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State of direct fuel cell/turbine systems development☆

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Abstract

FuelCell Energy Inc. (FCE) is actively developing fuel cell/gas turbine hybrid systems, DFC/T®, for generation of clean electric power with very high efficiencies. The gas turbine extends the high efficiency of the fuel cell without the need for supplementary fuel. Key features of the DFC/T system include: electrical efficiencies of up to 75% on natural gas (60% on coal gas), minimal emissions, simple design, reduced carbon dioxide release to the environment, and potential cost competitiveness with existing combined cycle power plants. FCE successfully completed sub-MW scale proof-of-concept tests (pre-alpha DFC/T hybrid power plant). The tests demonstrated that the concept results in higher power plant efficiency. A small packaged natural gas fueled sub-MW unit is being developed for demonstrations (alpha and beta units). Also, the preliminary design of a 40 MW power plant including the key equipment layout and the site plan was completed.

Keywords: Carbonate fuel cell; Internal reforming fuel cell; Gas turbine; Hybrid power plant; Multi-MW plant design; MCFC

1. Introduction

In recent years, there has been a surge of interest in the integration of the fuel cells with gas turbines for electric power generation. The premise of these power cycles are ultra high efficiency and very low emissions. Among various types of fuel cells, the high temperature type (>600 °C), including solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC), is suitable for integration with gas turbines [1]. The gas turbines being mechanical energy conversion devices operate more efficiently at higher temperatures (turbine inlet). The hybrid fuel cell/gas turbine systems using SOFC [2] and MCFC [3] have been studied and optimized for performance.

FCE's DFC/T hybrid system concept is based on integration of the company's internal reforming Direct FuelCell® [4,5] with an indirectly heated gas turbine to supplement fuel cell generated power. The fuel cell plays the key role by producing the larger share of the power (>80%). The gas turbine is utilized for generation of additional power by recovering the fuel cell byproduct heat in a Brayton cycle, as well as for providing the air for fuel cell operation. The power plant design consists of a novel waste heat recovery approach for extraction of heat from the fuel cell exhaust [6]. Because of the indirect heat transfer to the turbine expander and absence of a combustor, NO_x is not generated by the gas turbine.

One of the key features of DFC/T concept is the independent (uncoupled) operating pressure of the fuel cell and turbine. Hence, the system works very efficiently with a wide range of air compression ratios (3–15). Typically, small-scale gas turbines (micro-turbines) use a low compression ratio (3–4), while the MW-size units are designed for high compression ratios (7–15). The DFC/T system design is suitable over a range of applications from sub-MW industrial to medium scale (MW) distributed generation to large central station plants. The concept also features adeptness to the existing industrial frame gas turbines. Based on these features, FCE embarked on the proof-of-concept tests integrating a fuel cell stack with a micro-turbine. The results of these tests were also used to provide the design (mechanical and control) information for development of multi-MW scale power plants. The current Vision 21 project is intended to move

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forward the development of multi-MW power plants for the wholesale market.

2. System description

The DFC/T system concept is schematically shown in Fig. 1. The system includes a heat recovery unit (HRU) consisting of a series of heat exchangers arranged to maximize the heat recovery from the cathode exhaust gas. The HRU has a dual functionality of preparing the anode gas, and also, transferring a portion of system exhaust heat to the gas turbine air (in low temperature recuperator, LTR). The preparation of anode gas includes humidification of natural gas by the feed water, and preheating of the anode gas to the fuel cell operating temperature. The humidification process provides the steam needed for the reforming of natural gas. Typically a steam-to-carbon ratio of two and higher is required for steam reformation of natural gas to prevent carbon formation. The mixed fuel and steam are preheated to the temperature of about 550 °C prior to entering the fuel cell anode. The methane in the natural gas is steam reformed in the direct carbonate fuel cell (internal reforming) to hydrogen, which is the primary fuel for the fuel cell. The fuel cell reactions are:

Anode

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad \text{reforming} \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \text{water gas shift} \tag{2}$$

$$H_2 + {CO_3}^{2-} \rightarrow H_2O + CO_2 + 2e^- \quad \text{electrochemical} \tag{3}$$

Cathode

$$\tfrac{1}{2}O_2 + CO_2 + 2e^- \rightarrow {CO_3}^{2-} \quad \text{electrochemical} \tag{4}$$

At the anode, hydrogen is electrochemically reacted producing dc electricity, and CO_2 and water vapor as byproducts. The availability of water vapor at anode as a product of electrochemical reaction helps drive the reforming reaction to completion and minimizes the need for feed water to the system. The anode exhaust containing some unreacted fuel is mixed with air and then oxidized completely in a catalytic oxidizer.

