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Pacific Northwest National Laboratory
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M. Friedrich
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U.S. Department of Energy
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Federal Energy Management Program
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and the
U.S. Army Forces Command
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Pacific Northwest National Laboratory
Richland, Washington

Executive Summary

Escalating energy costs and concerns about electric system reliability, most notably in California and the Northeast, have heightened interest in small-scale power generation as an alternative to dependence on the power grid. Natural gas-fired microturbines can provide both electricity and thermal energy when equipped with a cogeneration package, and they have great overall system efficiencies and low emissions.

In FY 2001, the U.S. Army Forces Command (FORSCOM), with technical assistance from Pacific Northwest National Laboratory, successfully competed for a Federal Energy Management Program (FEMP) Call for Distributed Energy Resources grant to support the demonstration of a small-scale, combined heat and power-configured microturbine system. The demonstration was hosted by the Fort Drum Department of Public Works. Additional support was provided by FORSCOM, the FEMP New Technology Demonstration activity, and the U.S. Army Corps of Engineers-Construction Engineering Research Laboratory.

The purpose of the project was to demonstrate and evaluate a combined heat and power-configured microturbine system. The project planned to reduce costs for both electrical energy and electrical demand, reduce environmental emissions, and improve military readiness. The system was designed to supplant a fraction of electrical grid-supplied power and demand while operating in grid-dependent mode. While in grid-independent mode, the system was to be a source of electrical power to operate natural gas-fired boilers in the barracks and handle other minimal loads. The system also provided a portion of the domestic hot water for the barracks and kitchen.

Fort Drum is a 107,000-acre U.S. Army facility located in New York's North Country region a few miles east of Watertown. The Fort consists of over 1,350 buildings totaling more than 7.6 million square feet, and another 7.2 million square feet is family housing facilities.

The Fort Drum microturbine system was installed in the mechanical room of a 500-man barracks and administration complex with full dining facilities. The system included a Capstone 30-kW recuperated microturbine and a micoGen™ plate/fin-type heat recovery heat exchanger. It used natural gas to produce electricity from the microturbine and used the exhaust gas to heat domestic hot water for the barracks and dining hall.

The electrical output was monitored from startup in May 2002 through July 2003. The heat exchanger output was monitored from September 2002 through July 2003. This report assesses the efficiency of the microturbine and measures gas emissions, noise level, power quality, microturbine electric power output, and heat exchanger thermal power output over varying operating conditions.

Results

One-time tests were performed to determine the sound levels, emissions, and power quality. Measurements of sound indicated 58 dBA at 33 feet, 74 dBA at 18 feet and 85 dBA at 1 foot. Measurements of nitrous oxide (NOx) emissions were 1.5 ppm NOx (at 18% O_2) at full load operation and less than 20 ppm at partial load. Carbon monoxide (CO) emissions were also measured, though not given in manufacturer's specifications, and were found to be 10 ppm (at 18% O_2) at full load operation and less than 100 ppm at partial load. Data support that the microturbine does not degrade electrical power quality in the building.

Operational performance measurements of electrical capacity at varying air inlet temperature found the microturbine to track specifications very closely, while electrical generating efficiency did not fall as rapidly as the specification does with an increase in temperature and was almost 21% at 33°C (specification is 19.6% at 33°C). The heat recovery during operation followed the manufacturer's specifications with deviations up to 15%. The overall system efficiency average was 80% of fuel higher heating value (HHV) when the system was functioning without faults.

The total energy dollars saved at Fort Drum was calculated to be approximately $2,670 per year for the first year. The savings would have been higher if the system had been available for operation a larger percentage of the time and if it had been operating without faults. However, the purpose of this demonstration was to validate efficiency performance, not to justify Life Cycle Cost (LCC) at Fort Drum. The savings associated with operating the microturbine include the reduction in utility-supplied electricity and peak demand–plus the value of the recovered waste heat minus the cost of the natural gas consumed by the microturbine.

The demonstration was affected by numerous operations and maintenance problems. Natural gas was delivered to the building at 15 psig, and the fuel gas compressor elevated that pressure to 55 psig for use by the microturbine. During the one year of operation, the system required four replacement compressors. Until the reliability of fuel gas compressors is improved, microturbines of this type should be installed only where 55 psig natural gas is available. In addition, there were repeated circuit board failures of the fuel gas compressor controller, the modem, and the heat recovery heat exchanger.

Acknowledgments

The authors would like to thank Steve Rowley, energy manager, and Gordon Greene, Chief, JOC/Utility at Fort Drum, for their assistance, energy, and time in making this demonstration a success; John Ashcroft, owner of JW Mechanical, for assisting beyond the scope of his contract; and Steven Parker (PNNL) for his guidance in the conduct of the project. We would also like to thank Steve Jackson (FORSCOM), Ted Collins (FEMP), and Shawn Herrera (FEMP) for their programmatic support of this technology demonstration.

Acronyms and Abbreviations

Btu	British thermal units
CERL	U.S. Army Construction Engineering Research Laboratory
CFM	cubic feet per minute
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
C_p	specific heat
dB	decibel
dBA	decibel measurement using “A” weighted scale
DDC	direct digital controls
DER	distributed energy resources
DHW	domestic hot water
DOE	U.S. Department of Energy
dP	differential pressure
FEMP	Federal Energy Management Program
FORSCOM	U.S. Army Forces Command
FS	full scale
GPM	gallons per minute
h	hour
HHV	higher heating value
HP	horse power
inWC	inches water column
ISO	International Organization for Standardization
kW	kilowatt
LHV	lower heating value
LMTD	log-mean temperature difference
mBar	millibar
MT	microturbine
NOx	nitrous oxides
NTU	number of transfer units
O_2	oxygen
P	pressure
PNNL	Pacific Northwest National Laboratory
ppm	parts per million
psig	pounds per square inch gauge
ρ	density
Rdg	reading
RHX	recovery heat exchanger
RTD	resistance temperature detector

SCF	standard cubic foot
SOW	statement of work
T	temperature
THD	total harmonic distortion
U	overall heat transfer coefficient
UA	U times the Area (heat exchanger specification)
VAC	volts alternating current
vf	volumetric flow

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1.0 Introduction

Escalating energy costs and concerns about electric system reliability, most notably in California and the Northeast, have heightened interest in small-scale power generation as an alternative to dependence on the power grid. This demonstration project supports the U.S. Army's desire to successfully demonstrate new technologies on their installations and the U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP) New Technology Demonstration activity's mission to demonstrate new energy-saving technologies at federal facilities.

The demonstration was cosponsored by the DOE Federal Energy Management Program and the U.S. Army Forces Command (FORSCOM). Technical assistance was provided by the Pacific Northwest National Laboratory (PNNL) and the U.S. Army Corps of Engineers, Energy Research and Development Center (ERDC), Construction Engineering Research Laboratory (CERL). On site support and coordination was provided by the Department of Public Works' Energy Branch at the host site, Fort Drum, New York.

The purpose of this technology demonstration was to verify the field performance of a microturbine in a combined heat and power configuration. The U.S. Army received an award from the 2001 FEMP call for projects in the amount of $100,000 to cover the purchase, design, installation, and maintenance contract, which was used for this technology demonstration. This amount ($100,000) best reflects the overall cost of the project excluding the additional costs associated with the nature of a demonstration project. The microturbine was purchased by CERL through an existing contract mechanism. JW's Mechanical, located in Carthage, New York, was contracted to furnish, install, and maintain the combined heat and power microturbine for the demonstration at Fort Drum.

Microturbines are a new form of distributed generation device manufactured and marketed in the United States. They can provide both electricity and thermal energy (when equipped with a cogeneration package) with good overall system efficiencies. Natural gas-fired microturbines have the potential to deliver multiple benefits, particularly when configured for cogeneration.

The Fort Drum system included a Capstone 30-kW recuperated microturbine that was capable of both grid-parallel and grid-independent operation and a micoGen™ heat recovery unit. The system was installed in Building P-175, which is a 119,000-square foot, 500-man barracks and administration complex with full (three meals per day) dining facilities. The system used natural gas to produce enough electricity to supplant a fraction of the grid-supplied electricity and used the cogenerated heat for domestic hot water (DHW). A step-down transformer reduced the microturbine generator's 480-volt, three-phase output to 208-volt, three-phase to match the barracks electrical distribution system. The microturbine exhaust was ducted to a micoGen plate/fin-type heat exchanger to preheat domestic hot water for the barracks and dining hall. Based on utility tariffs and costs of both electricity and natural gas, Fort Drum was identified as one of the most suitable sites within FORSCOM for this installation. Operational data were collected to demonstrate the performance of the technology for military and other installations. The system's energy performance was monitored by PNNL staff under the FEMP New Technology Demonstration activities. That performance is assessed and reported in this document.

Grid failure initiates a microturbine shutdown and disconnection from the grid. Restart is delayed for approximately five minutes. Upon restart, the microturbine will function in grid-independent mode, with the generated electricity serving only dedicated circuits, including lighting within the mechanical room, natural gas-fired boilers, and a hot-water circulation pump that provides space conditioning for the barracks. Restoration of grid power causes the microturbine to shut down and to restart in grid-parallel mode.

The following are some of the benefits generally attributed to distributed generation and combined heat and power systems:

- Reduced consumption of grid-supplied electrical energy
- Reduced grid-supplied electrical demand
- Reduced costs for both electrical energy and electrical demand
- Reduced environmental emissions
- Increased electrical system reliability
- Improved readiness capability.

This report describes the installed cogeneration equipment and its interface with Building P-175's existing DHW and electrical systems. The instrumentation used for performance verification is also described. Actual performance, based on continuous monitoring and one-time tests, is analyzed and documented. Performance measured under field conditions is compared with rated performance, operational experience is summarized, and recommendations are made for improved commissioning, operation, and efficiency.

2.0 Microturbine and Heat Exchanger System

The equipment procured and used in this demonstration includes a Capstone Turbine Corporation model 330 low-pressure, natural gas-fired microturbine and a Unifin International micoGen model MG1-C1 heat-recovery, heat-exchanger system. The micoGen MG-C1 is specifically designed for integration with the Capstone model 330 microturbine. The manufacturers' equipment specifications are shown Tables 2.1 and 2.2.

Table 2.1. Microturbine Specifications at Full Power and ISO[(a)]

Capstone	Model 330
Full-load power output at ISO	28 kW electrical
Output voltage	400-480 VAC
Electrical frequency	50/60 Hz, 3-phase
Efficiency at ISO	26 % LHV (23% HHV)
Natural gas consumption	122 kW HHV
Exhaust gas Temperature	261°C
Exhaust gas energy	85 kW thermal
NOx production	<9 ppm @ 15% O_2
Sound level	58 dBA @ 10 m
Weight	490 kg
(a) International standard temperature, 15˚C, and pressure, 1 atmosphere.	

Table 2.2. Heat Exchanger Specifications with Capstone 330 at Full Power

Unifin micoGen	MG1-C1
Gas side flow rate	1096 kg/hr
Water side flow rate	0.63-3.15 L/sec
Gas side differential Pressure (max)	76 mm H_2O
Water side differential Pressure (max)	11 m H_2O
Maximum water inlet Temperature	93°C
Maximum water outlet Temperature	93°C
Heat recovery	41-73 kW thermal
Electric power consumption	1.1 kW

The equipment was placed inside the existing boiler room, which had ample space for installation. Room revisions included pouring an elevated concrete pad for the microturbine, removing an old insulated water storage tank, purchasing and installing a new 1000-gallon insulated water storage tank, plumbing an existing 1200-gallon storage tank, rewiring the emergency electrical panel, and purchasing and installing a step-down transformer to reduce the microturbine generator's 480-volt, three-phase output to 208-volt, three-phase to match the barracks' electrical distribution system. The system layout is shown schematically in Figure 2.1 and pictured in Figure 2.2.

