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Subcontractor Report: National Account Energy Alliance Final Report for the Basin Electric Project at Northern Border Pipeline Company's Compressor Station #7, North Dakota

December 2007

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Engineering Science and Technology Division

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Executive Summary

Four recovered energy generation power plants with a total net capacity of 22 megawatts (MW) were installed to provide baseload generation to Basin Electric Power Cooperative consumers. The recovered energy generation plants also provide reactive power support for critical loads such as hospitals to help ensure high reliability and power quality in a challenging grid sector. The Organic Rankine Cycle (ORC)-based plants improve overall energy efficiency by recuperating compressor system exhaust heat to generate electrical power (for the grid). One plant is located in North Dakota near St. Anthony, and the other three are in South Dakota near Wetonka, Clark, and Estelline. Construction on the plants began in September 2005. The four plants were put into operation between July and October 2006.

A field research test and verification project was conducted at the recovered energy generation plant at Northern Border Pipeline Company Compressor Station #7 (CS#7) near St. Anthony. Recovered energy generation plant equipment was supplied and installed by ORMAT Technologies, Inc. Basin Electric is purchasing the electricity under a purchase power agreement with an ORMAT subsidiary, which owns and operates the plant.

ORMAT designed, manufactured, built, owns and operates the ORC power plant. This project is the result of the cooperation with Northern Border Pipeline Company which sells the resource (waste heat) to ORMAT, which uses that resource to produce electricity with its technology and delivers power to the MorGranSou Electric Cooperative grid through a Basin Electric grid interconnection at CS#7. MorGranSou integrates the recovered energy generated electricity into its grid, firming the power supply to consumers in a remote section of the grid. A flow diagram of the business process is shown below:

Northern Border Pipeline Company sells waste heat to ORMAT.

ORMAT financed entirely by equity the ORC plant that it manufactured and built supplying power under a Power Purchase Agreement (PPA) with Basin.

Basin executes 25-year PPA with ORMAT for all electricity produced at a very competitive price (no fuel cost except waste heat royalty).

MorGranSou Electric Cooperative builds distribution wires to Basin interconnection at CS#7 and agrees to buy all electricity supplied. This power provides critical voltage support to their gird.

The result is cost effective, clean electric power also providing critical voltage support to a hospital.

When operating at full recovered heat input, the ORC system consistently delivered 5.5 MW or more output to the grid at up to 15 percent ORC conversion efficiency (electricity output / recovered heat input), and an estimated 9 percent overall efficiency. The ORC system improved the overall energy efficiency by 28%, from 32% simple cycle efficiency to 41% for the combined system. The system is entering its second year of operation with the expectation of consistently achieving near 100% availability when the pipeline compressor is operating. Based on operating history during the test period, a 90% design load factor was used to predict annual output and routine maintenance costs. Approximately 43 million kWh will be supplied to the grid per year, with projected annualized operating and maintenance costs to ORMAT of less than $200,000 per year.

The capital cost to ORMAT for the 5.5 MW recovered energy generation plant at CS#7 was $13.75 million, or $2,500 / kW. ORMAT estimates that future projects would require a minimum purchase price of 5¢ / kWh based on projected output for an acceptable return on investment.

The Net Present Value (NPV) of this project was examined with various contract terms (15 to 25 years in duration) and cost of capital ranging from 6% to 10% for clean energy projects. Positive NPV values ranged from $2 million to $12 million. The Internal Rate of Return (IRR) ranged from a low of 5% for a 15 year contract to a high of 15% for a 25 year contract. These values do not include any federal or state subsidies for providing pollution-free electricity.

Lessons learned that may be useful for evaluating future recovered energy generation plant opportunities include:

- There is an economic model that makes existing ORC technology applied to pipeline compressor stations cost-competitive with coal generation.
- Remote pipeline-based ORC systems can provide baseload power.
- Cold ambient operation provided challenges, including the need to replace frozen flow transmitters and change certain valve designs that were prone to freezing.
- There was minimal environmental impact, minimal permitting, and virtually zero incremental emissions related to the CS#7 installation.
- The pipeline compressor was shut down several times during the test period due to market demand fluctuations. Since compressor downtime affects annual waste heat availability and baseload power output, it is important to obtain good estimates of annual compressor run hours from the pipeline when selecting project locations. It should be noted that the operation of the ORC systems are subordinate to pipeline operations and Northern Border Pipeline Company may curtail the usage or shut-down its compressors for any period of time.
- The significant operating constraints identified were: heat input (temperature and mass flow) that was dictated by the gas turbine's operation; the selection of pentane over steam for the Rankine cycle; the material selection for the waste-heat-to-oil heater, which limited the minimum heat exchanger exhaust gas temperature to prevent condensation; the DowTherm Q maximum operating temperature of 625ºF, which required a control limit between 580ºF and 600ºF for safe operation; and pentane condenser surface area.
- Areas for potential improvement in performance that should not negatively impact capital cost (and may reduce capital cost) are to consider other working fluids and consider eliminating the oil loop. Care must be taken on both instances – particularly eliminating the hot oil loop. Risks of alternative approaches to pentane and hot oil must be carefully analyzed before making any recommendation.

