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Cost and Performance Report

(EW-201251)

Conversion of Low Quality Waste Heat to Electric Power with Small-Scale Organic Rankine Cycle (ORC) Engine/Generator Technology

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An Organic Rankine Cycle generator (ORC) converts low-grade waste heat (<250 °C) into electric power using organic working fluids with lower boiling points than the common steam-based Rankine cycle. The demonstration objectives were to verify the performance, economics and applicability of the ElectraTherm ORC in both controlled load and real world conditions at a DoD site.

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ACRONYMS AND ABBREVIATIONS

AIRR	Adjusted Internal Rate of Return
BLCC	Building Life-Cycle Cost
BoP	Balance of plant
CHP	Combined heat and power
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CRM	Cummins Rocky Mountain
dB	Decibel
DoD	United States Department of Defense
DOE	US Department of Energy
EGHX	Exhaust gas heat exchanger
EIA	US Energy Information Administration
EO	Executive Order
EPA	U.S. Environmental Protection Agency
ESTCP	U.S. Department of Defense Environmental Security Technology Certification Program
F	Fahrenheit
FEMP	Federal Energy Management Program
FTP	File Transfer Protocol
FXWC	Naval Facilities Engineering and Expeditionary Warfare Center
GHG	Greenhouse Gas
gph	gallons per hour
gpy	gallons per year
GTMO	Naval Station Guantanamo Bay
GWP	Global Warming Potential
IC	Internal Combustion
ISO	International Organization for Standardization
kW	kilowatt
kWe	kilowatt-electric
kWh	kilowatt-hour
Lb	Pound
LCCA	Life Cycle Cost Analysis
LCOE	Levelized Cost of Energy
LFG	Landfill gas
LLR	Liquid Loop Radiator

MW	Megawatt
N_2O	Nitrous Oxide
NIST	National Institute of Standards and Technology
NPV	Net Present Value
NSPS	New Source Performance Standard
O&M	Operations and Maintenance
OM&R	Operations, Maintenance and Repair
OMB	Office of Management and Budget
ORC	Organic Rankine Cycle
PFD	Process Flow Diagram
P&ID	Piping and Instrumentation Diagram
PLC	Program Logic Controller
PTO	Power take-off
SERDP	Strategic Environmental Research and Development Program
SIR	Savings to Investment Ratio
USEPA	Environmental Protection Agency
VFD	Variable Frequency Drive

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EXECUTIVE SUMMARY

An Organic Rankine Cycle (ORC) generator converts low-grade waste heat (<250 ºC) into electric power using organic working fluids with lower boiling points than the common steam-based Rankine cycle. For this demonstration, Southern Research identified the ElectraTherm ORC as a well-designed and supported, cost effective, and appropriate ORC technology with a wide range of applications within DoD. The ElectraTherm ORC integrates proven components and optimized thermodynamics and controls to effectively utilize waste heat from comparatively small but ubiquitous sources such as internal combustion engines, gas fired boilers, turbines, oxidizers, process heat, solar thermal and geothermal, flares, compressors, and other sources.

One of ElectraTherm's target markets is utilizing waste heat from large stationary reciprocating engines. The ORC model demonstrated was optimized to utilize waste heat from 1 Megawatt (MW) class diesel generator sets commonly deployed in prime power applications at remote United States Department of Defense (DoD) sites and forward operating bases worldwide. The system was packaged in two, standard 40-foot International Organization for Standardization (ISO) containers: the first containing a packaged Cummins 1.2 MW diesel generator, an exhaust gas heat exchanger plus switchgear and controls; and the other containing the ORC generator and a high efficiency radiator. The engine's stock, power take off (PTO)-driven, radiator was removed and significant additional energy savings were realized by allowing the high efficiency ORC radiator to also cool the engine.

The demonstration objectives were to verify the performance, economics, and applicability of the ElectraTherm ORC in both controlled load and real world conditions at a DoD site. Southern and ElectraTherm were supported by the Navy's Mobile Utilities Support Equipment (MUSE) Division.

Controlled load baseline tests of the unmodified genset and intensive tests of the fully integrated system were successfully conducted at the MUSE yard in Pt. Hueneme, CA. The equipment was heavily instrumented to allow for detailed performance assessment and optimization. The unit was then deployed to Guantanamo Bay Naval Station (GTMO) for further monitoring during extended operation under field conditions. Installation and initial off-grid commissioning at GTMO went well. However, repeated efforts to commission the system to operate in parallel mode on the GTMO grid was not successful, and the demonstration was terminated before field data could be collected. These issues were ultimately traced to poor workmanship on the generator controls installation during packaging. The ORC itself performed as expected in the field and tests conducted at GTMO confirmed that the issues encountered were in no way related to ORC or to integration of the ORC with the genset.

Sufficient data were collected during the controlled load tests to fully characterize the performance of the integrated system compared to baseline. During the controlled load tests, the ORC produced a net output of 38.7 kilowatt (kW) at 900 kW generator load under prime, unlimited service. The reduction in cooling load on the engine due to the radiator improvements was measured at 87.7 kW under these same conditions; however, this high measured value was not fully explainable. Based on our investigations, Southern believes that a conservative value for the reduction in cooling load is 45 kW additional power output for the same fuel input.

Taken together, direct ORC power output (38.7 kW) and the conservative estimate of reduction in cooling load due to the radiator improvements (45 kW) amounted to a 9.3 (±0.65) percent increase in overall fuel economy or, alternatively, an 83.7 kW increase in power output for the same fuel input. This value is used for calculation of Greenhouse Gas (GHG) reductions and economic results.

Life cycle economics of the system are favorable with better than five-year payback for base load operation at moderate expected prices projected for diesel fuel ($3.25/gallon). Note that economics would not be favorable for typical backup generator operating scenarios. System operability is very good, with low maintenance and minimal training requirements over those for baseline generator set operation.

1.0 INTRODUCTION

The U.S. Department of Defense (DoD) is America's largest energy consumer, representing over 75% of federal energy consumption and spending over $4 billion annually on facility energy as of FY 2014. The Department has been making significant efforts toward reducing the intensity of energy consumption, improving energy efficiency, increasing renewable energy usage, and improving energy security [1].

Application of novel technologies can result in significant energy and cost savings and progress toward achieving the energy efficiency and renewable energy directives set forth by the DoD, Congress, and the President.

This project was proposed as a DoD field demonstration under the Environmental Security Technology Certification Program (ESTCP) program to evaluate the performance and efficacy of a waste heat to energy technology that addresses DoD energy goals.

1.1 BACKGROUND

In efforts to improve the overall efficiency of energy generation and use at DoD facilities, attention must be given to waste energy sources in existing and planned energy systems at DoD installations. One of the largest sources of wasted energy is in the form of waste heat – thermal energy emitted via hot exhaust and heat rejection systems associated with engine and other electric generator systems, waste heat from steam or heat distribution, waste heat from boiler exhausts, and heat emitted from cooling systems. A very large number of waste heat sources occur at DoD sites. Steam boilers, hot water boilers, engine generators, and similar equipment typically lose 20-60% of the energy input to the system as waste heat. These types of waste heat sources and others are ubiquitous at DoD facilities domestically, worldwide, and in deployed scenarios.

In current energy systems, recovery and use of waste heat is often possible but rarely accomplished due to a lack of knowledge about technology options and benefits, the difficulty of finding ways to effectively use the waste heat available, a lack of viable technology options for low quality heat (< 250 °C), and other factors. The ability to recover the heat for useful purposes is the foundation of the high efficiency achievable in combined heat and power (CHP) applications. Where applicable, CHP systems are an excellent solution to the waste heat problem, as are improvements in building energy management, insulation, and system optimization. However, for those applications where heat cannot be used cost effectively, there are additional options that can provide improved energy system efficiency and cost savings.

The Organic Rankine Cycle (ORC) engine-generator converts low quality waste heat directly into electric power, allowing for utilization of a large domestic energy resource that can reduce grid electricity use, offset fossil fuel combustion with the associated emissions, and minimize security risks. Higher grade industrial waste heat has been recovered for years using steam driven Rankine Cycle engines. Until recently, however, technology was not available commercially to recover low quality waste heat at smaller scales – and low grade heat is where the greatest opportunities exist. Recent advancements with ORC engines make tapping this resource viable [2].

The ORC can provide significant energy cost savings in certain applications, and can improve energy security by providing increased on-site energy production or fuel economy. A summary of potential applications and benefits of ORC technology to DoD is given in Table 1.

Table 1. Potential DoD Applications for ORC Technology

ORC Application Type	Available Heat Source (continuous operation)	ORC Benefits	Potential DoD Sites
Engine Generators – remote and deployed locations (FOBs)	Waste heat from engine jacket water and/or exhaust	Increased efficiency Reduced power costs Reduced fuel consumption, transportation and costs Reduced emissions intensity.	**Mobile:** MUSE (35 units, >1MW) Army (>200 units, 840 kW) Air Force (~100 units, 800 kW) **Stationary:** Many in standby and prime service, e.g., GTMO (10+ units, >1MW), Maine (4+ units, >1MW)
Steam Boilers and CHP Systems	Waste heat from stack exhaust, excess capacity in economizers and heat exchangers, condensate / steam returns	Increased system efficiency, added on-site power generation, reduced emissions intensity	41 appropriately sized boilers at steam plants at 12 Army Installations 5 large CHP systems (engine and turbine), other locations possible
Engine Generators – Landfill Gas (LFG) / Biogas	Waste heat from engine jacket water and/or exhaust	Increased system efficiency, added on-site power generation, reduced emissions intensity	MCAS Miramar, Hill AFB, Ft. Richardson, CGS Curtis Bay, MCLB Albany, 26 MW of planned installations by 2020
Biomass Power and/or Heating Systems	Waste heat or increased heat output (due to low fuel costs)	Increased efficiency Increased renewable energy generation.	Handful of sites currently using biomass, but more potentially coming as renewable energy targets are addressed
Solar Thermal Systems	Excess or unused heat capacity in the solar thermal system	Increased efficiency Increased renewable energy generation	Large installation at Camp LeJeune (900 homes). Other examples include Port Hueneme Naval Base, Mayport Naval Station, the Army Parks Reserve Forces Training Area, Fort Hood and Moody and Kirtland AFB. Current ODUSD I&E initiative to expand deployment. If heat not used year round, ORC could be implemented.