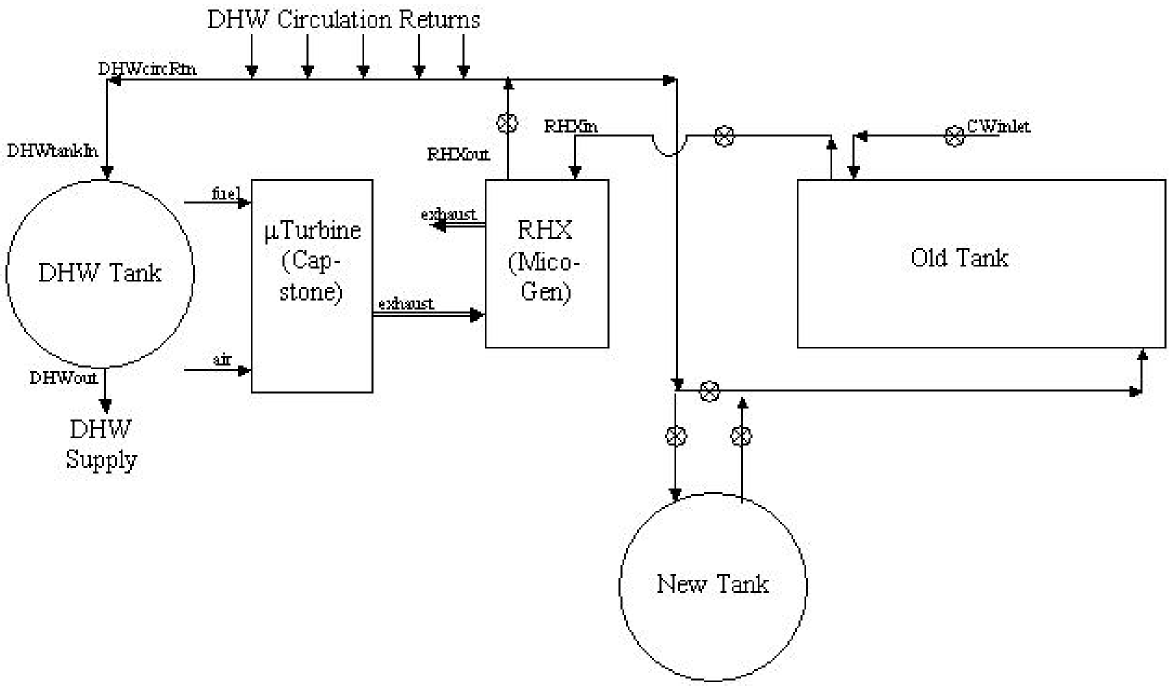

Figure 2.1. Layout of Microturbine, Heat Exchanger, Tanks, and Circulation Loop

Figure 2.2. Installation of Microturbine and Heat Exchanger

The system was configured to use the microturbine's electrical output as backup power to boiler room equipment when the electric grid goes down and to supplement the grid when it is active. The existing direct digital control (DDC) system was programmed to start boiler room equipment in case of an electrical grid outage. This equipment includes a 15-HP main circulation pump for building heating, one natural gas-fired boiler for building heat, one DHW boiler, boiler room lights, and a DHW circulation pump.

The heat-recovery, heat-exchanger (RHX) system is designed to heat water to 49°C (120°F) for DHW. Cold makeup water is preheated through a continuous closed-loop system with a storage capacity of 2250 gallons. A 1000-gallon DHW system draws from this loop and further heats the water to 60°C (140°F) for delivery to the barracks and kitchen DHW system.

A turbine is a constant-volume flow device, but its performance depends on mass flow. Therefore, the density of the inlet air, which is a function of its temperature and pressure (altitude), affects the performance of the system. The microturbine used in this demonstration is rated to produce 28 kW at standard conditions (15°C, sea level) but is constrained by actual turbine inlet air density and gas inlet pressure. The performance (output capacity) of the microturbine will be less than 28 kW if the turbine is installed at an elevation above sea level and when the temperature rises above 15°C. The temperature and elevation deratings are given in Appendix C. The installation at Fort Drum was inside a warm boiler room, so an outside air vent was installed near the turbine to provide cooler air at the microturbine air inlet.

Natural gas is delivered to the building at 15 psig. The low-pressure natural gas microturbine model includes a gas booster compressor that degrades the performance of the microturbine by 2 kW at standard conditions. If 55-psig natural gas could be obtained from the utility, the high-pressure natural gas model could be used, and there is an increase not only in electrical output but also in system reliability. Capstone makes models that will operate on gaseous fuels with heat contents ranging from 700 Btu/SCF to 2516 Btu/SCF (natural gas, methane, ethane, propane). They also make a low Btu fuel model that will operate on high-pressure gaseous fuels that are between 350 and 700 Btu/SCF (landfill or digester gas).

3.0 Metering for Performance Verification

3.1 Data Collection

Instrumentation was installed and data collected to assess the efficiency of the microturbine (fuel energy in/electric + heat energy out) and to measure gas emissions (CO, NOx), noise level, power quality, microturbine electric power output, and heat exchanger thermal power output over varying operating conditions. Figure 3.1 shows all the measuring points used in the performance verification.

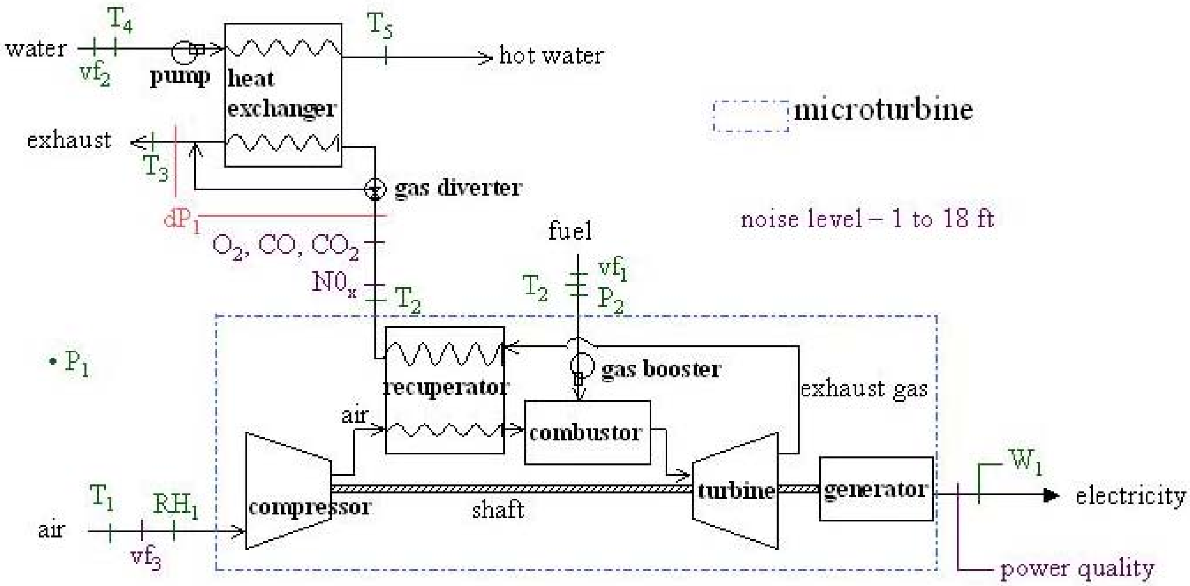

Figure 3.1. Data Collection for Performance Verification

To calculate the efficiency of the microturbine, the fuel energy in and the electric energy and water heating energy out needed to be measured. The volumetric flow rate, pressure, and temperature of the fuel were measured to calculate the mass flow of fuel. The higher heating value (HHV) of the fuel was obtained from the natural gas utility. We were not able to obtain information regarding the composition of the fuel, so the lower heating value (LHV) was estimated to be the higher heating value (HHV) divided by 1.1. (This is the assumption made by Capstone in their specifications.) A watt transducer was used to measure power out of the microturbine. The volumetric flow rate and temperature differential of the water in the recuperative heat exchanger were measured to calculate the heat recovered by the heat exchanger. The specific heat of the water was assumed to be constant in the heat exchanger.

The gas exit flow rate of the microturbine was to be measured so that a mass and energy balance could be done on the system for error-of-measurement calculations. However, because no mass flow meter exists for combustion exhaust gas, both a combustion analyzer and volumetric flow meter would be needed to determine the mass flow of the exhaust. The cost of those two instruments was beyond the project's budget, however, so that measurement was not made.

The inlet and outlet water temperatures and inlet and outlet gas temperatures of the heat recovery heat exchanger (RHX) were also measured to calculate the log-mean temperature difference (LMTD), effectiveness, number of transfer units (NTU), and overall heat transfer coefficient times the area (UA) of the heat exchanger. A gas differential transducer was installed to measure the gas pressure drop across the heat exchanger. This measurement can be used to measure back pressure on the microturbine and show fouling on the tubes. Technical difficulties were experienced with the transducer; therefore, these data were not collected.

The pressure and temperature of the fuel as well as the temperature, humidity, and pressure of the air were measured to assess their effect on the performance of the microturbine. Figure 3.2 shows the gas piping and measurement layout and Figure 3.3 shows the final gas metering installation.

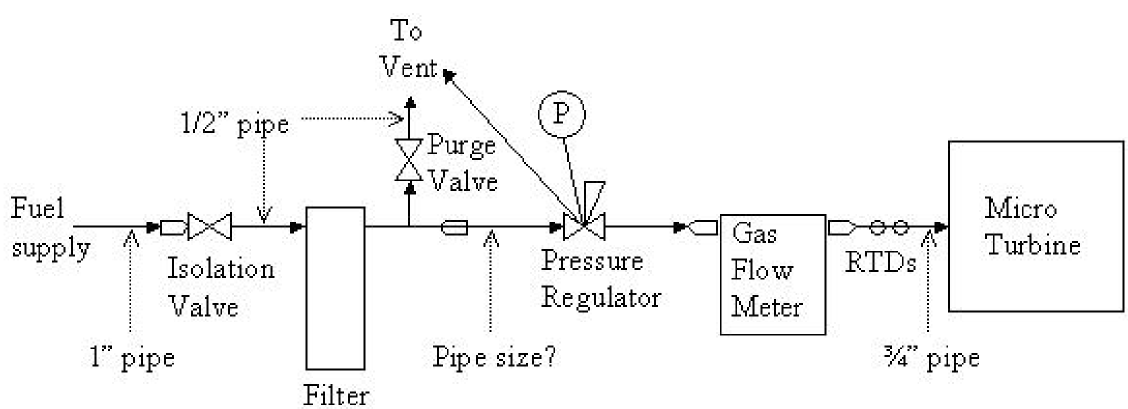

Figure 3.2. Gas Piping Schematic

All of the data collected on the data acquisition system were sampled at a rate of 0.2 Hz (once every 5 seconds) and at an aggregating and logging rate of once every 5 minutes. The sensors are described by function in Table 3.1.

Figure 3.3. Volumetric Flow Meter with Gas Temperature and Pressure Sensors at the Outlet (Right-Hand Riser) and Filter Situated on the Inlet Line (Left-Hand Riser)

Table 3.1. Equipment List for Performance Monitoring

Sensor Measurement	Manufacturer	Model	Unit	Accuracy
Air temperature at inlet	CS Gordon	Type T, special limits	°C	0.2°C
Air relative humidity	Vaisala	HMD-30YB	%RH	1.5% RH
Air flow meter (dP)	Setra	264	inWC	0.005 inWC
Atmospheric pressure	Setra	270	mBar	5.5 mBar
Fuel flow meter	American	AL-898	ACFM	0.5% of rdg
Fuel delivery temperature	CS Gordon	Type T, special limits	°C	0.2°C
Fuel delivery pressure	Setra	206	psig	0.1 psig
Water flow/Btu meter	Niagara/Hersey	413/7437	gpm/kBtu	1% FS
Water temperature	CS Gordon	Type T, special limits	°C	0.2°C
Watt meter	Veris/Hawkeye	H6005	kW	0.2 kW
RHX gas differential pressure	Setra	264	inWC	0.1 inWC
Exhaust temperature	Eustis	Type T, special limits	°C	0.2°C
Data acquisition system	Campbell Scientific	CRX-10 & AM25T	-	-
Power quality	Fluke	41	% of 1st	1% FS
Exhaust gas NOx	Enerac	3000	ppm	1 ppm
Exhaust gas CO	Enerac	3000	ppm	5% of rdg
Exhaust gas O_2	Enerac	3000	%	1%
Notes: ACFM = actual cubic feet per minute kW = kilowatts electricity RH = relative humidity inWC = inches water column rdg = reading FS = full-scale				

3.2 Data Reduction

A short program was written to aggregate the data over an hour and print them out to a new file. The temperature sensors had intermittent ground loop problems that caused over-range signals (indicated by -6999). The aggregation file ignored the bad data and only aggregated valid temperature readings.

