CONSULTANT REPORT

PIER
Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Environmentally-Preferred
Advanced Generation

MICRO TURBINE GENERATOR (DISTRIBUTED GENERATION) PROJECT

Gray Davis, *Governor*

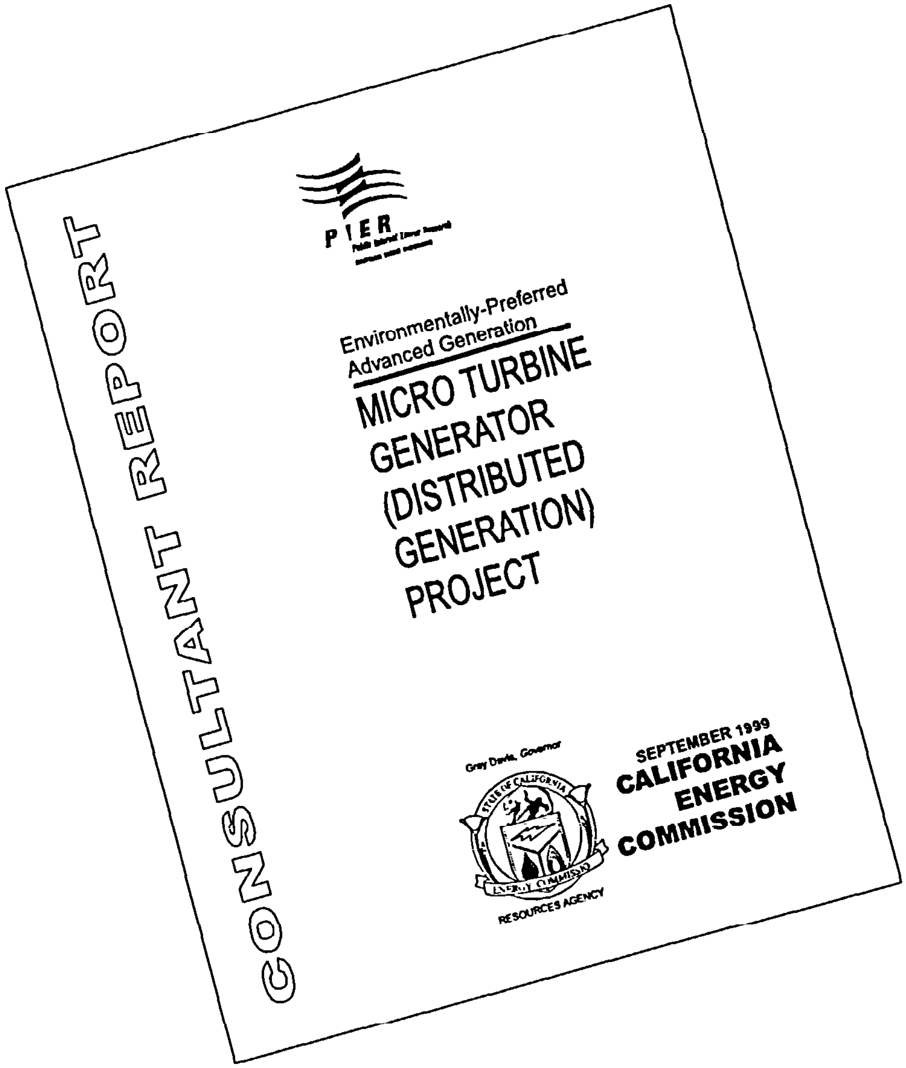
STATE OF CALIFORNIA
ENERGY COMMISSION

RESOURCES AGENCY

SEPTEMBER 1999

CALIFORNIA
ENERGY
COMMISSION

P600-00-016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Contract No. 500-97-012
Project No. 08

Contract Amount: $500,000

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Acknowledgements

Participating organizations and technology partners:

- California Energy Commission
- Edison Technology Solutions
- Electric Power Research Institute
- United States Department of Energy
- University of California, Irvine Combustion Laboratory
- Bowman Power Systems
- CAMS Welding and Design
- Capstone Turbine Corporation
- Paragon Consulting Services.

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

In 1998, the Commission awarded approximately $17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

Edison Technology Solutions (ETS) is an unregulated subsidiary of Edison International and an affiliate of Southern California Edison Company (SCE). As a result of a corporate restructuring, ETS ceased active operations on September 30, 1999. ETS' remaining rights and obligations were subsequently transferred to SCE.

What follows is the final report for the Micro Turbine Generator project, 1 of 10 projects conducted by ETS. This project contributes to the Strategic Energy Research program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Description of Micro Turbine Generator (MTG) Technology

MTGs are small, high-speed, integrated power plants that include a turbine, compressor, generator, and power electronics to produce power. MTGs are Brayton cycle machines that come in sizes of power output ranging from 30 to 300 kW. Some package designs are configured for combined heat and power, cogeneration, production. Cogeneration units include additional components, such as hot water heat exchangers, which capture heat from the MTG exhaust to produce useful thermal energy. Typical MTGs claim the following advantages: few moving parts, relatively small unit footprints, and the ability to be configured to operate on a variety of fuels.

Several manufacturers are currently marketing MTG systems that are promoted to meet distributed generation needs of the power industry. However, impartial and independently verified performance data is not available for MTGs and prospective MTG purchasers are totally dependent on manufacturer's specifications.

Objectives:

- Compare manufacturers' performance claims against actual experience from project activities. This independently developed information is intended to aid prospective MTG users in evaluating the usefulness of MTG technology for potential applications.
- Compare manufacturers' performance with industry standards for power quality and local emissions rules.

Data gathered by this project will be available to sponsoring agencies, participating manufacturers, and the energy industry. This project was part of a broader program to collect and disseminate independently verified operational and performance data collected from several commercially available MTGs, under standard and replicable operating conditions.

Approach and Methodology:

Three MTGs were installed at the University of California, Irvine (UCI) Combustion Laboratory and operated through July 1999. The installation dates and operating hours were:

- Bowman 35 kW, installed February 1999, operated 100.6 hours
- Bowman 60 kW, installed June 1999, operated 4.2 hours
- Capstone 28 kW, installed April 1999, operated 1,879.0 hours.

Since MTGs require natural gas pressures three to four times higher than gas delivered to commercial customers, a compressor had to be connected to the MTGs to increase the gas pressure to 60 psia.

Outcomes:

- During the test period covered by this report, both Bowman units operated on a sporadic basis due to component failures and operational restrictions imposed by unacceptably high noise levels.

- The Bowman 35 kW unit had many technical issues such as boiler leaks, failed welds, and high exhaust gas temperatures. As a result, pertinent operational data such as emissions test data could not be obtained.
- The Bowman 60 kW unit also encountered startup and operations issues relative to an inverter failure, various component failures, and difficulties adjusting air to fuel ratio.
- The emissions test results for the Bowman 60 kW unit at full load (48.3 kW) for ambient conditions yielded NOx measurements of 0.196 lbs./hour, below the 0.200 lbs./hour SCAQMD standard.
- CO of 0.73 lbs./hour was measured for the Bowman 60 kW unit at full load (48.3 kW) for ambient conditions, which was also below the SCAQMD limit of 11.0 lbs./hour.
- At full load, the Capstone 28 kW unit's efficiency averaged 23.7 percent ± 0.45, at 70 °F at low heating value (LHV). This was within the manufacturer's claim of 24.5 percent ± 0.5, at 70 °F.
- Emission test results for the Capstone 28 kW unit at full load (22.6 kW) for ambient conditions with natural gas fuel, yielded NOx measurements of 0.003 lbs./hour. This was below the 0.200 lbs./hour SCAQMD standard.
- When the Capstone unit operated at part load, efficiency was lower by three to four percent.
- For the Capstone unit during the same test period, CO of 0.11 lbs./hour was measured, which was also below the SCAQMD limit of 11.0 lbs./hour.

Conclusions:

- Testing of this technology is limited by the few micro turbine generators available for purchase.
- The Bowman units could not be operated long enough to fully capture the data sets required to make calculations for comparison to manufacturer claims.
- The Bowman units made available for testing required additional enhancements to improve operability and reliability.
- Power quality measurements were made on the Capstone 28 kW unit at full load (apparent power at 24kVA). On average, the Capstone 28 kW unit yielded current total harmonic distortion (THD) of 5.87 percent, and voltage THD of 1.6 percent. Both measurements meet IEEE 519 standard for harmonic control in electric power systems.