MUSE Mobile Utilities Support Equipment
MW Megawatt
kW Kilowatt

1.1 OBJECTIVE OF THE DEMONSTRATION

The overall objectives of the demonstration were to (1) install and evaluate an ORC system that produces electric power from waste heat using a heat source representative of commonly available low quality heat sources within DoD, and (2) assess the applicability of ORC implementation across the DoD. These objectives were evaluated by the following activities.

- Design, build, and package for deployment an ORC generation system that optimizes utilization of jacket water and exhaust gas waste heat from a diesel genset of a capacity (~ 1MW) commonly deployed at DoD sites.
- Determine the technical and financial performance of the ORC system through rigorous performance verification during short term intensive testing and longer term deployment as described in this plan.
- Assess ORC technology transfer potential across DoD facilities.
- Deliver a final report that fully documents all project activities, data collection, and analyses, results, conclusions, and recommendations.
- Deliver a cost and performance report focused on providing information that program, facility, and installation managers, regulators, and other stakeholders can use in making implementation decisions.
- Provide guidance within the above reports for determining the applicability of the ORC to a variety of site types, conditions, and economics.
- Conduct outreach activities such as presentations at conferences and symposia to publicize the activities and results of the demonstration.

Success factors validated during the demonstration include ORC energy production and integrated system efficiency gains, economics, and operability including reliability and availability.

The fully integrated packaged ORC/generator set system was deployed at the Naval Station Guantanamo Bay (GTMO) as determined by the DoD project partner in accordance with Southern's site selection criteria.

The demonstration evaluated and demonstrated the potential for the application of ORC technology to improve energy efficiency at DoD facilities. A field demonstration is necessary to ensure that:

- the ORC performs as anticipated under the conditions at which DoD equipment operates;
- the ORC system reliability, availability, and operability are sufficient for DoD applications, which can include critical energy supply applications;
- the integration of the system in the proposed applications with the required balance of plant and waste heat source equipment does not negatively impact site operations; and
- the system economics and other benefits are attractive enough to justify broader implementation of the technology within DoD.

1.2 REGULATORY DRIVERS

Energy security, environmental sustainability, and cost savings are all drivers for adoption of ORC waste heat to energy technology. The ORC utilizes low grade waste heat (less than 250 ºC), improves energy efficiency by reducing energy consumption associated with electrical generation and reduces greenhouse gas emissions by increasing electrical generating efficiency.

This demonstration addresses several specific drivers for DoD energy efficiency and renewable energy goals, specifically:

- Reduce annual fuel usage [National Defense Strategy June 2008]
- Reduce installation energy usage by 30% by 2015 [Executive Order (EO) 13423 /2007 Energy Act]
- By 2010, reduce fossil fuel in all buildings: 55%; 100% by 2030 [2007 Energy Act]
- Increase non-petroleum fuel by 10% per year [EO 13423/2007 Energy Act]
- Maintain Federal leadership in sustainability and greenhouse gas emission reductions [EO 13693/2015]

2.0 TECHNOLOGY DESCRIPTION

The ORC engine converts waste heat into electric power and is able to use low quality (<250 ºC) heat through the use of organic working fluids with lower boiling points than the common steam-based cycle. Small scale ORC engines have recently become available which allow recovery of waste heat from comparatively small but ubiquitous sources like internal combustion (IC) engines, gas fired boilers, turbines, waste oxidizers, process waste heat, solar thermal applications, and other sources [2].

2.1 TECHNOLOGY OVERVIEW

Southern Research identified the ElectraTherm ORC generator as a well-designed and supported, cost effective, and appropriate ORC technology with a wide range of applications within DoD.

ElectraTherm's Power+ 6500 ORC generator (see Figure 1) is a compact, packaged system with gross output up to 110 kilowatt-electric (kWe). The Power+ generator boasts simple installation, low maintenance, and integrated controls that allow the system to continue producing power from a variable waste heat supply without affecting the operation of upstream systems.

Figure 1. ElectraTherm Power+ 6500 Generator (panels removed)

The Power+6500 utilized for this demonstration is a next generation model of ElectraTherm's GM4000 model optimized to effectively utilize as much waste heat as thermodynamically practicable from a 1MW class diesel generator set, maximizing ORC power output. This class of generator set is commonly deployed to serve DoD installations and forward operating bases, utility peak load and industrial/commercial peak shaving applications, oil and gas exploration, and emergency standby generation.

The ElectraTherm ORC heats and vaporizes the working fluid in two stages; first through a preheater (heated by engine jacket water), and then through the evaporator (heated by exhaust gas). In the demonstrated application, the advantage of the split preheater/evaporator configuration is that a higher evaporation temperature (and thus pressure) can be achieved if the working fluid is first heated to the jacket water temperature, allowing full advantage to be taken of the high grade exhaust gas heat. The two-stage heat input configuration also provides design flexibility for adapting the ElectraTherm ORC to most efficiently utilize waste heat from a variety of sources.

ElectraTherm began commercial production of the first series 4000 ORC units in mid-2011. At the time the proposal for this demonstration was submitted, the series 4000 was recently introduced and had accumulated fewer than 100 hours. Prototype and beta versions of the ElectraTherm ORC had accumulated only about 9,000 hours at that time.

As of April 2016, ElectraTherm's fleet of 50 commissioned units installed in 14 countries had accumulated over 520,000 hours (nearly 60 years) of run time at an average availability of >97%. ElectraTherm has made very rapid progress in successfully bringing their product to market and the larger 6500 series unit developed during this demonstration now represents the majority of new installations and new customer enquiries.

Much of the early market penetration occurred in Europe where incentives for energy efficiency and clean, renewable energy generation are generally greater than in US markets. ElectraTherm is actively seeking greater domestic market penetration in both government (e.g., DoD) and private sectors, as well as developing new markets in Asia.

About half of the installed fleet is utilizing waste heat from generator sets, followed by applications in district heating and biomass applications. Other units are installed in geothermal, process heat, and solar thermal applications. Genset applications in the 0.5-2MW range remain a primary market focus along with flare to power and geothermal applications.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The chief advantage of ORC generators is the ability to recover useful energy from low grade (< 250 ºC) waste heat. The availability of small, economical ORC generators allows for efficient utilization of available waste heat from common sources within DoD such as diesel generators.

Compared to steam cycle generators, the low working pressure in ORC power plants reduces capital costs for machinery and piping. In addition to lower up-front costs, the operational lifetime of ORC system components is increased relative to steam-cycle systems due to the non-eroding and non-corroding nature of the organic working fluids.

The ElectraTherm ORC design takes full advantage of the inherent benefits of smaller ORC generators over steam cycle and larger scale ORC designs and implements a number of improvements that result in a more economical, robust, and efficient system than competing small scale ORC designs. The ElectraTherm ORC is intended to be a plug-in appliance and is designed to avoid the need for custom engineering – reducing installation costs.

Central to ElectraTherm's ORC technology improvements is the use of a twin screw expander. The ElectraTherm expander is based on a common, commercially available refrigeration compressor that has been adapted to operate in reverse as a radial inflow turbine. The use of this type of expander introduces a number of advantages including:

- Low cost and high reliability of proven ‘off the shelf’ components
- Low RPM – allowing for direct coupling to a standard induction generator – which reduces capital and maintenance costs, and improves reliability and efficiency
- Wet vapor tolerance – improves cycle efficiency, reduces demand for high grade heat that would be required for dry vapor systems, and allows for in-process lubrication [4]

In the ElectraTherm ORC designs, lubricant is carried with the refrigerant in a closed loop system and the unit requires no oil changes or lubrication sub-system, reducing capital and maintenance costs and improving reliability. ElectraTherm systems utilize R245fa organic refrigerant approved by the U.S. Environmental Protection Agency (EPA) in the U.S. and the Montreal protocol in the U.K. and Europe. Some ORC systems use toxic or flammable working fluids.

The complete system (less radiator) is housed in a compact 6.5 x 8.8 x 7.5 ft. frame that can be moved with a forklift. For the DoD packaged unit demonstrated, installation consisted of four pipe connections (supply/return for the jacket water and exhaust gas loops) and electrical and control connections (see section 5.3.1).

The system implements fully automated controls with remote access diagnostics. The system configuration and control strategy allow the Power+ to follow a varying heat supply over a 5:1 turndown ratio. This turndown capability greatly improves up-time and cumulative energy production over time. If the heat supply is interrupted, the system will automatically ramp down power output until residual heat is consumed and then resume output once the heat source returns. Controls integration with upstream equipment is not required to accomplish this heat source following behavior.

The Power+ 6500 uses an induction generator rated at 110 kW for electric power production. An induction generator does not require synchronization to the grid. Voltage and frequency regulation are naturally provided from the connection to the power grid. Similar to industrial motors, induction generators are inexpensive, robust, and proven; employing no brushes, commutator, slip rings, exciter, regulator, synchronizer, or other complex parts. The Power+ units use integral power factor correction capacitors to improve the inherently low power factor of the induction generator to a value from 0.90 to unity, depending on load.

In most applications, waste heat rejection <u>requires</u> energy. For example, the radiator on a diesel engine requires a fan, and cooling may represent a parasitic load on the system of as much as 5% of system power output. That cooling requirement is paid for in kW (electric driven fans) or horsepower (shaft driven fans). The ORC engine can replace a portion of this parasitic load, resulting in gains in overall system efficiency. While ORC thermal to electrical efficiency is low (typically 5-15%) and ORC generator output may represent only a 5-10% increase in total generating system efficiency, careful integration of the ORC within the overall system can yield overall system efficiency improvements that are much greater than that represented by the ORC generator output alone. In addition, if there is a local use for heat remaining after the ORC, further overall system efficiency gains can be realized.

The integrated system designed for this demonstration replaces the engine's power take off (PTO)-driven, constant load radiator fan with a high efficiency radiator and Variable Frequency Drive (VFD)-driven fan that allows the cooling benefit of ORC integration to be realized and results in an additional total system efficiency gain of up to 5% over the net output of the ORC engine alone.