In the turbine cycle, air is compressed to the operating pressure of the gas turbine and heated in the LTR using waste heat from the fuel cell. The compressed air is then heated further to the operating temperature of the gas turbine expander by a high temperature recuperator (HTR) located between the oxidizer and fuel cell (cathode). The hot compressed air is expanded in the turbine providing additional electricity. The expanded air then flows into the oxidizer. The oxidizer exhaust, containing excess air, flows into HTR, and subsequently into the fuel cell cathode. At the cathode, oxygen (in the air) and CO_2 (from the anode exhaust) are reacted to complete the fuel cell electrochemical reaction. The heat generated in the fuel cell as the byproduct of the electrochemical reaction is utilized partly to support the endothermic (methane) reforming reaction. The thermal integration of the fuel cell electrochemical and methane reforming reactions offered by the internal reforming direct fuel cell enhances the fuel cell electrical efficiency while helping in the thermal management of fuel cell stack/module. The cathode exhaust, containing the heat from fuel cell, provides the heat for preheating the air (in LTR) and fuel, and for generation of steam in HRU before exiting from the power plant.

3. Proof-of-concept tests

The focus of proof-of-concept tests was on the verification of the DFC/T concept, the developmental testing of critical system components and acquiring design information for development of power plant products. The first series of tests involved integration of a 250 kW (full-size) DFC stack with a modified Capstone Simple Cycle Model 330 micro-turbine. The micro-turbine was constructed with a compressed air exhaust port and expander inlet pipe to provide flow connections

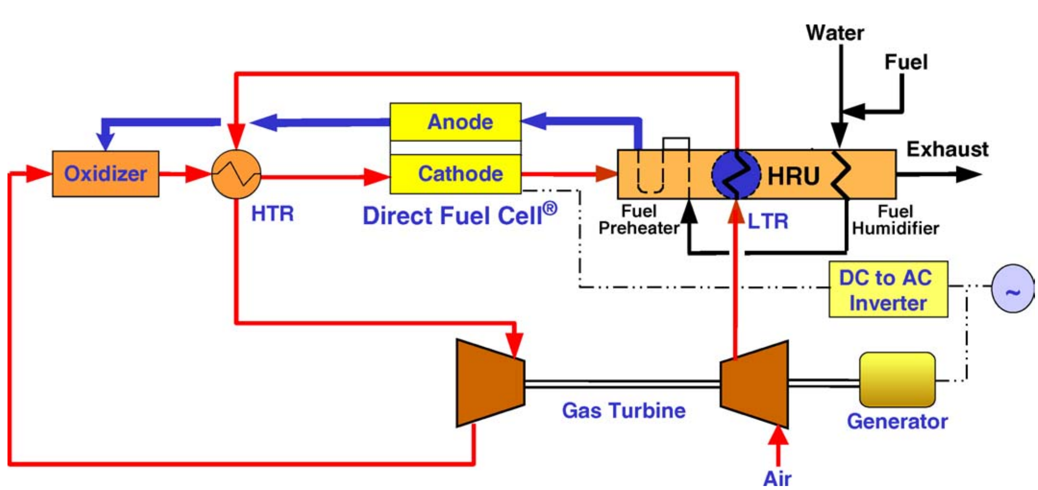

Fig. 1. DFC/T® ultra high efficiency system concept: fuel cell byproduct heat is utilized in gas turbine to supplement fuel cell power.

to the fuel cell system. An air blower was also included in the power plant, which increased the flexibility of operation for the testing purposes. The power plant was capable of operating in dual modes: fuel cell/turbine integrated mode and fuel cell only mode. The dual mode capability was used to evaluate the benefits of the DFC/T cycle over the fuel cell-only cycle. The results of the first phase of tests have previously been presented and published [7,8]. The dual mode operation confirmed that greater efficiencies could be obtained by integration of micro-turbine with the fuel cell. As micro-turbine with higher airflow became available, the next phase of tests were conducted after replacing Capstone Model 330 with Capstone C60. These tests also benefited from the next generation of full-size fuel cell stack. Fig. 2 shows a picture of the DFC/T power plant facility with the C60 micro-turbine integrated in the fuel cell system. Fig. 3 shows a simplified process flow sheet for the sub-MW DFC/T power plant, including a typical set of process operational data. Three heat recuperators for indirect heating of air from the compressor side of the micro-turbine were included. The anode exhaust oxidizer included a high temperature catalytic section.

