Direct Fuel Cell/Turbine Power Plant

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ABSTRACT

This report includes the progress in development of Direct FuelCell/Turbine® (DFC/T®) power plants for generation of clean power at very high efficiencies. The DFC/T power system is based on an indirectly heated gas turbine to supplement fuel cell generated power. The DFC/T power generation concept extends the high efficiency of the fuel cell by utilizing the fuel cell's byproduct heat in a Brayton cycle. Features of the DFC/T system include: electrical efficiencies of up to 75% on natural gas, 60% on coal gas, minimal emissions, simplicity in design, direct reforming internal to the fuel cell, reduced carbon dioxide release to the environment, and potential cost competitiveness with existing combined cycle power plants.

The operation of sub-MW hybrid Direct FuelCell/Turbine power plant test facility with a Capstone C60 microturbine was initiated in March 2003. The inclusion of the C60 microturbine extended the range of operation of the hybrid power plant to higher current densities (higher power) than achieved in previous tests using a 30kW microturbine.

The design of multi-MW DFC/T hybrid systems, approaching 75% efficiency on natural gas, was initiated. A new concept was developed based on clusters of One-MW fuel cell modules as the building blocks. System analyses were performed, including systems for near-term deployment and power plants with long-term ultra high efficiency objectives. Preliminary assessment of the fuel cell cluster concept, including power plant layout for a 14MW power plant, was performed.

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1.0 EXECUTIVE SUMMARY

Operation of the subMW hybrid DFC/T power plant facility, modified with a Capstone C60 microturbine, was initiated. The integration of the C60 microturbine extended the capability of the hybrid power plant to operate at high power ratings with a single gas turbine without the need for supplementary air. The objectives of this phase of subMW hybrid power plant tests are to support the development of process and control parameters and to provide the insight for the design of the packaged subMW hybrid demonstration units.

The design of the subMW hybrid packaged unit was initiated. The design basis for the subMW hybrid unit will be derived from FCE's existing DFC300 product line. The key modifications include the integration of the microturbine and heat recovery recuperators in the DFC300 design.

The development of the ultra high efficiency Multi-MW power plants was focused on the design of power plants with efficiencies approaching 75% (LHV of natural gas). The design efforts included thermodynamic cycle analysis of key gas turbine parameters such as compression ratio. The power plant designs were studied for near-term deployment utilizing the existing commercially available gas turbines and long-term deployment requiring advanced gas turbine technologies. A new fuel cell cluster concept was developed for mechanical design of Multi-MW systems. The concept utilizes the existing one-MW fuel cell modules as the building block for the Multi-MW hybrid systems. A conceptual layout for a 14MW hybrid power plant for near term application was developed utilizing commercially available gas turbines.

2.0 EXPERIMENTAL

In this reporting period, the tests of the subMW power plant facility were initiated for the next phase of operation of a 250 kW fuel cell stack integrated with the Capstone C60 microturbine. Figure 1 shows a picture of the DFC/T power plant facility with the C60 microturbine integrated in the fuel cell system.

Prior to installation of the fuel cell stack, the process and control tests of the balance-of-plant (BOP), including the microturbine, were performed. Various power plant operational modes were tested successfully, including start-up, open circuit voltage, and plant trip with a simulated gas environment. The objectives of these tests were to ensure the functionality of the equipment, instrumentation and control, and operational procedures prior to the installation of the stack.

Figure 1. SubMW DFC/T Hybrid Power Plant Integrated with Capstone C60

Upon completion of the process and control tests, the fuel cell stack was connected to the BOP, and operation of the hybrid subMW DFC/T system was initiated. The tests were conducted with the power plant connected to the utility grid and providing real time grid connected operational experience. The fuel cell stack dc power was inverted to alternating current. The fuel cell inverter and the microturbine were connected to the grid in parallel. A schematic of the power plant electric one-line diagram is shown in Figure 2. The microturbine generator was connected to the fuel cell inverter critical bus. Provisions were made for transfer of the load from grid to an AC-load bank in plant trip events. The operation of the subMW DFC/T was demonstrated at high power ratings in grid-connected mode. Figure 3 shows the subMW DFC/T power plant process flow diagram, including a typical set of process operating conditions.