The hourly data were then loaded into a spreadsheet and the following calculations made:

RHX heat recovery (kW) = vf_w*0.0037854 m^3/gal*ρ_w*Cp_w*dT_w/60 s/min

RHX LMTD (C) = (Tgasin-Twout)-(Tgasout-Twin)/ln ((Tgasin-Twout)/(Tgasout-Twin))

RHX UA (kW/°C) = RHX heat recovery/RHX LMTD

RHX Effectiveness = (Tgasin - Tgasout)/(Tgasin - Twin)

Cmax (kW/°C) = $mdot_w$* Cp_w

Cmin (kW/°C) = Cmax * (Twout-Twin)/(Tgasin-Tgasout)

RHX NTU = RHX UA/Cmin

SCFMgas (cfm) = ACFMgas *Pgas/14.695 * 273/Tgas

Fuel in power (kW) =SCFMgas * 60 min/hr * HHVgas/3.413 Btu/W

Efficiency of microturbine = electric P/fuel in power

Efficiency of RHX = RHX heat recovery/fuel in power

Efficiency of system = (electric P + RHX heat recovery)/fuel in power

where

vf_w is the water volumetric flow rate in gallons per minute

ρ_w is the water density in kg/m^3

Cp_w is the water specific heat for inlet conditions in J/kg-K

dT_w is the water differential temperature (°C)

Tgasin is the temperature of the exhaust gas into the heat exchanger (°C)

Twout is the temperature of the water out of the heat exchanger (°C)

Tgasout is the temperature of the exhaust gas out of the heat exchanger (°C)

Twin is the temperature of the water into the heat exchanger (°C)

$mdot_w$ is the water mass flow rate in kg/hr

ACFMgas is the actual volumetric flow of natural gas in cubic feet per minute

Pgas is the absolute pressure of the natural gas (psia)

Tgas is the temperature of the natural gas (K)

HHVgas is the monthly average higher heating value of the gas given by the utility (Btu/ft^3)

Electric P is the electric power out of the microturbine (kW).

4.0 One-Time Test Performance

In the spring of 2002, the turbine was operated manually to obtain performance data at a series of partial load operating points. In addition to the variables measured by the PNNL data acquisition system, several one-time measurements were made to characterize emissions, combustion efficiency, and inlet air flow. The results of these tests are reported in this section.

4.1 Average Input, Output, and Inferred Losses

The values measured by the data acquisition system and associated derived values are reported in Table 4.1 for six periods of quasi-steady operation. Electrical efficiency was measured two ways. The first is from the combustion analysis based on measured intake air and exhaust temperatures and excess air percent based on exhaust oxygen (O_2) content. The second is electrical output divided by the higher heating value of fuel.

The last five rows express the outputs and losses as a percent of the fuel HHV input. The HHV is assumed to be 1006 Btu/ft^3 (utility monthly average). The first four of these numbers come directly from the kBtu values reported earlier in the table. The last row expresses the sum of electrical and heat exchanger output, i.e., the combined thermal and electrical outputs, as a percent of input. This is defined as CHP overall efficiency.

Table 4.1. Average Input, Output, and Inferred Losses for Quasi-Steady Operation

Description (units)	Percent Full Load					
	100%	**86%**	**75%**	**56%**	**37%**	**18%**
Electric output (kW)	26.6	22.9	19.9	14.8	9.8	4.8
Energy Balance (units)						
Fuel input [HHV] (kBtu/hr)	429	377	341	283	218	159
Heat recovered [RHX] (kBtu/hr)	233	208	185	152	122	49
Electric output (kBtu/hr)	91	78	68	51	33	16
Jacket loss [approx.] (kBtu/hr)	77	64	64	68	51	77
Exhaust loss [approx] (kBtu/hr)	28	27	24	12	11	16
Efficiency(1)						
Heat recovered	54.3%	55.1%	54.3%	53.7%	56.0%	31.0%
Electric output	21.2%	20.7%	19.9%	17.9%	15.4%	10.4%
Jacket loss	17.9%	17.0%	18.8%	21.4%	23.5%	48.6%
Exhaust loss	6.5%	7.2%	7.0%	4.2%	5.1%	10.1%
Overall CHP efficiency(2)	75.5%	75.9%	74.3%	71.6%	71.4%	41.4%

(1) Efficiency calculations based on fuel higher-heating value.
(2) Overall CHP efficiency determined as:
= [(electricity generated) + (heat recovered)]/(fuel input)

A comparison between the Capstone specifications and the test data for partial load efficiency is shown in Figure 4.1. The Capstone data was modified to account for air pressure and temperature derating at the test conditions. As you can see, the microturbine efficiency decreases only 17% with a 50% reduction in electrical power generation.

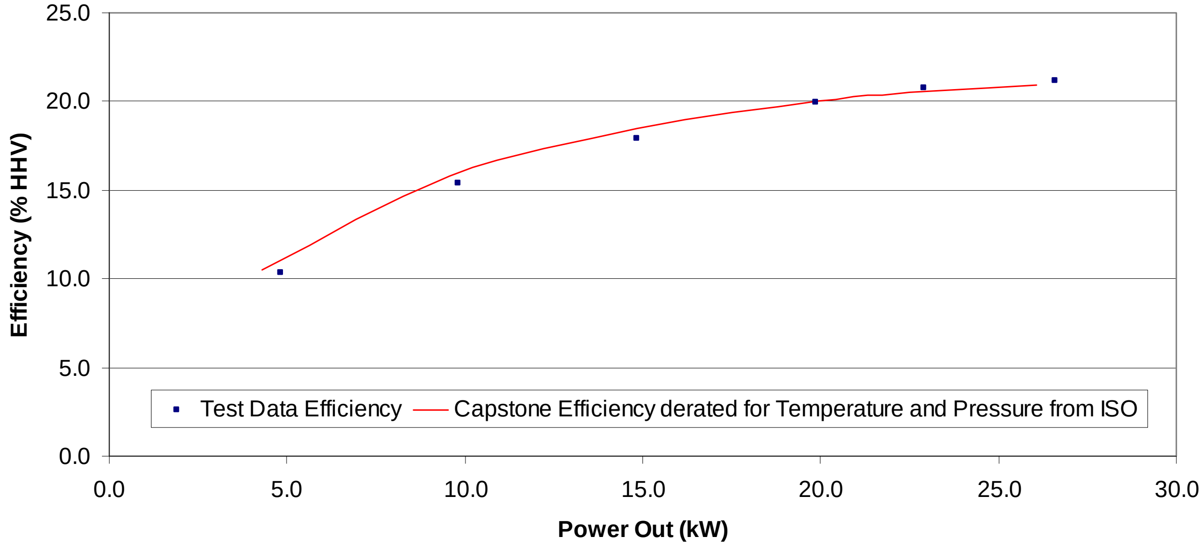

Figure 4.1. Comparison of Capstone Specifications of Partial Load Efficiency (% of HHV) with Measured Data

Jacket losses are calculated as follows:

$$\text{RHX heat recovery} = (\text{Twout} - \text{Twin}) * \rho_w * Cp_w * vf_w$$

where Cp_w is water specific heat (4177 J/kg-K), vf_w is the water volumetric flow rate, Twout is the temperature of the water out of the heat exchanger, Twin is the temperature of the water into the heat exchanger and ρ_w is the water density.

$$Q_{RHXexh} = Q_{MTexh}(T_{gasout} - T_{air})/(T_{gasin} - T_{air})$$

where Q_{MTexh} is the energy in exhaust gas leaving the microturbine and is equal to the fuel HHV minus electrical output (thermal equivalent), Q_{RHXexh} is the energy in the exhaust gas leaving the RHX, Tgasin is the temperature of the exhaust gas into the heat exchanger and Tgasout is the temperature of the exhaust gas out of the heat exchanger.

$$\text{Jacket loss} = \text{HHV} - Q_{MTexh} - Q_{RHXexh} - \text{RHX heat recovery}$$

4.2 Air Flow Measurement

Inlet air flow rate cannot be measured directly without interfering with turbine operation (e.g., increased pressure drop). However, the existing inlet channel can serve as a flow element if properly calibrated. A one-time calibration has been performed using a standard flow hood. Figure 4.2 shows the flow hood installed on the microturbine. Additional pressure drop from the flow hood means that performance is a little off during the process, but the temporary loss of turbine efficiency affects neither the resulting calibration curve nor its subsequent application.

Figure 4.2. Air Intake Measured by a Flow Hood During the One-Time Test

The data are plotted with regression curves in Figure 4.3. Air conditions at the time were 22 to 28°C, 988 mB, and 33 to 45% relative humidity, implying an air density of 1.3 kg/m^3. A log-log regression results in

$$vf = 2035\ dP^{0.5}$$

with standard error = 4.7%, vf is CFM and dP is inWC.

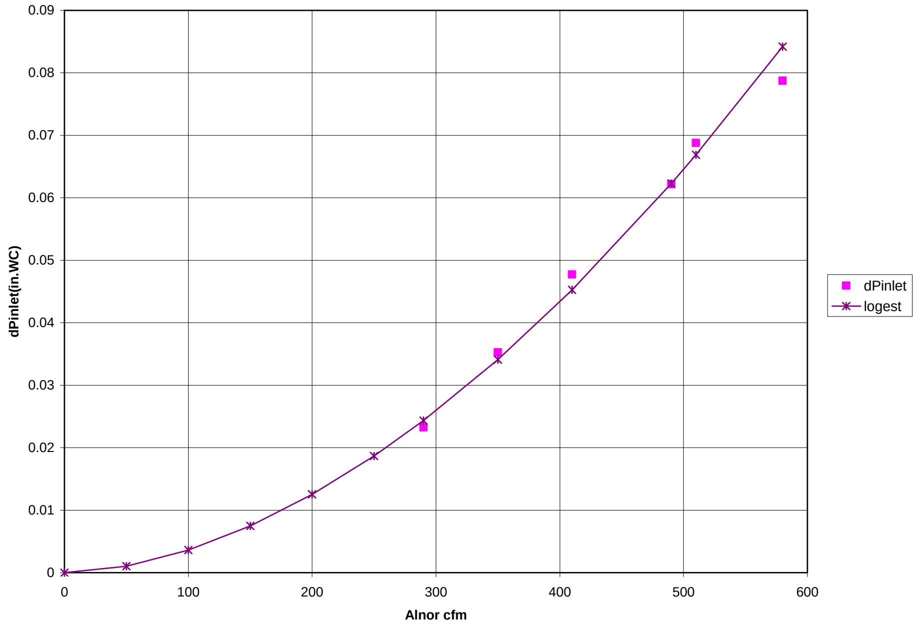

Figure 4.3. Air Flow-Pressure Relation: Data Points and Curve Fit Based on $dP^{0.5}$ Log-Log Regression

4.3 Combustion Efficiency and Emissions

Emissions were measured using a combustion gas analyzer. Calibration gases were shipped to the site, but no adjustments were needed because the analyzer was found to be in good calibration. Exhaust gas constituents were measured at each of six microturbine firing rates, as summarized in Table 4.2. The analyzer also calculates excess air as a percent of the

Table 4.2. Combustion Analysis Summary

Description	Percent Full Load					
	100%	**86%**	**75%**	**56%**	**37%**	**18%**
Electric output	26.6 kW	22.9 kW	19.9 kW	14.8 kW	9.8 kW	4.8 kW
Efficiency (from Eneract, based on HHV)	19.2%	17.8%	17.8%	16.9%	16.1%	11.9%
O_2	18.2%	18.3%	18.4%	18.4%	18.6%	18.7%
CO	10 ppm	27 ppm	74 ppm	93 ppm	50 ppm	99 ppm
Combustibles	0%	0.1%	0.5%	0.1%	0.1%	0.1%
CO_2	1.6%	1.6%	1.5%	1.5%	1.4%	1.3%
NO_x	1.5 ppm	0.5 ppm	0 ppm	0 ppm	20 ppm	11 ppm
Excess air (O_2 based)			630%	660%	710%	770%
Excess air (flow based)	600%	650%	680%	720%	800%	860%
Time stamp for test						
Start	13:30	13:45	13:51	13:57	14:02	14:07
End	13:44	13:50	13:56	14:01	14:06	14:11

stoichiometric flow rate (flow rate that will theoretically result in 100% fuel combustion with complete depletion of the oxygen from the combustion air). These excess air numbers are compared with the values calculated on the basis of measured gas and inlet air flow rates converted to standard volume units. The latter estimates of excess air are 9 to 12% higher than estimates based on O_2 concentration. The discrepancies are not surprising. With such large excess air fractions, a tiny error in O_2 concentration corresponds to a large error in the calculated volume of excess air.

