Fuel Cell/Gas Turbine Hybrid Systems

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Abstract

The National Fuel Cell Research Center (NFCRC) was established to accelerate the evolution of fuel cells and fuel cell systems. In addition to addressing the key research challenges in the emergence of fuel cells, the Center assists the market to understand this unusual power system and the opportunities for both central and distributed generation. An intriguing fuel cell research initiative in which the NFCRC is focused addresses the development of hybrid turbocell systems. With an unusually high fuel-to-electrical efficiency, hybrid systems portend a major paradigm shift for the future generation of power in a variety of applications. The first demonstrations of both high-pressure and atmospheric pressure hybrid systems verify the basic principles of the technology, delineate the component features that require technology advances, and confirm the viability of the product for a near-term and long-term market for a broad variety of applications in both stationary and transportation. Both the Molten Carbonate Fuel Cell (MCFC) and the Solid Oxide Fuel Cell (SOFC) are attractive for hybridization due to the high operating and effluent temperature. Systems are emerging for distributed generation (15kW to 50 MW) with combinations of high-temperature fuel cells (HTFCs) and micro-turbine generators (MTGs). Concepts are also evolving for central plant configurations (~300MW) where ultra high-efficiency on both natural gas and coal are desired in combination with zero-emission of criteria pollutants, CO2 sequestration, and hydrogen co-production.

1.0 Introduction

The application of fuel cell technologies to advanced power generation systems signifies the most significant advancement in energy conservation and environmental protection for the next decade. The National Fuel Cell Research Center (NFCRC) was established in 1998 to provide key leadership in the development and application of these new technologies. The mission is to promote and support the genesis of fuel cell power generation systems by providing technological leadership with a vigorous program of research and beta testing, coupled with education and technology transfer to and from the marketplace.

For several reasons, the NFCRC offers a timely focus on an emerging new power technology. First, fuel cells represent the most important new power generation technology of this decade. Second, the technology's successful emergence is constrained in the absence of an institutional "magnet" that can attract and coalesce the various stakeholders into an integrated effort to pursue technical development and raise awareness of fuel cells. One example of a major new fuel cell technology is the "Hybrid System" where a fuel cell is combined with another power generation device to create a synergy with attributes that exceed the sum of the two when combined.

2.0 Hybrid Systems

The NFCRC is engaged in a variety of fuel cell initiatives. One of the more intriguing is the development of "Hybrid Systems." The NFCRC is developing steady-state and dynamic models, applying these models to a wide spectrum of Hybrid concepts, and is currently hosting the demonstration of the first Hybrid system to be fabricated and operated.

"Hybrid Systems" are power generation systems in which a heat engine, such as a gas turbine, is combined with a non-heat-engine, such as a fuel cell. The resulting system exhibits a synergism in which the combination performs with an efficiency that far exceeds that which can be provided by either system alone. Thus the combination performs better than the sum of its parts. The working definition of "Hybrid Power Systems" is evolving, but currently the following statement captures the basic elements:

> " Hybrid Power Systems combine two or more energy conversion devices that, when integrated provide (1) additional advantages over those devices operated individually, and (2) a synergism that yields performance that exceeds the sum of the components. "

With these attributes, combined with an inherent low level of pollutant emission, Hybrid configurations are likely to represent a major percentage of the next generation advanced power generation systems.

A Hybrid Power System that combines a gas turbine (GT) with a high-temperature fuel cell (HTFC) has been extensively analyzed and studied over the past five years by the U.S. Department of Energy (DOE), industry, and the NFCRC. These efforts have revealed that this combination is capable of providing remarkably high efficiencies. The historical record of the evolution of the GT-HTFC technology has been documented by White (1999), and the various technical elements of the GT-HTFC technology have been presented in a series of sessions sponsored by the American Society of Mechanical Engineers (ASME) International Gas Turbine Institute (IGTI) (1999, 2000, 2001, 2002, and 2003). The IGTI Board of Directors have adopted the term "Turbo-Fuel Cell" to depict this remarkable, emerging technology.