One limitation of ORC generators in general is that performance can depend on the heat sink temperature. Performance of air cooled systems can be significantly degraded in very hot ambient conditions. For DoD deployments, closed loop, air cooled systems are a general requirement since water availability is often restricted.

A limitation specific to the ElectraTherm units is that, due to the use of the induction generator, the system cannot operate in a stand-alone 'island mode' without a large prime mover (approx.. 10X ORC output) to sync to. As mentioned above, the induction generator requires grid interconnection to function. In the event of a grid loss, the Power+ ORC units will automatically shut down, and cannot be re-started until line conditions return to normal. This is not a limitation in genset applications of this scale since, at normal load conditions; the generator set provides sufficient frequency regulation for the ORC to operate. The Department of Energy did fund ElectraTherm for a preliminary off-grid design but market pull has not lead to further investment to complete detailed design and testing of a true off-grid solution.

3.0 PERFORMANCE OBJECTIVES AND RESULTS

The performance objectives for this demonstration system relate to power output and system efficiency gains, reliability/operability, emissions reductions, and economics of the integrated ORC/genset system compared with baseline conditions. The baseline consists simply of operating the diesel genset as originally configured by the manufacturer. The system under test includes the engine-genset, the ORC system, and the cooling system.

3.1 SUMMARY OF PERFORMANCE OBJECTIVES AND RESULTS

Key demonstration objectives were achieved, including verification of overall system performance and economics, during baseline and intensive testing of the integrated system prior to deployment; however, some of the demonstration objectives (e.g., availability/reliability) could not be fully quantified due to lack of longer term, deployed testing caused by the failure to commission the genset on the GTMO grid following deployment. Details concerning this issue are presented in full in section 8.0. Note, however, this issue was in no way caused by the ORC itself or by the integration of the ORC with the genset.

Data requirements and success criteria for each demonstration objective are summarized in Table 2. Details for each objective are provided under section 3.2.

Table 2. Performance Objectives and Results

Performance Objective	Metric	Success Criteria	Results
Increase energy output using waste heat without additional fuel input	ORC electric output kW, genset fuel efficiency (kWh/gallon)	Net energy output from ORC >50kW at design conditions (900 kW load) to be achieved without reducing genset efficiency or operability.	Objective met: Net energy output of integrated system conservatively increased by 83.7 (±7.9) kW. Measured integrated system output was as high as 130.2 kW at design conditions.
Increase integrated power system efficiency	System efficiency gain (%), fuel economy gain (kWh/gallon)	Total power system efficiency increase >5% at design conditions in prime unlimited service.	Objective met: Conservative overall system efficiency gain was 9.3 (±0.65) percent. Measured efficiency gain was as high as 14.5%.
Determine ORC internal efficiency	Thermal/electric efficiency (%)	ORC internal efficiency > 7%. Net ORC efficiency (including all parasitic loads) > 5%.	Not determined: Deployed test data not available. Modeled net efficiency (5.9 to 6.8%) meets objective.
Demonstrate high availability and reliability	Service hours as percentage of period hours (%)	Availability >95%, reliability >97% on fully commissioned system.	Not demonstrated: Field demonstration was terminated due to commissioning issues. ElectraTherm has extensive fleet data showing >97% availability.
Demonstrate Operability	Qualitative	Use of system does not impose an excessive burden on operations and maintenance staff and deployment operations.	Partially demonstrated: Initial indications are all good, but insufficient information was collected due to early termination of the demonstration.

Table 2. Performance Objectives and Results (Continued)

Performance Objective	Metric	Success Criteria	Results
Economics	Life cycle NPV net savings ($), SIR and AIRR (%), simple and discounted paypack period (yrs)	Simple payback < 5 years.	Objective met: Simple/discounted payback occurs in year 4 at current GTMO fuel prices ($3.25/gallon).
Determine GHG emissions reductions	metric ton/yr CO_2e	GHG emissions reductions greater than 200 metric ton CO_2e/yr.	Objective met: 464 metric ton CO_2e total emissions reduction.

AIRR Adjusted Internal Rate of Return
CO_2e Carbon Dioxide Equivalent
GHG Greenhouse Gas
kWh kilowatt-hour
NPV Net Present Value
SIR Savings to Investment Ratio

3.2 RESULTS AND DESCRIPTIONS FOR EACH PERFORMANCE OBJECTIVE

The following subsections provide additional detail on the considerations involved in evaluating performance and determining results for each objective. A description of the data analyses conducted in support of these assessments is presented in Section 6.0 of this report. Full details are available in the final report.

3.2.1 Increase Energy Output

This objective is to increase integrated system power output by a total of at least 50 kW over baseline at design conditions using waste heat and without additional fuel input. This increase benefits DoD installations by either providing additional power or reducing fuel consumption. An important additional benefit for DoD is recovered capacity. The power output for generating units is frequently de-rated in hot climate deployments due to decreased cooling capacity. ORC integration recovers a portion of this diminished generating capacity in two ways: by generating power from waste heat and increasing engine cooling capacity.

The total increase in energy output is defined here as the sum of the net electric power (less parasitic loads) generated directly by the ORC engine and the effective increase in integrated system power output due to the reduction in cooling load on the engine. The 50 kW goal is stated in terms of this total increase.

The reduction in cooling load was achieved primarily by replacing the KTA50's radiator with the ORC's high efficiency radiator driven by VFD-controlled fans in place of the stock mechanically (PTO) driven radiator fan. According to Cummins specifications, the stock radiator fan load for the KTA50 is 56 kW.

Southern completed a baseline fuel economy test on the unmodified engine over the range of expected operating conditions (700-1100 kW) on May 14, 2013 and then conducted fuel economy testing over the same range on the integrated system during the intensive tests completed on July 17, 2015.

The difference in baseline and integrated system test fuel economy offset by the VFD-controlled radiator fan load measures the energy gain due to removal of the radiator fan load from the engine PTO (see section 6.1 for details). As a corroborating measure, Southern compared net power consumption for engine cooling on the VFD controlled radiator fan with the 56 kW Cummins fan load specification.

The net increase in integrated system energy output for the same fuel input at nominal load conditions (900 kW) was determined to be 83.7 ±7.9 kW, representing a 9.3 ±0.65% increase in fuel economy. This result is based on 38.7 kW directly measured ORC output plus 45 kW net reduction in cooling load determined from the 56 kW Cummins specification less 11 kW in radiator and ventilation fan loads.

Note that the total *measured* reduction in cooling load was 87.7 kW at nominal engine load conditions with a total increase in equivalent power output of 130.2 kW, which corresponds to a fuel economy increase of 14.5%. Although the measurements were validated, despite a thorough investigation, these higher values could not be fully explained, so the results based on the Cummins specification are considered to be a conservative representation of performance. A fully detailed description of the investigations that were undertaken related to this issue can be found in the final report.

Fuel consumption and fuel economy data at nominal load conditions for the baseline and integrated system 'intensive' tests are presented in Table 3. To enable comparison, the results have been scaled to exact nominal conditions from (slightly varying) actual test conditions by linear interpolation. Table 4 compares the baseline and integrated test results in terms of the increase in fuel economy, fuel consumption, and equivalent additional power output for a given fuel input. Conservative results, and associated uncertainties (one sigma) based on propagation of measurement error and test statistics determined per the demonstration plan are given in Table 5.

Table 3. Baseline and Integrated Test Fuel Consumption and Fuel Economy at Nominal Load Conditions

Nominal Load (kWe)	Measured Fuel Consumption (gph)	Measured Fuel Economy (kWh/gallon)
Baseline - Unmodified Genset Only		
700	54.5	12.8
900	67.0	13.4
1100	79.5	13.8
Integrated System - ORC Bypassed		
700	48.8	14.3
900	61.0	14.7
1100	73.3	15.0
Integrated System - ORC Online		
700	46.8	15.0
900	58.5	15.4
1100	70.2	15.7

Gph Gallons per hour

Table 4. Measured Fuel Savings or Equivalent Additional Power at Nominal Load Conditions

Nominal Load (kWe)	Fuel Economy (kwH/gallon) Increase (%)	Fuel Consumption (gph) Decrease (%)	Equivalent Additional Power Output at Given Fuel Input (kW)
Savings Due to Reduction in Cooling Load Only (ORC bypassed) - vs. Baseline			
700	11.7%	-10.5%	81.9
900	9.7%	-8.9%	87.7
1100	8.4%	-7.8%	92.9
Total Savings (ORC Online) vs. Baseline			
700	16.4%	-14.1%	114.9
900	14.5%	-12.6%	130.2
1100	13.2%	-11.6%	144.9
ORC Only (ORC Online vs. ORC Offline)			
700	4.2%	-4.1%	29.5
900	4.3%	-4.1%	38.7
1100	4.4%	-4.2%	47.9

Table 5. Conservative Savings at Design Conditions (with 45 kW Reduction in Cooling Load) with Propagated Uncertainty

Nominal Load (kWe)	Fuel Economy (kwH/gallon) Increase (%)	Fuel Consumption (gph) Decrease (%)	Fuel Consumption Decrease (gph)	Equivalent Additional Power (kW)
900	9.3%	-8.1%	5.44	83.7
Uncertainty (+/-)	0.65%	0.57%	0.39	7.9

3.2.2 Increase Integrated Power System Efficiency

At first consideration, ORC integration can be thought of simply as increasing the output of the power system while fuel consumption remains constant. In this case, the percentage efficiency gain is readily conceived of as the ratio of the total power increase due to ORC integration (as defined in section 3.2.1 above) to the KTA50 power output.

In this instance, the 83.7 kW increase in energy output due to ORC integration as presented above can readily be viewed as a 9.3% *{1-(900+83.7)/900) *100}* percent increase in integrated system efficiency (or fuel economy), but reporting this efficiency gain requires some additional consideration.

