SRI/USEPA-GHG-VR-13
September 2001

Environmental Technology Verification Report

Mariah Energy Corporation Heat PlusPower™ System

Prepared by:

Greenhouse Gas Technology Center
Southern Research Institute

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

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Greenhouse Gas Technology Center

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

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Heat PlusPower™ System

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Under EPA Cooperative Agreement CR 826311-01-0

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TABLE OF CONTENTS

Page

(continued)

TABLE OF CONTENTS
(continued)

Page

APPENDICES

LIST OF FIGURES

LIST OF TABLES

(continued)

LIST OF TABLES
(continued)

ACKNOWLEDGMENTS

The Greenhouse Gas Technology Center wishes to thank the members of the GHG Center's Electricity Generation Stakeholder Group and Distributed Generation Technical Panel for reviewing and providing input on the testing strategy and this Verification Report. This includes R. Neal Elliott of ACEEE, Jerry Bernards of Portland General Electric, Charles Underhill of Vermont Public Power Supply Authority, and Ted Bronson and Todd Kolross of the Gas Technology Institute. Thanks are also extended to Brock John of the KEFI Exchange for compiling the Alberta Power grid electricity and emissions data for this verification. Special thanks are also extended to David Hajesz of Natural Resources Canada – TEAM Operations Office, Rob Brandon of CANMET Energy Technology Centre, and Ian Potter of the Alberta Research Council for supporting this international verification.

ACRONYMS/ABBREVIATIONS

AC	alternating current
acf	actual cubic feet
Btu	British thermal units
Btu/ft^3	British thermal units per cubic foot
Btu/hr	British thermal units per hour
CANMET	Canada Center for Mineral and Energy Technology
CBECS	Commercial Buildings Energy Consumption survey
CETC	CANMET Energy Technology Centre
CH_4	methane
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
DG	distributed generation
DHW	domestic hot water system
DP	differential pressure
DQI	data quality indicator
DQO	data quality objective
dscf/MMBtu	dry standard cubic feet per million British thermal units
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification
^oF	degrees Fahrenheit
ft^2	square feet
gal	U.S. Imperial gallons
gpm	gallons per minute
GHG Center	Greenhouse Gas Technology Center
HI	heat input, Btu/hr
hr	hours
Hz	hertz
kVA	kilovolt-amps
kVAR	reactive kilovolt-amps
kW_e	kilowatts electric power
kW_{th}	kilowatts heat
kW_{tot}	kilowatts total power
kWh_e	kilowatt hours electricity
kWh_{th}	kilowatt hours thermal energy
kWh_{tot}	kilowatt hours total energy
lb/hr	pounds per hour
lb/kWh	pounds per kilowatt-hour
LHV	lower heating value
Mariah	Mariah Energy Corporation
Mariah CHP System	Heat PlusPower™ System
min	minutes
MBtu/h	thousand British thermal units per hour
MMBtu/h	million British thermal units per hour
N_2	nitrogen
NDIR	nondispersive infrared detector

(continued)

ACRONYMS/ABBREVIATIONS
(continued)

NIST	National Institute for Standards and Technology
NO_X	nitrogen oxides
NRCan	Natural Resources Canada
O_2	oxygen
ORD	Office of Research and Development
PG	propylene glycol
ppmv	parts per million volume
ppmvd	parts per million by volume dry
psia	pounds per square inch absolute
psig	pounds per square inch gauge
QA/QC	Quality Assurance/Quality Control
QMP	Quality Management Plan
RH	relative humidity
RTD	resistance temperature detector
scfm	standard cubic feet per minute
temp	temperature
THCs	total hydrocarbons
THDs	total harmonic distortions
U.S.	United States
V	volume, volts
VAC	volts alternating current
VDC	volts direct current

1.0 INTRODUCTION

1.1. BACKGROUND

The U.S. Environmental Protection Agency's Office of Research and Development (EPA-ORD) operates a program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of the Environmental Technology Verification (ETV) program is to further environmental protection by substantially accelerating the acceptance and use of improved and innovative environmental technologies. The ETV program is funded by Congress 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 several verification organizations operating under the ETV program. The GHG Center is managed by U.S. EPA's partner verification organization, Southern Research Institute (SRI), which conducts verification testing of promising GHG 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 peer-review input, and reporting findings. Performance evaluations are conducted according to externally reviewed verification Test Plans and established protocols for quality assurance.

The GHG Center is guided by volunteer groups of stakeholders. These stakeholders offer advice on specific technologies most appropriate for testing, help disseminate results, and review Test Plans and Verification Reports. The GHG Center's stakeholder groups consist of national and international experts in the areas of climate science and environmental policy, technology, and regulation. Members include industry trade organizations, technology purchasers, environmental technology finance groups, governmental organizations, and other interested groups. In certain cases, industry specific stakeholder groups and technical panels are assembled for technology areas where specific expertise is needed. The GHG Center's Electricity Generation Stakeholder Group and a specially formed Distributed Generation (DG) Technical Panel offer advice on next generation power technologies where independent performance testing is needed. They also assist in selecting verification factors and provide guidance to ensure that the performance evaluation is based on recognized and reliable field measurement and data analysis procedures.

One technology of interest to the GHG Center's stakeholders is the use of microturbines as a distributed energy source. DG refers to power generation equipment, typically in the range of 5 to 1,000 kilowatts (kW) power output, that provides electricity at a site closer to customers than a central power station. A distributed power unit can be connected directly to the customer and/or to a utility's transmission and distribution system. These technologies provide customers one or more of the following main services: stand-by generation (i.e., emergency backup power), peak shaving capability (generation during high demand periods), baseload generation (constant generation), or cogeneration (combined heat and power generation). Examples of technologies available for distributed power generation include gas turbine generators, internal combustion engine generators (gas, diesel, other), photovoltaics, wind turbines, fuel cells, and microturbines.

Microturbines coupled with heat recovery systems for cogeneration are a relatively new technology, and the availability of performance data is limited and in demand. The GHG Center's stakeholder groups and other organizations have expressed interest in obtaining verified field data on the technical, economic, emissions, and operational performance of the microturbine-based combined heat and power (CHP) systems. Mariah Energy Corporation (Mariah) committed to participate in an independent verification of their Heat PlusPower™ system (Mariah CHP System) at the Walker Court condominium project in Calgary, Alberta, Canada. The Mariah CHP System uses a Capstone MicroTurbine® for electricity generation. It also includes: (1) a specially designed and insulated microturbine enclosure, (2) a turbine exhaust waste heat recovery unit, and (3) an integrated building energy management system. All three components are designed, installed, and offered by Mariah. The system is designed to produce electric power in stand-alone or grid-connected applications.

The Mariah CHP System at Walker Court is the first commercial installation of the Heat PlusPower™ system. The electricity generated by the system is used on-site, and excess electrical energy is interconnected to the Alberta electric utility grid for sale. The thermal energy generated by the system is used to heat domestic hot water and provide comfort heating for the facility. The GHG Center evaluated the performance of the Mariah CHP System at the Walker Court facility, in collaboration with Natural Resources Canada (NRCan) and the Canada Center For Mineral and Energy Technology-Energy Technology Centre (CANMET-CETC). Field tests were performed by the GHG Center over a 5 week verification period to independently determine the electricity generation and use rate, thermal energy recovery and use rate, electrical power quality, energy efficiency, emissions, and GHG emission reductions. GHG emission reductions are also estimated for Mariah CHP System installations at model sites in the U.S. This report presents the results of the verification test conducted from April 2 through May 25, 2001.

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 for the Mariah Energy Corporation Heat PlusPower™ System* (SRI 2001). It can be downloaded from the GHG Center's Web site (www.sri-rtp.com). The Test Plan describes the rationale for the experimental design, the testing and instrument calibration procedures planned for use, and specific QA/QC goals and procedures. The Test Plan was reviewed and revised based on comments received from Mariah, CANMET, NRCan, selected members of the GHG Center's stakeholder groups, and the EPA Quality Assurance Team. The Test Plan meets the requirements of the GHG Center's Quality Management Plan (QMP), and satisfies the ETV QMP requirements. In some cases, deviations from the Test Plan were required. These deviations, and the alternative procedures selected for use, are discussed in this report.

The remaining discussion in this section describes the Mariah CHP System technology and test facility and outlines the performance verification procedures that were followed. Section 2 presents test results, and Section 3 assesses the quality of the data obtained. Section 4, submitted by Mariah, presents additional information regarding the Mariah CHP System. Information provided in Section 4 has not been independently verified by the GHG Center.

1.2. MARIAH CHP SYSTEM TECHNOLOGY DESCRIPTION

Large- and medium-scale gas-fired turbines have been used to generate electricity since the 1950s. Recently they have become more widely used because of their ability to provide electricity at the point of use. Technical and manufacturing developments during the last decade have enabled the introduction of microturbines, with generation capacity ranging from 30 to 200 kW. The Mariah CHP System is the first North American single-package microturbine with heat recovery systems (Figure 1-1). There are similar concepts in Japan and the U.S. that consist of add-on heat recovery systems. Mariah has developed this technology through two prototype systems. The verification testing was performed on the most recent prototype design which is planned to be the basis of production units. Figure 1-2 illustrates a simplified process flow diagram of the Mariah CHP System, and a discussion of key components is provided below.

Figure 1-1. The Mariah Combined Heat and Power System

Electric power is generated with a Capstone MicroTurbine™ Model 330, with a nominal power output of 30 kW_e (60 ^oF, sea level). Table 1-1 summarizes the physical and electrical specifications reported by Mariah. The system incorporates an air compressor, recuperator, combustor, turbine, and a permanent-magnet generator. Filtered air enters the compressor where it is pressurized. It then enters the recuperator, which is a heat exchanger that uses exhaust heat to add heat to the compressed air. The air then enters the combustor where it is mixed with fuel and heated further by combustion. The resulting hot gas is allowed to expand through the turbine section to perform work, rotating the turbine blades to turn a generator which produces electricity. The inverter-based electronics enable the generator to operate at high speeds and frequencies, so the need for a gearbox and associated moving parts is eliminated. The rotating components are mounted on a single shaft, supported by patented air bearings that rotate at over 96,000 rpm (full load). The exhaust gas exits the recuperator through a muffler and into Mariah's heat recovery unit. Mariah provides an optional muffler system to further reduce sound levels in sensitive installations.

Figure 1-2. Mariah CHP System Process Diagram

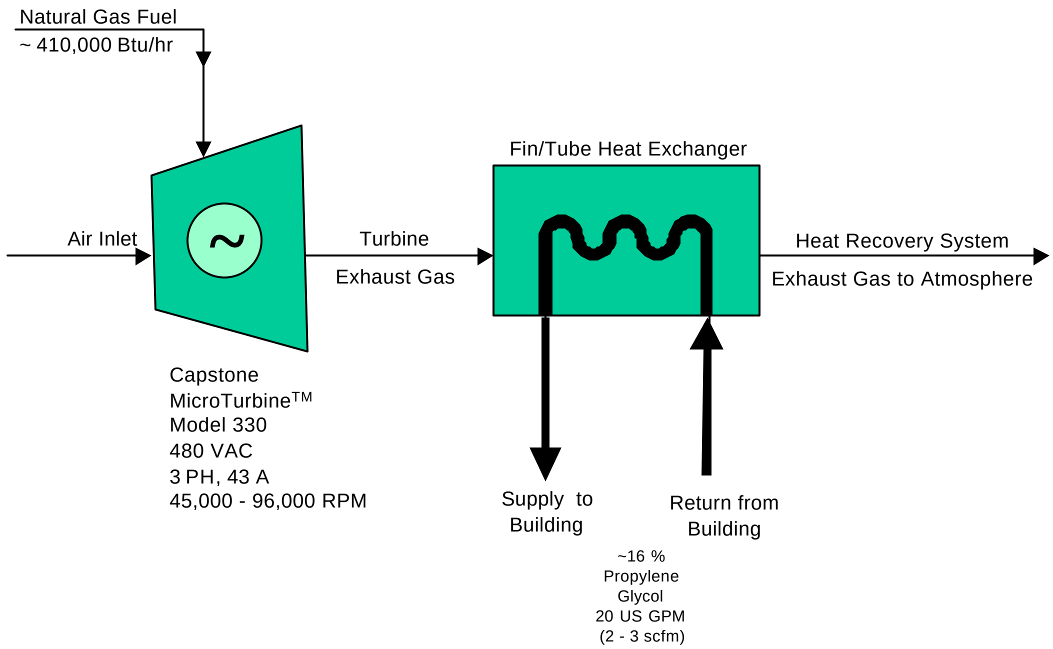


Table 1-1. Mariah CHP System Physical, Electrical, and Thermal Specifications
(Source: Mariah Energy Corp.)

Dimensions (Mariah CHP System)	Width Depth Height	30 in. 59.7 in. 76.5 in.
Weight	Turbine only	891 lb
Electrical Inputs	Power (start-up) Communications	Utility Grid or Black Start Battery Ethernet IP or Modem
Electrical Outputs	Power at ISO Conditions (59 °F @ sea level)	30 kW, 400-480 VAC, 50/60 Hz, 3-phase
Noise Level	Mariah CHP System	55 dBA at 10 m; <70 dBA at 1 m in turbine room
Fuel Pressure Required	w/o Natural Gas Compressor (Mariah CHP System) w/ Natural Gas Compressor	52 to 55 psig 5 to 15 psig
Fuel Flow Rate	Higher heating value Volumetric flow rate	420,000 Btu/hr 7.06 scfm at full load
Electrical Efficiency (LHV basis)	w/o Natural Gas Compressor (ISO Conditions) w/ Natural Gas Compressor (ISO Conditions)	27 % (± 2 %) 26 % (± 2 %)
Thermal Efficiency (LHV basis)	Mariah CHP System (derated for elevation and ambient conditions)	59 % (estimated)
Heat Rate	w/o Natural Gas Compressor: Electrical Thermal	 12,600 Btu/kWh 235,000 Btu/h (estimated)
Emissions (full load)	Nitrogen oxides (NO_X) Carbon monoxide (CO) Total hydrocarbon (THC)	< 9 parts per million volume (ppmvd) @ 15 % O_2 < 40 ppmvd @ 15 % O_2 < 9 ppmvd @ 15 % O_2

(continued)

Table 1-1. Mariah CHP System Physical, Electrical, and Thermal Specifications (continued)
(Source: Mariah Energy Corp.)

Over-Voltage Protective Functions				
	Thresholds		**Time to Trip**	
	Range	**Setting**	**Range**	**Setting**
Primary Trip	208 - 228.8 V	229 V	0.01 - 10.00 sec 0.01 sec increments	1 sec
Secondary Trip	Fixed offset from Primary Trip	240 V	50 % of Primary Trip	500 msec
Fast Trip	208 - 275 V	275 V	Not adjustable	10 msec
Under-Voltage Protective Functions				
Thresholds			**Time to Trip**	
	Range	**Setting**	**Range**	**Setting**
Primary Trip	156 - 208 V	184 V	0.01 - 10.00 sec 0.01 sec increments	2 sec
Secondary Trip	Fixed offset from Primary Trip	173 V	50 % of Primary Trip	1 sec
Fast Trip	0 - 208 V	104 V	Not adjustable	10 msec
Frequency Protective Functions				
Thresholds			**Time to Trip**	
	Range	**Setting**	**Range**	**Setting**
Under Frequency	45.0 - 60 Hz 0.1 Hz increments	57.8 Hz	0.01 - 10.00 sec 0.01 sec increments	1.5 sec
Over Frequency	60.0 - 65.0 Hz 0.01 Hz increments	60.5 Hz	0.01 - 10.00 sec 0.01 msec increments	150 msec

The permanent-magnet generator produces high frequency alternating current which is rectified, inverted, and filtered by the line power unit into conditioned alternating current at 480 volts. The unit has a selectable electrical frequency of 50 or 60 hertz (Hz), and is supplied with a control system which allows for automatic and unattended operation. An external voltage transformer converts the 480 volt, alternating current (VAC) output to 208 VAC for use at Walker Court. An active filter in the turbine is reported by the turbine manufacturer to provide power free of spikes and unwanted harmonics. All operations, including startup, setting of programmable interlocks, grid synchronization, operational setting, dispatch, and shutdown, can be performed manually or remotely using an internal power controller system.

The Mariah CHP System runs parallel with the local power utility. If the power demand exceeds the available capacity of the turbine, additional power is drawn from the grid. In the event of a power grid failure, the system is designed to automatically disconnect from the grid and run stand-alone, which isolates the on-site electrical system from grid faults. Additionally, the control system is designed to automatically shed lower priority loads, if necessary (e.g., in the event of grid failure), to ensure that local loads never exceed stand-alone generator capacity. When grid power is restored, the Mariah CHP System can either automatically reconnect, or await a manual command. When excess power is available, it is exported back to the grid. A bidirectional time-of-use meter records energy feeding into the grid.

The turbine at the Walker Court facility uses natural gas supplied at about 52 to 60 psig. Capstone offers an optional booster compressor which is not required at the test site due to availability of high pressure gas. Based on manufacturer specifications, the use of a booster compressor can decrease overall electrical efficiency by about 1 percent. The Mariah CHP System uses the Capstone Industrial Housing with modifications. This supports the weight of an overhead heat recovery unit. The housing was modified to alter the exhaust flow path, and for improved sound attenuation. The heat recovery system consists of a fin-and-tube heat exchanger, which circulates a 15 to 17 percent propylene glycol (PG) mixture through the heat exchanger at approximately 20 gallons per minute (gpm). The primary heating loop is driven by an existing circulation pump, so no additional pumping is required. The recovered heat is circulated through the building's mechanical rooms, a domestic hot water system, and a secondary loop which provides comfort heat to 12 units at Walker Court. After the heat transfer is complete, the PG mixture is circulated back to the fin-and-tube heat exchanger, energy is exchanged between the PG mixture and the hot turbine exhaust gas, and the circulation loop is repeated. If the Walker Court heat load is significantly lower than the heat transferred with the Mariah CHP System, such that overheating of the glycol loop could occur, the system will automatically shut off. The thermal control system, which monitors the supply and return temperatures of the PG mixture, is programmable. The maximum return temperature was set to not exceed 203 ^{o}F.

During the peak heating season, if necessary, supplementary heat may be provided by natural-gas-fired hot water heaters and a backup boiler (see Section 1.3 for further discussion). For periods when the heat generated cannot be consumed on site, Mariah has developed a proprietary method for eliminating and discarding excess heat. This method is currently undergoing internal testing, and was not evaluated by the GHG Center. The exhaust gases leave the heat recovery unit at less than 212 ^{o}F, and are vented through the turbine/boiler room roof and a further acoustical damper.

1.3. WALKER COURT TEST FACILITY DESCRIPTION

The Walker Court condominium site (Figure 1-3) is located in Inglewood, an inner city community east of downtown Calgary. The site is a live/work arrangement consisting of 12 condominium units that combine a street-level retail or office space with basement, and a one- or two-level residence above. Mariah operates the Mariah CHP System as a service provider under contract to the building tenants. Mariah retains all responsibility for operation and maintenance of the equipment. Condominium owners receive monthly statements indicating the amount of heat and electricity consumed as well as an estimate of emissions displaced in the previous month. Mariah has coined the term "Distributed Micro-Utility" to describe this model.

The 12 unit condominium has two L-shaped buildings surrounding a courtyard. The back wall of the courtyard is formed by the common garages joining the two buildings. The central unit of the common garage block includes the main turbine/boiler room, electrical room, and garbage room. Each of the 12 units in the development has approximately 1,800 square feet (ft^2) of living space, plus 750 ft^2 of commercial/storefront space and a full basement. Each unit also includes a roof-top patio/garden area.

The commercial and residential floors are heated using a hydronic radiant floor heating system embedded in a 2-inch "light-crete" concrete slab. All exterior walls, except the front of each unit, are constructed of "Blue-Maxx," a system involving Styrofoam blocks that create a form and are subsequently filled with 6-inches of concrete. The result is a high thermal mass wall with an R50 insulation factor. The front walls of each unit are constructed using steel studs and are insulated to an R22 rating. All walls between units are 6-inch poured concrete from foundation to parapet. This provides additional insulation between units, while contributing to the thermal storage capacity of the building structure.

Each unit has three comfort heating zone controls with manual balancing between rooms within each zone. An injection pump draws heating fluid from the secondary loop to control the temperature of the water in each zone loop. The secondary loops circulate a portion of the heating medium from the primary loop through the length of each of the two L-shaped building structures.

Figure 1-3. Walker Court Condominium Project

Each of the two main buildings has a small mechanical room below the rear garage level. The primary loop circulates heating medium through both mechanical rooms, to the secondary loops via manifolds, and to the domestic hot water (DHW) systems. The DHW tanks are manifolded off the primary loop. These tanks have an internal heating coil, through which the turbine-heated medium can heat the DHW. When comfort heating is required, the dual-fired DHW tanks burn natural gas, freeing the heat from the Mariah CHP System to be used for comfort heating. The "Combi-Cor™" DHW tanks have a storage capacity of 61 Imperial gallons (gal). There are three such tanks in each of the two buildings. Backup and peaking heat for use during prolonged extreme cold periods is provided by a Raypack natural draft boiler rated at 1 million British Thermal Units per hour (MMBtu/h).

The Walker Court facility is located in an established inner-city community. Sensitivity to intrusion, such as odor or noise, is very high. Mariah does not expect the backup boiler system to be operated often. As a result, costly forced draft or high efficiency condensing boilers were not selected. The selected natural draft boiler required a 20-inch flue, resulting in a substantial path for boiler room noise to reach the exterior of the building. To minimize this impact, and to increase comfort while working in the boiler room, substantial attenuation was added to the turbine housing and duct work. The air intake for both combustion and electronics cooling is drawn from an acoustically damped plenum. Further acoustic damping was added to the exterior exhaust duct which also provides a small amount of attenuation as the heat recovery unit itself acts as an acoustic damper. The sound level at the property line is required to be below 55 dBA to meet night-time municipal restrictions. The Mariah CHP System is located about 100 feet from the line, and based on an independent verification, Mariah reports this requirement to be met (Patching and Morozumi 2000).

1.4. PERFORMANCE VERIFICATION PARAMETERS

The verification test design was developed to evaluate the performance of the combined heat and power system only, and not the overall building integration or specific management strategy. Testing started on April 2, 2001, and was completed on May 25, 2001. It consisted of a series of short periods of load testing, in which the GHG Center intentionally modulated the unit to produce electricity at 50, 75, 90, and 100 percent of rated capacity (30 kW nominal). During these load tests, simultaneous monitoring for power output, heat recovery rate, fuel consumption, ambient meteorological conditions, and exhaust emissions was performed. Manual samples of natural gas and PG solution were collected to determine fuel lower heating value and specific heat of the heat transfer fluid, respectively. Average electrical power output, heat recovery rate, energy conversion efficiency (electrical, thermal, and total), and exhaust stack emission rates are reported for each load. The testing period for each load was about 30 minutes in duration, and the entire load testing activity took about 4 days to complete. The turbine was allowed to stabilize at each load for 15 to 30 minutes before starting the tests.

Following the load testing, daily performance of the Mariah CHP System was characterized over a 4 week monitoring period. During this period, 4 of the 12 residential units were occupied with 3 commercial spaces operational. The Mariah CHP System was operating 24 hours per day at maximum electrical power output (30 kW). Excess electricity, not consumed by the site, was exported to the grid. A backup boiler was not operating during the test because the site was not fully occupied, and the thermal demand was low. The Mariah CHP System was forced to recover the maximum heat possible by artificially increasing the thermal load. This was accomplished by discarding unused heat through open windows and doorways. The results from the extended test are reported as total electrical energy generated and used on-site, maximum thermal energy recovered, maximum GHG emission reductions, and electrical power quality. Actual GHG emission reductions are reported using measured GHG emission rates, emissions for generating electricity at central power plants, and emissions for producing heat using a standard gas-fired boiler. GHG emission reductions are also estimated for model sites which are possible candidates for Mariah CHP Systems in the U.S.

The specific verification factors associated with the test are listed below, followed by a discussion of each verification factor and its method of determination. Detailed descriptions of testing and analysis methods are not provided here, but can be found in the Test Plan.

Heat and Power Production Performance

- Electrical power output and heat recovery rate at selected loads
- Electrical, thermal, and total system efficiency at selected loads
- Total electrical energy generated and used
- Total thermal energy recovered

Power Quality Performance

- Electrical frequency
- Voltage output
- Power factor
- Voltage and current total harmonic distortion

Emissions Performance

- Nitrogen oxides (NO_X) concentrations and emission rates
- Carbon monoxide (CO) concentrations and emission rates
- Total hydrocarbon (THC) concentrations and emission rates
- Carbon dioxide (CO_2) and methane (CH_4) concentrations and emission rates

- Maximum possible GHG emission reductions in Calgary
- Estimated GHG emission reductions for model sites

1.4.1. Power and Heat Production Performance

Power production performance is an operating characteristic of microturbines that is of great interest to purchasers, operators, and users of electricity generating systems. Electrical efficiency determination was based upon guidelines listed in ASME PTC-22 (ASME 1997). Test runs, in duration of 30 minutes, were executed at constant operating loads. Electrical efficiency was calculated using directly measured average power output, average fuel flow rate, and fuel lower heating value (LHV). The electrical power output in kilowatts (kW) was measured with a 7600 ION Power Meter (Power Measurements Ltd.). Fuel input was measured with an in-line orifice type flow meter (Rosemount, Inc.). Fuel gas sampling and energy content analysis (via gas chromatograph) was conducted according to ASTM procedures to determine the lower heating value of natural gas. Ambient temperature, relative humidity, and barometric pressure were measured near the turbine air inlet to support determination of electrical conversion efficiency as required in PTC-22. Energy-to-electricity conversion efficiency at each load was computed by dividing the average electrical energy output by the average energy input using Equation 1.

$$h_E = \frac{3412.14\, kW_e}{HI} \qquad \text{(Eqn. 1)}$$

where :

ç$_E$ = electrical efficiency (%)

3412.14 Btu/hr per kW$_e$

kW$_e$ = average electrical power output (kW$_e$)

HI = average heat input (Btu/hr); determined by multiplyin g the average mass flow rate of natural gas to the Mariah CHP System (converted to scfm) times natural gas LHV (Btu/std ft^3) times 60 (min/hr)

Simultaneous to electrical power measurements, heat recovery information was collected using an in-line heat meter. The meter enabled 1 minute measurements of differential heat exchanger temperatures and PG mixture flow rates to be monitored. Manual samples of the PG solution were collected to determine PG concentration, fluid density, and specific heat such that heat recovery rates could be calculated at actual conditions per ANSI/ASHRAE Standard 125, shown below in Equation 2 (ANSI 1992).

$$\textit{Heat Recovery Rate (Btu/min)} = V r\ Cp\ (T1-T2) \qquad \text{(Eqn. 2)}$$

where:

V = total volume of liquid passing through the sensor during a minute (ft^3)
ρ = density of PG solution (lb/ft^3), evaluated at the avg. temp. (T2+T1)/2
C_p = specific heat of PG solution (Btu/lb ^{o}F), evaluated at the avg. temp. (T2+T1)/2
T1 = temperature of heated liquid exiting heat exchanger, Figure 1-4 (^{o}F)
T2 = temperature of cooled liquid entering heat exchanger, Figure 1-4 (^{o}F)

During the test, the heat demand at the site was artificially manipulated by increasing the thermostatic settings in the buildings. This was done to discard excess heat which was unused by the partially occupied Walker Court facility, and to determine the maximum heat recovery potential of the Mariah CHP System at the conditions encountered during testing. The average heat recovery rates measured at the four loads represent the heat recovery performance of the Mariah CHP System. Thermal energy conversion efficiency was computed as the average heat recovered divided by the average energy input (Equation 3).

$$\eta_{Th} = \frac{60\ Heat\ Recovery\ Rate}{HI} \qquad \text{(Eqn. 3)}$$

where :

η_{Th} = *thermal energy* efficiency (%)

Heat recovery rate = average 1 minute rate using Equation 2 (Btu/min)

HI = average heat input (Btu/hr); determined by multiplying the 1 minute average mass flow rate of natural gas to the Mariah CHP System (converted to scfm) times natural gas LHV (Btu/std ft^3) times 60 (min/hr)

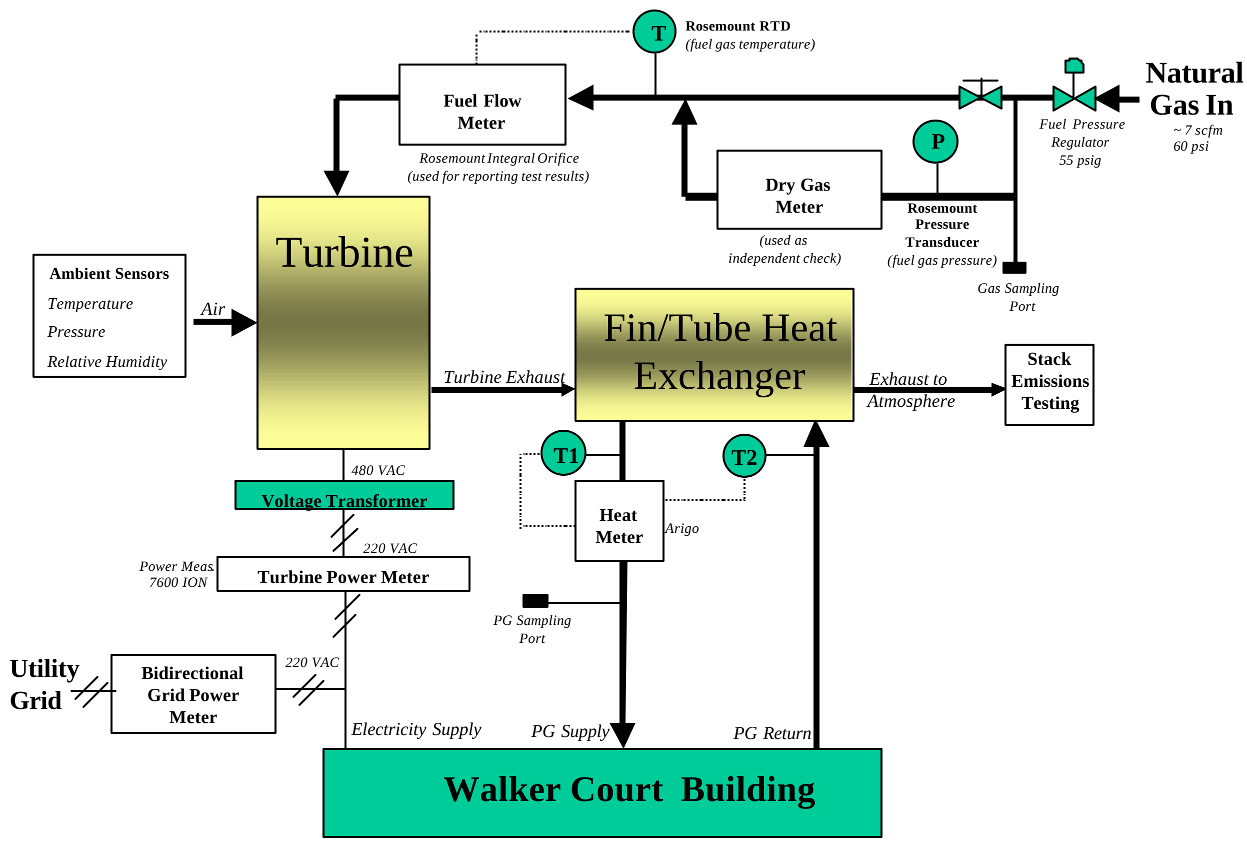
After the load tests, the turbine was operated at full load for about 4 weeks, and electrical power output, fuel input, and ambient conditions were continuously monitored to verify total electricity generated and used during the verification period. Excess electrical power not consumed by the site and exported to the grid was monitored with an existing electric meter. This meter was a bidirectional time-of-use rate meter that was installed by the local power utility, and allowed the Mariah CHP System to be operated in parallel with the grid. Actual electricity used at the site was determined as the difference between electricity generated with the Mariah CHP System (measured with the 7600 ION) and excess electricity supplied to the utility grid (measured with the bidirectional power meter). The electricity transfer data are used to determine electricity offset from central power stations supplying the grid, and to compute greenhouse gas emission reductions, as described in Section 1.4.3.1.