In the past three years, two application regimes have emerged for GT-HTFC Power Systems (Table 1). The anchor regime is the distributed generation application where units ranging from 10kW to 50MW are envisioned to participate in the new market. Recently, combinations of gas turbine engines with HTFCs are showing the potential for reaching the ultra-high fuel-to-electricity efficiencies (e.g., 75% on natural gas) established for the U.S. Department of Energy (DOE) Vision 21 Program (Rao and Samuelsen, 2002). This program is focused on next-generation Central Power Plants that will generate 300MW and higher. As a result, the two regimes receiving attention are

Table 1. GTE-HTFC Application Regimes

Regime	Range	Designation
Distributed Power Generation	15 kW to 50 MW	MTG-HTFC
Central Power Generation	100MW to 1000MW	GTE-HTFC

where MTG stands for Micro-Turbine Generator. Hybrid MTG-HTFC Power Systems will require a substantial development effort the technology is to be realized. Balance-of-plant issues, the required infrastructure, and the resolution of technical hurdles that are as yet ill defined, will all have to be addressed. While commercial product for Distributed Power Generation will emerge within five years, application of Hybrid GTE-HTFC technology to Central Power Generation will not be realized for a decade or more, if at all. However, the early analyses are showing that such systems are indeed technologically viable.

Given what is known about MTG-HTFC and GTE-HTFC Hybrids, a variety of technical issues are emerging. At the DOE/United Nationals Second Annual Hybrid Workshop held in Charlotte, North Carolina in April 2002, a working group of participants established and prioritized a list of immediate needs (Table 2).

Table 2. Immediate Requirements for Hybrid Systems

PRIORITY	REQUIREMENT
HIGH	Turbine Compatibility
	Hybrid Behavior –Load Loss –Load Following –Thermal Management –System Optimization
	High Temperature Fuel Cell Behavior
	Safety, Training
STRONG	Sensors and Controls
	Fuel Flexibility, Reformation
	Invertors and Power Electronics
	Analyses –Steady-State Models –Dynamic Models –Market
MODEST	Combustors

Developing Hybrid MTG-HTFC and GTE-HTFC Power Systems will be a complicated and difficult process. The power cycles consist of a series of modules or building blocks. Many of these blocks are available or will be available in the near future. Many such building blocks or subsystems are under development in programs that are partnerships between the NFCRC, the U.S. Department of Energy (USDOE) National Energy Technology Laboratory (NETL), and U.S. industry. These key subsystems include the products of the advanced turbine systems programs and various fuel cells also developed under NETL sponsorship. By carefully integrating these developed subsystems, with the results of future programs aimed at solving the remaining technical challenges, Hybrid power cycles will become a reality. These early Hybrid systems will provide efficiencies of 60 percent or higher and will meet the required emissions and cost criteria necessary to be successful in the marketplace. Later systems are projected to reach fuel-to-electrical efficiencies approaching 80% on natural gas.

3.0 Technical Features

A fuel cell generates electricity directly through electrochemical reactions and is more efficient than a heat engine because it eliminates the mechanical or rotating machinery (Figure 1). Because the performance of a fuel cell is not restricted by the Carnot Law constraints that limit heat engine efficiencies, the fuel cell will likely be the core of a high-efficiency hybrid power cycle

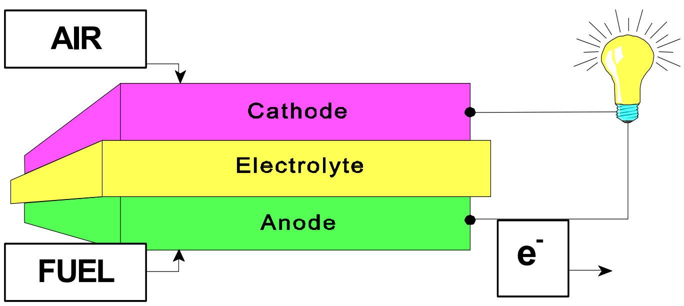

Figure 1. Fuel Cell

The electrical energy conversion efficiency of most fuel cells ranges from 40 to 60 percent based on the lower heating value (LHV) of the fuel. Fuel cells operate at high efficiency, regardless of size and load, and the by-product heat from fuel cell reactions can be efficiently used in cogeneration applications.

High temperature fuel cells (HTFCs), such as solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC) are especially well suited for Hybrid operation. These systems provide high temperature exhaust gas flows and allow the waste heat to be transformed to electricity. The gas turbine in a Hybrid system, for example, can be arranged to extract the thermal energy from the high temperature exhaust flow to drive the compressor, which in turn supplies pressurized air to the fuel cell. The residual enthalpy is available to expand through additional turbine stages and thereby produce additional electricity through a shaft connected generator. Fuel-to-electrical efficiencies in approaching 80% LHV are potentially possible. Furthermore, because fuel cells have extremely low NOx emission, the Hybrid is particularly environmentally sensitive.