Recommendation:

- Further testing of micro turbine generators is required to test the validity of their claims and to determine if they can become a vital part in the electrical generating capacity mix.

Benefits to California

By gaining direct experience in the installation and start-up procedures, associated with MTG operation, knowledge is gained and data is gathered on their performance and other metrics. This information is provided to the Commission, and then made available to interested groups.

This test program also helps to bring out technical issues that manufacturers need to address and to quantify costs and efforts required for ongoing operation and maintenance of MTGs.

Abstract

The commercial availability of micro turbine generators (MTG) has been attracting the attention of potential end-users such as utilities and energy service providers.

MTG manufacturers had made performance claims that were not verified by independent, third party testing organizations. The purpose of this project was to provide an independent, third party testing and performance assessment based on data collected under standardized operating conditions. The results of this project will be available to potential customers for use in designing micro turbine applications for their specific situations.

The California Energy Commission, the United States Department of Energy, and the Electric Power Research Institute jointly funded this project from January 1998 through September 1999.

As part of a California Energy Commission funded project, ETS was able to purchase two Bowman MTGs and one Capstone MTG for testing. The Capstone MTG is a fourth generation product and ETS testing validated Capstone's performance claims. Both Bowman MTGs are first generation products and neither unit operated long enough to determine whether or not they met the manufacturer's performance claims. Bowman has offered to replace both units with "next generation" machines for testing as a part of the overall MTG testing program.

A major component of MTG performance is efficiency. Efficiency is specified by the manufacturer at a defined temperature and elevation, two variables that impact performance efficiency. MTG manufacturers base performance specifications on the International Standards Organization (ISO) standard test condition, which is 59 °F at sea level. MTG manufacturers also provide derating efficiency curves that project their product's performance at various elevations and temperatures using the ISO standard as a base reference point.

Although ISO standard test conditions could not be replicated, ETS verified the Capstone MTG efficiency claims as presented by derating curves. The Capstone unit was also assessed against the industry standard for power quality (IEEE 519) and met the standard for typical commercial operation and site location. The Capstone and one Bowman unit were assessed against the South Coast Air Quality Management District's (SCAQMD) Rule 1303 and both units tested under the rule's limits for NO_X and CO.

MTGs require gas pressures at three to four times higher than gas delivered to commercial customers. None of the MTGs tested during this funding period had installed compressors but received compressed gas from an external gas compressor. Efficiency results stated in this report are higher than would be achieved by units with installed compressors. This study could not determine how much the addition of a compressor would lower overall unit performance.

Currently available MTG units generate noise levels that must be taken into consideration in the selection of sites.

1.0 Introduction

Micro Turbine Generators (MTG) are envisioned as integral components of the future utility infrastructure that places dispersed (distributed) generation assets closer to the loads they are serving. Figure 1 depicts a MTG. The value of these units is that they allow siting of numerous, small generating assets throughout a utility's traditional distribution network where they can be operated in conjunction with the traditional power distribution system working in parallel with a central power plant. Some believe that the deployment of MTGs will advance the decentralization of power production and distribution in much the same way that personal computers and local area networks have decentralized the data processing industry.

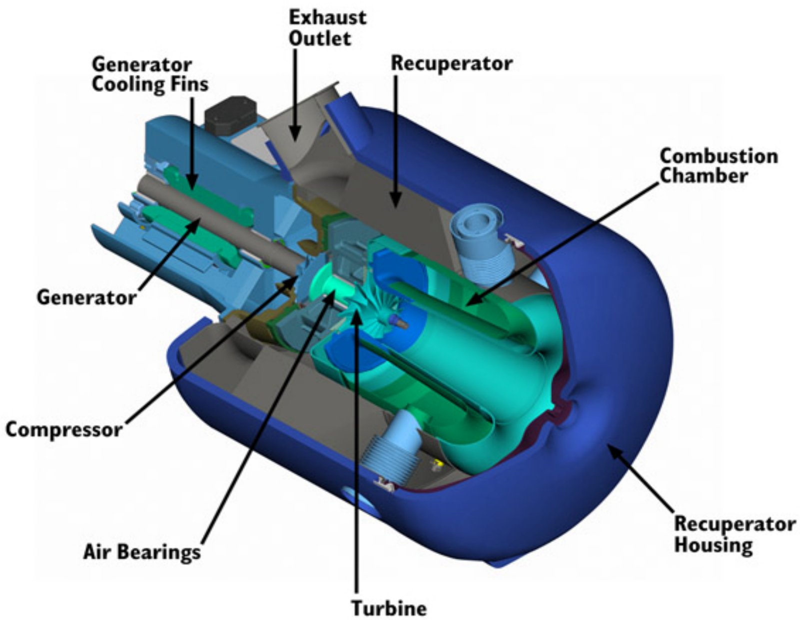

Figure 1. Micro Turbine Generator

Notwithstanding their promise, MTGs will be considered only if they perform acceptably. The MTGs now in production must meet user requirements for power quality, reliability, availability, environmental considerations, cost effectiveness, usability and system efficiency.

1.1 Project Goals

Edison Technology Solutions' goals were to demonstrate operation of small gas turbine generators, to assess the operating characteristics and to evaluate their performance. The results of this project are available for use by the Commission and by those interested in purchasing MTGs.

1.2 Summary of Funding

The total authorized budget for the overall MTG testing program is $2.1 million. Funding for the activities addressed by this report was partially provided by the Commission. Table 1 illustrates the funding share distribution for the overall program.

Table 1. Co-Funding by Agencies

Co-Funding Agency	Funding Commitment
Southern California Edison	$500,000
Electric Power Research Institute	$500,000
US Department of Energy	$600,000
California Energy Commission (PIER Funding)	$500,000

1.3 Technology Description

MTGs are small, high-speed, integrated power plants that usually include the turbine, compressor, generator, and power electronics to deliver the power to the grid. Currently available MTGs typically operate on natural gas. Future units may have the potential to use lower energy fuels such as landfill or digester gas.

The term "Micro Turbine Generator" is not formally defined by a published standard. For the purpose of this project, an MTG is a small gas turbine wholly contained in a small package, typically about 3 feet wide by 7 feet long by 6 feet high. In order to achieve the small package size, the turbine will likely be a single-stage, small diameter (less than 1 foot) radial turbine and compressor on a single shaft. It will likely be recuperated to partially offset the efficiency loss of a single-stage design. It will also likely operate at high RPM (revolutions per minute) to increase power.

During engine operation, engine air is drawn into the unit and passes through the recuperator where temperature is increased by hot exhaust gas. The airflows into the combustor where it is mixed with fuel, ignited and burned. The igniter is used only during startup, then the flame is self-sustaining.

The combusted gas passes through the turbine nozzle and turbine wheel, converting thermal energy of the hot expanding gases to rotating mechanical energy of the turbine. The turbine drives the internal compressor and generator. The gas exhausting from the turbine is directed back through the recuperator, and then out the stack.

In most cases, high-speed turbine engines drive an integrated electrical generator that produces power in the 20 kW to 100 kW range while operating at a high speed that ranges from 50,000 to 120,000 RPM. Electric power is produced in the 10,000s of Hz, converted to high voltage DC, and then inverted back to 60 Hz, 3-phase, 480 VAC by an inverter. The inverter produces current proportional to the power produced by the generator. A 480 VAC 30 kW MTG will produce about 35 amps in each phase with larger MTGs producing proportionally greater currents.

1.4 Technical Approach

The MTG Test Program is designed to identify and quantify performance parameters by installing, operating, maintaining, and testing units over time under controlled operating conditions that simulate industry operating practices. The outcome of this program will advance commercialization of the technology by providing reliable, third party data based upon actual performance measurements and observations for utilities and other potential customers.

The project attempted to procure commercially available MTGs from a variety of vendors. In addition to Bowman and Capstone, other potential turbines included units from Allied Signal, Elliott Energy Systems, and Northern Research and Engineering Corporation (NREC). The Allied Signal and Elliott MTGs were not available for testing during this project, but are expected to be procured and tested as part of the ETS distributed generation program that extends into 2000. No commercial machines were available from NREC.