The heat recovery rate was also continuously monitored and recorded throughout the extended test period at a sampling rate of one measurement per minute. During this period, the Mariah CHP System was providing maximum heat recoverable with the system, and excess heat not used by the site was discarded. Actual thermal energy recovered was determined as the sum of measured heat recovery rates times the measurement interval.

1.4.1.1. Measurement Equipment

Figure 1-4 illustrates the location of measurement instruments that were used in the verification.

Figure 1-4. Schematic of Measurement System



The 7600 ION electrical power meter continuously monitored the kilowatts of power at a rate of one reading per minute. The minute readings correspond to the last complete voltage and current cycle occurring during the monitoring event. The 7600 ION was factory calibrated by Power Measurements, and complied with ISO 9002 requirements and NIST traceability requirements. The electric meter was located after the building's 208 volt transformer, and represented power delivered to Walker Court. The real-time data collected by the 7600 ION were downloaded and stored on a data acquisition computer using Power Measurements' PEGASYS software. The logged kW readings were averaged over the duration of the load test periods (30 minutes) to compute electrical efficiency. For the extended test period, kW readings were integrated over the duration of the verification period to calculate total electrical energy generated in units of kilowatt hours (kWh).

Excess electricity supplied to the grid was measured using ENMAX (local utility) bidirectional time-of-use meter. This meter logged 15 minute average electricity transfer records to the Alberta Power Pool (i.e., electricity supplied to and received from Walker Court). Positive values indicated that electricity was transferred from the grid to Walker Court, and negative values indicated excess electricity was supplied to the grid. These data was synchronized with the 7600 ION power generation data, and the difference between the two data sets were used to compute total electricity used at Walker Court.

The mass flow rate of the fuel was measured using an integral orifice meter (Rosemount Model 3095/1195). The orifice meter contained a 0.150 in. orifice plate to enable flow measurements at the ranges expected during testing (3 to 8 scfm natural gas). The orifice meter was temperature- and pressure-compensated to provide mass flow output at standard conditions (60 ^{o}F, 14.696 psia). The meter was configured to continuously monitor the average flow rate per minute. Prior to testing, the orifice meter was factory calibrated using a National Institute of Standards and Technology (NIST) traceable instrument. QA/QC checks for this meter were performed routinely in the field using an on-line diaphragm type dry gas meter. As shown in Figure 1-4, the two meters were installed in series to allow natural gas to flow through both meters while the turbine was operating. The dry gas meter, manufactured by American Meter Company (Model AL800), was capable of metering flow rates up to 28 scfm. It was factory calibrated prior to testing using a NIST-traceable volume prover (primary standard) at the range of flows expected during the verification test.

Natural gas samples were collected and analyzed to determine gas composition and heating value. Samples were collected in a 500 milliliter (mL) evacuated stainless steel canister during each load condition. This sampling interval was selected based on pre-test sampling and analysis, which showed that heating value does not change significantly at the test facility. Replicate samples were collected once during the load test to quantify potential errors introduced by gas sampling and analysis. The collected samples were returned to a certified laboratory (Core Laboratories, Inc. of Calgary, Alberta) for compositional analysis in accordance with ASTM Specification D1945 for quantification of methane (C1) to hexanes plus (C6+), nitrogen, oxygen, and carbon dioxide (ASTM 2001a). The compositional data were then used in conjunction with ASTM Specification D3588 to calculate lower heating value (LHV), and the relative density of the gas (ASTM 2001b). Duplicate analyses were performed by the laboratory to determine the repeatability of the LHV results.

The heat meter was manufactured by Arigo Software GmBH (Model – Dialog WZ LON Multistream Electronic Heat Meter), and was certified to meet Europe's custody transfer standards. It measured volumetric flow rate of the PG solution using a multi-impeller wheel contact water counter. It also had the capability to measure PG solution temperature in the supply and return lines, using two resistance temperature detectors (RTDs) located in thermal wells.

As shown in Equation 2, heat recovery rate determination requires measurement of the physical properties of the heat transfer media. PG samples were collected from a fluid discharge spout located on the hot side of the heat recovery unit using precleaned glass vials of 100 to 500 mL capacity. Samples were collected during each of the 50, 75, 90, and 100 percent load tests, and at least once during the extended test period. Each sample collection event was recorded on field logs, and shipped to Philip Analytical Laboratories along with completed chain-of-custody forms. At the laboratory, samples were analyzed for PG concentration and fluid density using gas chromatography with a flame ionization detector (GC/FID). Using the measured concentrations, specific heat of the PG solution was selected using published correlations (ASHRAE 1997).

1.4.2. Power Quality Performance

When an electrical generator is connected in parallel and operated simultaneously with the utility grid, operational characteristics should closely match grid performance. Parameters such as voltage frequency indicate synchronization with the utility grid. Time series voltage readings can be used to indicate how well the voltage-following capabilities of the turbine match the grid. The Mariah CHP System power electronics contain circuitry to detect and react to abnormal conditions that, if exceeded, cause the unit to automatically disconnect from the grid. These interconnection protection functions for over-voltage, under-voltage, and frequency were described in Table 1-1. For this test, out-of-tolerance conditions were defined as measured voltage outside the range of 208 volts ± 10 percent (line-to-line and line-to-neutral) and electrical frequency of 60 ± 0.01 Hz. One minute average voltage and frequency measurements were collected continuously throughout the verification period using the 7600 ION electric meter.

Other power quality performance parameters, such as power factor and total harmonic distortions (THDs), characterize the quality of electricity supplied to the building occupants. Power factor quantifies the reaction of alternating current (AC) electricity to various inductive loads. These electrical loads are found in motors, drives, and fluorescent lamp ballasts, and cause the voltage and current to shift out of phase. Additional power, measured in kilovolt-amps (kVA) must be generated to compensate for phase shifting. Mathematically, power factor is expressed as real power (kW) divided by apparent power (kVA). Under ideal conditions, current and voltage are in phase which results in a power factor equal to 1.0 or 100 percent. If inductive loads are present, power factors are less than this optimum value. In such instances, reactive components produce the magnetic field for the operation of a motor, drive, or other device which performs no useful work and does not register on measurement equipment such as the watt meter. The reactive components, expressed as reactive kilovolt-amps (kVAR), contribute to undesirable heating of electrical generation and transmission equipment and real power losses to the source supplying electricity (e.g., utility). Power factors ranging between 0.80 and 0.90 are common.

During the verification test, the Mariah CHP System was programmed to operate at a power factor setting of 1.0 or 100 percent. To determine the unit's ability to supply power at this setting, 1 minute average measurements were collected with the 7600 ION.

Similar to power factor, harmonic distortions in voltage and current were also measured for the duration of the verification period. Harmonic distortions can damage or disrupt the proper operation of many kinds of industrial and commercial equipment. Voltage distortion is defined as any deviation from the nominal sine waveform of AC line voltage. A similar definition applies for current distortion; however, voltage distortion and current distortion are not the same. Each affects loads and power systems differently, and thus are considered separately. The guidelines listed in the Institute of Electrical and Electronics Engineers' Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems (IEEE 519) were followed in determining current and voltage THDs (IEEE 1993). During four specific time intervals, baseline THD was measured for the utility grid. This activity consisted of manually turning off the Mariah CHP System for about 1 hour, and measuring the power factor at the 208 volt external transformer. The measurements were repeated after the Mariah CHP System was brought back on line, and then used to characterize the change in THD after the Mariah CHP System came back on line.

1.4.3. Emissions Performance

Pollutant concentration and emission rate measurements for nitrogen oxides (NO_X), carbon monoxide (CO), total hydrocarbons (THCs), and carbon dioxide (CO_2) were conducted on the turbine exhaust stack during the four load conditions. Testing for methane was specified in the Test Plan but, after observing extremely low levels of THC using an on-site analyzer, the methane testing was canceled. Emissions testing coincided with the electrical efficiency determination at the four power commands described earlier. All of the test procedures are U.S. EPA Federal Reference Methods, which are well documented in the Code of Federal Regulations. The Reference Methods include procedures for selecting measurement system performance specifications and test procedures, quality control procedures, and emission calculations (40CFR60, Appendix A). Table 1-2 summarizes the standard test methods that were followed. A complete discussion of the data quality requirements (e.g., NO_X analyzer interference test, NO_2 converter efficiency test, sampling system bias and drift tests) is presented in the Test Plan.

Table 1-2. Summary of Emissions Testing Methods

Exhaust Stack			
Pollutant	EPA Reference Method	Number of Loads Tested	Number of Tests
NO_X	20	4	3 per load (30 minutes each)
CO	10	4	3 per load (30 minutes each)
THC	25A	4	3 per load (30 minutes each)
CO_2	3A	4	3 per load (30 minutes each)
O_2	3A	4	3 per load (30 minutes each)

Three test runs were conducted at 50, 75, 90, and 100 percent loads. During each test, sampling was conducted for approximately 30 minutes at a single point near the center of the 12-inch diameter stack. Results of the instrumental testing are reported in units of parts per million by volume dry (ppmvd) and ppmvd corrected to 15 percent O_2. The emissions testing was conducted by Entech Environmental Services of Calgary, Alberta, under the on-site supervision of the GHG Center Field Team Leader. A detailed description of the sampling system used for criteria pollutants, GHGs, and O_2 is provided in the Test Plan, and is not repeated in this report. A brief description of key features is provided below.

In order for the CO_2, O_2, NO_X, and CO instruments to operate properly and reliably, the flue gas must be conditioned prior to introduction into the analyzers. The gas conditioning system used for this test was designed to remove water vapor and/or particulate from the sample. Gas was extracted from the turbine exhaust gas stream through a stainless steel probe and heated sample line and transported to ice-bath condensers, one on each side of a sample pump. The condensers removed moisture from the gas stream. The clean, dry sample was then transported to a flow distribution manifold where sample flow to each analyzer was controlled. Calibration gases were routed through this manifold to the sample probe to perform bias and linearity checks.

NO_X concentrations were determined using a Monitor Labs, Inc. Model 8840 chemiluminescence analyzer. This analyzer catalytically reduces NO_2 in the sample gas to NO. The gas is then converted to excited NO_2 molecules by oxidation with O_3 (normally generated by ultraviolet light). The resulting NO_2 emits light (luminesces) in the infrared region. The emitted light is measured by an infrared detector and reported as NO_X. The intensity of the emitted energy from the excited NO_2 is proportional to the concentration of NO_2 in the sample. The efficiency of the catalytic converter in making the changes in chemical state for the various NO_X is checked as an element of instrument setup and checkout. The NO_X analyzer was calibrated to a range of 0 to 25 ppmvd.

A Monitor Labs, Inc. Model 8830 gas filter correlation analyzer with an optical filter arrangement was used to determine CO concentrations. This method provides high specificity for CO. Gas filter correlation uses a constantly rotating filter with two separate 180-degree sections (much like a pinwheel.) One section of the filter contains a known concentration of CO, and the other section contains an inert gas without CO. The sample gas is passed through the sample chamber containing a light beam in the spectral region absorbed by CO. The sample is then measured for CO absorption with and without the CO filter in the light path. These two values are correlated, based upon the known concentrations of CO in the filter, to determine the concentration of CO in the sample gas. The CO analyzer was operated on a range of 0 to 20 ppmvd.

THC concentrations in the exhaust gas were measured using a California Analytical Model 300M flame ionization analyzer and quantified as propane. This detector analyzes gases on a wet, unconditioned basis. Therefore, a second heated sample line was used to deliver unconditioned exhaust gases directly to the

THC analyzer. All combustible hydrocarbons were analyzed. Emission rates are reported on an equivalent methane basis.

For determination of CO_2 concentrations, a Nova Model 372WP analyzer equipped with a non-dispersive infrared (NDIR) detector was used. NDIR measures the amount of infrared light that passes through the sample gas versus through a reference cell. Because CO_2 absorbs light in the infrared region, the degree of light attenuation is proportional to the CO_2 concentration in the sample. The CO_2 analyzer range was set at 0 to 20 percent.

A California Analytical Model 100P paramagnetic analyzer was used to monitor O_2 concentrations. The paramagnetic technology used by this instrument determines levels of O_2 based on the level of physical deflection of a non-diamagnetic material caused by exposure to the stack gas. Because O_2 is diamagnetic, the higher the O_2 concentrations, the greater the material is deflected. An optical system with an amplifier detects the level of deflection, which is linearly proportional to the O_2 level in the gas. The O_2 analyzer range was set at 0 to 25 percent.

The instrumental testing for CO_2, O_2, NO_X, CO, and THC yielded concentrations in units of ppmvd and ppmvd corrected to 15 percent O_2. The Test Plan specified that exhaust gas volumetric flow rate determinations would be conducted following EPA Method 2 procedures. However, field gas velocity measurements revealed that the exhaust stack flow was too low to make accurate measurements using Method 2 (differential pressure across the pitot tube was less than 0.01 inches H_2O). Therefore, EPA Method 19 was followed to convert measured pollutant concentrations into emission rates in units of pounds per hour (lb/hr).

The fundamental principle of Method 19 is based upon F-factors. F-factors are the ratio of combustion gas volume to the heat content of the fuel, and are calculated as a volume/heat input value, (e.g., standard cubic feet per million Btu). This method specified all calculations required to compute the F-factors and provides guidelines for their use. The F-factors used to determine emission rates for each load test were calculated using the actual gas composition as determined using fuel samples collected in the field. Equation 19-13 of Method 19 was followed to calculate the F-factors in units of dry standard cubic feet per million Btu (dscf/MMBtu). After converting the pollutant concentrations from a ppmvd basis to lb/dscf, the calculated F-factor was used, in conjunction with the measured heat input to the turbine (MMBtu/hr) and stack gas O_2 concentration (dry basis), to calculate emission rates in terms of lb/hr using Equation 4.

$$\textit{Mass Emission Rate (lb/hr)} = \textit{HI} * \textit{Concentration} * \textit{F-factor} * [20.9 / (20.9 - \%\, O_{2,d})] \qquad \text{(Eqn. 4)}$$

Where:

HI = heat input (MMBtu/hr)
Concentration = measured pollutant concentration (lb/dscf)
F-factor = calculated exhaust gas flow rate (dscf/MMBtu)
$O_{2,d}$ = measured O_2 level in exhaust stack, dry basis (%)

The mass emission rates as lb/hr were then normalized to electrical power output by dividing the mass rate by the average power output measured during each load test, and are reported as pounds per kilowatt-hour electrical (lb/kWh$_e$).

1.4.3.1. Maximum Possible Emission Reductions for the Verification Period

Walker Court was new during the verification period, and had achieved only a 25 percent occupancy. Thus, demand for electricity and heat was significantly lower than what the unit is capable of producing. As such, electricity and heat used on-site were lower than the maximum potential of the system. Mariah estimates that the base-loaded heating requirement for a fully occupied Walker Court will be about 200,000 Btu/hr, which is sufficient to utilize the maximum recovery potential of the CHP system. It was also assumed that all electricity generated can be used on-site at full occupancy, and that excess energy, measured during the verification period, will not be supplied to the grid in the future. This is a reasonable assumption because the current daily power consumption was measured to range between 6 and 12 kW, and this demand will likely increase to make full use of the 30 kW electricity generation potential of the Mariah CHP System. Based on Mariah's electrical consumption projections, the base-load electrical power requirement for Walker Court is about 29 kW. To determine maximum possible heat that can be recovered, and the maximum emissions that can be reduced, the heat demand of the facility was artificially increased during the verification period (i.e., heat was discarded through open windows in all units).

Emissions from the Mariah CHP System are compared with a baseline system to estimate emission reductions in percent and pounds CO_2. The baseline system is that which would have been used to meet the site's energy needs in the absence of the Mariah CHP System. The baseline system for Walker Court is defined to be electricity supplied by the Alberta utility grid and thermal energy supplied by a new standard natural-gas-fired boiler. Subtraction of the Mariah CHP System emissions from the baseline emissions yields an estimate of net emission reductions, as shown in Equation 5. Emission reductions are reported for CO_2 only because it is the primary GHG emitted from combustion processes, and because emission factors for electric utility and natural gas boilers are available for CO_2 only. The Mariah CHP System emissions and emission reductions reported here correspond to maximum levels possible since the electricity and heat recoverable with the Mariah CHP System are assumed to be used on-site, and additional energy is not needed from a backup boiler or the utility grid.

$$\textit{Emission Reductions (lb } CO_2\textit{)} = \textit{[Grid Emissions + Boiler Emissions] - Mariah CHP System Emissions} \qquad \text{(Eqn. 5)}$$

Mariah CHP System Emissions

Mariah CHP System emissions are computed by multiplying hourly electricity generated (kW_e) with the CO_2 emission rate at full load (lb/kW_e). The hourly electricity generated was obtained from the 7600 ION power meter data, and the CO_2 emission rate was assigned based on emission test results that correspond to full load conditions.

As previously described, it is assumed that the Mariah CHP System provides all of the site's base-loaded heat requirements and a backup boiler is not needed. Thus, emissions associated with a backup boiler, which would be operating in conjunction with the Mariah CHP System, only during peak season, are assumed to be zero. As such, CO_2 emissions for the heat recovery portion are assigned a value of zero.

Grid Emissions

For each kWh of electricity produced and used with the Mariah CHP System, an equivalent amount of electricity is no longer required from the utility grid and the central power stations that supply the grid. The electricity offset is defined as the electricity used plus additional electricity that must be generated to account for transmission and distribution line and transformer losses between the plant fence-line and the end-user. The average line losses for the Alberta Power grid are estimated to be 7.87 percent, which means that for every kWh electricity used on-site with the Mariah CHP System, 1.0787 kWh_e will be offset from the utility grid. Total electricity offset by the Mariah CHP System was computed as the electricity generated times 1.0787. Hourly total electricity offset values (kWh_e), calculated as described above, were multiplied by the hourly average CO_2 emission factor for the utility grid (lb CO_2/kWh_e) to compute total emissions for the utility grid (lb CO_2).

The hourly average grid emission factors for the Alberta grid were developed for this verification by the KEFI-Exchange, a privately owned, industry-sponsored, commodity exchange firm which operates under an order from the Alberta Securities Commission. The KEFI-Exchange uses accepted methodologies developed by Canada's Emissions Quantification Working Group to estimate hourly average grid emission factors. Details of the approach are discussed in the Test Plan. Briefly, an inventory of all power plants generating electricity during a specific operating hour is developed using actual electricity transfer metering records which are maintained by the Alberta Power Pool, and available on the Internet. The KEFI-Exchange multiplies the plant-specific electricity generation data by published emission factors for that plant to derive total CO_2 emissions for the plant. The sum of emissions from all plants, operating during the hour, divided by the total electricity generated is the average grid emission factor. A similar approach is used for any electricity imported into Alberta. However, during the verification period, there were no recorded imports of electricity into the Alberta grid, and therefore, there were no emissions related to imports for the period. Historically, emissions from import activities are relatively small. In 2000, net imports represented only 1.1 percent of the total electricity consumption in the province, making imports a very small portion of the Alberta energy transactions.

Boiler Emissions

For each Btu or kW_{th} of thermal energy recovered and used at Walker Court, an equivalent amount of energy is no longer needed from the baseline gas-fired boiler. The approach for computing emissions for the boiler consists of first estimating the fuel that would have to be combusted to produce heat that is equivalent to the heat recovered by the Mariah CHP System. The baseline comfort heating and hot water system is a new natural-gas-fired boiler system, manufactured by Raypack (Model 1826). The boiler is sized for peak consumption, with a thermal output of 1460.5 MBtu/hr and an efficiency of 80 percent (after accounting for a jacket loss of 3 percent). For use at higher elevations (e.g., 3,370 ft for Walker Court), the manufacturer derates the boiler efficiency to 70 percent. As a result, fuel needed for the boiler is equal to the heat used at Walker Court times 1.43 (1/0.70).

The hourly fuel consumption rates were multiplied by the CO_2 emission factor to determine boiler emissions in pounds of CO_2. EPA accepted procedures were followed to compute the CO_2 emission factor. Details of the approach are provided in the Test Plan. Briefly, fuel carbon content, as measured from natural gas heating value analysis done on site, were multiplied by oxidation rates for natural gas to determine the number of pounds of CO_2 per Btu of fuel combusted.

1.4.3.2. Estimated Annual Emission Reductions for Model Sites

It is acknowledged that the energy demand and operational characteristics of the Walker Court test site are unique to this location. To assist in determining broad applicability of this technology and the resulting potential emissions reductions, a comparative analysis of the application of the Mariah CHP System to other locations and building types was undertaken. To accomplish this, electrical and thermal energy consumption data for different building types where the CHP technology may be feasible were compiled. These model sites consisted of (1) several prototype commercial buildings in Chicago and

Atlanta, and (2) a medium-scale textile manufacturing plant in North Carolina. The following describes the methodology employed to determine monthly electrical and thermal demands, baseline systems, energy offset by Mariah CHP System unit(s), and net CO_2 emission reductions.

Energy demand characteristics for commercial buildings in Chicago and Atlanta were obtained from a report prepared for the U.S. DOE Office of Building Technologies: *The Final Report on Fuel Cells for Building Cogeneration Applications - Cost/Performance Requirements and Markets*, (DOE 1995). In this report, an analysis was conducted to assess fuel-cell-based combined heat and power systems for varying building types. The analysis used the industry-accepted DOE2 building energy simulation software program to project the monthly energy consumption for nine classes of buildings in two geographic locations. The DOE2 is widely used for analytical purposes in the HVAC and buildings industries. The commercial buildings modeled in this report were classified as: "Medium Office," "Large Office," "Medium Hotel," "Large Hotel," "Hospital," "Retail," and "Junior High School." Also modeled were a single-family residence and a multi-family residence.

The thermal load for medium office and multi-family residence buildings was so low that substantial amounts of thermal energy from even one Mariah CHP System unit could not be used. If the CHP system is operated at part load or its thermal energy is discarded, the environmental performance will be significantly reduced. Thus, these building types were not examined further. Based on results of a second DOE and Gas Research Institute (GRI) study, which ranked the market potential of cogeneration systems for different building types (GRI 1991), the GHG Center has selected the following model sites for the verification:

- Large Office
- Medium Hotel
- Large Hotel
- Hospital

The model sites selected for evaluation are also consistent with a recent NRCan/CANMET investigation which examined the technical and economic potential of microturbines, fuel cells, and packaged cogeneration system for applications in Canadian buildings. The study concluded that economics of DG systems were best at hotels, followed by hospitals, and multi-unit residential buildings. Table 1-3 summarizes key characteristics of each model site. A description of the emission-reduction estimation methodology is provided below.

Table 1-3. Key Characteristics of Model Sites

Building Type	Gross Floor Area (ft^2)	No. of Mariah CHP System Units [a]	Monthly Peak Electric (kWh_e)		Monthly Peak Water Heating (kWh_{th})	Monthly Peak Space Heating (kWh_{th})		HVAC System
			Chicago	Atlanta	Chicago & Atlanta	Chicago	Atlanta	
Large Office	792,095 (40 floors)	2	845,121	809,669	20,277	693,130	561,545	• Perimeter systems – variable volume reheat • Hermetic centrifugal chillers
Medium Hotel	68,808 (3 floors)	2	222,193	246,713	51,173	165,713	104,715	• 4 pipe fan coil in guest rooms • Variable air volume in public areas, single zone system • Hermetic centrifugal chiller
Large Hotel	315,500 (10 floors)	3	463,709	512,255	73,301	461,713	337,493	• 4 pipe fan coil in guest rooms • Variable temperature, constant volume system • Hermetic centrifugal chiller
Hospital	291,512 (4 floors)	14	1,205,694	1,373,359	221,069	956,593	601,936	• Dual duct fan system • 4 pipe fan coil for patient rooms • Hermetic centrifugal chiller

[a] Assigned based on monthly thermal demand (i.e., all units are base loaded such that the net recovered from CHP systems is fully used during 9 months out of a full operating year)

The design and evaluation of Mariah CHP Systems must take into account the daily and seasonal variations in both electric and thermal loads. Of particular importance for system design and analysis is the coincidence of electric and thermal loads, because the production of these two energy forms is essential to making full use of the CHP system. For these purposes, the electric loads (non-HVAC and HVAC related) and thermal loads (potable hot water and space heating) reported in the DOE report (DOE 1995) are used. Energy consumption data for model sites in Chicago and Atlanta are summarized in Appendix A.

The monthly data for each model site were entered into a spreadsheet, and the energy demand data for each location were analyzed to determine the number of Mariah CHP System units that would be applicable for each situation. The number of Mariah CHP System units required at each model site was selected based on full utilization of heat produced by the system for at least 9 months in a year. For each model site evaluated, the heating requirement during the summer months was the limiting factor [i.e., heat demand was generally lower than the heat recovery potential of the CHP unit(s)]. Conversely, the electricity demand for each model site exceeded the maximum electric energy output of the CHP units; thus, all the electricity generated could be used on site. In fact, demand for electricity is highest in summer months, when the demand for waste heat is significantly lower. For this reason, for some sites, economic impetus to operate the unit in summer may be greater when electricity prices are highest. This scenario was not examined in the verification. In conclusion, two CHP units were projected for use in the “Large Office” and "Medium Hotel” buildings. The “Large Hotel” building was estimated to be able to fully utilize three CHP units, and the large year-round demand for thermal energy projected for the “Hospital” justified modeling 14 CHP units.