The proof-of-concept test was completed verifying the DFC/T concept. The world's first grid-connected fuel cell/turbine hybrid system operated for >6600 h. Thermal management of the system was confirmed by increasing micro-turbine expander inlet temperature while controlling the fuel cell operating temperature. The control strategies were refined based on the operational experience. The tests successfully demonstrated the ability of the control system to follow prescribed load ramps and to respond to abrupt utility grid outages. The system trip/emergency shutdown scenarios were tested successfully. The power plant operation was demonstrated using the micro-turbine as the only source of fresh air supply to the system. The operational tests, as well as the tests of the power plant heat-up during the process and control checkout of the balance-of-plant (BOP), confirmed the stable and well-controlled operation of the DFC/T power plant with the micro-turbine. NO_x emission levels of less than 0.25 ppm were achieved. Computer simulation of the power plant including mass and energy balances was utilized as analytical tool during the testing period. The BOP equipment and the micro-turbine performance were monitored and eval-

Fig. 2. Sub-MW DFC/T hybrid power plant facility: full-size DFC stack was integrated with capstone C60 micro-turbine.

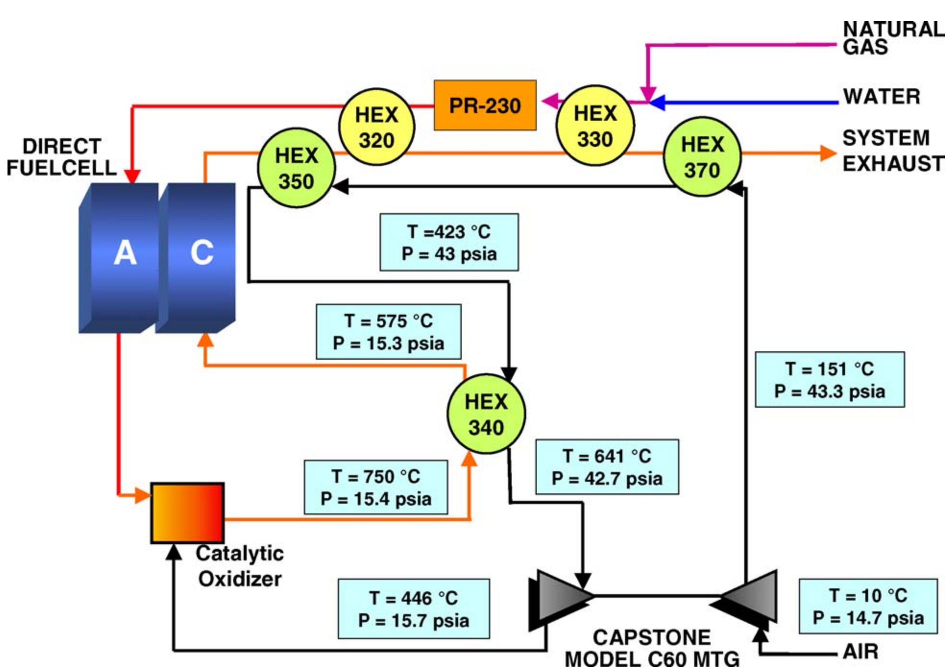

Fig. 3. Sub-MW DFC/T hybrid power plant facility process flow diagram: a typical set of operational data are included.

uated. The heat transfer coefficients for the heat exchangers were analyzed against the vendor supplied information. The heat losses from the pipes and equipment in the power plant test facility were estimated. The results of the sub-MW system tests have indicated that effective recuperation of heat to the gas turbine and minimization of the heat loss from the BOP equipment are important factors in the design of DFC/T power plants.

4. Sub-MW power plant design and demonstrations

Demonstration of DFC/T system configuration in sub-MW class power plant units for distributed generation is the next step in evolution of the hybrid systems. FuelCell Energy has planned to build and test a packaged DFC/T power plant at its facility in Danbury, CT (alpha unit), and then demonstrate the second DFC/T power plant (beta unit) in Montana. These DFC/T sub-MW plants will demonstrate grid-connected operations, help assess the efficiency potential of the sub-MW plants and provide valuable data on integration and operation of DFC/T power plants under laboratory and field conditions.