1.5 Schedule

The tasks conducted under the MTG Test Project included site preparation, testing of two Bowman units and one Capstone unit. Figure 2 shows the project schedule.

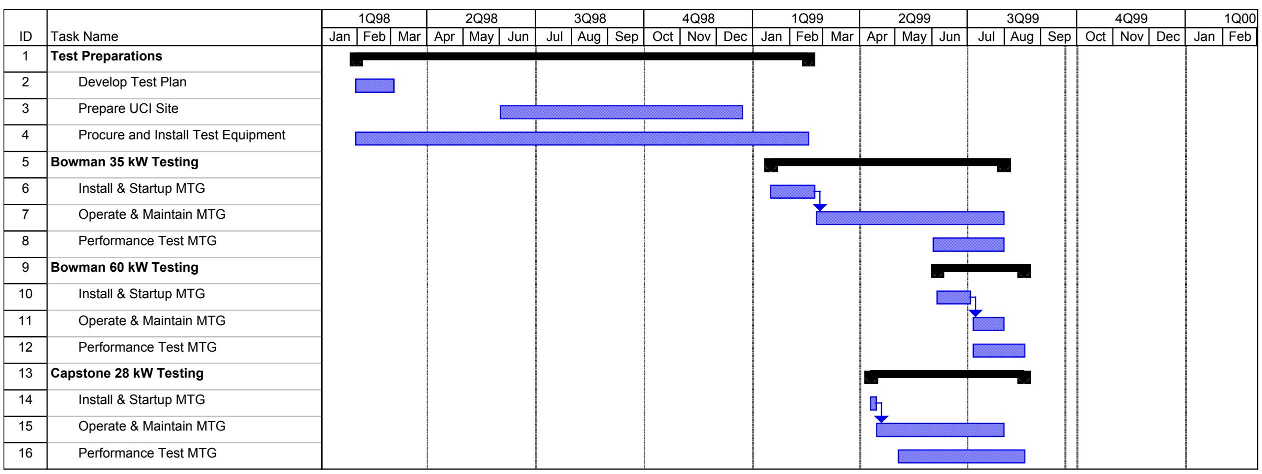

Figure 2. MTG Test Project Schedule

2.0 Project Approach

2.1 Micro Turbine Generator Technical Specifications

2.1.1 Bowman 35-Kilowatt Micro Turbine Generator

The Bowman Power Systems 35 kW MTG is ISO rated to produce continuous output power of 35 kW (44 kVA at 0.8 Power factor), 480 Volt; 3-phase, 60 Hz at ISO standard operating conditions, 15 °C (59 °F), at sea level. The range of operating temperatures specified by Bowman is –10 °C to +30 °C. The Bowman 35 kW unit uses Elliott Energy System's 45 kW engine, but is limited by the inverter to 35 kW. This unit is an early production model.

The Bowman MTG is a recuperated single stage radial flow compressor and turbine on a single shaft that is integrated with the generator. The engine operates at a normal speed of 116,000 RPM. The shaft is supported by oil lubricated bearings.

The line commutated inverter is rated for 35 kW. The inverter develops 3-phase 480 VAC line voltage (nominal). The unit's power factor is adjustable at startup during inverter calibration. Single phase 277 VAC power is required for the MTG package auxiliary systems during startup. A 4-wire 480 VAC system connection is appropriate to provide single phase 277 VAC, phase to neutral.

This unit is configured for cogeneration and has a heat exchanger for waste heat recovery (called "boiler" by Bowman) attached at the exhaust of the recuperator. The "boiler" is actually a water heater; boiling does not occur. Water is heated from a nominal inlet temperature of 158°F to 194°F at the outlet. The water pressure is 45 psig. A unique feature of the Bowman MTG is the ability to follow thermal load between about 4 therms per hour and 8 therms per hour. This is accomplished by modulating a recuperator bypass valve. Effectively, this sacrifices turbine generator efficiency (less recuperation) for increased thermal capacity. Despite the reduction in turbine generator efficiency caused by reduced recuperation, total combined heat and power efficiency increases because of the increased thermal output, and increased waste heat recovery efficiency. Increased "boiler" efficiency occurs because of the higher gas inlet temperatures that result from bypassing the recuperator. At full recuperator bypass, the inlet temperature is effectively the turbine exhaust temperature.

An external high pressure natural gas source at 87 psig is required with a maximum flow rate of 18 SCFM for full recuperator bypass operation, maximum boiler output. Thirteen SCFM is required for fully recuperated operation, minimum boiler output. Bowman now offers a natural gas compressor that was not available at the time this unit was purchased. Physical dimensions of the 35 kW unit are 78.7 inch length x 31.5 inch width x 86.6 inch height.

Figure 3 shows the Bowman 35 kW unit and 60 kW unit.

Figure 3. Bowman 60 kW (left) and Bowman 35 kW (right) MTG Units

2.1.2 Bowman 60-Kilowatt Micro Turbine Generator

The Bowman 60 kW MTG is ISO rated to produce continuous output power of 60 kW (75 kVA at 0.8 Power factor), 480 Volt; 3-phase, 60 Hz at ISO standard operating conditions, 15 °C (59 °F), at sea level. The range of operating temperatures specified by Bowman is –10 °C to +30 °C. The Bowman TG60 unit uses Elliott Energy System's 80 kW engine, but is limited by the inverter to 60 kW. This unit is an early production model.

The Bowman Power Systems 60 kW MTG is a recuperated single stage radial flow compressor and turbine on a single shaft integral with the generator. The engine operates at a normal speed of 106,000 RPM; 10,000 RPM lower than the Bowman 35 kW. The shaft is supported by oil lubricated bearings.

The line commutated inverter is rated for 60 kW, but uses an Elliott Energy Systems' engine that is the same as that used in an 80 kW package. The inverter develops 3-phase 480 VAC line voltage (nominal). Power factor is adjustable at startup during inverter calibration. Single phase 277 VAC power is required for the MTG package auxiliary systems during startup. A four-wire 480 VAC system connection is appropriate to provide single phase 277 VAC, phase to neutral

This unit is configured for cogeneration and has a waste heat recovery "boiler" attached at the exhaust of the recuperator. The boiler and recuperator are the same size as the 35 kW package. The recuperator bypass valve also allows thermal load following between about 4 therms per hour and 8 therms per hour.

An external high pressure natural gas source at 87 psig is required with a maximum flow rate of 19 SCFM for full recuperator bypass operation, maximum boiler output. Fourteen SCFM is required for fully recuperated operation, minimum boiler output.

The physical dimensions of this package are a foot longer than the 35 kW package (90.7 inch length x 31.5 inch width x 86.6 inch height); width and height dimensions are the same. Figure 3 provides a picture of the 60 kW unit.

Both designs include three compartments: the front containing the inverter and control system, the mid containing the engine, oil sump, and site service connections, and the rear containing the recuperator with the waste heat recovery boiler on top.

Minor changes in component arrangements were included with the longer 60 kW package length. The oil cooler, located in the rear compartment in the 35 kW, is located on top of the rear compartment adjacent to the front end of the "boiler." The recuperator bypass valve, located in the rear compartment in the 35 kW package, is located in the mid-compartment in the 60 kW package.

2.1.3 Bowman Micro Turbine Generator Operation Description

The Bowman MTGs generate electricity by drawing air in through the generator housing after passing beneath an oil sump. This provides additional cooling to the oil, cools the generator and provides some preheating of air. Air from the generator then flows into the compressor where it is pressurized and forced into the cold side of the recuperator. Here, exhaust heat is used to further preheat the air before it enters the combustion chamber. The pre-heating of combustion air in the recuperator reduces amount of fuel required to further heat the air to the design turbine inlet temperature. For fully recuperated operation, the recuperator reduces the fuel required by about 40 percent.

The combustion chamber mixes the heated air with fuel and burns it. This mixture expands through the turbine, which drives the compressor and generator. The combusted air exhausts through the hot side of the recuperator before discharge to the waste heat recovery boiler.