The baseline system selected for model sites consists of electricity supplied by the utility grid and thermal energy supplied by an on-site gas boiler(s) in Chicago and electric heat pump/hot water units in Atlanta. Region specific emission factors for the utility grid were obtained from a recent EPA/EIA report (DOE/EPA 2000), and a national average transmission and distribution line loss of 5.1 percent was applied. Appendix A summarizes electric utility emission factors assigned to model sites in Chicago, Atlanta, and North Carolina. The baseline boiler was selected to be fueled by natural gas in Chicago and electricity in Atlanta. The fuel types represented here are based on the most recent Commercial Buildings Energy Consumption survey (CBECS). According to the survey in 1995, natural gas systems provided about 52 percent of the thermal energy demand in the North Central region, and electrical systems provided about 68 percent of the thermal energy demand in the South Central region (CBEC 2000).

Boiler efficiencies can vary greatly depending on the age of equipment, overall system design, combustion efficiency, and type of technology. According to a training manual sponsored by DOE and prepared by Rutgers University for end users interested in performing industrial assessments at existing small to medium sized manufacturing plants, there are no standard performance efficiency levels to which commercial boiler manufacturers must adhere (Miller 2000). As a result, efficiency is reported in different terms: thermal efficiency (a measure of effectiveness of the heat exchanger, which does not account for radiation and convection losses), fuel-to-steam efficiency (a measure of the overall efficiency of the boiler, which accounts for radiation and convection losses), and boiler efficiency (used both ways). The report estimates that the overall efficiency of commercial gas boilers ranges between 70 and 82 percent. This range is consistent with typical boiler efficiencies reported by DOE and EPA -- 70 to 85 percent (EPA 1998). Actual boiler efficiency can decrease by as much as 20 percent depending on improper maintenance and load management practices, less than optimum air/fuel ratio, and excessive stack losses. The baseline boiler systems in this verification were assigned an overall boiler efficiency of 70 percent. This was based on the studies cited above, and conversations with boiler manufacturers, DG panel members, and trade associations (e.g., Boiler Manufacturers Association). Table 1-4 provides an example summary of monthly energy demands, utility grid emission levels, and boiler emissions levels for the hospital model in Chicago.

Using the number of CHP units selected for each model site, monthly thermal and electrical output characteristics (compensated for temperature and elevation) were computed for the Mariah CHP System. Given that the elevation of each location evaluated was approximately 1,000 feet or less above sea level, elevation did not significantly derate the Mariah CHP System energy production potential. However, the derating of the microturbine's output at higher temperatures caused less electricity to be generated during the summer months when the buildings' electrical demand was highest. Emissions associated with the Mariah CHP System were computed as the direct emissions from the Mariah CHP System units plus emissions from any backup energy sources that may be needed during high demand periods (e.g., boilers in peak winter season). Table 1-4 illustrates example emission reduction calculations for a large hotel in Chicago.

The same strategy discussed above was applied to a textile manufacturing plant in North Carolina. Monthly electrical and natural gas consumption data were obtained from the plant operator. Using monthly fuel consumption data, the thermal energy requirement for each month were computed for three baseline gas-fired boilers with a reported boiler efficiency of 60 percent. The monthly electricity and thermal demands are summarized in Appendix A. It is estimated that this plant has sufficient continuous electrical and thermal demand such that about 28 Mariah CHP System units could operate continuously for 12 months. In addition to this, a backup gas-fired boiler would require between 0.2 and 0.7 MWh_{th} additional thermal energy per month. Annual emissions for the baseline system and Mariah CHP System scenario are computed using the same methodology described above.

Table 1-4 Example Energy Requirements and Emission Reduction Calculations for a Model Hospital in Chicago

Building Type:	Hospital
Location:	Chicago, IL
Baseline Scenario:	Electricity from utility grid Space heating and hot water from standard equipment (70% efficient natural gas boiler)
Mariah CHP Scenario:	14 Mariah CHP units Makeup electrical energy supplied by utility grid Makeup space heating and hot water supplied by standard equipment (70% efficient natural gas boiler)

	Building Energy Demand			Baseline Scenario: Energy Supplied by Grid	Baseline Scenario: Energy Supplied by Gas Boiler	Baseline Scenario: Emissions		
	Electric	Space Heating	Hot Water	Electric	Thermal	Grid	Gas Boiler	Total
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(lb CO2)	(lb CO2)	(lb CO2)
Jan	827,501	956,593	221,069	827,501	1,177,662	1,461,102	668,454	2,129,556
Feb	748,640	866,268	199,675	748,640	1,065,943	1,321,859	605,041	1,926,899
Mar	841,979	719,324	221,069	841,979	940,393	1,486,665	533,777	2,020,443
Apr	883,140	412,119	213,938	883,140	626,057	1,559,343	355,357	1,914,699
May	1,031,208	254,757	221,069	1,031,208	475,826	1,820,783	270,084	2,090,867
Jun	1,118,899	164,989	213,938	1,118,899	378,927	1,975,618	215,083	2,190,701
Jul	1,205,694	132,046	221,069	1,205,694	353,115	2,128,870	200,432	2,329,302
Aug	1,194,862	137,235	221,069	1,194,862	358,304	2,109,744	203,377	2,313,121
Sep	1,092,102	179,441	213,938	1,092,102	393,379	1,928,303	223,286	2,151,589
Oct	968,378	296,527	221,069	968,378	517,596	1,709,846	293,793	2,003,639
Nov	835,591	537,730	213,938	835,591	751,668	1,475,386	426,655	1,902,041
Dec	835,737	842,638	221,069	835,737	1,063,707	1,475,644	603,772	2,079,416
Annual Total	11,583,731	5,499,667	2,602,910	11,583,731	8,102,577	20,453,163	4,599,111	25,052,273

	Mariah CHP Scenario: Energy Supplied by Mariah CHP Units		Mariah CHP Scenario: Makeup Energy Supplied by Grid and Gas Boiler		Mariah CHP Scenario: Emissions				Estimated Emission Reductions	
	Electric	Thermal	Electric	Thermal	Mariah CHP	Grid	Gas Boiler	Total		
	(kWh)	(kWh)	(kWh)	(kWh)	(lb CO2)	(lb CO2)	(lb CO2)	(lb CO2)	(lb CO2)	%
Jan	310,360	598,995	517,141	578,667	480,140	913,105	328,457	1,721,702	407,854	19
Feb	280,325	541,028	468,315	524,915	433,675	826,894	297,947	1,558,516	368,383	19
Mar	277,460	535,497	564,519	404,896	429,241	996,761	229,823	1,655,825	364,618	18
Apr	262,609	506,836	620,531	119,221	406,267	1,095,658	67,671	1,569,597	345,102	18
May	249,192	480,941	782,016	-	385,510	1,380,790	-	1,766,300	324,567	16
Jun	236,556	456,554	882,343	-	365,962	1,557,935	-	1,923,897	266,804	12
Jul	230,564	444,989	975,130	-	356,692	1,721,767	-	2,078,459	250,843	11
Aug	232,518	448,760	962,344	-	359,715	1,699,191	-	2,058,906	254,215	11
Sep	242,028	467,113	850,074	-	374,426	1,500,959	-	1,875,386	276,203	13
Oct	257,138	496,277	711,240	21,319	397,803	1,255,822	12,101	1,665,726	337,913	17
Nov	273,812	528,457	561,779	223,211	423,598	991,922	126,697	1,542,217	359,824	19
Dec	280,325	541,028	555,412	522,679	433,675	980,679	296,678	1,711,032	368,384	18
Annual Total	3,132,887	6,046,475	8,450,844	2,394,908	4,846,704	14,921,483	1,359,374	21,127,563	3,924,710	16

2.0 VERIFICATION RESULTS

The verification period started on April 2, 2001, and continued through May 25, 2001. A series of load tests were conducted between April 2 and April 5. The load tests were designed to measure Mariah CHP System emissions and efficiency performance at 100, 90, 75, and 50 percent of rated power output. This was followed by an extended period of continuous monitoring to examine heat and power output, power quality, and emission reductions. They are based on data collected while the Mariah CHP System was operating on the following 38 days:

- April 7, 11, 12, 16 through 21, 23 through 27, 30
- May 2, 4 through 25

The days listed above include periods when the unit was operating normally, and excludes days when it was manually shut down by operators or as requested by the GHG Center. Appendix C summarizes the test days, times, and parameters verified. Although the GHG Center has made every attempt to obtain a reasonable set of data to examine daily trends in atmospheric conditions, electricity and heat production, and power quality, the reader is cautioned that these results may not represent performance over longer operating periods or at significantly different operating conditions.

Verification testing occurred at high altitude (3,370 ft above sea level) during late winter and early spring months. The Mariah CHP System and its intake air were located indoors, which resulted in air temperatures being relatively consistent throughout the test period. Temperatures ranging between 38 and 65 ^{o}F were encountered, and as a result, the test results do not provide information related to the system's response to higher ambient temperatures that may be encountered in other regions. Operating microturbines at higher elevations and elevated temperatures can result in derating of these units, as efficiency levels decrease. In addition, as the unit attempts to operate at lower efficiencies, it is likely that environmental emissions introduced to the atmosphere may increase. Using the manufacturer's performance ratings, the GHG Center has attempted to provide the reader with sufficient information to relate power output and efficiency performance at site conditions relative to standard conditions.

Test results are presented in subsections and include the following:

Section 2.1 – Heat and Power Production Performance
(short-term load testing and 38 days of extended testing)
Section 2.2 - Power Quality Performance
(38 days of extended testing)
Section 2.3 - Emissions Performance
(short-term load testing)

The results show that the quality of power generated by the Mariah CHP System is generally high, and that the unit is capable of operating in parallel with the utility grid. The unit produced between 23 and 28 kW of electrical power depending on ambient temperature (38 to 65 ^{o}F). The maximum heat recovery rate measured was 195,000 Btu/hr. At full load, electrical efficiency was 24.6 percent and thermal efficiency was 47.2 percent. Total Mariah CHP System efficiency at full load was 71.7 percent, and total efficiencies as high as 80 percent were observed after an air inlet design modification was made by Mariah. NO_X and CO emissions at full load were less than 5 ppmvd (corrected to 15 percent O_2). Maximum NO_X and CO_2 emission reductions are estimated to be 97 and 55 percent, respectively.

An assessment of the quality of data collected throughout the verification period is provided in Section 3.0. The data quality assessment is then used to demonstrate whether the data quality objectives (DQOs) introduced in the Test Plan were met for this verification.

2.1. HEAT AND POWER PRODUCTION PERFORMANCE

The heat and power production performance evaluation included electrical power output, heat recovery, and efficiency determination at selected loads. The performance evaluation also included determination of total electrical energy generated and used and thermal energy recovered over the extended test period.

Load testing occurred between April 2 and 5, 2001. At the end of load testing on April 3, the measured temperature differentials at the heat recovery unit were lower than expected (i.e., total Mariah CHP System efficiency was about 66 percent). Mariah operators measured higher efficiencies during internal testing, and hypothesized that one of the three measurement instruments used to compute heat recovery rate may be suspect. In response to this, two different quality assurance checks were performed by the GHG Center on the heat meter RTDs.

The RTDs were removed from the heat recovery unit piping system and compared to reference thermocouples in ice bath, hot water bath, and ambient conditions. During all comparisons, the RTDs agreed with the reference measurements and were consistent within the allowable instrument errors. This check confirmed that the RTDs were functioning properly, and suggested that potential error existed in their installation within the thermal wells. A second check was performed by installing and insulating two reference thermocouples on the glycol return and supply lines, and their readings were compared with the RTD readings. This check revealed a low bias in the RTD readings, which resulted in the heat recovery unit differential temperatures to be about 16 ^{o}F instead of 19 ^{o}F. Based on these findings, the heat meter RTDs were reinstalled with fresh thermal compound to ensure good thermal conductivity within the wells, and comparisons with reference thermocouples were repeated. The differential temperature measurements for both instruments agreed (18.6 ^{o}F for Arigo RTDs and 19.1 ^{o}F for reference thermocouples), and were within the allowable instrument errors.

Based on these findings, the heat recovery performance data for April 2 and 3 (Run 1 through 12) were invalidated, and are not used to compute average thermal efficiency and total efficiency for the load tests. The efficiency tests were repeated on April 4 and 5 (Runs 13 through 18) at each operating load, and these results are used to compute actual heat and power production performance. The ambient conditions (i.e., air inlet temperature, pressure, and relative humidity) were generally consistent during the 4 testing days. Thus, significant variation in power and heat production was not expected, and results of all tests, excluding invalid heat recovery data, are used to form conclusions regarding the Mariah CHP System heat and power production performance.

2.1.1. Electrical Power Output, Heat Recovery Rate, and Efficiency During Load Tests

Table 2-1 summarizes the power output, heat recovery rate, and efficiency performance of the Mariah CHP System. All load testing occurred during relatively consistent atmospheric conditions: 42 ^{o}F average ambient temperature, 50 percent average RH, and 13 psia average barometric pressure. Actual conditions encountered during testing were lower than standard conditions defined by the International Standards Organization (59 ^{o}F, 60 percent RH, and 14.696 psia), as a result, deration of the electrical power and efficiency was expected in the verification results. The natural gas LHV results were also consistent for all samples collected during each load test, and ranged between 907.2 and 915.9 Btu/ft^3. Due to the stability in ambient conditions and natural gas heating value, cross comparisons between operating loads can be made. The reader is cautioned that the results shown in Table 2-1 and the discussion that follows are representative of conditions encountered during testing, and are not intended to indicate performance at other operating conditions (e.g., warmer temperatures, lower elevations).

The average electrical power delivered was 28.39 kW_e at full load, and the average electrical efficiency corresponding to these measurements was 24.61 percent. The power output, compensated for ISO standard sea level, is estimated to be 29.5 kW_e at 40 ^oF and 27.4 kW_e at 59 ^oF. Electric power generation heat rate, which is an industry accepted term to characterize the ratio of heat input to electrical power output, was measured to be 13,865 Btu/kWh_e at full power. Net heat rate, which accounts for waste heat recovery, is 5,170 Btu/kWh_{tot} at full power. The average heat recovery rate at full load was 186,853 Btu/hr or 54.76 kW_{th}, and thermal efficiency was 47.20 percent. Based on results of five runs at full load, the total efficiency (electrical and thermal combined) was 71.71 percent. Natural gas fuel input characteristics and heat recovery unit operation data corresponding to these efficiency results are summarized in Table 2-2.

As the electrical power output was reduced from 100 to 50 percent, both actual power delivered and heat recovery rate dropped to 14.54 kW_e and 113,400 Btu/hr, respectively. A 2.81 percent decrease in electrical efficiency was observed at 50 percent load. Conversely, a small increase in thermal efficiency was observed, so the total efficiency of the Mariah CHP System remained relatively consistent (72 percent).

At the conclusion of the official load testing, Mariah requested that the GHG Center collect additional data at different loads to further understand the CHP system performance. An additional test run, which was beyond the scope of the official verification, was conducted at loads ranging between 40 and 100 percent of rated capacity. The test was conducted by collecting 5 to 10 minutes of data at power commands starting at full power and incrementally decreasing by 1 kW to a low of 13 kW. The only deviations from the standard test methods were that three replicate tests were not conducted, the duration of sampling at each power command was shorter, and the power command changes between successive load changes occurred relatively rapidly.

The PTC-22 allows between 4 and 30 minutes of continuous electrical power and fuel data to compute efficiency, provided maximum deviation in key measurement parameters (e.g., power factor, air temperature/pressure, fuel flow rate) do not exceed maximum thresholds defined in PTC-22. The operating condition encountered during each load condition satisfied the PTC-22 requirements. Based on this, direct comparisons between these efficiency results and those verified during the official load tests were made. The efficiency results for the non-standard test run are illustrated in Figure 2-1. The figure shows that, when electrical power output decreased from 28 to 13 kW_e (a 56 percent drop in power output), electrical efficiency decreased by about 5 percent. The drop in electrical efficiency is related to the natural gas fuel input levels because efficiency is defined as energy out divided by energy in. At the load conditions described above, fuel input decreased by 43 percent when power output decreased by 56 percent.

Conversely, a significantly smaller decrease in heat recovery rate (181,017 to 112,594 Btu/hr) was measured, which resulted in a 2 percent increase in thermal efficiency. The small increase in heat recovery rate is believed to be related to turbine exhaust gas conditions. Gas turbines operate on a constant mass basis. As such, a decrease in fuel input at lower power settings requires additional combustion intake air. Measured O_2 levels at 28 and 13 kW_e power output were 18.09 and 18.54 percent, respectively. The resulting exhaust gas flow rates remained relatively consistent, which results in essentially the same mass available for heat transfer to occur. Based on these observations and conditions encountered during testing, it can be concluded that the total Mariah CHP System efficiency can remain relatively consistent, despite a significant decrease in electrical power output and electrical efficiency.

Table 2-1. Heat and Power Production Performance										
	Test Condition		Heat Input	Electrical Power Generation Potential[a]		Maximum Heat Recovery Potential		Total Mariah CHP System Efficiency	Ambient Conditions[b]	
				Power Delivered[d]	Electrical Efficiency	Heat Recovery Rate[e]	Thermal Efficiency			
	% of Rated Power	Nominal kW	(M Btu/hr)	(kW_e)	(%)	(M Btu/hr)	(%)	(%)	Temp. (^oF)	RH (%)
Run 1	100	30	392.7	28.45	24.7	159.3 [c]	40.6 [c]	65.3 [c]	42.05	51
Run 2			391.1	28.29	24.7	162.4 [c]	41.5 [c]	66.2 [c]	42.44	51
Run 3			390.5	28.32	24.8	163.1 [c]	41.8 [c]	66.5 [c]	41.72	54
Run 13			396.8	28.47	24.5	185.3	46.7	71.2	40.86	46
Run 14			395.7	28.45	24.5	187.4	47.4	71.9	41.06	48
Run 15			395.1	28.38	24.5	187.9	47.6	72.1	40.90	49
Avg.			**393.7**	**28.39**	**24.6**	**186.9**	**47.20**	**71.7**	**41.51**	**50**
Run 4	90	27	366.8	26.44	24.6	153.9 [c]	42.0 [c]	66.6 [c]	40.56	52
Run 5			365.7	26.47	24.7	154.4 [c]	42.2 [c]	66.9 [c]	40.87	52
Run 6			366.8	26.46	24.6	162.2 [c]	44.2 [c]	68.8 [c]	40.90	52
Run 16a			370.9	26.46	24.3	168.9	45.6	69.9	43.77	44
Run 16b			364.1	26.37	24.7	173.8	47.8	72.5	42.75	50
Avg.			**366.9**	**26.44**	**24.6**	**171.4**	**46.7**	**71.2**	**41.77**	**50**
Run 7	75	22.5	313.9	22.04	24.0	140.6 [c]	44.8 [c]	68.8 [c]	41.14	52
Run 8			312.9	22.05	24.1	141.6 [c]	45.3 [c]	69.4 [c]	41.41	53
Run 9			310.7	22.05	24.2	141.4 [c]	45.5 [c]	69.7 [c]	41.44	52
Run 17			318.2	22.02	23.6	149.3	46.9	70.5	44.05	44
Avg.			**313.9**	**22.04**	**24.0**	**149.3**	**46.9**	**70.5**	**42.01**	**50**
Run 10	50	15	228.1	14.54	21.8	107.1 [c]	47.0 [c]	68.7 [c]	41.75	52
Run 11			228.1	14.52	21.7	106.8 [c]	46.8 [c]	68.6 [c]	41.95	52
Run 12			228.1	14.53	21.7	105.3 [c]	46.2 [c]	67.9 [c]	41.66	52
Run 18a			230.3	14.54	21.6	114.1	49.6	71.1	43.96	44
Run 18b			223.3	14.56	22.6	112.6	50.5	72.7	43.59	49
Avg.			**227.6**	**14.54**	**21.9**	**113.4**	**50.1**	**72.2**	**43.78**	**50**

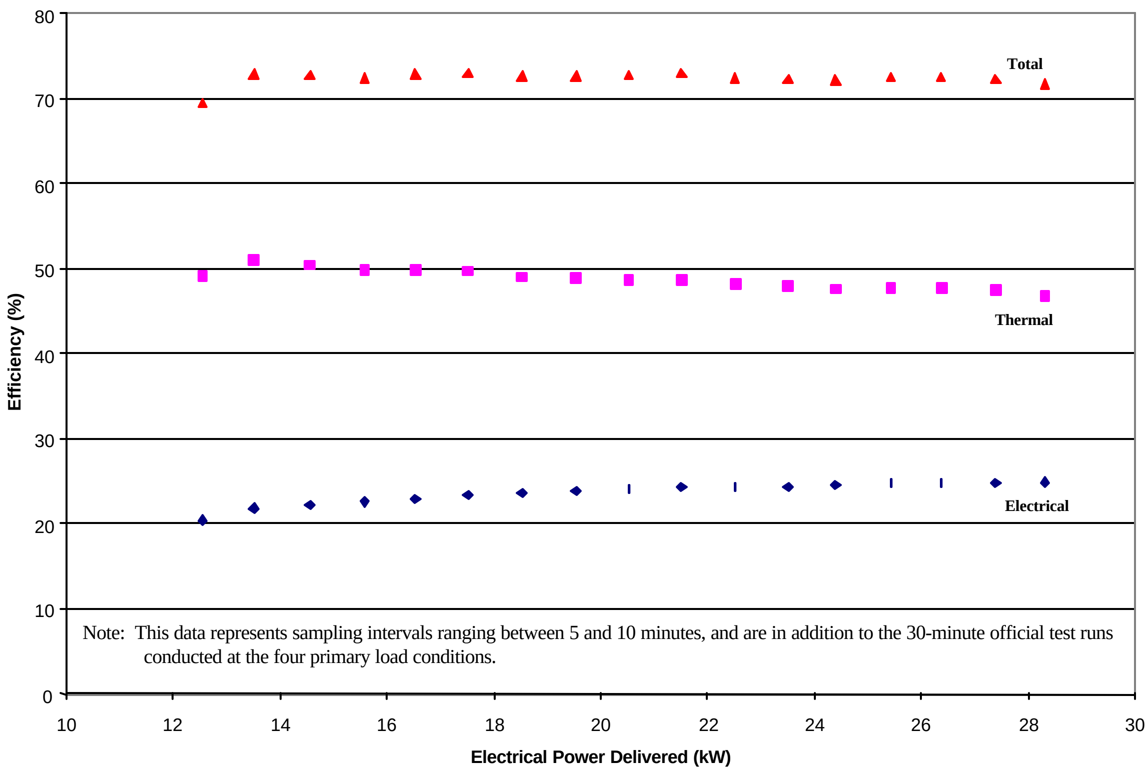
[a] Represents actual power available for consumption at the test site. Includes losses from site transformer.
[b] Barometric pressure remained relatively consistent throughout the test runs (12.90 to 13.11 psia).
[c] Heat recovery data for these runs were invalidated due to biased temperature readings, and are excluded from the average values reported.
[d] Represents actual power available for consumption, includes losses from step-down transformer
[e] To convert to equivalent kilowatts (kW_{th}), divide by 3412.14.

Table 2-2. Fuel Input and Heat Recovery Unit Operating Conditions

	Test Condition		Natural Gas Fuel Input				PG Fluid Conditions				
			Gas Flow Rate	LHV[c]	Gas Pressure	Gas Temp.	PG Composition[e]	Fluid Flow Rate	Outlet Temp.	Inlet Temp.	Temp. Diff.
	% of Rated Power	Nominal kW	(scfm)	(Btu/ft^3)	(psig)	(°F)	(% volume)	(scfm)	(°F)	(°F)	(°F)
Run 1	100	30	7.16	914.1	69.26	46.65	16.47[a]	2.58	109.39[a]	92.57[a]	16.82[a]
Run 2			7.13	914.1	69.22	48.75	16.47[a]	2.70	119.84[a]	103.48[a]	16.36[a]
Run 3			7.12	914.1[b]	69.14	50.42	16.47[a,d]	2.71	125.99[a]	109.68[a]	16.31[a]
Run 13			7.22	915.9[b]	69.35	54.05	15.78	2.69	151.46	132.94	18.52
Run 14			7.20	915.9	69.30	54.73	15.78[d]	2.72	144.10	125.53	18.57
Run 15			7.19	915.9	69.31	55.73	15.78	2.72	142.53	123.92	18.61
Avg.			**7.17**	**915.0**	**69.26**	**51.72**	**15.78**	**2.71**	**146.03**	**127.46**	**18.57**
Run 4	90	27	6.73	908.4[b]	69.31	48.57	16.57[a,d]	2.73	115.01[a]	99.67[a]	15.34[a]
Run 5			6.71	908.4	69.36	49.38	16.57[a]	2.73	117.72[a]	102.38[a]	15.34[a]
Run 6			6.73	908.4	69.50	50.25	16.57[a]	2.84	120.02[a]	104.50[a]	15.52[a]
Run 16a			6.75	915.9	69.21	54.18	16.08	2.51	149.97	131.81	18.16
Run 16b			6.63	915.9	NA	NA	16.08	2.60	147.18	129.19	17.99
Avg.			**6.71**	**911.4**	**69.35**	**50.60**	**16.08**	**2.56**	**148.58**	**130.50**	**18.08**
Run 7	75	22.5	5.76	908.4	69.94	50.63	15.98[a]	2.84	120.16[a]	106.75[a]	13.41[a]
Run 8			5.74	908.4	69.88	51.25	15.98[a]	2.84	121.03[a]	107.53[a]	13.50[a]
Run 9			5.70	908.4	70.09	51.47	15.98[a,d]	2.85	120.89[a]	107.43[a]	13.46[a]
Run 17			5.79	915.9	69.59	54.38	16.08[d]	2.54	146.09	130.25	15.84
Avg.			**5.75**	**910.3**	**69.88**	**51.93**	**16.08**	**2.54**	**146.09**	**130.25**	**15.84**
Run 10	50	15	4.19	907.2[b]	70.52	52.46	15.98[a]	2.85	116.03[a]	105.84[a]	10.19[a]
Run 11			4.19	907.2	70.13	52.30	15.98[a]	2.85	114.92[a]	104.75[a]	10.17[a]
Run 12			4.19	907.2	70.13	52.66	15.98[a]	2.78	115.92[a]	105.67[a]	10.25[a]
Run 18a			4.19	915.9	70.13	55.00	16.08	2.55	139.35	127.27	12.08
Run 18b			4.06	915.9			16.08	2.60	134.78	123.11	11.67
Avg.			**4.16**	**910.7**	**70.23**	**53.11**	**16.08**	**2.58**	**137.07**	**125.19**	**11.88**

[a] These results were invalidated due to errors in temperature readings, and are not used to compute averages.
[b] Represents results of actual gas samples collected during that run.
[c] Lower Heating Value. For Runs 3, 4, 10, and 13, LHV results are based on actual gas samples collected during these runs. Gas samples collected during 75 percent load test were contaminated, thus LHV for Runs 7 through 9 is assigned same as Run 4. For Runs 14 through 18, LHV is assigned same as directly measured data for that day of testing (Run 13). LHV for all remaining runs are assigned same as directly measured data for sample collected during that operating load.
[d] Represents results of actual PG samples collected during that run.
[e] For Runs 3, 4, 9, 14, and 17, PG results are based on actual gas samples collected during these runs. PG results for all remaining runs are assigned same as directly measured data for samples collected during that operating load or testing day.
NA: not available

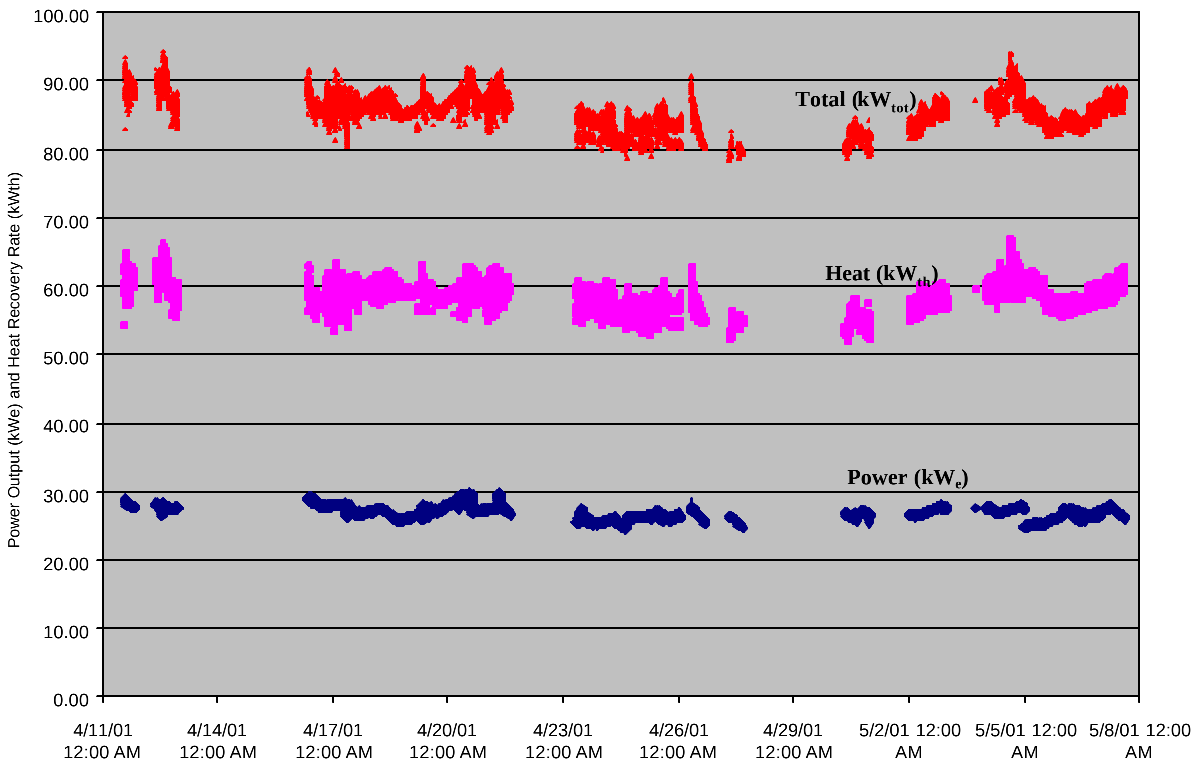
Figure 2-1. Efficiency Performance at Different Operating Loads
Ambient Temperature = 42 to 44 °F, RH = 49 to 51 %



2.1.2. Electrical and Thermal Energy Production and Efficiencies Over the Extended Test

Figure 2-2 presents a time series plot of power production and heat recovery during the 38 day verification period. The plot includes only times when the Mariah CHP System was operating and excludes downtimes that were related to verification testing (Appendix C). The system was operating 24 hours per day, and was programmed to produce full electrical power. A total of 10,438 kWh_e electricity was generated during a total operating time of 390 hours. Of this total electricity generated, 2,860 kWh_e was used on site and 7,578 kWh_e was exported to the utility grid. The system recovered 22,749 kWh_{th} of thermal energy during the 390 hour operating period. The thermal to electrical energy production ratio was 2.18.