The preliminary design of the sub-MW packaged demonstration unit has been completed. Steady-state mass and energy balances for the power plant were performed for various modes of operation; including start-up, standby, and full load operation; using the CHEMCAD process simulation software. The process equipment specifications were prepared and issued to original equipment manufacturers (OEM) and suppliers for quotation. A process flow diagram of the power plant including major operating equipment along with the plant start-up equipment was generated. The design modifications of existing DFC300A fuel cell module for application to the DFC300/T system were completed. A safety review of the DFC300T system was conducted based on the Hazop methodology utilized widely by the process industries. A set of piping and instrumentation diagrams (P&IDs), with instrument and equipment design information, was also prepared incorporating design information and recommendations from sub-MW proof-of-concept test results, DFC300 product data and the Hazop safety review mentioned above. Suppliers for key equipment such as micro-turbine, recuperators and anode gas oxidizer have been selected. Three-dimensional equipment (process, utility and other) and piping layout drawings were prepared using the intergraph plant design software. Pipe stress analysis was completed using Caesar II software, generating specifications for expansion joints and pipe supports. Specifications for all valves including safety valves and pressure regulators were prepared, and bids were solicited from the suppliers. Design parameters and specifications have been developed for key instrument and control equipment. All major equipment and instrument items have been ordered. The procurement is in progress.

A preliminary review of potential demonstration sites in Montana for the beta sub-MW unit was completed. Two venues in Montana, including the Engineering/Physical Science Building at Montana State University (Bozeman, MT) and the Deaconess Billings Clinic (Billings, MT), were investigated. Both sites were found to be suitable for the demonstration.

5. Multi-MW power plant design

The baseline DFC/T configuration included a high temperature recuperator. The multi-MW power plant performance (power output and efficiency) estimates for the near, intermediate and long-term systems, based on this configuration, are presented in Table 1. For comparison, performance estimates for the DFC-only systems are also shown in the table. Based on the comparison, the integration of the fuel cell with turbine in a hybrid system offers significant improvement in power plant electrical efficiency. The mid-term and long-term estimates are both based on improved fuel cell performance expected with fuel cell developments. The long-term system, in addition, employs an advanced gas turbine featuring in-

Table 1
Multi-MW DFC/T power plant (baseline configuration) performance projections

	Near-term		Mid-term		Long-term
	DFC	DFC/T hybrid	Improved DFC	DFC/T hybrid with improved DFC	DFC/T hybrid with intercooled & re-heat gas turbine
Fuel cell					
dc power out (MW)	12.0	12.0	16.8	16.8	33.5
ac power out, gross (MW)	11.3	11.3	16.4	16.3	32.7
Gas turbine					
Expander power (MW)		7.9		8.7	20.7
Compressor power (MW)		(5.3)		(5.9)	(10.9)
Net ac out (MW)		2.5		2.6	9.3
Air blower power (MW)	(0.3)		(0.3)		
Auxiliary power consumption (MW)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)
Net power output (MW)	11.0	13.7	15.9	18.8	41.8
Efficiency (%) (LHV natural gas)	49.9	62.0	57.0	67.0	74.6

Hybrid system has potentially significant efficiency gain over DFC-only system.