Because the recuperator bypass valve can divert some of the compressor discharge air directly to the combustor, the amount of fuel required to further heat the air to design turbine inlet temperature varies proportionately with the amount of air bypassing the recuperator. For fully recuperated operation (no compressor discharge air bypasses the recuperator), the recuperator heats the compressor discharge air at a rate of about 3 therms/hr using thermal energy from the turbine exhaust gasses. With unrecuperated operation (all compressor discharge air bypasses the recuperator), the compressor discharge air is not heated in the recuperator.

In the unrecuperated case, the 3 therms/hr not gained by the compressor discharge air in the recuperator is added by burning more fuel in the combustor. In both modes, recuperated and unrecuperated, turbine power output is constant. Because more fuel is required for unrecuperated operation, the generator efficiency decreases. However, since the recuperator does not extract thermal energy from the turbine exhaust gases during unrecuperated operation, more thermal energy is available for recovery by the boiler. In addition, the exhaust gas entering the boiler for unrecuperated operation is at a higher temperature than for recuperated operation. The higher gas temperature results in a higher boiler efficiency. The combined effect of increasing available energy by 3 therms/hr and increasing boiler efficiency results in an increase in boiler capacity of 4 therms/hr.

The high-speed generator delivers power at high frequency, 18,000 to 20,000 Hz. The power conditioner rectifies the high frequency and boosts the voltage to 800 VDC. It then inverts this DC to useful 50/60 Hz at 3-phase, 440 to 480 VAC.

2.1.3.1 Capstone 28-Kilowatt Micro Turbine Generator

The Capstone Turbine 28 kW MTG (ISO rated) is a recuperated single stage radial flow compressor and turbine on a single shaft that is integrated with the generator. The engine operates at a normal speed of 96,000 RPM. The shaft is supported by air bearings. The line commutated inverter is rated for 30 kW. The inverter develops 3-phase 480 VAC line voltage (nominal). Auxiliary systems are powered internally. This model of Capstone is equipped with a low NOx combustor. At the time of this purchase a natural gas compressor option was not available. An external high pressure natural gas source at 50-52 psig is required at a maximum flow rate of 7 SCFM. This unit is not equipped with a waste heat recovery boiler. The Capstone unit is mounted on a rack in a single enclosure. The rack is on rollers which enables the unit to be rolled out for easy access to all components. Physical dimensions of the unit are 52.9″ length x 28.1″ width x 74.8″ height. Figure 4 shows the Capstone 28 kW MTG.

Figure 4. Capstone 28 kW MTG

2.1.4 Capstone Micro Turbine Generator Operation Description

The Capstone Micro Turbine generates electricity by drawing air in through the generator cooling fins before it flows to the compressor inlet. This cools the generator and eliminates the need for any liquid cooling. Air from the generator then flows into the compressor where it is pressurized and forced into the cold side of the recuperator. Here, exhaust heat is used to preheat the air before it enters the combustion chamber. The preheating of combustion air reduces fuel consumption by about 50 percent.

The combustion chamber then mixes the heated air with fuel and burns it. This mixture expands through the turbine, which drives the compressor and generator at up to 96,000 RPM. The combusted air is then exhausted through the recuperator before being discharged at the exhaust outlet. The high-speed generator delivers power at up to 1,600 Hz. The power controller converts the power to useful 50/60 Hz at 400 to 480 VAC.

Operators can set the output power at the front panel controls. The Capstone MTGs reduces RPM as well as fuel flow at power settings below 20 kW. Lower RPM results in a lower air flow rate, and the combination of reduced air flow and fuel flow reduces power. At power settings greater than 20 kW, RPM is maintained at 96,000 RPM. Fuel flow is increased to increase power, but not to exceed a turbine exhaust temperature of 565 °C. If an increase in ambient temperature raises exhaust temperature, the control system will lower fuel flow and reduce power to maintain turbine exhaust temperature at 565 °C.

2.2 Test Procedures

To fully evaluate the MTGs, a series of tests were developed. Testing of MTGs has been categorized into the following phases:

- Installation and Startup.
- Operation and Maintenance.
- Performance.

2.2.1 Installation and Startup Procedures

Each MTG delivered to the test site was inspected and confirmed to include:

- Operating instructions.
- Repair parts or a recommended spare parts list.
- Consumable supplies.
- Troubleshooting and maintenance procedures/guides.
- Drawings and diagrams sufficient to support maintenance.

Using the operating documentation provided by the manufacturer, ETS installed and attempted to startup the units. Any difficulties resulting in the installation and startup attempt were discussed with the manufacturers to determine the proper procedure for troubleshooting or replacement of components.

2.2.2 Operation and Maintenance Procedures

After the unit was installed and successfully started, operational testing began. The first step was to be able to operate each unit reliably, until a determination could be made that the unit would not trip or malfunction. In order to do so, the MTGs start and stop capabilities were tested. In commercial use, MTGs will be expected to withstand the wear of daily starts and stops. Operators at the test site manually shut down the units several times per month to simulate operating conditions likely to be present in commercial use. At other times, the units automatically shut down due to loss of grid connection and were manually restarted.

Maintenance was conducted based on manufacturer guidelines. As instructed by the operating instructions, maintenance actions were conducted based on hours of operation.

2.2.3 Performance Procedures

System performance was determined via several tests.

2.2.3.1 Endurance and Measured Operating Parameters

For the test program, MTGs were operated for as long as practicable at the full load the units were capable of producing under ambient conditions. Daily operating parameters: fuel flow, ambient air pressure, temperature and humidity, energy output, operating temperatures, and pressures were recorded. The recorded MTG parameters were used to determine heat rate and efficiency, gross and net peak kilowatts, operating hours, capacity factor and availability. Capacity factor for an operating period is the ratio of the actual kilowatt hours generated to the maximum potential kilowatt hours for the rating of the unit. Availability for an operating period is the ratio of the hours the unit was not restricted from operation due to maintenance or repairs unit to the maximum possible hours of operation.

Peak gross power is defined as the peak power output by the MTG inverter, prior to the subtraction of any auxiliary loads. Peak net power measures the peak gross power output with the peak auxiliary load subtracted. Average net power is determined by dividing the total energy output (kWh) by the total hours of operation.

2.2.3.2 Harmonic Distortion

Harmonic distortion is a measure of the power quality. Ideally, voltage and the resulting load current are perfect sinusoids. In practice, deviations from a perfect sinusoid occur. The deviation is usually expressed in terms of harmonic distortion of the fundamental sinusoid form. Distortions normally occur in multiples of the fundamental frequency. For a 60 Hz system, the second, third, and fourth harmonics are 120 Hz, 180 Hz, and 240 Hz respectively. A distorted wave is composed of the fundamental wave combined with all of the harmonics. The Total Harmonic Distortion (THD) is measured as a percentage deviation of the composite waveform from the fundamental waveform.

Typically, distortions are caused by non-linear loads connected to the utility grid. The power inverter commonly used in MTGs is a non-linear device that injects harmonic currents into the grid as it generates power. The utility grid’s system capacitance and inductance can form resonant circuits. If a harmonic current injected is near the resonant frequency of the utility grid, a high oscillating current between resonant components could result in high harmonic voltages, which could cause adverse effects to the power system, customer loads and communication equipment.

The industry has addressed the problem of harmonics in IEEE 519, "Recommended Practices and Requirements for Harmonic Control in Electric Power Systems." The primary recommended limit is on the amount of harmonic current that a consumer (or local generator, in this case a MTG) can inject into a utility network. The recommended current limit is based on the size of the consumer relative to the size of the network. The larger the consumer, the larger the restriction. IEEE 519 quantifies the relative size of the consumer to the size of the network. It defines a short circuit ratio (SCR) and the point of common coupling (PCC) where the consumer's load connects to the network. The consumer's size is defined by total current in the site load, I_L. The network size is defined as the magnitude of the short circuit current I_{SC} at the PCC. The SCR is the ratio of I_{SC} to I_L. Installations with low SCRs are more restricted by IEEE 519 on the amount of harmonic currents that can be injected into the network than those with high SCRs.

Whether or not the harmonic distortion caused by the inverters in MTGs will exceed the limits of IEEE 519 is site dependent. The project measures total harmonic distortion with Basic Measurement Instruments (BMI) power monitoring equipment.