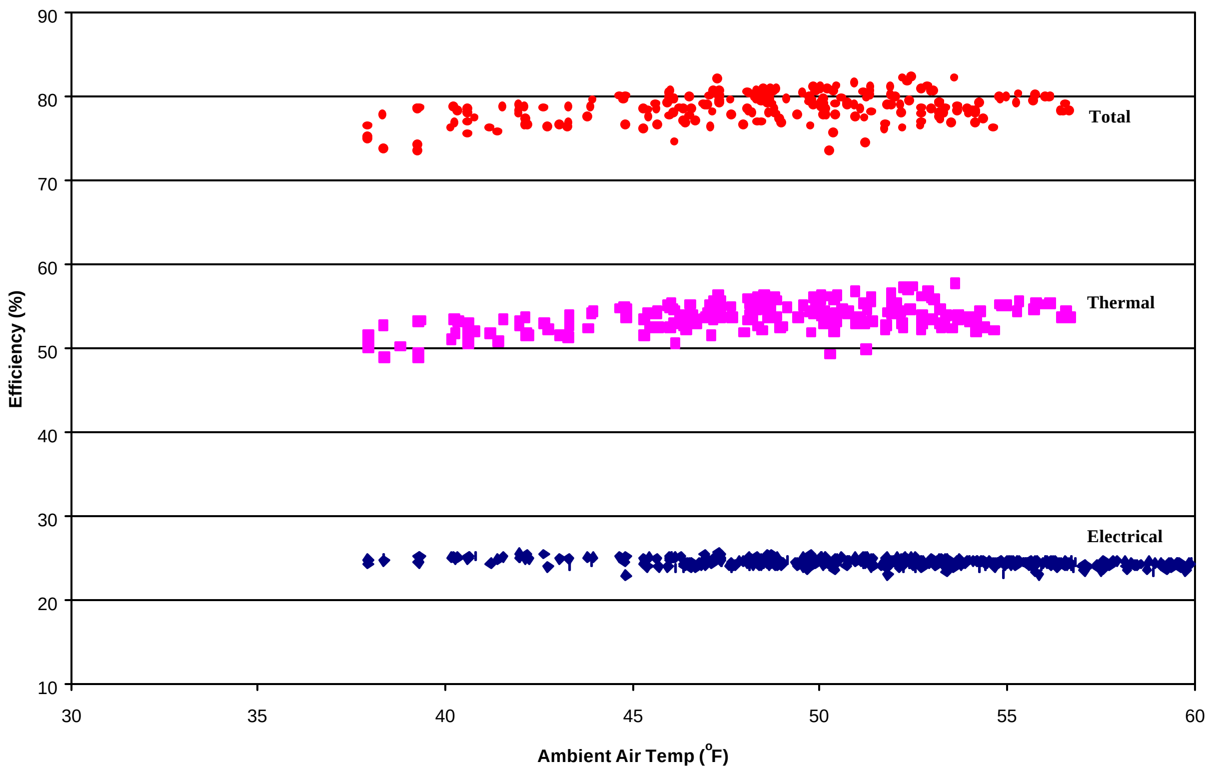
Figure 2-2. Power and Heat Production over the Verification Period
(full electrical power setting)



The average power generated was 26.1 kW$_e$, and average heat recovery rate was 57.9 kW$_{th}$. The average electrical efficiency and thermal efficiency were measured to be 24.5 percent and 53.9 percent, respectively. In comparison to the load testing, electrical efficiency remained unchanged over the 38 day test period. However, the heat recovery rate and thermal efficiency increased, resulting in an overall average system efficiency of 78.4 percent (Figure 2-3). The total efficiency measured during the simulated full load test was 71.7 percent (Table 2-1). The 7 percent increase in efficiency observed during the 38 day monitoring period is expected to be related to several factors.

First, a 30 ^oF increase in ambient temperatures was measured, and as shown in Figure 2-4, power output decreased at higher ambient temperatures. Figure 2-4 shows that power output decreases from 28 to 23 kWe at ambient temperatures of 37 ^oF and 63 ^oF, respectively. This drop is consistent with industry knowledge of turbine performance (i.e., electrical power output generally decreases at increasing temperatures). However, electrical efficiency did not change significantly because fuel input decreased proportionately to power output, as shown in Figure 2-4.

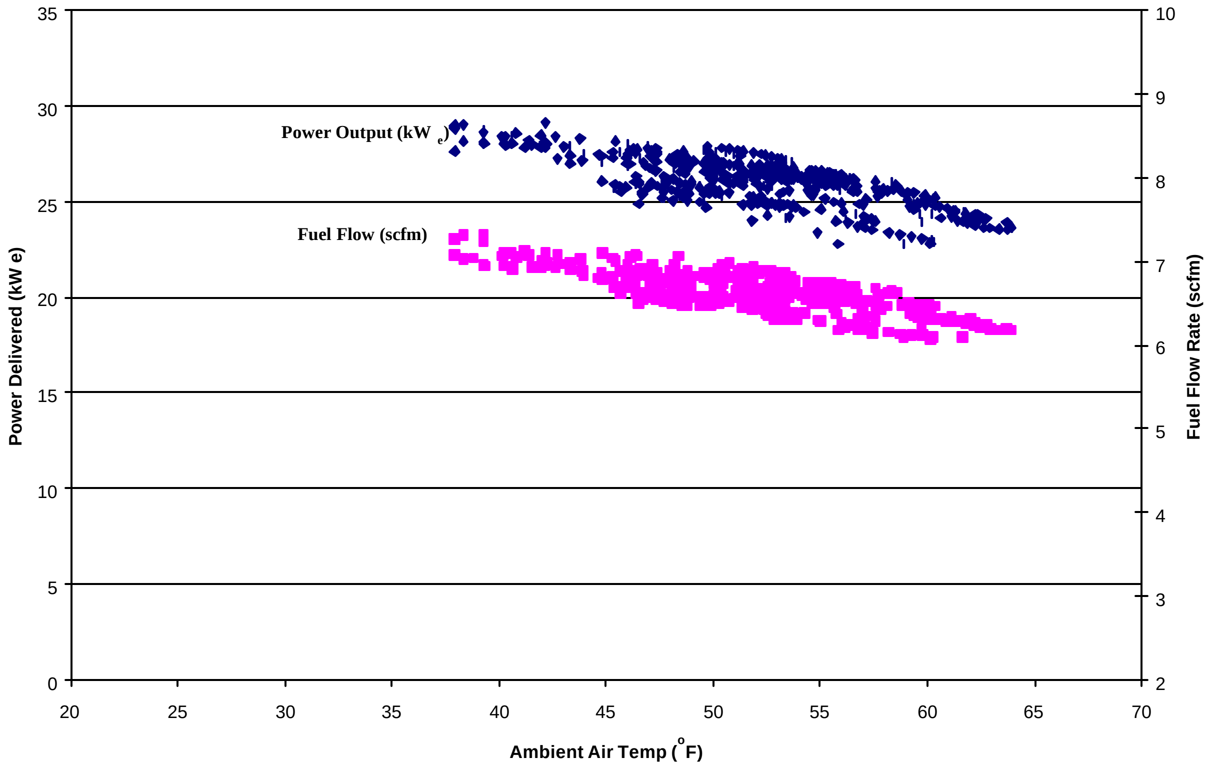
Figure 2-3. Ambient Temperature Effects on System Efficiency During Extended Test Period
(full load setting)



As shown in Figure 2-3, an increase in heat recovery rate and thermal efficiency was observed. This increase is expected to be related to a CHP system design change that was implemented by Mariah on April 17. Several days into the extended verification testing, Mariah discovered that the 12 inch circular combustion air inlet pipe was restricting airflow to the turbine. The restriction resulted in a negative pressure in the intake box, causing heated air to flow from the turbine section of the CHP into the intake air section. The resulting intake air temperature increase lowered heat output. Mariah rectified the problem by increasing the size of the intake air duct to 24 x 24 inches square. The average heat recovery rate, after the design modification, was 199,567 Btu/hr, which is 7 percent higher than the rate measured during full load testing (i.e., with initial system design). Based on these findings, it is concluded that the system can achieve over 78 percent total efficiency after the design change. The increase in heat recovery rate is also related to inlet air temperature. Elevated air temperature results in higher turbine exhaust gas temperature, which enables more heat to be recovered.

The design modification is not expected to affect electrical power production and efficiency performance. For example, electrical power output and efficiency verified during the official load tests (i.e., with original design) were 28.39 kW and 24.6 percent at 42 °F, respectively. After the design modifications, power output was 28.59 kW and electrical efficiency was 24.7 percent at 41 °F. This indicates no significant change in electrical efficiency. Conversely, heat recovery rate increased from 186.9 to 195.7 MBtu/hr and thermal efficiency increased from 47.2 to 49.5 percent. This corresponds to about a 5 percent increase in heat recovery potential at nearly the same ambient conditions.

Figure 2-4. Ambient Temperature Effects on Power Production During Extended Test Period
(full load setting)



2.2. POWER QUALITY PERFORMANCE

2.2.1. Electrical Frequency

Electrical frequency measurements (voltage and current) were monitored simultaneously for the Mariah CHP System. The 1-minute average data collected by the electrical meter were analyzed to determine maximum frequency, minimum frequency, average frequency, and standard deviation for the verification period. These results are illustrated in Figure 2-5 and summarized in Table 2-3. The average electrical frequency measured was 60.000 Hz, and the standard deviation was 0.014 Hz.

Figure 2-5. Mariah CHP System Electrical Frequency During Extended Test Period

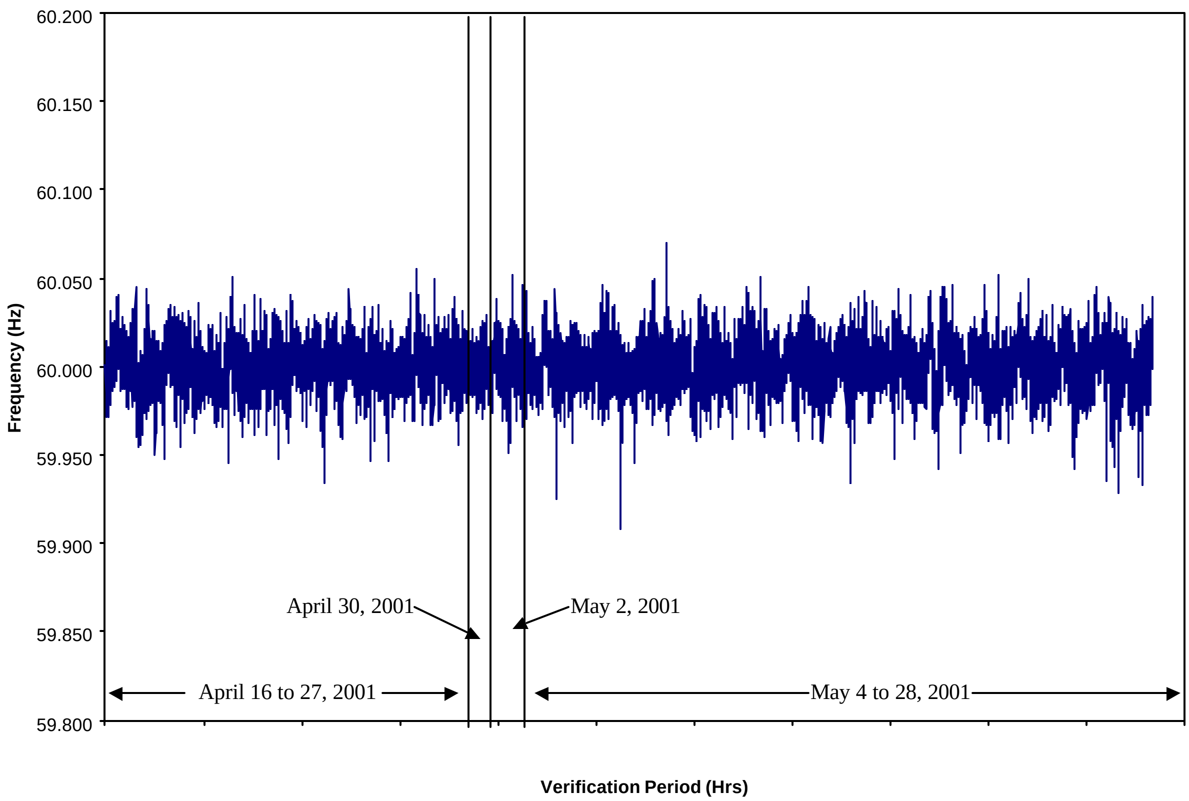


Table 2-3. Electrical Frequency Results	
Parameter	**Frequency (Hz)**
Average Frequency	60.000
Minimum Frequency	59.908
Maximum Frequency	60.070
Standard Deviation	0.014

2.2.2. Voltage Output and Transients

Traditionally, it is accepted that voltage output can vary within ± 10 percent of the standard voltage (208 volts) without causing significant disturbances to the operation of most end-use equipment (ANSI 1996). Voltage was monitored on the turbine using the 7600 ION electric meter. The meter was configured to measure 0 to 600 VAC. Since the turbine was grid connected, it was operating as a voltage-following current source. As a result, the voltage levels measured with the 7600 ION are indicative of the grid voltage levels.

Figure 2-6 plots 1-minute average voltage readings, and Table 2-4 summarizes the statistical data for the voltages measured on the turbine throughout the verification period. The voltage levels that were well within the normal accepted range of ± 10 percent.

Figure 2-6. Mariah CHP System Voltage Output During Extended Test Period

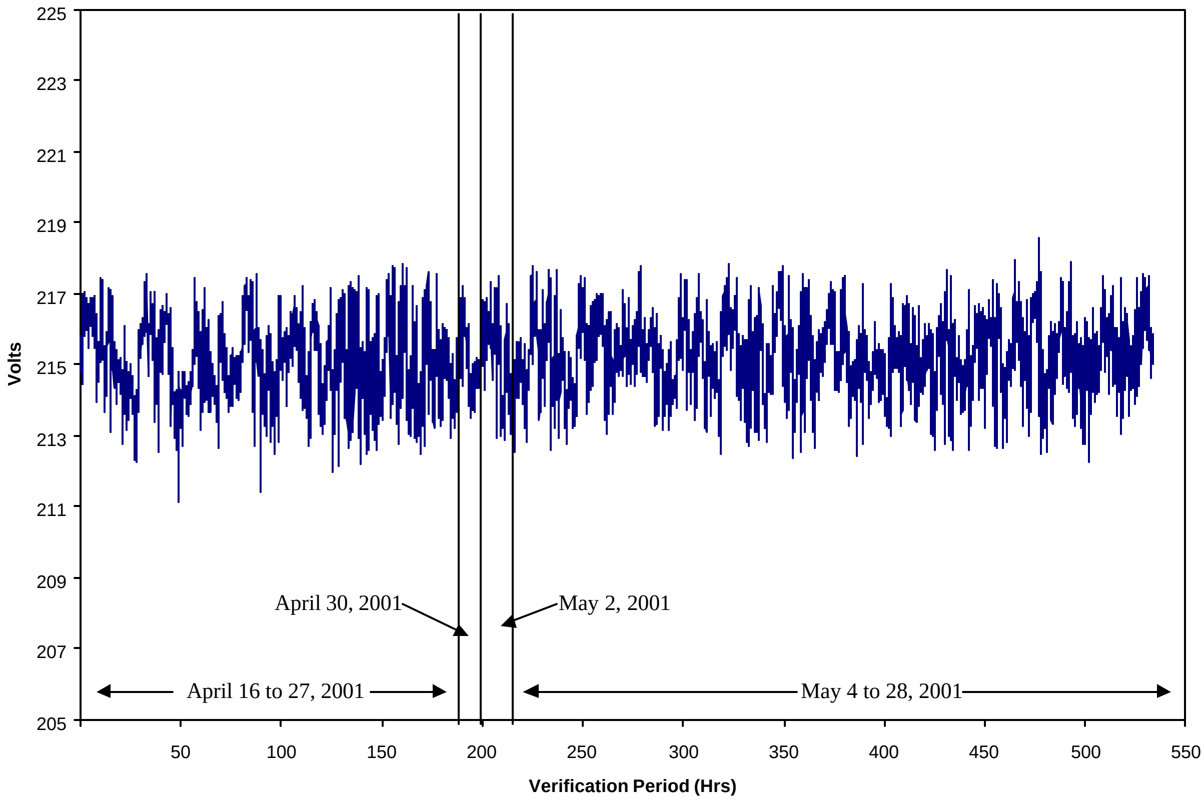


Table 2-4. Turbine Voltage Output

Parameter	Volts
Average Voltage	215.21
Minimum Voltage	211.04
Maximum Voltage	218.54
Standard Deviation	0.94

A voltage transient is a sub-cycle disturbance in the alternating current waveform that is evidenced by a sharp brief change in the system voltage. Transients are also known as spikes or surges that are normally on-line for a few seconds, and are often not detected by the 1-minute average voltage measurements described above. Mariah CHP System voltage transients were continuously monitored and recorded throughout testing. The 7600 ION was configured to identify line-to-neutral surges up to 8 kV at a rate of one reading per 60 milliseconds. The number of transient occurrences and the magnitude of the transients (greater than 208 volts ± 10 percent) were logged. No voltage transients were measured during the 38 day monitoring period.

2.2.3. Power Factor

Power factor is the phase relationship of current and voltage in AC electrical distribution systems. Under ideal conditions, current and voltage are in phase which results in a power factor equal to 1.0 or 100 percent. If inductive loads (e.g., motors) are present, power factors are less than this value. Although it is desirable to maintain power factor at 100 percent, the actual utility grid power factor may be much lower because of electrical demands of different end users.

Throughout the verification test period, the Mariah CHP System was preset to operate at unity or 100 percent power factor. Figure 2-7 illustrates time series power factor data for the turbine. The figure shows that the turbine was able to maintain its set-point power factor. Daily measurements data were analyzed to determine the average, maximum, minimum, and standard deviation (Table 2-5). The daily average power factor remained relatively constant for all 38 monitoring days, and the average value was 99.13 percent. The unit was not tested at varying power factors, thus any variation in the unit's performance at other power factor settings could not be verified.

Figure 2-7. Mariah CHP System Power Factors During Extended Test Period

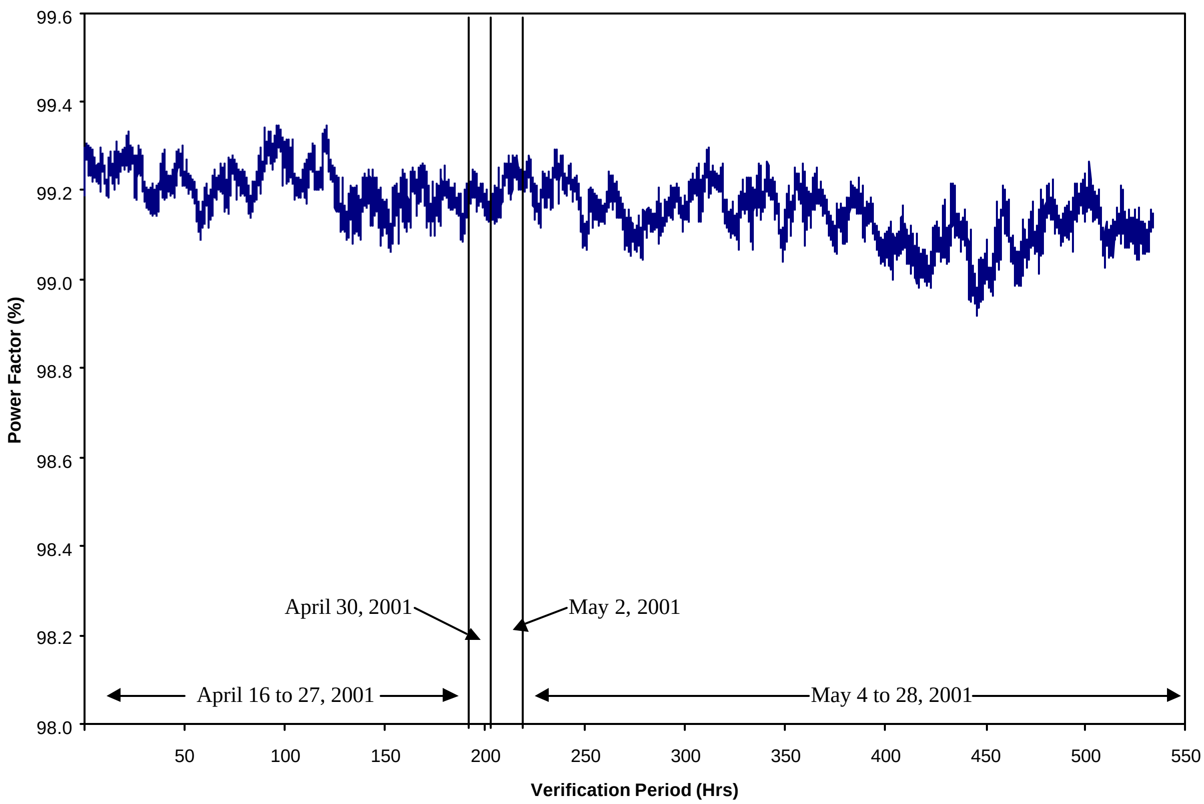


Table 2-5. Turbine Power Factors	
Parameter	**%**
Average Power Factor	99.13
Minimum Power Factor	98.71
Maximum Power Factor	99.35
Standard Deviation	0.09

2.2.4. Current and Voltage Total Harmonic Distortion

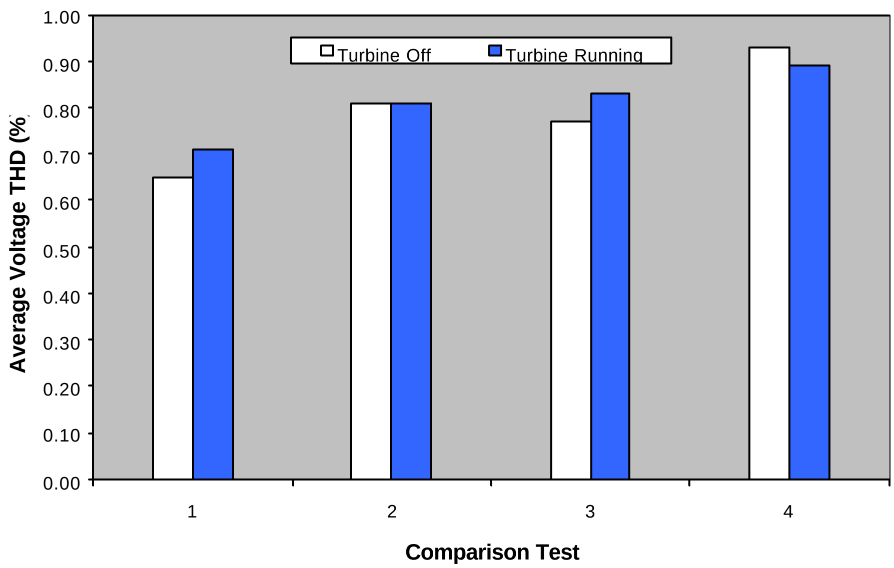
The turbine total harmonic distortion, up to the 63rd harmonic, was recorded for voltage and current output using the 7600 ION. The average current and voltage THDs were measured to be 3.37 percent and 0.94 percent, respectively (Table 2-6). Throughout the 38 day verification period, the Mariah CHP System satisfied the 5 percent maximum current and voltage THD limit specified in IEEE 519.

Table 2-6. Turbine THDs During Verification Period		
Parameter	**Current THD (%)**	**Voltage THD (%)**
Average	3.37	0.94
Minimum	2.84	0.64
Maximum	4.92	4.76
Standard Deviation	0.25	0.19

To compare current and voltage THD with the grid, the turbine was shut down for four time periods during the extended test. They ranged in duration of approximately 1 to 3 hours. During these periods, the power quality of grid electricity supplied to the voltage transformer was measured and recorded with the 7600 ION.

Current THDs for the Mariah CHP System were lower by a factor of 6 than those measured through the transformer when the unit was shut off. The current THD across the transformer was over 40 percent and, since the transformer appears to distort grid current, further comparative analysis of this data was not conducted. However, voltage THDs are not affected by the transformer (i.e., same voltage is delivered to the transformer as the CHP System). As shown in Figure 2-9, the voltage THD with the turbine was slightly higher than the grid THD. This increase is relatively small, and still enables the unit to meet the ± 5 percent threshold specified in IEEE 519.

Figure 2-8. Voltage THD on Grid and Turbine During Select Test Periods



2.3. EMISSIONS PERFORMANCE

2.3.1. Mariah CHP System Stack Exhaust Emissions

Mariah CHP System emissions testing was conducted to determine emission rates for criteria pollutants (NO_X, CO, and THC) and greenhouse gases (CO_2). Stack emission measurements were conducted at 50, 75, 90, and 100 percent of rated power output, and coincided with electrical power output and efficiency measurements. At each operating condition, three replicate test runs were conducted, each approximately 30 minutes in duration. All testing was conducted in accordance with EPA Reference Methods listed in Table 1-2. The Mariah CHP System was maintained in a stable mode of operation during each test run using PTC-22 variability criteria (Sections 2.2 and 3.2.2.1). The Mariah CHP System was allowed to stabilize for at least 15 minutes after changing loads before testing was started.

Emissions results are reported in units of parts per million corrected to 15 percent O_2 (ppmvd @ 15 percent O_2) for NO_X, CO, and THC. Emissions of O_2 and CO_2 are reported in units of volume percent. These concentration and volume percent data were converted to mass emission rates using computed exhaust stack flow rates, and are reported in units of pounds per hour (lb/hr). Appendix B contains F-Factor and exhaust gas flow rate computations for each test run. The emission rates are also reported in units of pounds per kilowatt hour electrical output (lb/kWh_e). They were computed by dividing the mass emission rate by the electrical power delivered.

To ensure the collection of adequate and accurate emissions data, sampling system QA/QC checks were conducted in accordance with Test Plan specifications. These included analyzer linearity tests, sampling system bias and drift checks, interference tests, and use of audit gases. Results of the QA/QC checks are discussed in Section 3. The results show that DQOs for all gas species met the Reference Method requirements. A complete summary of emissions testing equipment calibration data is presented in Appendix B.

As described in the system efficiency performance discussion, the original set of Mariah CHP System performance tests were conducted on April 2 and 3, 2001, and were then repeated on April 4 and 5 after correcting a heat recovery temperature measurement error. Emissions testing was repeated at all load conditions to confirm that system emissions were consistent with the first round of tests. As shown in Appendix B-4, the concentration levels were consistent with the initial round of tests. The concentration levels were within 2 percent of the initial round of tests. These results confirmed that corrective actions taken on the heat recovery temperature measurements did not affect the physical operation of the Mariah CHP System, and emission test data collected on April 2 and 3 could be considered representative of the unit's typical performance. This is a reasonable assumption because significant differences in ambient conditions were not observed, as shown in Table 2-1.

