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September 2007

Environmental Technology Verification Report

FuelCell Energy, Inc. - DFC 300A Molten Carbonate Fuel Cell Combined Heat and Power System

Prepared by:

Greenhouse Gas Technology Center

Operated by
Southern Research Institute

Under a Cooperative Agreement With
U.S. Environmental Protection Agency

and

Under Agreement With
New York State Energy Research and Development Authority

EPA REVIEW NOTICE

This report has been peer and administratively reviewed by the U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

ETV Joint Verification Statement

TECHNOLOGY TYPE:	Molten Carbonate Fuel Cell
APPLICATION:	Combined Heat and Power System
TECHNOLOGY NAME:	DFC 300A Molten Carbonate Fuel Cell
COMPANY:	FuelCell Energy, Inc.
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The U.S. Environmental Protection Agency's Office of Research and Development (EPA-ORD) operates the Environmental Technology Verification (ETV) program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of ETV is to further environmental protection by accelerating the acceptance and use of improved and innovative environmental technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the purchase, design, distribution, financing, permitting, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations, stakeholder groups that consist of buyers, vendor organizations, and permitters, and with the full participation of individual technology developers. The program evaluates the performance of technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests, collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Greenhouse Gas Technology Center (GHG Center), operated by Southern Research Institute (Southern), is one of six verification organizations operating under the ETV program. A technology area of interest to some GHG Center stakeholders is distributed electrical power generation (DG), particularly with combined heat and power (CHP) capability. An added environmental benefit of some DG technologies is the ability to fuel these systems with renewable energy sources such as anaerobic digester

gas or landfill gas. These gases, when released to atmosphere, contribute millions of tons of methane emissions annually in the United States.

The GHG Center collaborated with the New York State Energy Research and Development Authority (NYSERDA) to evaluate the performance the FuelCell Energy, Inc. (FCE) DFC 300A molten carbonate fuel cell CHP system currently in use at the State University of New York, College of Environmental Science and Forestry (SUNY-ESF) located in Syracuse, New York

TECHNOLOGY DESCRIPTION

The following technology description is based on information provided by FCE and does not represent verified information. The DFC 300A is a natural gas fueled molten carbonate fuel cell from which excess heat is recovered for use on-site. This technology provides a maximum 250 kW electrical output at 480 V three phase in parallel with the utility supply. Some of the waste heat produced by the fuel cell is recovered from the exhaust gases and supplied to the host sites' space heating system. Table S-1 summarizes the physical and electrical specifications for the unit.

Table S-1. FuelCell Energy DFC 300A Specifications

Physical Specifications	Width	9.0 ft
	Length	28.1 ft
	Height	10.5 ft
	Weight	90,000 lb
Electrical Specifications	Electrical Input	Interconnection of DC conversion + inverter
	Electrical Output	250 kW, 480 V, three phase; decline 10 % over 3 years
	Generator Type	Solid state inverter
	Power Generating Efficiency	45 % ; decline 4.5 % over 3 years
	Total CHP Efficiency	60 – 80 %

The performance verification of the DFC 300A took place at the SUNY-ESF, located in Syracuse, New York. The DFC 300A is located outdoors next to Walters Hall on the SUNY-ESF campus. The DFC 300A provides a 250 kW electrical output to the building in parallel with the utility supply. It is also used to provide supplemental water heating for a reheat loop in Walters Hall's air distribution system. The reheat loop helps control room temperature in Walters Hall.

The fuel cell is fueled with natural gas provided by National Grid. Hot exhaust gases exiting the fuel cell are directed to a Cain Industries heat recovery unit. If the water temperature in the reheat loop from Walters Hall is sufficiently high (approximately 155 ^{o}F or more), a valve in the heat recovery unit vents the exhaust gas to atmosphere. When reheat loop temperatures are below approximately 155 ^{o}F, the exhaust gas from the fuel cell is directed through a heat exchanger and heats the water in the reheat loop. A 1 hp pump located in Walters Hall circulates water through the reheat loop.

VERIFICATION DESCRIPTION

Field testing was conducted from March 13, 2007 through March 22, 2007. The defined system under test (SUT) was tested to determine performance for the following verification parameters:

- Electrical Performance
- Electrical Efficiency
- CHP Thermal Performance
- Emissions Performance
- NO_X and CO_2 Emission Offsets

The verification included a series of controlled test periods on March 13 and 14 in which the GHG Center maintained steady system operations for three one-hour test periods at two loads (250 kW and 200 kW) to evaluate electrical and CHP efficiency and emissions performance. The controlled tests were followed by a 7-day period of continuous monitoring to examine power output, power quality, efficiency, and estimated annual emission reductions.

Rationale for the experimental design, determination of verification parameters, detailed testing procedures, test log forms, and QA/QC procedures can be found in the draft ETV Generic Verification Protocol (GVP) for DG/CHP verifications developed by the GHG Center. Site specific information and details regarding instrumentation, procedures, and measurements specific to this verification are detailed in the Test and Quality Assurance Plan titled *Test and Quality Assurance Plan – FuelCell Energy, Inc. DFC 300A Molten Carbonate Fuel Cell Combined Heat and Power System.*

Quality assurance (QA) oversight of the verification testing was provided following specifications in the ETV Quality Management Plan (QMP). The GHG Center's QA manager conducted an audit of data quality on a representative portion of the data generated during this verification and a review of this report. Data review and validation was conducted at three levels including the field team leader (for data generated by subcontractors), the project manager, and the QA manager. Through these audits, the QA manager has concluded that the data meet the data quality objectives that are specified in the Test and Quality Assurance Plan.

VERIFICATION OF PERFORMANCE

Electrical and Thermal Performance

Table S-2. DFC 300A Electrical and Thermal Performance

Test ID		Heat Input (MBtu/h)	Electrical Power Generation Performance		Heat Recovery Performance		Total CHP System Efficiency (%)	Ambient Conditions	
			Power Generated by DFC 300A (kW)	Electrical Efficiency (%)	Heat Recovered (MBtu/h)	Thermal Efficiency (%)		Temp (^oF)	Pbar (psia)
250 kW	Run 1	1.76	250	48.4	0.302	17.2	65.6	50.9	14.6
	Run 2	1.76	250	48.5	0.305	17.4	65.9	54.7	14.6
	Run 3	1.76	249	48.3	0.305	17.4	65.7	58.0	14.6
	Avg.	**1.76**	**250**	**48.4**	**0.304**	**17.3**	**65.7**	**54.5**	**14.6**
200 kW	Run 1	1.44	210	49.9	0.267	18.6	68.5	65.0	14.5
	Run 2	1.45	210	49.6	0.272	18.8	68.4	59.2	14.5
	Run 3	1.45	211	49.7	0.271	18.7	68.4	60.9	14.5
	Avg.	**1.44**	**210**	**49.7**	**0.270**	**18.7**	**68.4**	**61.7**	**14.5**

- Electrical efficiency averaged approximately 48 percent at this site at 250 kW and 50 percent at 200 kW.

- The amount of heat recovered and used averaged 0.304 million Btu per hour (MBtu/h) at 250 kW and 0.270 MBtu/h at 200 kW. Corresponding thermal efficiency was 17.3 percent at 250 kW and 18.7 percent at 200 kW. Site personnel confirmed that, in some cases, DFC 300A heat recovery rates exceed Walters Hall demand, necessitating venting of the exhaust gas to atmosphere. Determination of the total potential heat recovery from the DFC 300A was not included in this verification, but rather the actual heat recovery and use at this site. Total potential heat recovery from the DFC 300A, and therefore thermal efficiency, may be higher than that reported here for users with higher heat demand. Total CHP efficiency (electrical and thermal combined) averaged 65.7 percent at 250 kW and 68.4 percent at 200 kW at this site under these conditions.

- During the 7-day monitoring period, the DFC 300A generated a total of 41,900 kWh of electricity and mean electrical efficiency was 48 percent. The GHG Center intended to collect heat recovery data over the extended test period, but the data logger malfunctioned during logging and no heat recovery data was recorded other than during the controlled test periods on March 13 and 14.