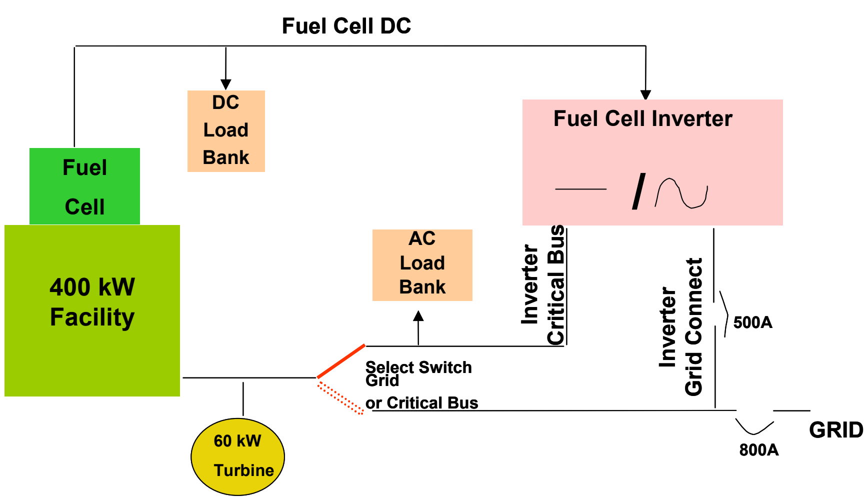

Figure 2. Schematic of the subMW DFC/T electric connection

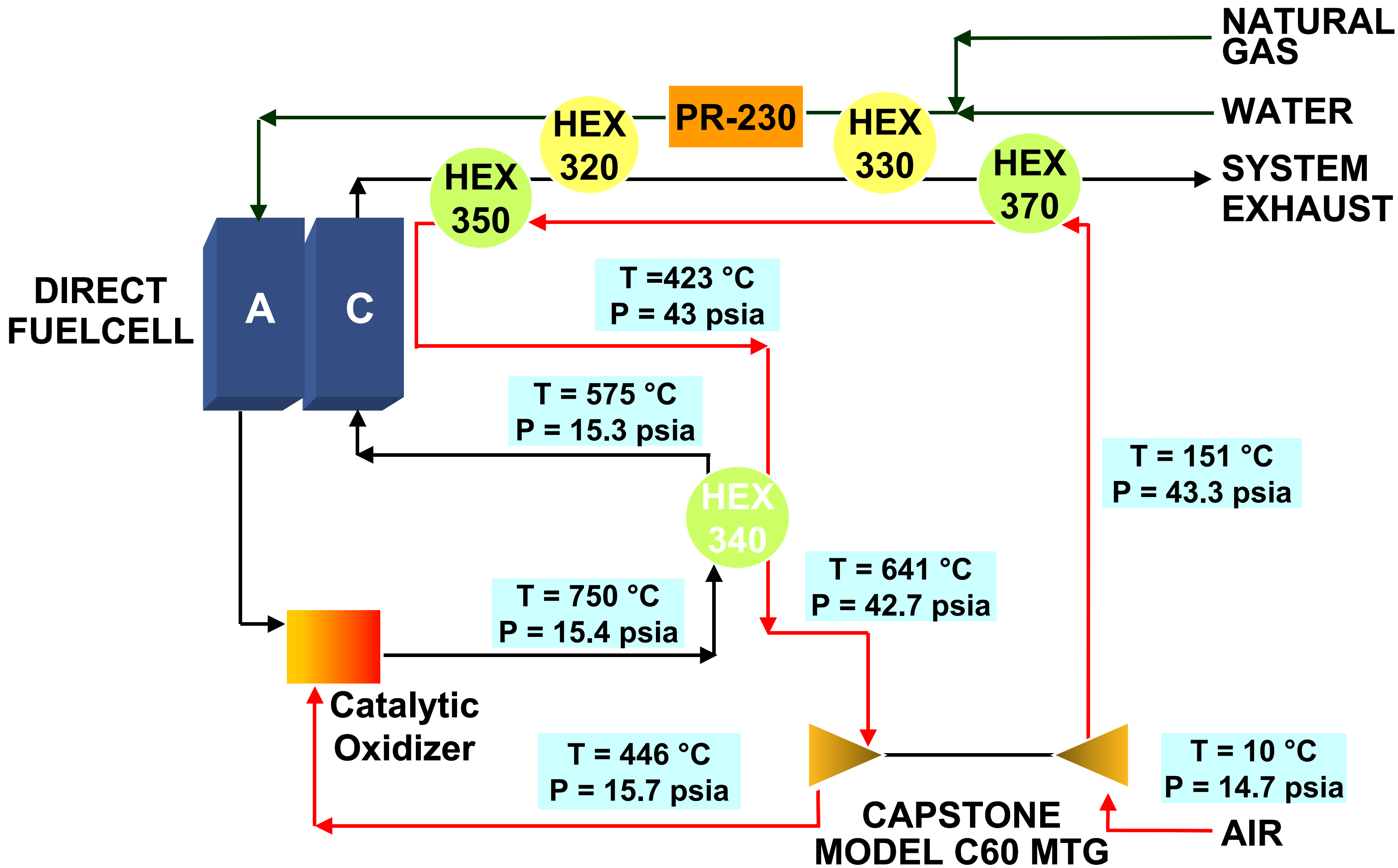

Figure 3. Sub-MW hybrid DFC/T Power Plant Facility Process Flow Diagram

3.0 RESULTS AND DISCUSSIONS

3.1. SubMW Power Plant Design

3.1.1. Design Development

The design of the subMW packaged, demonstration unit was initiated. The design activities accomplished are listed below:

- A power plant flowsheet and model were prepared, using Chemcad simulation software. The flowsheet was used to generate operating conditions of the various streams in the model.

