THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

SOUTHERN RESEARCH INSTITUTE

ETV Joint Verification Statement

TECHNOLOGY TYPE:	Biogas-Fired Internal Combustion Engine Combined With Heat Recovery System
APPLICATION:	Distributed Electrical Power and Heat Generation
TECHNOLOGY NAME:	Martin Machinery Internal Combustion Engine
COMPANY:	Colorado Pork, LLC
ADDRESS:	Lamar, Colorado

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the purchase, design, distribution, financing, permitting, and use of environmental technologies.

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

The Greenhouse Gas Technology Center (GHG Center), one of six verification organizations under the ETV program, is operated by Southern Research Institute in cooperation with EPA's National Risk Management Research Laboratory. A technology of interest to GHG Center stakeholders is the use of microturbines and engines as distributed generation sources. Distributed generation (DG) refers to power-generation equipment that provides electric power at a site much closer to customers than central station generation. Recently, biogas production from livestock manure management facilities has become a promising alternative for fueling DG technologies. These technologies, commonly referred to as anaerobic digesters, decompose manure in a controlled environment and recover methane produced from the manure digestion. The recovered methane can fuel power generators to produce electricity, heat, and hot water. Digesters also reduce foul odor and can reduce the risk of ground- and surface-water pollution.

The GHG Center collaborated with the Colorado Governor's Office of Energy Management and Conservation (OEMC) to evaluate the performance of two combined heat and power systems (CHP systems) that operate on biogas recovered from anaerobic digestion of swine waste at the Colorado Pork farm in Lamar, Colorado. This verification statement provides a summary of the test results for the internal combustion (IC) engine CHP system designed and installed by Martin Machinery, Inc.

TECHNOLOGY DESCRIPTION

The following technology description is based on information provided by Martin Machinery and OEMC and does not represent verified information. The CHP system tested includes an IC engine, a generator, and a heat exchanger. Power is generated with a Caterpillar (Model 3306 ST) IC engine with a rated nominal power output of 100 kW (60 °F, sea level). The engine is a 6 cylinder, 4-stroke, naturally aspirated unit with a 10.5:1 compression ratio and a speed range of 1,000 to 1,800 rpm. The IC engine is used to drive an induction generator manufactured by Marathon Electric (Model No. MCTG-80-3).

The generator produces nominal 208 volts alternating current. The unit supplies a constant electrical frequency of 60 Hz, and is equipped with a control system that allows for automatic and unattended operation. All operations, including startup, operational setting (kW command), dispatch, and shutdown, are performed manually. Electricity generated at this load is fully consumed by equipment used at the facility. During normal farm operations, power demand exceeds the available capacity of the engine/generator set, and power is drawn from the grid. On rare occasions when the power generated exceeds farm demand, a reverse power relay (required by the utility company) throttles down the engine. In the event of a grid power failure, the biogas induction generator is shut down, and the facility has a backup emergency generator to provide power for farm operations.

No digester gas conditioning or compression is needed to operate the engine under site conditions. Digester gas is directed to the engine and fired at the pressure created in the digester (approximately 17 to 18 inches water column). Because the digester gas is not conditioned (e.g., moisture and sulfur removal), engine lubrication oil is changed every 10 days as precautionary maintenance. The configuration of the engine's fuel input jets, along with the low heating value of the biogas (approximately 625 Btu/scf), currently restrict the engine's power output to approximately 45 kW. This is lower than the equipment manufacturer's (Caterpillar) recommended minimum rating for this engine.

The engine is equipped with a Thermal Finned Tube (Model 12-12-60CEN-W) heat exchanger for heat recovery. The heat recovery system consists of a fin-and-tube heat exchanger that circulates water through the heat exchanger at approximately 120 gallons per minute (gpm). The engine exhaust, at approximately 1,100 °F, is the primary source of heat to the exchanger. The engine cooling water is also cycled through the digester heating loop to recover additional heat and provide engine cooling. Circulation of engine coolant is thermostatically controlled to maintain coolant temperature at approximately 175 °F. In the event temperatures exceed 185 °F, excess heat is discarded with the use of an external radiator. The radiator's return water line serves as the coolant for the engine water jacket.