Emissions Performance

Table S-3. DFC 300A Emissions during Controlled Test Periods

Test ID		Power (kW)	CO Emissions			NOx Emissions			CO_2 Emissions		
			ppm, dry	lb/hr	lb/kWh	ppm, dry	lb/hr	lb/kWh	ppm, dry	lb/hr	lb/kWh
250 kW	Run 1	250	< 0.5	< 0.002	< 7E-06	< 0.5	< 0.003	< 1E-05	47800	264	1.06
	Run 2	250	< 0.5	< 0.002	< 7E-06	< 0.5	< 0.003	< 1E-05	47400	255	1.02
	Run 3	249	< 0.5	< 0.002	< 7E-06	< 0.5	< 0.003	< 1E-05	47200	252	1.01
	Avg.	**250**	**< 0.5**	**< 0.002**	**< 7E-06**	**< 0.5**	**< 0.003**	**< 1E-05**	**47500**	**257**	**1.03**
200 kW	Run 1	210	< 0.5	< 0.001	< 7E-06	< 0.5	< 0.002	< 1E-05	48000	219	1.04
	Run 2	210	< 0.5	< 0.001	< 7E-06	< 0.5	< 0.002	< 1E-05	47700	220.0	1.05
	Run 3	211	< 0.5	< 0.001	< 7E-06	< 0.5	< 0.002	< 1E-05	48100	221	1.05
	Avg.	**210**	**< 0.5**	**< 0.001**	**< 7E-06**	**< 0.5**	**< 0.002**	**< 1E-05**	**47900**	**220.0**	**1.04**

Table S-3 (continued). DFC 300A Emissions during Controlled Test Periods

Test ID		Power (kW)	TNMHC (as propane) Emissions			THC (as methane) Emissions		
			ppm, dry	lb/hr	lb/kWh	ppm, wet	lb/hr	lb/kWh
250 kW	Run 1	250	0.909	0.00502	2.01E-05	176	0.354	1.42E-03
	Run 2	250	0.830	0.00447	1.79E-05	184	0.360	1.44E-03
	Run 3	249	2.64	0.0141	5.66E-05	176	0.341	1.37E-03
	Avg.	**250**	**1.46**	**0.00786**	**3.15E-05**	**179**	**0.352**	**1.41E-03**
200 kW	Run 1	210	1.22	0.00557	2.65E-05	136	0.226	1.07E-03
	Run 2	210	1.42	0.00657	3.13E-05	128	0.215	1.02E-03
	Run 3	211	1.55	0.00713	3.38E-05	143	0.238	1.13E-03
	Avg.	**210**	**1.40**	**0.00642**	**3.05E-05**	**136**	**0.226**	**1.08E-03**

- NO_X and CO emissions were consistently low throughout the testing and averaged less than 1E-05 lb/kWh and less than 7E-06 lb/kWh, respectively at 250 kW. CO_2 emissions averaged 1.03 lb/kWh at 250 kW.

- Emissions of TNMHC (as propane) averaged 3.15E-05 lb/kWh at 250 kW. Emissions of THC (as methane) averaged 1.41E-03 lb/kWh at 250 kW.

- Compared to the baseline emissions scenarios for the New York State and national grid, annual NO_X emissions are estimated to be reduced by 1.97 tons per year (tpy) for New York State and reduced by 3.52 tpy for the national scenario. For CO_2, estimated annual emissions are expected to reduce by 588 tpy for New York State and by 1,020 tpy for the national grid.

Power Quality Performance

- Average electrical frequency was 60.0 Hz and average power factor was 99.9 percent.
- The average voltage THD was 1.63 percent, well within the IEEE recommended threshold of 5 percent on all occasions. Current THD was not able to be measured.

Details on the verification test design, measurement test procedures, and Quality Assurance/Quality Control (QA/QC) procedures can be found in the Test Plan titled *Test and Quality Assurance Plan – FuelCell Energy, Inc. DFC 300A Molten Carbonate Fuel Cell Combined Heat and Power System* (Southern 2007). Detailed results of the verification are presented in the Final Report titled *Environmental Technology Verification Report for FuelCell Energy, Inc. DFC 300A Molten Carbonate Fuel Cell Combined Heat and Power System* (Southern 2007). Both can be downloaded from the GHG Center's web-site (www.sri-rtp.com) or the ETV Program web-site (www.epa.gov/etv).

Signed by Sally Gutierrez (10/09/2007)	**Signed by Tim Hansen (09/26/2007)**
Sally Gutierrez Director National Risk Management Research Laboratory Office of Research and Development	Tim Hansen Director Greenhouse Gas Technology Center Southern Research Institute

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Greenhouse Gas Technology Center

A U.S. EPA Sponsored Environmental Technology Verification (ETV) Organization

Environmental Technology Verification Report

FuelCell Energy, Inc. - DFC 300A Molten Carbonate Fuel Cell Combined Heat and Power System

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ACKNOWLEDGMENTS

The Greenhouse Gas Technology Center wishes to thank NYSERDA, especially Jim Foster, for supporting this verification and reviewing and providing input on the testing strategy and this Verification Report. Thanks are also extended to FuelCell Energy personnel, especially Patrick Tong and Dana Brown, for their input supporting the verification and assistance with field testing activities. Finally, thanks go out to SUNY-ESF, especially Bruce Marcham and Gary Colella, for hosting the test and accommodating and assisting with field testing activities.

ACRONYMS AND ABBREVIATIONS

ADQ	Audit of Data Quality
Btu	British thermal units
Btu/h	British thermal units per hour
BTU/kWh	British thermal units per kilowatt-hour
Btu/scf	British thermal units per standard cubic feet
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
CT	current transformer
DG	distributed generation
DQO	data quality objective
DUT	device under test
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification
FCE	FuelCell Energy, Inc.
GHG Center	Greenhouse Gas Technology Center
GVP	generic verification protocol
gph	gallons per hour
gpm	gallons per minute
Hz	hertz
kVA	kilovolt-amperes
kVAR	kilovolt-amperes reactive
kW	kilowatts
kWh	kilowatt hours
lb/h	pounds per hour
lb/kWh	pounds per kilowatt-hour
lb/MWh	pounds per megawatt-hour
LHV	lower heating value
MBtu/h	million British thermal units per hour
MCFC	molten carbonate fuel cell
MQO	measurement quality objective
MWh	megawatt-hour
NIST	National Institute of Standards and Technology
NO_X	nitrogen oxides
NYSERDA	New York State Energy Research and Development Authority
O_2	oxygen
ppm	parts per million volume, dry
psia	pounds per square inch, absolute
QA/QC	Quality Assurance/Quality Control
QMP	Quality Management Plan
RTD	resistance temperature detector
scfh	standard cubic feet per hour
SUNY-ESF	State University of New York, College of Environmental Science and Forestry
SUT	system under test
Tpy	tons per year
TQAP	Test and Quality Assurance Plan
TNMHC	total non-methane hydrocarbons
THC	total hydrocarbons
THD	total harmonic distortion

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1.0 INTRODUCTION

1.1. BACKGROUND

The U.S. Environmental Protection Agency's (EPA) Office of Research and Development operates the Environmental Technology Verification (ETV) program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of ETV is to further environmental protection by accelerating the acceptance and use of improved and innovative environmental technologies. Congress funds ETV in response to the belief that there are many viable environmental technologies that are not being used for the lack of credible third-party performance data. With performance data developed under this program, technology buyers, financiers, and permitters in the United States and abroad will be better equipped to make informed decisions regarding environmental technology purchase and use.

The Greenhouse Gas Technology Center (GHG Center) is one of six verification organizations operating under the ETV program. The GHG Center is managed by EPA's partner verification organization, Southern Research Institute (Southern), which conducts verification testing of promising greenhouse gas mitigation and monitoring technologies. The GHG Center's verification process consists of developing verification protocols, conducting field tests, collecting and interpreting field and other data, obtaining independent stakeholder input, and reporting findings. Performance evaluations are conducted according to externally reviewed verification Test and Quality Assurance Plans (TQAPs) and established protocols for quality assurance.

The GHG Center is guided by volunteer groups of stakeholders who direct the GHG Center regarding which technologies are most appropriate for testing, help disseminate results, and review Test Plans and Technology Verification Reports. A technology area of interest to some GHG Center stakeholders is distributed electrical power generation (DG), particularly with combined heat and power (CHP) capability. DG refers to electricity generation equipment, typically less than 1,000 kilowatts (kW), that provides electric power at a customer's site (as opposed to central station generation). A DG unit can be connected directly to the customer or to a utility's transmission and distribution system. Examples of technologies available for DG include gas turbine generators, internal combustion engine generators (gas, diesel, or other), photovoltaics, wind turbines, fuel cells, and microturbines. DG technologies provide customers one or more of the following main services: standby generation (i.e., emergency backup power), peak shaving generation (during high-demand periods), base-load generation (constant generation), and CHP generation. An added environmental benefit of some DG technologies is the ability to fuel these systems with renewable energy sources such as anaerobic digester gas or landfill gas. These gases, when released to atmosphere, contribute millions of tons of methane emissions annually in the U.S. Cost-effective technologies are available that significantly reduce these emissions by recovering methane and using it as an energy source.

The GHG Center and the New York State Energy Research and Development Authority (NYSERDA) have agreed to collaborate and share the cost of verifying several new DG technologies located throughout the State of New York. The verification described in this document evaluated the performance of one such DG system: the FuelCell Energy, Inc. (FCE) DFC 300A molten carbonate fuel cell CHP system currently in use at the State University of New York, College of Environmental Science and Forestry (SUNY-ESF) located in Syracuse, New York.

The GHG Center evaluated the performance of the DFC 300A system by conducting field tests over an 11-day verification period (March 12 – 22, 2007). These tests were planned and executed by the GHG Center to independently verify the electricity generation rate, thermal energy recovery rate, electrical power quality, energy efficiency, emissions, and greenhouse gas emission reductions for the unit as operated at SUNY-ESF. Details on the verification test design, measurement test procedures, and quality assurance/quality control (QA/QC) procedures are contained in two related documents.