- 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.

- Data sheets and equipment specifications were prepared for various balance-of-plant equipment, including recuperators, microturbine, and the anode exhaust oxidizer.

- The BOP equipment specifications were issued to Original Equipment Manufacturers (OEM) and suppliers for quotation. Review of the preliminary quotations and budgetary cost estimates was initiated.

- A Process Flow Diagram (PFD) of the power plant was prepared.

- A preliminary set of Piping and Instrumentation Diagrams (P&ID), with inclusion of instrument and equipment design information, was prepared.

- Preliminary review of potential demonstration sites in Montana for the beta subMW 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. Site selections criteria; including site preparation requirements, natural gas quality, and water quality, were prepared for the final site selection. Both sites were found to be suitable for the demonstration of the hybrid DFC/T beta unit.

3.1.2. Test Results

Operational and control testing of the DFC/T subMW power plant facility was conducted in support of the subMW hybrid design activities. The tests successfully demonstrated the ability of the control system to follow prescribed load ramps and to respond to abrupt utility grid outages. The Capstone 60 microturbine supplied sufficient air for operation of the DFC/T subMW power plant during the tests. The operational tests, as well as the tests of the power plant heat-up accomplished during the process and control checkout of the balance-of-plant, confirmed the stable and well-controlled operation of the DFC/T power plant with a single gas turbine.

In this reporting period the power plant benchmarked the operation at ~ 250 kW in grid connected mode with a dc-to-ac inverter and the microturbine connected to the grid in parallel.

3.2. Multi-MW Power Plant Design

The design of Multi-MW DFC/T hybrid systems, approaching 75% efficiency on natural gas, was continued. The current approach is based on a flexible design, utilizing FCE's one-MW fuel cell modules (M10) as the building block. In this reporting period a new concept was developed, based on clusters of one-MW fuel cell modules as the building blocks. The fuel cell cluster concept utilizes clusters of the M10 modules with common gas headers for the fuel and oxidant delivery. In addition to the fuel cell modules, the clusters may include some of the balance-of-plant equipment in order to minimize the system piping and cost.

One of the key features of the DFC/T power cycle is its adaptability in incorporating a wide range of existing gas turbine frames with minimal hardware modifications, consisting of gas inlet/outlet ports. Compared with the microturbine used in the subMW DFC/T power plants, MW-sized gas turbines are designed to operate at high-pressure ratios and high airflow rates. The MW-sized gas turbines have higher specific power and efficiency. However, the net gain in performance (overall system efficiency) and the incremental cost due to integration of the gas turbine depend on a multitude of design variables such as gas turbine pressure ratio (PR), turbine inlet temperature (TIT), and heat recuperator temperature, and materials. A basic study was performed to clarify the impact of these parameters on the performance of DFC/T power plants. The results of this fundamental study, as described here, were used to set forth the criteria for selection of the existing gas turbines and the guidelines for R&D needs for the ultra high efficiency DFC/T power plants.

The study consists of an indirectly heated Brayton cycle (open cycle). The compressor was assumed to be a two-stage compressor with inter-cooling. The compressor isentropic efficiency was assumed to be 84% for each stage, and the turbine isentropic efficiency was assumed to be 90%. The computer simulations were carried out using ChemCad process simulation software (Chemstations, Inc).

Figure 4 shows the effects of PR and TIT on the gas turbine performance. The inter-cooling for the compressor reduces the compressor power consumption, which leads to a higher gas turbine efficiency at high-pressure ratios, especially for low TIT cases. As expected, the gas turbine specific work increases with increasing TIT. The specific work does not drop significantly with PR in the high-pressure ratio range for each constant TIT curve as illustrated in Figure 4.

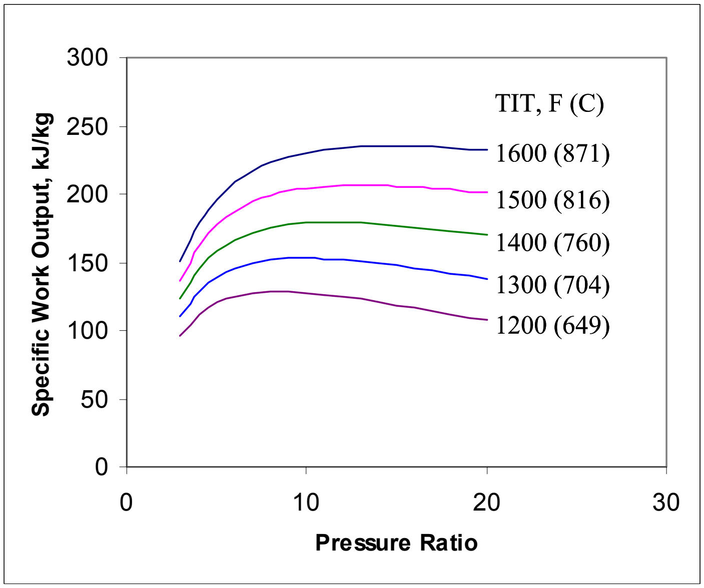

Figure 4. Specific Work Output as a Function of Pressure Ratio and Turbine Inlet Temperature for Indirectly Heated Inter-Cooled Gas Turbine

Figures 5 shows the dependency of the gas turbine efficiency on PR and TIT. The results show that for a given gas turbine design (fixed pressure ratio), the gas turbine is more efficient in conversion of the recuperated heat to useful work at higher turbine inlet temperatures. However, the turbine inlet temperature effect is more pronounced at PR>9.