A summary of emission levels, before and after the temperature correction, is provided in Appendix B. Table 2-7 summarizes the emission rates measured during each run and the overall average Mariah CHP System emissions at each output level tested. Figure 2-9 shows Mariah CHP System emissions in units of lb/kWh $_e$ at each of the four load test conditions.

Figure 2-9. Emission Rates for the Four Load Test Conditions

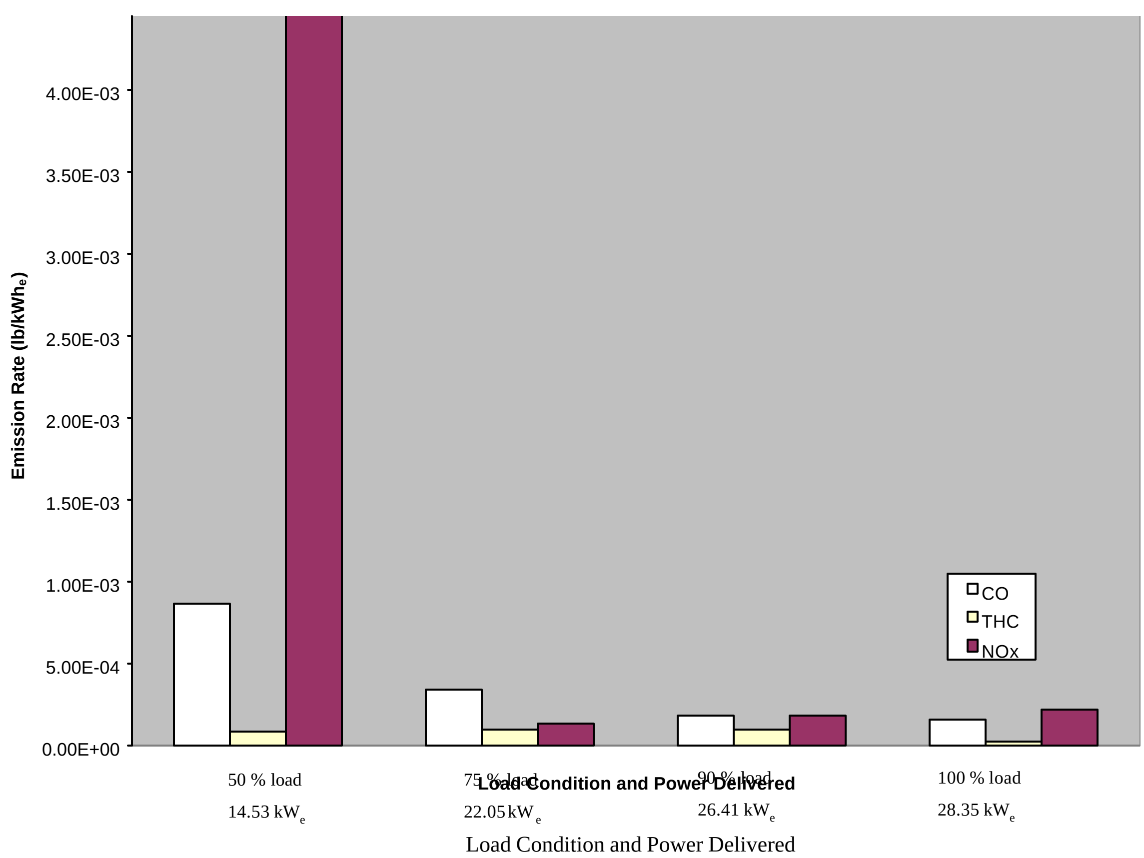


Table 2-7. Summary of Mariah CHP System Emissions Performance

	Test Condition		Electrical Power Delivered (kW_e)	Ambient Temp (°F)	Exhaust O_2 (%)	CO Emissions			NO_x Emissions			THC Emissions			CO_2 Emissions		
	% of Rated Power	Nominal kW				(ppm @ 15% O_2)	lb/hr	lb/kWh $_e$	(ppm @ 15% O_2)	lb/hr	lb/kWh $_e$	(ppm @ 15% O_2)	lb/hr	lb/kWh $_e$	%	lb/hr	lb/kWh $_e$
Run 1			28.45	42.05	18.06	4.97	0.00428	1.51E-04	4.30	0.00609	2.14E-04	< 0.20	<3.1E-04	<1.1E-05	1.41	39.7	1.40
Run 2			28.29	42.44	18.09	4.98	0.00428	1.51E-04	4.25	0.00600	2.11E-04	0.47	6.9E-04	2.4E-05	1.60	45.3	1.59
Run 3	100	30	28.32	41.72	18.09	4.92	0.00422	1.49E-04	4.26	0.00600	2.11E-04	0.38	5.6E-04	2.0E-05	1.65	46.7	1.64
AVG			**28.35**	**42.07**	**18.08**	**4.96**	**0.00426**	**1.50E-04**	**4.27**	**0.00603**	**2.12E-04**	**0.35**	**5.2E-04**	**1.8E-05**	**1.55**	**43.9**	**1.54**
Run 4			26.44	40.56	18.18	6.24	0.00503	1.90E-04	3.53	0.00468	1.77E-04	1.39	1.92E-03	<7.26E-05	1.50	41.2	1.56
Run 5			26.47	40.87	18.23	5.59	0.00449	1.70E-04	3.53	0.00466	1.76E-04	2.07	2.85E-03	1.08E-04	1.22	34.1	1.29
Run 6	90	27	26.46	40.91	18.12	5.58	0.00450	1.70E-04	3.45	0.00457	1.73E-04	1.65	2.28E-03	8.62E-05	1.35	36.3	1.37
AVG			**26.46**	**40.78**	**18.18**	**5.80**	**0.00467**	**1.77E-04**	**3.50**	**0.00464**	**1.75E-04**	**1.70**	**2.35E-03**	**8.89E-05**	**1.36**	**37.2**	**1.41**
Run 7			22.04	41.14	18.20	10.75	0.007418	3.366E-04	2.62	0.00297	1.35E-04	1.88	2.22E-03	<1.01E-04	1.27	30.1	1.37
Run 8			22.05	41.41	18.19	11.28	0.007757	3.518E-04	2.61	0.00295	1.34E-04	1.62	1.91E-03	8.66E-05	1.23	28.9	1.31
Run 9	75	22.5	22.05	41.44	18.27	10.16	0.006938	3.146E-04	2.73	0.00306	1.39E-04	2.21	2.59E-03	1.17E-04	1.22	29.4	1.33
AVG			**22.05**	**41.33**	**18.22**	**10.73**	**0.007371**	**3.343E-04**	**2.65**	**0.00300**	**1.36E-04**	**1.90**	**2.24E-03**	**1.02E-04**	**1.24**	**29.5**	**1.34**
Run 10			14.54	41.75	18.55	25.55	0.01280	8.805E-04	79.87	0.06578	4.524E-03	2.47	2.12E-03	<1.46E-04	1.05	20.8	1.43
Run 11			14.52	41.95	18.57	24.84	0.01245	8.572E-04	78.77	0.06488	4.462E-03	0.52	4.5E-04	3.1E-05	1.05	20.9	1.44
Run 12	50	15	14.53	41.66	18.56	24.72	0.01239	8.525E-04	78.63	0.06476	4.454E-03	1.20	1.03E-03	7.09E-05	1.06	21.1	1.45
AVG			**14.53**	**41.79**	**18.56**	**25.04**	**0.01255**	**8.634E-04**	**79.09**	**0.06514**	**4.480E-03**	**1.40**	**1.2E-03**	**8.20E-05**	**1.05**	**20.9**	**1.44**

Notes: Consistent with EPA Reference method, THC measurements are quantified as ppmvd propane. THC emission rates (lb/hr and lb/kWh$_e$) are reported as methane equivalent, assuming all THC is methane.

NO_X emissions at full power output averaged 4.27 ppmvd corrected to 15 percent O_2, and remained low until the system power command was dropped to 15 kW, at which time the emission rate averaged 79.09 ppmvd @ 15 percent O_2. NO_X emission rate, normalized to power output, was 0.000212 lb/kWh$_e$, which is well below the 0.00684 lb/kWh reported for the Alberta Power Pool. The benefits of lower NO_X emissions from the Mariah CHP System are further enhanced when exhaust heat is recovered and used. Based on annual published data by U.S. DOE, the measured Mariah CHP System emission rate is also below the average rate for coal and natural-gas-fired power plants in the U.S., 0.0074 and 0.0025 lb/kWh, respectively (EIA 2000). The emission rates are further increased when transmission and distribution system losses are accounted for providing electricity to the end user. The primary reason for such differences is that NO_X emissions from electric utilities are often 10 times greater than the levels measured for the Mariah CHP System. There are, however, state-of-the-art natural gas power plants, which are more efficient, and result in comparable emissions and emission rates as the Mariah CHP System.

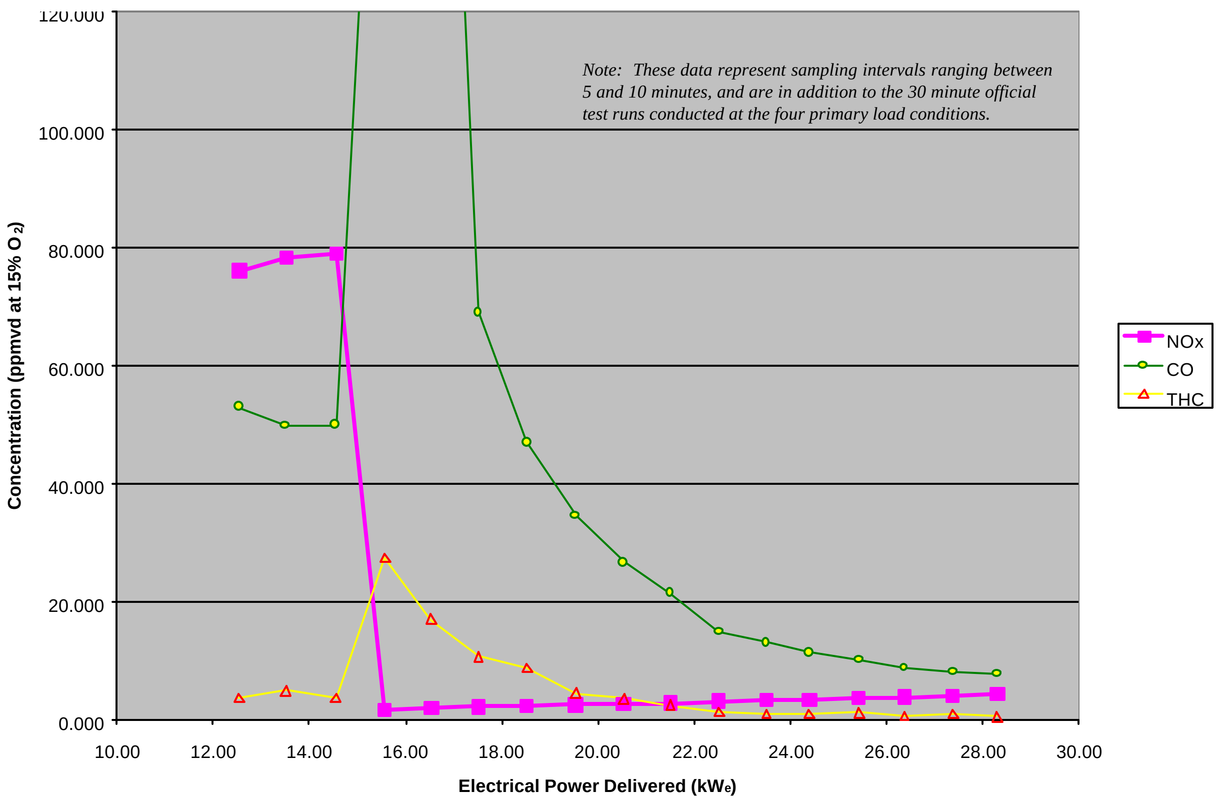
Emissions of CO were also low at full power, averaging 4.96 ppmvd @ 15 percent O_2, or 0.000150 lb/kWh$_e$. Concentrations increased to over 25 ppmvd at low loads. Emissions of THC were low during all test periods and were at or near the sensitivity of the sampling system during all of the tests. The lower detectable limit was 2 percent of instrument span, or 2 ppmvd. The highest single-run average observed during the testing was 2.47 ppmvd @ 15 percent O_2 (quantified as propane). Because THC concentrations were so low during all test periods, samples were not collected for subsequent methane analysis. By assuming all of the THC measured in the field were methane, the highest value observed would only equate to an uncorrected methane concentration of less than 3 ppmvd.

Concentrations of CO_2 in the Mariah CHP System exhaust gas ranged from a low of 1.05 percent at 50 percent of full load to 1.55 percent at full power command. The measured concentrations correspond to average CO_2 emission rates of 1.44 lb/kWh$_e$ at 50 percent rated power output to 1.54 lb/kWh$_e$ at full power. The measured emission rate at full load is consistent with 1.6 lb/kWh$_e$ reported by Capstone (Capstone 2000). The measured emission rate at full load is well below the current average emission rate for Alberta power pool (2.18 lb/kWh electricity delivered). The Mariah CHP System CO_2 emission rate is also below the average rate for coal-fired power plants in the U.S. (2.26 lb/kWh), and slightly higher than natural-gas-fired power plants (1.41 lb/kWh). The U.S. average emission factors reported here account for an estimated line loss of 5.1 percent between power plant fence line to the end user.

As discussed earlier, an additional test run, which was beyond the scope of the official verification, was conducted at loads ranging between 40 and 100 percent of rated capacity. It was executed by collecting 5 to 10 minutes of data at power commands starting at full power and incrementally decreasing by 1 kW to a low of 13 kW. At each power command setting, emissions data were collected and averaged for each load condition. The results of this test are plotted in Figure 2-10.

The GHG Center recognizes that full 30-minute test runs, as specified in the Test Plan for meeting EPA Reference Method requirements, were not satisfied for the additional test run. Thus, precautions were taken to document the data quality of this test run. The sampling procedures and analytical instruments used during this test were the same as those used during the official verification tests. The same analyzers, sampling system, calibration gases, and calibration procedures were followed to ensure that accurate emissions concentrations were recorded (results are presented only as concentrations for this test). Consistent with the official tests, all of the reference method calibration criteria were satisfied for this test. The primary differences were that three replicate tests were not conducted, the duration of sampling at each power command was shorter, and the power command changes between successive load changes occurred relatively rapidly.

Figure 2-10. Mariah CHP System Emission Levels at Various Electrical Power Commands



The data indicate that NO_X concentrations remained low throughout a large range of operation, and steadily decreased from full power to a power command of 15 kW. At that point, NO_X emissions increased sharply to approximately 78 ppmvd @ 15 percent O_2. Although this test did not follow strict EPA method guidelines, the emission rates measured are consistent with rates measured at the four power commands tested during the official load tests (i.e., 30, 27, 22.5, and 15 kW).

Emissions of CO increased sharply as power command dropped, eventually reaching a point that was above the operating range of the analyzer (greater than 200 ppmvd @ 15 percent O_2). This off-scale peak was not observed during the official load testing because the spike occurred at 55 percent load setting, which was between the 75 and 50 percent official tests. Mariah has indicated that the CO spike is probably related to turbine dynamics. Mariah speculates that because the turbine operates in a constant turbine exit temperature and variable speed control strategy, mechanical effects (e.g., turbulence, gas vortex rotation rate inside the combustion chamber) could have affected combustion efficiency. Details of turbine dynamics, especially relating to combustion processes, are proprietary information, and additional explanation of the CO spike cannot be obtained.

Emissions of NO_X and CO are typically inversely proportional, which is also demonstrated in Figure 2-10. At the 15 kW power command, NO_X emissions increased dramatically, and CO emissions dropped from over 200 ppmvd to approximately 50 ppmvd. It should be noted that, at the 15 kW power command, the average CO concentration was about 2 times higher (49 ppmvd) than that measured during the official load test (25 ppmvd). This difference is not related to ambient air conditions because both temperature and relative humidity were nearly identical: 44 °F and 47 percent RH (during official load test) and 43 °F and 49 percent RH (during the additional short duration test).

The concentration differences between official load tests and the single relative quick non-standard test were not observed for other pollutants. The 2-fold increase in CO concentration may be due to the time allowed for the unit to stabilize between load changes. As explained earlier, PTC-22 requirements for electricity generation were satisfied, and (electrically) the unit was operating in a stable manner during the 5 to 10 minute sampling duration. However, the rapid load changes may have resulted in the unit's operating in a manner that may have caused the emissions not to be stabilized. For this reason, the 25.04 ppmvd CO concentration, measured during the official 30 minute test runs, is considered representative of true emissions.

Concentrations of CO_2 are not plotted in Figure 2-10, but were consistent throughout the range. The highest CO_2 emissions occurred at full load (1.58 percent) and the lowest at 15 kW (1.40 percent).

Finally, the air inlet duct design modification, which occurred after the official load testing was performed, is not expected to change the emission results. Turbine emissions performance is directly related to electricity generation and, since significant differences in power output and efficiency were not observed after the design changes, emissions will remain relatively same.

2.3.2. Maximum Possible Emission Reductions for Walker Court

The electricity and heat generated by the Mariah CHP System will offset the electricity supplied by the utility grid and a standard gas-fired boiler. As discussed in Section 1.4.3.1, emission reductions are estimated for the verification period with a key assumption that all energy (power and heat) produced by the Mariah CHP System is consumed on site, and represents the maximum emission reductions possible in Calgary. Table 2-8 summarizes the results. Emission reductions for NO_X are also estimated because the extremely low measured emission rates correlate to significant reductions when compared to baseline systems.

Table 2-8. Estimated Emission Reductions for Verification Period

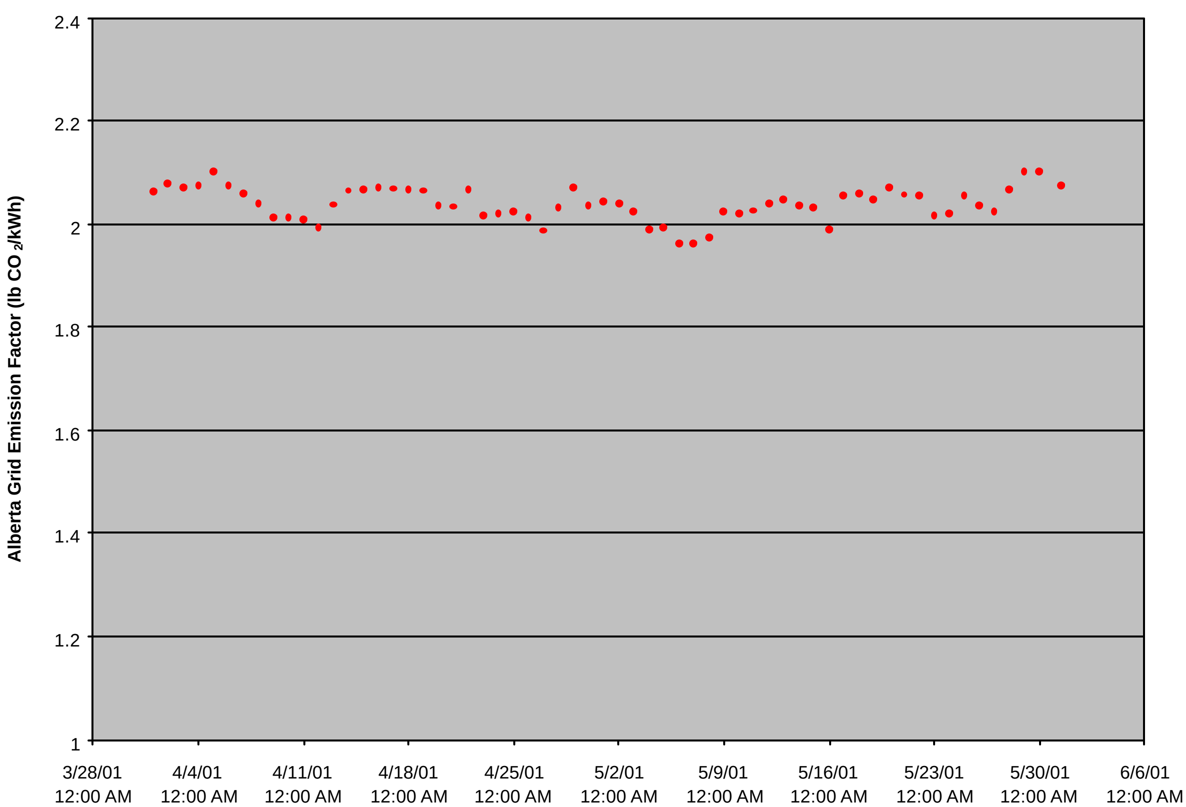
	Electrical Energy Generated[a] (kWh_e)	Thermal Energy Recovered[b] (kWh_{th})	Mariah CHP System		Baseline Scenario				Maximum Emission Reductions[f]	
					Alberta Power Pool		Natural Gas Boiler			
			Emission Rate[c] (lb/kWh_e)	Emissions (lb)	Emission Rate[d] (lb/kWh_e)	Emissions (lb)	Emission Rate[e] (lb/kWh_{th})	Emissions (lb)	lb	%
CO_2	10,438	22,749	1.54	16,116	2.18	22,714	0.57	12,919	19,517	55
NO_X	10,438	22,749	0.000212	2.213	0.006839	71.386	0.000451	10.260	79.433	97

[a] Sum of power measurements data collected with the 7600 ION electric meter
[b] Sum of heat recovery data collected with the heat meter
[c] Based on measured emission factors at full load per kWh of electricity delivered to the site
[d] CO_2 emission rate based on hourly average, power plant specific emissions compiled by the KEFI Exchange per kW of electricity delivered to the site
NO_X emission rate obtained from Alberta Electric Industry annual report (EUB 2000)
Includes 7.87 percent electricity losses from transmission and distribution systems
[e] CO_2 emission rate based on manufacturer specified boiler efficiency of 70 percent
NO_X emission rate estimated using USEPA published rates for gas-fired boilers
[f] Reductions are reported as maximum possible with the Mariah CHP System in Calgary

CO_2 emission rates for the Mariah CHP System are lower than the utility grid and, because heat is produced without the combustion of additional fuel (i.e., local boiler is not required), a 55 percent maximum reduction in CO_2 emission can occur. Emission reductions from grid electricity offsets account for about 35 percent of the total CO_2 reduction. The remaining 20 percent is due to thermal energy offset from a standard gas-fired boiler. As shown in Figure 2-11, the hourly average CO_2 emission rate for the Alberta Power Pool was consistently above 1.95 lb/kWh throughout the verification period. This high emission rate occurs because more than 90 percent of the grid's electricity is supplied by coal-fired power plants. It should be noted that CO_2 reductions will be lower when compared to efficient natural gas power plants. NRCan often reports emission reductions for displacing electricity from gas-fired combined-cycle systems that are 55 percent efficient.

Using an average emission factor for the Alberta Power Pool, NO_X emission reductions for the Mariah CHP System are estimated to be 97 percent. Over 85 percent of these reductions are due to electricity displacement from the utility grid. The high reductions are the result of the large percentage of coal-fired power plants operating in the region, which have significantly higher NO_X emission rates. Significant reductions can also be achieved where natural-gas-fired power plants (lowest NO_X emitting fossil units) exist. The U.S. average NO_X emission rate for natural gas plants is 0.0025 lb/kWh. Electricity displacement from these plants can still result in a 94 percent decrease in NO_X emissions with a Mariah CHP System. It should be noted that these reductions assume that no heat is wasted or discarded.

Figure 2-11. Hourly CO_2 Emission Rates for the Alberta Grid



2.3.2.1. Estimated Annual Emission Reductions for Model Sites

Using the approach described in Section 1.4.3.2, annual emission reductions for the following model sites were estimated:

- Textile Plant in North Carolina
- Large Offices in Chicago and Atlanta
- Medium Hotels in Chicago and Atlanta
- Large Hotels in Chicago and Atlanta
- Hospitals in Chicago and Atlanta

Table 2-9 summarizes the results. The reductions are highest for sites that are able to consistently use the recovered heat (i.e., medium size manufacturing plant and hospitals). These results are consistent with a recent study on CO_2 emission reductions from commercial buildings which concluded that microturbine and fuel-cell-based CHP technologies will emit 14 to 65 percent less carbon than grid and conventional heat sources (Kaarsberg et al. 1998). The annual reductions are lower than those estimated for Walker Court because the CO_2 emission rate for the Atlanta, Chicago, and North Carolina electrical utility grids are significantly lower than the Alberta Power Pool.

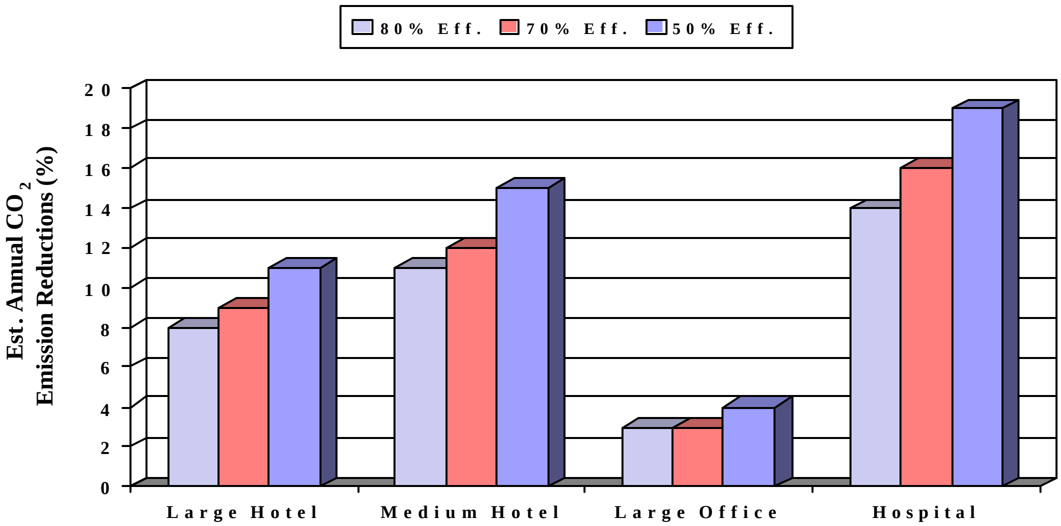
Table 2-9. Estimated Annual CO_2 Emission Reductions for Model Sites

Model Site		Baseline System		Annual CO_2 Emission Reductions	
		Electricity Provided By:	Heat Provided By:	lb	%
NC	Textile Plant	Utility Grid[a]	Natural Gas Boiler (60 % efficiency)	5,418,735	27
Chicago	Large Office	Utility Grid[b]	Natural Gas Boiler (70 % efficiency)	526,678	3
	Medium Hotel			557,608	12
	Large Hotel			884,276	9
	Hospital			3,924,710	16
Atlanta	Large Office	Utility Grid[a]	Electric Boiler[a] (95 % efficiency)	1,048,338	6
	Medium Hotel			1,160,960	22
	Large Hotel			1,701,375	17
	Hospital			9,765,554	34

[a] EPA reported CO_2 emission factor for the Southeast region is 1.334 lb/kWh
[b] EPA reported CO_2 emission factor for the North Central region is 1.68 lb/kWh

The primary focus of the Mariah CHP System verification test was to determine the system's technical performance and the emission reduction estimations which were developed using available published data. As discussed in Section 1.4.3.2, the emission estimation approach used here relied on this published information, industry standards, and discussions with stakeholder members. The GHG Center recognizes that emission reductions can vary greatly based on small deviations in assumptions used to compute annual emissions. For example, total system efficiencies of new natural gas boilers can exceed 80 percent while some existing, older boilers operate at less than 50 percent efficiency. For this reason, a sensitivity analysis was performed. Emissions were estimated at boiler efficiencies equal to 80 percent and 50 percent. The results, shown in Figure 2-12, indicate that CO_2 emission reductions vary by less than 4 percent at the two extreme levels in boiler efficiency examined.

Figure 2-12. Emission Reduction Estimates for Varying Boiler Efficiencies
(Chicago)



3.0 DATA QUALITY ASSESSMENT

3.1. DATA QUALITY OBJECTIVES

In verifications conducted by the GHG Center and EPA-ORD, measurement methodologies and instruments are selected to ensure that a desired level of data quality occurs in the final results. Data quality objectives (DQOs) are stated for key verification parameters before testing commences. These objectives must be achieved in order to draw conclusions with the desired level of confidence. The process of establishing DQOs starts with identifying the measurement variables that affect the verification parameter. For example, the electrical efficiency verification parameter requires measurement of three separate variables: fuel flow rate, LHV, and power output. The errors associated with each measurement must be accounted for to determine their cumulative effect on this verification parameter. This is done by assuming that measurement errors are not random, and that these errors can be combined to produce a worst-case overall error in the verification parameter. The worst case error is determined through an assessment of measurement errors expected in the field when instrument and sampling errors are accounted for. The resulting error, propagated using maximum and minimum errors in the measurements, is used to establish the DQO for the verification parameter. Table 3-1 lists the DQOs for key verification parameters and the actual errors achieved, and Section 3.2 describes how these objectives were reconciled.