In the normal operating scenario, the power system output will follow the installation demand. For example, if the installation demand is 900 kW and the ORC generates 50 kW net, then the KTA50 will throttle back to produce approximately 850 kW so that the total load on the system remains at 900 kW. This example neglects the fact that ORC output would be somewhat reduced at the lower engine load (due to lower exhaust mass flow and jacket water heat rejection), so that the actual KTA50 load would be somewhat more than 850 kW. This is, in fact, the scenario decided upon by power plant operators at GTMO where the power plant would take a constant 900 kWe load from the demo unit.

A more representative characterization of the efficiency gain that fits the normal operating scenario is the decrease in KTA50 fuel consumption between the installation demand load and the reduced KTA50 load due to ORC integration as a percentage of the fuel consumption at the demand load. Details of the measurements and calculations used to determine integrated power system efficiency in this manner are presented in section 6.2 below.

Note that the efficiency calculations described in section 6.2 are based on baseline/integrated fuel economy measurements, which, as discussed above, may overstate efficiency improvements due to the higher than expected measurement of the reduction in cooling load. Based on the measured data, the overall system efficiency (fuel economy) gain is 14.5% at 900 kWe nominal load. Per considerations presented above the conservative efficiency gain is considered to be 9.3% at 900 kW load. As the 5% demonstration objective was to be evaluated relative to the nominal (900 kWe) load condition, the objective was met.

3.2.3 Determine ORC Efficiency

Since waste heat is used to power the ORC and otherwise unused waste heat is free of cost, the efficiency of the ORC would not normally be a primary concern of end-users. That said, in order to fully characterize the performance of the ElectraTherm ORC and provide comparative information on system performance for DoD energy managers and other interested parties, Southern monitored the net heat input and energy output of the ORC to determine the thermal electrical efficiency of the system. Heat input is the sum of heat input from the jacket water and exhaust gas heat exchanger circuits and is determined from the flow rate, density, and heat capacity of the heat transfer fluids and the temperature differential across the heat exchangers in each loop.

Typical ORC engine efficiency ranges from 5-15%, depending largely on the quality (temperature) of the heat source. Based on ElectraTherm's bench testing and thermodynamic modeling, the internal efficiency of ORC engine in the DoD system is expected to range from 7.0 to 9.0 percent depending on engine load and ambient conditions. Net ORC efficiency, including all parasitic loads is expected to range from 5.9 to 6.8 percent. TORQUE model results are expected to be conservative, so greater internal efficiency may have been realized under test. The success criteria were based on the expected results.

Per the demonstration plan, ORC efficiency was to be reported on an integrated basis over a range of characteristic operating conditions encountered during the deployed testing (e.g., engine load and ambient conditions). In addition, the cooling load for the ORC was to be determined in the same manner as the heat input. These data would have allowed for determination of an energy balance across the ORC which provides a check on the quality of the efficiency determination. Details of the measurements and calculations that were planned to determine ORC efficiency are presented in section 6.3 of the full report, but are omitted here.

Due to the commissioning issues at deployment, data were not available to determine efficiency per the demonstration plan. An effort was made to determine ORC efficiency based on the integrated test data; however, there was not enough run time during that test to accumulate sufficient steady state data at nominal operating conditions to support a reliable energy balance across the ORC necessary to determine ORC efficiency.

3.2.4 Verify Availability, Reliability, and Operability

ElectraTherm's current fleet of about 50 of ORC units operating in the field recently surpassed 520,000 hours of operation at over 97% availability. Availability and Reliability were not quantitatively determined during the demonstration due to the failure to commission the unit for long term monitoring at the deployment site (GTMO).

During operator training and limited operations during commissioning activities at GTMO, there were no operability issues. After training and hands-on demonstrations, on-site operators at GTMO quickly grasped the monitoring, operations and maintenance requirements of the system. Once the generator comes on line, the ORC waits for heat to become available and then starts automatically. A red light is displayed on the ORC panel when the genset is not operating. Once the generator set comes online, a yellow light indicates that the ORC is waiting for the jacket water and exhaust gas heat exchanger (EGHX) loops to come up to temperature. A green light then indicates that the ORC is online and generating power. Flow readouts are conveniently located to allow the operator to verify jacket water, exhaust gas, and cooling loop flows. Routine maintenance involves little more than lubricating the pumps with a grease gun. A full maintenance schedule and detailed operating manual were provided for longer term maintenance. The GTMO operators appeared to find all of this easy to grasp and expressed full confidence in their ability to operate the system following the training provided.

Due to early termination of the field portion of the demonstration, availability, reliability, and operability are considered un-demonstrated.

Details of the methods that would have been employed to verify availability, reliability, and operability are presented in section 6.4 of the full report, but are omitted here for brevity.

3.2.5 Evaluate System Economics

To be economically viable, the value of the power produced by the ORC and the cooling capacity offset by ORC integration must offset the capital, operating, and maintenance costs of the ORC over a reasonable period of time. In this demonstration, the value of the power produced is most appropriately stated in terms of the cost of diesel fuel required to generate an equivalent amount of power. Diesel fuel costs can be very high in remote installations and forward operating bases.

The metrics used are standard indicators of economic performance including the simple and discounted payback period, life cycle net savings, adjusted internal rate of return (AIRR), and savings to investment ration (SIR). These indicators are determined from the initial capital and incremental operating and maintenance costs for the integrated system, offset by the value of the diesel fuel saved due to the electric power produced by the ORC over the lifetime of the system.

For the purpose of the economic analysis, the capital cost of the KTA50 genset is considered to be a sunk cost and is not accounted for. In any case, the capital and Operations and Maintenance (O&M) cost of the KTA50 is the same for the baseline and integrated system test cases, so zeros out in the Life Cycle Cost Analysis (LCCA) results.

The success criterion is that the simple payback period should be less than five years. This result is achievable at fuel prices exceeding about $3.00/gallon. The payback could be much faster if the fully burdened cost of fuel at remote installations and FOBs is used.

Projected system economics based on ORC performance testing and actual capital and O&M costs are presented in Section 7.0 of this report.

3.2.6 Determine GHG Emissions Reductions

GHG emission reductions were determined based on the equivalent emissions from stationary source diesel fuel combustion that are offset by the ORC energy output and engine cooling energy savings. Preliminary calculations indicated that GHG reductions based on ORC power output only would exceed 200 metric tons CO_2e per year so that figure was adopted as the success criterion. The actual GHG reduction based on baseline and integrated test data including the effect of the reduction in cooling load was 464 metric tons CO_2e per year. This figure is based on 95% system availability. Based on ElectraTherm's fleet operating experience, ORC availability is expected to exceed 97 percent; however, maximum availability for the KTA50 genset is 95 percent due to maintenance requiring approximately 1.5 days per month engine downtime.

Data requirements are the fuel savings (gallons/hour) due to ORC integration, operating hours per year, and current EPA GHG emission factors and global warming potentials (GWPs) for methane and Nitrous Oxide (N_2O). Details of data collection and analysis to determine GHG reductions are provided in section 6.6.

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4.0 FACILITY/SITE DESCRIPTION

Following initial commissioning and controls optimization at the ElectraTherm facility in Reno, Nevada, the integrated ORC-genset system was demonstrated during intensive testing at the Navy MUSE facility in Port Hueneme, California and then deployed to GTMO for longer term evaluation under field conditions. The deployment site was selected by MUSE based on their customer requirements and demonstration site selection criteria. The MUSE facility at Pt. Hueneme is equipped with a high capacity load bank that provided precise controlled loads during baseline and intensive testing as well as shop facilities, machinery, tools, and personnel to facilitate testing.

Early in the demonstration, MUSE offered that an unused 1.2 MW Cummins KTA50 diesel genset could be made available for the demonstration. The KTA50 was manufactured in 1998, but had accumulated less than two operating hours prior to the demonstration and was in new condition. ElectraTherm proposed to design a packaged ORC system around the KTA50 that could easily be deployed as required. This strategy was adopted for the demonstration as it met the needs of MUSE and provided deployment flexibility as well as wider DoD applicability. With the packaged system, it is not necessary to find a suitably configured deployment site as the integrated system is deployable as and where needed. As with the generator sets currently deployed by MUSE, the packaged ORC-genset integrated system may be deployed wherever there is a need for the power.

Southern worked with MUSE to identify suitable candidate sites for the demonstration. MUSE required that they would be the point of contact for all discussions with candidate sites and all communications were conducted through MUSE. The intent was that MUSE would select the deployment site in response to the regular needs of their customers. Six candidate sites were identified. A discussion of the relative merits of the six candidate sites is available in the site selection memorandum approved by ESTCP for this demonstration and appended to the demonstration plan document. The site selection memorandum also provides complete GTMO-specific details for technical, logistical, organizational, and economic factors that could impact the success of the demonstration.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

GTMO was selected as the deployment site as it met all of the selection criteria, held the highest level of interest in the demonstration from facility command and public works staff, and is in close proximity to the continental US. GTMO demonstrated a high level of interest in the demonstration as it coincided with their efforts to reduce fuel costs at the installation. The power demand at GTMO is more than sufficient (12-21 MW) and GTMO was able to provide 24/7 operation over sufficient operating hours to fully demonstrate the performance of the system. Site preparation at GTMO was minimal as existing concrete pads and other necessary infrastructure that remained from decommissioned MUSE generators were utilized.

Figure 2 shows the location of the ORC installation on MUSE pads 3 and 4 at the main GTMO power plant. Figure 3 is a photograph of the ORC container installed at GTMO.

Figure 2. GTMO Installation Site

Figure 3. ORC Unit Installed at GTMO

4.2 FACILITY/SITE REQUIRED CONDITIONS

The packaged ORC-genset system is designed for deployment at any location where there is sufficient continuous power demand (greater than about 600 kW for the configuration demonstrated). Such locations include fixed bases in remote locations, forward operating bases, and deployments for disaster relief or other federal activities.

Very remote sites were considered unsuitable for the demonstration due to high transportation costs and limited access. Finally, deployment of the KTA50 was limited to where EPA New Source Performance Standard (NSPS) stationary diesel emissions standards do not apply or may be temporarily waived. This restriction does not apply to the ORC itself.

