value is 6.825% for the conditions shown in Table 1.

APSAT simulation results of the 220 kW hybrid system based on the conditions established in Table 1 are compiled in Table 2. This table presents the comparison of simulated overall system performance to actual data. For all of these major system performance parameters the errors between experiment and model are less than 3%.

Table 3 presents the state array for the entire system with comparison between simulation results and actual data for the conditions of Table 1. For every state point, the three critical parameters (temperature, pressure and mass flow rate) are listed and compared. The model states are shown to simulate the actual states well. The comparisons presented in Table 2 and Table 3 well validate the performance of the APSAT tool for simulation of these types of hybrid fuel cell systems.
### Table 1. 220 kW hybrid system operating conditions.

| System Parameters | Inlet Streams | Turbine Values | SOFC Values | Others |
|-------------------|---------------|----------------|-------------|--------|
|                    | Observed      | Simulation     |             |        |
| **Inlet Streams** |               |                |             |        |
| Natural gas fuel flow, kg/s | 0.007023 | 0.007023 |                |        |
| Compressor airflow, kg/s   | 0.635 | 0.635 |                |        |
| SOFC air inlet, kg/s       | 0.4953 | 0.4953 |                |        |
| **Turbine Values**         | 79  | 79  | 3  | 3  |
| Compressor Isentropic efficiency, % | 85 | 85 | | |
| Compressor pressure ratio | 65  | 65  | 22 | 22 |
| **SOFC Values**            | 1152 | 1152 | 82 | 82 |
| Cell number, cells         | 150 | 150 | | |
| Cell length, cm            | 2.1 | 2.1 | | |
| Cell inside diameter, cm   | 5.1 | 5.2 | | |
| Fuel utilization, %        | 5.1 | 5.2 | | |
| Airflow stoich ratio       | 82  | 82  | 89 | 90 |
| **Others**                 | 22  | 22  | 95 | 95 |
| Air bypass, %              | 22  | 22  | | |
| Recuperator effectiveness, % | 90 | 90 | | |

### Table 2. Comparison of system performance: simulation vs observed.

| System Parameters | Observed | Simulation | Error (%) |
|-------------------|----------|------------|-----------|
| Turbine power output, kW | 21       | 21.60      | 2.86      |
| **SOFC Stack**    |          |            |           |
| Operating temperature, °C | 995     | 1000       | 0.50      |
| Operating pressure, bars | 2.9     | 2.94       | 1.38      |
| Cell Voltage, Volts | 0.639    | 0.633      | 0.93      |
| Voltage, Volts     | 244      | 243.1      | 0.36      |
| Current, Amps      | 700      | 694.2      | 0.83      |
| DC Power output, kW | 170.8    | 168.78     | 1.18      |
| **Total System**   |          |            |           |
| Adjusted AC power output, kW | 183.45  | 181.94     | 0.82      |
| System efficiency, % | 52.44   | 51.92      | 1.00      |
Table 3. Comparison of system states: simulation vs observed.

| System States          | Point | Temp (°C) | Pressure (bar) | Mass (kg/s) | Temp (°C) | Pressure (bar) | Mass (kg/s) |
|------------------------|-------|-----------|----------------|-------------|-----------|----------------|-------------|
| Process Air            |       |           |                |             |           |                |             |
| Compressor inlet       | 2     | 15        | 1.013          | 0.635       | 15        | 1.01           | 0.635       |
| Comp. outlet (recup. cold in) | 3 | 155      | 3              | 0.635       | 147       | 3.00           | 0.635       |
| Recuperator cold outlet | 4     | 500       | 2.9            | 0.635       | 500       | 2.94           | 0.635       |
| SOFC bypass            | 6     | 500       | 2.9            | 0.140       | 500       | 2.94           | 0.140       |
| SOFC air inlet (post pipe) | 17 | 500       | 2.9            | 0.495       | 497       | 2.94           | 0.495       |
| Stack exhaust (post combust) | 9 | 780       | 2.8            | 0.642       | 770       | 2.82           | 0.502       |
| HP turbine inlet (pre pipe) | 10 | 730       | 2.8            | 0.642       | 714       | 2.82           | 0.642       |
| HP turbine outlet      | 11    | 610       | -              | 0.642       | 575       | 1.54           | 0.642       |
| LP turbine outlet (pre pipe) | 12 | 550       | -              | 0.642       | 545       | 1.24           | 0.642       |
| System exhaust        | 16    | 210       | 1.1            | 0.642       | 202       | 1.22           | 0.642       |
| Fuel Stream            |       |           |                |             |           |                |             |
| SOFC fuel inlet NG     | 1     | 15        | 6              | 0.00702     | 15        | 2.94           | 0.007       |