Table 3-1. Data Quality Objectives

Verification Parameter	Required	Achieved
Electrical Power Output	± 0.2 % of reading or ± 0.06 kW at full load	± 0.05 % of reading or ± 0.01 kW at full load
Electrical Efficiency	± 0.38 % at full load	± 0.38 % at full load
Heat Recovery Rate	± 2.18 % at full load	± 3.45 % at full load
Thermal Efficiency	± 1.86 % at full load	± 2.38 % at full load
Total Efficiency	± 1.11 % at full load	± 3.73 % at full load
Emission Levels		
NO_X	± 0.5 ppmvd	± 0.4 ppmvd
CO	± 1.0 ppmvd	± 0.5 ppmvd
CO_2	± 1.0 %	± 0.4 %
THC	± 1.5 ppmvd	± 0.8 ppmvd

To help ensure that the DQOs listed above are met, data quality indicator (DQI) goals are established for key measurements performed in the verification test. The DQI goals, specified in Table 3-2, contain accuracy, precision, and completeness levels that must be achieved to ensure that DQOs can be met. Reconciliation of DQIs is conducted by performing independent performance checks in the field with certified reference materials, by following approved reference methods, factory calibrating the instruments prior to use, and conducting QA/QC procedures in the field to ensure that instrument installation and operation checks are verified. The following discussion illustrates that most DQI goals were achieved. With this, the DQOs were satisfied for all verification parameters with the exception of heat recovery rate, thermal efficiency, and total system efficiency. This was due to the initial assumption that heat recovery rate for the Mariah CHP System would be about 235 MBtu/hr (as initially expected by Mariah), but the actual measured rate was about 187 MBtu/hr. The increased error in heat recovery rate also contributed to the thermal and total efficiency errors. Further discussion of this and other data quality results is provided below.

3.2. RECONCILIATION OF DQOS AND DQIS

Table 3-2 summarizes the range of measurements observed in the field and the completeness goals. Completeness is defined as the number of valid determinations expressed as a percent of the total tests or readings conducted. The completeness goals for the load tests were to obtain electrical and thermal efficiency and emission rate data for all three test runs within a load condition, and to analyze a minimum of one gas sample during each of the four load test conditions. A total of four samples were collected, one at each load condition, during the initial April 2 and 3 load testing. However, the completeness goal for LHV was not met because the gas sample collected during the 75 percent load test was invalidated due to insufficient sample volume. The relatively consistent fuel heating values measured for other valid samples (90 percent to 916 Btu/ft^3) indicate that the quality of data for this run was not significantly compromised.

During the repeat load testing (i.e., after heat meter temperature correction was made), one gas sample was collected at the full load condition. The completeness goal for electrical efficiency was exceeded (i.e., more than three valid test runs were conducted). However, errors in heat recovery system temperature measurements invalidated thermal efficiency results for some of the runs. The repeat efficiency testing resulted in one valid run for 75 percent load test and two valid runs, each for 90 and 40 percent load test. As such, the heat recovery completeness goal was not satisfied for 90, 75, and 50 percent load testing.

The completeness goals for the extended test was to obtain 90 percent of 4 weeks (25 days) of power quality, power output, fuel input, and ambient measurements. This goal was exceeded, and 13 days of additional data (total of 38 days) were collected. As discussed in Section 2, these data were useful in establishing trends in power and heat performance capability at varying ambient temperatures.

Table 3-2 also includes accuracy goals of measurement instruments that are used to compute DQOs for key verification parameters. Measurement accuracy was evaluated using instrument calibrations conducted by manufacturers, field calibrations, reasonableness checks, and/or independent performance checks with a second instrument. The accuracy results for each measurement, and their effects on the DQOs are discussed below.

Table 3-2. Summary of Data Quality Goals and Results

Measurement Variable		Instrument Type / Manufacturer	Instrument Range	Range Observed in Field	Accuracy			Completeness	
					Goal	Actual	How Verified / Determined	Goal	Actual
Mariah CHP System Power Output and Quality	Power	Electric Meter/ Power Measurements 7600 ION	0 to 100 kW	0 to 29 kW	± 0.20 % reading	± 0.05 % reading	Instrument calibration from manufacturer just prior to testing	load tests: 3 valid runs per load using PTC 22 criteria extended test: 1 minute readings for 25 days	load tests: 3 valid runs at all loads extended test: 1 minute readings for 38 days
	Voltage		0 to 600 V	0 to 220 V	± 0.1 % reading	± 0.1 % reading			
	Voltage Transients		600 to 8000 V	none	not defined	NA			
	Frequency		49 to 61 Hz	59.908 to 60.070 Hz	± 0.01 % reading	± 0.01 % reading			
	Current		0 to 100	0 to 80	± 0.1 % reading	± 0.1 % reading			
	Voltage THD		0 to 100 %	0 to 100 %	± 1 % FS	± 1 % FS			
	Current THD		0 to 100 %	0 to 100 %	± 1 % FS	± 1 % FS			
	Power Factor		0 to 100 %	0 to 100 %	± 0.5 % reading	± 0.5 % reading			
Mariah CHP System Heat Recovery Rate	Inlet Temperature	Arigo Meter RTDs	37 to 356°F	120 to 135°F	RTD differential temps must be ± 1.8°F of ref. thermocouples	±0.3°F	Independent check with calibrated thermocouples	load tests: 3 valid runs extended test: 1 minute readings for 25 days	load tests: 2 runs at @ 75%, and 1 run @ 90 and 50 %, load condition invalidated extended test: 1 minute readings for 38 days
	Outlet Temperature		37 to 356°F	135 to 155°F					
	PG Flow	Arigo Meter Liquid Flow Sensor	2.53 to 5.89 cfm	2.5 to 3.0 cfm	±1.0 % reading	± 1.0 % reading	Instrument calibration from manufacturer just prior to testing		
	PG Concentration and Specific Heat	GC/FID	PG Conc: 10 to 20 %	PG Conc: 15.7-16.5 %	PG Conc: ±3 %	PG Conc: ±0.7 %	Independent check with blind sample		
			PG Sp Ht: 0.900 to 0.981 Btu/lb °F	PG Sp Ht: 0.962 to 0.971 Btu/lb °F	PG Sp Ht: ±0.2 %	PG Sp Ht: ±0.1 %	Using specific heat versus concentration charts published by ASHRAE		
Ambient Conditions	Ambient Temperature	RTD / Vaisala Model HMP 35A	-50 to 150 °F	25 to 65 ° F	± 0.2 °F	± 0.2 °F	Instrument calibration from manufacturer just prior to testing	load tests: 1 minute readings for all runs extended test: 1 min readings for 25 days	load tests: 1 minute readings for all runs extended test: 1 min readings for 38 days
	Ambient Pressure	Vaisala Model PTB220 Class B	14.80 to 32.56 in. Hg	28 to 31 in. Hg	± 0.1 % FS	± 0.1 % FS			
	Relative Humidity	Vaisala Model HMP 35A	0 to 100 % RH	40 to 55 % RH	± 2 % (0 to 90 % RH) ± 3 % (90 to 100 % RH)	± 2 % (0 to 90 % RH,) ± 3 % (90 to 100 % RH)			

(continued)

Table 3-2. Summary of Data Quality Indicator Goals and Results (continued)

Measurement Variable		Instrument Type / Manufacturer	Instrument Range	Measurement Range Observed	Accuracy			Completeness	
					Goal	Actual	How Verified / Determined	Goal	Actual
Fuel Input	Gas Flow Rate	Mass Flow Meter / Rosemount 3095 w/ 1195 orifice	0 to 10 scfm	0 to 8 scfm	1.0 % of reading	± 1.1 % overall average for all loads, ± 1.4 % for full load	In-line comparison with calibrated dry gas meter in field	load tests: 1 minute readings for all runs extended test: 1 min readings for 25 days	load tests: 1 minute readings for all runs extended test: 1 min readings for 38 days
	Gas Pressure	Pressure Transducer / Rosemount or equiv.	0 to 100 psig	69 to 71 psig	± 0.75 % FS	± 0.75 % FS	Instrument calibration from manufacturer just prior to testing		
	Gas Temperature	RTD / Rosemount Series 68	-58 to 752 °F	30 to 70 °F	± 0.10 % reading	± 0.09 % reading			
	LHV	Gas Chromatograph / HP 589011	0 to 100 % CH_4	90 to 95 % CH_4	± 0.2 % for CH_4 concentration	± 0.2 % for CH_4 concentration	Analysis of NIST-traceable CH_4 audit gas	load tests: one valid sample per load	load tests: 1 sample @ 75% load condition invalidated
				907 to 916 Btu/ft^3	± 0.2 % for LHV	± 0.09 % overall average LHV	Conducted duplicate analyses on 4 samples and 1 audit gas sample		
Exhaust Stack Emissions	NO_X Levels	Chemiluminescent/ Monitor Labs 8840	0 to 25 ppmvd	0 to 31 ppmvd	± 2 % FS or ± 0.5 ppmvd	≤ 1.6 % FS or ± 0.4 ppmvd	Calculated following EPA Reference Method calibrations (Before and after each test run)	load tests: 3 valid runs per load	load tests: 3 valid runs per load
	CO Levels	NDIR / Monitor Labs 8830	0 to 20 ppmvd/ 0 to 200 ppmvd	5 to 25 ppmvd	± 5 % FS or ± 1.0 ppmvd	≤ 2.5 % FS or ± 0.5 ppmvd			
	THC Levels	FID / California Analytical 300M	0 to 30 ppmvd	0 to 2 ppmvd	± 5 % FS or ± 1.5 ppmvd	≤ 6.0 % FS or ± 0.8 ppmvd			
	CO_2 Levels	NDIR / Nova Model 372WP	0 to 20 %	1.05 to 1.65 %	± 5 % FS or ± 1.0 %	≤ 2.0 % FS or ± 0.4 %			
	O_2 Levels	Paramagnetic/ California Analytical 100P	0 to 25 %	18 to 19 %	± 5 % FS or ± 1.25 %	≤ 0.6 % FS or ± 0.15 %			

FS: full scale
NA: not applicable

3.2.1. Power Output

Precise determination of electric power generated by the Mariah CHP System was required because it was a key verification parameter for the turbine. Instrumentation used to measure power was introduced in Section 1.0 and included a Power Measurements Model 7600 ION. The data quality objective for power output was ± 0.2 percent of reading, which exceeds the typical uncertainty set forth in PTC-22 of 1.8 percent. To determine if the power output DQO was met, the Test Plan specified factory calibration with a NIST-traceable standard, and using the differences between meter readings and standard readings to assign actual errors in power measurements. The Test Plan also required the GHG Center to perform several reasonableness checks in the field to ensure that the meter was installed and operating properly. The following summarizes the results.

The meter was factory calibrated by Power Measurements prior to being used at the test site. Calibrations were conducted in accordance with Power Measurements strict standard operating procedures (in compliance with ISO 9002:1994) and are traceable to NIST standards. The meter was certified by Power Measurements to meet or exceed the accuracy values summarized in Table 3-2 for power output, voltage, current, and frequency. NIST-traceable calibration records are archived by the GHG Center. Pretest factory calibrations on the meter indicated that power output was within ± 0.05 percent of reading, exceeding the ± 0.2 percent DQO. Using the manufacturer certified calibration results, the error at all loads tested (100, 90, 75, and 50 percent load) is determined to be ± 0.01 kW.

After installation of the meters at the site and prior to the start of the verification test, additional QC checks were performed in the field to verify the operation of the electrical meter. The results of these QC checks (summarized in Table 3-3) are not used to reconcile the DQI goals, but to give further information about the measurement's data quality. One of the QC checks consisted of reasonableness check between the 7600 ION reading and power output reported by the Mariah CHP System's own software system. During this check, the 7600 ION reported 28.7 kW during steady operation at full load. The corresponding power output reported by the Mariah CHP System was 29.2 kW. After accounting for a 0.5 kW loss from the 208 volt transformer (measured when the unit was off), this reading agrees exactly with the power recorded by the 7600 ION.

Current and voltage readings were also checked for reasonableness using a hand-held Fluke Multimeter. These checks confirmed that the voltage and current readings between the 7600 ION and the Fluke were within the range specified in the Test Plan.

Based on these results, it was concluded that the 7600 ION was installed and operating properly during the verification test. The ± 0.05 percent error in power measurements, as certified by the manufacturer, was used to reconcile the power output DQO (discussed above) and the electrical efficiency DQO (discussed in Section 3.2.2).

Table 3-3. Results of Additional QA/QC Checks

Measurement Variable	QA/QC Check	When Performed/Frequency	Allowable Result	Results Achieved
Power Output	Reasonableness checks	Beginning of test	Readings should range between 27 and 30 kW at full load	7600 ION readings exactly matched Mariah CHP System software output
	Sensor diagnostics in field – voltage and current comparisons with a digital multimeter	Beginning of test	Voltage and current checks within ± 1 % reading	± 0.49 % voltage ± 0.39 % current
Fuel Flow Rate	Instrument calibration by manufacturer	Beginning and end of test	± 1.0 % reading	Certified accuracy of ± 1.0 %
	Sensor diagnostics	Beginning of test	Pass	Passed all sensor diagnostic checks
	Reasonableness checks	Throughout test	Readings should be between 7 and 8 scfm at full load	All readings within specified range
Ambient Meteorological Conditions	Reasonableness checks	Throughout test	Recording should be comparable with airport data	Readings were consistent with airport data
Fuel Gas Pressure	Reasonableness checks	Throughout test	Readings should range between 55 and 65 psig	All readings were within specified range

3.2.2. Electrical Efficiency

The DQO for electrical efficiency was to achieve an uncertainty of ± 0.38 percent at full electrical load. This exceeds the typical uncertainty levels set forth in PTC-22 of 1.7 percent. Recall from Equation 1 that electrical efficiency determination consists of three direct measurements: power output, fuel flow rate, and fuel LHV. The accuracy goals specified to meet the electrical efficiency DQO consisted of ± 0.2 percent for power output, ± 1.0 percent for fuel flow rate, and ± 0.2 percent for LHV. The accuracy goals for each measurement were met, and in some cases they were exceeded. The following summarizes actual errors achieved, and the methods used to compute them.

Power Output: As discussed in Section 3.2.1, factory calibrations of the 7600 ION with a NIST-traceable standard resulted in ± 0.05 percent error in power measurements. Reasonableness checks in the field verified that the meter was functioning properly. The average power output at full load was measured to be 28.39 kW, and the measurement error is determined to be ± 0.01 kW.

Fuel Flow Rate: The goal for fuel flow rate was reconciled by comparing the integral orifice meter reading with a calibrated, in-line, dry-gas meter. In addition to independent verification of the orifice meter, three additional QA/QC checks were performed on this meter. This included calibration with a NIST-traceable standard and performing reasonableness checks in the field. Complete documentation of data quality results is provided in Section 3.2.2.3. The comparison between the orifice meter and the dry-gas meter readings resulted in an overall average difference of ± 1.1 percent for all load conditions, and ± 1.4 percent at full load. Although the goal was missed slightly, the results did not compromise the electrical efficiency DQO. The average flow rate at full load was 7.17 scfm, and the measurement error is determined to be ± 0.10 scfm.

Fuel LHV: Data quality of fuel analysis was assessed by comparing laboratory results with NIST-traceable audit gas and conducting duplicate analysis of the same sample. The Test Plan specified using the results of duplicate analysis to reconcile electrical efficiency DQO. The average percent difference between five duplicate analyses was ± 0.09 percent (Section 3.2.2.3). As such, the LHV goal of ± 0.2 percent was exceeded. At full load, the average LHV was verified to be 915.0 Btu/ft^3, and the measurement error corresponding to this heating value is ± 0.8 Btu/ft^3.

Using the actual errors achieved in power output, fuel flow rate, and fuel LHV measurements, electrical efficiency at full load is 24.61 ± 0.38 percent. Per Equation 1, this was computed as follows: [3412.14 * (28.39 ± 0.01 kW)] / [60*(7.17 ± 0.10 scfm) * (915.0 ± 0.8 Btu/ft^3)]. In conclusion, the ± 0.38 percent DQO for electrical efficiency was met.

Using the same approach for the remaining operating conditions, measurement errors in electrical efficiency are computed as follows: ± 0.31 percent at 90 percent load, ± 0.15 percent at 75 percent load, and ± 0.36 percent at 50 percent load. The primary reason for these differences is varying levels of errors observed in fuel flow rates at different operating loads (discussed in Section 3.2.2.3).

3.2.2.1. PTC-22 Requirements for Electrical Efficiency Determination

Per PTC-22 guidelines, efficiency determinations were to be performed within time intervals in which maximum variability in key operational parameters did not exceed specified levels. This time interval could be as brief as 4 minutes or as long as 30 minutes. Table 3-4 summarizes the maximum permissible variations observed in power output, power factor, fuel flow rate, barometric pressure, and ambient temperature during each test run. As shown in the table, the requirements for all parameters were met for all test runs. Thus, it can be concluded that the PTC-22 requirements were met and the efficiency determinations are representative of stable operating conditions.

For the "non-standard" test run conducted to evaluate performance at loads ranging between 40 and 100 percent of the unit's rated electric power output (Figure 2-10), turbine operating data were analyzed to assess conformance with PTC-22 requirements and to calculate efficiency. The maximum deviation between any 1-minute observed value and the average for the each of the 17 different power output levels was computed according to PTC-22 guidelines. Despite the duration of the unplanned tests being less than 30 minutes, the maximum deviation of ± 2 percent for power output, power factor, and fuel flow rate, ± 0.5 percent for ambient pressure, and ± 4 ^{o}F for ambient temperature was satisfied for each load condition.

Table 3-4. Variability Observed In Operating Conditions

	Maximum Observed Variation[a] in Measured Parameters				
	Power Output (%)	Power Factor (%)	Fuel Flow Rate (%)	Inlet Air Press. (%)	Inlet Air Temp. (°F)
Maximum Allowable Variation	**± 2**	**± 2**	**± 2**	**± 0.5**	**± 4**
Run 1	0.81	0.03	0.51	0.01	0.53
Run 2	0.27	0.03	0.88	0.01	0.59
Run 3	0.47	0.02	0.85	0.01	0.18
Run 4	0.42	0.04	0.58	0.02	0.17
Run 5	0.38	0.02	0.63	0.02	0.35
Run 6	0.37	0.21	0.61	0.01	0.27
Run 7	0.31	0.03	0.98	0.01	0.26
Run 8	0.38	0.02	0.91	0.02	0.26
Run 9	0.35	0.02	0.81	0.01	0.14
Run 10	0.40	0.06	0.10	0.01	0.12
Run 11	0.51	0.12	0.00	0.00	0.28
Run 12	0.25	0.03	0.00	0.01	0.15
Run 13	0.60	0.02	0.45	0.02	0.31
Run 14	0.56	0.03	0.76	0.03	0.25
Run 15	0.28	0.01	0.84	0.04	0.22
Run 16	0.21	0.01	0.00	0.01	0.11
Run 17	0.26	0.03	0.74	0.01	0.19
Run 18	0.31	0.04	0.00	0.01	0.18

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

3.2.2.2. Ambient Measurements

Ambient temperatures and pressures at the site were monitored throughout the extended verification period and the load tests. Relative humidity was also recorded during the load tests. The instrumentation used is identified in Table 3-2 along with instrument ranges, data quality goals, and data quality achieved. The pressure sensor and the relative humidity probe were factory calibrated prior to the verification testing using reference materials traceable to NIST standards. The temperature sensor was calibrated at the U.S. EPA laboratory facility in Research Triangle Park, NC, using a NIST-traceable reference standard. Results of these calibrations indicate that the ± 2 °F accuracy goal for temperature, ± 0.1 percent for pressure, and ± 3 percent for relative humidity were met.

3.2.2.3. Fuel Flow Rate

The Test Plan specified the use of an integral orifice meter (Rosemount Model 3095) to measure the flow of natural gas supplied to the Mariah CHP System. The integral orifice meter was factory calibrated prior to installation in the field, and its calibration records were reviewed to ensure that the ± 1.0 percent instrument accuracy goal was satisfied. QC checks (sensor diagnostics) listed in Table 3-4 were conducted to ensure proper function in the field. In addition, independent verification with a second meter was performed in the field to reconcile ± 1.0 percent DQI goal.

Sensor diagnostic checks consisted of zero flow verification by isolating the meter from the flow, equalizing the pressure across the differential pressure (DP) sensors, and reading the pressure differential and flow rate. The sensor output must read zero flow during these checks. Transmitter analog output checks, known as the loop test, consist of checking a current of known amount against a Fluke multimeter to ensure that 4 mA and 20 mA signals are produced. These results were found to be within ± 0.01 mA. Reasonableness checks revealed that measured flow rates were within the range specified by Mariah.

Finally, a dry gas meter (Equimeter Model R-1600), installed in series with the orifice, was used to independently verify the Rosemount flow meter output. The dry gas meter was calibrated by the manufacturer using a volume prover, and the meter calibration proof was 100.0 percent at full scale. During the field testing, dry gas meter readings were obtained and compared with the Rosemount flow data. The dry gas meter flow rates were computed by taking manual dry gas meter readings over a period of time [in units of actual cubic feet (acf)], and then correcting the dry gas meter readings to standard conditions. Actual gas pressure and temperature measurements, were used to make the corrections using Equation 5.

$$\text{Dry Gas Meter Reading (scf)} = \text{Gas Volume Measured (acf)} * (T_{std}/T_g) * (P_g/P_{std}) * C_m \qquad \text{(Eqn. 5)}$$

Where:
T_{std} = standard temperature (519.67 ^{o}R)
T_g = measured gas temperature (^{o}R)
P_g = measured gas pressure (psia)
P_{std} = standard pressure (14.696 psia)
C_m = meter calibration coefficient (1.00)

The standardized gas volume was then divided by the duration of the sampling interval to yield average gas flow in standard cubic feet per minute (scfm). These values were then compared to the average gas flow rate recorded by the integral orifice meter during the same period. The results of field comparisons between the integral orifice meter and the in-line dry gas meter are presented in Table 3-5. On average, the integral orifice flows were 1.1 percent higher than dry gas meter readings, which resulted in slightly missing the ± 1.0 percent DQI goal. The differences at full load were the greatest (average of ± 1.4 percent); however, as discussed earlier, this did not compromise the electrical efficiency DQO.

Table 3-5. Comparison of Integral Orifice Meter With Dry Gas Meter During Load Testing

Test Condition (% of Rated Power)	Run ID	Power Delivered (kW)	Integral Orifice Meter Reading (scfm)	Gas Pressure (psia)	Gas Temp. (^oF)	Dry Gas Meter Reading (scfm)	Absolute Difference[a] (scfm)	Absolute Percent Difference[b] (%)
100	1	28.45	7.16	52.77	46.65	7.15	0.01	0.14
	3	28.32	7.12	52.54	50.42	7.17	0.05	0.70
	13	28.47	7.22	52.86	54.05	7.07	0.15	2.12
	14	28.45	7.20	52.62	54.73	7.08	0.12	1.69
	15	28.38	7.19	52.79	55.73	7.04	0.15	2.13
90	4	26.44	6.73	52.71	48.57	6.68	0.05	0.75
	5	26.47	6.71	52.86	49.38	6.64	0.07	1.05
	6	26.32	6.73	52.83	50.25	6.67	0.06	0.90
	16	26.46	6.75	52.78	54.18	6.64	0.11	1.66
75	7	22.04	5.76	53.24	50.63	5.73	0.03	0.52
	8	22.05	5.74	53.25	51.25	5.73	0.01	0.17
	9	22.02	5.79	53.09	54.38	5.75	0.04	0.70
50	10	14.54	4.19	53.76	52.46	4.13	0.06	1.45
	11	14.52	4.19	53.48	52.30	4.12	0.07	1.70
	12	14.54	4.19	53.63	55.00	4.14	0.05	1.21
						Overall Average	0.07	1.13

[a] = | Integral Orifice Reading – Dry Gas Reading |
[b] = [(| Integral Orifice Reading - Dry Gas Reading |) / Dry Gas Reading] * 100

3.2.2.4. Fuel Lower Heating Value

Fuel gas samples were collected no less than once per test load condition. Full documentation of sample collection date, time, run number, and canister ID was logged along with laboratory chain of custody forms and shipped along with the samples. Copies of the chain of custody forms and results of the analyses are stored in the GHG Center project files. Collected samples were shipped to Core Laboratories of Calgary for compositional analysis and determination of LHV per ASTM test methods D1945 and D3588, respectively. The DQI goals were to measure methane concentration that was within ± 0.2 percent of a NIST-traceable calibration gas and a certified audit gas, and to achieve less than ± 0.2 percent difference in LHV duplicate analyses results.

The GC/FID was calibrated daily using a continuous calibration verification standard (NIST-traceable) and upper and lower control limits maintained by Core Laboratory. Copies of the GC/FID calibration records are maintained at the GHG Center, and indicate that instrument responses were well within the control limits for all analyses conducted. A certified natural gas audit sample was submitted to Core Laboratory, and its results were reviewed to determine analytical error and repeatability for major gas components. Results of the audit sample, summarized in Table 3-6, show acceptable accuracy and repeatability for major gas components. High levels of error were evident only on components that were present in very low concentrations (e.g., n-butane and n-hexane). The results also show that the ± 0.2 percent goal for methane concentration was achieved.

Table 3-6. Results of Natural Gas Audit Sample Analysis					
Gas Component	**Certified Component Concentration (%)**	**Analytical Result (%)**	**Combined Sampling and Analytical Error (%)[a]**	**Duplicate Analytical Result (%)**	**Analytical Repeatability (%)[b]**
n-butane	0.386	0.43	11.4	0.40	7.0
carbon dioxide	3.01	3.20	6.3	3.18	0.6
ethane	3.52	3.52	0.0	3.50	0.6
n-heptane	0.020	0.02	0.0	0.02	0.0
n-hexane	0.049	0.05	2.0	0.06	20.0
Iso-butane	0.396	0.40	1.0	0.40	0.0
Iso-pentane	0.150	0.15	0.0	0.15	0.0
n-pentane	0.150	0.15	0.0	0.15	0.0
nitrogen	2.50	2.53	1.2	2.57	1.6
propane	1.00	1.01	1.0	1.01	0.0
methane	88.72	88.53	0.2	88.48	0.05

[a] Calculated as: Error = (certified conc. – analytical result) / certified conc. * 100
[b] Calculated as: Error = (initial result – duplicate result) / initial result * 100

Duplicate analyses were conducted on four samples and the certified audit sample. Duplicate analyses is defined as the analyses performed by the same operating procedure, and using the same instrument for a given sample volume. Results are presented in Table 3-7. The results demonstrate that the ± 0.2 percent LHV accuracy goal was achieved for four samples, while one sample resulted in a difference that was slightly higher. The overall average difference was ± 0.09 percent, which is lower than the goal. As a result, the DQO for electrical efficiency was not compromised.

Table 3-7. Summary of Fuel Sampling Duplicate Analyses				
Sample Collection Date (Time)	**Run ID**	**Methane Concen. (%)**	**LHV (real, Btu/ft^3)**	**Notes**
4/2/01 (15:18)	3	95.17	914.9	Valid sample, duplicate analyses differ by 0.02 %
		95.16	914.8	
4/3/01 (09:40)	4	94.29	908.8	Valid sample, duplicate analyses differ by 0.04 %
		94.38	908.0	
4/4/01 (10:35)	13	93.43	923.3	Valid sample, duplicate analyses differ by 0.25 %
		94.30	921.0	
4/4/01 (10:35)	13	94.15	910.0	Valid sample, duplicate analyses differ by 0.11 %
		94.51	909.0	
4/4/01	Audit Gas	88.53	926.4	Valid sample, duplicate analyses differ by 0.03 %
		88.48	926.1	
Overall Average Difference				± 0.09 %

3.2.3. Heat Recovery Rate

Precise determination of CHP heat recovery rate was required because it represents a primary performance parameter for the verification. Referencing Equation 2, determination of heat recovery rate requires direct measurements of PG flow rate, PG supply and return line temperatures, and PG solution specific heat. The manufacturer-specified accuracy for the Arigo flow measurement was ± 1.0 percent of reading and ± 1.8 ^{o}F for differential temperatures. These accuracy specifications were defined as the DQI goals for the heat meter. The accuracy goal for PG specific heat was ± 0.2 percent (assuming 3 percent variability in PG concentration measurements).

Based on these accuracy goals, the DQO for heat recovery rate was set at ± 2.18 percent at full load. Actual error achieved was ± 2.73 percent. This is largely due to lower than anticipated heat recovery rates. Actual heat recovery rate at full load was 187 MBh/hr, while the initial heat recovery projections (provided by Mariah) consisted of heat recovery rate of 235 MBh/hr. Table 3-2 summarizes the data quality results for the three measurements that were used to calculate heat recovery rate DQO. The following discussion supports these conclusions.

