ESTCP
Cost and Performance Report

(EW-200823)

Demonstration and Verification of a Turbine Power Generation System Utilizing Renewable Fuel: Landfill Gas

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ESTCP

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ACRONYMS AND ABBREVIATIONS

AEWRS	Army Energy and Water Reporting System
AIRR	adjusted internal rate of return
ANSI	American National Standards Institute
BLCC	building life-cycle cost
BTU	British thermal units
CARB	California Air Resource Board
cfm	cubic feet per minute
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_{2e}	carbon dioxide equivalent
DASA E&S	Deputy Assistant Secretary of the Army for Energy & Sustainability
dBA	decibel, A weighting
DG	distributed generation
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
dscf	dry standard cubic feet
ECAM	Environmental Cost Analysis Methodology
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act
ESTCP	Environmental Security Technology Certification Program
FAT	factory acceptance test
FEMP	Federal Energy Management Program
FP250	Ener-Core Powerstation™, 250 kW gross output
GHG	greenhouse gas
HAZOP	hazard and operability review
IC	internal combustion
kW	kilowatt
kWh	kilowatt-hour
lb/lbmol	pounds per pound mole
LCCA	life cycle cost analysis
LCOE	levelized cost of energy
LFG	landfill gas
LFGE	landfill gas to energy

ACRONYMS AND ABBREVIATIONS (continued)

LMOP	Landfill Methane Outreach Program
MILCON	military construction
MM	million
mm Hg	millimeters of mercury
MWh	megawatt hours
NAAQS	National Ambient Air Quality Standards
NIST	National Institute of Standards and Technology
NMOC	non-methane organic compound
NO_x	oxides of nitrogen
NPV	net present value
NREL	National Renewable Energy Laboratory
NSPS	New Source Performance Standard
O&M	operations and maintenance
O&MR	operations, maintenance and repair
OMB	Office of Management and Budget
OPIS	Oil Price Information Service
PM	particulate matter
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch absolute
psig	pounds per square inch gauge
PV	present value
REC	renewable energy credit
scf	standard cubic feet
scfm	standard cubic feet per minute
SIR	savings-to-investment ratio
SO_2	sulfur dioxide
Southern	Southern Research
SCAQMD	South Coast Air Quality Management District
VOC	volatile organic compound
yd^3	cubic yards

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The objective of this demonstration is to provide a credible, independent, third party evaluation of the performance, economics and environmental impacts of the Ener-Core Powerstation™ (FP250) technology in a landfill gas (LFG) energy recovery application at a U.S. Department of Defense (DoD) site. Ener-Core Power, Inc. was formerly known as Flex Power Generation, Inc. The evaluation was designed to provide sufficient data to allow end-users, purchasers, and others to determine the feasibility of the technology at DoD sites and other applications.

Success factors that were validated during this demonstration include energy production, emissions, and emission reductions compared to alternative systems, economics, and operability, including reliability and availability.

TECHNOLOGY DESCRIPTION

The FP250 is a unique power plant that is able to generate electric power using low energy content gas or vapor while emitting low levels of atmospheric pollutants. The FP250 integrates a modified conventional micro-turbine (Ingersoll Rand MT250, now manufactured by FlexEnergy Energy Systems) of proven design with a proprietary gradual thermal oxidizer in place of the conventional turbine's combustor. Gradual oxidation is the 1- to 2-second conversion of a dilute fuel air mixture to heat energy, carbon dioxide (CO_2) and water. Compared to traditional combustion processes, which occur in milliseconds, the Ener-Core oxidation process is more gradual. The FP250 is able to operate using low heating value fuel sources (theoretically as low as 15 British thermal units [BTU]/standard cubic feet [scf]) that would not support operation of conventional gas turbines or reciprocating engines, which require a minimum fuel heating value of 300-500 BTU/scf.

DEMONSTRATION RESULTS

Table 1 summarizes the performance results for each demonstration plan objective. Key outcomes from the demonstration include:

- The FP250 met or exceeded the objectives for energy production, low oxides of nitrogen (NO_x) emissions, non-methane organic compound (NMOC) destruction efficiency and greenhouse gas (GHG) reductions associated with its use. NO_x emissions were much lower than the California Air Resource Board (CARB) 2013 standard for distributed generation.
- Exhaust carbon monoxide (CO) emissions were comparable to typical emissions from gas turbines and reciprocating engines in LFG service, but did not meet the demonstration plan objective. CO emissions at the oxidizer outlet do meet CARB 2013 standards and a new system configuration currently offered by Ener-Core is designed to meet the CARB standard for CO.
- Based on a life cycle cost analysis (LCCA) analysis for a typical FP250 installation, the economics for the FP250 are on par with competing distributed generation and LFG to energy technologies, but did not meet demonstration plan objectives at current electricity prices at Fort Benning.

- The system is capable of fully automated and unattended operation, but this capability was not fully demonstrated at Fort Benning.
- System availability and reliability did not meet the demonstration plan objectives during operations at Fort Benning. This was due, in part, to site-specific circumstances extraneous to the FP250, including insufficient LFG supply and unusually frequent grid outages. Ener-Core worked closely with Southern Research (Southern) throughout the demonstration to adapt the FP250 to overcome these difficulties and these efforts led to a number of enhancements to the commercial FP250 including the capability for supplemental fuel blending and full island mode operability. Ener-Core maintains that, had these modifications been fully implemented at the start of the demonstration, system availability and reliability would have been within Ener-Core specifications (90-95%).

Table 1. Performance results.

Objective	Metric	Success Criteria	Result
Energy: Verify power production & quality.	Net real power delivered (kilowatt-hour [kWh]).	Nominal 200 kilowatt (kW) gross continuous (1750 megawatt hours [MWh]/year) less temperature dependent derating (to be established). Power quality meets utility inter-connection requirements.	Objective met. Average net real power generation of 220 kW during oxidation-mode operation with G3 engine design.
Emissions: Verify emissions meet regulatory requirements and are lower than best alternate LFG emissions control technology.	Pound (lb)/hour, lb/MWh or parts per million (ppm) emitted.	Emissions meet or exceed CARB 2013 requirements for distributed generation and host site air permit requirements. Emissions are lower than U.S. Environmental Protection Agency (EPA) AP42 typical values for best alternate LFG control technology (boiler/steam turbine).	Objective met for NOx and NMOC. CO emissions from the turbine exhaust did not meet the objective; however, CO emissions measured at the oxidizer outlet do meet the objective.
Emissions: Verify NMOC destruction efficiency.	Percent destruction efficiency for NMOC.	Destruction efficiency exceeds EPA AP42 typical value for enclosed flare (97.7%) and meets AP42 value for Boiler/Steam Turbine (98.6%).	Destruction efficiency meets the objective at 99.6%.
Emissions: Verify GHG emissions reductions.	Metric tons carbon dioxide equivalent (CO_2e)/year reduction relative to site specific baseline conditions.	Greater than 800 metric tons CO_2e avoided emissions due to power generation (above baseline). Greater than 6000 metric tons CO_2e reduction due to destruction of CH4. Greater than 10% increase in GHG reduction compared to flare only.	Objectives met without consideration of GHG emissions due to supplemental propane use. Objectives nearly met when propane use is considered.
Assess economic performance.	Simple payback (years), net present value (NPV) ($).	Simple payback < 5 years; positive NPV.	Objective not met at the current grid electricity price at Fort Benning ($0.069/kWh). A 5 year payback is achieved at a grid electricity price of $0.18/kWh, and a positive NPV is reached at $0.10/kWh.
Determine system availability/reliability and operating impacts.	Percent availability/ reliability, plus descriptive narrative.	Availability exceeds 95%. Reliability exceeds 97%. Operability is acceptable to operating authority.	Availability was 57% and reliability was 82%. Availability net of forced and planned outages was 76%.

IMPLEMENTATION ISSUES

This report provides detailed information on the performance, operability, economics, and development status of the FP250 that can be used by installation managers to assess the applicability of the FP250 for generating energy from low quality waste fuel streams at their facilities.

Installation managers should understand that the FP250, like other turbine-based technologies, requires a steady fuel supply with minimum total energy content of about 3.4 million (MM)BTU/hour (higher heating value). That is, the FP250 is only capable of operating near 100 percent of rated capacity and has little or no turn-down capability. In addition, the FP250 does not tolerate excessive thermal cycling. As with larger frame size industrial gas turbines, continuous 24/7 operation is recommended and the number of restarts over the system lifetime should be minimized to avoid excessive maintenance. It is important that a sufficient, continuous fuel supply be verified during site selection. It is also important to verify the reliability of the grid interconnect (if any) at candidate sites.

At the time of this writing, the FP250 is still undergoing minor modifications to improve reliability and operability. These modifications include:

- Prevention of turbine wear due to particulate breakthrough from the gradual oxidizer,
- A new startup protocol utilizing the warmer only,
- Full automation of system startup, and
- The capability to continue operation in ‘island mode’ to prevent unnecessary shut downs due to transient grid faults (applicable to sites where there may be frequent grid interruptions).

Ener-Core has conducted testing and/or engineering evaluations for each of these modifications at their engineering development facility and maintains that these modifications will allow the system to operate unattended with high reliability (>90%) and minimal unplanned downtime. The performance of these modifications was not verified during this demonstration.

Due to the system’s low emissions, minimal noise, and small footprint, Southern does not expect permitting or other site approvals to present any significant obstacle to implementation at most sites. For this demonstration, permitting and required approvals required minimal effort.

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1.0 INTRODUCTION

Since 1996, Southern Research (Southern) has conducted independent verification and demonstration studies to evaluate the performance, economics and environmental benefit of innovative clean or renewable energy technologies. As such, Southern keeps abreast of developments in such technologies and maintains a network of contacts throughout the industry. Environmental Security Technology Certification Program's (ESTCP) energy and water technology demonstration program is a natural fit with Southern's goals and expertise and Southern has been able to offer proposals that meet ESTCP's goal "to promote the transfer of innovative technologies that have successfully established proof of concept to field or production use."

The Ener-Core Powerstation™ (FP250) is able to extract useful energy from low quality waste fuel sources with low environmental impact. Southern proposed an ESTCP demonstration of the FP250 based on an assessment that the technology has the potential to help address energy security and environmental sustainability mandates and goals established by the U.S. Department of Defense (DoD). In addition, Southern's assessment was that the FP250 technology was sufficiently well developed and market ready that rapid deployment would be feasible following a successful demonstration.

A valuable resource for the production of renewable energy is landfill gas (LFG) from DoD owned landfills at domestic bases. The FP250 is ideally suited for this application and Ener-Core successfully demonstrated a prototype of the technology using LFG prior to the ESTCP demonstration (see section 2.2).

Early in this project, Southern identified and collected data from 471 landfills operated within DoD. This information was used to direct site selection for the FP250 demonstration as well as to assess the potential benefit of this application within DoD. A database and report resulting from this effort were submitted to ESTCP in 2010 [3]. Site selection activities for the demonstration were also completed in 2010 and arrangements were made with Fort Benning to host the demonstration at their 1st Division Road landfill.