Technology and site specific information can be found in the document titled *Test and Quality Assurance Plan – FuelCell Energy, Inc. DFC 300A Molten Carbonate Fuel Cell Combined Heat and Power System* [1]. It can be downloaded from the GHG Center's web-site (www.sri-rtp.com) or the ETV Program web-site (www.epa.gov/etv). This TQAP describes the system under test (SUT), project participants, site specific instrumentation and measurements, and verification specific QA/QC goals. The TQAP was reviewed and revised based on comments received from NYSERDA, FCE, and the EPA Quality Assurance Team. The TQAP meets the requirements of the GHG Center's Quality Management Plan (QMP) and satisfies the ETV QMP requirements.

Rationale for the experimental design, determination of verification parameters, detailed testing procedures, test log forms, and quality QA/QC procedures can be found in the Association of State Energy Research and Technology Transfer Institutions (ASERTTI) DG/CHP Distributed Generation and Combined Heat and Power Performance Protocol for Field Testing [2]. It can be downloaded from the web location www.dgdata.org/pdfs/field_protocol.pdf. The GHG Center has adopted portions of this protocol as a draft generic verification protocol (GVP) for DG/CHP verifications [3]. It can be downloaded from the web location http://www.sri-rtp.com/03_vp_dgchpft.pdf. This ETV performance verification of the FCE system was based on the GVP.

The remainder of Section 1.0 describes the FCE DFC 300A system technology and test facility, and outlines the performance verification procedures that were followed. Section 2.0 presents test results, and Section 3.0 assesses the quality of the data obtained. Section 4.0, submitted by FCE, presents additional information regarding the CHP system. Information provided in Section 4.0 has not been independently verified by the GHG Center.

1.2. FUELCELL ENERGY DFC 300A TECHNOLOGY DESCRIPTION

The DFC 300A is a natural gas fueled molten carbonate fuel cell (MCFC) from which excess heat is recovered for use on-site. This technology provides a maximum 250 kW electrical output at 480 V three phase in parallel with the utility supply. Some of the waste heat produced by the fuel cell is recovered from the exhaust gases and supplied to the host sites' space heating system. Table 1-1 summarizes the physical and electrical specifications for the unit.

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Physical Specifications	Width	9.0 ft
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	Weight	90,000 lb
Electrical Specifications	Electrical Input	Interconnection of DC conversion + inverter
	Electrical Output	250 kW, 480 V, three phase; decline 10 % over 3 years
	Generator Type	Solid state inverter
	Power Generating Efficiency	45 % ; decline 4.5 % over 3 years
	Total CHP Efficiency	60 – 80 %

Molten carbonate fuel cells use an electrolyte composed of a molten mixture of carbonate salts. Two mixtures are currently used: lithium carbonate and potassium carbonate, or lithium carbonate and sodium carbonate. To melt the carbonate salts and achieve high ion mobility through the electrolyte, MCFCs operate at high temperatures (nominal 1202 ºF).

When heated to a temperature of around 1202 ºF, these salts melt and become conductive to carbonate ions (CO_3^{2-}). These ions flow from the cathode to the anode where they combine with hydrogen to give water, carbon dioxide and electrons. These electrons are routed through an external circuit back to the cathode, generating electricity and by-product heat.

Anode Reaction: $CO_3^{2-} + H_2 \rightarrow H_2O + CO_2 + 2e^-$

Cathode Reaction: $CO_2 + \frac{1}{2}O_2 + 2e^- \rightarrow CO_3^{2-}$

Overall Cell Reaction: $H_2(g) + \frac{1}{2}O_2(g) + CO_2\ (\text{cathode}) \rightarrow H_2O(g) + CO_2\ (\text{anode})$

The higher operating temperature of MCFCs has both advantages and disadvantages compared to the lower temperature phosphoric acid fuel cells and polymer electrolyte fuel cells. At the higher operating temperature, fuel reforming of natural gas can occur internally, eliminating the need for an external fuel processor. Additional advantages include the ability to use standard materials for construction, such as stainless steel sheet, and allowing the use of nickel-based catalysts on the electrodes. The by-product heat from an MCFC can be used to generate high-pressure steam that can be used in many industrial and commercial applications.

The high temperatures and the electrolyte chemistry also have disadvantages. The high temperature requires significant time to reach operating conditions and responds slowly to changing power demands. These characteristics make MCFCs more suitable for constant power applications. The carbonate electrolyte can also cause electrode corrosion problems. Furthermore, since carbon dioxide (CO_2) is consumed at the cathode and transferred to the anode, introduction of CO_2 and its control in air stream becomes an issue for achieving optimum performance that is not present in any other fuel cell.

1.3. SUNY-ESF FACILITY AND SYSTEM INTEGRATION

The performance verification of the DFC 300A took place at the SUNY-ESF, located in Syracuse, New York. The DFC 300A is located outdoors next to Walters Hall on the SUNY-ESF campus. Electric service is provided by the New York Power Authority. The DFC 300A provides a 250 kW electrical output to the building in parallel with the utility supply. It is also used to provide supplemental water heating for a reheat loop in Walters Hall's air distribution system. The reheat loop helps control room temperature in Walters Hall.

The fuel cell is fueled with natural gas provided by National Grid. Hot exhaust gases exiting the fuel cell are directed to a Cain Industries heat recovery unit. If the water temperature in the reheat loop from Walters Hall is sufficiently high (approximately 155 ^{o}F or more), a valve in the heat recovery unit vents the exhaust gas to atmosphere. When reheat loop temperatures are below approximately 155 ^{o}F, the exhaust gas from the fuel cell is directed through a heat exchanger and heats the water in the reheat loop. A 1 hp pump located in Walters Hall circulates water through the reheat loop.

The unit is located outdoors next to Walters Hall on the SUNY-ESF campus. Figure 1-1 shows the DFC 300A as it is currently installed.

Figure 1-1. FuelCell Energy DFC 300A Molten Carbonate Fuel Cell at SUNY-ESF

1.4. PERFORMANCE VERIFICATION OVERVIEW

Following the GVP, the verification included evaluation of the FCE system performance over a series of controlled test periods. The TQAP specifies testing at three loads: 100%, 75%, and 50% of capacity (250, 188, and 125 kW, respectively). FuelCell Energy, however, explained that the fuel cell does not operate efficiently at loads below 200 kW. Consequently, controlled tests were performed at 100% and 80% of capacity only (250 and 200 kW, respectively). The GHG Center issued a corrective action report to document this change to the TQAP. In addition to the controlled test periods, the GHG Center collected one week of continuous fuel consumption, power generation, and power quality data to characterize the DFC 300A performance over normal facility operations. Heat recovery rate data was intended to be collected, but the data logger malfunctioned during logging and no heat recovery data was recorded other than during the controlled test periods on March 13 and 14.

The DFC 300A verification was limited to the performance of the SUT within a defined system boundary. Figure 1-2 illustrates the SUT boundary for this verification. The figure indicates two distinct boundaries. The device under test (DUT) or product boundary includes the DFC 300A fuel cell and all of its internal

components. The SUT includes the DUT as well as the heat recovery unit, fluid circulation pump, and fluid turbine meter. Following the GVP, this verification incorporated the system boundary into the performance evaluation.

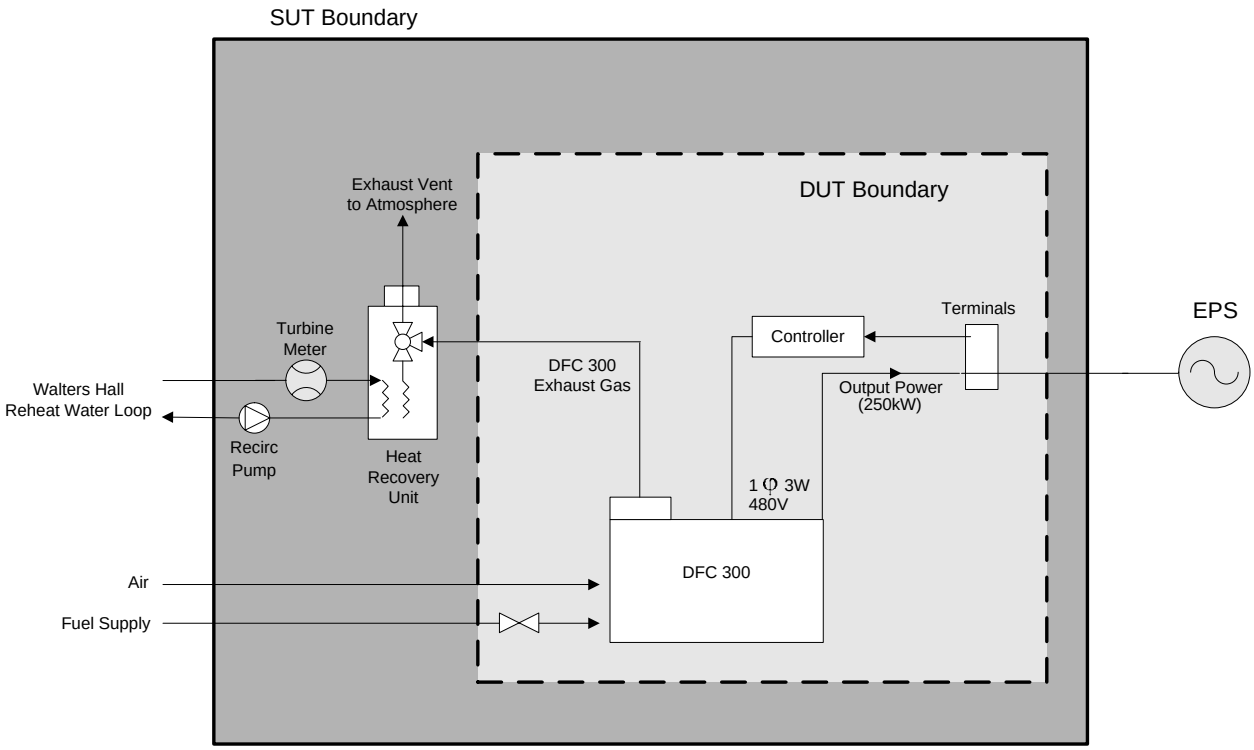

Figure 1-2. FuelCell Energy DFC 300A System Boundary Diagram

The defined SUT was tested to determine performance for the following verification parameters:

- Electrical Performance
- Electrical Efficiency
- CHP Thermal Performance
- Emissions Performance
- Nitrogen Oxides (NO_X) and CO_2 Emission Offsets

Each of the verification parameters listed above were evaluated during the controlled or extended monitoring periods as summarized in Table 1-2. This table also specifies the dates and time periods during which the testing was conducted. Simultaneous monitoring for power output, heat recovery rate, heat input, ambient meteorological conditions, and exhaust emissions was performed during each of the controlled test periods. Fuel gas samples were collected to determine fuel lower heating value and other gas properties. Average electrical power output, heat recovery rate, energy conversion efficiency (electrical, thermal, and total), and exhaust stack emission rates are reported for each test period.

Results from the extended monitoring test are used to report total electrical energy generated and used on site, estimated greenhouse gas emission reductions, and electrical power quality.

Table 1-2. Controlled and Extended Test Periods

Controlled Test Periods			
Start Date, Time	**End Date, Time**	**Test Condition**	**Verification Parameters Evaluated**
03/13/07, 08:45	03/13/07, 12:16	Power command 250 kW, three 60 minute test runs	NO_X, CO, CO_2, THC, and TNMHC emissions; electrical, thermal, and CHP efficiency
03/13/07, 16:30	03/14/07, 09:20	Power command 200 kW, three 60 minute test runs	NO_X, CO, CO_2, THC, and TNMHC emissions; electrical, thermal, and CHP efficiency

Extended Test Period			
Start Date, Time	**End Date, Time**	**Test Condition**	**Verification Parameters Evaluated**
03/15/07, 00:00	03/22/07, 00:00	Unit operated at normal power command (250 kW)	Daily and total electricity generated; power quality; emission offsets

The following sections identify the sections of the GVP that were followed during this verification, identify site specific instrumentation for each, and specify any exceptions or deviations.

1.4.1. Electrical Performance (GVP §2.0)

Determination of electrical performance was conducted following §2.0 and Appendix D1.0 of the GVP. The following parameters were measured:

- Real power, kW
- Apparent power, kilovolt-amperes (kVA)
- Reactive power, kilovolt-amperes reactive (kVAR)
- Power factor, %
- Voltage total harmonic distortion (THD), %
- Current THD, %
- Frequency, hertz (Hz)
- Voltage, V
- Current, A

The TQAP specifies that the verification parameters would be measured with a digital power meter manufactured by Power Measurements Ltd. (Model 7500 ION). However, one of the three current transformers (CTs) needed to employ current measurements on all three electrical phases with the ION power meter was damaged during shipping and was unusable. Electrical performance data including voltage, current, real power (kW), reactive power (kVAR), and power factor was instead logged by a power meter internal to the DFC 300A fuel cell. FuelCell Energy provided the GHG Center with time-stamped files recording one-minute averages for these parameters. The specified accuracy of the fuel cell power meter is ± 2%. Independent QA checks on the FCE meter demonstrated that it met the GVP requirements (see section 3.2.1 for details).

The GHG Center's Power Measurements ION power meter was used to measure voltage THD and frequency. The ION meter also provided a redundant source of voltage data. These measurements are not affected by the broken CT. Current and current THD data from the ION power meter, however, were unusable due to the broken CT.

1.4.2. Electrical Efficiency (GVP §3.0)

Determination of electrical efficiency was conducted following §3.0 and Appendix D2.0 of the GVP. The following parameters were measured:

- Real power production, kW
- External parasitic load power consumption, kW
- Ambient temperature, ^{o}F
- Ambient barometric pressure, pounds per square inch, absolute (psia)
- Fuel lower heating value (LHV), British thermal units per standard cubic feet (Btu/scf)
- Fuel consumption, scfh

Real power production was measured by the DFC 300A fuel cell and, for some parameters, the ION 7500 power meter (as described in §1.4.1 above). Ambient temperature was recorded manually during the controlled test periods using a Fluke 52 Type K thermocouple. The specified accuracy of the thermocouple is ± 1 ^{o}F. Ambient barometric pressure was measured by an Omega PX205 ambient pressure sensor with a full scale (FS) of 0 – 30 psia and an accuracy of ± 1% FS. This is an equivalent substitute for the Setra Model 280E pressure transducer that was specified in the test plan.

Gas flow was measured by a Model 3M175 Roots Meter manufactured by Dresser Measurement with a specified accuracy of ± 1% of reading. Gas temperature was read manually off of the DFC 300A fuel cell. Gas pressure was read from an on-site pressure gauge. Three gas samples were collected and shipped to Empact Analytical of Brighton, Colorado for LHV analysis.

The external parasitic load introduced by the heat transfer fluid circulation pump was nominal and insignificant (approximately 1.1 kW) and was therefore not measured during the verification. It was not included in the analysis.

1.4.3. CHP Thermal Performance (GVP §4.0)

Determination of CHP thermal performance was conducted following §4.0 and Appendix D3.0 of the GVP. The following parameters were quantified:

- Thermal performance in heating service, British thermal units per hour (Btu/h)
- Thermal efficiency in heating service, %
- Actual SUT efficiency in heating service as the sum of electrical and thermal efficiencies, %

To quantify these parameters, heat recovery rate was measured throughout the verification. This verification used Istec 1820 turbine flow meter with a range of 0.88 – 131 gallons per minute (gpm). An Onset Hobo Weather Station data logger logged the pulse output. Accuracy of this system was ± 1.0 % of reading. Class A 4-wire platinum resistance temperature detectors (RTDs) were used to determine the transfer fluid supply and return temperatures. The specified accuracy of the RTDs, including a Dataq Instruments 715B-ES data logger, is ± 0.6 ^{o}F. Pretest calibrations documented the RTD performance. The density and specific heat of the fluid (water) was obtained from standard tables [4].

1.4.4. Emissions Performance (GVP §5.0)

Determination of emissions performance was conducted following §5.0 and Appendix D4.0 of the GVP and included emissions of NO_X, carbon monoxide (CO), CO_2, total hydrocarbons (THC), and total non-methane hydrocarbons (TNMHC). The TQAP states that emissions testing would be performed by GHG Center personnel. Scheduling conflicts prevented the use of GHG Center emissions testing equipment, so emissions testing was instead performed by O'Brien & Gere, Inc. of Syracuse, New York. A fully equipped mobile emissions testing laboratory was transported to the facility to conduct the EPA Reference Methods emission testing. Results for each pollutant are reported in units of parts per million volume, dry (ppm), pounds per hour (lb/h), and pounds per kilowatt-hour (lb/kWh).

1.4.5. Field Test Procedures and Site Specific Instrumentation

Field testing followed the guidelines and procedures detailed in the following sections of the GVP:

- Electrical performance - §7.1
- Electrical efficiency - §7.2
- CHP thermal performance - §7.3
- Emissions performance - §7.4

Controlled tests were conducted as three one-hour test replicates at power commands of approximately 250 kW and 200 kW. The load was controlled remotely by FCE.

In addition to the controlled tests, system performance was monitored continuously for a period of one week while the unit operated under normal facility operations. Continuous measurements were recorded during the entire period including:

- Power output;
- Power quality parameters;
- Fuel consumption (gas flow); and
- Ambient conditions (temperature and pressure).

Using these data, the GHG Center evaluated DFC 300A system performance for this site under typical facility operations. Site specific measurement instrumentation is summarized in Table 1-3. The location of the instrumentation relative to the SUT is illustrated in Figures 1-3 and 1-4. All measurement instrumentation met the GVP specifications. Some of the instrument ranges and accuracies are different than those specified in the test plan, but these changes were demonstrated to not have an impact on achievement of the verifications data quality objectives.