3.2.3.1. Arigo Heat Meter

The Arigo heat meter was supplied and installed by Mariah. To assess the data quality of PG flow rate measurements, the Test Plan specified GHG Center to review manufacturer's instrument calibrations. The data quality of differential temperature was to be assessed through independent performance checks with calibrated reference thermocouples. A review of the factory calibrations revealed that the Arigo heat meter was certified to meet Europe's custody transfer standard, and the accuracy goal for PG flow rate was satisfied.

Independent performance check of the Arigo RTDs was performed in the field, prior to initiation of load testing. In this procedure, the RTDs were removed from the fluid pipe and placed in an ice water bath along with a calibrated thermocouple of known accuracy. Temperature readings from both sensors were recorded for comparison. The procedure was then repeated in a hot water bath and in room air. The goal was to achieve a maximum difference in the differential temperature of ± 1.8 ^{o}F. Table 3-8 summarizes the readings for the reference thermocouple, inlet RTD, and output RTD. The overall average difference in the temperature readings is ± 0.3 ^{o}F. The temperature readings for all three sensors are nearly identical in the hot water bath. Since the actual temperatures observed during verification test (125 to 150 ^{o}F) were at this level, the quality of verification test data is considered good, and the DQI goal of ± 1.8 ^{o}F was exceeded.

Table 3-8. Heat Exchanger RTD Performance Test Results

	Reference Temperature (^{o}F)	Inlet RTD Reading (^{o}F)	Outlet RTD Reading (^{o}F)	Absolute Difference[a] (^{o}F)
Ice Bath	37.6	39.5	38.9	0.6
Room Temperature	66.2	65.5	65.7	0.2
Hot Water Bath	149.9	148.8	148.8	0.0
			Overall average	0.3

[a] Defined as (Inlet RTD – Outlet RTD) or [(Ref. – Inlet RTD) – (Ref. – Outlet RTD)]

At the conclusion of the first set of load tests, the facility discovered the heat recovery system RTDs were reporting questionable inlet and outlet temperatures. The RTDs were removed, calibrated, cleaned, and reinstalled with fresh thermal sealing compound. To confirm that the readings from the RTDs were reasonable after this exercise, the GHG Center conducted another field QC check. Specifically, two calibrated reference thermocouples were surface mounted on the heat exchanger inlet and outlet lines as close as possible to the Arigo RTDs. The surface mounted reference thermocouples were well insulated and allowed to stabilize. Concurrent readings from the two reference thermocouples (inlet and outlet) and corresponding RTDs (inlet and outlet) were then recorded for a period of approximately 60 minutes. During this test, the average delta T (heat exchanger outlet minus inlet temperature) recorded by the reference thermocouples was 19.11 ^{o}F, while the average delta T reported by the Arigo RTDs was 18.62 ^{o}F, with a difference of only 0.49 ^{o}F. Based on this validation test, the GHG Center concluded that the delta Ts reported by the reinstalled Arigo RTDs were accurate and, subsequently, efficiency testing was repeated.

3.2.3.2. PG Sampling

The DQI goal for laboratory analyses of PG mixture was to achieve PG concentrations that are within ± 3 percent. Using this goal and an initial estimate of PG concentration expected in the field (16 percent), specific heats were selected from published ASHRAE charts at minimum concentration (15.7 percent) and maximum concentration (16.3 percent). The error in specific heat was determined to be ± 0.2 percent at the two extreme levels in PG concentration. This was set as the DQI goal for specific heat.

The DQI goals for PG concentration and specific heat were reconciled by comparing a blind/audit sample of known PG concentration with those analyzed and reported by Core Laboratory. The PG concentration in the audit solution was 16.25 percent, and the laboratory measured this to be 16.37 percent. The difference in PG concentration is ± 0.7 percent, which exceeded the ± 3 percent goal. The ± 0.7 difference observed in PG concentration was also assigned as the error in PG density measurements. Using ASHRAE charts, PG specific heat is selected to be 0.971 lb/Btu °F at 16.27 percent (audit solution) and 0.970 lb/Btu °F at 16.37 percent (laboratory reported concentration). This equates to a difference of ± 0.1 percent in PG specific heats, which exceeded the ± 0.2 percent goal in specific heat.

3.2.4. Thermal Efficiency

Thermal efficiency is defined as heat recovered divided by heat input. The DQO for thermal efficiency was set to be ± 1.86 percent. Meeting this objective consisted of meeting fuel heating value, fuel flow rate, heat meter flow rate and temperature, and PG concentration DQI goals. The data quality results for each measurement were discussed above, and are not repeated. Using the actual errors achieved at full load, the error in thermal efficiency is computed to be ± 2.38 percent. As discussed earlier, this is due to initial assumption that the system may be able to recover more heat.

Using actual data quality results for other load conditions, the errors in thermal efficiency are computed to be ± 2.22 percent, ± 2.07 percent, and ± 3.04 percent for 90, 75, and 50 percent electrical load, respectively.

3.2.5. Total Efficiency

Total Mariah CHP System efficiency is defined as the sum of energy recovered (electricity and heat) divided by heat input. The DQO for total efficiency was set to be ± 1.11 percent. Actual total efficiency at full load is computed to be within ± 3.73 percent.

3.2.6. Exhaust Stack Emission Measurements

EPA Reference Methods were used to quantify emission rates of criteria pollutants and greenhouse gases. The Reference Methods specify the sampling and calibration procedures, and data quality checks that must be followed to collect data that meets the methods required performance objectives. These Methods ensure that run-specific quantification of instrument and sampling system drift and accuracy occurred throughout the emissions tests. The DQOs specified in the Test Plan were based on the requirements of the Reference Methods. Specifically, these are ± 0.50 ppmvd for NO_X, ± 1.00 ppmvd for CO, ± 1.50 ppmvd for THC, and ± 1.00 percent for CO_2, CH_4, CO, and THC. The data quality indicator goals required to meet the DQO consisted of an assessment of sampling system error (bias) and drift for NO_X and THC, and bias and drift for CO, CO_2, and O_2.

<u>NO_X and THC</u>

The NO_X and THC sampling system calibration error test was conducted prior to the start of each test run. The calibration was conducted by sequentially introducing a suite of calibration gases into the sampling system at the sampling probe, and recording the system responses. Calibrations were conducted on all analyzers using Protocol No. 1 calibration gases. Four calibration gas concentrations of NO_X and THC were used including zero, 20 to 30 percent of span, 40 to 60 percent of span, and 80 to 90 percent of span. The results of sampling system error tests are summarized in Appendix B.

As shown in Table 3-2, the system calibration error goal for NO_X was ± 0.50 ppmvd, and the maximum actual measured error was ± 0.40 ppmvd, which indicates the goal was met. For THC, the maximum system error was determined to be ± 0.8 ppmvd, which is within the ± 1.50 ppmvd goal. The system error and drift are calculated only for the mid-level calibration gas, based on following Method 25A requirements.

Uncorrected NO_X concentrations during the 50 percent load tests were approximately 30 ppmvd. This was the highest level measured. The NO_X analyzer used for all tests had a full-scale range of 0 to 100 ppmvd, but was calibrated to a range of 0 to 25 ppmvd (uncorrected) because of the extremely low concentrations at the other test loads. The NO_X analyzer was calibrated with certified concentrations 0, 7, 12, and 22.5 ppmvd NO_X at the beginning of each day to establish linearity. Results of these calibrations (Appendix B-1) indicate excellent instrument linearity with calibration errors of 0.2 percent of span or less. Because of the level of linearity demonstrated, exceeding the 25 ppmvd calibration range by only 5 ppmvd is not expected to have significant effect on data quality at this load. Note that the high level calibration gas (22.7 ppmvd) was used to conduct the pre- and post-test system bias checks (the 12.1 ppmvd calibration gas was used for the system bias checks during all other tests).

At the conclusion of each test, zero and mid-level calibration gases were again introduced to the sampling systems at the probe and the response recorded. System response was compared to the initial system calibration error to determine sampling system drift. The sampling system drift was determined to be 0.2 ppmvd for NO_X and 0.84 ppmvd for THC, which were both below the Method's required goal. Sampling system calibration error results and drift results for all runs conducted during the verification are summarized in Appendix B.

Two additional QC checks were performed to better quantify the NO_X data quality. In accordance with Method 20, an interference test was conducted on the NO_X analyzer once before the testing started. This test confirms that the presence of other pollutants in the exhaust gas do not interfere with the accuracy of the NO_X analyzer. This test was conducted by injecting the following calibration gases into the analyzer and recording the response of the NO_X analyzer, which must be zero ± 2 percent of span (or 0.50 ppmvd).

As shown in Table 3-9, the maximum measured value was well below the 0.50 ppmvd required by the method.

- CO – 602 ppmvd in balance nitrogen (N_2)
- SO_2 – 251 ppmvd in N_2
- CO_2 – 9.9 percent in N_2
- O_2 – 20.9 percent in N_2

The NO_X analyzer converts any NO_2 present in the gas stream to NO prior to gas analysis. The second QC check consisted of determining NO_2 converter efficiency prior to beginning of emissions testing. This was done by introducing to the analyzer a mixture of mid-level calibration gas and air. The analyzer response was recorded every minute for 30 minutes. If the NO_2 to NO conversion is 100 percent efficient, the response will be stable at the highest peak value observed. If the response decreases by more than 2 percent from the peak value observed during the 30-minute test period, the converter is faulty and the analyzer must be either repaired or replaced prior to testing. As shown in Table 3-9, the converter efficiency was measured to be 100 percent and was above the efficiency level required.

As an additional QC check for low-range NO_X measurements, the GHG Center provided an EPA Protocol mixture of 5.18 ppmvd NO_X in N_2 as an audit of Entech's sampling system. The gas was introduced to the sampling system as a blind audit and the system response was recorded by Center personnel. A stable system response of 5.10 ppmvd was recorded, corresponding to a system error of 1.54 percent.

<u>CO, CO_2, and O_2</u>

Analyzer calibrations were conducted to verify the error in CO, CO_2, and O_2 measurements relative to calibration gas standards. The calibration error test was conducted at the beginning of the day, and again after switching the CO analyzer to a higher range for the low load testing. A suite of calibration gases were introduced directly to the analyzer, and analyzer responses were recorded. Three gases were used for CO_2 and O_2: zero, 40 to 60 percent of span, and 80 to 100 percent of span. Four gases were used for CO: zero and approximately 30, 60, and 90 percent of span. The analyzer calibration errors for all gases were below the allowable levels, as shown in Table 3-9.

Before and after each test run, zero and mid-level calibration gases were introduced to the sampling system at the probe, and the response was recorded. System bias was calculated by comparing the system responses to the calibration error responses recorded earlier. As shown in Table 3-2, the system bias goal for all gases was achieved: ± 0.50 ppmvd for CO, ± 0.40 percent (absolute) for CO_2, and ± 0.15 percent (absolute). Subsequently, the DQO was satisfied.

The pre- and post-test system bias calibrations were also used to calculate sampling system drift for each pollutant. As shown in Table 3-9, the maximum drift measured was 2.5 percent of span for CO, 1.0 percent for CO_2, and 0.5 percent for O_2. In conclusion, the drift goals were also met for all pollutants.

Results of each of the analyzer and sampling system calibrations conducted, including linearity tests and sampling system bias and drift checks, are presented in Appendix B.

Table 3-9. Additional QA/QC Checks for Emissions Testing

Parameter	QA/QC Check	When Performed/Frequency	Expected or Allowable Result	Maximum Results Measured[a]
NO_X	Analyzer interference check	Once before testing begins	± 2 % of analyzer span or less	0.40 % of span or 0.10 ppmvd
	NO_2 converter efficiency	Once before testing begins	98 % efficiency or greater	100.0 %
	Sampling system drift checks	Before and after each test run	± 2 % of analyzer span or less	0.8 % of span or 0.50 ppmvd
CO, CO_2, O_2	Analyzer calibration error test	Daily before testing	± 2 % of analyzer span or less	CO: 1.5 % of span or 0.30 ppmvd CO_2: 1.0 % of span or 0.20 % absolute O_2: 0.0 % of span and absolute
	Calibration drift test	After each test	± 3 % of analyzer span or less	CO: 2.5 % of span or 0.50 ppmvd CO_2: 1.0 % of span or 0.20 % absolute O_2: 0.5 % of span or 0.12 % absolute
THC	System calibration drift test	After each test	± 3 % of analyzer span or less	2.8 % of span or 0.84 ppmvd

[a] See Appendix B for individual test run results

4.0 TECHNICAL AND PERFORMANCE DATA SUPPLIED BY MARIAH ENERGY CORP.

NOTE: This section provides an opportunity for Mariah Energy Corp. to provide additional comments concerning the Mariah CHP System, and its features not addressed elsewhere in this Verification Report. The GHG Center has not independently verified the statements made in this section.

This rigorous, structured performance study was undertaken using the first *beta* unit of the 60/30 Heat PlusPower™ system from Mariah Energy Corp. Much had been learned in 6 months of testing and refinement that Mariah had achieved running the prototype system at the Walker Court site, and this unit reflected many technical refinements.

The results of the testing bear out the excellent performance of the resulting system. Even so, as noted, the team identified a performance constraint imposed by a restriction on the combustion air intake. Alleviation of that one constraint raised the performance to near 79 percent efficiency (this at an altitude of 3,370 ft ASL). In response to this learning, Mariah has developed a standardized air intake plenum that ensures appropriate air flow, while reducing sound levels from the air intake side.

Mariah continues to refine and improve the performance of the Heat PlusPower series. The 60/30 Heat PlusPower unit was designed to deliver 60 kW thermal and 30 kW electrical power under standard conditions. The 120/60 Heat PlusPower package, to be commercially released in January 2002, provides 120 kW thermal and 60 kW electrical power. The 120/60 represents not just a step up in scale, but a generation forward in performance.

At the same time that performance improvements have been made in basic heat recovery, developments are being made in advanced controls, remote operation, transfer switching, acoustic attenuation, and other areas. Several of these simplify design and implementation of microturbine installations in general, while others relate specifically to clean heat and power systems.

4.1. "A HOT WATER HEATER THAT GENERATES ELECTRICITY"

In general, the aim of Mariah Energy Corp. is to move distributed generation and CHP from the realm of exotic generating technology to that of a standard appliance. In order to do this, the mystery of appropriate site selection, equipment sizing, and installation has to be removed.

Ultimately the aim of the PlusPower series of appliances is to put this technology into the standard vocabulary of mechanical and electrical contractors, engineers, and architects.

4.2. A DISTRIBUTED MICRO-UTILITY

The application of CHP requires looking beyond short-term capital cost budgeting.

When Mariah Energy Corp. was founded, a number of barriers to acceptance were identified. These include:

- High capital equipment cost and relatively long payback (in many markets);
- Fear of new technologies;
- Operation & Maintenance cost risk;

- Level of effort to learn about the technology and correct implementation;
- Level of effort required to confirm to economics;
- Barriers to interconnection with distribution wires owners;
- Barriers to exporting power for sale;
- Concerns about turbine noise levels;
- Space constraints made existing MicroTurbine CHP systems difficult to site in multi-unit residential and hotel sites – especially for retrofits;
- Unfamiliarity factor.

In response to these barriers, Mariah Energy conceived the Distributed Micro-Utility model. In this structure Mariah builds, owns, and operates equipment on behalf of the customer. The customer provides a location and agrees to purchase heat and power on contract and may provide the fuel. Mariah assumes the capital, technical, and operation and maintenance (O&M) risks, deals with interconnection requirements, and handles energy exports, if any.

Each site is web enabled, allowing for secure (encrypted) internet monitoring and economic optimization of a network of installations. This affords an opportunity to further reduce O&M costs, improves response time to any operational problems, and allows transfer of power from one site to another through the distribution system, where applicable.

To address the space constraint issue, Mariah Energy developed a closely coupled CHP package with the same footprint as the original turbine housing. A side benefit of such tight coupling is enhanced performance, as reflected by the test results outlined above.

4.2.1. Equipment Requirements

The Distributed Micro-Utility model assumes an economic lifetime of 10 to 20 years. This requires careful selection and/or design of all system components. The 20 year life has been at the center of all of Mariah Energy's development decisions.

The selection of the Capstone MicroTurbine® as the main generator component reflects this concern for quality and lifecycle cost of operation. Where suitable equipment is not available off the shelf, Mariah Energy has developed their own.

Concern about sound levels led Mariah to substantially enhance the performance of the existing Capstone Industrial Housing, as well as pay particular attention to sound damping in the air intake and exhaust. The Walker Court installation represents an excellent test case in which nearby established residents are not even aware whether the CHP system is running or not. In order to verify the performance of the acoustical measures taken, an independent study was commissioned (Patching and Morozumi 2000). In the course of this study, data were collected in the closest neighbor's yard, about 20 to 30 feet from the CHP system. At 3:00 am, CHP system operation was interrupted for 30 minutes. No detectable change was able to be extracted from the data. It is common practice, when outside on a deck within 10 feet of the air intake and 20 feet of the exhaust outlet, to enter the building and check instrumentation to confirm whether the system is running or not.

In order to ensure flexibility exists to address unforeseen installation requirements, standards were embraced wherever possible. An example of this is the use of LonWorks communication for all internal controls. This allows simple expansion to add new functionality, such as sub-metering, load shedding, and integration with absorption chilling equipment.

An example of a supplementary function is Mariah's On-Guard™ controller. The On-Guard controller is an energy security watchdog. If the CHP system detects a grid failure, it begins to shut down and signals the On-Guard controller. The On-Guard unit then assesses the grid status. If the grid service returns quickly, it signals the CHP system to restore grid-connected service. If not, it sends a signal to a contactor to isolate protected loads from the grid and signals the CHP system to restore stand-alone service. The On-Guard controller continues to monitor the grid status. When grid service returns to normal, the controller can automatically initiate a safe transfer back to grid-connected operation, or it can be configured to wait for operator intervention to restore normal service.

After considerable examination of existing communication devices, Mariah is developing a unique 'Triple-Gate' system to provide in-depth CHP diagnostics and controls over a secure internet link. This product is not available for sale at this time; however, it is key to the operation of the Distributed Micro-Utility model.

4.3. AN EQUIPMENT SUPPLIER

The products developed by Mariah Energy to meet the requirements of the Distributed Micro-Utility business model address the requirements of many others who wish to:

- Purchase turn-key solutions;
- Offer turn-key solutions to their own customers;
- Develop a Distributed Micro-Utility model (or some other build-own-operate variant) in their own area;
- Purchase auxiliary components and systems.

Mariah Energy offers many of the products described here for sale. For more information contact Myra Berrub at:

Info@mariahpower.com or call (403) 264-2880 or fax (403) 264-2881.

4.4. CHP ECONOMICS

CHP systems efficiently produce heat and power. Because of their relatively high capital cost, optimal economic performance is attained when utilization of both products approaches 100 percent. Typically the value of each product is assumed to be equivalent to that of the nearest competing technology.

Domestic hot water may be valued equal to the cost of producing heat in a hot water heater. This may be gas fired, electrical, or oil fired depending on the location. This means that the value of a delivered Btu of hot water is the same as the value of 1 Btu of fuel divided by the efficiency of the hot water heater. In the case of a steam fired domestic hot water system, the reference efficiency takes into account the boiler efficiency, steam loop losses, and the steam converter efficiency.

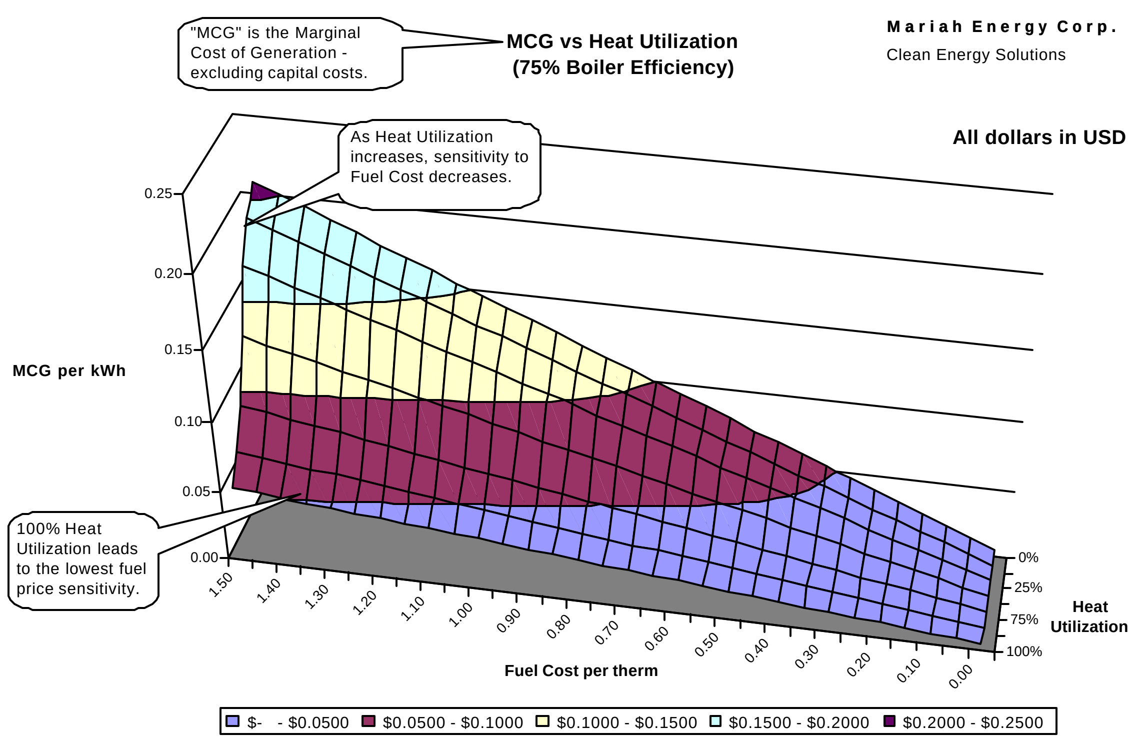
Electric power value includes the value of energy from the grid, plus all connection fees that are calculated on a per-kWh basis. Additional savings may be factored in to cover reductions in demand charges and deferred capital investment.

Often, the desire to base-load both thermally and electrically will result in displacement of one or more base-loaded hot water heaters. It may also result in cost reductions on electrical interconnection such as transformer down-sizing, and elimination of pad-mounted transformers. If the CHP system operates as a standby generator, then the displaced cost of a generator must be taken into account. All of these savings are balanced off against the capital cost of the CHP installation.

The Marginal Cost of Generation (MCG) can be used as an economic guide, based on the assumption that all the savings from heating and power generation are to accrue to the value of power. MCG is determined by the cost of fuel, operation and maintenance cost (O&M), and the value and amount of heat recovered and used.

The first area to be considered is heat utilization.

Figure 4-1. Marginal Cost of Generation Dependency on Heat Utilization

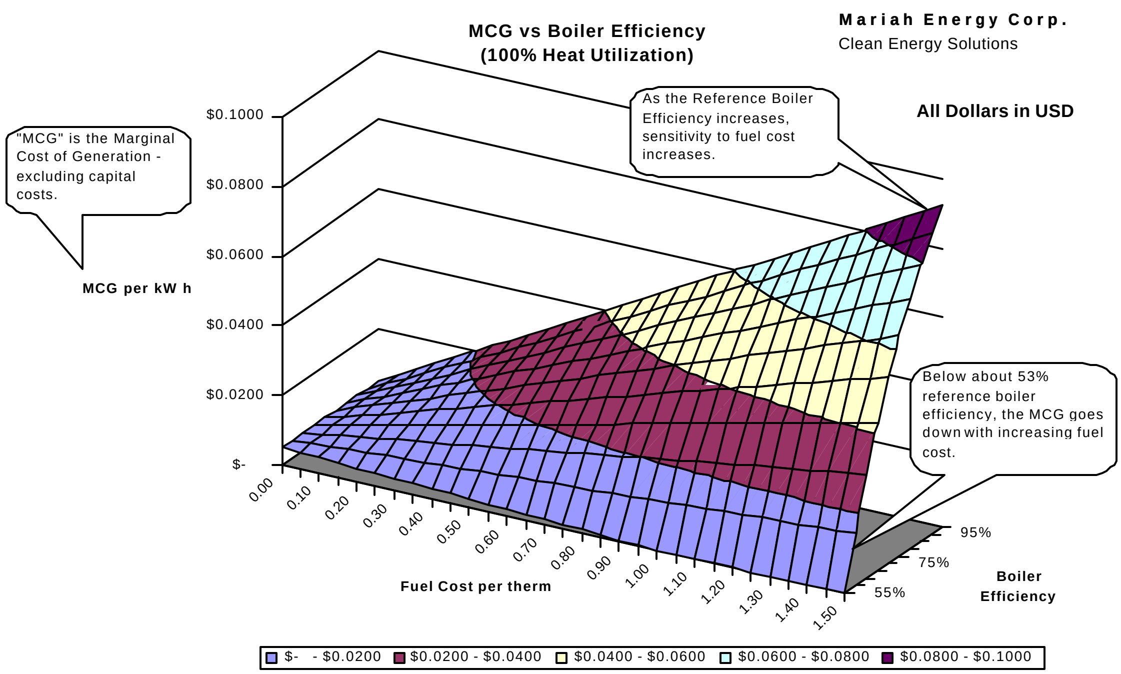


As can be seen from Figure 4-1, as heat utilization approaches 100 percent, the dependency on fuel cost is at a minimum.

The second consideration is the efficiency of displaced heating systems (Figure 4-2). These may range from as low as 50 percent up to the latest high efficiency condensing systems at 90 percent plus. Most gas fired domestic hot water systems presently in service operate in the 60 to 75 percent efficiency range.

If the CHP unit is base loaded under these conditions, sensitivity to fuel prices is reduced because about two thirds of the fuel consumed by the CHP system would have been consumed to provide the heating.

Figure 4-2. Marginal Cost of Generation Dependency on Reference Boiler Efficiency (Typical values range from 60 to 75 percent)

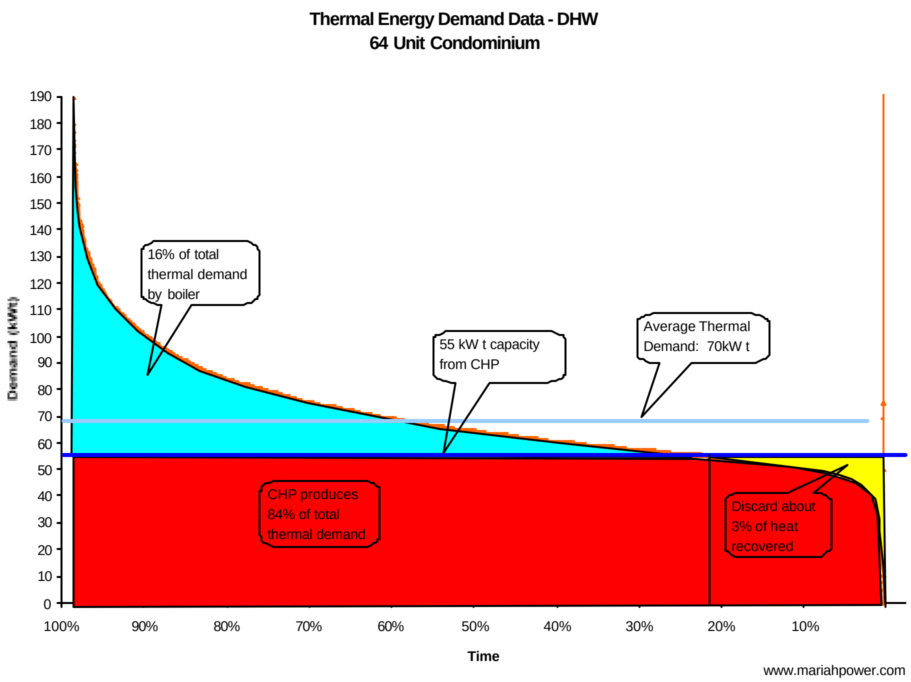


A typical domestic hot water demand profile for a 64 unit apartment building is illustrated in Figure 4-3.

With a single 60/30 Heat PlusPower system installed, providing at least 55 kW thermal energy into the system, the remaining hot water heaters provide heat only during peak times, resulting in less than 16 percent of the total energy consumed. The Heat PlusPower system provides the remaining 84 percent of the domestic hot water energy for the building. For a small portion of time, the Heat PlusPower system heat is not fully required. This amounts to about 3 percent of the energy available and may be discarded through a discretionary load, or the system may be operated at less than maximum output during these times.

The economic performance of CHP systems in general, and the Heat PlusPower family in particular, indicates that emissions reductions and enhanced power security are attainable while saving on energy costs.

Figure 4-3. Typical DHW Demand Profile for a 64 Unit Apartment



4.5. A PARTNER

Mariah Energy Corp. works with utilities and others as a partner or as an advisor in integrating the Distributed Micro-Utility concept into existing operations. Mariah Energy applications engineers can help you to assess the economic viability of potential sites. They can also help you understand the key features of a good host site.