In late 2010, Ener-Core provided drawings and specifications for the Fort Benning installation and, during the first weeks of 2011, participated in a formal hazard and operability review (HAZOP) conducted by Southern to identify and provide for mitigation of all hazards and operability concerns. In March 2011, Southern observed a successful factory acceptance test (FAT) of the FP250 at a test facility outside San Diego, CA. Site preparation and construction/installation began at Fort Benning during April 2011 and the system was first operated on July 12, 2011. Southern completed installation of monitoring and data acquisition equipment and began collecting monitoring data on July 5, 2011.

Commissioning and shakedown activities continued into the Fall of 2011 and the system was officially deemed operational on September 29, 2011. A ribbon cutting ceremony was held at Fort Benning on November 8, 2011. During late 2011 and early 2012, Ener-Core continued to refine the system while accumulating operating hours. The one year demonstration period was officially concluded on September 29, 2012; however operations continued through November

18, 2012 to allow for completing emissions testing. Details on system operations, modifications and performance are provided in this report.

1.1 BACKGROUND

The DoD occupies over 620,000 buildings at more than 400 installations in the United States, spending over $2.5 billion on energy consumption annually. Reductions in energy consumption from these facilities and utilization of renewable energy sources has become a primary goal of the DoD for several reasons: (1) to reduce emissions and environmental impacts related to power production and consumption in response to air pollution and climate change issues; (2) to reduce costs associated with energy consumption, resulting in additional resources aimed at DoD primary missions; and (3) to improve energy security, flexibility, and independence. More recently, these priorities have been re-enforced through the release of Executive Order 13423, Strengthening Federal Energy, Environmental and Transportation Management (January 2007).

The FP250 utilizes a conventional 250 kilowatt (kW) micro-turbine of proven design with many years of field operation. The major modification made by Ener-Core replaces the conventional combustion chamber with a thermal oxidizer, enabling the system to operate with low heating value fuels and with low atmospheric pollutant emissions – as thermal oxidizers are conventionally used as air pollution control devices. The FP250 is able to operate using low heating value fuel sources that would not support the operation of conventional devices such as conventional gas turbines or internal combustion (IC) engines. The FP250 requires less waste gas cleaning than conventional engines and gas turbines, and requires a lower fuel supply pressure compared to gas turbines. Conventional turbines and IC engines need fuel cleanup that typically involves water removal, chilling and media treatment. Typical turbines require fuel delivery pressures of 100 pounds per square inch gauge (psig) or higher, while reciprocating engines require fuel delivery at 2 psig or higher. The FP250 uses gas delivered at 5 psig.

The FP250 is potentially applicable to a variety of DoD sites, including landfills, facilities with anaerobic digesters for wastewater treatment, painting or printing operations, volatile organic compound (VOC) remediation systems, as well as typical fossil fuel applications. An important additional benefit of the FP250 includes offsetting the cost and environmental impact of destruction of these waste streams, which is often energy intensive and may result in significant atmospheric emissions.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this demonstration is to provide a credible, independent, third party evaluation of the performance, economics and environmental impacts of the FP250 technology in a LFG energy recovery application at a DoD site. The evaluation was designed to provide sufficient data to allow end-users, purchasers, and others to determine the feasibility of the technology at DoD sites. Such information is needed to build market acceptance of the technology within DoD and other potential markets.

Success factors that were validated during this demonstration include energy production, emissions and emission reductions compared to existing systems, economics, and operability, including reliability and availability.

1.3 REGULATORY DRIVERS

Energy security, environmental sustainability, and long-term savings are all drivers for the subject technology. On October 5, 2009 President Obama issued Executive Order 13514 titled "Federal Leadership in Environmental, Energy and Economic Performance." Among other things, this Order challenges Federal agencies to increase energy efficiency, reduce direct and indirect greenhouse gas (GHG) emissions and prevent pollution. Executive Order 13423, signed January 24, 2007, also directs Federal agencies to increase use of renewable energy. The Energy Independence and Security Act of 2007 also emphasized the development and use of renewable energy. The Energy Policy Act (EPAct) of 2005 seeks to promote innovative technologies that avoid GHGs, including renewable energy technologies.

The implementation of the FP250 using LFG has potential impacts in all of these areas by:

- Using a renewable fuel resource (LFG);
- Improving energy efficiency by reducing energy consumption associated with flare use and utility transmission/distribution losses;
- Reducing GHG emissions by offset of grid electricity and destruction of methane (if not flared)

In National Ambient Air Quality Standards (NAAQS) non-attainment areas, or other areas with strict emissions limits such as California, the FP250 offers the means for DoD installations to meet applicable air quality regulations while generating power from renewable or non-renewable energy sources.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

The FP250 is a unique power plant that is able to generate electricity using low energy content gas or vapor while emitting low levels of atmospheric pollutants. The FP250 integrates a modified conventional micro-turbine (Ingersoll Rand MT250, now manufactured by Flex Energy Systems) of proven design with a proprietary gradual thermal oxidizer in place of the conventional turbine's combustor. Gradual oxidation is the 1- to 2-second conversion of a dilute fuel air mixture to heat energy, carbon dioxide (CO_2) and water. Compared to traditional combustion processes, which occur in milliseconds, the Ener-Core oxidation process is more gradual. The FP250 is able to operate using low heating value fuel sources (theoretically as low as 15 British thermal units [BTU]/standard cubic feet [scf]) that would not support the operation of conventional gas turbines or reciprocating engines, which require a minimum fuel heating value of 300-500 BTU/scf.

The FP250 is theoretically cable of utilizing fuels with heating values as low as 15 BTU/scf, though practical considerations for fuel supply equipment and fuel rate control will increase this minimum value somewhat in most applications. Conventional gas turbines and reciprocating engines require fuels with minimum heating values in the range of 300-500 BTU/scf. In the Fort Benning demonstration, the FP250 was able to operate on LFG alone with fuel heating values in the range of 250 BTU/scf.

During normal operation, the fuel gas (or vapor), regardless of energy content, is diluted with ambient air to 15 BTU/scf and drawn into the turbine's compressor. Following condensate knockout, the LFG is filtered with a coarse filter and also flows through the air inlet filter of the turbine's compressor. Some fuel sources may require additional treatment to remove liquids/water and particulates if they are excessive. The compressed air/fuel mixture (~55 pounds per square inch absolute [psia]) enters the thermal oxidizer where contaminants are destroyed and energy is extracted to power the turbine and generate electricity. Exhaust gas from the turbine is used to preheat the air/fuel mixture entering the oxidizer. Between the oxidizer and the turbine, a hot gas filter is used to remove fine particulates that may be present due to siloxane oxidation, oxidizer media or insulation breakdown, or corrosion of hot metal components exposed to the hot gas stream.

During startup, the oxidizer must be preheated and the turbine brought to operating conditions before the system can operate in steady state gradual oxidation mode. For this purpose, a startup system is provided that fires combustors at the oxidizer and turbine inlets. Figure 1 provides an overall schematic flow diagram for the system. Figure 2 shows the FP250 installed at the 1st Division Road landfill.

The FP250 is potentially capable of utilizing waste streams other than LFG as the fuel input, such as paint booth or other VOC-laden industrial process exhausts, off-spec fuels, waste solvents, and other low BTU or high contaminant waste gases, liquids or vapors. The FP250 is also available with a heat recovery option for applications where there is a local use for the recovered heat.

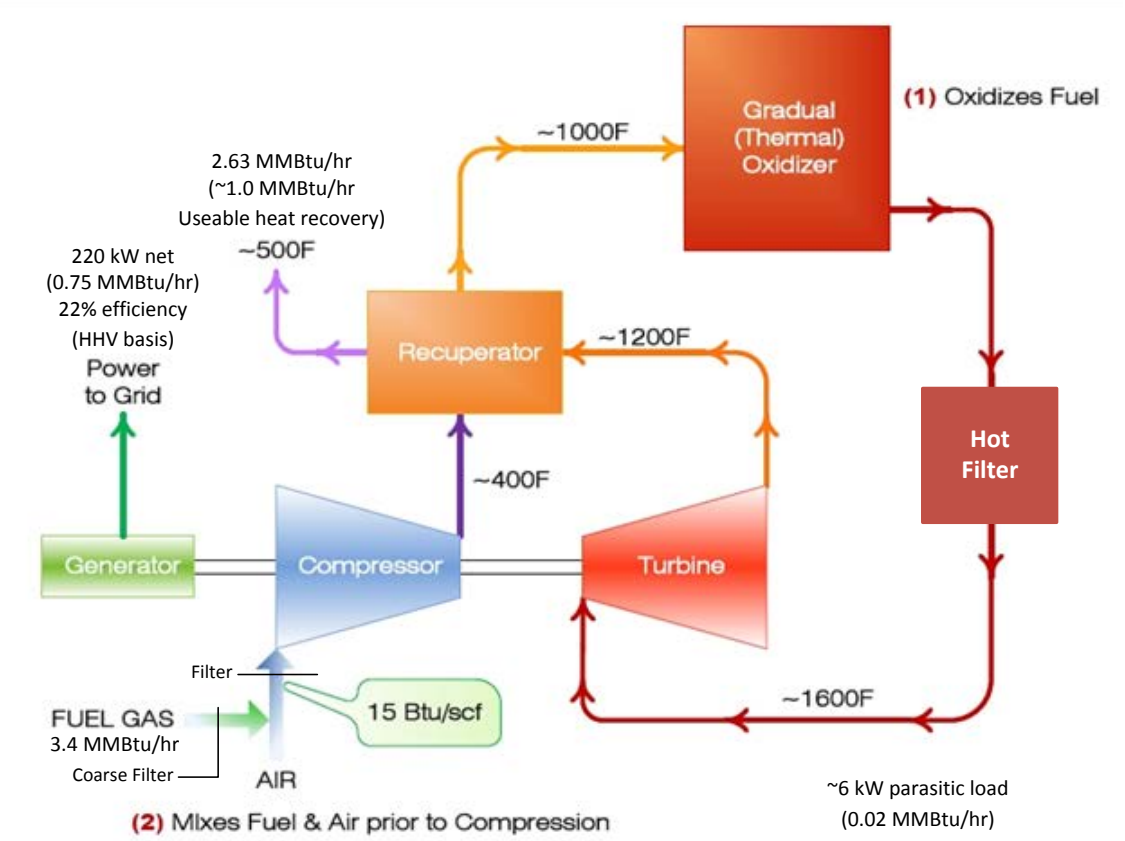

Figure 1. FP250 schematic.

Figure 2. FP250 installed at 1st Division Road landfill.

2.2 TECHNOLOGY DEVELOPMENT HISTORY

For over a decade prior to this demonstration, Ener-Core (and its predecessor companies) pursued the development of a power plant that could operate on a wide variety of low quality fuels. Research was supported by government grants from the U.S. Department of Energy (DOE), the National Renewable Energy Laboratory (NREL), California Energy Commission, and other agencies. In 2002 Ener-Core received a U.S. patent for a "Method for Collection and Use of Low Level Methane Emissions" (US 6,393,821 B1).

The original design employed a catalytic combustor coupled with a 30 kW micro-turbine. The useful life of the catalytic combustor was severely compromised by contaminants in the waste gas streams of interest. Experience with the catalytic unit led to the adoption of a non-catalytic thermal oxidizer in its place. A thermal oxidizer was chosen due to its ability to tolerate contaminants in waste streams.