4.4 Sound Level Measurement

Sound level measurements were taken by Industrial Health staff at Fort Drum. The sound level was measured with all other boiler room equipment turned off. Measurements are shown in Table 4.3. Overall noise was not objectionable, although hearing protection should be worn for extended exposure. Because the microturbine was located in the boiler room there were no complaints of noise. If the unit had been installed outside there might have been complaints about the high-pitched whine.

Table 4.3. Sound Level Measurements

Distance from microturbine (ft)	Location of measurement	Frequency of sound (Hz)	Sound intensity level (dBA)
1	front	All	85
1	rear	All	81
1	side	All	81
18	front	All	74
18	front	12,500 to 20,000	57
18	front	2,840 to 5,680	74
18	front	177 to 710	68

4.5 Electrical Quality Measurement

To address power quality concerns regarding the installation of the microturbine, power quality measurements were made on the electrical distribution system in the immediate vicinity of the equipment. The first measurements were taken on May 23–24, 2002, with the micro-turbine connected and delivering power. The second set of measurements was taken on March 26, 2003, with the microturbine disconnected. The same recording instrument, a Fluke 41 power harmonics analyzer, was used in both instances.

Total harmonic distortion (THD) is a commonly used measure of power quality. THD measures the amount of energy present outside of the primary power frequency, in this case

60 Hz. For example, 50% THD would indicate that the energy present at frequencies other than 60 Hz is equal to 1/2 the energy present at 60 Hz.

THD measured in the current waveform with the microturbine operating was shown to be on the order of 5%. In the May 23–24 testing, the project team found that THD actually was higher when measured at points farther from the microturbine. These results indicated that harmonics created by the building's loads were actually worse than those created by the microturbine. Electronic ballasts often produce electrical harmonics and can cause power quality problems.

The hypothesis of the May 23–24 testing was confirmed in follow-up testing conducted March 26 of the next year. THD in the current waveform was shown to be on the order of 10% on the electrical system without the microturbine connected. Because the majority of the load in the March 26 testing was determined to be lighting, it can be concluded that electronic ballasts within the facility are producing harmonic currents and that the harmonics produced by these devices are significantly greater than those produced by the microturbine. Results of these power-quality field tests are encouraging but not definitive because the existing load is highly nonlinear.

4.6 Stand-Alone Test

In addition to the performance verification performed under this demonstration project, the Army requested that a stand-alone or grid-independent test be performed. The purpose of this test was to determine if the combined heat and power system, and the service hot water system it supported, could operate in a grid-independent mode, should the electric utility system go off line. The primary electric end use was a 15-horsepower motor driving a hot water circulation pump.

During a power outage, the microturbine was expected to provide the energy necessary to operate the hot water circulation pump. The microturbine and the 15-horsepower circulation pump motor were isolated from the main electric utility system, simulating a power outage. The system was then tested in the stand-alone configuration. The testing revealed that during the motor startup, the current draw (in-rush amps) by the motor exceeded the output capacity of the generator resulting in the system tripping off line.

On reflection, this result should have been anticipated regardless of the generator type (microturbine, internal combustion engine, fuel cell, etc.). The starting current (in-rush amps) of an induction electric motor can be several hundred times that of its full-load operating current. Although the in-rush current draw lasts for only a small fraction of a second, it must still be provided by the electric supply system to start the electric motor. A significantly larger generator would be necessary to meet the in-rush power requirements of a 15-horsepower motor.

Although unsuccessful, an electronic soft start was procured and installed in an attempt to reduce the in-rush current requirements of the 15-horsepower motor to a level where the 28-kW generator could start the system and remain on line. The generator's overcurrent protection continued to function—tripping the microturbine off. While this does demonstrate that the microturbine's overcurrent protection controls work, it also demonstrates to the users that stand-alone generators must have the capacity to meet start-up requirements and not just operating requirements.

5.0 Operational Performance

5.1 Microturbine Performance

The microturbine electric power output and efficiency were graphed in reference to air inlet temperature and compared with the manufacturer's specifications. The manufacturer's specification data curve was made by using the output values given in Appendix C and derating for the elevation and pressure at Fort Drum by multiplying by 0.978 (derating value for 14.38 psia atmospheric pressure). The specification data curve was not derated for back pressure because we were unable to measure the backpressure due to a faulty instrument. As can be seen from the graphs in Figures 5.1 and 5.2, the measured data at Fort Drum closely matches the manufacturer's specifications for performance at different air inlet temperatures.

During the demonstration at Fort Drum the atmospheric pressure and natural gas pressure did not vary enough to show the effects of these parameters on performance. The relative humidity was measured and did vary considerably during the demonstration. Analysis of the variation of performance with respect to air humidity on microturbine performance indicated no change in performance with change in humidity.

The electrical output of the microturbine from July 31, 2002 to July 6, 2003 is shown in Figure 5.3. Between February 14 and April 23, 2003, the microturbine was scheduled to be operational during peak electric hours only (8 am to 10 pm). The graph shows output going to zero every night during that period, but the availability is considered 100% during that time.

For the first year of operation (July 31, 2002 to July 6, 2003) the availability was 74%. Availability is defined here as the actual operating hours divided by scheduled run hours multiplied by 100%. The reasons for the microturbine being unavailable can be found in Appendix B, Operational Log.

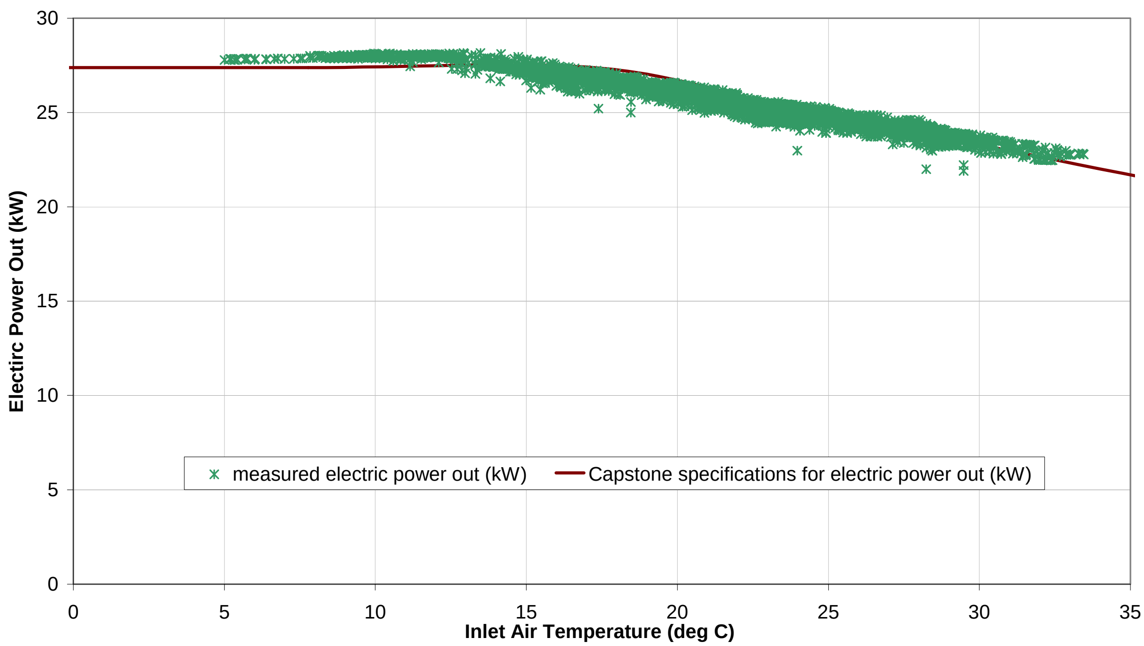

Figure 5.1. Microturbine Electric Power Output in Relation to Air Inlet Temperature