Table 1-3. Site Specific Instrumentation for DFC 300A System Verification

Verification Parameter	Supporting Measurement	Actual Range of Measurement	Instrument	Instrument Range	Instrument Accuracy
Electrical Performance	Real power	207 – 252 kW	DFC 300A power meter (Real power, power factor, voltage, and current) / ION 7500 power meter (voltage THD and frequency)	0 – 300 kW	± 2 % of reading
	Power factor	99 – 100 %		0 – 100%	± 0.25 % of reading
	Voltage THD	1.10 – 2.24 %		0 – 100%	± 1% FS
	Current THD	n/a[a]		n/a[a]	
	Frequency	59.9 – 60.1 Hz		57 – 63 Hz	± 0.01% of reading
	Voltage	482 – 494V		0 – 600 V	± 0.15 % of reading
	Current	236 – 312 A		0 – 400 A	± 1 % of reading
	Ambient temperature	50 – 65 °F	Fluke 52 Type K thermocouple	-328 – 2498 °F	± 1 °F
	Barometric pressure	14.45 – 14.57 psia	Omega PX205	0 – 30 psia	± 0.1 % FS
	Parasitic loads	1.1 kW	Fluke Model 336 portable power meter	0 – 260 kW	± 2 % of reading
Electrical Efficiency	Gas flow	1574 – 1926 scfh	Model 3M175 Roots Meter	0 – 3000 acfh	± 1 % of reading
	Gas pressure	23 psia	On-site pressure gauge	0-60 psia	± 3 % of reading
	Gas temperature	61 – 66 °F	DFC 300A fuel cell	Unknown	Unknown
	Fuel LHV	912 – 914 Btu/scf	Gas chromatograph	n/a	± 1 % of reading
CHP Thermal Performance	Reheat loop flow	30 – 40 gpm	Istec 1820 Turbine Meter	0.88 – 131 gpm	± 1 % of reading
	Reheat loop supply temp.	135 – 149 °F	Omega Class A 4-wire RTD	0 – 250 °F	± 0.6 °F
	Reheat loop return temp.	125 – 134 °F	Omega Class A 4-wire RTD	0 – 250 °F	± 0.6 °F
Emissions Performance	NO_X concentration	< 0.5 ppmv	Advanced Pollution Instrumentation Model 200 AH chemiluminescent analyzer	0 – 9.3 ppmv	± 2% FS
	CO concentration	< 0.5 ppmv	Thermo Environmental Instruments Model 48C gas filter correlation analyzer	0 – 15.4 ppmv	± 2% FS
	CO_2 concentration	4.72 – 4.81 %	Servomex 1415C NDIR	0 – 18%	± 2% FS
	O_2 concentration	12.2 – 12.4 %	Servomex 1420C Paramagnetic	0 – 21%	± 2% FS
	TNMHC concentration	0.83 – 2.64 ppmv	California Analytical Instruments Model 300M flame ionization detector	0 – 350 ppmv	± 5% FS
	THC concentration	128.3 – 184.1 ppmv, wet	California Analytical Instruments Model 300M flame ionization detector	0 – 350 ppmv	± 5% FS

[a] Current THD is not applicable because no data was available to log for this parameter.

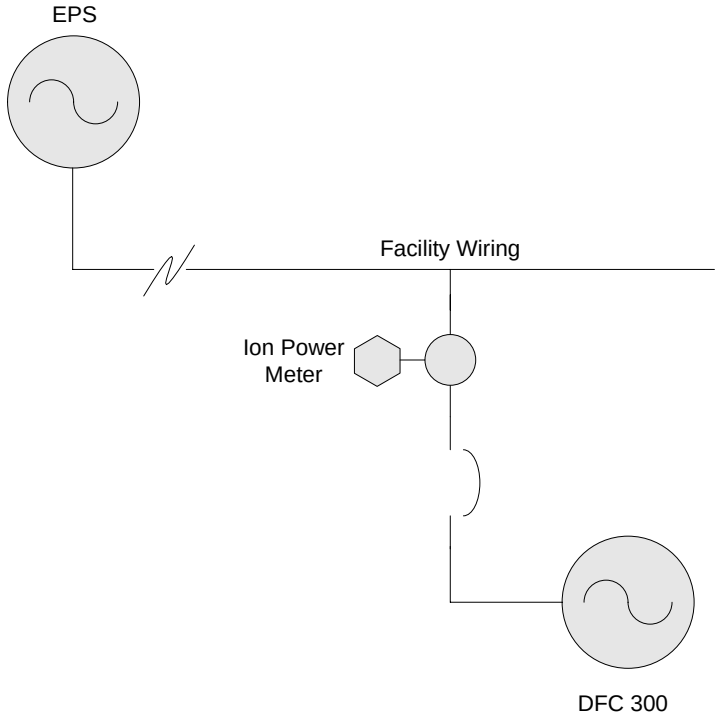

Figure 1-3. Location of Test Instrumentation for SUT Electrical System

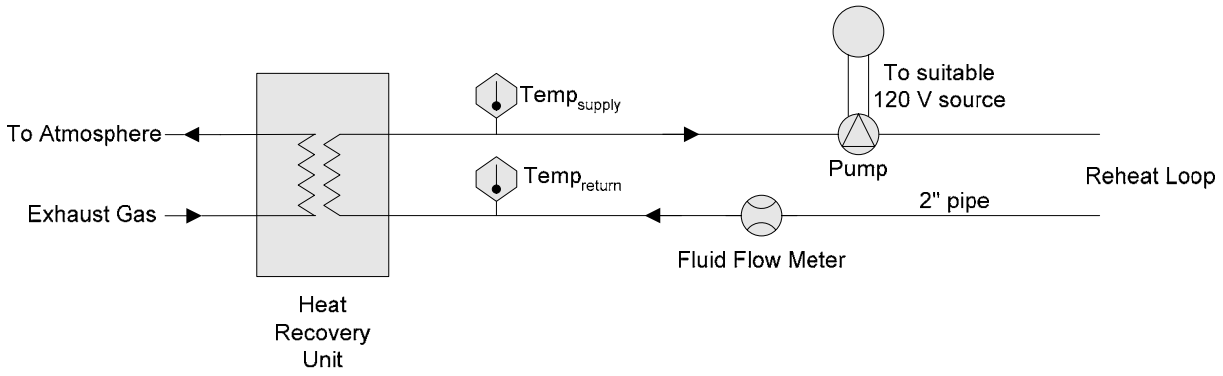

Figure 1-4. Location of Test Instrumentation for SUT Thermal System

1.4.6. Estimated NO_X and CO_2 Emission Offsets

Use of the DFC 300A fuel cell changes the NO_x and CO_2 emission rates associated with the operation of the SUNY-ESF facility. Annual emission offsets for these pollutants were estimated and reported by subtracting emissions of the on-site CHP unit from emissions associated with baseline electrical power generation technology and baseline space heating equipment.

The TQAP provided the detailed procedure for estimating emission reductions resulting from electrical generation. The procedure correlates the estimated annual electricity savings in MWh with New York State and nationwide electric power system emission rates in lb/MWh. For this verification, analysts assumed that the DFC 300A generates power at a rate similar to that recorded during the one week continuous monitoring period throughout the entire year.

The amount of heat recovered and used for water heating offsets an equivalent amount of energy that would otherwise be consumed by the facility's baseline space heating system. The facility's space heating demand is met by a large neighboring gas-fired co-generating facility, the Project Orange Cogeneration Plant. Emissions from the Project Orange plant associated with the equivalent amount of heat produced by the DFC 300A fuel cell are eliminated. As with the offsets attributable to power generation, analysts assumed that the DFC 300A provides heat to the facility throughout the entire year at a rate similar to that recorded during the full load controlled tests.

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2.0 VERIFICATION RESULTS

2.1. OVERVIEW

The verification period started on March 13, 2007, and continued through March 22, 2007. The controlled tests were conducted on March 13th and 14th, and were followed by a one week period of continuous monitoring to examine power output, power quality, efficiency, and emission reductions.

The GHG Center acquired several types of data that represent the basis of verification results presented here. The following types of data were collected and analyzed during the verification:

- Continuous measurements (power output and quality; heat recovery rate; ambient pressure)
- Manual data recording (fuel gas temperature, pressure, and flow rate; ambient temperature)
- Fuel gas heating value data
- Emissions testing data

The field team leader reviewed collected data for reasonableness and completeness while in the field. The field team leader also reviewed data from each of the controlled test periods to verify that variability criteria specified below in Section 2.2 were met. The emissions testing data was validated by reviewing instrument and system calibration data and ensuring that those and other reference method criteria were met. Calibrations for fuel flow, pressure, temperature, electrical and thermal power output, and ambient monitoring instrumentation were reviewed on site to validate instrument functionality. Other data such as fuel LHV analysis results were reviewed, verified, and validated after testing had ended. All collected data was classified as either valid, suspect, or invalid upon review, using the QA/QC criteria specified in the TQAP. Review criteria are in the form of factory and on-site calibrations, maximum calibration and other errors, audit gas analyses, and lab repeatability. Results presented here are based on measurements which met the specified data quality objectives (DQOs) and QC checks, and were validated by the GHG Center.

The GHG Center attempted to obtain a reasonable set of short-term data to examine daily trends in electricity and heat production, and power quality. It should be noted that these results may not represent performance over longer operating periods or at significantly different operating conditions.

Test results are presented in the following subsections:

Section 2.1 – Electrical and Thermal Performance and Efficiency
Section 2.2 – Power Quality Performance
Section 2.3 – Emissions Performance and Reductions

The results show that the DFC 300A fuel cell produces high quality power and is capable of operating in parallel with the utility grid. At SUNY-ESF, the fuel cell produces a steady 250 kW of electrical power and electrical efficiency at full load averaged 48 percent. The average heat recovery rate measured during the controlled test periods at this installation was 0.3 million British thermal units per hour (MBtu/h) and thermal efficiency averaged 17 percent.