Specific MUSE siting criteria for diesel genset deployments include the following:

- Site provides drainage away from the plant.
- Provision of adequate electrical grounding.
- Provision of fire protection equipment as required by local regulations.
- Support personnel including one mechanic and one electrician.
- Adequate support of the plant is required. The surface should be smooth, level, firm, and not settle with time.
- The plant shall not be located within ten feet of any other plant, building or obstruction.
- The clearance at the radiator discharge shall not be less than 40 feet.

Hearing protective devices should be worn within 50 feet on all sides of the plant. This should be considered when locating near offices, housing developments, and other concentrated personnel areas.

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5.0 TEST DESIGN

The demonstration was designed to provide data as required to fully evaluate project objectives (see section 3.1) and provide additional information as needed to ensure the quality and representativeness of these data.

5.1 CONCEPTUAL TEST DESIGN

The hypothesis under test is that ORC-genset integration will increase the effective genset power output by at least 50 kW using waste heat from the genset without placing an undue burden on operations compared to operating the genset alone. The independent variable is the addition of the ORC to utilize the waste heat from the genset. In addition to the direct ORC power output, ORC integration will also result in a reduction of the cooling load on the engine, which acts to further increase the effective power output or fuel savings.

The dependent variable is the increase in effective power output for the same fuel input or increase in fuel economy for the same power output. Load and ambient conditions will affect the ORC power output. These are site and time specific variables that are uncontrolled except to the extent that a suitable site must have sufficient load to operate the genset at a minimum of 60% of the rated output (1100 kW) in prime unlimited service. The genset will not operate efficiently at loads lower than 60%.

Controlled variables include the operating condition of the genset and the consistency of the quality of the fuel used between the baseline and intensive testing. Routine maintenance of the genset per manufacturer specifications is important for the demonstration so that measured fuel economy changes are clearly attributable to ORC integration and not a change in engine performance. Monitoring of engine operating parameters and fuel, oil and coolant samples was used to verify consistent engine performance during both the intensive testing and deployed phases of the demonstration. Consistency of the fuel quality was especially important between the baseline and intensive tests to ensure the reliability of the results for the performance improvement due to the reduction in cooling load.

At a minimum, all that is necessary to demonstrate the performance of the ORC is to monitor the power output of the ORC and generator set and compile and analyze operational and economic data. In addition to these basic requirements, the following additional determinations were made:

- The increase in genset efficiency due to the reduction in cooling load provided by ORC integration was quantified by measuring the difference in baseline and integrated system fuel economy over a representative range of controlled load conditions.
- The heat input to the ORC was measured so that ORC system efficiency could be determined. Heat removal from the ORC was also monitored to establish an energy balance for the system.
- Ambient conditions were monitored in order to characterize changes in ORC and generator set power output with varying temperature, humidity, and barometric pressure. These data were also used to establish comparability of baseline and integrated system fuel economy measurements.

- Selected KTA50 operating parameters were monitored as an indication of generator set 'health' and operational status (i.e., normal operation). Fuel, oil, and coolant analyses were conducted during intensive testing and at regular maintenance intervals (approximately every 500 hours operation) as further indicators of generator set 'health.'

In the initial design phase of the demonstration, ElectraTherm conducted modeling and bench testing to optimize ORC/genset integration in an effort to maximize the use of waste heat from the KTA50 and ORC power output. In this phase, ElectraTherm also designed the packaged system layout and configuration with the goals of facilitating deployment, meeting Navy packaging requirements, and providing for safety and ease of use. A preliminary design review was completed by ElectraTherm, Southern, and MUSE on June 6, 2013. A 'final' design review was completed on November 4, 2013; however, additional design changes were made in 2014 to allow for a single radiator to be used for both the ORC and genset. This change lowered costs and increased deployment flexibility as a second high efficiency radiator for the engine was no longer required. The final 'final' design review and approval was completed June 17, 2014 following the site survey visit to GTMO.

Concurrent with the design phase, Southern conducted acceptance testing and baseline fuel economy testing of the KTA50 under controlled load conditions at the MUSE facility in Port Hueneme, CA. Once the design was near completion, Southern began preparation of the demonstration plan and specification, evaluation, and selection of monitoring instrumentation and data acquisition systems.

The second phase of the demonstration involved generator set packaging, ORC integration, and commissioning. During this phase, Southern stayed abreast of all developments, compiled and reviewed system component specifications, and documented progress and issues encountered.

Once the system was assembled and initially commissioned at ElectraTherm's facility in Reno, intensive testing under controlled load conditions was conducted at the MUSE facility in Port Hueneme, CA on July 17, 2015. During intensive testing, the system was connected to a load bank to provide stable and precise load conditions over the normal operating range of the system (700-1100 kWe). Fuel economy measurements were made to quantify generator set efficiency gains due to the reduction of the cooling load provided by ORC integration.

Longer term monitoring of integrated system performance in an actual deployment comprising approximately 2,000 total hours of operation was planned for the final phase of the demonstration. Given the typical generator rotation schedule at the selected deployment site (Guantanamo Bay Naval Station), 2,000 hours represents approximately one full year of operation. Due to commissioning issues encountered at GTMO (see section 8.0), the long term monitoring portion of the demonstration plan was not completed.

5.2 BASELINE CHARACTERIZATION

Southern conducted a baseline fuel economy test at Port Hueneme on May 14, 2013. Fuel supply and return flows were measured with Coriolis mass flow meters (Krohne Optimass 7000), nominally accurate to ±0.1% of reading and with calibration certificates showing uncertainty of ±0.035%. The total uncertainty in the difference in supply and return fuel flows was calculated at ±0.12% based on the variation in the data collected.

Fuel economy data were taken over a range of load conditions spanning the normal expected load for MUSE deployments (85%). The nominal load values for the baseline test were 700, 900, and 1,100 kW or 64-100% of rated load in prime unlimited service. The genset performed well during baseline testing with measured fuel economy within five percent of rated consumption.

Duplicate fuel samples were obtained from a fresh fuel fill and analyzed by Titan laboratories for API gravity, cetane number, sulfur, and contaminants (water and bacteria/fungi). Titan also provided the heating value of the fuel. The fuel quality met API standards. The baseline fuel analysis results were later compared with intensive test fuel analyses to verify the consistency of the fuel supply.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

During the design phase, ElectraTherm conducted modeling of integrated system performance and bench testing of system components. The design intent was to maximize ORC power output by optimizing the utilization of waste heat from the KTA50 genset and minimizing parasitic loads. ElectraTherm provided Southern with full details of the design process and results in monthly reports to Southern, and frequent emails and teleconferences. Prior to the commencement of Phase II construction work, ElectraTherm submitted and Southern reviewed a complete design package consisting of a piping and instrumentation diagram (P&ID), process flow diagram (PFD), control specification, piping layout, and packaging specifications.

A key component of the design was to utilize the higher temperature waste heat from the KTA50 exhaust in the ORC's evaporator loop while utilizing the lower temperature heat from the engine's jacket water in a separate preheater loop. In existing GM4000 ORC installations, the same heat source is used in both the preheater and evaporator, so this effort represented a new capability for ElectraTherm.

The design effort included modeling and bench testing of key ORC system components including the evaporator and preheater heat exchangers, the exhaust gas heat exchanger, the expander, generator, and condenser. This effort resulted in detailed specifications for each component.

ElectraTherm has developed and continues to refine a proprietary thermodynamic system model (known as the TORQUE model) that is used to predict ORC performance in various application scenarios and to optimize component selection to maximize thermal efficiency and power output and minimize parasitic loads for optimal overall system performance. The model is based on thermodynamic principles and theoretical analysis coupled with empirical bench testing and performance data acquired from ElectraTherm's existing fleet of machines. ElectraTherm maintains an in-house bench testing apparatus that is used to obtain empirical data for various system components and configurations.

In ElectraTherm's final design, all of the available high grade heat from the exhaust gas is utilized, but only about 20% of the jacket water flow is passed through the preheater (capturing about 30% of the available heat in that circuit). On the surface, it might appear that this arrangement does not fully utilize the available heat; however the preheater brings the working fluid to within 1-2 °F of the jacket water temperature, so no further heat capture is thermodynamically possible.

During the design phase, multiple TORQUE model iterations were conducted to evaluate the optimum utilization of waste heat from the jacket water and exhaust of the KTA50. In these model runs, the waste heat capture from the exhaust gas was optimized and the expander speed and jacket water temperature and flow were varied. Maximum ORC power output was taken as the primary design goal. Expander sizing and other component selections were made based on this design goal.

The EGHX performance, sizing, and control were also evaluated as part of the design effort. Under normal operations, diesel engine exhaust will quickly foul the heat exchanger, thus the normal operating scenario is the fouled case which fixes evaporator sizing and heat capture. In the clean case, it is possible for the evaporator to lower the exhaust gas temperature to the point where the exhaust gas condenses. The condensate is corrosive and will degrade the component lifetime, so condensation must be avoided. Since the ORC evaporator can remove only a fixed amount of heat, a larger portion of the EGHX loop flow is bypassed during clean case operation to maintain the exhaust gas temperature above the condensing temperature (180 °C). The bypass flow is controlled by a flow control valve set to maintain the exhaust gas temperature above this point.

A liquid loop radiator (LLR) was employed to reject heat from the ORC and genset. An alternative ORC condensing configuration involves passing the working fluid directly through the condenser as opposed to transferring the heat to an external water loop. This configuration avoids the need for an additional pump to circulate the cooling fluid; however, there are a number of advantages to the LLR configuration.

- A much smaller volume of refrigerant is required for the LLR option and thus installed cost, as well as installation and maintenance cost, are reduced.
- Direct condensing requires that the condenser be located above the ORC to allow drain back, which complicates packaging and deployment.
- The direct condenser must be larger than a liquid loop radiator to avoid excessive pressure drop that would impact ORC performance – further complicating packaging and deployment. The larger condenser would also require additional cooling fans, increasing parasitic load.
- A very low pressure drop brazed plate condenser is used with the LLR configuration, so there is little, if any, sacrifice in ORC efficiency.

The additional parasitic load for the extra pump required in the LLR configuration (2.8 kW) is more than offset by the improvements in packaging, installation, refrigerant cost, and maintenance.