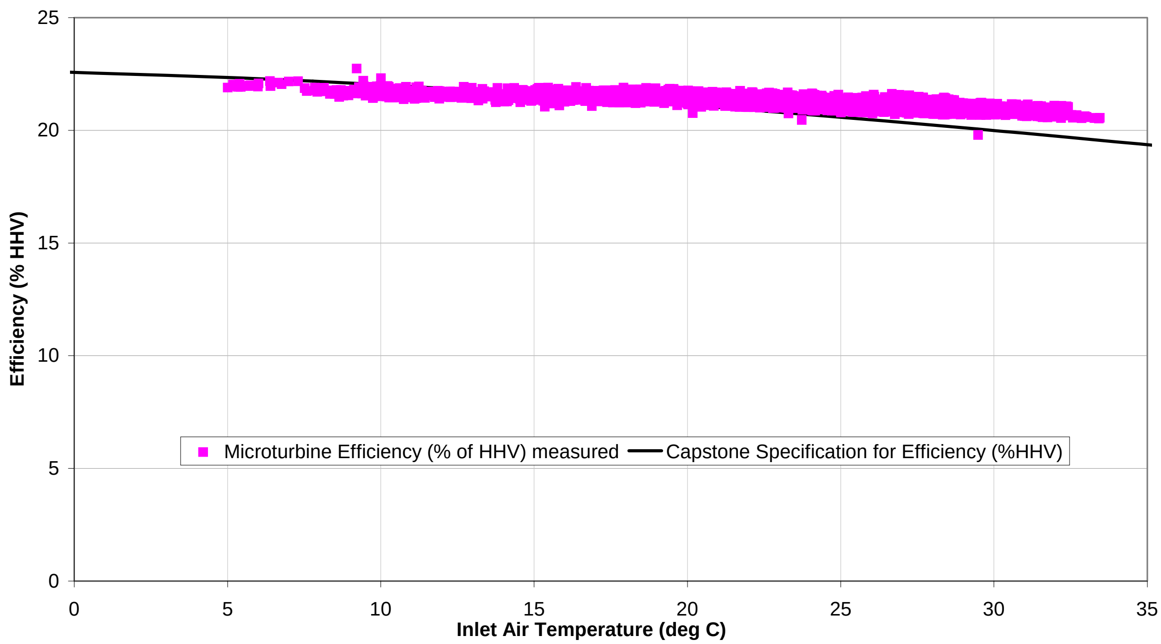

Figure 5.2. Microturbine Efficiency in Relation to Air Inlet Temperature

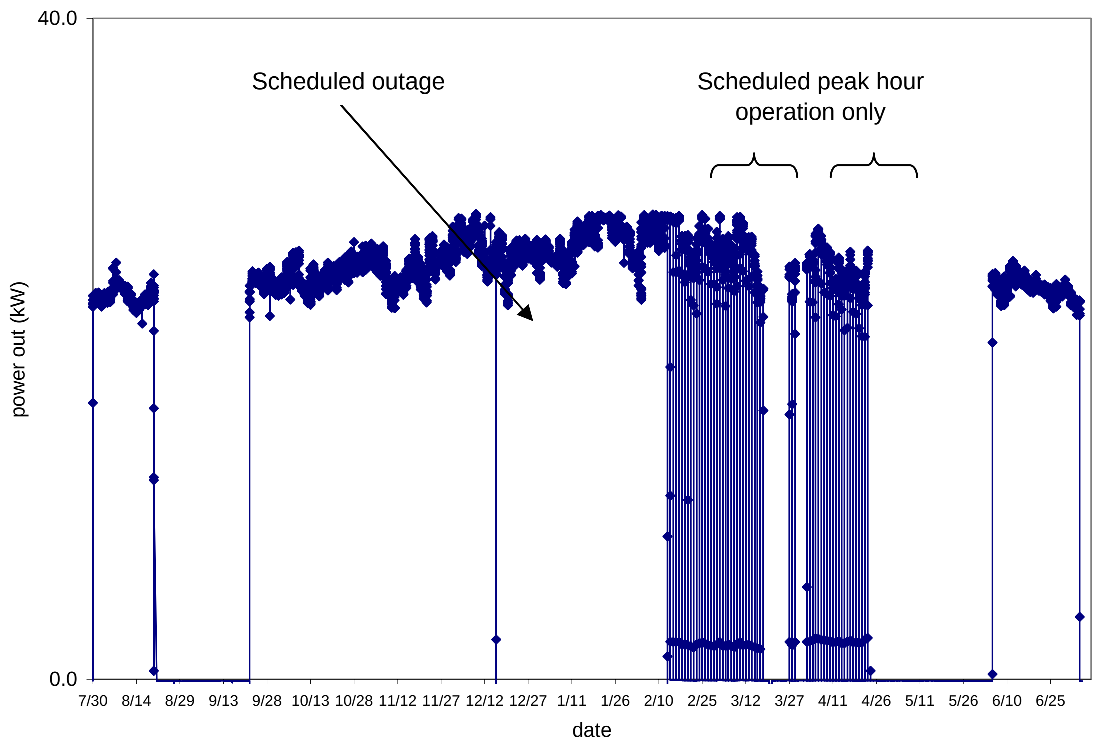

Figure 5.3. Fort Drum Microturbine Electric Availability from July 2002 to July 2003

5.2 RHX Performance

The RHX performance was compared with manufacturer's data. Because Unifin has stopped manufacturing the micoGen heat exchangers, the comparisons on the heat exchanger performance are not rigorous. Manufacturer's specifications provide graphs of outlet water temperature and heat recovered versus inlet water temperature. Figures 5.4 and 5.5 compare these parameters with manufacturer's specifications. As can be seen from the graphs, the heat exchanger performed very close to specifications for the water exit temperature, but the heat recovery data seem to indicate that the inlet water temperature had no effect on performance. The data points graphed were taken between September 22, 2002 and January 11, 2003.

As can be seen from Figure 5.6, the heat exchanger had an increase in gas outlet temperature and a drop in heat recovered on January 12, 2003. The gas diverter had stuck partially closed and a fault-detection light did not illuminate on the panel. This reduced the effectiveness of the heat exchanger from 0.89 to 0.70. The UA of the heat exchanger was 0.66 to 0.69 kW/°C when the diverter was operating correctly and dropped to 0.39 to 0.32 kW/ºC when it was not. The NTU dropped from 2.3 in early operation to 1.2 with the stuck diverter.

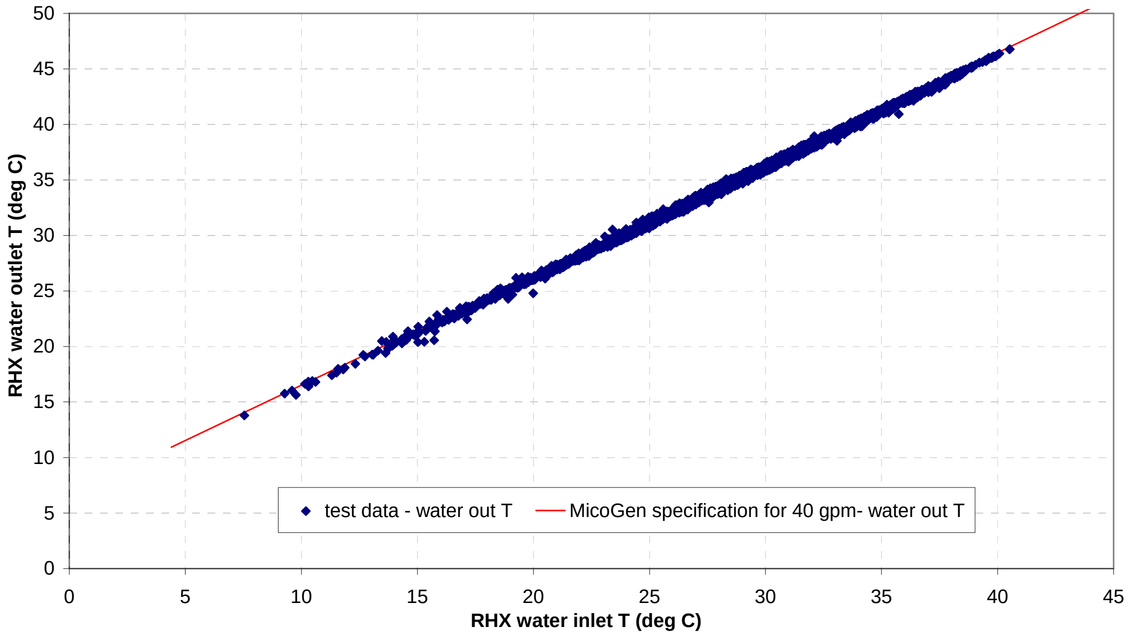

Figure 5.4. Heat Exchanger Water Outlet Temperature Versus Inlet Temperature from September 2002 to January 2003

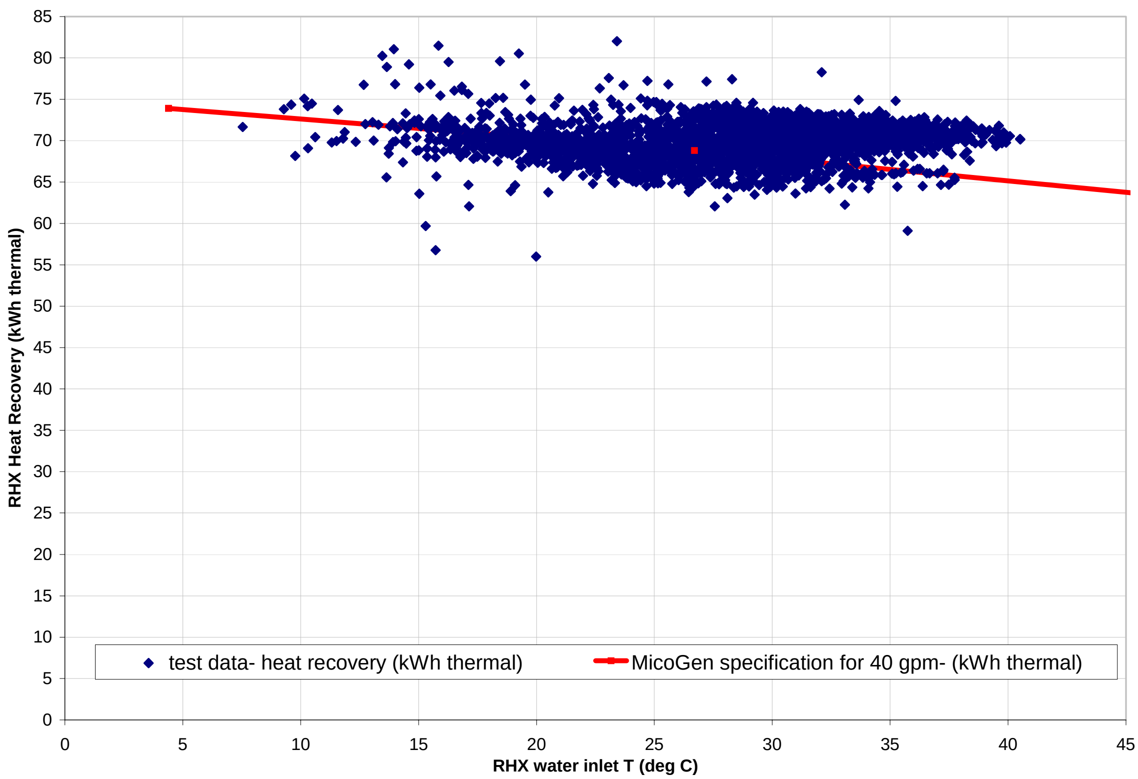

Figure 5.5. Heat Exchanger Heat Recovery Versus Water Inlet Temperature from September 2002 to January 2003

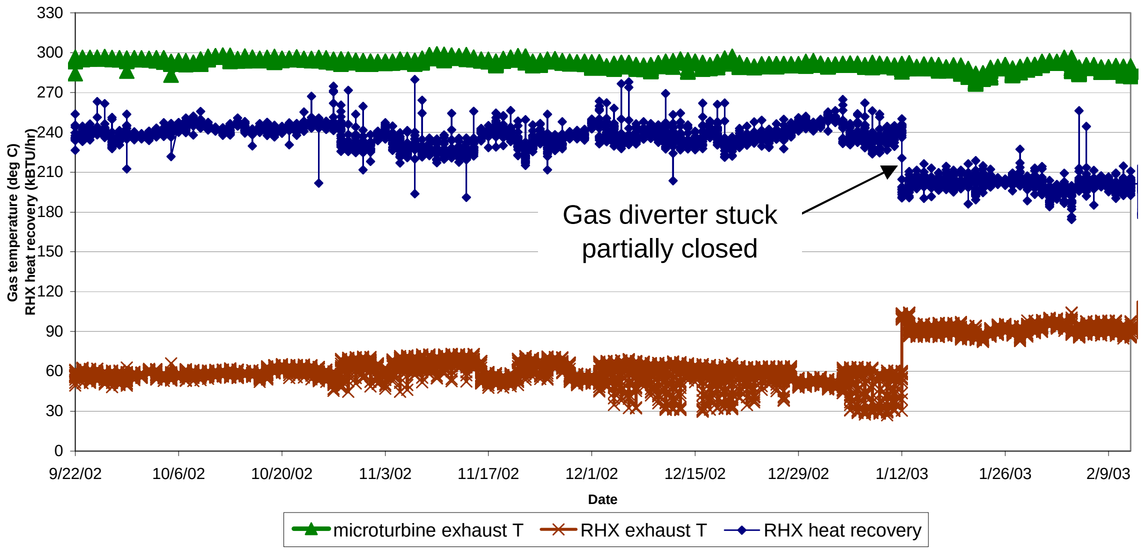

Figure 5.6. Heat Exchanger Gas Temperatures and Heat Recovered from September 2002 to February 2003

5.3 System Performance

Figure 5.7 shows the system performance for the first six months of operation. The system efficiency is approximately 80% until January 12, 2003, when the gas diverter in the heat exchanger stuck partially closed and system efficiency dropped to approximately 67%.