NO_X and CO emissions at full load averaged less than 1.13E-02 and 6.90E-03 pounds per megawatt-hour (lb/MWh), respectively. Emissions of TNMHC averaged 3.15E-02 lb/MWh and emissions of THC

averaged 1.41 lb/MWh. CO_2 emissions averaged 1,030 lb/MWh. Detailed analyses are presented in the following sections.

In support of the data analyses, the GHG Center conducted an audit of data quality (ADQ) following procedures specified in the QMP. A full assessment of the quality of data collected throughout the verification period is provided in Section 3.0.

2.2. ELECTRICAL AND THERMAL PERFORMANCE AND EFFICIENCY

The heat and power production performance evaluation included electrical power output, heat recovery, and CHP efficiency determinations during controlled test periods. Following the test runs, analysts reviewed the data and determined that all test runs were valid by meeting the following criteria:

- at least 90 percent of the one-minute average power meter data were logged
- data and log forms that show SUT operations conformed to the permissible variations throughout the run (refer to Table 2-1)
- ambient temperature and pressure readings were recorded at the beginning and end of the run
- field data log forms were completed and signed
- records demonstrate that all equipment met the allowable QA/QC criteria

Based on ASME PTC-17, the GVP-specified guidelines state that efficiency determinations were to be performed within 60 minute test periods in which maximum variability in key operational parameters did not exceed specified levels. Table 2-1 summarizes the maximum permissible variations observed in power output, ambient temperature, and ambient pressure for each test run. The table shows that the PTC-17 requirements for these parameters were met for all test runs.

Table 2-1. Variability in Operating Conditions During Controlled Test Periods

		Maximum Observed Variation in Measured Parameters		
		Power Output[a]	**Ambient Temp. (^oF)**	**Ambient Pressure[a]**
Maximum Allowable Variation		**± 5 %**	**± 5 ^oF**	**± 1 %**
250 kW	Run 1	1.1	0.5	0.03
	Run 2	1.1	1.7	0.05
	Run 3	1.1	1.2	0.03
200 kW	Run 1	0.8	0.8	0.03
	Run 2	1.3	0	0.03
	Run 3	0.4	1.3	0.02

[a] Maximum (Average of Test Run – Observed Value) / Average of Test Run * 100

2.2.1. Electrical Power Output, Heat Production, and Efficiency during Controlled Tests

Table 2-2 summarizes the power output, heat production, and efficiency performance of the SUT. The heat recovery and heat input determinations corresponding to the test results are summarized in Tables 2-3 and 2-4. A total of three fuel samples were collected for compositional analysis and calculation of LHV for heat input determinations. There was very little variability in any of the measurements associated with the efficiency determinations.

The average net electrical power delivered to the facility was 250 kW during 100% load tests and 210 kW during 80% load tests. The average electrical efficiency at 100% load was 48.4 percent. At 80% load, average electrical efficiency was 49.7 percent. Electric power generation heat rate, which is an industry-accepted term to characterize the ratio of heat input to electrical power output, averaged 7040 British thermal units per kilowatt-hour (Btu/kWh) at 100% load and 6860 Btu/kWh at 80% load.

Heat recovery and use during the controlled test periods averaged 0.304 MBtu/h at 250 kW and 0.270 at 200 kW. Thermal efficiency at this site averaged 17.3 percent at 250 kW and 18.7 percent at 200 kW. Site personnel confirmed that, in some cases, DFC 300A heat recovery rates exceed Walters Hall demand, necessitating venting of the exhaust gas to atmosphere. Determination of the total potential heat recovery from the DFC 300A was not included in this verification, but rather the actual heat recovery and use at this site. Total potential heat recovery from the DFC 300A, and therefore thermal efficiency, may be higher than that reported here for users with higher heat demand. Total CHP efficiency (electrical and thermal combined) averaged 65.7 percent at 250 kW and 68.4 percent at 200 kW at this site under these conditions.

Table 2-2. DFC 300A Electrical and Thermal Performance

Test ID		Heat Input (MBtu/h)	Electrical Power Generation Performance		Heat Recovery Performance		Total CHP System Efficiency (%)	Ambient Conditions	
			Power Generated by DFC 300A (kW)	Electrical Efficiency (%)	Heat Recovered (MBtu/h)	Thermal Efficiency (%)		Temp (°F)	Pbar (psia)
250 kW	Run 1	1.76	250	48.4	0.302	17.2	65.6	50.9	14.6
	Run 2	1.76	250	48.5	0.305	17.4	65.9	54.7	14.6
	Run 3	1.76	249	48.3	0.305	17.4	65.7	58.0	14.6
	Avg.	**1.76**	**250**	**48.4**	**0.304**	**17.3**	**65.7**	**54.5**	**14.6**
200 kW	Run 1	1.44	210	49.9	0.267	18.6	68.5	65.0	14.5
	Run 2	1.45	210	49.6	0.272	18.8	68.4	59.2	14.5
	Run 3	1.45	211	49.7	0.271	18.7	68.4	60.9	14.5
	Avg.	**1.44**	**210**	**49.7**	**0.270**	**18.7**	**68.4**	**61.7**	**14.5**

Table 2-3. DFC 300A Heat Recovery Conditions

Test ID		Walters Hall Reheat Loop			
		Fluid Flow Rate (gph)	Supply Temp. (°F)	Return Temp. (°F)	Heat Recovery Rate (MBtu/h)
250 kW	Run 1	2080	146	129	0.302
	Run 2	2070	146	129	0.305
	Run 3	2070	147	129	0.305
	Avg.	**2070**	**146**	**129**	**0.304**
200 kW	Run 1	2110	145	130	0.267
	Run 2	2110	145	130	0.272
	Run 3	2050	146	130	0.271
	Avg.	**2090**	**145**	**130**	**0.270**

Table 2-4. DFC 300A Heat Input Determinations

Test ID		Fuel Input				
		Heat Input (MBtu/h)	Gas Flow Rate (scfh)	LHV (Btu/scf)	Gas Pressure (psia)	Gas Temp. (^{o}F)
250 kW	Run 1	1.76	1930		23	61
	Run 2	1.76	1930		23	61
	Run 3	1.76	1920		23	61
	Avg.	**1.76**	**1930**	**914[a]**	**23**	**61**
200 kW	Run 1	1.44	1570		23	65
	Run 2	1.45	1580		23	62
	Run 3	1.45	1580		23	66
	Avg.	**1.44**	**1580**	**914[a]**	**23**	**64**

[a] Reported LHV is the average of three fuel gas samples collected on March 14, 2007

2.2.2. Electrical Energy Production and Efficiency during the Extended Test Period

Power production on each of the 7 days monitored was fairly consistent. Figure 2-1 presents a time series plot of 1-minute average real power generated for one randomly selected day (March 17, 2007). The black line on the plot represents a 60-minute rolling average, which smoothes out fluctuations in the data to show the trends more clearly. The data shown for this day are consistent with each of the other days.

The SUT produced 5,968 kilowatt-hours (kWh) of net power on the day shown. Over the entire 7-day period, 41,900 kWh of net power was produced at the site for a daily average of 5,986 kWh. Mean electrical efficiency over the 7-day period was 48 percent.

The GHG Center intended to collect heat recovery rate data over the extended test period, but the data logger malfunctioned during logging and no heat recovery data was recorded other than during the controlled test periods on March 13 and 14.