In the final design, the LLR was also used to reject heat from the KTA50, eliminating the need for a separate radiator for the engine. The advantages of this approach include significantly lower cost and simpler installation. The tradeoff is that, if the engine/EGHX container is to be used alone as a CHP unit (without the ORC) a radiator will have to be provided to reject heat from the engine.

The final design calls for an air cooled condenser (dry cooler). This option has no water consumption which is a benefit for deployment in areas with limited water supply. However, in areas with very high ambient temperatures and moderate humidity, an evaporative cooler (cooling tower) would be more efficient and result in greater ORC output – provided that a sufficient water supply is available. ElectraTherm estimates that the evaporative cooling option would consume 10 gph on a continuous basis, accounting for evaporative losses, maintenance blow downs, and other periodic losses. A dry cooler was used for this demonstration.

5.3.1 System Layout

The integrated ORC/genset system is housed in two standard 40 foot International Organization for Standardization (ISO) shipping containers for ease of deployment. The first container houses the genset, switchgear, fuel supply, and EGHX. The second container houses the ORC generator and dry cooler. The two containers may be deployed as an integrated ORC/genset or the genset container may be utilized as a stand-alone CHP system (using an external radiator) and the ORC container may be utilized as a standalone ORC system that could be utilized with any suitable hot water supply.

Field setup is straightforward. All that needs to be done when the equipment arrives on site is to make electrical connections and connect supply and return hot water piping between the containers, fill the EGHX circuit with water and the jacket and condenser water circuits with water/glycol mix. The refrigerant is completely contained within the ORC unit and may be shipped in place. Figure 4 shows a perspective view of the engine/EGHX (CHP) and ORC containers, identifying major components, and piping connections.

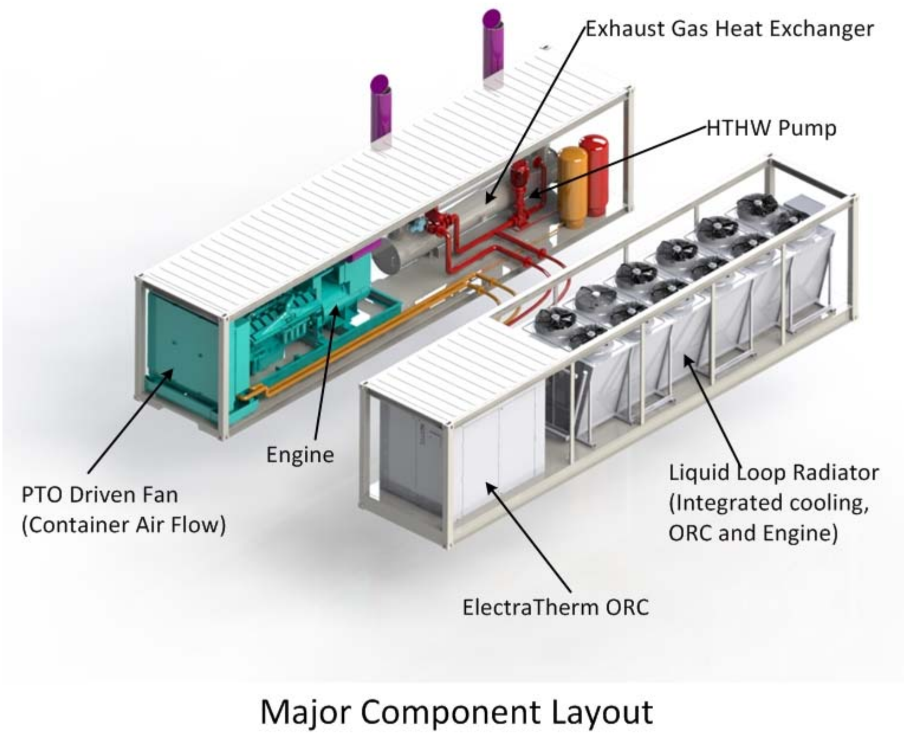

Figure 4. Engine/EGHX Container Layout

5.4 OPERATIONAL TESTING

Operational testing was conducted in several stages. The unit was first integrated and commissioned at ElectraTherm's plant in Reno, NV. An intensive test was then conducted at the MUSE facility in Pt. Hueneme, CA once the packaged system had been fully integrated, commissioned, optimized and was ready for operation. The goal of the commissioning in Reno was to fine tune controls and operational set points to optimize performance prior to testing.

The goal of the intensive test was to collect detailed performance data under controlled load conditions matching baseline conditions and also to verify load following and load paralleling behavior that could not be tested in Reno. Following the intensive test, the packaged unit was deployed and plans were to monitor operations remotely over up to a one year period (at least 2,000 hours operation).

The integrated system was fully instrumented in order to collect all data required to evaluate the performance objectives. A list of specific instruments to be monitored is appended to the full report. The instrument list provides expected nominal readings and operating ranges, accuracy specifications, and the manufacturer/model selected for each SRI/ElectraTherm instrument. In addition to the SRI/ElectraTherm measurements, a number of parameters from the engine control module were logged. These data recorded the genset power output and provide indications of genset ‘health’ or proper operation. Full details on how sensor data were used to evaluate performance objectives are provided in subsections for each performance objective under Section 3.0 of this report.

5.4.1 Intensive Testing

The primary goal of the intensive test was to quantify the increase in total integrated system efficiency over the baseline genset efficiency in terms of power output per unit fuel consumption (kWh/gallon). The intensive test effort required precise fuel consumption measurements and verification of consistent fuel quality between baseline and intensive tests. Apart from these measurements, all other data collected during the intensive tests was the same as were collected during the long term monitoring. Prior to the intensive testing, ElectraTherm conducted commissioning test runs under controlled loads to fine tune controls and operational set points in order to optimize system performance per the commissioning plan.

Test runs were conducted over the expected range of deployed load conditions. The load set points were nominally 700, 900, and 1,100 kWe, or 64 to 100% of full load in prime unlimited service, matching the baseline test conditions. After ORC output had stabilized, approximately 20-30 minutes of data collection (at a 1 minute data recording interval) at each condition provided sufficient data to evaluate fuel economy at each load with good statistical confidence. These data were compared to the baseline results to determine the total integrated system efficiency gain including the gains due to ORC power output, radiator improvements, and the direct ORC cooling benefit.

A final set of test runs was conducted over the range of load conditions with the ORC offline. These results indicate the efficiency gain due to the radiator improvements alone. With the ORC offline, the working fluid (refrigerant) flow through the expander is stopped and there is no ORC cooling benefit. The difference between the efficiency gain with the ORC online and offline is the efficiency gain due to ORC cooling alone. This difference is expected to be small (1-2 kW), and is not within the statistically quantifiable range. In addition, this sequence of tests was used to determine the radiator fan load for engine cooling only as the dry cooler load with the ORC offline.

5.4.2 Long-term Monitoring

The primary goal of the long term monitoring was to monitor operations under real world conditions over a sufficient period that representative determinations of availability, reliability, and operability could be made. The nominal, long term, monitoring period was to have been 2,000 hours operation over a period of up to one year. This period was intended to capture system performance under typical variation in ambient conditions and over the range of site load conditions. A shorter monitoring period may have been deemed sufficient provided that expected variations in site conditions were captured and there was sufficient run time to adequately characterize availability/reliability. The monitoring period might also have been reduced if, for reasons outside of the control of Southern or ElectraTherm, the unit had to be taken offline or redeployed. As mentioned above, the unit was never fully operational at GTMO due to issues presented in section 8.0 below.

5.5 SAMPLING PROTOCOL

A complete list of all of the continuous monitoring data collected is appended to the full report. This list includes instruments that are integral to the ORC and KTA50 systems and instruments that have been added specifically for the purpose of the demonstration. A P&ID appended to the full report schematically shows the location of each instrument within the process. Data were logged centrally on the ORC Program Logic Controller (PLC). The data were accessed remotely via File Transfer Protocol (FTP) file transfer over a secure internet connection.

During the intensive tests, the data compilation interval was one minute. During long term monitoring, the data compilation interval was set to six minutes. This interval is based on the steady state operating characteristics of the ORC and the KTA50 and was chosen to capture significant changes in performance while avoiding collection of an excessive volume of data which might impede data transfer and analysis. The ORC PLC logged data at a ten-second sample rate. The logged data were averaged into six-minute data compilation intervals for analysis and reporting. The ten-second data were available as needed for system troubleshooting and diagnostics.

The only actual sampling that was conducted as part of the demonstration was for the fuel samples used to verify the consistency of the fuel supply between the baseline and intensive tests and oil and coolant samples that were used to verify that elevated jacket water temperatures did not cause oil oxidation or excessive engine wear.

Fluid samples were collected during the baseline and intensive tests and again during commissioning at GTMO. For the deployed testing, fuel, oil, and coolant samples were obtained at the start of operation and were to have been taken after each interval of approximately 500 hours operation, for a total of five sets of samples over 2,000 hours operation.

The fuel, oil, and coolant analyses were completed by Titan laboratories in Denver, CO which is an ISO/IEC 17025:2005 certified test lab (certificate number L12-210). Sampling and shipping containers were provided by Titan labs and were filled to the specified level by pumping from the day tank using a clean disposable sampling pump to avoid contamination. Oil and coolant sample containers were filled from drained fluids or through use of the sample pump.

Qualitative information on system reliability and operability were to have been gained from formal and informal interviews with project participants and operating staff conducted throughout the duration of the deployed test. Participants were to have been asked to complete a brief survey; however, in Southern's experience, the most valuable information is gained from less formal, day to day interactions. Southern was to have documented these interactions in a daily project log. These data were to have been compiled into a narrative description in the final report, citing specific examples from the log as required.

6.0 PERFORMANCE ASSESSMENT METHODS

This section provides details of the measurements and calculations used to arrive at reported performance results.

6.1 INCREASE ENERGY OUTPUT

The total increase in energy output for the integrated ORC/genset system is comprised of the direct electric power output of the ORC and the equivalent power output due to the reduction of the cooling load on the engine. As discussed above (section 3.2.1), the reduction in cooling load is due to improvements to the engine radiator and the additional, though small in this instance, direct cooling provided by the ORC.