The Colorado Pork facility is a sow farrow-to-wean farm in Lamar, Colorado that began operation in 1999 and houses up to 5,000 sows. The facility employs a complete mix anaerobic digester to reduce odor and meet water quality regulations mandated by the Colorado Department of Public Health and Environment. The anaerobic digester promotes bacterial decomposition of volatile solids in animal wastes. The resulting effluent stream consists of mostly water, which is allowed to evaporate from a secondary lagoon. Solids produced by the process accumulate in the digester and are manually removed. Recovered heat from the IC engine CHP is circulated through the waste in the digester to maintain the digester temperature at approximately 100 °F. Cool water returning from the digester remains relatively constant throughout the year (approximately 100 °F). A temperature sensor continuously monitors this temperature, and in the event this temperature exceeds 105 °F, an automated mixing valve reduces the flow of hot water entering the digester.

VERIFICATION DESCRIPTION

Testing was conducted during the period of February 2 through 13, 2004. The verification included a series of controlled test periods in which the GHG Center intentionally controlled the unit to produce electricity at three power output levels within its range of operation at this site including 30, 38, and 45 kW. Three replicate test runs were conducted at each setting. The controlled test periods were preceded by 9 days of continuous monitoring to verify electric power production, heat recovery, and power quality performance over an extended period. Normal site operations were maintained during all test periods, where heat was recovered and routed through the digester at temperatures of approximately 105 °F. The classes of verification parameters evaluated were:

- **Heat and Power Production Performance**
- **Emissions Performance (NO_x, CO, CH_4, SO_2, TRS, TPM, NH_3, and CO_2)**
- **Power Quality Performance**

Evaluation of heat and power production performance included verification of power output, heat recovery rate, electrical efficiency, thermal efficiency, and total system efficiency. Electrical efficiency was determined according to the ASME Performance Test Code for Internal Combustion Engines (ASME PTC-17). Tests consisted of direct measurements of fuel flow rate, fuel lower heating value (LHV), and power output. Heat recovery rate and thermal efficiency were determined according to ANSI/ASHRAE test methods and consisted of direct measurement of heat-transfer fluid flow rate and differential temperatures. Ambient temperature, barometric pressure, and relative humidity measurements were also collected to characterize the condition of the combustion air used by the engine. All measurements were recorded as 1-minute averages during the controlled test periods and throughout the 7-day monitoring period.

The evaluation of emissions performance occurred simultaneously with efficiency testing. Pollutant concentration and emission rate measurements for nitrogen oxides (NO_X), carbon monoxide (CO), total hydrocarbons (THC), methane (CH_4), sulfur dioxide (SO_2), total reduced sulfur (TRS), total particulate matter (TPM), ammonia (NH_3), and carbon dioxide (CO_2) were conducted in the engine exhaust stack. All test procedures used in the verification were U.S. EPA reference methods recorded in the Code of Federal Regulations (CFR). Pollutant emissions are reported as concentrations in parts per million volume, dry (ppmvd) corrected to 15-percent oxygen (O_2), and as mass per unit time (lb/hr). The mass emission rates are also normalized to engine power output and reported as pounds per kilowatt hour (lb/kWh).

Annual NO_X and CO_2 emissions reductions for the engine were estimated by comparing measured lb/kWh emission rates with corresponding emission rates for the baseline power-production systems (i.e., average regional grid emission factors for U.S. and Colorado). Electrical power quality parameters, including electrical frequency and voltage output, were measured during the 9-day extended test. Current and voltage total harmonic distortions (THD) and power factors were also monitored to characterize the quality of electricity supplied to the end user. The guidelines listed in "The Institute of Electrical and Electronics Engineers' (IEEE) Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems" were used to perform power quality testing.

Quality Assurance (QA) oversight of the verification testing was provided following specifications in the ETV Quality Management Plan (QMP). The GHG Center's QA manager conducted an audit of data quality on at least 10 percent of the data generated during this verification and a review of this report. Data review and validation was conducted at three levels including the field team leader (for data generated by subcontractors), the project manager, and the QA manager. Through these activities, the QA manager has concluded that the data meet the data quality objectives that are specified in the Test and Quality Assurance Plan.

VERIFICATION OF PERFORMANCE

Test results are representative of engine operations at this site only. Although not independently verified, heat and power production performance and particularly CO and THC emissions performance were likely negatively impacted by operating the engine below manufacturer's recommended minimum rating. The digester system's operation, maintenance, or design could have also negatively impacted engine performance.