SENSITIVITY ANALYSES

Sensitivity analyses were performed for the current system using the APSAT program and a design of experiments (DOEx) approach. DOEx is a planned approach for determining cause and effect relationships that can be applied to any process with measurable inputs and outputs. DOEx provides a statistical means for analyzing the effects of multiple variables and their interactions. The current effort used a canned software package called Design-Expert by Stat-Ease (9). In this effort the APSAT program was used to produce the results ("data") that is statistically analyzed using design expert.

Pressure Ratio

The sensitivity analyses show that system pressure ratio has a positive impact on the system efficiency as indicated in Figure 4. When the pressure ratio increases from 2.8 to 3.2, the system efficiency increases by 0.54 percentage points. The performance of both the SOFC and gas turbine portions of the cycle are enhanced when operating at a higher pressure. This is balanced by increased compressor losses and possible increases in thermal losses. As such, although the increase in pressure ratio appears to increase overall system efficiency the increase is not statistically significant in this narrow range of pressure ratio increases.
Compressor Efficiency

Simulation results presented in Figure 4 show that the overall system efficiency is enhanced with increases in compressor efficiency. The increase of system efficiency is 1.69 points, when the compressor efficiency is improved by 8 points. When compressor efficiency is higher, the turbine energy consumed by the compressor to compress air is lower. Also, the output temperature of compressor is lower, which enables the recuperator to recover more heat from the turbine exhaust. Therefore, in the reasonable range of compressor efficiencies presented in Figure 5, a statistically significant positive impact of increasing the compressor efficiency of the current system is demonstrated.

Figure 5. Sensitivity of system efficiency to pressure ratio.  Figure 4. Sensitivity of system efficiency to compressor efficiency.

Turbine Efficiency

The turbine efficiency is shown in Figure 6 to have a positive effect on overall system performance. When turbine efficiency is increased by 10% (from 81% to 89% for the compressor turbine and from 62% to 68% for power turbine), the system efficiency is increased by 1.8%. It is noteworthy that when turbine efficiencies are higher, the turbine exhaust temperature is lower. When the heat exchanger duty in the recuperator is fixed, which is required to maintain SOFC air inlet temperature at around 500°C, the requirement for the recuperator effectiveness increases. This could result in increased recuperator size, which comes at substantial cost to the current system.

Bypass

The percentage of airflow that bypasses the SOFC via the module bypass valve has a significant effect on the system performance as shown in Figure 7. The bypass is used to detour air around the stack is order to maintain adequate operating temperature. But as shown in Figure 7, the addition of bypass air decreases the system performance. This is due primarily to a reduction in the temperature of the gases entering the turbines, which reduces their output and efficiency. Then minimizing bypass flow during operation is desired to enhance system performance.
Heat Losses

In the range of heat losses studied, they did not demonstrate a significant effect on the overall system efficiency. In practice, heat losses do affect overall system efficiency and can reduce effectiveness of the recuperator. In the current simulation, the heat duty in the recuperator is fixed. Thus, increasing heat loss in the current model produces a more efficient recuperator, which will increase the cost but offset the decrease of the system efficiency. Reductions in heat losses improve overall system efficiencies in practice and should be a major focus of hybrid system development for both efficiency and overall system cost reasons.