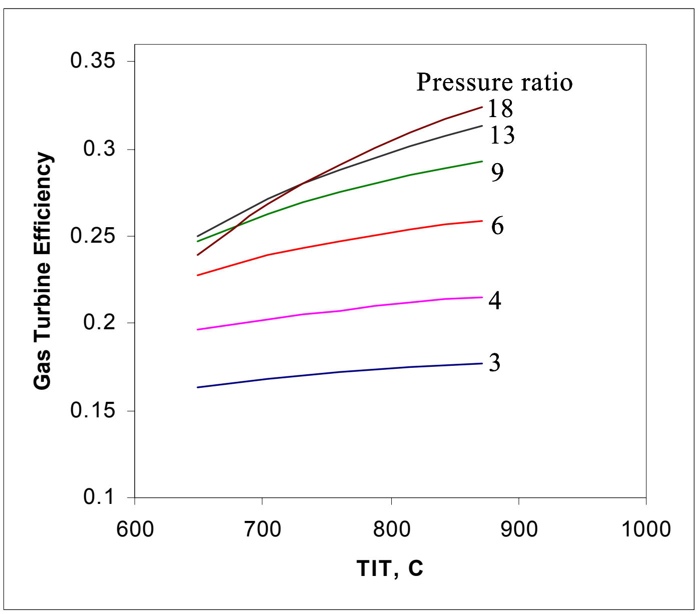

Figure 5. Gas Turbine Efficiency as a Function of Pressure Ratio and Turbine Inlet Temperature for Indirectly Heated Inter-cooled Gas Turbine

Figure 6 shows a simplified design concept for the 40 MW power plant design with a two-stage inter-cooled compressor. The system performance summary is shown in Table 1. The gas turbine is assumed to have an isentropic efficiency of 87% for compression and 93% for expansion with an overall compression ratio of about 1:9. In this system, the natural gas fuel is humidified in a heat recovery unit, utilizing the waste heat from the fuel cell cathode off-gas. The humidified fuel is then superheated in the heat recovery unit before entering the fuel cell anode. The air is compressed in the two-stage compression section of the gas turbine and is heated in two recuperators before entering the turbine section. The expanded turbine air is then mixed with the fuel cell anode off-gas before entering the anode gas oxidizer (AGO). The AGO effluent is cooled to provide the heat to the compressed turbine air prior to entering the fuel cell cathode. The cathode off-gas is used in the heat recovery section to heat the turbine air and provide heat for fuel humidification.

Table 1. The Performance characteristics of the 40MW ultra high efficiency system (Configuration 1)

	With Inter-cooled Gas Turbine
Fuel Cell:	
DC Power Out, MW	**33.55**
AC Power Out, Gross, MW	**32.71**
Gas Turbine:	
Compressor Power, MW	**(10.73)**
Expander Power, MW	**20.97**
Net AC Out, MW	**9.73**
Auxiliary Power Consumption, MW	**(0.22)**
Net Power Output, MW	**42.22**
Fuel Heating Value, MW	**55.89**
Efficiency, % LHV Natural Gas	**75.6%**