2.2.3.3 Noise Measurement

Ambient noise levels were measured using a handheld noise meter. Each unit was operated independently to acquire the noise measurements during operations within the configuration and operating limitations of the outdoor test site. The test site is restricted by walls, fences, and adjacent equipment that limited the distance at which sound levels could be taken. Also, because other sources of noise, such as the UCI site gas compressor were operating during the noise testing, accurate noise levels could not be measured. Therefore measurements were taken to determine general noise levels of the units.

2.2.3.4 Emissions Measurement

For each MTG type tested, at least one certified test was conducted to determine compliance with South Coast Air Quality Management District Rule 1303 for NO_X and CO emissions. Following certified tests, periodic measurements with available portable equipment may be made to determine trends and any condition of degradation that may occur with operating hours. For this MTG Test Project, one set of certified tests was conducted in August 1999.

2.3 Test Results

2.3.1 Installation and Startup Results

2.3.1.1 Results for Bowman 35 Kilowatt Micro Turbine Generator

The Bowman 35 kW was received on January 15, 1999. Installation was completed on February 11, 1999. Some delays were encountered in receiving clarification of installation drawings from Bowman. The installation of water system components resulted in a longer installation time than a package not configured for combined heat and power (cogeneration). Initial start up of the Bowman 35 kW required 6 days, concluding February 20, 1999. A Bowman start up engineer was required to be on-site for startup.

2.3.1.2 Results for Bowman 60 Kilowatt Micro Turbine Generator

The Bowman 60 kW was received on June 4, 1999. Installation was completed on June 16, 1999. Initial start up of the Bowman 60 kW required 14 days, concluding July 2, 1999.

A Bowman start up engineer was required to be on-site for startup. The extended startup date was due to an inverter failure and delay in obtaining repair parts. A second Bowman engineer more familiar with the inverter was required to support the inverter repair work.

2.3.1.3 Results for Capstone 28 Kilowatt Micro Turbine Generator

The Capstone 28 kW was received April 9, 1999. Installation was completed in 2 days. Installation interface points were easy to reach, and operating manual instructions are clear and concise. The initial start attempt failed. An electrical fault, which prevented turbine rotation was determined to be caused by a loose connector on the generator terminal housing. After tightening the connector, subsequent start attempts spun the turbine, but failed to achieve ignition. The problem was isolated to the SPV (smart proportional valve), which controls gas flow to the combustor. The valve was stuck open causing excess fuel flow. The valve was removed and returned to Capstone. A replacement was received the following day, reinstalled, and the MTG was started without problem. This installation and startup went relatively smoothly and successful start up did not require a Capstone representative to be on site.

2.3.2 Operation and Maintenance Results

2.3.2.1 Results for Bowman 35 Kilowatt Micro Turbine Generator

After initial start up, the Bowman 35 kW experienced a succession of operating problems and component failures. These included:

- Boiler leaks
- A fuel line leak due to an incomplete weld
- High exhaust gas temperatures
- Failed recuperator weld
- Inadequate recuperator weld repair
- Failed igniters
- Air to fuel ratio adjustment difficulties
- Excessive noise.

The incomplete fuel line weld required removal of the combustor for return to its manufacturer, Elliott Energy Systems (EES). The failed recuperator weld required a site visit by an EES service representative, who was unable to successfully complete a weld repair.

As a result of these problems, ETS has only been able to operate the Bowman 35 kW for a total of 100.6 hours through July 1999. ETS has been unable to obtain meaningful test data for the Bowman 35 kW due to the frequent component failures and operating problems. ETS and Bowman agreed to stop testing the 35 kW, and Bowman has agreed to replace the 35 kW with a 45 kW at no cost.

2.3.2.2 Results for Bowman 60 Kilowatt Micro Turbine Generator

The Bowman 60 kW was also unable to operate adequately to enable meaningful data collection. It operated 4.2 hours through July 1999. Emissions tests were conducted while the system was operational during a short period in August 1999.

Major operating problems and component failures include:

- Inverter failure during startup
- Inverter calibration difficulty
- Failed minor components: igniters, and a wiring harness
- Air to fuel ratio adjustment difficulties
- Excessive noise.

As of September 1999, the 60 kW unit is not operational. Bowman representatives have offered to replace the 60 kW, which is an early production model, with an 80 kW at a reduced cost.

2.3.2.3 Results for Capstone 28 Kilowatt Micro Turbine Generator

The Capstone 28 kW has operated very reliably during the test period. Capstone personnel quickly resolved one observed problem. The MTG tripped on overspeed on four occasions, May 17, 1999, May 27, 1999, May 29, 1999 and June 5, 1999. Capstone provided a modem, which site operators connected to the MTG. Using the modem, Capstone remotely downloaded historical operating data, analyzed the problem, and uploaded revised control system software, which provided finer flame control. The MTG was restarted, and has operated without any subsequent overspeed faults. Two other trips occurred due to loss of site power. The unit operated 1879.0 hours between April and July 1999.

The Capstone 28 kW operation and maintenance was relatively straightforward. Operations were conducted from an operator interface screen with easy to use menu selections for desired operations. The operator interface screen is located on the front of the unit above the circular air intake vents.

Regular maintenance consisted of cleaning the air filter at about every 500 hours of operation. Air filter cleaning required the shut down of the unit and removal and cleaning of the filter. Other routine maintenance (not yet conducted due to the number of hours of operation) includes replacement of all filters at 8,000 hours, replacement of the exhaust thermocouple at 8,000 hours, and the replacement of igniters and injectors at 16,000 hours.

2.3.3 Performance Results

Performance results were quantified to provide comparisons against manufacturer claims and applicable industry standards. Because manufacturer claims are not listed at actual test conditions, ETS has included the derated values at test conditions. The following tables identify each test parameter, corresponding manufacturer claim, derated manufacturer claim, industry standard and actual test result. Also, notes are listed for test results that require further clarification.

For Endurance and Measured Operating Parameters, manufacturer claims are at ISO conditions; no standards apply to these results. For Harmonic Distortion, there are no manufacturer claims; ETS applied IEEE 519 as the industry standard for comparison. For Noise, manufacturer claims are based on measurements at 10 meters; no standards apply to these tests. For Emissions, ETS applied SCAQMD Rule 1303 as the basis for comparison.

2.3.3.1 Results for Bowman 35 Kilowatt Micro Turbine Generator

Performance data is limited for the Bowman 35 kW MTG, as it has not operated sufficiently to provide meaningful data. Subjectively this unit has not been easy to operate or maintain. Frequent material and design problems have prevented sustained operation, and as a result, the Bowman 35 kW unit operated only 100.6 hours between February and July 1999.

Noise was an issue that limited operation of the unit. The unit was deemed too loud to operate during the evening (due to the close proximity of tenants). A silencer was retrofitted on the unit, which resulted in a reduction in noise by about 10 dBA at 2 meters.

Table 2 summarizes results subsequent to silencer retrofitting of the Bowman 35 kW MTG. The test facility did approve evening operation for this unit towards the end of the test period, however, the unit was not operational.

Peak gross power and peak net power were measured. Peak gross power was measured at the output of the inverter at 35.0 kW, which met the claim of the manufacturer. Auxiliary loads decreased this value to 33.6 kW, which is referred to as the peak net power.