The electric power output of the ORC was measured using a revenue grade power meter. The reduction in cooling load was determined from the difference in baseline and intensive test fuel economy measurements offset by the power consumption for engine cooling of the VFD controlled radiator fan that replaced the PTO driven radiator fan in the baseline engine.

The increase in power output is determined as a function of engine load across the typical load range of the KTA50 genset (700-1,100 kW). Equation 1 describes the total gain in power output due to ORC integration. Equation 2 describes the effective power gain due to the reduction in cooling load.

Equation 1. Total Effective Increase in Power Output

$$Total\ Effective\ Power\ Increase(L) = ORC_{net\_electric(L)} + ORC_{cooling(L)}$$

Equation 2. Power Increase due to Cooling Load Reduction

$$ORC_{cooling(L)} = \left[\left(FE_{test\ (L)} - FE_{baseline(L)}\right) * FC_{baseline(L)} - RF_{(L)}\right]$$

Where,
$ORC_{net\_electric(L)}$ is the ORC electric power output (kW), net of parasitic loads at a given load condition
$ORC_{cooling(L)}$ is the effective power gain due to the reduction in cooling load (kW) at a given load condition
$FE_{baseline(L)}$ is fuel economy (kWh/gallon) at a given load condition as determined during the baseline tests
$FE_{test(L)}$ is fuel economy (kWh/gallon) at a given load condition as determined during the intensive tests and corrected to baseline ambient conditions
$FC_{baseline(L)}$ is fuel consumption (gallon/hour) at a given load condition as determined from baseline test data
RF is the VFD controlled radiator fan average power consumption for engine cooling only (kW)
L is the load condition (kW)

Parasitic loads include power necessary to operate:

- pumps for the exhaust gas heat exchanger and dry cooler loops,
- the ORC refrigerant pump, air compressor (for pneumatic valve control), and controls (metered together), and
- dry cooler fans.

6.2 INCREASE INTEGRATED POWER SYSTEM EFFICIENCY

As discussed above (section 3.2.2), the integrated power system efficiency gain is most appropriately evaluated under the normal operating scenario where the power system load follows the installation demand. In this scenario, the efficiency gain would be the decrease in KTA50 fuel consumption between the installation demand load and the reduced KTA50 load due to ORC integration as a fraction of the fuel consumption at the installation demand load as shown in Equation 3. To account for the effective power gain due to the reduction in cooling load, the fuel consumption at the installation demand load must be taken at baseline conditions and the fuel consumption at the actual load must be taken at integrated system conditions.

Equation 3. Integrated Power System Efficiency Gain

$$Efficiency\ Gain(DL) = \frac{FC_{baseline(DL)} - FC_{test^*(AL)}}{FC_{baseline(DL)}}$$

Where,
FC is fuel consumption (gallons per hour)
DL is the installation demand load on the integrated genset/ORC system
AL is the actual KTA50 load at the installation demand load
baseline refers to KTA50 baseline fuel economy test conditions
*test** refers to integrated system fuel economy test conditions

This computation requires prediction of fuel consumption over baseline and integrated system load conditions. The data to support this computation were obtained from fuel consumption versus load curves developed from the baseline and intensive test data collected under controlled load conditions. The fuel consumption versus load curves were highly linear with a correlation coefficients (r2) all greater than 0.999. As such, these predictions may be considered very accurate.

6.3 DETERMINE ORC EFFICIENCY

Performance assessment methods and calculations for determining ORC efficiency may be found in the full report, but are omitted from this summary report since ORC efficiency was not determined in the demonstration due to lack of data (see section 3.2.3).

6.4 VERIFY AVAILABILITY, RELIABILITY AND OPERABILITY

Performance assessment methods and calculations for determining availability, reliability and operability may be found in the full report, but are omitted from this summary report since these objectives were not evaluated due to lack of data (see section 3.2.4).

6.5 EVALUATE SYSTEM ECONOMICS

The economic analysis conducted for this demonstration implements a life cycle cost analysis (LCCA) approach. The LCCA 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 latest version of the National Institute of Standards and Technology (NIST) Building Life Cycle Cost (BLCC) software was used to model inputs and calculate the LCCA results for various scenarios. A full description of the cost model, cost drivers, and a presentation of the cost analysis results and comparisons for various meaningful scenarios is provided below in Section 7.0.

6.6 DETERMINE GHG EMISSIONS REDUCTIONS

For this demonstration, the GHG reductions associated with ORC integration are attributable to the diesel fuel usage offset by the electricity produced by the ORC using waste heat and the reduction in cooling load on the engine. The means to quantify these fuel savings (gallons/year) is presented above in section 6.1. GHG emissions factors (kg/gallon) and 100 year global warming potentials from the current (2014) edition of EPA Emission Factors for Greenhouse Gas Inventories [6] were applied to arrive at GHG reductions in terms of metric tons per year CO_2 equivalent (CO_2e).

Figures and assumptions used in the estimate of GHG emissions reductions are fully documented in the full report.

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7.0 COST ASSESSMENT

This section identifies the information that was used and the methods that were employed to establish realistic life cycle costs for implementing the packaged ORC technology. The determination of the diesel fuel savings that determine the 'revenue' attributable to ORC integration is described and economic results are given for a range of economic conditions based on baseline/intensive test results at nominal prime power service conditions.

7.1 COST MODEL

The economic analysis presented here was informed by the demonstration, but the presentation is generalized so that the results are applicable over a range of representative site conditions. All assumptions and information sources are documented to lend credibility to the results and to aid in adaptation of the analysis to the user's unique situation.

The life cycle assessment approach conforms to the requirements and conventions specified in the Life Cycle Costing Manual for the FEMP - also known as 'Handbook 135'. The discount rate used for this analysis was obtained from the annual supplement to Handbook 135 current to the year of the demonstration (2015). The latest version of the NIST BLCC software was used to model inputs and calculate the LCCA results for various scenarios.

The life cycle economic analysis presented here is based on capital and operation/maintenance costs and revenues associated with diesel fuel savings projected over the expected lifetime of the equipment. Costs specifically associated with the demonstration program (e.g., additional instrumentation) 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 (other than cost of money or discount rate) 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.

The life cycle economic performance of the ORC system is assessed based on standard economic indicators of financial performance including the NPV, AIRR, SIR, and simple and discounted payback periods. 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 modeled in real terms (without inflation). Initial investment costs are modeled as 'overnight' costs as of the service date. This practice is consistent with the US Department of Energy (DoE) practice for determining levelized costs for renewable energy technologies.

An inventory of cost elements associated with the life cycle analysis along with a description of the data tracked and identification of the source of this information is provided in the full report.

7.2 COST DRIVERS

In addition to the capital and operating costs associated with ORC integration, the key economic driver is the cost of diesel fuel consumption avoided due to the increased efficiency of the engine/genset with ORC integration. The annual fuel savings is the difference in baseline fuel consumption at the installation demand load (900 kWe) and the equivalent fuel consumption accounting for ORC power output and the reduction in cooling load, multiplied by the number of operating hours per year. In this analysis, the fuel savings is the total increase in energy input for a given fuel input at nominal load conditions, as given in Table 4 in section 3.2.1 above.

Conservatively, this amounts to 83.7 kW equivalent additional power output without additional fuel input, or an equivalent fuel savings of 5.44 gallons per hour.

Diesel fuel prices have fluctuated wildly in recent years. According to the Energy Information Administration (EIA), the current US average diesel price is roughly $2.25 per gallon; however, this price follows a nearly two-year-long decline in global fossil fuel prices. EIA expects that prices are beginning to increase again and projects a rate of increase of roughly two percent per year. Prior to the recent drop in oil prices, US diesel prices were relatively stable at around $4.25/gallon. GTMO is currently paying $3.25/gallon for diesel.

In active combat zones or occupied areas, fuel costs can be extremely high and relatively small fuel savings can be very important in terms of both dollars and lives. Depending on circumstances, the 'fully burdened' cost of a gallon of fuel to DoD has been cited as ranging between $10 and $1000 per gallon – with a frequently quoted value of $400/gallon for 'in-theater' fuel deliveries (DSB 2009). In addition, there is a significant cost in equipment and lives as fuel convoys are targeted and resources are diverted from defending troops to defending fuel deliveries. The payback period could indeed be very short under very high fuel cost scenarios; however, in these scenarios, it is not clear that ORC deployment would be deemed practical or warranted by commanders on the ground – as ORC deployment would involve additional equipment, training, maintenance requirements, etc. As the demonstration did not attempt to assess such factors, a very high fuel cost scenario was not included in the economic analysis.

7.3 COST ANALYSIS AND COMPARISON

ElectraTherm provided current initial MSRP capital and operating/maintenance costs over the 20-year expected lifetime of the unit. ElectraTherm makes available a very detailed 20-year maintenance schedule validated based on actual operating experience

Southern modeled expected economic performance based on these data, measured performance data, and current diesel fuel costs for GTMO and representative diesel fuel costs for the US as discussed above (section 7.2). Inputs to the BLCC model are documented in Table 6 below including all data sources and assumptions. BLCC model results for varying fuel costs are given in Table 7 below. Fuel cost changes over the system lifetime are modeled using US average escalation rates per BLCC version 5.3-15.

Economic results are based on 95% availability or 8,322 operating hours per year. This is a reasonable assumption as ElectraTherm's current fleet has accumulated well over half a million operating hours at >97% availability.

The results in Table 7 assume an ORC integration cooling benefit or reduction in cooling load on the engine of 45 kW, which is considered a conservative value for this demonstration based on test data and additional considerations as presented above in section 3.2.1.

Economic results are representative of a 65 °F annual average ambient temperature corresponding to Pt. Hueneme baseline/integrated test conditions. This temperature is representative of global average temperatures in temperate latitudes. In tropical latitudes, integrated system performance will be somewhat reduced due to reduced performance of the air-cooled dry cooler. In high latitudes, system performance will be enhanced due to increased cooling system performance.

At current fuel costs ($2.25/gallon), adding the ORC to a packaged genset will pay for itself in year six. That said, fuel costs are currently at a historic low and are projected to increase. At current GTMO fuel costs ($3.25/gallon) and at recent stable trending fuel costs ($4.00/gallon), the system pays for itself in year 4. These economic results are based on measured performance at the ambient temperature during the baseline/integrated ambient temperature during testing at Pt. Hueneme, CA (~65°F), representative of temperature latitudes.