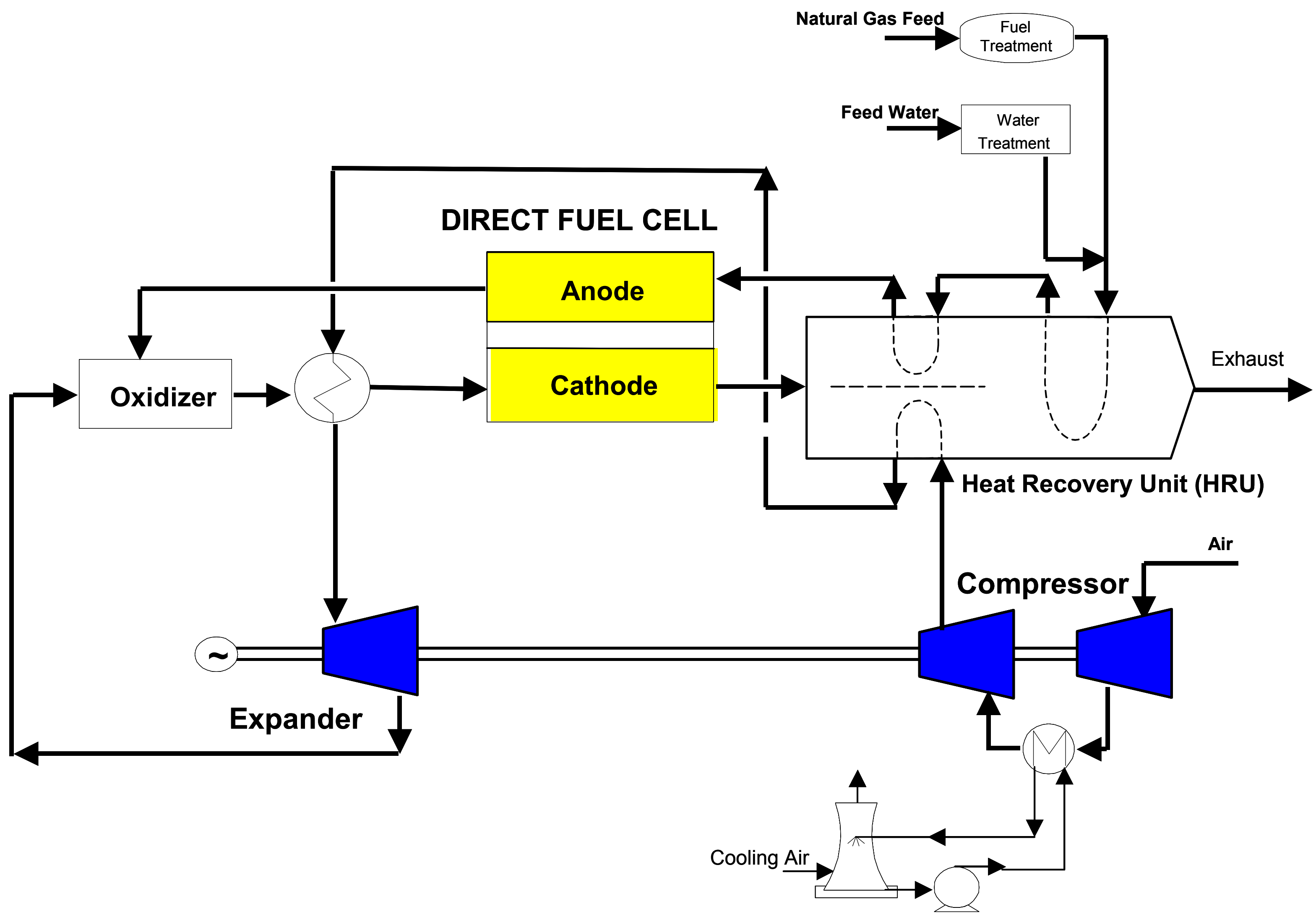

Figure 6. Hybrid DFC/T Power Plant Design with Inter-cooled Gas Turbine (Configuration 1)

An alternative system configuration, shown in Figure 7, was also developed. In this design, a multi-stage reheat cycle is implemented in the expansion section of the gas turbine. The addition of the re-heat section lowers the recuperation temperature and thus has the potential for lowering the cost of the power plant. The net efficiency of the system is about 75%, assuming a gas turbine with isentropic efficiencies of 87% for compression and 93% for expansion and an overall compression ratio of 1:9. The breakdown of the power generation (and consumption) of the 40 MW hybrid power plant utilizing both inter-cooled and re-heat cycles is summarized in Table 2.

Table 2. The Performance characteristics of the 40MW ultra high efficiency system (Configuration 2)

	With Inter-cooled and Reheat Gas Turbine
Fuel Cell:	
DC Power Out, MW	**33.55**
AC Power Out, Gross, MW	**32.71**
Gas Turbine:	
Compressor Power, MW	**(10.73)**
Expander Power, MW	**20.68**
Net AC Out, MW	**9.46**
Auxiliary Power Consumption, MW	**(0.22)**
Net Power Output, MW	**41.95**
Fuel Heating Value, MW	**55.89**
Efficiency, % LHV Natural Gas	**75.1%**