A prototype oxidizer-based system was assembled in October 2008, with the first successful operation accomplished after 10 months of development testing. Re-packaging of the prototype system into a 100 kW pilot field system (FP100) was started in November, 2009. The pilot system was delivered to Lamb Canyon Landfill in Beaumont, California, in May 2010, and was successfully operated on LFG starting in June 2010. By September 2010, the pilot unit had accumulated over 480 hours of operation on LFG. The pilot plant demonstrated the ability of the oxidizer-based system to continue operation during intermittent fuel supply interruptions. The pilot plant operation continued at Lamb Canyon for engineering control development and integration with the day to day operation at a landfill until early 2011, accumulating 648 total hours of operation before it was decommissioned. The FP100 was a proof of concept prior to scaling to the FP250 and was never intended for commercial deployment. The unit was in operable condition at the time of decommissioning, though turbine wear had been observed.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The chief advantage of the FP250 is the ability to utilize low quality fuel sources to provide electrical energy and heat recovery. Since these low value fuel sources are often waste streams, a related advantage is reducing costs associated with treatment of these wastes and realizing offsets of energy and emissions associated with waste treatment. The FP250 configuration evaluated at Fort Benning also eliminates the need for a separate fuel compressor, as the blended low-BTU fuel-air mixture is compressed by the turbine's integrated compressor.

The FP250 incorporates a proprietary thermal oxidizer within a recuperated Brayton cycle. Thermal oxidation is an effective means of destroying non-methane organic compounds (NMOC) and other organic pollutants. As a result, observed FP250 emissions of atmospheric pollutants are lower than alternate LFG destruction/utilization technologies such as conventional gas turbines or reciprocating engines. In addition, the oxidizer minimizes oxides of nitrogen (NO_x) formation while destroying carbon monoxide (CO) and VOCs.

The FP250 operates without a complex gas cleanup system. The system is designed to trap particulates formed from siloxane oxidation within the oxidizer while destroying other

pollutants. The FP250 runs quietly (<83 decibels, A weighting [dBA] at 1 meter), making it potentially suitable for locations near residential or office areas.

The FP250 can be used with fuel input heat rates as low as 3.4 million (MM)BTU/hour (56 standard cubic feet per minute [scfm] of 100% methane). If the fuel input heat rate is below 3.4 MMBTU/hour, supplemental natural gas or propane can be blended with the available waste fuel to allow the system to operate. Since the unit is designed to be fuel flexible and adaptable to changes in fuel concentration, it can be utilized with fuel sources that change energy density levels (BTU/scf) during operation from a minimum of zero (for brief periods) to a maximum determined by the fuel delivery and control equipment which is designed specific to each application. During the acceptance test, Southern observed continued FP250 operation during a complete, 3-minute, shut off of the fuel source. An average fuel input heat rate of 3.4 MMBTU/hour is required for operation.

The chief limitations of the FP250 are that it is unproven in applications beyond energy recovery from LFG and, as a newly commercialized technology, has not yet achieved a long-term record of continuous field operation. In the FP250 configuration demonstrated at Fort Benning, the LFG is diluted with ambient air and aspirated directly into the turbine's compressor with minimal pretreatment (see section 2.1). Some alternative fuel sources (e.g., spent solvent vapors) may require additional gas cleaning, cooling, or pretreatment to avoid excessive compressor maintenance.

Life cycle costs and the levelized cost of energy for a typical FP250 installation are on par with competing turbine-based distributed generation and LFG to energy (LFGE) technologies. A detailed analysis of comparative costs is presented in Section 7.3.1.

3.0 PERFORMANCE OBJECTIVES

The performance results for each demonstration plan objective are summarized in the executive summary of this cost and performance report. Section 6.0 of this report provides a more detailed discussion for each result. A complete presentation of the results and all issues encountered is provided in the full report.

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4.0 FACILITY/SITE DESCRIPTION

The demonstration took place at the 1st Division Road landfill at Fort Benning, Georgia. The following material provides a detailed characterization of the Fort Benning site conditions with respect to FP250 operation and the conduct of the demonstration.

4.1 FACILITY/SITE LOCATION, OPERATIONS, AND CONDITIONS

The 1st Division Road Landfill is located on Fort Benning grounds near the intersection of 1st Division Road and U.S. highway 27/280 (Figure 3). The landfill was initially reported by Fort Benning to contain approximately 48 acres of waste material at an average depth of 30 feet (approximately 2.3 million cubic yards waste volume). During the demonstration, however, it was discovered that the actual fill area is approximately 26.5 acres and the best estimate of waste-in-place volume is approximately 1.5 million cubic yards (yd^3). The density of this material is unknown, but the best estimate is about 1000 pounds/yd^3 yielding a waste in place mass of about 750,000 tons [1].

The landfill accepted municipal solid waste and construction/demolition debris starting in 1985 and continuing into1997. The landfill was formally closed in 1998. The landfill is unlined and has a sand drainage layer that should allow leachate to filter through and leave the site. The cap consists of a subgrade layer, a geocomposite liner, and 24 inch cover soil layer.

Figure 3. 1st Division Road landfill location.

The electric power supplier on base is Flint Energy. Power is supplied to Flint Energy by Georgia Power at three entry points on the base. All sub-metering within the base by Flint Energy is for the purpose of allocating operational costs within Fort Benning. The power generated by the FP250 offsets on-base electricity consumption. There was no commercial

export agreement required with Flint Energy. The point of interconnection with the Flint Energy grid is within approximately 100 yards of the FP250 location.

4.1.1 LFG Supply

Initial estimates of expected LFG collection volume during the demonstration were based on monthly wellhead monitoring data collected from June 2008 through January 2011. These data showed aggregate landfill gas production rates averaging 190 scfm (range 2 to 635 scfm) at an average methane content of 42 percent (range 26 to 58 percent) – or an average of 4.8 MMBTU/hour. The monthly monitoring was conducted only at the wellheads and there was no historical monitoring of the total LFG as delivered to the flare. Further confirmation of the expectation that there would be sufficient fuel supply to operate the FP250 came from a 2004 report that estimated the landfill was capable of producing 700 scfm of landfill gas at 40 to 50 percent methane from 2005 through 2020-2025 [2].

During FP250 commissioning over the summer of 2011, it became apparent that the landfill was not consistently producing LFG of sufficient quantity and quality (heat content) to allow the FP250 to operate. In response, Ener-Core installed a system to augment LFG with propane to provide sufficient fuel heat input to allow the system to operate. At the same time, Southern initiated efforts to investigate whether LFG production from the landfill could be increased and to obtain a realistic estimate of expected LFG production over time. These efforts are described in detail in the full report. While some improvement in LFG recovery was realized, supplemental fuel continued to be necessary throughout the demonstration and it is expected that supplemental fuel will be required for continuous operations at the site.

It should be noted that the LFG collection system was designed to prevent off site methane migration and was never intended to supply LFG for energy production. As such, well spacing, well construction, the design and construction of the collection system piping and blowers, and operating procedures for the LFG collection system were not optimized for an LFG to energy application. Throughout the demonstration, prevention of off-site methane migration necessarily remained a priority over LFG production and quality, although the two goals are not mutually exclusive.

Detailed criteria for siting FP250 units at other DoD sites and an assessment of the availability of suitable sites within DoD are provided in the full report.

5.0 TEST DESIGN

The FP250 demonstration plan was designed to provide all data required to satisfy objectives as defined in the demonstration plan and to provide additional information as needed to ensure the quality and representativeness of these data.

5.1 CONCEPTUAL TEST DESIGN

At a minimum, all that is required to demonstrate achievement of the FP250 performance objectives is monitoring the net power production, conducting an emissions test, and compiling and analyzing economic and operational data. In addition to these basic requirements, the following additional supporting determinations were made:

- The heat input to the system was measured during operations so that the system efficiency could be determined.
- Ambient conditions were monitored in order to determine variation in power output and system efficiency with varying temperature, humidity and barometric pressure.
- Selected FP250 operating parameters (e.g., oxidizer inlet/outlet temperatures, LFG feed rate, run state) were monitored as an indication of overall system "health" and operational status. Exhaust temperature was monitored in order to support an estimate of the heat recovery potential of the system. The system installed at Fort Benning is not currently equipped for heat recovery.
- LFG extraction system health and gas production were monitored via monthly wellhead checks and flow and methane concentration of the LFG delivered to the flare.

5.2 BASELINE CHARACTERIZATION

The baseline datum for this test is simply continued operation of the extraction system and flare without the FP250. As such, the overall LFG extraction rate and gas quality are inconsequential to the objectives of the demonstration so long as sufficient methane is produced to operate the FP250. Excess LFG would be consumed by the flare. In practice, as discussed above, the LFG recovered by the extraction system was normally insufficient to operate the FP250. The flare was bypassed during FP250 operation and supplemental fuel (propane) was used to make up the balance of the fuel energy required.

The majority of GHG reductions attributable to the FP250 result from utility offsets due to the power produced. The difference in methane destruction efficiency between the FP250 and the flare is small and is it is not practical to measure the actual destruction efficiency of the flare. Thus, the existing "baseline" system played no significant role in determining performance results for this demonstration apart from the estimated cost of installing a gas extraction system and flare if it does not already exist at a given site.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

Figure 4 is a site plan of the layout of the FP250 system components in relation to the existing flare pad located immediately south of the landfill area. The function of the FP250 and integral components has been described in section 2.1 above.

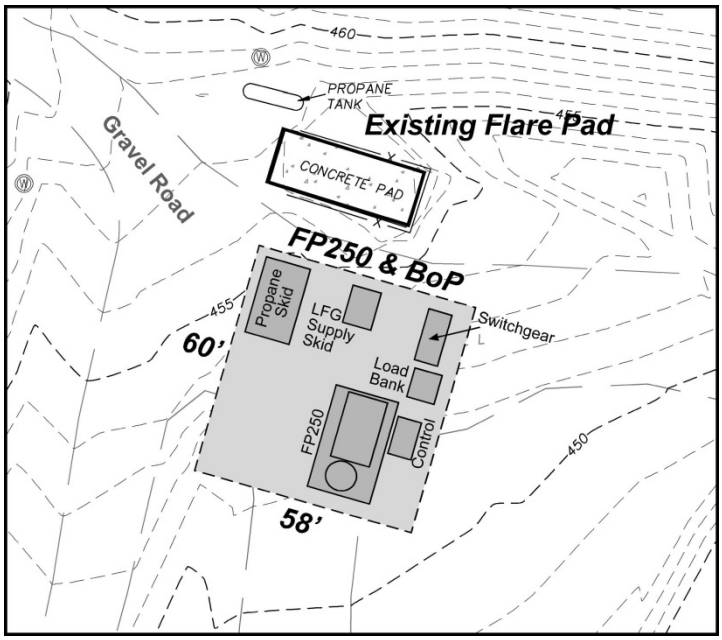

Figure 4. FP250 site plan (schematic).

The propane skid consists of two 1000 gallon propane tanks, an evaporator and controls to provide propane fuel for startup and fuel augmentation as needed.