The fuel cell and gas turbine can be configured in several different fashions. For the SOFC, the air stream can be first pressurized through the compressor of the turbine (Figure 2). The pressurized air stream is then fed to the SOFC where fuel (typically natural gas) is added, and the resultant electrochemical reactions lead to the direct production of electrical energy. The elevated pressure operation provides increases in both fuel cell efficiency and power density. The high-pressure, high-temperature fuel cell effluent can then be expanded in the turbine to provide (1) the compressor work, and (2) even more electrical energy. This effective utilization of "waste heat" to produce, in this case electricity rather than serve a thermal load, further increases the fuel-to-electricity efficiency.

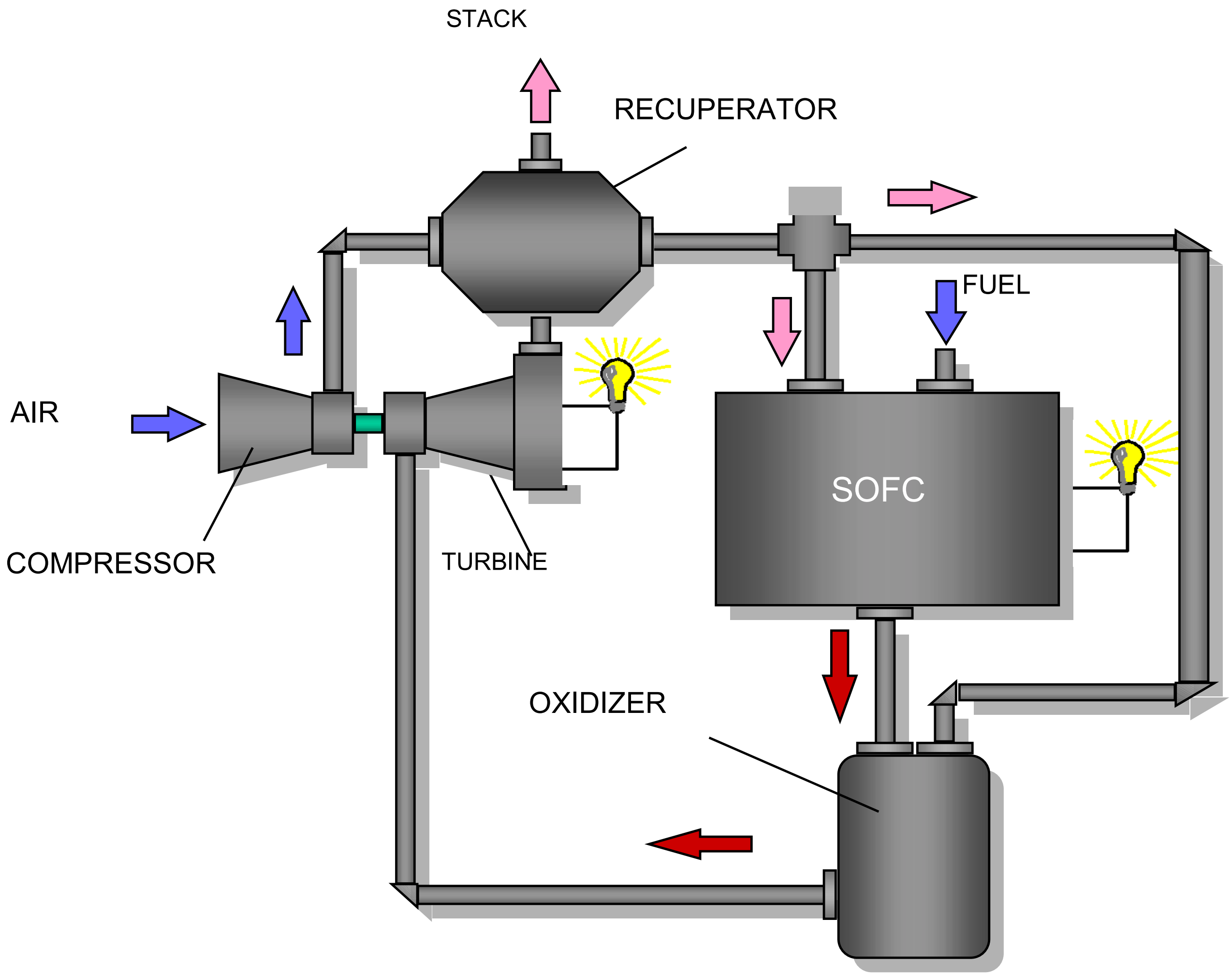

Figure 2. MTG-SOFC Hybrid Configuration

Another configuration is well suited for Molten Carbonate fuel cells and is being actively developed by Fuel Cell Energy, Inc. In this configuration (Figure 3), the fuel cell is located in the exhaust stream of the turbine and operates at atmospheric pressure.

For this paper, examples are provided for the MTG-SOFC for both Distributed Generation and Central Distribution. It is noteworthy that a 250 kW MTG-MCFC has been operated by FuelCell Energy Incorporated in Danbury Connecticut, in cooperation with Capstone Turbine Corporation, for over 4,500 hours in a successful demonstration.

4.0 MTG-SOFC: Distributed Power Generation

The first Hybrid demonstration of a pressurized MTG-SOFC (Figure 1) is being conducted at the NFCRC (Figure 4). This initiative, lead by Southern California Edison, is a 220 kW unit that utilizes a Siemens Westinghouse SOFC and an Ingersoll-Rand Energy Systems microturbine generator (MTG). The system to date has achieved over 2,000 hours of operation and attained the world record in fuel-to-electricity conversion efficiency. The unit is natural gas fired and the load is controlled through two (an AC for the turbine output, and a DC for the fuel cell output) dissipaters.