Heat and Power Production Performance

ENGINE CHP HEAT AND POWER PRODUCTION					
Test Condition (Power Command)	Electrical Power Generation		Heat Recovery Performance		Total CHP System Efficiency (%)
	Power Delivered (kW)	Efficiency (%)	Heat Recovery (10^3Btu/hr)	Thermal Efficiency (%)	
45 kW	44.7	19.7	250	32.4	52.1
38 kW	37.5	17.1	227	30.3	47.4
30 kW	29.6	13.8	219	30.0	43.8

- At a 45 kW power command, average power output was 44.7 kW and electrical efficiency averaged 19.7 percent.

- Electrical efficiency at the reduced loads was 17.1 percent at a power output of 37.5 kW, and 13.8 percent at 29.6 kW.

- Total CHP efficiency during the controlled test periods ranged from 52.1 percent at the 45 kW load to 43.8 percent at 30 kW. Normal heat recovery operations were maintained during the controlled test periods with the system configured to maintain the digester temperature at approximately 100 °F.

- During the 9-day monitoring period, the engine operated on biogas for a total of 75 hours. During this time, a total of 3,358 kWh electricity was generated at an average rate of 44.6 kW, and 17.85 million Btu (5,232 kWh) of heat was recovered and used at an average heat recovery rate of 238 x 10^3 Btu/hr.

Emissions Performance

ENGINE EMISSIONS (lb/kWh)								
Power Command	NO_X	CO	CH_4	SO_2	TRS	TPM	NH_3	CO_2
45 kW	0.012	0.058	0.112	0.023	0.005	0.00009	0.000004	1.97
38 kW	0.006	Above range	0.114	0.024	0.007	Not tested	Not tested	2.07
30 kW	0.002	Above range	0.150	0.030	0.009	Not tested	Not tested	2.21

- NO_X emissions at 45 kW were 0.012 lb/kWh and decreased as power output decreased. CO emissions averaged 0.058 lb/kWh at 45 kW and exceeded the analytical range of the CO analyzer at the lower loads (greater than 10,000 ppm).

- Hydrocarbon emissions were also very high. THC concentrations were above the analyzer range (10,000 ppm as CH_4) and therefore not reported. Using an on-site gas chromatograph and flame ionization detector, analysts were able to quantify CH_4 emissions at an average of 0.112 lb/kWh at 45 kW. CH_4 emissions increased to a high of 0.150 lb/kWh at the 30 kW power command.

- Emissions of SO_2 and TRS averaged 0.023 and 0.005 lb/kWh respectively at 45 kW. Both increased slightly at the lower loads tested. Emissions of TPM and NH_3 were very low during the full load tests.

- NO_X emissions per unit electrical power output at 45 kW (0.012 lb/kWh), are higher than the average fossil fuel emission levels reported for the U.S. and Colorado regional grids (0.0066 and 0.0077 lb/kWh respectively). The average fossil fuel CO_2 emissions for the U.S. and Colorado regional grids are estimated at 2.02 and 2.13 lb/kWh, both slightly higher than the engine CHP emissions of 1.97 lb/kWh at maximum power output. These values yield an average annual emission increase of 0.37 and 0.29 tons (82 and 55 percent) for NO_X for the two scenarios. Annual CO_2 emissions are estimated to be reduced by the CHP by 137 and 145 tons (2.2 and 7.6 percent) for the two scenarios. These estimated changes in annual emissions are based on electrical generation only and do not include environmental benefits that may be realized through recovery and use of waste heat.

Power Quality Performance

- Average electrical frequency was 59.998 Hz and average voltage output was 208.63 volts.
- The power factor remained relatively constant for all monitoring days with an average of 79.74 percent.
- The average current total harmonic distortion was 5.23 percent and the average voltage THD was 0.92 percent. The THD threshold specified in IEEE 519 is ± 5 percent.

Details on the verification test design, measurement test procedures, and Quality Assurance/Quality Control (QA/QC) procedures can be found in the Test plan titled *Test and Quality Assurance Plan for Swine Waste Electric Power and Heat Production Systems: Capstone MicroTurbine and Martin Machinery Internal Combustion Engine* (SRI 2002). Detailed results of the verification are presented in the Final Report titled *Environmental Technology Verification Report for Swine Waste Electric Power and Heat Production - Martin Machinery Internal Combustion Engine* (SRI 2004). Both can be downloaded from the GHG Center's web-site (www.sri-rtp.com) or the ETV Program web-site (www.epa.gov/etv).

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