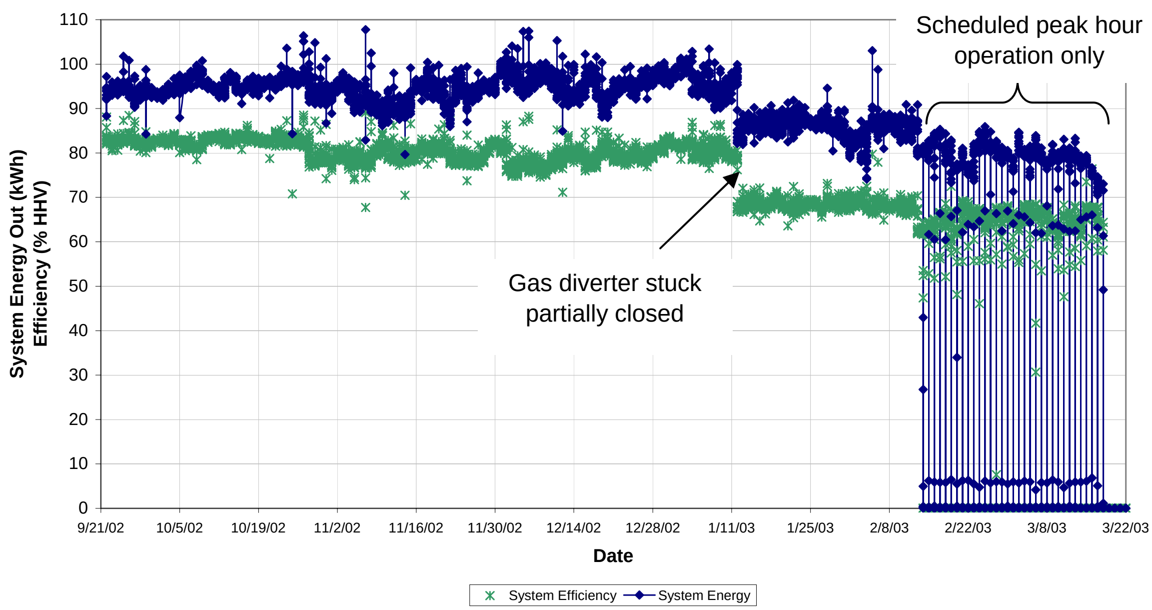

Figure 5.7. System Energy Output and Efficiency from September 2002 to March 2003

6.0 Findings

6.1 Measured Performance

One-time tests confirmed the manufacturer's ratings for sound levels and stack emissions. Field measurements are not generally considered to be as accurate as the laboratory measurements upon which the manufacturer's ratings are presumably based.

Total harmonic distortion (THD) in the microturbine output current was measured as 5% during grid-connected operation. THD of the current at the building service entrance was measured as 10%. This large THD is apparently due to the use of electronic ballasts in almost all of Building P-175's lighting fixtures. We concluded that the microturbine did not degrade power quality significantly in the building.

Electrical capacity was measured over a range of inlet air temperatures and closely tracks the rated sea-level capacity of 27.5 kW from 5 to 17°C, diminishing linearly to 22 kW at 33°C. However, the measured capacity actually starts to drop sooner, as inlet air temperature approaches 15°C. Generating efficiency also tracked or exceeded 22% at 5°C, diminishing linearly to 19% at 33°C. In fact, the measured efficiency did not drop off as rapidly as the rating. The best-fit line gave almost 21% efficiency at 33°C.

RHX performance is first-order sensitive to water inlet temperature and flow rate, as indicated in the previous analysis section. The heat exchanger's UA was determined from the measured data to be 0.66–0.69 kW/°C when the diverter was operating correctly for the first 9 months of operation. This is consistent with the manufacturer's rating.

6.2 Energy and Cost Savings

The total saved energy dollars at Fort Drum between August 24, 2002 and July 6, 2003 were calculated. Because the RHX Btu meter was not operational between June and August of 2002 we could not calculate the savings during that time. The calculation was made by adding the cost savings of electricity generated by microturbine, including demand savings, to the cost of natural gas savings for the water heating (assume alternative boilers to have 90% efficiency) then subtracting the cost of natural gas used to operate the microturbine. The average monthly cost of natural gas at Fort Drum was used, which was between $0.47 and $0.69/therm during this period. The electric cost was assumed to be $0.0662/kWh On-Peak (8 am-10 pm Monday -Friday) and $0.0414/kWh Off-Peak. Electric demand savings were calculated by taking the minimum electric output from microturbine for the month during Fort Drum peak electric periods and multiplying it by $ 5.48/kW-month. Any month the microturbine was not operating during any of the peak hours the demand savings was $0. (If we had date and time of demand charge for the base we could have checked for operation just at that time.) The total utility savings for August 24, 2002 to July 7, 2003 was $2310. This is approximately $2670/year (on an annualized basis) for the first year of operation.[a] At Fort Drum the water heat recovery was approximately 1.4 billion Btu/yr, or 400,000 kWh thermal/year.

While energy may be saved at the source, energy consumption at the site is increased. This is because of the efficiency of the on-site power generation. DOE is working on a revised energy reporting criteria for federal agencies. The proposed reporting criteria, however, have not yet been approved by the Inter-Agency Task Force. In addition, the proposed reporting criteria have not been integrated into the Army's current energy reporting procedures.

6.3 Potential Performance Improvements

Several performance improvements are suggested by the Fort Drum experience with this cogeneration equipment. A small increase in microturbine capacity and improved turbine efficiency can be achieved by providing outside air, via an adequately sized duct, directly to the turbine combustion air inlet. Inlet air cooling could be used to achieve further improvements, albeit at the expense of system complexity and higher first cost.

The RHX diverter damper, which prevents overheating on the water side, could be better controlled to also avoid condensation of the exhaust gas. The gas should be partially diverted when water outlet temperature falls below a specified set point, e.g., 91°F (33°C).

6.4 Lessons Learned

Some important lessons were gleaned from the demonstration. The reliability of the gas booster pump must be improved. Until then, gas turbine packages of this type should only be installed where 55 psig of gas is available.

For maximum overall efficiency it is important that sufficient thermal load exist and to install sufficient hot water storage so that the RHX is rarely, if ever, bypassed. In this case there was sufficient thermal load but not sufficient storage. An accurate estimate of hot water demand and its day-to-day variation is important for correctly sizing the system.

The emergency load served in this application was a pump whose in-rush current on startup proved too much for a 28-kW generator. A two-speed motor or delta-wye starter might solve this problem. In any case, it is crucial that the peak start current and duration of such loads be known and matched to the microturbine capability.

(a) Savings would have been greater if gas diverter had not been stuck partially closed for 6 months and if the microturbine had been available during all peak hours.

According to Unifin and Capstone, the micoGen heat exchanger will no longer be manufactured by Unifin. Capstone now offers a cogeneration package unit with a 60-kW microturbine, but a 30-kW microturbine CHP packaged system is no longer available. If a heat recovery system is to be used with a 30-kW unit, a heat exchanger would need to be procured with the specifications of the micoGen reported earlier in this report.

Based on the operational experience at Fort Drum, there is a clear need for thorough commissioning of the CHP system and associated building controls immediately after installation and before the start of performance monitoring activities.

6.5 Fort Drum Energy Manager Feedback

The project was affected by numerous nuisance problems that continually interrupted the test effort. Foremost was the issue of obtaining a reliable gas compressor. Four different compressors have been installed since the microturbine was commissioned. Failures of the circuit boards for the controllers of the gas compressor, modem, and heat exchanger contributed to the problems. The operational log in Appendix B details the problems encountered. During the test effort (May 22, 2002 to July 14, 2003) the microturbine had 69.7% availability (operational 285 days out of 409). The rest of the time (125 days) the machine was down, waiting for parts or repairs. Capstone is aware of the field problems that we encountered, and they are addressing these quality control issues.

Appendix A

Design, Installation, and Startup Time Table

Appendix A

Design, Installation, and Startup Time Table

Task	Date	Comment
Received DOE-FEMP DER grant	April 2001	
USACE-CERL open market purchase order	June 14, 2001	Not to exceed $100K; selected as acquisition plan
SOW and other information provided to CERL contracts office	August 3, 2001	SOW developed with assistance of CERL
Announcement posted in Commerce Business Daily	August 10, 2001	100% set aside for small business; firm fixed-price purchase order; closing date of September 14, 2001
Due date for bids on revised SOW	October 29, 2001	Original bids exceeded the $100K threshold
Purchase order issued	November 2001	
Draft system design	December 2001	Drawings were less than 100% complete
Capstone microturbine unit delivered to Fort Drum	December 2001	
Unifin micoGen heat exchanger delivered	February 2002	
Design review meeting with contractor	February 7, 2002	Drawings essentially 100% complete; videoconference
Installation began	February 2002	
PNNL staff install performance monitoring and data acquisition system	April 2002	
Installation of CHP-configured microturbine system completed and microturbine commissioned according to Capstone guidelines.	May 2002	System operating and data are being collected; commissioning was incomplete due to inability to restart 15-hp circulation pump in stand-alone mode
One time testing of the 15-hp circulation pump in the stand alone mode remains incomplete	June 2002	Soft-start device does not effect successful restart; requirement may be beyond system capability

Appendix B

Operational Log

Appendix B
Operational Log

Capstone Microturbine 330 at Fort Drum, New York
Location: Building P-175
System # 1933
Serial # 100110
Service Provider: JW's Mechanical, LLC
21 Liberty St.
Carthage, NY 13619

4-26-02, 2 hours
Commissioning Day unit failed to start.
Followed trouble-shooting guide. Called Capstone. Unit had RFC with ceramic bearing, will ship RFC with foil bearing.

5-01-02, 6 hours
Installed new RFC. Unit on line. Commissioning restarted. Unit will not go into stand-alone. Found bad diode in dual-mode controller. Capstone will overnight.

5-04-01, 1.5 hours
Installed diode. Unit will transfer into stand-alone mode but will not maintain load.

5-08-02, 2 hours
Trouble-shooting stand-alone problem

5-12-02, 2.5 hours
Commissioned microturbine. Worked on emergency equipment commissioning. Trouble-shooting stand-alone problem. Unit will run through program on Trane Tracer and start everything except 15 HP pump.

6-01-02, 2 hours
Trouble-shooting micoGen. No response from display. Bad board; Capstone will send new one.

6-04-02
Microturbine repaired and back on line

7-01-02, 3 hours
Microturbine down; trouble-shooting

7-08-02, 2 hours
Trouble-shooting

7-10-02, 2 hours
Trouble-shooting

7-20-02, 4 hours
Found microturbine down, fault code 6006.
Went through test routine in trouble-shooting manual. Cannot pinpoint problem; will return next week when John Ashcroft can call Capstone.

7-23-02, 3.5 hours.
Leak-checked gas lines between RFC and solenoid block. Tightened loose flare nuts. Plugged bottom of solenoid block, it still leaked. Taped, doped, and retightened, it still leaks. Pulled electrode out and checked end. Found electrode fouled. Dale at Capstone will send solenoid block and electrode overnight. Will upgrade software to unit at time of part installation.

7-25-02, 4 hours
Installed solenoid block and electrode.
Leak tested.
Found leak at nut leaving SPV.
Leak at male threads entering solenoid block.
Re-used plug for bottom of solenoid block; still did not seal, will purchase new pipe plug.

7-30-02, 3 hours
Installed new plug in solenoid block. Leak checked gas train. All leaks repaired. Unit back on line.

8-26-02, 2 hours
Trouble-shooting; checked voltages and fuses.

9-12-02, 2 hours
Fault code #9394 #9395
Called Capstone, checked RFC. Checked fuses on DPC fuse: F-1 blown- 5 amp fuse; needs to be 8amp fuse for F-1 and F-2 plus software upgrade to recognize fuse.
Will return with fuses.

9-17-02, 3.5 hours
Replaced fuses F-1 and F-2 ok. Called Capstone talked with Dale and Igor.
Checked IGB on battery and RFC board.
RFC and RFC controller failed; will ship asap.
Did other trouble-shooting with Capstone.