The fuel delivery skid consists of condensate removal followed by a positive displacement compressor to provide up to 310 scfm saturated LFG at a delivery pressure of approximately 5 pounds per square inch (psi). The LFG is pressurized to allow for downstream flow control that regulates the fuel supply into the ambient air aspirated into the turbine's compressor.

The load bank (generator braking resistor) is sized to take the entire output of the FP250 and normally receives the load for brief periods during startup and shutdown when the FP250 is not synchronized to the grid. The load bank can also be employed to allow the system to continue operating in standby "island" mode when the grid is offline. Grid faults were unusually frequent occurrences at the demonstration site, occurring up to several times per month.

Ener-Core implemented a standby "island" mode solution allowing the FP250 to operate for up to 5 minutes during a grid interruption; however full "island" mode capability, including the ability to power the fuel delivery skid from the FP250 during a grid outage, was not fully implemented as of the end of the demonstration period. Ener-Core has provided specifications for switchgear and controls necessary to implement full island mode capability and has recommended that Fort Benning implement these modifications prior to taking over operation of the system in order maximize uptime and avoid excessive thermal cycling.

The LFG fuel is taken off the existing extraction system piping at a tee located between the extraction system blowers and the flare. The initial plan was to operate the extraction system in the usual manner. The FP250's fuel delivery system compressor would pull off the fuel required to operate the FP250 and any excess LFG would be destroyed in the flare. As discussed above (section 4.1), the extraction system generally did not provide sufficient fuel to operate the FP250. At times, it was possible for the FP250 fuel delivery system to cause a back flow of ambient air through the flare. This was remedied by installing an air actuated valve downstream of the LFG takeoff tee which is closed when the FP250 is operating. Mid-way through the demonstration, it was discovered that the FP250's fuel delivery compressor provided sufficient suction on the extraction system piping and it was unnecessary to operate the extraction system blowers during FP250 operation. From this point forward, the extraction system blowers were shut down (manually) when the FP250 was operating. This also appeared to improve control over the extraction rate resulting in a more consistent quality LFG supply to the FP250.

Figure 5 is a schematic diagram of the FP250 system and the existing LFG collection/flare system. Figure 5 shows the location of each measurement that was made in support of quantitative determination of the demonstration's performance objectives. Details on instrumentation and data collection are given in the full report.

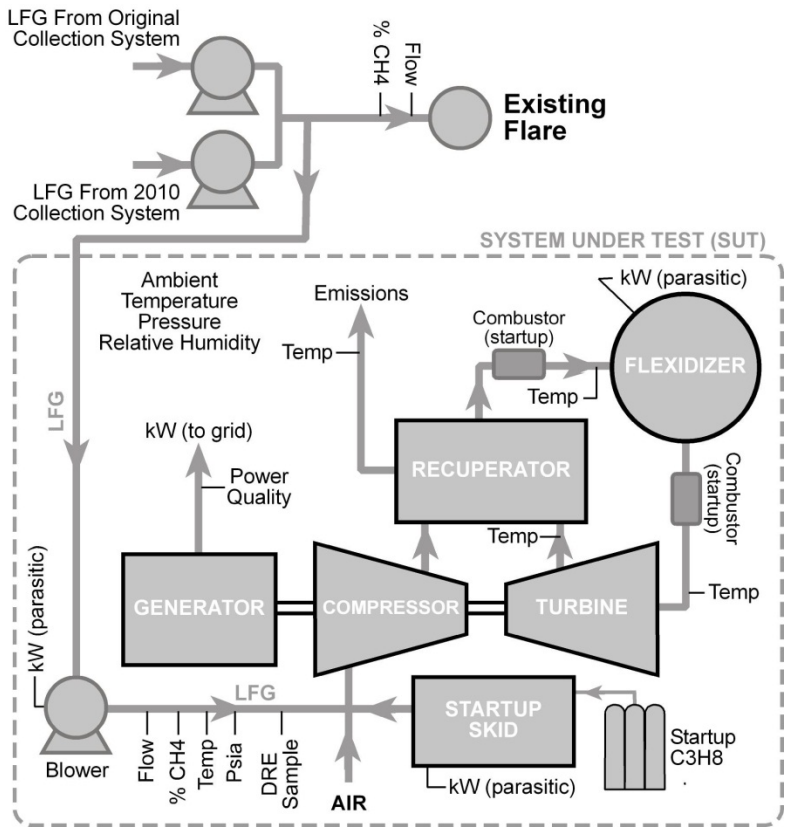

Figure 5. FP250 monitoring schematic.

5.4 OPERATIONAL TESTING

Operational phase of the FP250 performance assessment included acceptance testing, system installation and commissioning, steady state operations, and emissions testing. Formally, the demonstration objectives are concerned only with steady state operations and emissions testing; however, Southern documented the acceptance testing and commissioning phases to capture information relevant to understanding FP250 performance.

The FP250 design represented a scale-up and turbine manufacturer change from Ener-Core's 100 kW pilot units installed and operated at a landfill in Lamb Canyon, CA (see section 2.1). In order to verify the performance of the scaled-up oxidizer and verify engine and controls modifications necessary to integrate the scaled up oxidizer with the 250 kW turbines, Ener-Core installed and operated a test unit at the Alturdyne turbine packaging facility near San Diego, California. The testing and modifications took place between September 2010 and April 2011. Southern was on site in late March 2011 to witness and document acceptance testing of the newly integrated system.

In early February 2011, Southern and Ener-Core met with all project stakeholders at Fort Benning to work out construction details including site preparation, permitting, utility interconnection, etc. Draft site plan and electrical, mechanical, civil and structural drawings and details were shared with Fort Benning staff. Southern began work on permitting activities with Fort Benning staff.

Site preparation and installation activities at the 1st Division Road landfill began in April 2011 and continued through early July 2011. During this time Southern installed monitoring and data acquisition equipment on site to collect and provide remote access to data collected in support of the demonstration. The FP250 was first run on July 12, 2011. Commissioning and shakedown activities continued through September 2011.

The FP250 was officially deemed fully commissioned and ready for continuous operation by Ener-Core on Sept. 29, 2011. A ribbon cutting ceremony was held at the 1st Division Road landfill on November 8, 2011.

On November 9, 2011, the FP250 was shut down for inspection and maintenance. Abnormal wear on the turbine nozzle and rotor was observed and Ener-Core decided to replace the engine and initiate a root cause analysis to determine the cause of the wear. Engine 1 ran a total of 369.3 hours with 308.8 hours operating in gradual oxidation mode at an average net power output of 208.8 kW. There were 13 start cycles on the engine at the time of replacement.

The results of the root cause analysis were submitted to Southern on January 10, 2012 [7]. The root cause of the turbine wear was determined to be particulate originating from the media in the gradual oxidizer entering the turbine section of the engine and eroding the nozzle and turbine rotor. Ener-Core consulted with a turbine erosion specialist and university researchers to investigate whether changes in turbine and nozzle material or coatings could prevent wear. No changes were recommended. Ener-Core also evaluated options for preventing particulate from originating in the oxidizer media, but did not elect to make any changes to the media in the Fort Benning unit. Ener-Core relocated the dump valves on the Fort Benning unit to prevent debris

from back flowing into the compressor during shutdown and improved shutdown control logic to minimize the use of the dump valves.

Ener-Core also initiated an effort to improve filtration between the oxidizer and the turbine. Two interim "drop-in" filter solutions were installed in the spring and summer of 2012, and a third solution was installed in September 2012. A complete history and discussion of the filtration issue is given in section 8.1.

Engine 2 was installed in early February 2012 and first ran on February 22. Engine 2 logged a total of 1710.3 oxidation mode run hours with an average net power output of 189.9 kW, before being taken out of service in July 2012 for the planned install of the new design "G3" engine.

The G3 design incorporated turbine cooling system modifications to reduce or eliminate the passage of aspirated fuel/air mixture around the oxidizer and into the turbine exhaust stream. This is necessary to achieve the ultra-low atmospheric emissions that the FP250 is potentially capable of. Engine 3 logged a total of 1862.8 oxidation mode run hours at an average run-mode net power output of 211.2 kW before it was shut down on November 18, 2012 pending completion of system handover negotiations.

A fully U.S. Environmental Protection Agency (EPA)-compliant emissions test on the G3 engine was completed on October 17, 2012.

The project participants (Southern, Ener-Core and Fort Benning) initiated handover discussions during the fall of 2012. Operations and maintenance (O&M) manuals and annual and variable-period maintenance cost estimates were requested from Ener-Core and delivered to the Fort Benning energy manager so that an O&M contract could be developed and sent out for bid. Ener-Core submitted recommendations and costs for system updates to be completed before system handover. It has remained Fort Benning's intention to continue operation of the plant so long as this can be accomplished on a revenue-neutral basis.

5.5 SAMPLING PROTOCOL

Demonstration data collection began on July 5, 2011 and continued through the end of operations on November 18, 2012. Data for all parameters (see Figure 5) were stored at 10 minute intervals on Southern's DataTaker™ data logger and retrieved via cellular router on a weekly basis.

Raw data were retrieved each week and appended into the "raw data" tab of Southern's data analysis spreadsheet. To preserve traceability, raw data were never altered in any way. Weekly raw data files as downloaded from the logger were backed up on Southern's server. There were no significant data collection or retrieval issues during the extended monitoring period. Corrected or calculated values were computed from raw data in the "calc_data" tab of the data analysis spreadsheet. All constants and calibration factors used are stored in the same spreadsheet and referenced by cell label to facilitate traceability and auditability of the results. These calculations and corrections included:

- Conversion of ambient pressure measurements in millimeters of mercury (mm Hg) to psia.
- Correction of Southern's flow measurements to standard conditions (1 atm. and 60EF) using pressure and temperature sensor data located in line with the flow meter.
- Correction of LFG temperature measurements based on a calibration curve developed in Southern's laboratory prior to deployment.
- Conversion of logged pulse data from Southern's power meters to kW and kilowatt hour (kWh).
- Calculation of net kW output as the difference of gross output and parasitic load power measurements.
- Compensation of Southern's methane meter measurements for LFG temperature and pressure. Correction factors were provided by the manufacturer.

The data analysis spreadsheet also includes a complete downtime log and a record of supplemental fuel usage provided by Ener-Core.

Calculated results were automatically summarized over discrete time periods of interest using Excel database statistical functions. Summary performance data were submitted to project stakeholders each month starting January 2012. For the final report, the time periods of interest corresponded to when each of the three engines installed at Fort Benning were operated.

5.6 SAMPLING RESULTS

Table 2 is a performance summary giving operating hours and power generation for periods when each of the three engines installed at Fort Benning was operating as well as the combined totals for all three engines. Note that the cumulative power and average power outputs are based on run mode hours, which include startup time where power output is ramping up. As there was significant startup time during the demonstration due to frequent restarts, the average power output values are somewhat lower than would be the case in continuous full oxidation mode operation.

Table 2. FP250 performance summary.