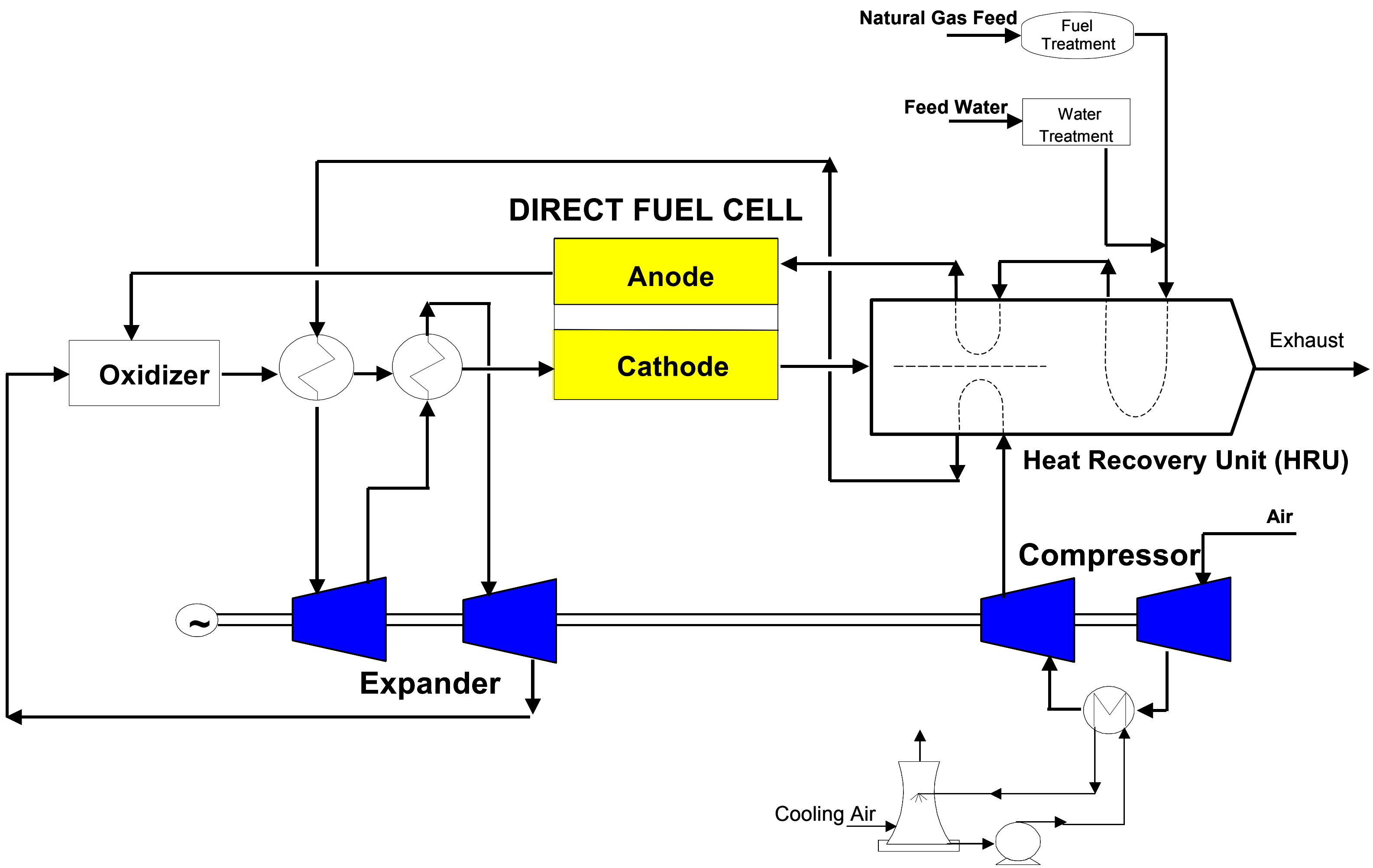

Figure 7. Hybrid DFC/T Power Plant Design with Inter-cooled and Re-heat Gas Turbine (Configuration 2)

In addition to the 40 MW power plant design for long-term development; Multi-MW system configurations were also developed for the short and mid-term applications. The design concepts for the near-term to mid-term applications utilize commercially available gas turbines with operating data provided by the gas turbine manufacturer. The gas turbine data were analyzed and incorporated into the steady-state hybrid DFC/T models. System efficiencies of 62 percent (LHV based) are projected for near term applications. A summary of the power plant design studies is presented in Table 3.

The path to long-term 75% high efficiency system product development may include the near-term systems with a nominal ~14 MW rating, utilizing commercially available turbines and one-MW fuel cell modules (M10) as the building blocks. The design will evolve to a nominal 20 MW capacity for the long-term ultra-high efficiency application with net efficiency of 75% (LHV natural gas). The increase in efficiency (and the power plant generation capacity) will be due to the anticipated increase in the fuel cell module performance and advanced inter-cooled gas turbines. Based on this approach for Multi-MW products development, the 40 MW power plant design will constitute two hybrid 20 MW clusters, sharing many of the balance-of-plant equipment; including water treatment, fuel preparation, control system, and power conversion units.