Table 2. Bowman 35 kW MTG Performance Results

Test	Test Parameter	Mfg. Claim	Derated Mfg. Claim	Industry Standard	Actual Test Result	Notes
Endurance and Measured Operating Parameters	Cumulative Operating Hours	N/A	N/A	N/A	100.6	1
	Cumulative Energy (kWh)	N/A	N/A	N/A	2416	
	Efficiency (%)	None	None	None	Insufficient Data	
	Heat Rate (BTU/kWh)	None	None	None	Insufficient Data	
	Fuel Rate (Therms/Hr)	13 to 18	N/A	None	Insufficient Data	2
	Waste Heat Recovery (Therms/Hr)	4 to 8	N/A	N/A	Insufficient Data	2
	Capacity Factor (%)	None	None	None	Insufficient Data	
	Availability (%)	None	None	None	Insufficient Data	
	Peak Gross Power (kW)	35	35.0	None	35.0	
	Peak Net Power (kW)	None	None	None	33.6	
	Avg. Net Power (kW)	None	None	None	Insufficient Data	
Harmonic Distortion	Total Harmonic Distortion (THD)	None	None	IEEE 519	Insufficient Data	
Noise	Noise Level (dBA)	70 dBA at 10m	N/A	None	90 dBA at 2m	3
Emissions (measured constituents at full load)	NOx (ppm corrected to 15%)	None	None	SCAQMD Rule 1303 [0.2 lbs./hr]	Not Tested	
	CO (ppm corrected to 15%)	None	None	SCAQMD Rule 1303 [11.0 lbs./hr]	Not Tested	

Table 2 Notes:

1 Bowman 35 kW MTG evaluation period: 2/21/99 to 7/30/99.

2 Performance results variable due to recuperator bypass.

3 The site configuration, proximity to fences, walls, nearby equipment, etc. prevented measurements at 10 meters. This test was conducted with an exhaust silencer retrofitted. The test result of 90 dBA at 2 meters is similar to sound levels in a noisy factory, and defined as "Very Loud." The manufacturer's claim of 70 dBA at 10 meters does not include an exhaust silencer (70 dBA is comparable to average street noise and is defined as "Loud," as defined in Marks' Standard Handbook for Mechanical Engineers, 7th edition, McGraw-Hill, p. 12-181.).

2.3.3.2 Results for Bowman 60 Kilowatt Micro Turbine Generator

The Bowman 60 kW unit has also had its share of technical issues that required much troubleshooting and repair work. As a result, the unit operated only 4.2 operating hours through July 1999. This unit also exhibited excessive noise during operation. ETS measured 100 dBA at 2 meters (subsequent to silencer retrofitting), that exceeded its 70 dBA at 10 meters claim. A handheld meter was used to take measurements at 2 meters, since the surrounding equipment prevented taking measurements at 10 meters. Note that due to the outdoor location of the test site and the surrounding noise contributions of other machinery (namely, site gas compressor) these tests are not precise, but provide an indication of the noise level.

Table 3 shows the manufacturer's claimed peak gross power to be 60 kW; limited testing only allowed a peak value of 50.0 kW to be achieved. This is a result of the unit running during days with relatively high ambient temperatures that limited the unit from operating any higher than 50.0 kW. During this same test period, the peak net power was measured to be 48.6 kW.

Table 3. Bowman 60 kW MTG Performance Results

Test	Test Parameter	Mfg. Claim	Derated Mfg. Claim	Industry Standard	Actual Test Result	Notes
Endurance and Measured Operating Parameters	Cumulative Operating Hours	N/A	N/A	N/A	4.2	1
	Cumulative Energy (kWh)	N/A	N/A	N/A	40.6	
	Efficiency (%)	None	None	None	Insufficient Data	
	Heat Rate (BTU/kWh)	None	None	None	Insufficient Data	
	Fuel Rate (Therms/Hr)	14 to 19	N/A	None	Insufficient Data	2
	Waste Heat Recovery (Therms/Hr)	4 to 8	N/A	N/A	Insufficient Data	2
	Capacity Factor (%)	None	None	None	Insufficient Data	
	Availability (%)	None	None	None	Insufficient Data	
	Peak Gross Power (kW)	60	54.0	None	50.0	3
	Peak Net Power (kW)	None	None	None	48.6	
	Avg. Net Power (kW)	None	None	None	Insufficient Data	
Harmonic Distortion	Total Harmonic Distortion (THD)	None	None	IEEE 519	Insufficient Data	
Noise	Noise Level (dBA)	70 dBA @ 10m	N/A	None	100 dBA @ 2m	4
Emissions (measured constituents at full load)	NOx (ppm corrected to 15%)	None	None	SCAQMD Rule 1303 [0.2 lbs./hr]	62 ppm; 0.196 lbs./hr	5
	CO (ppm corrected to 15%)	None	None	SCAQMD Rule 1303 [11.0 lbs./hr]	376 ppm; 0.73 lbs./hr	

Notes:

1 Evaluation Period: 7/2/99 to 7/30/99.

2 Variable due to recuperator bypass.

3 The manufacturer's claim of 60 kW is at ISO conditions (59 °F, sea level). The test site is approximately at sea level, ambient temperature was 84 °F at the time the test result value was recorded. The manufacturer's derating curves claim a reduction to 54.0 kW at 84 °F.

4 The site configuration, proximity to fences, walls, nearby equipment, etc. prevented measurements at 10 meters. The test was conducted with an exhaust silencer installed. The result of 100 dBA at 2 meters is typical of the sound level in a boiler factory; between "Very Loud" and "Deafening," as defined in Marks' Standard Handbook for Mechanical Engineers, 7th edition, McGraw-Hill, p. 12-181. The manufacturer's claim of 70 dBA at 10 meters does not include an exhaust silencer installed (70 dBA is typical of average street noise, and "Loud," as defined in Marks' Standard Handbook for Mechanical Engineers, 7th edition, McGraw-Hill, p. 12-181).

5 Test conditions: Load at 48.3 kW; flue conditions at 217 °F, 17.97 percent O_2, 1.71 percent CO_2. Results from Emissions Test Report by Fossil Energy Research Corporation.

The unit was operational during emissions testing conducted in August 1999. This equipment is classified under New Source Review with SCAQMD Rule 1303 establishing the requirements. Table A-1 of Rule 1303 sets NOx and CO emission limits of 0.2 lbs./hr and 11.0 lbs./hr respectively. Emissions were less than the limits established by SCAQMD Rule 1303 for both NO_X and CO.

2.3.3.3 Results for Capstone 28-Kilowatt Micro Turbine Generator

The Capstone 28kW MTG operated reliably throughout the test period. Tabulated operating hours are at full load through July 1999. The full load rating of 28 kW at ISO conditions, 59 °F ambient temperature and sea level, was not achieved because local ambient temperatures averaged between 67 to 72 °F. The reduced output due to ambient conditions has been consistent with the manufacturer's claims and with derating curves published in the operating manual.

Noise levels were not measured in a manner that enabled direct comparison to the manufacturer's claims. As previously stated, the presence of other sources of noise at the outdoor test site prevents accurate sound measurements. The results presented in the following table do indicate that the 70 dBA measured at 2 meters are close to the manufacturer's claim of 65 dBA at 10 meters.

Capstone 28 kW Power Quality Test Results

A Basic Measurement Instruments (BMI) power quality meter was used to capture waveform snapshots of the Capstone 28 kW MTG on June 22nd. Figure 5 and Figure 6 show a sample 3-phase waveform captured at full power (Apparent power at 24 kVA), for voltage and current, respectively. Total Harmonic Distortion (THD), as defined in Section 3.4.3.2, in the voltage snapshot is at 1.6 percent, and was constant throughout the test. The current snapshot shows some distortion. The range of measurements for current THD is from 3.86 to 7.63 percent, based on snapshots that were captured in 1-second intervals for a total test period of 10 seconds. Current THD measured per phase yielded an average value of 5.87 percent.

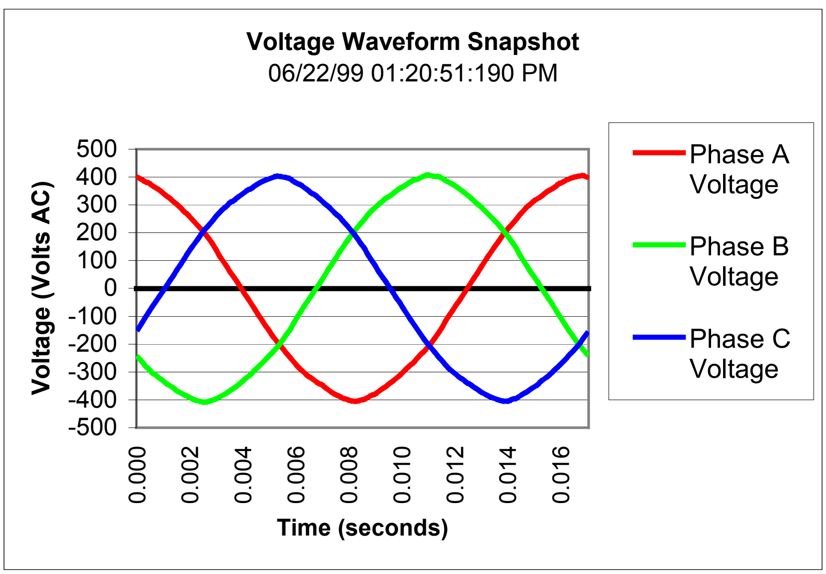

Figure 5. Capstone 28 kW MTG Voltage Waveform Snapshot

Figure 6 represent the THD value for current (which is higher than that of voltage THD) as unclean sinusoidal waveforms.