Engine 1 Performance Summary		
Start Date	7/12/11 0:00	
End Date	11/10/11 0:00	
Available Hours	2904	hours
Cumulative Run Mode Hours	369.3	hours
Cumulative Flex Mode Hours (Service Hours)	308.8	hours
Cumulative Time during Startups	60.5	hours
% of available hours in Flex mode	10.6%	percent
Total Number of startups	13	
Cumulative Gross Generated (SRI)	82.8	MWh
Cumulative Net Generated (SRI)	78.2	MWh
Average Net Power Output During Operation	211.8	kW

Table 2. FP250 performance summary (continued).

Engine 2 Performance Summary		
Start Date	2/22/12 0:00	
End Date	7/8/12 0:00	
Available Hours	3,288	hours
Cumulative Run Mode Hours	1822.3	hours
Cumulative Flex Mode Hours (Service Hours)	1710.3	hours
Cumulative Time during Startups	112.0	hours
% of available hours in Flex mode	52.0%	percent
Total Number of startups	18	
Cumulative Gross Generated (SRI)	365.4	MWh
Cumulative Net Generated (SRI)	355.8	MWh
Average Net Power Output During Operation	195.3	kW
Engine 3 Performance Summary		
Start Date	7/23/12 0:00	
End Date	11/19/12 0:00	
Available Hours	2,856	hours
Cumulative Run Mode Hours	1980.2	hours
Cumulative Flex Mode Hours (Service Hours)	1862.8	hours
Cumulative Time during Startups	117.3	hours
% of available hours in Flex mode	65.2%	percent
Total Number of startups	24	
Cumulative Gross Generated (SRI)	434.2	MWh
Cumulative Net Generated (SRI)	426.1	MWh
Average Net Power Output During Operation	215.2	kW
Combined Performance Summary (Engines 1, 2 and 3)		
Available Hours	9,048	hours
Cumulative Run Mode Hours	4171.8	hours
Cumulative Flex Mode Hours (Service Hours)	3882.0	hours
Cumulative Time during Startups	289.8	hours
% of available hours in Flex mode	42.9%	percent
Total Number of startups	55	
Cumulative Gross Generated (SRI)	882.4	MWh
Cumulative Net Generated (SRI)	860.2	MWh
Average Net Power Output During Operation	206.2	kW

MWh = megawatt hours

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6.0 PERFORMANCE ASSESSMENT

The results of the demonstration for each performance objective are presented in summary below. The methods employed to verify each demonstration objective are presented in Section 5.0 above and further detail is available in the full report and in the demonstration plan. The objectives related to energy production, reliability and operability address energy security at DoD installations. The economic assessment objective addresses DoD energy cost reductions. Installation GHG reductions and other environmental benefits are addressed by way of the objectives related to emissions measurements, destruction efficiency and determination of GHG reductions.

6.1 VERIFY POWER PRODUCTION

The success criterion for this objective was to generate 200 kW gross output during operations. The FP250 exceeded this goal generating an average of 211.5 gross kW power output based on total run-mode operating hours and cumulative power output by all three engines installed at Fort Benning during the demonstration period. Net power output averaged 206.2 kW. Net power output is the difference between gross power output and the parasitic loads. The parasitic load includes the power required to run the LFG supply compressor, controls, oxidizer heater banks and auxiliary loads. All parasitic loads were wired through a single bus so that only a single power measurement was required to capture the total parasitic load.

Parasitic loads averaged 12.4 kW for engine 1, 5.3 kW for engine 2 and 4.1 kW for engine 3. The reduced parasitic loads for engine 2 and 3 are due to a reduction or elimination of the use of electric heaters installed in the gradual oxidizer to assist in startup and achieving stable operations. With greater operating experience, it was determined that the use of these heaters is unnecessary.

Table 2 (above) summarizes performance results for each of the three engines installed at Fort Benning during the demonstration. The performance of Engine 3 was improved over the first two engines installed, with Engine 3 net power generation of 215.2 kW averaged over all operating run-mode hours including startup periods. During full oxidation-mode operation, engine 3 produced an average net power output of 220 kW. Southern considers that the 220 kW net power output value will reflect the performance of future installations and this value is used in the economic assessment.

At 90% availability, cumulative net power output is expected to amount to 1,735 MWh per year. Actual availability achieved during the demonstration is discussed in section 6.6 below.

Interconnection with the distribution grid operated by Flint Energy was successful.

Demonstration results for generating efficiency and an estimate of potential heat recovery from the FP250 are provided in the full report.

6.2 VERIFY LOW EMISSIONS

A full EPA compliance level emissions test was conducted on the FP250 on October 17, 2012. The engine under test was Ener-Core's "G3" design intended to eliminate "leak paths" that allow a portion of the aspirated fuel/air mixture to bypass the oxidizer and exit at the turbine exhaust. These "leak paths" are a normal element of the conventional turbine design that use aspirated air to provide cooling and sealing to internal turbine components.

In addition to the planned emissions testing at the turbine exhaust, Ener-Core contracted with the testing contractor (Integrity Air) to perform a single, 35-minute sampling run at the oxidizer outlet (turbine inlet). The purpose of the test at the oxidizer outlet was to characterize emissions directly from the oxidizer in order to obtain results independent of any excess emissions due to bypass of the aspirated fuel/air mixture around the oxidizer through the "leak paths" within the turbine.

Table 3 summarizes the emissions test results and compares emissions from the turbine and oxidizer with the California Air Resource Board (CARB) Distributed Generation (DG) 2013 standard [8] and with EPA AP-42 [9] emission factors for best available control technology for LFGE technologies. Note that the AP-42 best listed control device is an enclosed flare for NO_x, and is a boiler/steam turbine for CO and particulate matter (PM).

Table 3. Emissions results and comparisons.

	FP250 (turbine exhaust)	**FP250 (oxidizer exhaust)**	**CARB 2013[1]**	**AP42[3]**
NO_x (lb/hr)	0.0005	0.0016	0.0150	0.1310
CO (lb/hr)	0.0750	0.0120	0.0210	0.0240
Sulfur Dioxide (SO_2) (lb/hr)	0.0110	0.0050	NA	NA
Total PM (lb/hr)	0.0360	NA	NA	0.0101
NMOC as Carbon (lb/hr)	0.0500	0.0071	NA	NA
NMOC as Hexane (lb/hr)[2]	0.0035	0.0005	0.0042	NA
Percentage Comparisons				
	FP250 (Turbine): CARB 2013	**FP250 (Turbine):AP42**	**FP250 (Oxidizer): CARB 2013**	**FP250 (Turbine):FP250 (Oxidizer)**
NO_x	3.5%	0.4%	11%	33%
CO	357.0%	312.5%	57%	625%
SO_2	NA	NA	NA	220%
Total PM	NA	357.1%	NA	NA
NMOC as Carbon	NA	NA	NA	704%
NMOC as Hexane[2]	82.9%	NA	12%	704%

[1] The CARB 2013 DG standards are expressed in terms of lb/MWh. Lb/hr values given here are computed based on net FP250 power output during the emissions test, or 210 kW.
[2] The CARB 2013 standard for NMOC emissions is expressed in terms of lb/hr as hexane. According to South Coast Air Quality Management District (SCAQMD) method 25.3, a factor of 14.36 pounds per pound mole (lb/lbmol) Carbon should be used to convert lb/hr as Carbon to lb/hr as hexane. This factor has been applied here to the FP250 measurements to allow comparison with the CARB standard.
[3] The AP42 emission factors are given in terms of pound pollutant per million dry standard cubic feet (dscf) methane. Results in lb/hr are calculated using 56 scfm pure methane to obtain the 3.4 MMBTU/hour heat input needed to operate the FP250.
NA = not applicable
lb/hr = pounds per hour

The success criteria for this performance objective were to meet the CARB 2013 distributed generation standards for NO_x, CO and NMOC and the AP-42 NO_x, CO and PM emissions for the best listed control device.

The FP250 demonstrated extremely low NO_x emissions at 3.5% of the CARB 2013 standard and 0.4% of the AP-42 emission factors for the best listed control device (enclosed flare). NMOC emissions from the FP250 turbine exhaust also met the CARB 2013 standard.

The FP250 did not meet the success criteria for CO emissions at the turbine exhaust. CO emissions were 357.0% of the CARB 2013 standard and 312.5% of AP-42 emissions for best control device (boiler/steam turbine). However, emissions at the oxidizer outlet were lower than the CARB 2013 standards and the best AP-42 emission factor.

The difference in the results at the turbine exhaust and oxidizer outlet is due to a small, residual leak path allowing aspirated LFG/air mixture to bypass the oxidizer and appear in the turbine exhaust. The methane in the LFG is thought to be partially oxidized to CO as it passes over hot surfaces in the engine and recuperator after it is re-introduced into the flow path. The presence of such leak paths was a known design issue from the beginning of the project and Ener-Core engineers worked throughout the demonstration period on means to eliminate these paths. These efforts culminated in the modified "G3" design that was tested at Fort Benning. Ener-Core modified the "G3" engine by separating the primary and secondary flows such that aspirated fuel did not bypass the oxidizer. The design intent was to have zero aspirated air/fuel mixture entering the secondary flow path.

A rough calculation of the leak rate can be made as follows. The CO in the exhaust was 4.5 parts per million (ppm) and methane (CH_4) in the exhaust was 5.8 ppm. Assuming all the CO and CH_4 was introduced through a seal leak and that all CH_4 was oxidized to CO, this amounts to 10.3 ppm CH_4 leaking. At 1.5% fuel/air ratio there is 15,000 ppm CH_4 aspirated in the system. This yields a leak rate of 10.3/15,000 = 0.07%. While the leak rate is quite small, it prevents the FP250 "G3" engine design from meeting the tightest CO emissions standards. Ener-Core has addressed this concern by offering a system configuration where the fuel is compressed and injected into the oxidizer instead of aspirated into the turbine's compressor. This solution avoids the secondary flow path issue.

Although the FP250 failed to meet the demonstration objectives for CO emissions, the CO emissions at the turbine exhaust were nonetheless considerably lower than uncontrolled emissions for conventional gas turbines or reciprocating engines based on emission factors given in AP42 sections 3.1 for gas turbines and section 3.2 for reciprocating engines. FP250 CO emissions at the turbine exhaust were 5-7% of the emissions for these competing technologies.

Total PM Emissions were measured at the turbine exhaust (but not at the oxidizer outlet). PM emissions exceeded the AP42 emission factor for best control device (boiler/steam turbine). The CARB 2013 standard does not state an emissions limit for PM.

6.3 NMOC DESTRUCTION EFFICIENCY

The success criterion for this objective was to achieve a NMOC destruction efficiency that meets or exceeds the EPA AP-42 destruction efficiency for best control device (boiler/steam turbine) of 98.6%.

NMOC (as Carbon) at turbine exhaust was 0.05 lb/hr. NMOC (as Carbon) at the fuel inlet was 11.6 lb/hr – resulting in a destruction efficiency of 99.6% [12]. The objective was met.

6.4 GREENHOUSE GAS REDUCTIONS

The demonstration plan success criteria for GHG reductions attributable to the FP250 and the demonstration results are as follows.