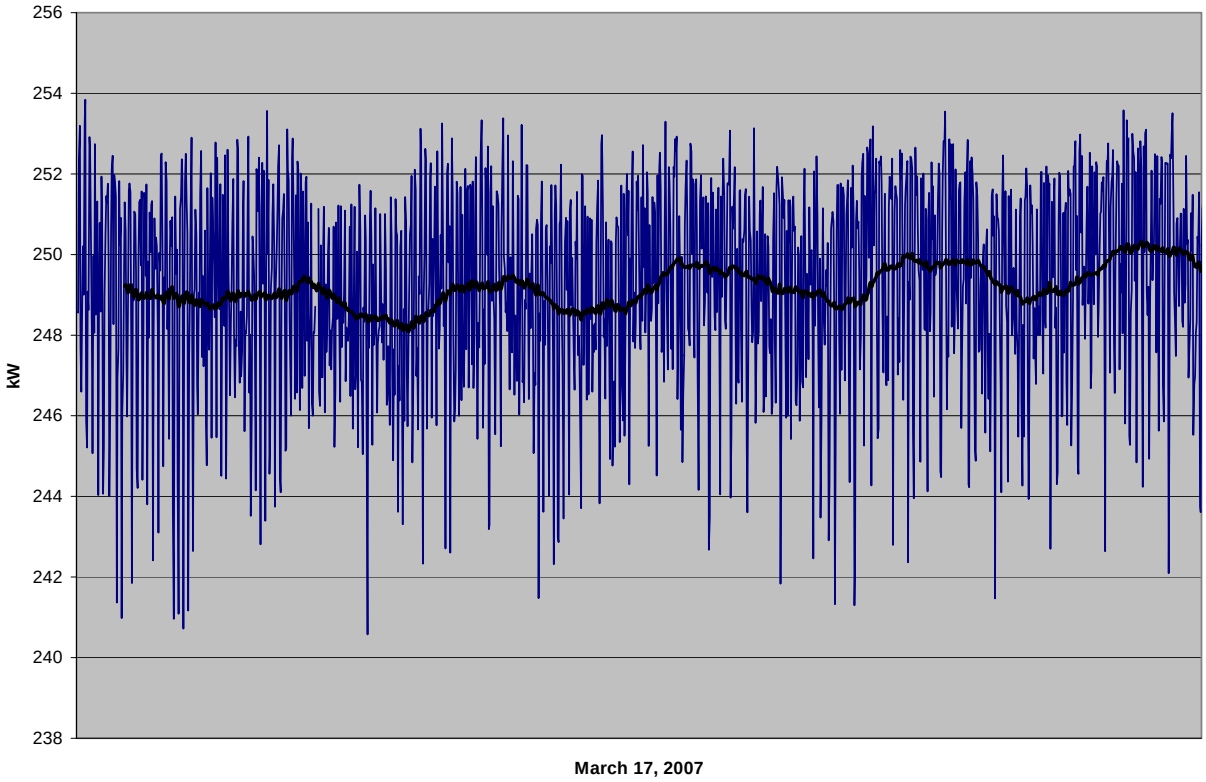

Figure 2-1. DFC 300A Power Generation for a Typical Day at SUNY-ESF

2.3. POWER QUALITY PERFORMANCE

Power quality parameters measured during the verification included: frequency, power factor, and voltage and current THD. The fuel cell power meter files provided to Southern included data for power factor only; the ION power meter recorded data for frequency and voltage THD. Current THD data was not available. Table 2-5 summarizes the power quality parameters recorded during the 7-day monitoring period.

Table 2-5. Summary of DFC 300A Power Quality

Parameter	Average	Maximum Recorded	Minimum Recorded	Standard Deviation
Frequency (Hz)	60.0	60.1	59.9	0.017
Voltage THD (%)	1.63	2.24	1.10	0.194
Power Factor (%)	99.9	100	99.6	0.148

2.4. EMISSIONS PERFORMANCE

2.4.1. DFC 300A Exhaust Emissions

Stack emission measurements were conducted during each of the controlled test periods in accordance with the EPA reference methods listed in the GVP. Following the GVP, the SUT was maintained in a stable mode of operation during each test run based on PTC-17 variability criteria. Results are summarized in Table 2-6.

Table 2-6. DFC 300A Emissions during Controlled Test Periods

Test ID		Power (kW)	CO Emissions			NOx Emissions			CO_2 Emissions		
			ppm, dry	lb/hr	lb/kWh	ppm, dry	lb/hr	lb/kWh	ppm, dry	lb/hr	lb/kWh
250 kW	Run 1	250	< 0.5	< 0.002	< 7E-06	< 0.5	< 0.003	< 1E-05	47800	264	1.06
	Run 2	250	< 0.5	< 0.002	< 7E-06	< 0.5	< 0.003	< 1E-05	47400	255	1.02
	Run 3	249	< 0.5	< 0.002	< 7E-06	< 0.5	< 0.003	< 1E-05	47200	252	1.01
	Avg.	**250**	**< 0.5**	**< 0.002**	**< 7E-06**	**< 0.5**	**< 0.003**	**< 1E-05**	**47500**	**257**	**1.03**
200 kW	Run 1	210	< 0.5	< 0.001	< 7E-06	< 0.5	< 0.002	< 1E-05	48000	219	1.04
	Run 2	210	< 0.5	< 0.001	< 7E-06	< 0.5	< 0.002	< 1E-05	47700	220.0	1.05
	Run 3	211	< 0.5	< 0.001	< 7E-06	< 0.5	< 0.002	< 1E-05	48100	221	1.05
	Avg.	**210**	**< 0.5**	**< 0.001**	**< 7E-06**	**< 0.5**	**< 0.002**	**< 1E-05**	**47900**	**220.0**	**1.04**

Table 2-6 (continued). DFC 300A Emissions during Controlled Test Periods

Test ID		Power (kW)	TNMHC (as propane) Emissions			THC (as methane) Emissions		
			ppm, dry	lb/hr	lb/kWh	ppm, wet	lb/hr	lb/kWh
250 kW	Run 1	250	0.909	0.00502	2.01E-05	176	0.354	1.42E-03
	Run 2	250	0.830	0.00447	1.79E-05	184	0.360	1.44E-03
	Run 3	249	2.64	0.0141	5.66E-05	176	0.341	1.37E-03
	Avg.	**250**	**1.46**	**0.00786**	**3.15E-05**	**179**	**0.352**	**1.41E-03**
200 kW	Run 1	210	1.22	0.00557	2.65E-05	136	0.226	1.07E-03
	Run 2	210	1.42	0.00657	3.13E-05	128	0.215	1.02E-03
	Run 3	211	1.55	0.00713	3.38E-05	143	0.238	1.13E-03
	Avg.	**210**	**1.40**	**0.00642**	**3.05E-05**	**136**	**0.226**	**1.08E-03**

Emissions results are reported in units of parts per million volume, dry for CO, NO_X, CO_2, TNMHC, and THC. Measured pollutant concentration data were converted to mass emission rates using EPA Method 19 and are reported in units of pounds per hour (lb/hr). The emission rates are also reported in units of pounds per kilowatt hour electrical output (lb/kWh). They were computed by dividing the mass emission rate by the electrical power generated during each test run.

NO_X and CO concentrations in the exhaust stack were consistently low throughout the testing. Results are reported as less than 0.5 ppm for both pollutants. The average NO_X emission rate normalized to power output was < 1E-05 lb/kWh for the 100% load tests and < 1E-05 lb/kWh for the 80% load tests. CO emission rates averaged < 7E-06 lb/kWh at 100% load and < 7E-06 lb/kWh at 80% load.

Concentrations of CO_2 in the exhaust gas averaged 47,500 ppm at 100% load and 47,900 at 80% load, with a corresponding average CO_2 emission rate of 1.03 lb/kWh at 100% load and 1.04 lb/kWh at 80% load.

Concentrations of TNMHC (as propane) averaged 1.46 ppm at 100% load and 1.40 ppm at 80% load. Corresponding emission rates averaged 3.15E-05 lb/kWh at 100% load and 3.05E-05 lb/kWh at 80% load. Concentrations of THC (as methane) averaged 179 ppm at 100% load and 136 ppm at 80% load. Corresponding emission rates averaged 1.41E-03 lb/kWh at 250 kW and 1.08E-03 lb/kWh at 200 kW. Fuel analyses showed that methane constitutes approximately 96 percent of the natural gas.

2.4.2. Estimation of Annual NO_X and CO_2 Emission Reductions

Section 1.4.6 outlined the approach for estimating the annual emission reductions that may result from use of the DFC 300A unit at this facility. The DFC 300A emissions were compared to both the New York State and national power system average emissions as published in EGRID. The detailed approach was provided in the TQAP.

Annual SUT Emissions

The first step in determining estimated annual emissions reductions is to estimate annual NO_X and CO_2 emissions from the SUT based on data generated during this verification. The average NO_X and CO_2 emission rates while operating at 250 kW during the verification were < 1.13E-02 and < 1,030 lb/MWh, respectively. The power delivered by the SUT during the verification period averaged 5.99 MWh per day. Assuming a system availability of 95 percent, this results in an estimated annual generating rate of 2,076 MWh per year. These values result in estimated annual NO_X and CO_2 emissions of 0.0118 and 1,070 tons per year (tpy), respectively.

Utility Grid Emissions

The average New York State NO_X and CO_2 emission rates published by EGRID for the year 2000 are used here and are 1.46 and 979.7 lb/MWh, respectively. Based on the measured DFC 300A generating rate described above, the annual estimated NO_X and CO_2 emissions for an equivalent amount of power from the grid are 1.52 and 1,020 tpy, respectively.

The average national NO_X and CO_2 emission rates published by EGRID and used here are 2.96 and 1,393 lb/MWh, respectively. Based on the measured DFC 300A generating rate described above, the annual estimated NO_X and CO_2 emissions for an equivalent amount of power from the grid are 3.07 and 1450 tpy, respectively.

Cogeneration Plant Emissions

Use of recovered heat from the SUT offsets an equivalent amount of heat that would otherwise be produced by the Project Orange Cogeneration Plant. The SUTs' emission rates for heat production are assigned as zero because emissions are accounted for in electricity generation. Emission factors for the cogeneration plant were obtained from EGRID, and were determined to be 1.25 lb/MWh and 1724 lb/MWh for NOx and CO_2, respectively. The heat recovered and used by the SUT during the verification period averaged 0.304 MBtu/h, or 0.0891 MW. These values result in estimated elimination of annual NO_X and CO_2 emissions from the cogeneration plant of 0.464 and 639 tpy of NO_X and CO_2, respectively.

Determination of Estimated Emission Reductions

Estimated annual NO_X and CO_2 emissions for the two regional scenarios described are summarized in Table 2-7. For the New York State region, NO_X and CO_2 emission reductions are estimated at 1.97 and 588 tpy. For the national grid, NO_X and CO_2 reductions are estimated to be approximately 3.52 and 1020 tpy, respectively.