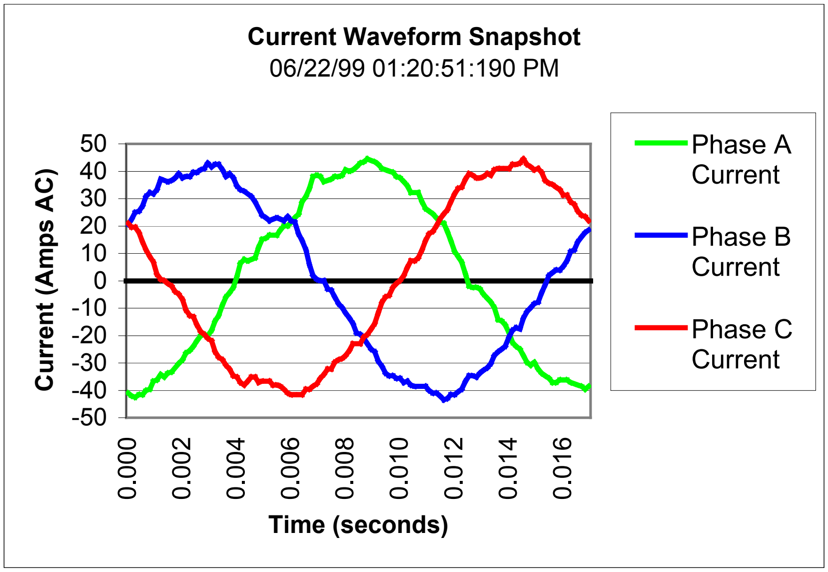

Figure 6. Capstone 28 kW MTG Current Waveform Snapshot

Guidelines on harmonics are provided by the IEEE 519-1992 Standard: IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, IEEE, New York. The primary limit on individual customers is the amount of harmonic current that they may inject into the utility network, based on the size of the consumer relative to the size of the supply at the point of common coupling (PCC). PCC is where the consumer's load connects to the other loads in the power system.

Compared to the IEEE 519 standard, the Capstone 28 kW MTG voltage THD of 1.60 percent is less than the 5 percent ceiling. Current THD of 5.87 percent is also within IEEE 519 limit of 8 percent, based on the ratio between supply size at UCI Combustion Laboratory and MTG output that is between 20:1 to 50:1.

Capstone 28 kW Emissions Test Results

Emissions tests were conducted on the Capstone unit. This unit does not fall under SCAQMD Rule 2005 as formerly exempted equipment under Rule 219, gas turbines with a maximum heat input of less then 2,975,000 BTU/hr. As such, it falls under New Source Review with Rule 1303 establishing the requirements. Table A-1 of Rule 1303 sets NOx and CO emission limits at 0.2 lbs./hr and 11.0 lbs./hr respectively for combustion sources with heat input of less than 2 million BTU/hr. Emissions were within limits established by SCAQMD Rule 1303 for both NOx and CO.

Capstone 28 kW Efficiency and Heat Rate Test Results

Capstone claims an efficiency of 26 percent ± 0.5 percent and heat rate 13,200 Btu/kWh at ISO standard conditions using the low heating value (LHV) of the fuel. The test results were conducted at ambient conditions, not ISO standards. Also high heating value (HHV) of the fuel was used to calculate heat rate and efficiency shown in the table. This is consistent with gas company billing and useful for economic analysis. At 70 °F, the test result was 16,209 BTU/kWh HHV heat rate (21.4 percent efficiency).

Capstone includes derating curves in the operating manual. The derating curves show the efficiency and net power with ambient temperature and elevation. Using the derating curve, the expected efficiency (based on LHV) for operation at 70 °F is about 24.5 percent ± 0.5. So the measured efficiency of 23.7 percent ± 0.45 percent is within the manufacturer's claims and its derating curves.

Capstone 28 kW Part Load Testing Results

On July 29th, ETS initiated part load tests on the Capstone unit. This test is intended to be analyzed as part of the ETS overall program. As such, the results were not included in the cumulative totals (Table 4). For several days of data collected as part of the MTG Test Project, the efficiency was reduced by three to four percent from full load efficiency.

Table 4 summarizes the performance test results for the Capstone 28 kW MTG.

Table 4. Capstone 28 kW MTG Performance Results

Test	Test Parameter	Mfg. Claim	Derated Mfg. Claim	Industry Standard	Actual Test Result	Notes
Endurance and Measured Operating Parameters	Operating Hours	N/A	N/A	N/A	1,793.0	1
	Energy (kWh)	N/A	N/A	N/A	42,947	1
	Efficiency (%)	See Section 3.5.3.3	None	None	21.1% at HHV	
			24.5 ±0.5 at LHV		23.7% ± 0.45 at LHV	
	Heat Rate (BTU/kWh)	See Section 3.5.3.3	None	None	16,209 at HHV	
			14,222 at LHV		14,415 at LHV	
	Fuel Rate (Therms/Hr)	7	None	None	6.35	
	Waste Heat Recovery (Therms/Hr)	N/A	N/A	N/A	N/A	
	Capacity Factor (%)	None	None	None	54.9%	2
	Availability (%)	None	None	None	94.4%	
	Peak Gross Power (kW)	None	None	None	27.0	3
	Peak Net Power (kW)	None	None	None	26.6	
	Avg. Net Power (kW)	None	None	None	24.0	
Harmonic Distortion	Total Harmonic Distortion (THD)	None	None	IEEE 519: Current < 8.0% Voltage < 5.0%	Current = 5.87% Voltage = 1.60%	4
Noise	Noise Level (dBA)	65 dBA @ 10m	N/A	None	70 dBA at 2m	5
Emissions (measured constituents at full load)	NO_X (ppm corrected to 15%)	<9 ppm <0.0225 lbs./hr	N/A	SCAQMD Rule 1303 [0.2 lbs./hr]	2.4 ppm; 0.0031 lbs./hr	6
	CO (ppm corrected to 15%)	None	N/A	SCAQMD Rule 1303 [11.0 lbs./hr]	143 ppm; 0.11 lbs./hr	

Notes:

1 Evaluation Period: 4/16/99 to 7/30/99. Part load test results, initiated on 7/28/99, are not included in this table. This accounts for the difference between 1,879.0 total operating hours recorded versus the 1793.0 hours listed in the table as hours operated at full load.

2 Low capacity factor is due to the down time when the site gas compressor was being serviced, and other down time due to maintenance or loss of grid.

3 Highest Peak Gross Power (kW) observed by operators occurred when local ambient temperature was 66 °F. Manufacturer derating curves predict peak power to decrease to 27.5 kW ±0.5 kW at 66 °F.

4 Both current and voltage THD are within IEEE 519.

5 The site configuration, proximity to fences, walls, nearby equipment, etc. prevented measurements at 10 meters. There was no silencer required for this unit. There was no silencer required for this unit. The test result of 70 dBA at 2 meters is typical of average street noise, and "Loud." The manufacturer's claim of 65 dBA at 10 m is typical of an average factory and "Loud." as defined in Marks' Standard Handbook for Mechanical Engineers, 7th edition, McGraw-Hill, p. 12-181.

6 Test conditions: Load at 22.6 kW; flue conditions at 545 °F, 18.68 percent O_2, 1.40 percent CO_2. Results from Emissions Test Report by Fossil Energy Research Corporation.

2.4 Installation and Operational Testing Obstacles

Three available MTGs were installed at UCI's Combustion Laboratory and operated through July 1999. The installation dates and operating hours for the units covered by this report were:

- Bowman 35 kW, installed February 1999, operated 100.6 hours
- Bowman 60 kW, installed June 1999, operated 4.2 hours
- Capstone 28 kW, installed April 1999, operated 1,879.0 hours

2.4.1 Obstacles for Bowman 35 Kilowatt and 60 Kilowatt Micro Turbine Generators

The very low operating hours are indicative of the many problems encountered in attempting to startup and operate the Bowman units. Both have been off-line extensively due to troubleshooting, repairs, getting components to and from the manufacturer, and inability to run units in the evenings due to excessive noise. These problems are discussed further in Section 3.0 of this report.