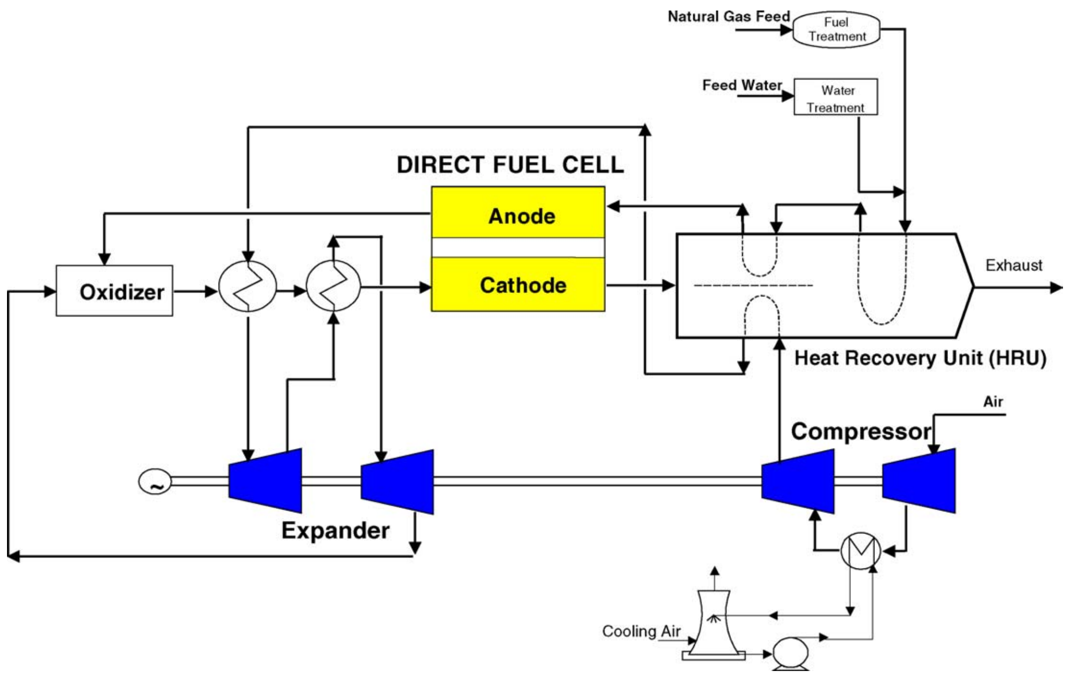

Fig. 4. Process flow diagram of the long-term multi-MW DFC/T hybrid system: system features an advanced gas turbine with intercooled and re-heat cycle.

tercooled and reheat cycle that might be available in future with gas turbine developments. Fig. 4 shows the process flow diagram of the system. The long-term system has a potential to offer system electrical efficiency approaching 75% (LHV natural gas).

The preliminary design of a 40 MW power plant for near-term application was completed. The design is based on a scalable approach using FCE's existing M-10 (MW-scale) fuel cell modules in a cluster arrangement. The fuel cell cluster design has five M-10 modules in a cluster with common distribution piping for the fuel and oxidant gases. Based on the scalable overall plant design concept, the plant is arranged in three sections in addition to the centralized equipment. Each section consists of two clusters of fuel cell modules together with supporting equipment. The centralized equipment, which supports all three sections, includes a gas turbine, an anode gas oxidizer and other common site equipment such as a fuel clean-up subsystem and a water treatment subsystem.

The process flow diagrams with process controls for normal operation and start-up heating were generated. Steady-state mass and energy balances for the power plant were completed for various modes of operation; including start-up, standby, and full load operation. The performance of the 40 MW power plant estimated based on near-term fuel cell performance and a commercially available gas turbine is presented in Table 2. Specifications were prepared for key pieces of equipment and subsystems. Potential suppliers were contacted, and preliminary configuration information and cost estimates were obtained. The gas turbine selected for the 40 MW plant design is a Man Turbo Model 1304-11. Man Turbo's THM heavy-duty gas turbine features a rugged industrial design. Key characteristics of the gas turbine include: pressure ratio of eight and turbine inlet temperature of 1800 °F. The fuel clean-up subsystem is a centralized desulfurizer for the natural gas fuel, which uses activated carbon in an epoxy lined carbon steel vessel. Electrical one-line diagrams were prepared for the power generation and auxiliary power needs. The power conditioning system (PCS) is designed to convert the 300 VDC from the fuel cells to 13.8 kV and is modular. A PCS module supports each fuel cell cluster. The 6000 kW modular unit is a packaged assembly that includes IGBT-based inverters and a step-up transformer. The central control system for the plant is designed to coordinate the output of the three plant sections (six PCS modules). It provides operational sequence control for plant start-up heating, on-load operation, and normal and emergency shutdowns.

An overall layout/plot plan of the 40 MW plant is shown in Fig. 5. The site is approximately 273′ × 325′ in size. The

Table 2
Forty-megawatt DFC/T hybrid power plant performance (estimate)

Fuel cell	
dc power output (MW)	36.1
ac power output (MW)	34.3
Gas turbine	
Expander power (MW)	21.8
Compressor power (MW)	(10.4)
Net ac power (MW)	10.8
Plant parasitic load	
Anode gas compressor (MW)	(3.6)
Other auxiliary loads (MW)	(0.8)
Net power output (MW)	40.8
Efficiency (%) (LHV of natural gas)	61.8

An electrical efficiency of 62% is expected in a near-term system.