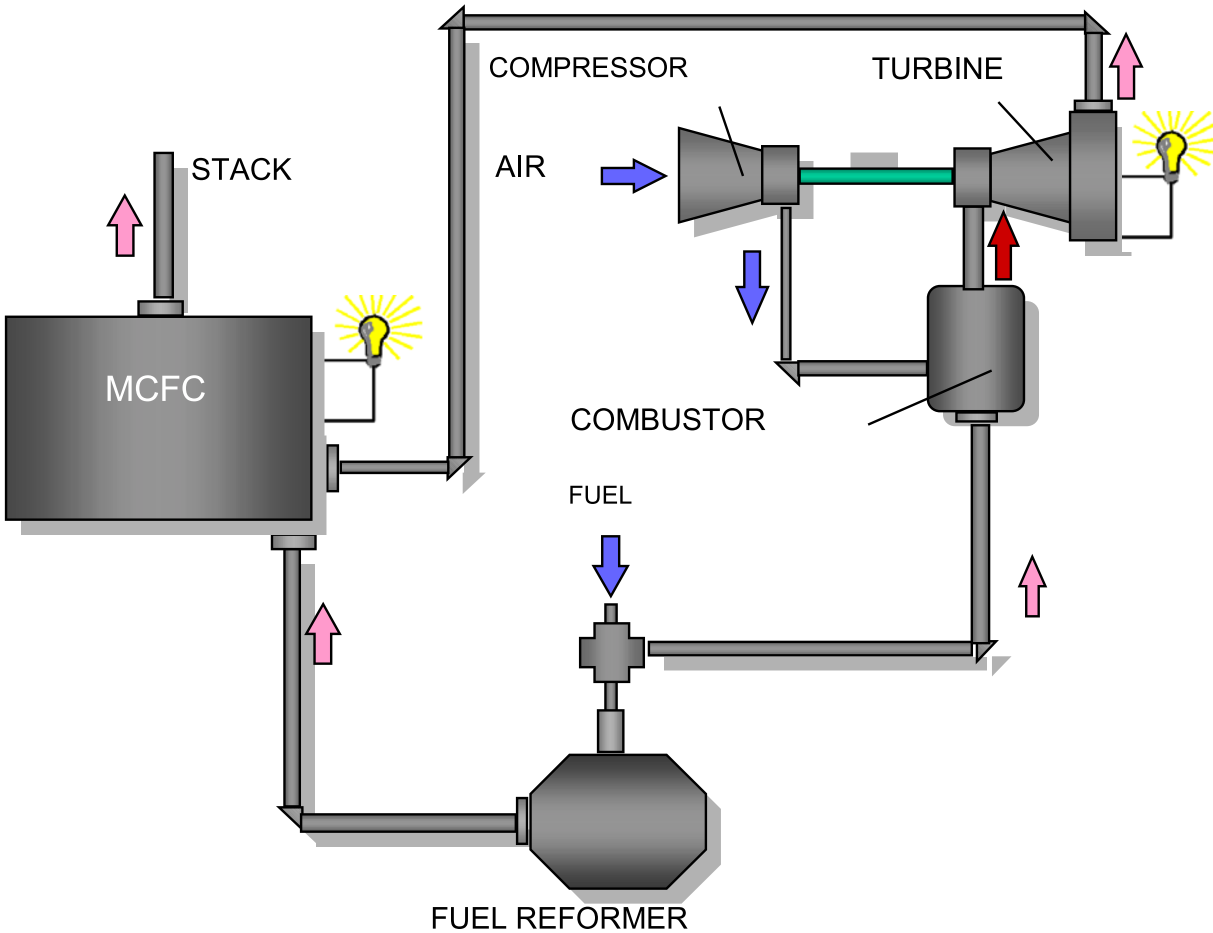

Figure 3. MCFC Configuration

The SOFC consists of a vertical cylindrical pressure vessel that houses a stack of 1152 tubular SOFCs. The MTG is a pre-commercial prototype 75 kW microturbine recuperated generator designed and built by Ingersoll-Rand Energy Systems, and modified for integration with the SOFC. The MTG is comprised of two shafts; a compressor-turbine, and a power turbine.

The MTG is not optimized for the 100 kW stack, but is instead oversized for the Brayton cycle heat input rate. As a result, the turbine inlet temperature and the power output at the MTG are lower than desired. For demonstration purposes, however, the system has proven invaluable in both (1) the demonstration of the credibility and potential for MTG-HTFC Power Systems, and (2) the identification of the critical engineering design issues that must be addressed in the design of a commercial prototype. In particular, the demonstration has shown that (Veyo, et. al, 2002):

- SOFC generator and MTG integration and operation, with the function of the MTG combustor supplanted by the SOFC generator, is viable and successful in achieving ultra-high fuel-to-electricity efficiency.

Figure 4. MTG-SOFC 220 kW Demonstration at the NFCRC

- A MTG-SOFC Hybrid Power System can be started, operated unattended, and shut down safely, and it can respond automatically and safely to upset conditions.

5.0 MTG-SOFC: Central Power Generation

Under the sponsorship of the DOE, a multi-disciplinary team led by the Advanced Power and Energy Program(APEP) of the University of California at Irvine is defining the system engineering issues associated with the integration of key components and subsystems into central power plant systems that meet stretch performance and emission goals for both natural gas and coal fuel fired operation. The myriad of fuel processing, power generation, and emission control technologies are narrowed down to selected scenarios in order to identify those combinations that have the potential to achieve the program goals of high efficiency and minimized environmental impact while using fossil