- Objective: Greater than 800 metric tons CO_2 equivalent (CO_2e) emissions avoided emissions due to power generation. This objective was met if propane use for LFG augmentation is not considered (1018 to 1153 metric tons CO_2e/yr) and was nearly met (737-767 metric tons CO_2e/yr) when propane usage during the demonstration period is accounted for.
- Objective: Greater than 8000 metric tons gross CO_2e emissions reduction due to CH_e destruction. This objective was met whether or not the increased FP250 destruction efficiency over the flare is taken into account (8461 to 8495 metric tons CO_2e/year). These results account for the percentage of propane used to supplement the LFG during the demonstration period; however it should be noted that the propane percentage will increase in out years as the LFG generation from the landfill declines.
- Objective: Greater than 10 percent increase in GHG reduction compared to the baseline flare. This objective was met if propane use for LFG augmentation is not considered (12 to 14 percent increase) and was nearly met (9 percent) when the demonstration period propane usage is accounted for.

The primary GHG emissions reduction for the FP250 demonstration is the result of electric utility emissions offset by the power produced by the FP250, or the avoided emissions that would have resulted from generating the same amount of power on the local (Georgia) utility grid. This amounts to GHG emissions reduction of 1018 metric tons CO_2e/yr.

The FP250 also destroys CH_4, and this direct emissions reduction is a much larger GHG reduction than the avoided emission reduction at 8495 metric tons CO_2e/yr (assuming 100% CH_4 destruction efficiency for both the FP250 and the Flare). However, $CH_4$is also destroyed by the existing (baseline) candlestick flare at the demonstration site, so any incremental reduction would be due to increased CH_4 destruction efficiency of the FP250 over the Flare. This incremental reduction could not be determined directly from demonstration data since the CH_4 destruction efficiency of a candlestick flare cannot be reliably measured. In addition, there is little data available on the destruction efficiency of open candlestick flares. The EPA New Source Performance Standard (NSPS) requirements for solid waste landfills specify an emissions control device capable of an NMOC destruction efficiency of 98% [13]. A CH_4/NMOC destruction efficiency of 98% is a common design specification for open flares. For the purpose

of estimating the potential magnitude of the incremental increase in GHG reduction, a 98 percent destruction efficiency is assumed for open flares and the measured NMOC destruction efficiency of 99.6% was used for the FP250. The estimated incremental increase in GHG emissions reductions amounts to 136 metric tons CO_2e/yr – for a total emissions reduction of 1153 metric tons CO_2e/year or about 13% additional reduction compared to the avoided emission alone.

Another potential source of GHG reductions attributable to the FP250 compared to the baseline flare is a reduction in supplementary fuel usage for the existing flare pilot since, at Fort Benning, the flare was not operated whenever the FP250 was operating. On an annual basis, this amounts to 29.6 metric tons CO_2e/yr.

Details of the methods, assumptions and calculations used to determine GHG reductions are given in the full report.

6.5 ECONOMIC PERFORMANCE

The demonstration performance objectives for economic performance were to obtain a positive life cycle net present value (NPV) and a simple payback of less than 5 years. According to the detailed economic assessment presented in section 7.0 below, these objectives were not met at current electricity prices at Fort Benning.

Positive life cycle NPV is achieved when the electricity price exceeds $0.10/kWh. A 5-year simple payback is achieved when the electricity price reaches $0.18/kWh. The current electric price at Fort Benning is $0.069/kWh excluding any renewable energy premium.

Ener-Core expects that, as manufacturing steps up and economies of scale are realized, capital and O&M costs will be reduced and future FP250 installations will show positive life cycle NPV at a lower electricity price.

6.6 AVAILABILITY, RELIABILITY AND OPERABILITY

In order to be successful, the FP250 must provide sufficient availability, reliability and ease of use so that the economic value of power production is realized and no undue burden is placed on operations staff.

Availability is a quantitative metric that is given as the percentage of time that the system is either operating or capable of operation if down for unrelated reasons (such as, in this application, a grid failure or failure of the LFG collection system). Reliability is both a quantitative and qualitative metric that assesses the robustness of the system in terms of likelihood of failure or operational problems, the consequences of such problems, and the ability to recover.

Availability and Reliability were assessed quantitatively in accordance with American National Standards Institute (ANSI) Standard 762 [10] which uses a specific categorization of operating and downtime hours. Data were downloaded and reviewed on a weekly basis. Whenever the system shut down, Southern requested an explanation of the cause for the shutdown and Ener-Core would typically respond within one to two business days.

Southern began logging downtime on the official commissioning date of September 29, 2011; however, due to particulate breakthrough issues, significant periods of operation did not begin until March 7, 2012. Ener-Core's primary goal stated when operation resumed in March 2012 was to accumulate operating hours. Thus, the period beginning March 7, 2012 and extending through the end of operation on November 18, 2012 is the most representative period during the demonstration to calculate availability and reliability. These figures are presented in Table 4. The downtime log, in its entirety, is included in the full report.

Table 4. FP250 availability and reliability: March 7 through November 18, 2012.

Classification	Hours	Events	Percentage of Period
Total Period Hours	6144.0		99.7%
Total SH Hours	3527.3	35	57.4%
Total RSH Hours	0.0	0	0.0%
Total POH Hours	388.3	1	6.3%
Total FOH Hours	1133.2	21	18.4%
Total MOH Hours	1075.0	12	17.5%
		Reliability	82%
		Availability	57%

Total availability was only 57 percent during the operational period as defined above—much lower than the 95 percent goal and the 90-95 percent currently specified by Ener-Core. Availability is low due, in part, to planned outages for filter replacements and the G3 engine replacement and, in part, due to a significant number of forced outages. There were also a significant number of unplanned maintenance events (MOH) that resulted in shutdowns. If the forced and planned outage hours are subtracted from the period hours, the availability increases to 76%.

The reliability logged in the demonstration (82%) comes closer to the goal due to the significant number of forced outages that occurred because of circumstances beyond the control of Ener-Core. Forced outages were primarily caused by unrecoverable grid faults and were also caused by failures of the LFG extraction system. In some cases, a shutdown was initiated by a grid fault, but the system remained down for a longer period than necessitated by the grid fault for troubleshooting or maintenance. Since all of the hours for these events were generally classified as forced outages, Southern feels that the reliability results give the benefit of the doubt to the FP250.

During normal operations, the FP250 operated automatically without intervention and Southern witnessed that the FP250 could be monitored and controlled remotely by laptop computer or smartphone. Fault detection and shutdown were fully automated. System startup continued to require operator monitoring and minimal intervention throughout the demonstration period. Ener-Core reports that startup has now been fully automated and that this capability has been demonstrated on their engineering development test system; however, Southern has not had the opportunity to witness automated startup. Southern's impression is that the FP250 has the near-term potential for fully automated, unattended operation; however this was not verified during the demonstration.

7.0 COST ASSESSMENT

This section presents a life cycle cost analysis (LCCA) for implementation of the FP250 in a LFG to energy application. The analysis is informed by the Fort Benning demonstration, but has been generalized so that the results are applicable at other suitable sites and with other similar fuel sources (e.g., digester gas). All assumptions and information sources are fully documented to give credibility to the results and to aid in adaptation of the analysis to the reader's unique situation.

The life cycle assessment approach used herein conforms to the requirements and conventions specified in the Life Cycle Costing Manual for the Federal Energy Management Program (FEMP)—also known as "Handbook 135." The discount rate used for this analysis (3%) was obtained from the 2012 annual supplement to Handbook 135. The National Institute of Standards and Technology (NIST) Building Life Cycle Cost (BLCC) software, version 5.3-12 was used to model inputs and calculate the LCCA results for various energy price scenarios.

A number of other resources were also used to guide the life cycle assessment for this demonstration. EPA's Landfill Methane Outreach Program (LMOP) Handbook Chapter 4, Project Economics and Financing [15] provided general guidance on evaluating economics for LFG to energy projects and specific cost figures for competing LFGE technologies. EPA's LMOP "LFG_Cost" model has been used as a guide to identify cost elements and default values particular to LFGE projects and is also used to estimate costs for comparable LFGE technologies. The Environmental Cost Analysis Methodology (ECAM) Handbook [16] was also consulted as a guide to conducting economic analyses where environmental costs are a factor.

7.1 COST MODEL

The life cycle economic analysis is based on capital and O&M costs and revenues associated with electricity production during the demonstration period and projected over the expected lifetime of the FP250 equipment. Costs specifically associated with the demonstration program or with product development are excluded as non-typical of a normal installation. The analysis is "simplified" in the sense that it does not account for costs associated with financing or taxes, or for "revenues" or cost offsets associated with renewable energy credits, tax credits or other incentives that may be available in some locales for LFGE or other waste to energy projects.

The LCCA presented here models a "typical" FP250 installation where (1) there is sufficient LFG (or other waste fuel) to fully operate the FP250 without augmentation, (2) there is a pre-existing LFG collection and extraction system and flare and (3) the flare operates concurrently with the FP250 to consume excess fuel.

The life cycle economic performance of the FP250 was assessed based on standard economic indicators of financial performance including the NPV, adjusted internal rate of return (AIRR) and simple and discounted payback periods. These indicators are derived from cash flow analysis accounting for initial capital and installation costs, ongoing O&M costs, and revenues representing the value of the power produced by the FP250 system over the projected useful life of the system. That analysis accounts for the time value of money at the prescribed discount rate.

According to Ener-Core, in a typical installation and with proper maintenance, the FP250 should provide service for 20 years or longer. This period equates to a lifetime of 160,000 hours at 8,000 operating hours per year. For the purpose of the economic assessment, the LCCA study period was taken as 20 years.

The LCCA was completed in constant dollars (excluding inflation) per recommendations for non-financed projects in the BLCC model documentation and Handbook 135. All discount rates and price escalation rates are entered in real terms (without inflation).

Initial investment costs are modeled as "overnight" costs as of the service date. This practice is consistent with DOE practice for determining levelized costs for renewable energy technologies. The service date is modeled as April 1, 2012 for consistency with DOE energy price escalation rate tables. As discussed above, the actual starting date with the goal of continuous operation was in March 2012.

7.1.1 Energy Costs and Revenues

Electrical energy generated by the FP250 is fed back into the local grid operated by Flint Energy at Fort Benning and directly offsets power purchases from Georgia Power. For the purpose of the analysis, the value of electric power at Fort Benning is modeled at $69/MWh ($0.069/kWh). This is the 2013 rate that Fort Benning charges to reimbursable customers on the base and is based on previous year billings in accordance with applicable regulations [17]. The rate that Fort Benning pays to Georgia Power varies with time of day and load conditions and includes various fees and facilities and access charges, making it difficult, if not impossible, to establish a representative rate based on actual charges.

The Fort Benning energy manager reported in early 2013 that there is no mechanism in place on the base to account for a premium value on renewable energy (over and above the energy price). The Department of the Army policy for renewable energy credits section 5.f.(1) [18] states that the Deputy Assistant Secretary of the Army for Energy & Sustainability (DASA E&S) is the point of contact for all renewable energy valuation issues. Southern contacted DASA E&S for clarification on renewable energy valuation in renewable energy project life cycle cost assessment. For appropriations funded projects such as the Fort Benning demonstration, there is no value assigned to renewable energy. Renewable energy valuation is monetized within the LCCA only in cases where renewable energy credits (REC) are to be sold and the revenue is used to reduce the cost of the project—a situation that may occur in privately financed projects. Army policy states that 100% of RECs associated with appropriations-funded projects will be kept and retired via the Army Energy and Water Reporting System (AEWRS). As such, there is no monetary value that can be applied for this demonstration. However, it is possible that a renewable energy premium might be applicable for a future, privately-financed project within DoD. As such, the value of such a premium is estimated for the LCCA and the economic impact is assessed in Section 7.3 below.