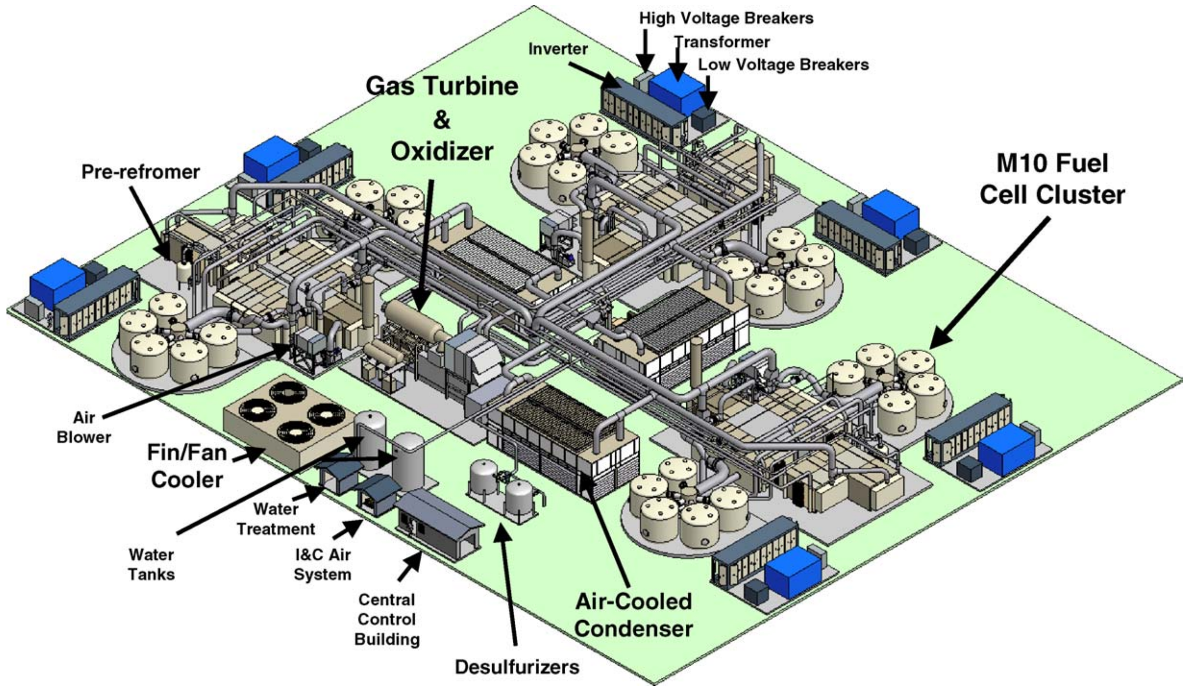

Fig. 5. Forty megawatt plant layout/plot plan: power plant is divided into three sections, each containing a pair of fuel cell module clusters.

arrangement of equipment on the site is designed to provide easy access to the equipment for maintenance and replacement, and minimize the length for the largest process piping. Design of the site arrangement included sizing of all the process piping and the development of process pressure profiles consistent with performance estimates. Thermal insulation requirements were established for all the process piping based on a surface touch temperature limit criteria. A computer model was developed for detailed design of the piping system including pipe sizes and insulation thickness requirements.

6. Conclusions

The proof-of-concept test of the DFC/T system in the sub-MW power plant facility was completed achieving the milestone of being the world's first grid-connected hybrid fuel cell/gas turbine power plant. Thermal management of the system was confirmed. The control strategies were refined. System trip/emergency shutdown scenarios were tested successfully. Power plant operation, using a microturbine as the only source of fresh air supply to the system, was demonstrated.

The preliminary design of the sub-MW hybrid packaged unit (for alpha demonstration) has been completed. Design modifications to the existing DFC-300A fuel cell module for its application to the DFC300/T unit were completed. A Hazop safety review of the DFC300/T system was completed and a set of P&IDs was refined. All major equipment and instrumentation items have been ordered. Procurement of parts and system components is in progress.

A scalable approach for the multi-MW plant design based on fuel cell clusters of the existing 1 MW (M-10) modules has been developed. Preliminary design for the 40 MW DFC/T hybrid system using a commercially available gas turbine was completed. The system electrical efficiency (LHV) based on near-term fuel cell performance was estimated to be 62%. Process flow diagrams with equipment and controls for operation and start-up have been prepared. Major equipment specifications were prepared and vendor quotes were solicited. Electrical one-line diagrams have been generated. Plant pipe sizing and insulation requirements were determined. Major equipment layouts and power plant plot plans have been generated.

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