To present an idea of expected economics in other conditions that might be encountered at installations across the globe, ElectraTherm's TORQUE model was used to estimate performance for installations in hypothetical tropical and high-latitude locations. On this basis, the expected economic performance at GTMO (tropical) can be estimated for various fuel costs, For example, at a fuel cost of $3.25/gallon (April 2016 GTMO value), simple and discounted payback would be expected to occur in year 5. Details are presented in Table 7.

Table 6. BLCC Inputs for Projected Economics

BLCC LCCA Element	Value	Units	Data Sources and Notes
BLCC Module v5.3-15, 2015	na	na	Milcon Analysis, Energy Project
Constant Dollar Analysis	Yes	na	Per non-financed project. Discount rate exclusive of inflation.
Discount Rate	3%	%	Per OMB Circular A94 2015. Mid-year discounting.
Base Date	4/1/2015	Date	Consistent with starting month for DOE energy price escalation rates used in the BLCC.
Service Date	4/1/2015	Date	Service date modeled to coincide with base date.
Study Period	20	years	Based on expected service life of the ElectraTherm ORC
Operating Hours per year	8322	hours	95% availability.
Nominal Engine Load	900	kWe	Prime unlimited service.
Baseline Engine Fuel Consumption at 900 kW Nominal Load	66.9/557,132	gph/gpy	Based on May, 2013 baseline fuel economy test conducted by Southern.
Integrated System Fuel Consumption at 900 kW Nominal Load	61.5/511,860	gph/gpy	Based on 'conservative' fuel savings as defined in section 0.
Annual Fuel Savings	5.44/45,272	gph/gpy	Difference
Energy Cost (Diesel)	3.25	$/gallon	GTMO fuel cost as of April, 2016. ROI also calculated based on $2.25 and $4.00 per gallon fuel cost reflecting recent volatility in fuel prices.
Capital Component: FP250, Investment Cost	$551,915	$	Total installed cost. Includes: ElectraTherm SRI/DoD ORC engine, system packaging/integration, exhaust gas heat exchanger, dry cooler, ISO containers, BoP, site prep, installation/ commissioning. Source: ElectraTherm.
Capital Component: FP250, Investment Cost, Residual Value	$0	%	Straight line proration over study period (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 presumed to be funded from operating accounts rather than from capital accounts.
20 year cumulative replacement parts cost	$45,370	$	ElectraTherm maintenance schedule. 2015 prices.
20 year cumulative labor cost	$12,458	$	ElectraTherm maintenance schedule. $55/hour labor rate.

Table 6. BLCC Inputs for Projected Economics (Continued)

BLCC LCCA Element	Value	Units	Data Sources and Notes
20 year annualized ElectraTherm OM&R	$2,891	$	Annual average parts and labor. 20 year lifetime. Does not include EGHX maintenance. Labor rate $55/hr. Source: ElectraTherm.
Annual EGHX Maintenance	$880	$	16 hours per year based on Aprovis requirements. Labor rate $55/hour.
Total annual OM&R	$3,771	$	ElectraTherm + Aprovis

BoP Balance of plant
gpy Gallons per Year
OMB Office of Management and Budget
OM&R Operations, Maintenance, and Repair

Table 7. Project Economics: Total System Benefit - ORC Electric Output plus Cooling Load Reduction (45 kW)

Case	Engine Load (kW)	Net ORC Output (kW)	Annual Average Temp	20 yr net savings ($1000's)	SIR	AIRR	Simple/ Discounted Payback (year occurs)	Annual Fuel Savings (gallons)
Results based on measured performance								
April 2016 Average US fuel cost (#2 diesel). $2.25/gallon	900	38.7	65F	$ 1,256	3.41	9.52%	6/6	45,272
April 2016 GTMO fuel cost (F76). $3.25/gallon	900	38.7	65F	$ 2,072	4.97	11.60%	4/4	45,272
2010-2014 average US fuel cost trend (#2 diesel). $4.00/gallon.	900	38.7	65F	$ 2,683	6.15	12.79%	4/4	45,272
Alternative Cases (based on model results)								
April 2016 Average US fuel cost (#2 diesel). $2.25/gallon	900	47.4	40F	$ 1,439	3.76	10.50%	5/6	49,769
April 2016 GTMO fuel cost (F76). $3.25/gallon	900	47.4	40F	$ 2,335	5.48	12.14%	4/4	49,769
2010-2014 average US fuel cost trend (#2 diesel). $4.00/gallon.	900	47.4	40F	$ 3,007	6.77	13.34%	3/4	49,769
April 2016 Average US fuel cost (#2 diesel). $2.25/gallon	900	30.2	80F	$ 1,078	3.07	8.94%	6/7	40,862
April 2016 GTMO fuel cost (F76). $3.25/gallon	900	30.2	80F	$ 1,814	4.48	11.02%	5/5	40,862
2010-2014 average US fuel cost trend (#2 diesel). $4.00/gallon.	900	30.2	80F	$ 2,366	5.54	12.20%	4/4	40,862
Note: All figures assume 45 kW additional savings due to cooling load reduction.								

8.0 IMPLEMENTATION ISSUES

No implementation issues were encountered with the ElectraTherm ORC generator itself, ORC packaging, or with the integration of the ORC, radiator, and genset. However, there were issues associated with the engine packaging and controls installation that caused significant project delays and ultimately resulted in failure to commission the integrated system on the GTMO grid leading to early termination of the demonstration before field measurements data could be collected. The following presents a brief history of these events and discusses the results of a root cause investigation into the ultimate cause of the failure.

Early in the project, ElectraTherm conducted an exhaustive search for a suitable packager that could install the Cummins KTA50 engine/genset, exhaust gas heat exchanger, fuel tank, switchgear, plumbing, and controls in a standard 40 foot ISO container for ease of deployment. Ultimately, Cummins Rocky Mountain (CRM) in Denver, CO was selected as they appeared to have the expertise and the facilities required to perform the work in a professional and timely manner. ElectraTherm and MUSE traveled to Denver, met with Cummins project management, engineers and technicians and surveyed facilities prior to making the selection. A very detailed scope of work was negotiated that met project and MUSE requirements – and an aggressive schedule was agreed to for completing the work. Southern, ElectraTherm and MUSE provided all necessary equipment, drawings and specifications to CRM within the agreed timeframe.

Southern and MUSE traveled to Denver in September 2014 to conduct a final inspection of the completed packaging, but found that Cummins had barely initiated work to complete the job. Cummins provided no notice prior to the inspection trip that the work had not been completed as agreed. Thus alarmed, Southern, MUSE, and ElectraTherm prepared a detailed punch list of items to be completed and requested weekly updates with photographs documenting progress. Despite diligent follow-up efforts on the part of the project team, progress reports from Cummins were sporadic and incomplete. A second inspection trip was made by ElectraTherm and MUSE in December and the punch list was updated with the hope of completing the work by the end of the year.

Although not all punch list items were fully completed, the engine container was finally shipped to Reno for integration with the ORC system in February 2015 in an effort to meet the much-delayed project schedule. CRM provided additional support in Reno; however, a significant number of incomplete items and workmanship issues were discovered during this time. Major concerns included: (1) engine control wiring and programming was incomplete and untested; and (2) proper provision for jacket water piping to the ORC and external radiator had not been made. These issues, and others discovered as work progressed, caused additional delays. MUSE took the initiative to complete the controls wiring and made several out of scope trips to Reno to help ensure that the work was properly completed and fully tested. Despite these efforts, integrated system operation and controls optimization was not completed until June 2015.

As Cummins was unable to provide facilities for fully testing engine controls in grid parallel operation, the decision was taken to move the equipment to the MUSE facility at Pt. Hueneme, CA in early July 2015 for final commissioning and testing. Southern completed intensive testing of the integrated system during this time. MUSE made extensive efforts in Pt. Hueneme to complete controls wiring and programing and test the system in grid parallel operation; however, difficulties were encountered stemming from further CRM workmanship issues and MUSE was unable to complete these tasks before the system was scheduled to be shipped to GTMO.

MUSE made the decision to complete final testing on site at GTMO. Southern was not made aware that the system had not been fully tested before shipment.

The engine (CHP) and ORC containers were successfully installed at GTMO during the week of August 17-24, 2015. During initial testing, the ORC operated and performed as expected, however, the engine would trip (shut itself down) after several hours of operation in parallel with the GTMO grid.

The MUSE team spent a great deal of time on site troubleshooting this issue with telephone support from CRM’s controls contractor (Winn-Marion, W-M); however, the problem remained unresolved as of September 1 when the MUSE team had to leave the site due to other commitments. An ElectraTherm (ET) engineer extended his stay on site to support the troubleshooting efforts in case the ORC may have been related to the issue. During this time, it was determined conclusively that neither the ORC, nor the cooling integration of the ORC with the engine was the cause of the trips. The trips occurred whether or not the ORC was connected to the system.

After much follow-on investigation, evaluation, and discussion among all parties, including expert advice from Winn-Marion and Cummins, the team came to believe with high confidence that the root cause of the problem had been identified and could be corrected in the field. A second trip to GTMO was made by ElectraTherm and a W-M controls engineer in October to complete commissioning of the genset on the GTMO grid. During this trip, a number of additional workmanship issues within the CRM scope were discovered and corrected, and the unit was made ready to run. Unfortunately, before successful operation could be demonstrated, an arc flash event occurred within the generator housing, damaging the equipment. The arc flash was caused by improper location and mounting of a terminal block by CRM that, along with a poor wire termination, caused a signal wire to come loose and into contact with high voltage components. Although the damage appeared to be relatively minor, and may have been repairable on site, project budgets for all participants were stretched to the breaking point by this time. Given the difficulty and cost of conducting additional work at GTMO, and given reasonable concerns that further problems might be encountered, ESTCP made the decision to terminate the field deployment. Arrangements were then made to return the equipment to the States and transfer ownership to DoD.

9.0 REFERENCES

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