9-22-02, 2.5 hours
Installed new RFC and RFC controller.
RFCs #200-500-60-52, pn# 511294101R,
RFC controllers #201377, pn# 509333303R.
Run hours 1666.33.
Leak checked gas connections, ok.
Unit on line.

11-6-02 2:30 pm
Activated DHW supply to kitchen hot water heater.

Nov., Dec., Jan.—Microturbine was on line, running continuously per Steve Parker's request. No indication of major problems. Datalogger data should confirm this; please advise if different.

Shut off kitchen hot water load; this was due to the fact that the heat recovery could not sufficiently pre-heat the makeup water. The AO Smith boilers were experiencing problems and the shops were looking to the microturbine to provide hot water for the building. Installed new board with James Pfeiffer's serviceman. Stand-alone test not successful. 15-hp circ pump will not start.

2-14-03 11 am–3:30 pm
Installed PNNL computer to gather data. Attempted emergency start. 15HP circ pump will not start under microturbine power. Set up microturbine to run.

Daily 8 am – 10 pm
Microturbine down. Attempted two manual restarts with no success. (Rowley)

Microturbine down: couldn't turn gas compressor by hand. Freed up with wrench. Started microturbine.

3-28-03
Microturbine down: attempted successful restart by Rowley.
Microturbine down. Restarted by Ashcroft

4-7-03
OK; still running; water in 53 degrees, water out 61 degrees; 192 starts.

OK; water in 61 degrees, water out 69 degrees F, 199 starts

OK; water in 61 degrees, water out 69 degrees; 199 starts

OK; 2:30 pm, 5 starts; water in 64 degrees, water out 74 degrees; 205 starts

OK; water in 72, water out 79.
Microturbine down, attempted manual start; won't even try (Rowley).

5-3-03
John installed new modem, modem not working.

5-28-03
Trouble-shooting by John Ashcroft.
USB board bad—codes 7010, 6010, 6012, 11023.
UCB board replaced by John Ashcroft. Turbine started and set to run continuously.

6-7-03 4 PM.
OK; 178 starts; water in @85, out @ 95 degrees.

6-17-03 noon
OK; gas pressure @ 12.0 psig; shutoff valve closed half way.

6-30-03 noon
OK; water in 89, out at 100 degrees F.

7-01-03
OK; water in 98, out 104 degrees.
Turbine down, fuel fault code H6012, suspect gas compressor.
Removed dataloggers (PNNL).
Trouble-shooting by John Ashcroft, RFC controller bad, J5 diode bad.

Appendix C

Technical Reference

Appendix C

Technical Reference

Capstone Model C30 Performance[(a)]

Introduction

This document presents performance information for the Capstone Turbine Corporation® Capstone (recuperated) Model C30 MicroTurbine™ operating on natural gas (B Range) fuel.

The Capstone Model C30 MicroTurbine system is a compact, low emission, power generator providing up to 30 kW of electrical power. The Model C30 MicroTurbine generates electricity from various fuels with low exhaust emissions. Solid-state power electronics allow Grid Connect or Stand Alone operation.

ISO Full Load Performance

Performance is listed at full load power and ISO conditions for the Capstone Model C30 MicroTurbine operating on natural gas (B Range) fuel, as defined in the Capstone MicroTurbine Fuel Requirements Technical Reference 410002. ISO conditions are defined as: 15°C (59°F), 60% relative humidity, at sea level altitude. Other items are defined as: HHV: Higher Heating Value, LHV: Lower Heating Value, HPNG: High Pressure Natural Gas, LPNG: Low Pressure Natural Gas, SG: Sour Gas, and UDG: Landfill/Digester Gas. Table 1 presents the (recuperated) Model C30 MicroTurbine performance.

Table 1. Capstone Model C30 MicroTurbine Performance (Grid Connect/Stand-alone)

Performance	Value
Rated Output	30.0 (+0/-1) kW
Thermal Efficiency	26.0 (+/-2)% LHV (Lower Heating Value)
Fuel Flow (LHV Based) (See Notes 1 and 2)	415,000 kJ/hr (394,000 Btu/hr)
Fuel Flow (HHV Based) (See Notes 1 and 2)	457,000 kJ/hr (433,000 Btu/hr)
Heat Rate (LHV Based) (See Notes 1 and 2)	13,800 kJ/kWh (13,100 Btu/kWh)
Exhaust Temperature	275°C (530°F)
Exhaust Heat Energy	327,000 kJ/hr (310,000 Btu/hr)
Exhaust Mass Flow	0.31 kg/s (0.68 lbm/s)
Note 1: These parameters are fuel-type dependent. Note 2: The ratio of higher heating value (HHV) to lower heating value (LHV) is assumed to be 1.1.	

Fuel Parameters

Refer to the Capstone MicroTurbine Fuel Requirements Technical Reference 410002 for detailed information regarding fuel parameters for the Model C30 MicroTurbine.

410004-001 Rev A (August 2002)

(a) Contact Capstone Turbine for current technical specifications.

Temperature Derating

Nominal net power output and efficiency versus ambient temperature at sea level for the Model C30 MicroTurbine operating on natural gas (B Range) fuel is presented in Table 2. These values are estimated from nominal performance curves.

Table 2. Nominal Net Power Output and Efficiency versus Ambient Temperature at Sea Level

Ambient Temp (°F)	Net Power (kW)	Net Efficiency (%)	Exhaust Temp (°F)	Exhaust Mass Flow Rate (lbm/s)	Exhaust Energy (Btu/hr)	Fuel Flow Energy (LHV)	Heat Rate (Btu/kWh) (LHV)
-4	30.0	27.9	442	0.67	279,000	367,000	12,200
-3	30.0	27.9	443	0.66	279,000	367,000	12,200
-2	30.0	27.9	445	0.66	279,000	367,000	12,200
-1	30.0	27.9	446	0.66	279,000	367,000	12,200
0	30.0	27.9	448	0.66	279,000	367,000	12,200
1	30.0	27.9	450	0.66	279,000	367,000	12,200
2	30.0	27.9	451	0.66	279,000	367,000	12,200
3	30.0	27.9	453	0.66	279,000	367,000	12,200
4	30.0	27.9	454	0.66	279,000	367,000	12,200
5	30.0	27.9	456	0.65	279,000	367,000	12,200
6	30.0	27.9	457	0.65	279,000	367,000	12,200
7	30.0	27.9	459	0.65	279,000	367,000	12,200
8	30.0	27.9	461	0.65	279,000	367,000	12,200
9	30.0	27.9	462	0.65	279,000	367,000	12,200
10	30.0	27.9	464	0.65	279,000	367,000	12,200
11	30.0	27.9	465	0.65	279,000	367,000	12,200
12	30.0	27.9	467	0.65	279,000	367,000	12,200
13	30.0	27.8	468	0.65	279,000	368,000	12,300
14	30.0	27.8	469	0.65	280,000	368,000	12,300
15	30.0	27.8	471	0.65	280,000	369,000	12,300
16	30.0	27.7	472	0.65	281,000	369,000	12,300
17	30.0	27.7	473	0.65	281,000	370,000	12,300
18	30.0	27.7	474	0.65	282,000	370,000	12,300
19	30.0	27.6	476	0.65	282,000	370,000	12,300
20	30.0	27.6	477	0.65	283,000	371,000	12,400
21	30.0	27.6	478	0.65	283,000	371,000	12,400
22	30.0	27.5	479	0.65	284,000	372,000	12,400
23	30.0	27.5	480	0.65	284,000	372,000	12,400
24	30.0	27.5	482	0.65	285,000	373,000	12,400
25	30.0	27.5	483	0.65	285,000	373,000	12,400

Table 2. Nominal Net Power Output and Efficiency versus Ambient Temperature at Sea Level

Ambient Temp (°F)	Net Power (kW)	Net Efficiency (%)	Exhaust Temp (°F)	Exhaust Mass Flow Rate (lbm/s)	Exhaust Energy (Btu/hr)	Fuel Flow Energy (LHV)	Heat Rate (Btu/kWh) (LHV)
26	30.0	27.4	484	0.65	286,000	373,000	12,400
27	30.0	27.4	485	0.66	286,000	374,000	12,500
28	30.0	27.4	487	0.66	287,000	374,000	12,500
29	30.0	27.3	488	0.66	287,000	375,000	12,500
30	30.0	27.3	489	0.66	288,000	375,000	12,500
31	30.0	27.3	490	0.66	288,000	376,000	12,500
32	30.0	27.2	492	0.66	289,000	376,000	12,500
33	30.0	27.2	493	0.66	289,000	377,000	12,600
34	30.0	27.2	494	0.66	290,000	377,000	12,600
35	30.0	27.1	496	0.66	291,000	377,000	12,600
36	30.0	27.1	497	0.66	291,000	378,000	12,600
37	30.0	27.1	498	0.66	292,000	378,000	12,600
38	30.0	27.0	499	0.66	292,000	379,000	12,600
39	30.0	27.0	500	0.66	293,000	379,000	12,600
40	30.0	27.0	502	0.66	293,000	380,000	12,700
41	30.0	26.9	503	0.66	294,000	380,000	12,700
42	30.0	26.9	504	0.67	295,000	381,000	12,700
43	30.0	26.8	506	0.67	295,000	382,000	12,700
44	30.0	26.8	507	0.67	296,000	382,000	12,700
45	30.0	26.8	508	0.67	297,000	383,000	12,800
46	30.0	267	510	0.67	298,000	383,000	12,800
47	30.0	26.7	511	0.67	298,000	384,000	12,800
48	30.0	26.6	512	0.67	299,000	385,000	12,800
49	30.0	26.6	514	0.67	300,000	385,000	12,800
50	30.0	26.5	515	0.67	301,000	386,000	12,900
51	30.0	26.4	517	0.67	302,000	387,000	12,900
52	30.0	26.4	518	0.68	303,000	388,000	12,900
53	30.0	26.3	520	0.68	304,000	389,000	13,000
54	30.0	26.3	521	0.68	305,000	390,000	13,000
55	30.0	26.2	523	0.68	306,000	391,000	13,000
56	30.0	26.2	524	0.68	307,000	391,000	13,000
57	30.0	26.1	526	0.68	308,000	392,000	13,100
58	30.0	26.1	527	0.68	309,000	393,000	13,100
59	30.0	26.0	529	0.68	310,000	394,000	13,100
60	30.0	25.9	530	0.68	311,000	395,000	13,200

Table 2. Nominal Net Power Output and Efficiency versus Ambient Temperature at Sea Level

Ambient Temp (°F)	Net Power (kW)	Net Efficiency (%)	Exhaust Temp (°F)	Exhaust Mass Flow Rate (lbm/s)	Exhaust Energy (Btu/hr)	Fuel Flow Energy (LHV)	Heat Rate (Btu/kWh) (LHV)
61	30.0	25.9	531	0.69	312,000	395,000	13,200
62	30.0	25.8	533	0.69	313,000	396,000	13,200
63	30.0	25.8	534	0.69	314,000	397,000	13,200
64	29.9	25.7	535	0.69	314,000	397,000	13,300
65	29.7	25.7	536	0.69	313,000	395,000	13,300
66	29.5	25.6	536	0.68	312,000	393,000	13,300
67	29.3	25.6	537	0.68	311,000	392,000	13,400
68	29.1	25.5	537	0.68	310,000	390,000	13,400
69	29.0	25.4	538	0.68	309,000	388,000	13,400
70	28.8	25.4	538	0.68	308,000	387,000	13,500
71	28.6	25.3	539	0.68	307,000	385,000	13,500
72	28.4	25.3	539	0.67	306,000	384,000	13,500
73	28.2	25.2	54()	0.67	305,000	382,000	13,500
74	28.0	25.1	54()	0.67	304,000	380,000	13,600
75	27.8	25.1	540	0.67	303,000	379,000	13,600
76	27.6	25.0	541	0.67	302,000	377,000	13,600
77	27.4	24.9	541	0.66	301,000	376,000	13,700
78	27.3	24.9	542	0.66	300,000	374,000	13,700
79	27.1	248	542	0.66	299,000	372,000	13,700
80	26.9	24.8	543	0.66	299,000	371,000	13,800
81	26.7	24.7	543	0.66	298,000	369,000	13,800
82	26.6	24.6	544	0.66	297,000	368,000	13,800
83	26.4	24.6	544	0.65	296,000	366,000	13,900
84	26.2	24.5	545	0.65	295,000	365,000	13,900
85	26.0	24.5	545	0.65	294,000	363,000	14,000
86	25.8	24.4	545	0.65	293,000	362,000	14,000
87	25.7	24.3	546	0.65	292,000	360,000	14,000
88	25.5	24.2	546	0.65	291,000	359,000	14,100
89	25.3	24.2	547	0.64	290,000	357,000	14,100
90	25.1	24.1	547	0.64	289,000	355,000	14,200
91	24.9	24.0	548	0.64	288,000	354,000	14,200
92	24.7	23.9	548	0.64	288,000	352,000	14,300
93	24.5	23.9	549	0.64	287,000	351,000	14,300
94	24.4	23.8	549	0.64	286,000	349,000	14,300
95	24.2	23.7	550	0.63	285,000	348,000	14,400
96	24.0	23.7	550	0.63	284,000	346,000	14,400