Table 3. Multi-MW Power Plant Design Summary

	Near-Term Hybrids		Mid-Term Hybrids	Long-Term Hybrids	
			With Improved DFC	With Intercooled Gas Turbine	With Intercooled & Re-heat Gas Turbine
Fuel Cell:					
DC Power Out, MW	3.6	12.0	16.8	33.5	33.5
AC Power Out, Gross, MW	3.4	11.3	16.3	32.7	32.7
Gas Turbine:					
Expander Power, MW	2.4	8.0	8.7	21.0	20.7
Compressor Power, MW	(1.6)	(5.4)	(6.0)	(10.7)	(10.7)
Net AC Out, MW	0.8	2.4	2.4	9.7	9.5
Auxiliary Power Consumption, MW	(0.1)	(0.1)	(0.1)	(0.2)	(0.2)
Net Power Output, MW	4.1	13.6	18.6	42.2	42.0
Efficiency, % LHV Natural Gas	62.6%	61.8%	66.7%	75.6%	75.1%

In this reporting period, a fuel cell cluster concept was developed, which includes a cluster of five one-MW fuel cell modules as the building block. Conceptual layout of a 14 MW power plant with two sets of clusters and supporting equipment was prepared to establish a footprint for the cluster concept (shown in Figure 8). A gas manifold system for delivery of the fuel and cathode gases to and from the fuel cell modules was also developed as shown in the power plant plan view in Figure 9. The water treatment, fuel preparation, control system and power conversion units were included in the conceptual layout. The sizes of the key system pipelines were based on estimates of the flows and allowances for pressure drops.