OPTIMIZATION

The 220 kW proof-of-concept project has demonstrated that integration of high temperature fuel cells and gas turbines is achievable, and that it leads to increased system efficiencies. In addition, the current project was the first to demonstrate continuous operation of a pressurized SOFC system. These are major accomplishments. In addition, the current system is providing insight into the complex interactions that exist between and amongst hybrid system components, where as a desired effect to a parameter change can be counteracted by the response of another system component. A significant interaction that has been identified, herein, is the interaction of the SOFC generator temperature and cell performance as it responds to airflow fluctuations. This interaction will be studied in more detail in future steady state and dynamic simulation analyses.

The current system was not designed to achieve optimal performance for a system of this size and characteristics. The system integrates a novel design for a tubular SOFC stack with integrated internal reformer with an emerging microturbine system. The system has nonetheless very successfully proven the hybrid concept and demonstrated its feasibility. The current analyses can provide direct insight, however, into how the current system could be optimized.
The DOEx analyses can determine significant interactions and parameter modifications that can lead to optimum system operation. The optimization analyses performed show that the highest system efficiency can be achieved when pressure ratio is higher and compressor and turbine efficiencies are higher, while bypass percentage is kept as low as possible. Analyses show that operation at the higher pressure ratio and increased compressor and turbine efficiencies, together with a low bypass ratio produces an optimized system with overall efficiency of 57.97%.

DISCUSSION

Through analyses conducted using the APSAT model, from operational experiences with the 220 kW hybrid systems, and from sensitivity analyses performed using a design of experiments approach several design objectives have been identified for improvement of future hybrid cycles of this class. Suggestions include:

1. Pressure ratio increases - higher pressure ratio if achieved at small incremental cost to both the fuel cell and microturbine components will improve overall microturbine performance and increase power density and efficiency (through enhancement of electrode kinetics) of fuel cell.

2. Compressor efficiency improvements - higher compressor efficiencies unequivocally increase system efficiency.

3. Turbine efficiency increases - higher turbine efficiencies tend to increase overall system performance; however, lower turbine exit temperatures could result in the need to increase recuperator size or effectiveness in this type of hybrid cycle for overall system efficiency improvement.

4. SOFC operating stoichiometric ratio reduction - the bypass ratio sensitivity analyses suggest that lowering of the SOFC stoichiometric ratio (which has implications regarding compressor and turbine sizing as well) would lead to significant improvements in overall system efficiency. This issue requires SOFC materials science advancement to improve power density and lower polarizations. This would result in lower airflow requirements for this type of hybrid system, which results in higher turbine inlet temperatures, lower compressor losses, and significant overall system performance gains.

5. Bypass elimination/reduction - whenever possible, hybrid systems should eliminate or minimize fuel cell bypass airflow, which reduces turbine inlet temperatures and results in unnecessary compressor losses due to increased flow.

6. Single shaft gas turbine - to aid in airflow management the application of a single shaft gas turbine would improve operational control by allowing electric loading to manipulate the rotational speed and then effecting the airflow.

7. Heat loss and pressure loss reduction - significant heat losses in the current system configuration result in an overall efficiency that is significantly lower than an optimal system. This could be improved by better physical integration of the SOFC and gas turbine engine to reduce losses to the environment.
CONCLUSIONS

System simulation capabilities of the APSAT simulation tools are presented and discussed. A model is constructed to simulate a 220 kW SOFC gas turbine hybrid system. Model results are presented and compared to data acquired from an operating 220 kW SOFC gas turbine hybrid cycle. The comparison shows no more than 1% error between system efficiency predicted by the model and observed in operation, which well validates the APSAT simulation package. Sensitivity analyses were conducted using a design of experiments approach to identify the statistically significant and independent operating parameters that most significantly impact performance for these types of hybrid fuel cell systems. The coupling of fuel cells and gas turbines is shown to be complex, both in simulation and in the proof-of-concept system. However, results to date demonstrate the synergy of hybrids which can lead to higher efficiency and lower pollutant emissions. The discussion identifies the need to advance both component efficiencies (e.g. compressor efficiency) and integration aspects (e.g. elimination of bypass air) of these cycles in order to maximize the synergistic benefits of hybrid fuel cell gas turbine cycles of this type.

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