The BLCC does not explicitly model revenues associated with energy generated from renewable energy projects. Southern contacted the BLCC developers at NIST for clarification and it was confirmed that the preferred approach for modeling revenues from energy generation using the BLCC is to apply a negative energy consumption value.

In addition to electricity, propane is used for startup fuel for the FP250 and is currently also used to supplement the LFG so that sufficient heat input is provided to operate the FP250. Propane is also used as fuel for the flare pilot. There is a savings in flare pilot fuel during FP250 operations at the 1st Division Road landfill since, as there is no excess LFG fuel, the flare is shut down during FP250 operation. Propane prices paid by Fort Benning are based on the Oil Price Information Service (OPIS) daily rate plus delivery on the day of delivery and varied from $1.04 to $2.05/gallon in 2012. U.S. Energy Information Administration (EIA) prices for propane in 2012 averaged $1.19 wholesale and $3.01 retail (per gallon). Since information on the average propane price per gallon paid at Fort Benning was unavailable, the average of the EIA wholesale and retail prices ($2.10/gallon) was used to model propane energy costs for the LCCA. In a typical application, Southern considers the EIA propane costs to be more representative than prices paid by Fort Benning.

7.1.2 LCCA Inputs and Assumptions: Typical Case

As discussed above (section 4.1) LFG recovery at the 1st Division Road landfill was lower than expected and proved insufficient to operate the FP250, necessitating the use of supplemental fuel to complete the demonstration. This situation is atypical in that site selection activities would normally be expected to verify that sufficient fuel was available before a system was installed. The typical case modeled here assumes that there is sufficient LFG (or other nominally zero-cost "waste" fuel) to fully operate the FP250 without augmentation, there is a pre-existing extraction system and flare and the flare operates concurrently with the FP250 to consume excess fuel.

Southern recognizes that, in many cases, potentially suitable landfills may not already be equipped with an extraction system; however, this lack would have to be addressed for the implementation of any LFGE technology and the extra costs are not representative of the performance or economics of the FP250 per se. For non-LFG fuel sources such as digester gas, extraction system costs are not relevant. Thus, Southern considers that the assumptions made here for the typical case provide broad, general comparability with other LFGE technologies and other non-landfill applications for the FP250. A discussion of LFG extraction system costs is provided in the full report.

Table 5 (below) presents BLCC inputs for each LCCA cost element that was modeled for the typical case. Notes are provided to document data sources and any special considerations for each model input.

Table 5. LCCA cost elements for the FP250: typical case.

LCCA Element	Value	Units	Data Sources and Notes
End of year discounting	yes	NA	Per non-military construction (MILCON) project.
Constant dollar analysis	yes	NA	Per non-financed project. Discount rate exclusive of inflation.
Discount rate	3%	%	Per Office of Management and Budget (OMB) Circular A94 2012 and 2012 annual supplement to Handbook 135.
Base date	4/1/2012	date	Consistent with starting date for DOE energy price escalation rates used in the BLCC.
Service date	4/1/2012	date	Service date modeled to coincide with base date.
Study period	20	years	Based on expected service life of FP250.
Energy production: electricity	-1,759,534	kWh/year	Negative value used to reflect energy production vs. usage. Based on demonstration data for G3 engine average net output (220 kW), annualized at 91.3% availability. Location: Georgia.
Energy cost: electricity	$0.069	$/kWh	Fort Benning rate charged to reimbursable customers (based on 2012 costs). Price escalation rates per BLCC/DOE. No annual demand charges or rebates.
Energy usage: propane	230	gallons/year	Average value from demo data. For startup only. Assumes two maintenance shut downs per year (best case). Assumes total gallons used per startup for (future) single burner, 20 hour startup program is the same as for current 2 burner 4-6 hour startup sequence.
Energy cost: propane	$2.10	$/gallon	Average of 2012 EIA wholesale and retail rates for Georgia. Price escalation rates per BLCC/DOE.
Capital component: FP250, investment cost	$1,254,313	$	Mid-range cost. Includes: FP250, BoP, site prep and installation. “Overnight” cost. No cost phasing.
Capital component: FP250, investment cost, residual value	0	%	Straight line proration over study period (same as system lifetime) per FEMP 135 manual.
Capital component: FP250, replacement cost	$0	$	Capital replacements are assumed to be funded from capital accounts rather than current accounts. This may have tax implications. For this analysis, replacements are presumed to be funded from operating accounts rather than from capital accounts and are entered as Non-annually recurring operations, maintenance and repair (OM&R) Costs.
Annual OM&R	$47,400	$	Operation ($16k) and maintenance (balance). Including filter cleanings. Materials and labor.
FP250, Non-annual OM&R cost, 1.5 year	$22,900	$	Filter replacement: 13 occurrences in 20 year study period.
FP250, Non-annual OM&R cost, 2.5 year	$2200	$	Replace igniter: 7 occurrences in 20 year study period
FP250, Non-annual OM&R cost, 5 year	$85,725	$	Engine overhaul and replace warmer/combustor: 3 occurrences in 20 year study period (years 6, 11, and 16)
FP250, Non-annual OM&R cost, 10 year	$207,500	$	Replace recuperator, oxidizer internals and media, transition tee and expansion joint (bellows): 1 occurrence in 20 year study period (year 11)
FP250, Non-annual OM&R cost, 15 year	$54,000	$	Replace/overhaul generator and gearbox. Year 16. Residual value of this replacement at year 20 is neglected.

FP250 availability for the typical case was modeled at 91.3%. This value was selected for consistency with Ener-Core's schedule for non-annual maintenance/overhaul of system components which presumes 80,000 hours of operation over 10 years—or 91.3% availability on average. According to Ener-Core, actual availability in typical service is expected to range from 90 to 95 percent.

Residual value after the 20 year study period was modeled as zero based on Handbook 135 guidance which recommends straight line pro-ration of capital costs over the system lifetime. Since, in this case, the system lifetime coincides with the study period; straight line proration gives zero residual value. Any residual value remaining after the system has exceeded its lifetime is presumed to be offset by decommissioning and disposal costs.

In the BLCC, non-annually recurring maintenance/overhaul or component replacement costs may be modeled as capital replacement costs or non-annual OM&R costs. The distinction is that capital replacements are funded from capital accounts whereas non-annual OM&R costs are funded from operating accounts. The distinction may have tax implications, but is unimportant within the context of this analysis.

The FP250 has significant non-annual overhaul/replacement costs occurring at various time intervals throughout the system lifetime. Over the system lifetime, the cumulative present value cost of these overhauls/replacements approaches the initial capital cost. Table 6 gives the schedule and costs for each of these elements (including parts, materials and labor). Labor costs are modeled at $50/hour based on U.S. Bureau of Labor Statistics average hourly labor rates for industrial mechanics (approximately $20/hour) multiplied by a cost of doing business factor of 2.5. Details of annual OM&R costs are given in Table 7.

Table 6. Non-annual OM&R cost detail.

Non-Annual Replacement/ Overhaul Item	Parts Cost	Labor Hours	Total Cost ($50/hour labor)	Interval
Replace oxidizer/turbine filter	$22,500	8	$22,900	1.5 year/12,000 hours
Replace combustor/warmer igniter	$1800	8	$2200	2.5 year/20,000 hours
Engine overhaul	$70,000	170	$78,500	5 year/40,000 hours
Replace warmer combustor	$6825	8	$7225	5 year/40,000 hours
Subtotal for 5 year interval OM&R	***$76,825***	***178***	***$85,725***	***5 year/40,000 hours***
Recuperator replacement (labor included with engine overhaul at same time)	$80,000	-	$80,000	10 year/80,000 hours
Replace oxidizer internals and media	$82,500	96	$87,300	10 year/80,000 hours
Replace transition tee and expansion joint (bellows)	$33,000	144	$40,200	10 year/80,000 hours
Subtotal for 10 year interval OM&R	***$195,500***	***240***	***$207,500***	***10 year/80,000 hours***
Overhaul generator and gearbox	$44,000	200	$54,000	15 year/120,000 hours

Table 7. Annual OM&R cost detail.

Maintenance Item	Q1	Q2	Q3	Q4	Totals
Engine borescope inspection		$3300		$3300	$6600
Filter cleaning		$4600		$4600	$9200
EX250 yearly maintenance				$6600	$6600
Recuperator cleaning		$4500		$4500	$9000
Weekly inspection	$4000	$4000	$4000	$4000	$16,000
Subtotal	**$4000**	**$16,400**	**$4000**	**$23,000**	**$47,400**

The capital investment cost modeled in the typical case represents the average of high and low range estimates provided by Ener-Core for base equipment and site specific equipment design, construction, and commissioning costs. The capital cost breakout including high and low range estimates is provided in Table 8.

Table 8. FP250 capital cost breakout.

Item	Typical Amount (low range)	Typical Amount (high range)	Typical Amount (Average)	Notes
Capital equipment costs (base)	$895,000	$895,000	$895,000	Current (2013) List price. Includes operator training costs.
Site specific engineering/design costs	$22,375	$35,800	$29,088	2.5-4% of list price. Includes permitting cost.
Management costs (for design/construction/ commissioning)	$17,900	$26,850	$22,375	2-3% of list price
Site specific capital costs	$134,250	$196,900	$165,575	Combined costs for electrical interconnect (10-15% of list price) and fuel delivery equipment (5-7% of list price). Fuel delivery system includes LFG and startup fuel systems.
Shipping	$13,425	$22,375	$17,900	1.5-2.5% of list price.
Site preparation/equipment installation	$89,500	$134,250	$111,875	10-15% of list price
Commissioning	$10,000	$15,000	$12,500	$40-60 per kW
Total	$1,182,450	$1,326,175	$1,254,313	Average value used for reported results.

7.2 COST DRIVERS

In terms of base capital and operating costs, the economics for a given FP250 installation are expected to be similar between sites. Ener-Core expects to be able to reduce capital and maintenance costs by approximately 20 percent once manufacturing steps up and economies of scale can be realized.

In terms of payback, the revenue associated with the electric power production of the FP250 depends on the value of the electric power produced, which will vary among different installations due to variations in the electricity price and whether a premium for renewable energy can be realized. Federal, state and local incentives may help to reduce direct costs or financing costs in some instances.

The most significant cost difference from one installation to another is the engineering and equipment required to capture and deliver the fuel source to the FP250. In the case of a landfill with an existing LFG extraction system, these costs should be nominal. Similarly, capturing and delivering digester gas for use in the FP250 should be a relatively simple and economical application. For other waste fuel sources such as spent solvents or fuels, more complex and expensive equipment will be required to deliver useable fuel to the FP250.

For Ener-Core's ultra-low emissions configuration, which may be required in some areas due to local air quality regulations, a fuel compressor will required, representing a significant additional cost.