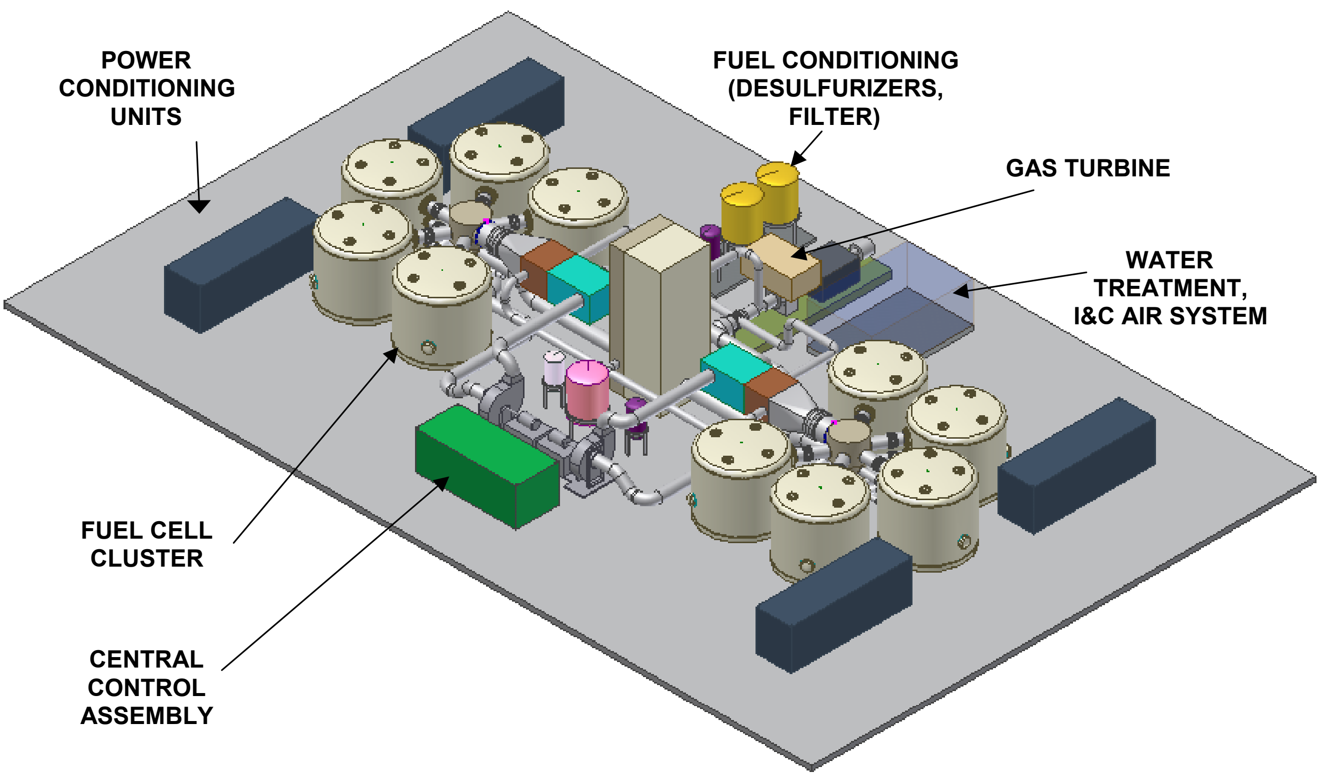

Figure 8. Layout of the 14 MW Hybrid DFC/T Power Plant

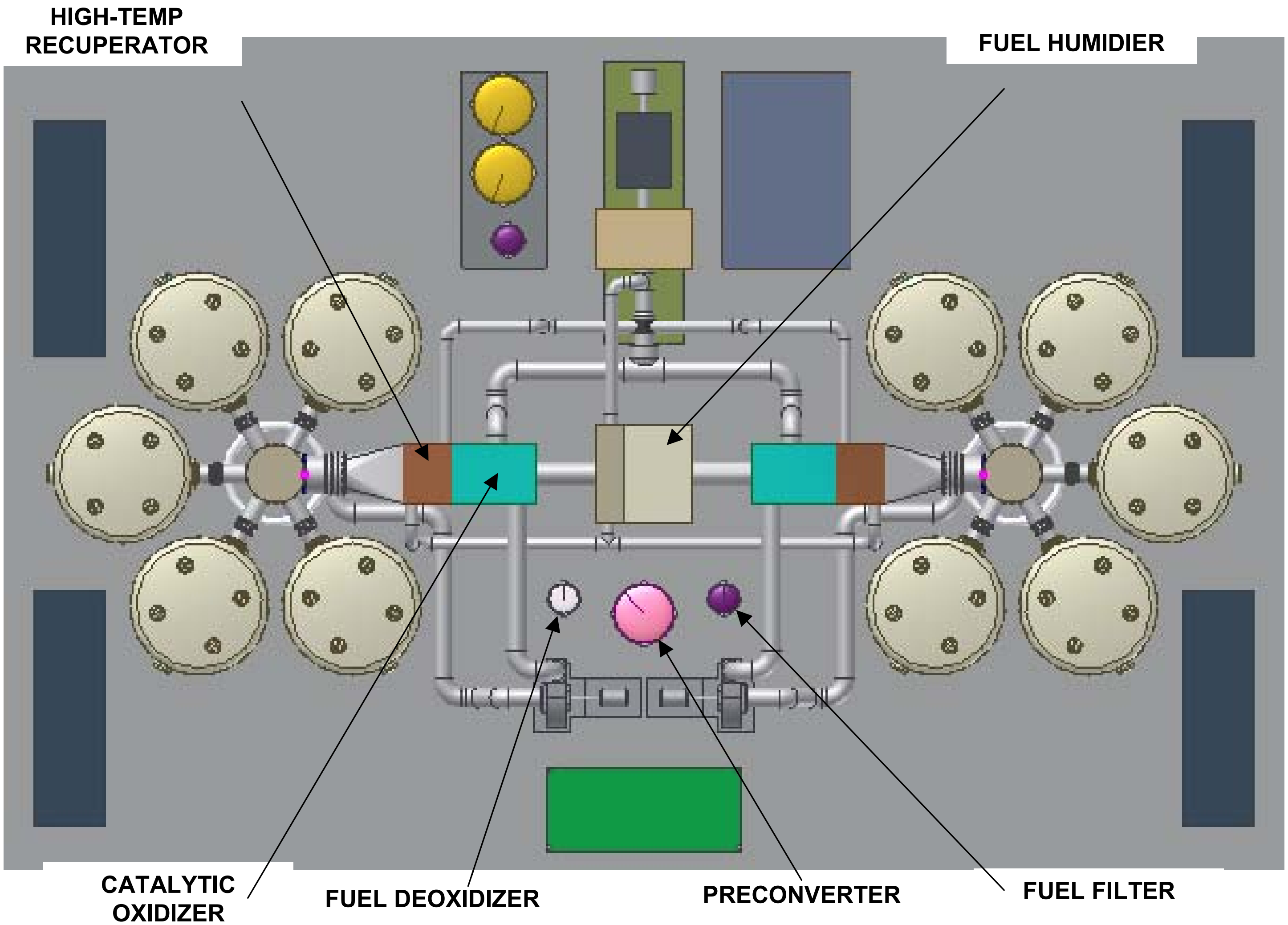

Figure 9. Plan View of the 14 MW Hybrid DFC/T Power Plant

4.0 CONCLUSION

The results of the subMW design tests confirmed the stability and controllability of operating the 250 kW fuel cell in combination with a microturbine. The results also confirmed the ability of the microturbine to supply adequate air to the DFC/T power plant.

The design activities for the packaged subMW units have been initiated. The design basis for the hybrid unit is the Company's DFC300 power plant. The DFC300 design will be modified to incorporate the microturbine and heat recovery subsystems.

The results of the fundamental analysis for the Multi-MW design have shown that gas turbines, with inter-cooled compression and high-pressure ratios, are candidates for achieving ultra high efficiencies, approaching 75% (LHV, natural gas). The heat rate and the cost of these systems can be optimized, depending on the gas turbine pressure ratio and design parameters such as turbine inlet temperature.

A Multi-MW hybrid design concept was developed, using clusters of one-MW fuel cell modules. The concept was utilized in the design of 14 MW hybrid systems with a commercially available gas turbine. The study shows that it is feasible to introduce the Multi-MW hybrid power plants in the market sooner than previously thought. The early market entry units of greater than 62% percent efficiency may evolve into 75% efficient systems in the long-term by using advanced inter-cooled gas turbines.

5.0 REFERENCES

H. Ghezel-Ayagh, J. Daly, and Z. Wang, "Advances in Direct FuelCell / Gas Turbine Power Plants," *To be published in Proceedings of ASME/IGTI Turbo Expo* 2003, ASME paper GT2003-38941.