fuels. The technology levels considered are based on projected technical and manufacturing advances being made in industry and on advances identified in current and future government supported research. Examples of systems included in these advanced cycles are high-temperature fuel cells, advanced gas turbines, ion transport membrane separation and hydrogen-oxygen combustion.

The overall objectives of DOE program are to:

- Produce electricity and transportation fuels at competitive costs
- Minimize environmental impacts associated with fossil fuel usage, and
- Attain high efficiency

The efficiency targets for natural gas fueled plants is 75% on a LHV basis while that for coal fueled plants is 60% on an HHV basis while producing electricity only, that is, without CO_2 capture and sequestration nor co-production of any transportation fuels, while the goal for coal based plants producing H_2 or transportation fuels only consists of achieving a minimum fuel utilization of 75% on an LHV basis.

The technology required to meet these goals are hybrid GTE-HTFC Power Systems.

As an example, consider the system depicted in Figure 5 (Rao, et. al, 2002). This concept is a GTE-SOFC integrated with a Humidified Gas Turbine (HAT) cycle. It consists of an intercooled gas turbine integrated with a pressurized tubular SOFC except that it incorporates humidification of the air and the humidified air is preheated in a recuperator in the turbine exhaust before it is fed to the SOFC. The fuel utilization in the SOFC is limited to 85%. The air leaving the high pressure compressor is first cooled in an aftercooler and then introduced into the humidifier column where it comes into counter-current contact with hot water. A portion of the water is evaporated into the air stream, the heat required for the humidification operation being recovered from the intercooler and the stack gas by circulating water leaving the humidifier. The desulfurized fuel is also humidified in a similar manner. The optimum efficiency of the cycle occurred at a pressure ratio of approximately 20 and a gas turbine firing temperature at a modest value of <1200 ºC.