For LFGE applications where an LFG extraction system is not already available, extraction system costs must be considered.

7.3 COST ANALYSIS AND COMPARISON

Based on the model inputs presented in detail in section 7.1 above, the FP250 BLCC results begin to show a positive return on investment once the price of electricity reaches $0.10/kWh. As noted above, Ener-Core expects equipment costs to decrease once manufacturing steps up and economies of scale are realized. In addition, current O&M cost estimates are conservative pending further operating experience that will allow Ener-Core to optimize maintenance and parts replacement schedules, thereby reducing the cost of maintenance labor and replacement parts. Lower capital and O&M costs would provide a return on investment at a lower electricity price.

Table 9 summarizes LCCA results from BLCC output for electricity prices ranging from $0.069 to $0.18 per kWh. In all cases, the total present value OM&R costs (annual and non-annual) over the 20 year study period is $1,319,978 and the total "overnight" capital investment cost is $1,254,313.

Table 9. Typical case BLCC LCAA results at varying electricity prices.

Electricity Price ($/kWh)	PV of Energy Savings ($)	PV of non-investment savings	Net Savings PV	Simple Payback (year)	Discounted Payback (year)	SIR	AIRR (%)
$0.069	$1,807,413	$487,435	($766,878)	not reached	not reached	0.39	-1.76%
$0.08	$2,096,837	$776,859	($477,454)	not reached	not reached	0.62	0.56%
$0.09	$2,359,950	$1,039,972	($214,341)	19	not reached	0.83	2.04%
$0.10	$2,623,063	$1,303,084	$48,771	15	20	1.04	3.20%
$0.11	$2,886,175	$1,566,197	$311,884	13	15	1.25	4.15%
$0.12	$3,149,288	$1,829,310	$574,997	9	13	1.46	4.96%
$0.13	$3,412,401	$2,092,423	$838,110	9	12	1.67	5.67%
$0.14	$3,675,514	$2,355,535	$1,101,222	8	9	1.88	6.30%
$0.15	$3,938,626	$2,618,648	$1,364,335	7	8	2.09	6.86%
$0.16	$4,201,739	$2,881,761	$1,627,448	6	7	2.30	7.37%
$0.17	$4,464,852	$3,144,873	$1,890,560	6	7	2.51	7.84%
$0.18	$4,727,964	$3,407,986	$2,153,673	5	6	2.72	8.28%

PV = present value SIR = savings to investment ratio

For the Fort Benning case, at $0.069/kWh, the life cycle NPV (net savings) is negative and payback is not reached during the study period. A 5-year simple payback is not achieved until the electricity price reaches $0.18/kWh.

The current Fort Benning electric price is consistent with the EIA December 2012 U.S. average industrial sector price ($0.0654/kWh), and somewhat higher than the industrial sector price in Georgia ($0.0565/kWh) [19]. Commercial sector electric prices (as of December 2012) are closer to the $0.10/kWh break-even price at $0.0982/kWh nationwide and $0.0923/kWh in Georgia. Electricity prices are currently trending downward in Georgia due to decreasing natural gas prices. That said, the Fort Benning energy manager reports that Plant Vogtle nuclear units 3 and 4 will cause a rate increase in early 2016 and again early in 2017.

Under its Green Energy Program, Georgia Power sells renewable energy at a premium of $35/MWh ($0.035/kWh) for standard green energy and $50/MWh for premium green energy (comprised of at least 50% solar). Georgia Power supports distributed generation and maintains a program to purchase renewable and non-renewable energy at their avoided energy cost. In 2012, Georgia Power's avoided energy costs were $123.26/MWh (peak) $75.12/MWh (peak season/off peak hours) or $74.16 (off peak) [20].

Although, at present, no monetary premium is recognized by the Army or the marketplace, a valuation of $35/MWh above Fort Benning's nominal current energy price ($69/MWh) yielding an energy price of $0.104/kWh would produce a positive life cycle net savings of $154,016 for the FP250 under the typical case model. In this instance, the SIR would be 1.12, the AIRR would be 3.60%, simple payback would occur in year 14 and discounted payback would occur in year 18.

7.3.1 Levelized Cost of Energy Comparison

The levelized cost of energy (LCOE) for an energy generating technology is the energy price at which the NPV of the life cycle cost of the technology over the equipment lifetime is zero. The energy price must reach the LCOE value for the project to break even and exceed the LCOE value for the technology application to produce a positive net savings or return on investment. The LCOE thus provides a common basis for comparing the cost of competing energy technologies and assessing the cost competiveness of a given technology.

According to DOE's NREL Open Energy Info database [24], the 2011 median LCOE for distributed generation technologies is $0.14/kWh. LCOE values in the OpenEI database range from $0.05/kWh to $0.48/kWh with an inter-quartile range of $0.08 to $0.35 per kWh. This is based on 17 cases in the database. NREL's 2012 projected average LCOE value for distributed generation is $0.09/kWh.

EPA's LMOP Project Development Handbook [15] gives typical costs for a micro-turbine (<1MW) in landfill gas applications of $5500/kW capital and $380/kW O&M annually. Using the NREL's online simple LCOE calculator [25], the LCOE for the typical micro-turbine is $0.094/kWh. For a small (<1MW) internal combustion engine in landfill gas application the LMOP handbook gives capital costs of $2300/kW with annual O&M costs of $210/kW. The NREL simple LCOE for the small IC engine is $0.045/kWh. A capacity factor of 91.3%,

discount rate of 3.0% and lifetime of 20 years was used in each of these cases for comparability with the FP250 economic analysis.

For the FP250 typical case LCCA modeling inputs ($5700/kW capital cost, $215/kW annual (fixed) O&M and $0.0236/kWh variable OM&R), the NREL simple LCOE for the FP250 is $0.098/kWh.

Based on this limited analysis, the levelized cost of the FP250 per kilowatt-hour appears to be on par with competing distributed generation and LFGE technologies.

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8.0 IMPLEMENTATION ISSUES

One of the lessons learned in this demonstration is that a landfill that, based on all readily available evidence, appears to be producing more than enough gas to operate the FP250 may not be producing nearly as much gas as expected. For the 1st Division Road site, methane flow data available from routine monthly readings at each well head yielded misleading information when aggregated to total well field production (see Section 4.1.1). The total landfill area was mistakenly recorded in site records as 48 acres while the actual active area was discovered to be 26.5 acres. The landfill had a history of problems with offsite CH_4 migration suggesting that high levels of gas were being produced. In 2003, modeling based on vent performance tests predicted the landfill would produce 700 cubic feet per minute (cfm) LFG with 40 to 50 percent CH_4 content (17-21 MMBTU/hr).

Even with all of this evidence indicating a more than sufficient fuel supply at the 1st Division Road landfill, it would have been prudent to obtain accurate measurements of CH_4 flow actually delivered to the flare during site selection activities. It is strongly recommended that a representative set of such measurements be obtained for future candidate sites, notwithstanding any other data that may be available.

In the case where an extraction system is not already in place, a thorough study should be conducted to verify sufficient gas is present and may be recovered. This would include a detailed examination of the landfill characteristics including information on the landfill structure and the rate and type of waste acceptance, surface testing to verify gas production and permeation, and, based on these data, careful modeling of the expected LFG recovery rate over time.

Installation managers should understand that the FP250, like other turbine-based technologies, requires a steady fuel supply with a minimum total energy content of about 3.4 MMBTU/hr. That is, the FP250 is only capable of operating near 100 percent of rated capacity and has little turn-down capability. In addition, the FP250 does not tolerate excessive thermal cycling. Continuous 24/7 operation is recommended and the number of restarts over the system lifetime should be minimized to avoid excessive maintenance. It is therefore critical that a sufficient, continuous fuel supply be carefully verified during site selection.

It is at least somewhat likely that a potential landfill site under consideration for FP250 application will not have an existing LFG extraction system and flare. In such cases, the cost of the required extraction system may make the project economics less attractive.

The FP250 is a newly commercialized technology that is still undergoing minor modifications to improve reliability and operability. These modifications include:

- Prevention of turbine wear due to particulate breakthrough (discussed in Section 8.1 below);
- A new startup protocol utilizing the warmer only (the combustor will be removed from the system);
- Full automation of system startup; and

- The capability to continue operation in “island mode” to prevent unnecessary shut downs due to transient grid faults (applicable to sites where there are frequent grid interruptions).

The performance of these proposed modifications was not verified as part of this demonstration.

Ener-Core has provided a summary O&M manual and is in the process of developing full O&M protocols and procedures and complete system documentation. Southern has reviewed and commented on the summary manual, but did not have the opportunity to review complete system documentation as part of this demonstration.

As the FP250 is a low emissions technology based on proven gas turbine technology, Southern anticipates that regulatory or permitting barriers for future installations will be low. Southern’s experience with the Fort Benning demonstration was that there were no significant regulatory or permitting barriers.

8.1 FILTRATION BETWEEN THE OXIDIZER AND TURBINE

Particulate matter may be introduced into the FP250 by oxidation of siloxanes present in the LFG, by breakdown of the heat transfer media or internal insulation within the gradual oxidizer, or as a consequence of corrosion of metallic components such as the combustor and warmer.

In order to prevent PM from damaging the turbine wheel or fouling the recuperator, the FP250 design incorporates a filter between the gradual oxidizer and the turbine. The original design employed a 150 micron filter.

After operating less than 400 hours, the original engine was found to have excessive wear on the nozzle and turbine rotor. A root cause analysis was conducted and concluded that the turbine wear was due to particulate originating from the gradual media oxidizer entering the turbine section of the engine and eroding the nozzle and turbine rotor [7]. Based on this, Ener-Core initiated an effort to improve filtration between the oxidizer and the turbine. Interim filter solutions were installed in order to be able to continue operations while a final solution was developed.

Ener-Core engineered and tested several filter solutions throughout 2012. The first was a 75 micron filter installed in February 2012. After initial testing, this filter was replaced with a 50 micron filter with additional open area in early March 2012. The 50 micron filter performed well over more than 1800 hours of operation. When the G3 engine design was installed in July 2012, the 50 micron filter was replaced with a 40 micron filter. The 40 micron filter performed well over nearly 900 hours of operation until it was replaced as planned in mid-September 2012 with a 5 micron pleated ceramic filter that was intended to be the final filter solution. This modification required minor piping modifications.

Excessive insulation wear was observed after about 290 hours of operation with the 5 micron filter, leading to filter erosion and particulate breakthrough, which allowed debris to enter the turbine. In order to continue operation, a 75 micron filter that was on hand was installed.

Ener-Core has determined that adding a liner in the hot piping upstream of the 5 micron filter will prevent insulation wear and filter erosion and has recommended that this be completed before resuming operations following the system handover. The performance of this solution was not verified as part of the demonstration.

Ener-Core recommends cleaning the filter after 4,000 hours operation and replacing the filter at 12,000 hours operation. The pressure drop across the filter is continuously monitored, and the filter need not be replaced so long as the pressure drop remains in specification. This maintenance interval can vary based on the system operation and application fuel. For future installations, Ener-Core has adopted special oxidizer media handling procedures to minimize debris generation during assembly.

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APPENDIX A

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