Table 2. Nominal Net Power Output and Efficiency versus Ambient Temperature at Sea Level

Ambient Temp (°F)	Net Power (kW)	Net Efficiency (%)	Exhaust Temp (°F)	Exhaust Mass Flow Rate (lbm/s)	Exhaust Energy (Btu/hr)	Fuel Flow Energy (LHV)	Heat Rate (Btu/kWh) (LHV)
97	23.8	23.6	551	0.63	283,000	345,000	14,400
98	23.7	23.5	551	0.63	282,000	343,000	14,500
99	23.5	23.4	551	0.63	282,000	342,000	14,500
100	23.3	23.4	552	0.63	281,000	341,000	14,600
101	23.1	23.3	552	0.62	280,000	339,000	14,700
102	23.0	23.2	553	0.62	279,000	338,000	14,700
103	22.8	23.1	553	0.62	278,000	336,000	14,700
104	22.6	23.1	554	0.62	277,000	335,000	14,800
105	22.5	23.0	554	0.62	276,000	333,000	14,800
106	22.3	22.9	555	0.62	275,000	332,000	14,900
107	22.1	22.9	555	0.61	275,000	331,000	14,900
108	22.0	22.8	555	0.61	274,000	329,000	15,000
109	21.8	22.7	556	0.61	273,000	328,000	15,000
110	21.6	22.6	556	0.61	272,000	326,000	15,100
111	21.5	22.5	557	0.61	271,000	325,000	15,100
112	21.3	22.5	557	0.60	270,000	324,000	15,200
113	21.1	22.4	558	0.60	270,000	322,000	15,200
114	21.0	22.3	558	0.60	269,000	321,000	15,300
115	20.8	22.2	558	0.60	268,000	319,000	15,400
116	20.6	22.1	559	0.60	267,000	318,000	15,400
117	20.5	22.1	559	0.60	266,000	317,000	15,500
118	20.3	22.0	560	0.59	265,000	314,000	15,500
119	20.1	21.9	560	0.59	265,000	322,000	15,600
120	20.0	21.8	561	0.59	264,000	313,000	15,600
121	19.8	217	561	0.59	263,000	311,000	15,700
122	19.7	21.7	561	0.59	262,000	310,000	15,800

Elevation Derating

Elevation affects power output by changing the density of the air. Although local weather changes in barometric pressure have the same effect, power derating for elevation may be estimated to be 1.0% per 100 meters above sea level (3.0% per 1000 feet above sea level), assuming equivalent ambient temperatures.

Use these derating estimates only for ambient temperatures above 15°C (59°F), as lower ambient temperatures may offset the effects of elevation. Elevation effect on efficiency is negligible.

Back Pressure Derating

The maximum allowable exhaust back pressure is eight inches of water. Nominal fraction of ISO net power output and efficiency versus back pressure at ISO ambient conditions for the Model C30 MicroTurbine operating on natural gas (B Range) fuel is presented in Table 3. These values are estimated from nominal performance curves.

Table 3. Nominal Fraction of ISO Net Power Output and Efficiency versus Back Pressure at ISO Ambient Conditions

Back Pressure (inches of water)	Net Power (kW)	Net Efficiency (%)	Power (power @ Pback = 0)	Efficiency (efficiency @ Pback = 0)
0	30.00	26.0	1.000	1.000
1	30.00	25.9	1.000	0.997
2	30.00	25.8	1.000	0.994
3	30.00	25.8	1.000	0.991
4	30.00	25.7	1.000	0.989
5	30.00	25.6	1.000	0.986
6	30.00	25.5	1.000	0.982
7	29.98	25.5	0.999	0.979
8	29.84	25.4	0.995	0.976

Appendix D

Additional Photographs of Demonstration Setup

Appendix D

Additional Photographs of Demonstration Setup

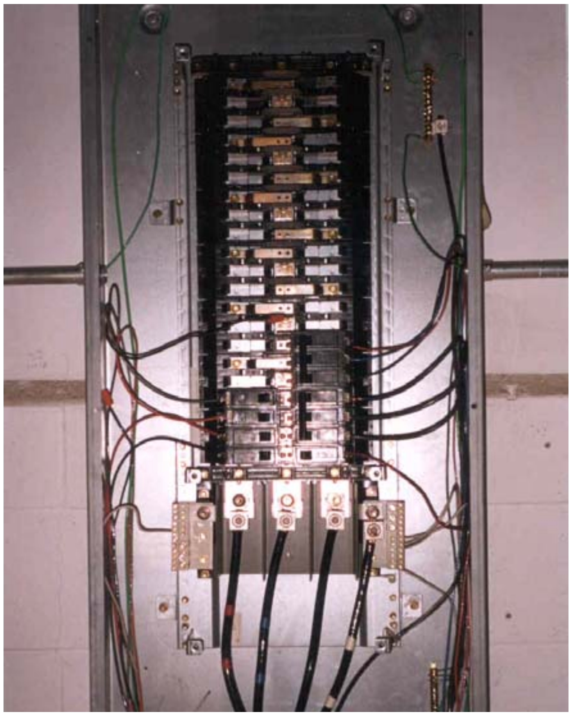

Figure D.1. Panel that serves the mechanical room pumps, fans, and power burners

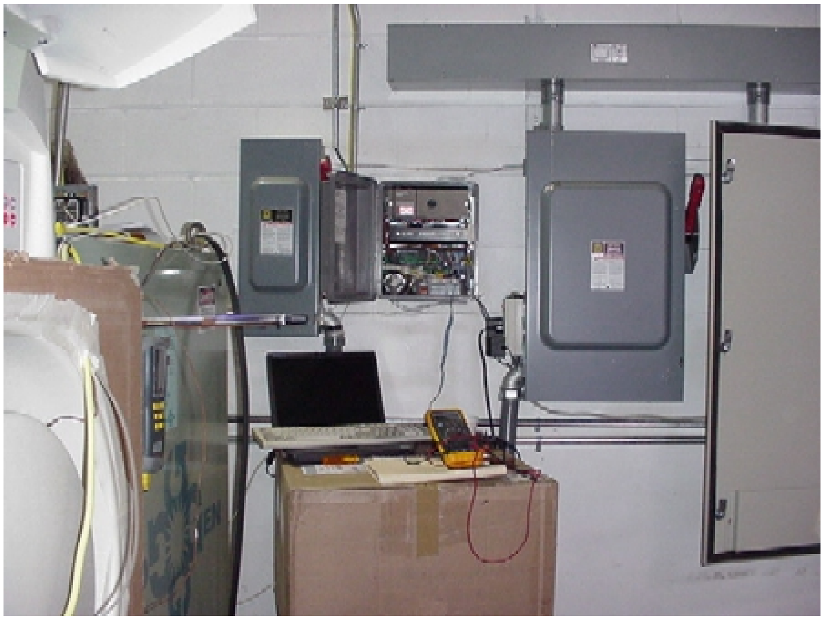

Figure D.2. Step-down transformer (bottom) with disconnects on 480V (left) side and 208V (right) side. MT and RHX are at far left. Data acquisition system is mounted on the wall between disconnects.

Figure D.3. Btu meter mounted on back access door of RHX (left) and RHX water-side thermowells mounted in the inlet and outlet T fittings (center).

Figure D.4. Control panel (top) with Dranetz power analyzer hooked up

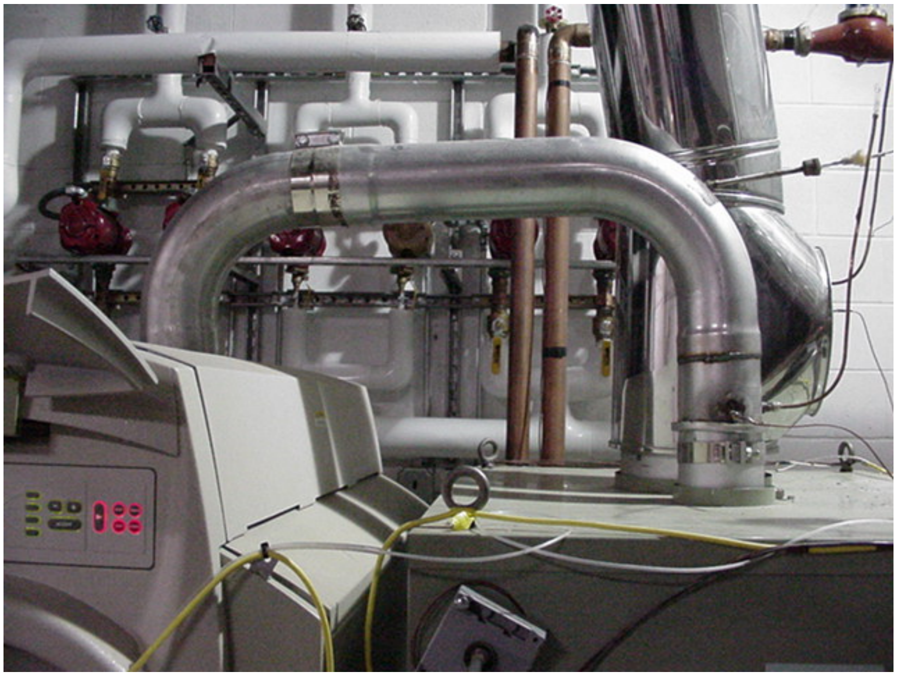

Figure D.5. Exhaust duct from MT to RHX. Larger RHX exhaust stack to roof is partially hidden. Water meter that measures RHX flow rate is just visible in upper right.

Figure D.6. Overview (L to R) of MT, RHX, transformer, and switchgear. Note DHW recirculation pumps on wall above and behind the microturbine.

Figure D.7. HW heaters

Figure D.8. New (left) and Existing (right) hot water storage tanks

Appendix E

Sources and Points of Contact

Appendix E

Sources and Points of Contact

Microturbine OEM

Capstone Turbine Corporation
21211 Nordhoff Street
Chatsworth, CA 91311
Phone: (818) 734-5300
www.microturbine.com

micoGen™ Heat Exchanger OEM

UNIFIN International, Inc.
1030 Clarke Side Road
London, Ontario, Canada N6A 4P4
Phone: (800) 567-5707
www.unifin.com

Microturbine and micoGen™ Heat Exchanger Distributorship

Enertec, LLC
55A East Ridgewood Ave., Suite 8
Ridgewood, NJ 07450
POC: James R. Pfeiffer, V.P. (201) 251-3815
Email: pfeifferjr@aol.com
www.enertecllc.com

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Carthage, NY 13619
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Champaign IL 61826-9005
Contract/Purchase Order #DACW42-02-P-0021

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