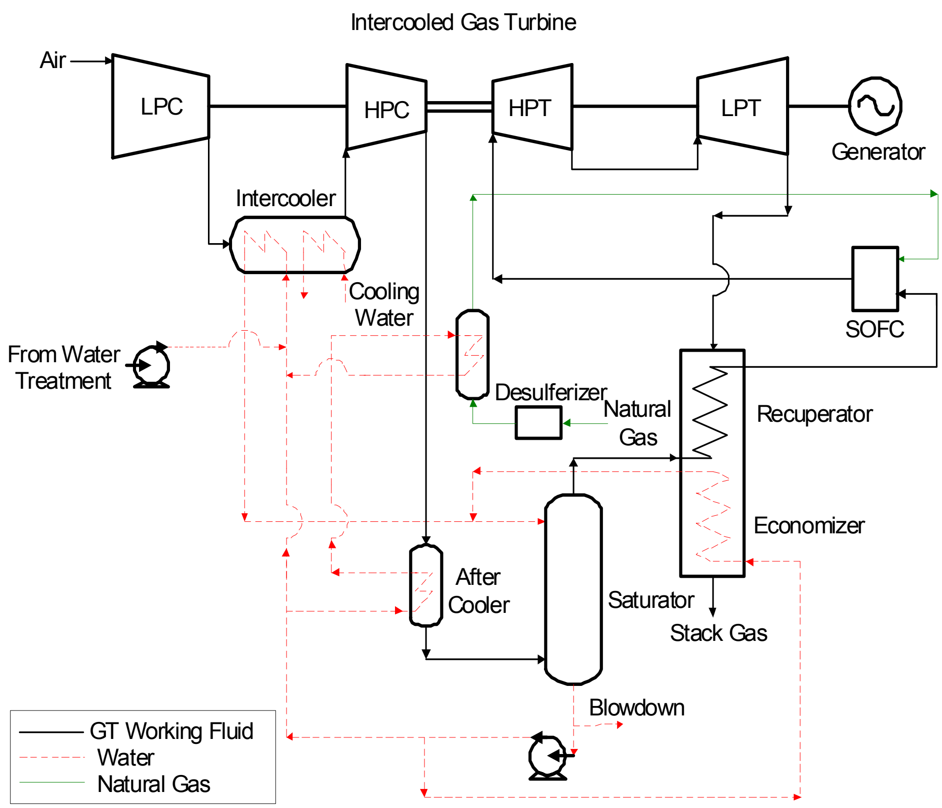

Figure 5. GTE-SOFC 300MW Central Generation Cycle

It was determined also for this configuration that, in order to reach the efficiency goal of 75% (LHV) on natural gas, the SOFC had to operate with a fuel to air ratio approaching stoichiometric. If higher air to fuel ratios were to be utilized in the SOFC, then an alternate approach is required (e.g., the installation of a second SOFC between the HP and LP turbines).

6.0 Summary

The current decade will witness the evolution of the Hybrid in a variety of configurations, and observe the commercialization of units into various applications from distributed generation, to power of ships, to rail locomotives. The opportunity to generate electricity at high efficiency and with near zero pollutant emission suggests a new era of power production that is attractive to both developed, nearly developed, and developing countries.

7.0 References

IGTI (1999). The Hybrid Cycle: Integration of the Gas Turbine with a Fuel Cell Session, The International Gas Turbine Institute Turbo-Expo, Indianapolis, June.

Developmental Status of Hybrids (1999). ASME 99-GT-400 (Abbie Layne, Mark Williams, Scott Samuelsen, Patricia Hoffman)

Hybrid Gas Turbine and Fuel Cell Systems in Perspective Review (1999). ASME 99-GT-419 (David White)

Solid Oxide Fuel Cell Power System Cycles (1999). ASME 99-GT-356 (Stephen E. Veyo, Wayne L. Lundberg)

The Hybrid Cycle: Integration of a Fuel Cell with a Gas Turbine (1999). ASME 99-GT-430 (John D. Leeper).