One of the issues that affected operation of the Bowman units was their excessive noise. Although both units are rated at 70 dBA at 10 meters, their actual noise levels are about 100 dBA at 2 meters (which is comparable to loud street noise as described in Marks' Standard Handbook for Mechanical Engineers, 7th edition, McGraw-Hill, p. 12-181). Silencers were retrofitted to reduce the turbine noise by 10 percent for both units. Site configuration, proximity to buildings and obstructing equipment prevented sound level measurements at 10 meters. Nearby apartment tenants complained about the noise during the evenings, and therefore the Bowman units were only allowed to operate in the daytime. Towards the end of the test period, ETS was granted permission to operate the 35 kW unit during the evening, however the unit was not operational. ETS did not receive permission to operate the 60 kW unit during the evening.

2.4.2 Obstacles for Capstone 28 Kilowatt Micro Turbine Generators

During the first month of operation, the Capstone 28 kW tripped four times on overspeed faults. A software upgrade, which corrected flame instability, was remotely uploaded by Capstone via phone modem. No subsequent overspeed trips have occurred.

The Capstone unit has operated reliably since the software upgrade. The unit operated continuously, with the exception of shut downs for scheduled MTG maintenance, site gas compressor repair and maintenance, and loss of grid (two occurrences).

2.5 General Information on Installation and Operational Testing Obstacles

Most MTGs operate at a pressure ratio in the 3:1 to 4:1 range. As such, the compressor discharge and combustor operating pressure are in the vicinity of 45 to 60 psia. The fuel needs to be at high enough pressure to inject fuel into the combustor for mixing and burning. Most sites do not have natural gas available at the high pressure required. MTG manufacturers recognized this limitation, and all either provide as an option or have programs to develop natural gas compressors suitable to meet the pressure and flow rate requirements for their MTGs. The addition of an integral gas compressor will increase the MTG parasitic auxiliary loads, and result in decreased efficiency.

When purchased, the three MTGs tested under the ETS program did not have gas compressor options available (though the manufacturers of these initial MTGs now offer compressor option packages). The UCI Combustion Laboratory site has a large gas compressor, which has sufficient capacity to provide the pressures and flow rates for the MTG project needs. The individual gas compressors to be retrofitted on MTGs are an auxiliary load that will reduce the net kilowatt output of the MTG (order of magnitude 1 to 5 kW), with a resultant adverse impact in efficiency. Larger MTGs will require higher power compressors to accommodate their higher fuel delivery rates. The actual power required is dependent on three factors: the MTG's pressure ratio, the fuel rate, and the compressor inlet pressure. At higher pressure ratios and fuel rates, and lower inlet pressures, the gas compressor will require more parasitic power. As a part of the overall MTG testing program, compressors provided by the manufacturer will be evaluated and parasitic loads determined. Parasitic loads without compressors for the three units tested are detailed in the performance summary tables in Section 3.5.3.

Gas turbine manufacturers evaluate turbine efficiency according to standards established by the turbine community. The purpose of the standards is to normalize turbine performance to a standard operating condition in order to compare different gas turbines fairly. Because gas turbine performance is significantly affected by ambient conditions, standard ambient conditions are defined and used. These are normal atmospheric pressure at sea level and air temperature of 59 °F. As actual ambient temperature increases, actual gas turbine performance decreases. Similarly, as actual elevation increases and actual atmospheric pressure decreases, actual gas turbine performance decreases. MTG manufacturers publish "derating curves" that define nominal MTG full load output power over the range of expected ambient conditions. The nominal rating of the MTG is based on the standard conditions. Consumers should evaluate prospective MTGs based on the expected ambient conditions (elevation and temperature) for their application location using the manufacturer derating curves.

Single stage recuperated gas turbines are limited in efficiency. Larger turbines operate at higher temperatures and have multi-stage compressors achieving higher pressure ratios with resultant increase in efficiency. Current materials used in construction of MTGs limits turbine inlet temperature, which when combined with single stage design results in MTG efficiency limits below 30 percent. Further studies on the impact of low efficiency distributed generation assets and their economic viability should be conducted.

3.0 Conclusions and Recommendations

3.1 Project Objectives

- Compare manufacturers' performance claims against actual experience from project activities. This independently developed information is intended to aid prospective MTG users in evaluating the usefulness of MTG technology for potential applications.
- Compare manufacturers' performance with industry standards for power quality and local emissions rules.

3.2 Project Outcomes

- During the test period covered by this report, both Bowman units operated on a sporadic basis due to component failures and operational restrictions imposed by unacceptably high noise levels.
- The Bowman 35 kW unit had many technical issues such as boiler leaks, failed welds, and high exhaust gas temperatures. As a result, pertinent operational data such as emissions test data could not be obtained.
- The Bowman 60 kW unit also encountered startup and operations issues relative to an inverter failure, various component failures, and difficulties adjusting air to fuel ratio.
- The emissions test results for the Bowman 60 kW unit at full load (48.3 kW) for ambient conditions yielded NOx measurements of 0.196 lbs./hour, below the 0.200 lbs./hour SCAQMD standard.
- CO of 0.73 lbs./hour was measured for the Bowman 60 kW unit at full load (48.3 kW) for ambient conditions, which was also below the SCAQMD limit of 11.0 lbs./hour.
- At full load, the Capstone 28 kW unit's efficiency averaged 23.7 percent ± 0.45, at 70 °F at low heating value (LHV). This was within the manufacturer's claim of 24.5 percent ± 0.5, at 70 °F.
- Emission test results for the Capstone 28 kW unit at full load (22.6 kW) for ambient conditions with natural gas fuel yielded NOx measurements of 0.003 lbs./hour. This was below the 0.200 lbs./hour SCAQMD standard.
- When the Capstone unit operated at part load, efficiency was lower by three to four percent.
- For the Capstone unit during the same test period, CO of 0.11 lbs./hour was measured, which was also below the SCAQMD limit of 11.0 lbs./hour.
- Power quality measurements were made on the Capstone 28 kW unit at full load (apparent power at 24kVA). On average, the Capstone 28 kW unit yielded current total harmonic distortion (THD) of 5.87 percent, and voltage THD of 1.6 percent. Both measurements meet IEEE 519 standard for harmonic control in electric power systems.

3.3 Project Conclusions

- Testing of this technology is limited by the few micro turbine generators available for purchase.
- The Bowman units could not be operated long enough to fully capture the data sets required to make calculations for comparison to manufacturer claims.
- The Bowman units purchased for testing required additional enhancements to improve operability, maintainability, reliability and noise reduction.
- The Capstone 28 kW met both the manufacturer's performance claims as well as applicable local and industry standards. The Capstone 28 kW was subjectively judged by the testing crew to be easy to install, maintain, and operate.
- Validation of efficiency claims for Capstone.
- Successful testing to meet the emission levels for Capstone and the Bowman 60 kW unit.

3.4 Project Recommendation:

Further testing of micro turbine generators is required to test the validity of their claims and to determine if they can become a vital part in the electrical generating capacity mix.

3.5 Commercialization Potential

The commercialization potential of MTGs in California is dependent on the ability of MTGs to function as viable, reliable products ready for deployment. End users are interested in factors such as cost-effectiveness and operational performance.

Capstone, a California-based manufacturer, is in the process of marketing their MTG, which is a fourth generation unit. Their product is already being sold for applications such as oilfield flare gas reduction and can be seen on www.capstonetubine.com. Capstone has been provided with technical feedback based on testing conducted by ETS.

Bowman, a United Kingdom-based manufacturer, is refining their first generation product for commercialization. Bowman has also been provided with technical feedback based on testing conducted by ETS.

3.6 Benefits to California

By gaining direct experience in the installation and start-up procedures, associated with MTG operation, knowledge is gained and data is gathered on their performance and other metrics. This information is provided to the Commission, and then made available to interested groups.

This test program also helps to bring out technical issues that manufacturers need to address and to quantify costs and efforts required for ongoing operation and maintenance of MTGs.