4.6. PRODUCT SPECIFICATIONS

See attached specifications for the 60/30 Heat PlusPower™ and for the 120/60 Heat PlusPower™.

Mariah Energy Corp.

Clean Energy Solutions

60/30 HEAT PLUSPOWER™ SYSTEM

Features

- Clean Heat and Power (CHP)
- 60 kW thermal, 30 kW electric
- High efficiency
- Grid connected or stand-alone
- Automated transfer control
- Load management
- Electrical submetering
- Thermal submetering
- Remote monitoring & diagnostics

Benefits

- Low NOx and CO_2 emissions compared to traditional based generation
- Flexible-fuel: natural gas, propane, diesel, kerosene, propane, ,methane, biogas
- Compact – can fit through a conventional 32" door
- High reliability
- Enhanced power supply security

Applications

- domestic hot water
- process hot water
- process fluids pre-heat
- back-up/stand-by generation
- odor control
- waste gas-fired

Specifications under ISO conditions using Natural Gas fuel (55 psig)

Efficiency:	up to 80% net
Maximum Heat:	60 kW 216 000 kJ/h (205 000 Btu/h)
Hydronic Temperature:	up to 105C (221°F)
Hydronic Flow Rate:	5 m^3/h (21 U.S. gpm)
Fluids:	water, propylene glycol, ethylene glycol
Maximum Power:	30 kW net
Combustion Air:	934.5 m^3/h (550 scfm)
Cooling Air (in grid connect mode):	934.5 m^3/h (550 scfm)
Emissions:	NO_x <9 ppmV @ 15% O_2
Fuel Flow:	440 000 kJ/h (420 000 Btu/h)

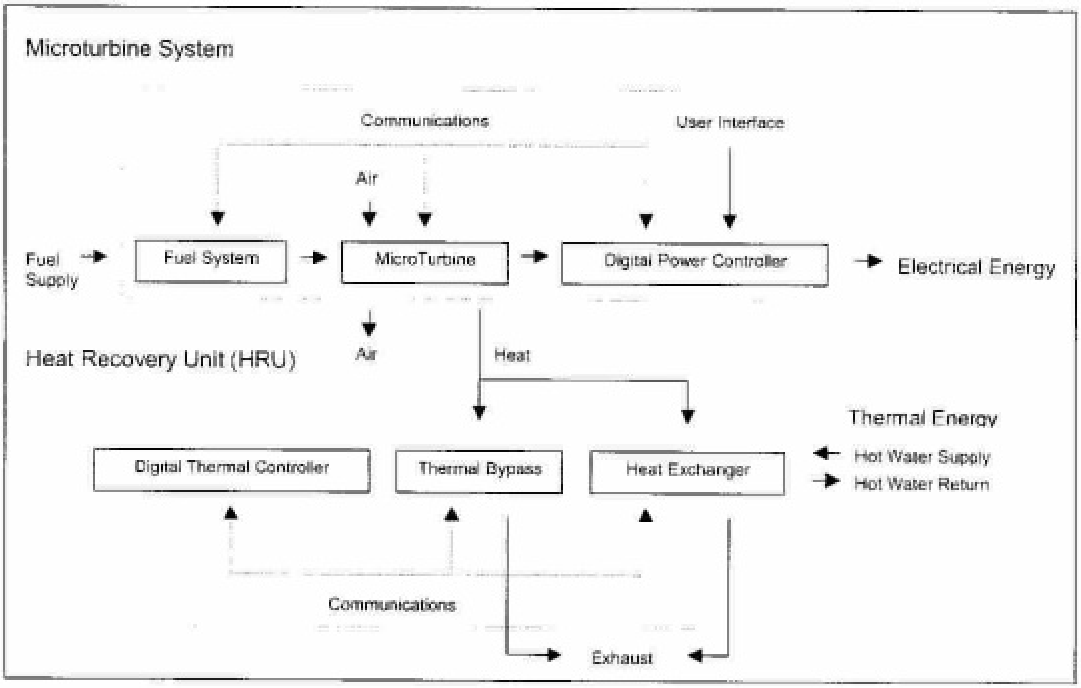
Dimensions: 2337mm (H) x 782mm (W) x 1518mm (D)
Weight: 511 kg (1126 lb)
Noise Level: 70 dBA at 1 m

Note: This information is preliminary. The manufacturer reserves the right to change or modify without notice the design or equipment specifications without incurring any obligation either with respect to equipment previously sold or in the process of construction.

Powered by Capstone MicroTurbine™

A hot water heater that generates electricity

Mariah Energy HEAT PLUSPOWER™ SYSTEM



The Mariah HEAT PLUSPOWER™ package can be thought of as a hot water heater that generates electricity. At the heart of the system is a natural gas-fired microturbine from Capstone Turbine Corporation, the industry leader with a proven track record for low maintenance and reliability. The turbine generates electricity, the Mariah Energy Heat Recovery Unit transfers heat from the exhaust to a working fluid such as water or glycol.

The HEAT PLUSPOWER™ system can run stand-alone or grid parallel. In parallel with the grid, should capacity exceed the demand on-site, additional power can be exported to the utility grid. If the grid fails, the HEAT PLUSPOWER™ system can provide back-up power on-site. Mariah Energy's intelligent control package allows automatic shedding of low-priority loads to ensure that the facility load never exceeds the generator capacity.

Unlike typical 'back-up' power systems, the HEAT PLUSPOWER™ system runs day and night, providing on-going cost savings. The system power is free of spikes and unwanted harmonics and therefore is well suited to today's sophisticated electronics equipment.

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Mariah Energy Corp.

Clean Energy Solutions

120/60 Heat PlusPower™ System

Features

- Clean Heat and Power (CHP)
- 120 kW thermal, 60 kW electric
- High efficiency
- Grid connected or stand-alone
- Automated transfer control
- Load management
- Electrical submetering
- Thermal submetering
- Remote monitoring & diagnostics

Benefits

- Low NOx and CO_2 emissions compared to traditional based generation
- Flexible-fuel: natural gas, propane, diesel, kerosene, propane, ,methane, biogas
- High reliability
- Enhanced power supply security

Applications

- domestic hot water
- process hot water
- process fluids pre-heat
- back-up/stand-by generation
- odor control
- off-spec fuels such as landfill or digester gas

Mariah Energy Corp.

Specifications under ISO conditions using Natural Gas fuel (55 psig)

Efficiency:	up to 80% net
Maximum Heat:	120 kW thermal 432 500 kJ/h (410 000 Btu/h)
Hydronic Temperature:	up to 121C (250°F)
Hydronic Flow Rate:	10 m^3/h (44 U.S. gpm)
Fluids:	water, propylene glycol, ethylene glycol
Maximum Power:	60 kW electric
Combustion Air:	1578 m^3/h (929 scfm)
Cooling Air (in grid connect mode):	1529 m^3/h (900 scfm)
Emissions:	NO_x <9 ppmV @ 15% O_2
Fuel Flow:	918 000 kJ/h (871 000 Btu/h)

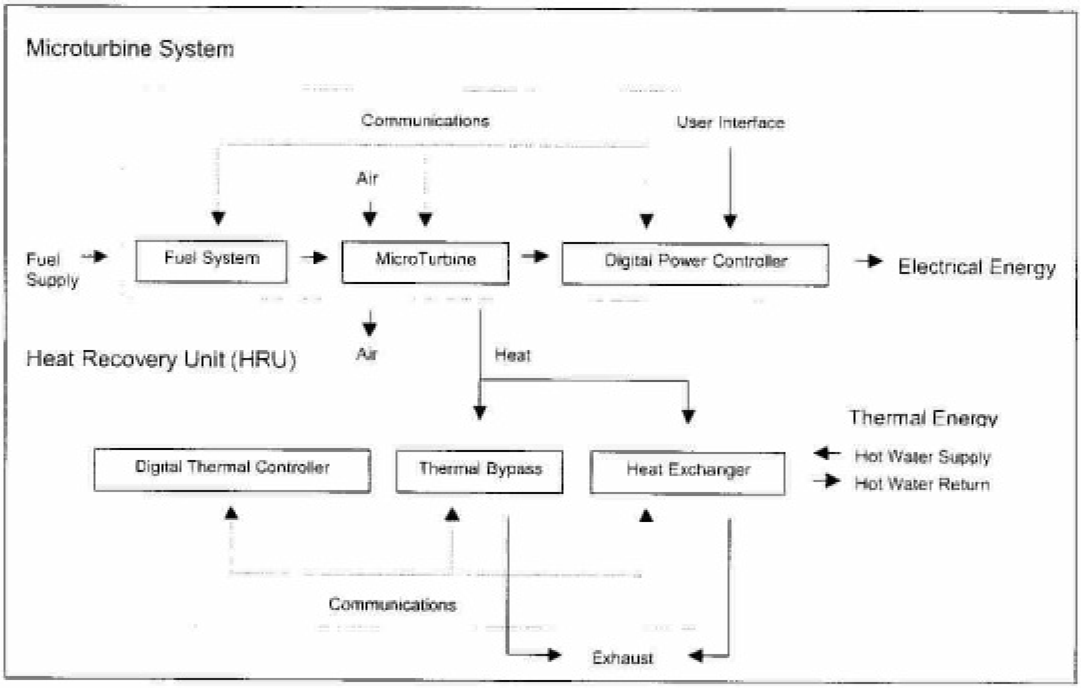
Note: This information is preliminary. The manufacturer reserves the right to change or modify without notice, the design or equipment specifications without incurring any obligation either with respect to equipment previously sold or in the process of construction.

Overall Dimensions:	2298mm (H) x 1067mm (W) x 2031mm (D) (90in (H) x 42in (W) x 80in (D))
Weight:	835 kg (*840 lb)
Noise Level:	70 dBA at 1 m

Powered by Capstone MicroTurbine

A hot water heater that generates electricity

Mariah Energy HEAT PLUSPOWER™ SYSTEM



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The HEAT PLUSPOWER™ system can run stand-alone or grid parallel. In parallel with the grid, should capacity exceed the demand on-site, additional power can be exported to the utility grid. If the grid fails, the HEAT PLUSPOWER™ system can provide back-up power on-site. Mariah Energy's intelligent control package allows automatic shedding of low-priority loads to ensure that the facility load never exceeds the generator capacity.

Unlike typical 'back-up' power systems, the HEAT PLUSPOWER™ system runs day and night, providing on-going cost savings. The system power is free of spikes and unwanted harmonics and therefore is well suited to today's sophisticated electronics equipment.

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APPENDIX A

Model Site Emission Reduction Data

Appendix A-1. Model Site Energy Demand						
	Chicago[1]			Atlanta[1]		
	Thermal		Electric	Thermal		Electric
	Space Heat (kWh_{th})	Water Heater (kWh_{th})	Total (kWh_e)	Space Heat (kWh_{th})	Water Heater (kWh_{th})	Total (kWh_e)
Large Hotel						
January	461,713	73,155	337,681	337,493	73,155	349,151
February	409,706	66,072	305,879	276,397	66,072	317,258
March	313,116	73,301	338,606	175,687	73,301	371,787
April	124,176	70,794	349,496	53,590	70,794	408,361
May	44,858	73,155	403,620	25,361	73,155	452,594
June	14,333	70,940	434,965	6,595	70,940	466,817
July	3,076	73,086	463,709	3,853	73,086	512,255
August	3,745	73,225	451,958	3,608	73,225	501,822
September	24,472	70,801	417,203	11,594	70,801	458,865
October	75,591	73,155	378,381	64,697	73,155	412,427
November	225,906	70,725	332,430	174,975	70,725	366,662
December	405,314	73,163	339,597	297,816	73,163	356,749
TOTAL	2,106,005	861,574	4,553,525	1,431,668	861,574	4,974,747
Medium Hotel						
January	165,713	51,071	163,751	104,715	51,071	169,481
February	148,680	46,126	178,658	83,663	46,126	153,282
March	113,394	51,173	169,359	59,894	51,173	184,280
April	56,983	49,423	177,601	18,604	49,423	199,361
May	24,483	51,071	198,889	8,462	51,071	218,643
June	8,443	49,525	209,047	803	49,525	226,384
July	1,128	51,023	222,193	72	51,023	246,713
August	2,055	51,120	218,133	62	51,120	242,513
September	13,474	49,428	203,370	2,986	49,428	224,190
October	38,411	51,071	188,384	23,622	51,071	200,929
November	85,500	49,374	164,087	57,824	49,374	179,647
December	145,677	51,076	165,262	91,135	51,076	173,611
TOTAL	803,939	601,481	2,228,735	451,843	601,481	2,419,035
Large Office						
January	693,130	20,010	752,056	561,545	20,010	778,604
February	580,291	17,427	664,924	447,578	17,427	673,388
March	457,262	20,277	758,385	312,726	20,277	790,500
April	179,445	19,149	700,087	110,857	19,149	742,425
May	51,814	20,010	738,379	53,924	20,010	717,330
June	23,051	19,416	771,322	20,938	19,416	727,327
July	11,105	19,149	786,691	10,641	19,149	749,351
August	18,805	20,871	845,121	11,641	20,871	809,669
September	41,617	17,694	670,813	26,133	17,694	648,220
October	156,348	20,010	790,076	128,652	20,010	786,979
November	392,232	18,288	715,702	304,215	18,288	752,993
December	612,263	18,555	711,814	479,648	18,555	744,780
TOTAL	3,217,363	230,857	8,905,369	2,468,499	230,857	8,921,566

(continued)

Appendix A-1. Model Site Energy Demand (continued)						
	Chicago[1]			**Atlanta**[1]		
	Thermal		Electric	Thermal		Electric
	Space Heat (kWh_{th})	Water Heater (kWh_{th})	Total (kWh_e)	Space Heat (kWh_{th})	Water Heater (kWh_{th})	Total (kWh_e)
Hospital						
January	956,593	221,069	827,501	601,936	221,069	865,584
February	866,268	199,675	748,641	491,714	199,675	791,995
March	719,324	221,069	841,979	399,010	221,069	941,597
April	412,119	213,938	883,140	218,647	213,938	1,044,246
May	254,757	221,069	1,031,208	170,734	221,069	1,165,262
June	164,989	213,938	1,118,899	124,643	213,938	1,242,013
July	132,046	221,069	1,205,694	108,261	221,069	1,373,359
August	137,235	221,069	1,194,862	110,065	221,069	1,348,535
September	179,441	213,938	1,092,102	125,092	213,938	1,245,341
October	296,527	221,069	968,378	221,285	221,069	1,050,431
November	537,730	213,938	835,591	370,924	213,938	931,599
December	842,638	221,069	835,737	530,803	221,069	894,247
TOTAL	5,499,668	2,602,911	11,583,732	3,473,113	2,602,911	12,894,208

[1] Estimated using data presented in DOE 1995

Appendix A-2. Grid and Boiler CO_2 Emission Rates Used in Computing Emission Reductions

	Chicago[1] (%)	Atlanta[2] (%)
Utility Grid Fuel Mix		
Coal	72.0	55.5
Petroleum	0.7	6.7
Gas	4.4	7.8
Other	0.4	0.7
Nonfossil	22.5	29.2
CO_2 Emission Rate[3] (lb/kWh_e)		
Coal	2.113	2.026
Gas	2.244	1.515
Oil	1.188	1.659
Other	1.124	1.377
Average (weighted based on electricity generation)	1.680	1.334

Natural Gas Boiler

Thermal Efficiency Rating (%)	CO_2 Emission Rate	
	$(lb/kWh)_{th}$	$(lb/kWh)_{fuel\ in}$
50	0.7947	0.3973
70	0.5676	0.3973
80	0.4905	0.3973

1 Based on latest available EIA data, East North Central Region (DOE/EPA 2000)
2 Based on latest available EIA data, South Atlantic Region (DOE/EPA 2000)
3 Represents kWh generated, does not include transmission and distribution losses

Appendix A-3. Space Heating and Water Heating Fuel Types Commonly Used in the Model Regions

Location	Electricity (%)	Natural Gas (%)	Fuel Oil (%)	District Heat (%)
Chicago[1]	36.51	51.79	0[3]	11.69
Atlanta[2]	67.55	27.32	5.13	0[3]

[1] Based on CBEC survey results for East North Central Region (CBEC 2000)
[2] Based on CBEC survey results for South Atlantic Region (CBEC 2000)
[3] Insufficient data

APPENDIX B

Emissions Testing QA/QC Results

Appendix B-1 presents instrument calibration error and linearity checks for each of the analyzers used for emissions testing. These calibrations are conducted once at the beginning of each day of testing, and after any changes or adjustments to the sampling system are conducted (changing analyzer range, for example). All of the calibration error results are within the specifications of the Reference Methods.

Appendix B-2 summarizes the system bias and drift checks conducted on the sampling system for each pollutant quantified. These system calibrations are conducted before and after each test run. Results of all of the calibrations are within the specifications of the Reference Methods.

Appendix B-3 presents the Method 19 Fuel F-factors and exhaust gas flow rates.

Appendix B-4 presents the comparison of emission levels before and after heat recovery unit temperature corrections were made.

Appendix B-1. Summary of Daily Reference Method Calibration Error Determinations

Date:	Gas	Measurement Range	Cal Gas Value	Analyzer Response	System Response	Calibration Error (% of Span)
		(ppm for NO_x, CO, and THC; % for O_2 and CO_2)				
4/2/2001	NO_x	25	0.00	na	0.00	**0.00**
(Runs 1 to 3)			7.00	na	6.95	**-0.20**
			12.00	na	12.10	**0.40**
			22.50	na	22.70	**0.80**
	CO	20	0.00	0.20	na	**1.00**
			7.50	7.70	na	**1.00**
			15.00	15.30	na	**1.50**
	CO_2	20	0.00	0.00	na	**0.00**
			9.90	10.00	na	**0.50**
			17.00	16.80	na	**-1.00**
	O_2	25	0.00	0.00	na	**0.00**
			10.00	10.00	na	**0.00**
			17.00	17.00	na	**0.00**
	THC	30	0.00	na	0.00	**na**
			6.00	na	5.90	**-1.67**
			15.00	na	15.00	**0.00**
			24.00	na	24.00	**0.00**
4/3/2001	NO_x	25	0.00	na	0.00	**0.00**
(Runs 4 to 12)			7.00	na	7.00	**0.00**
			12.00	na	12.00	**0.00**
			22.50	na	22.70	**0.80**
	CO	20	0.00	0.00	na	**0.00**
			7.50	7.70	na	**1.00**
			15.00	15.10	na	**0.50**
	CO_2	20	0.00	0.00	na	**0.00**
			9.90	10.00	na	**0.50**
			17.00	16.80	na	**-1.00**
	O_2	25	0.00	0.00	na	**0.00**
			10.00	10.00	na	**0.00**
			17.00	17.00	na	**0.00**
	THC	30	0.00	na	0.00	**na**
			6.00	na	5.90	**-1.67**
			15.00	na	15.00	**0.00**
			24.00	na	24.00	**0.00**

(continued)

Appendix B-1. Summary of Daily Reference Method Calibration Error Determinations
(continued)

Date:	Gas	Measurement Range	Cal Gas Value	Analyzer Response	System Response	Calibration Error (% of Span)
		(ppm for NO_x, CO, and THC; % for O_2 and CO_2)				
4/4/2001	NO_x	25	0.00	na	0.00	**0.00**
(Additional Load Tests)			7.00	na	6.95	**-0.20**
			12.00	na	12.00	**0.00**
			22.50	na	22.50	**0.00**
	CO	20	0.00	0.00	na	**0.00**
			7.50	7.70	na	**1.00**
			15.00	15.10	na	**0.50**
	CO_2	20	0.00	0.00	na	**0.00**
			9.90	10.00	na	**0.50**
			17.00	16.80	na	**-1.00**
	O_2	25	0.00	0.00	na	**0.00**
			10.00	10.00	na	**0.00**
			17.00	17.00	na	**0.00**
	THC	30	0.00	na	0.00	**na**
			6.00	na	5.90	**-1.67**
			15.00	na	15.00	**0.00**
			24.00	na	24.00	**0.00**

Appendix B-2. Summary of Reference Method System Bias and Drift Checks

Analyzer Spans: NO_x = 25 ppm, CO = 20 ppm, THC = 30 ppm, CO_2 = 20%, O_2 = 25%

Run Number:		Initial	1	2	3	4	5	6	7	8	9	10	11	12
NO_x Zero	System Response (ppm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4
	System Error (% span)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	1.6
	Drift (% span)	na	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0
NO_x Mid	System Response (ppm)	12.1	12.0	11.9	12.0	12.1	12.0	12.0	12.0	12.0	12.2	12.4	22.5	22.4
	System Error (% span)	0.2	0.1	-0.4	0.0	0.4	0.0	-0.2	0.0	0.0	0.8	1.6	0.0	-0.4
	Drift (% span)	na	-0.1	-0.5	0.4	0.4	-0.4	-0.2	0.2	0.0	0.8	0.8	0.0	-0.4
CO_2 Zero	System Response (%)	0.0	-0.4	-0.4	-0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	System Error (% span)	0.0	-2.0	-2.0	-2.0	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Drift (% span)	na	-2.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0
CO_2 Mid	System Response (%)	10.0	9.9	9.9	9.9	10.1	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
	System Error (% span)	0.0	-0.5	-0.5	-0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Drift (% span)	na	-0.5	0.0	0.0	1.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O_2 Zero	System Response (%)	0.00	0.00	0.00	0.00	0.00	-0.01	-0.02	-0.02	-0.02	-0.02	-0.02	-0.03	-0.02
	System Error (% span)	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
	Drift (% span)	na	0.0	0.0	0.0	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0	-0.1	0.1
O_2 Mid	System Response (%)	10.00	10.00	10.00	10.00	10.10	10.10	10.15	10.15	10.15	10.12	10.11	10.13	10.12
	System Error (% span)	0.0	0.0	0.0	0.0	0.4	0.4	0.6	0.6	0.6	0.5	0.4	0.5	0.5
	Drift (% span)	na	0.0	0.0	0.0	0.5	0.0	0.3	0.0	0.0	-0.2	0.0	0.1	-0.1
CO Zero	System Response (ppm)	0.2	-0.3	-0.5	-0.3	0.2	-0.1	-0.1	-0.3	-0.2	-0.3	-0.3	-0.3	-0.3
	System Error (% span)	1.0	-1.5	-2.5	-1.5	1.0	-0.5	-0.5	-1.5	-1.0	-1.5	-1.5	-1.5	-1.5
	Drift (% span)	na	-2.5	-1.0	1.0	2.5	-1.5	0.0	-1.0	0.5	-0.5	0.0	0.0	0.0
CO Mid	System Response (ppm)	7.7	7.3	7.4	7.3	7.4	7.3	7.3	7.5	7.4	7.5	7.5	7.4	7.4
	System Error (% span)	1.0	-1.0	-0.5	-1.0	-0.5	-1.0	-1.0	0.0	-0.5	0.0	0.0	-0.5	-0.5
	Drift (% span)	na	-2.0	0.5	-0.5	0.5	-0.5	0.0	1.0	-0.5	0.5	0.0	-0.5	0.0
THC Zero*	System Response (ppm)	0.0	-0.5	-0.6	-0.7	-1.8	-1.8	-1.8	-1.8	-1.8	-1.7	-1.3	-1.5	-0.5
THC Mid	System Response (ppm)	15.0	14.3	14.3	14.2	14.5	14.5	14.8	14.6	14.7	14.6	14.8	15.0	15.0
	System Error (% span)	0.0	-2.3	-2.3	-2.7	-1.7	-1.7	-0.7	-1.3	-1.0	-1.3	-0.7	0.0	0.0
	Drift (% span)	na	-2.8	0.0	-0.4	1.2	0.0	1.2	-0.8	0.4	-0.4	0.8	0.8	0.0

* Reference Method 25A for THC determinations specifies system error and drift criteria for mid-level calibrations only.
na = not applicable

Appendix B-3. Method 19 Fuel F-factors and Exhaust Gas Flow Rates

Run Number	Electrical Power Delivered (kW_e)	Heat Input (MMBtu/hr)	Fuel F-factor[a] Dscf/MMBtu)	Calculated Exhaust Gas Flow Rate[b] (dscf/min)
1	28.45	0.3927	8532	410.9
2	28.29	0.3911	8532	413.6
3	28.32	0.3905	8532	413.0
AVG	**28.35**	**0.3914**	**8532**	**412.5**
4	26.44	0.3668	8532	400.8
5	26.47	0.3657	8532	407.1
6	26.32	0.3668	8532	392.1
AVG	**26.41**	**0.3664**	**8532**	**400.0**
7	22.04	0.3139	8532	345.6
8	22.05	0.3129	8532	343.1
9	22.05	0.3107	8532	351.1
AVG	**22.05**	**0.3125**	**8532**	**346.6**
10	14.54	0.2281	8532	288.4
11	14.52	0.2281	8532	290.9
12	14.53	0.2281	8532	289.7
AVG	**14.53**	**0.2281**	**8532**	**289.7**

[a] Calculated using composition of collected fuel gas
[b] Calculated using Method 19

Appendix B-4. Comparison of Emission Levels

Test Condition (% Load)	NO_x Concentrations (ppmvd @ 15 % O_2)		CO Concentrations (ppmvd @ 15 % O_2)		THC Concentrations (ppmvd @ 15 % O_2)		CO_2 Concentrations (%)		O_2 Concentrations (%)	
	April 2-3	April 4-5	April 2-3	April 4-5	April 2-3	April 4-5	April 2-3	April 4-5	April 2-3	April 4-5
100	4.27	4.25	4.96	7.74	0.35	0.49	1.55	1.32	18.08	18.08
90	3.50	3.74	5.80	8.76	1.70	0.61	1.36	1.31	18.18	18.14
75	2.65	3.06	10.7	14.8	1.90	1.31	1.24	1.22	18.22	18.26
50	79.1	79.0	25.0	49.9	1.40	3.65	1.05	1.05	18.56	18.54

Appendix C. Verification Test Schedule

Load Testing			
Date	**Time**	**Test Condition**	**Verification Parameters Evaluated**
04/02/01	01:30pm - 03:48pm	Official 100 % Load Tests, three 30-minute test runs	NO_X, CO, THC, CO_2, O_2 emissions, and electrical, thermal, and total efficiency
04/03/01	08:40am - 12:18pm	Official 90 % Load Tests, three 30-minute test runs	
04/03/01	12:45pm - 02:55pm	Official 75 % Load Tests, three 30-minute test runs	
04/03/01	03:15pm - 05:27pm	Official 50 % Load Tests, three 30-minute test runs	
04/04/01	10:35am - 12:43pm	Official 100 % Repeat Load Tests, heat recovery unit temperature errors fixed, 30-minute test runs	
04/04/01	03:15pm - 04:50pm	Additional Load Test - Non-standard load testing between 40 and 100 percent (5 to 10 minute test runs)	
04/05/01	08:45am - 10:10am	Official 90, 75, and 50 % Repeat Load Tests - Heat recovery unit temperature errors fixed, 30 minute test runs	Electrical, thermal, and total efficiency

Extended Test Period		
Date	**Time**	**Verification Parameters Evaluated**
4/07/01	06:00 am - 03:18pm	Total electricity generation, total heat recovered, electrical, thermal, and total efficiency, power quality, and emission reductions
4/11/01	01:53pm - 08:26pm	
4/12/01	09:31am - 11:06pm	
4/16/01	07:52am - 11:59pm	
4/17/01	12:00am - 11:59pm	
4/18/01	12:00am - 11:59pm	
4/19/01	12:00am - 11:59pm	
4/20/01	12:00am - 11:59pm	
4/21/01	12:00am - 03:19pm	
4/23/01	08:11am - 11:59pm	
4/24/01	12:00am - 11:59pm	
4/25/01	12:00am - 11:59pm	
4/26/01	12:00am - 04:37pm	
4/27/01	07:50am - 04:31pm	
4/30/01	07:44am - 11:59pm	
5/02/01	12:00am - 11:59pm	
5/04/01	12:00am - 11:59pm	
5/05/01	12:00am - 11:59pm	
5/06/01	12:00am - 11:59pm	
5/07/01	12:37am - 11:59pm	
5/08/01	12:00am - 11:59pm	
5/09/01	12:00am - 11:59pm	
5/10/01	12:00am - 11:59pm	
5/11/01	12:00am - 11:59pm	
5/12/01	12:00am - 11:59pm	
5/13/01	12:00am - 11:59pm	
5/14/01	12:00am - 11:59pm	
5/15/01	12:00am - 11:59pm	
5/16/01	12:00am - 11:59pm	
5/17/01	12:00am - 11:59pm	
5/18/01	12:00am - 11:59pm	
5/19/01	12:00am - 11:59pm	
5/20/01	12:00am - 11:59pm	
5/21/01	12:00am - 11:01am	
5/22/01	05:59am - 11:59pm	
5/23/01	12:00am - 11:59pm	
5/24/01	12:00am - 11:59pm	
5/25/01	12:00am - 07:42am	