Table 2-7. Estimation of DFC 300A Emission Reductions at SUNY-ESF

Regional Power System Scenarios	Annual SUT Emissions[a] (tpy)		Baseline Case (without the DFC 300A) Annual Emissions (tpy)						Estimated Annual Emission Reductions (tpy)	
			Grid Emissions[b]		Project Orange Cogeneration Plant[b]		Total Emissions			
	NO_X	CO_2	NO_X	CO_2	NO_X	CO_2	NO_X	CO_2	NO_X	CO_2
New York State	0.0118	1070	1.52	1020	0.464	639	1.98	1660	1.97	588
Nationwide	0.0118	1070	3.07	1450	0.464	639	3.54	2080	3.52	1020

[a] Based on the SUT's emissions performance during the 250 kW testing period, an expected availability of 95 percent, and the average measured power output of 5.99 MWh per day.
[b] From EGRID

3.0 DATA QUALITY ASSESSMENT

3.1. DATA QUALITY OBJECTIVES

Under the ETV program, the GHG Center specifies DQOs for each verification parameter before testing commences as a statement of data quality. The DQOs for this verification were developed based on past DG/CHP verifications conducted by the GHG Center, input from EPA's ETV QA reviewers, and input from both the GHG Centers' executive stakeholders groups and industry advisory committees. As such, test results meeting the DQOs will provide an acceptable level of data quality for technology users and decision makers. The DQOs for electrical and CHP performance are quantitative, as determined using a series of measurement quality objectives (MQOs) for each of the measurements that contribute to the parameter determination:

Verification Parameter	DQO (relative uncertainty)
Electrical Performance	±2.0 %
Electrical Efficiency	±2.5 %
CHP Thermal Efficiency	±3.5 %

Each test measurement that contributes to the determination of a verification parameter has stated MQOs, which, if met, demonstrate achievement of that parameter's DQO. This verification is based on the GVP which contains MQOs including instrument calibrations, QA/QC specifications, and QC checks for each measurement used to support the verification parameters being evaluated. Details regarding the measurement MQOs are provided in the following sections of the GVP:

§ 8.1	Electrical Performance Data Validation
§ 8.2	Electrical Efficiency Data Validation
§ 8.3	CHP Performance Data Validation

The DQO for emissions is qualitative in that the verification will produce emission rate data that satisfies the QC requirements contained in the EPA Reference Methods specified for each pollutant. Details regarding the measurement MQOs for emissions are provided in the following section of the GVP:

§ 8.4	Emissions Data Validation

Completeness goals for this verification were to obtain valid data for 90 percent of the test periods (controlled test period and extended monitoring). These goals were met as all of the planned controlled tests were conducted and validated, and 99 percent of valid one-minute average electrical performance data were collected during the 7-day monitoring period. The only goal that was not met was for heat recovery performance data during the 7-day monitoring period. As mentioned in section 2.2.2, the data logger malfunctioned during testing and no data was recorded other than during the controlled test periods on March 13 and 14.

The following sections document the MQOs for this verification, followed by a reconciliation of the DQOs stated above based on the MQO findings.

3.2. DOCUMENTATION OF MEASUREMENT QUALITY OBJECTIVES

3.2.1. Electrical Generation Performance

Table 3-1 summarizes the MQOs for electrical generation performance.

Table 3-1. Electrical Generation Performance MQOs

Measurement	QA/QC Check	When Performed	Allowable Result	Result Achieved
kW, kVA, kVAR, PF, I, V, f(Hz), THD	Power meter National Institute of Standards and Technology (NIST) traceable calibration	18-month period	± 2.0%	FuelCell Energy did not have a NIST-traceable calibration, but provided internal calibration documents showing that the power meter meets spec.
	CT documentation	At purchase	ANSI Metering Class 0.3%; ± 1.0% to 360 Hz (6th harmonic)	n/a
V, I	Sensor function checks	Beginning of load tests	V: ± 2.01% I: ± 3.01%	Meets spec. Maximum differential: 0.25% for voltage; 1.45% for current
Ambient temperature	NIST-traceable calibration	18-month period	± 1 °F	Meets spec.
	Ice and hot water bath crosschecks	Before and after field testing	Ice water: ± 0.6 °F Hot water: ± 1.2 °F	Meets spec.
Barometric pressure	NIST-traceable calibration	18-month period	± 0.1 "Hg or ± 0.05 psia	Meets spec.

All of the MQOs met the performance criteria with the exception of those relating to the power meter. FuelCell Energy could not provide a NIST-traceable calibration for the fuel cell's power meter, but did validate the fuel cell's voltage and current readings with a Dranetz 4400 handheld clamp on meter. The crosscheck with the Dranetz meter showed a maximum differential of 0.25% for the voltage readings and 1.45% for the current readings. CT documentation, power meter sensor function checks, and power meter cross checks for the ION meter were completed, but are not applicable because the ION meter was not used to measure electrical performance.

Following the GVP, the MQO criteria demonstrate that the DQO of ±2% relative uncertainty for electrical performance was met.

3.2.2. Electrical Efficiency Performance

Table 3-2 summarizes the MQOs for electrical efficiency performance.

Table 3-2. Electrical Efficiency MQOs

Measurement	QA/QC Check	When Performed	Allowable Result	Result Achieved
Gas meter	NIST-traceable calibration	18-month period	± 1.0% of reading	Meets spec.
Gas pressure	NIST-traceable calibration	18-month period	± 0.5% of FS	Unknown
Gas temperature	NIST-traceable calibration	18-month period	± 1.0% of FS	Unknown
Fuel Gas LHV	NIST-traceable standard gas calibration	Weekly	± 1.0 % of reading	Meets spec.
	ASTM D1945 duplicate sample analysis and repeatability	Each sample	Within D1945 repeatability limits for each gas component	Meets spec.

The GHG Center was not able to demonstrate that the MQOs for the gas meter, gas pressure, and gas temperature were met. The gas meter was already in place at the site and a calibration for the meter was not available. However, Roots meter calibrations are permanent so it is assumed that the meter was in spec. The gas pressure sensor was also already in place at the site and did not have a calibration certificate available. Gas temperature was measured by instrumentation internal to the fuel cell. The accuracy of the sensor is unknown. However, there is no cause to question the measurements because they passed "reasonableness" checks.

3.2.3. CHP Thermal Efficiency Performance

Table 3-3 summarizes the MQOs for CHP thermal efficiency performance.

Table 3-3. CHP Thermal Efficiency MQOs

Description	QA/QC Check	When Performed	Allowable Result	Result Achieved
Heat transfer fluid flow meter	NIST-traceable calibration	18-month period	± 1.0% of reading	Unknown
	Sensor function checks	At installation	See Appendix B8	Meets spec.
T_{supply} and T_{return} sensors	NIST-traceable calibration	18-month period	± 0.6 ^{o}F between 100 and 210 ^{o}F	Meets spec.
	Ice and hot water bath crosschecks	Before and after field testing	Ice water: ± 0.6 ^{o}F Hot water: ± 1.2 ^{o}F	Meets spec.

All of the MQOs met the performance criteria, with the exception of the heat transfer fluid flow meter. The GHG Center was not able to demonstrate that the meter met the MQO. The fluid flow meter was already installed at the site and a NIST-traceable calibration was not available. There is no cause, however, to doubt the meter. The meter readings were consistent with what was expected at the site.

3.2.4. Emissions Measurement MQOs

Sampling system QA/QC checks were conducted in accordance with GVP and TQAP specifications to ensure the collection of adequate and accurate emissions data. The reference methods specify detailed sampling methods, apparatus, calibrations, and data quality checks. The procedures ensure the quantification of run-specific instrument and sampling errors and that runs are repeated if the specific performance goals are not met. Table 3-4 summarizes relevant QA/QC procedures.

Table 3-4. Summary of Emissions Testing Calibrations and QA/QC Checks

Description	QA/QC Check	When Performed	Allowable Result	Result Achieved
CO, CO_2, O_2	Analyzer calibration error test	Daily before testing	± 2% of analyzer span	All calibrations, system bias checks, and drift tests were within the allowable criteria.
	System bias checks	Before each test run	± 5% of analyzer span	
	System calibration drift test	After each test run	± 3% of analyzer span	
NO_x	Analyzer interference check	Once before testing begins	± 2% of analyzer span	All criteria were met for the NO_X measurement system.
	Sampling system calibration error and drift checks	Before and after each test run	± 2% of analyzer span	
THC	System calibration error test	Daily before testing	± 5% of analyzer span	All criteria were met for the THC measurement system.
	System calibration drift test	After each test run	± 3% of analyzer span	

Satisfaction and documentation of each of the calibrations and QC checks verified the accuracy and integrity of the measurements and that reference method criteria were met for each of the parameters.

3.3. AUDITS

This verification was supported by ADQ conducted by the GHG Center QA manager. During the ADQ, the QA manager systematically checked each data stream leading from raw data to final results. The ADQ confirmed that no systematic errors were introduced during data handling and processing. ADQ audits and findings, along with GHG Center responses and follow-up, are on file.

4.0 REFERENCES

[1] Southern Research Institute, *Test and Quality Assurance Plan – FuelCell Energy, Inc. DFC 300A Molten Carbonate Fuel Cell Combined Heat and Power System,* SRI/USEPA-GHG-QAP-41, www.sri-rtp.com, Greenhouse Gas Technology Center, Southern Research Institute, Morrisville, NC, March 2007.

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