The Hybrid Cycle: Integration of Turbomachinery with a Fuel Cell (1999). ASME 99-GT-361 (Sy Ali, Robert R. Moritz)

Technical Development Issues and Dynamic Modeling of Gas Turbine and Fuel Cell Hybrid Systems (1999). ASME 99-GT-360 (Eric Liese, Randall Gemmen, Faryar Jabbari, Jacob Brouwer)

IGTI (2000). The Hybrid Cycle: Integration of the Gas Turbine with a Fuel Cell Session, The International Gas Turbine Institute Turbo-Expo, Munich, May.

Hybrid Heat Engines: The Power Generation Systems of the Future (2002). ASME 2000-GT-0549 (Abbie Layne, Mark Williams, Scott Samuelsen, Patricia Hoffman)

Tubular Solid Oxide Fuel Cell/Gas Turbine Hybrid Cycle Power Systems Status (2002). ASME 2000-GT-0550 (Stephen Veyo, Larry Shockling, Jeffrey Dederer, James Gillett, Wayne Lundberg)

A Prototype for the First Commercial Pressurized Fuel Cell System (2002). ASME 2000-GT-0551 (Sy Ali, Robert Moritz)

Ultra High Efficiency Hybrid Direct Fuel Cell/Turbine Power Plan (2002). ASME 2000-GT-0552 (Anthony J. Leo, Hossein Ghezel-Ayagh, Robert Sanderson)

Analysis Strategies for Tubular SOFC Based Hybrid Systems (2002). ASME 2000-GT-0553 (Ashok Rao, Scott Samuelsen)

Development of Dynamic Modeling Tools for Solid Oxide and Molten Carbonate Hybrid Fuel Cell Gas Turbine Systems (2002). ASME 2000-GT-0554 (Randall Gemmen, Eric Liese, Jose Rivera, Faryar Jabbari, Jacob Brouwer)

IGTI (2001). The Hybrid Cycle: Integration of the Gas Turbine with a Fuel Cell Session, The International Gas Turbine Institute Turbo-Expo, June, New Orleans.

Hybrid Fuel Cell Heat Engines: Recent Efforts (2001). ASME 2001-GT-0588 (Abbie Layne, Mark Williams, Norman Holcombe, Scott Samuelsen)

A Turbogenerator for Fuel Cell/Gas Turbine Hybrid Power Plant (2001). ASME 2001-GT-0524 Sy Ali, Robert Moritz)

A Thermodynamic Analysis of Tubular SOFC Based Hybrid Systems (2001). ASME 2001-GT-0522 (Ashok Rao, G.S. Samuelsen)

A High-Efficiency SOFC Hybrid Power System Using the Mercury 50 ATS Gas Turbine (2001). ASME 2001-GT-0521 (Wayne Lundberg, Stephen Veyo, Mark D. Moeckel)

IGTI (2002). The Hybrid Cycle: Integration of the Gas Turbine with a Fuel Cell Session, The International Gas Turbine Institute Turbo-Expo, June, Amsterdam.

The National Energy Technology Laboratory's Hybrid Power Systems Program (2002). ASME GT-2002-30668 (Richard Dennis, Mark Williams, Abbie Layne, Scott Samuelsen, Norm Holcombe)

Status of Pressurized SOFC/Gas Turbine Power System Development at Siemens Westinghouse (2002). ASME GT-2002-30670 (Stephen Veyo, Kevin Litzinger, Shailesh Vora, Wayne Lundberg)

Power Plant System Configurations for the 21st Century (2002). ASME GT-2002-30671 (Ashok Rao, Scott Samuelsen, Fred Robson, Rodney Geisbrecht)

Rao, Ashok; Samuelsen, Scott; Robson, Fred; Geisbrecht, Rodney (2002). Power Plant System Configurations for the 21st Century, ASME GT-2002-30671

Veyo, Stephen; Litzinger, Kevin; Vora, Shailesh, and Lundberg, Wayne (2002). Status of Pressurized SOFC/Gas Turbine Power System Development at Siemens Westinghouse, ASME GT-2002-30670

White, David (1999). Hybrid Gas Turbine and Fuel Cell Systems in Perspective Review, ASME 99-GT-419, 1999.

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