Based on the successful results of this project, Basin Electric plans to purchase power from four of six new recovered energy generation plants that ORMAT plans to construct, own and operate along the pipeline owned by Northern Border Pipeline Company in Montana, North Dakota, and Minnesota. The new power plants are in addition to the existing four facilities in North and South Dakota that have been in commercial operation since autumn 2006. Under terms of the deal between Basin Electric and ORMAT, 22 additional megawatts of electricity from the four new power plants will be sold to Basin Electric under a long-term power purchase agreement, expected to add up to approximately $6.4 million in yearly revenues to ORMAT's electricity segment. Eleven MW of power from the other two sites will be contracted to two other utilities. Development of the additional six sites will increase the capacity of ORMAT's portfolio of owned and operated recovered energy generation power plants to approximately 55 MW.

ORMAT has already secured the rights to the waste heat for two of the new power plants and is in the process of obtaining the rights to the remaining four new power plants. The projected completion date of all six new sites is 2009.

1. Introduction

1.1 Background

The National Accounts Energy Alliance is a collaborative partnership that aims to increase awareness and facilitate adoption of cost-effective advanced energy technologies by national accounts and large commercial customers. The Gas Technology Institute manages the Alliance with support from the U.S. Department of Energy and the American Gas Association. The project described in this report was developed within the Alliance in response to a solicitation issued by the Oak Ridge National Laboratory on behalf of the U.S. Department of Energy.

Annually, the United States economy consumes over 98 quadrillion Btu (Quads) of energy in satisfying the demands of residential, commercial, and transportation users. Of this total, approximately 40% is directed to produce electrical power for buildings – residential, commercial, institutional, and industrial. Unfortunately, only 31% of this input energy is converted to electrical energy. Nearly 70% is wasted by central power plants that produce hot exhausts which are not used.

The US Department of Energy (DOE) has been developing technologies that can mitigate inefficient use of energy for electric power production. In particular, the Office of Distributed Energy (as a part of DOE Office of Energy Efficiency and Renewable Energy until October 2005) led efforts to develop Integrated Energy Systems that combine a power generation device with heat recovery to produce electrical energy and thermal energy. Such systems are also known as CHP systems, where CHP designates either “combined heating and power” or “cooling, heating, and power”, depending on the system manufacturer. Conventionally, CHP uses a power source to drive a generator and captures the waste heat for use in a thermally activated technology.

This project focuses on another form of CHP where thermal energy is available from the exhaust of a combustion turbine at a temperature that can be converted into shaft power and electric energy (see Figure 1). The system design intent is to have the gas turbine operate at about 32% thermal efficiency with 800ºF to 950ºF exhaust gas depending on ambient temperature. An ORMAT-designed turbine converts up to 15% of the reclaimed exhaust gas heat into electricity. At an 88% waste heat to oil heat exchanger efficiency, approximately 9% of the gas turbine input energy is converted to electricity. Therefore, the ORC system improves the compressor station gas turbine fuel efficiency by 28%, increasing it from 32% simple cycle efficiency to 41% for the combined system.

1.2 Objective

The objective of this project was to demonstrate the technical and economic feasibility of capturing thermal energy from a 27 MW (35,000 hp) gas turbine driving a natural gas pipeline compressor with an ORC system producing 5.5 MW of electricity with no additional fuel and virtually no emissions. The recovered energy generation plant was designed, manufactured, and installed by ORMAT Technologies, Inc., at Northern Border Pipeline CS#7 near St. Anthony, ND, to provide base load generation to Basin Electric Power Cooperative consumers. The plant is based on technology developed by ORMAT over four decades.

1.3 Company Profiles

The business structure involves cooperation between a pipeline, the recovered energy generation plant owner, and electric cooperative utilities. Northern Border Pipeline sells the resource (waste heat) to ORMAT Technologies, Inc, who uses that resource to produce electricity with its technology and delivers power to the grid through a Basin Electric Cooperative grid interconnection at CS#7. Company profiles for each participant are provided below.

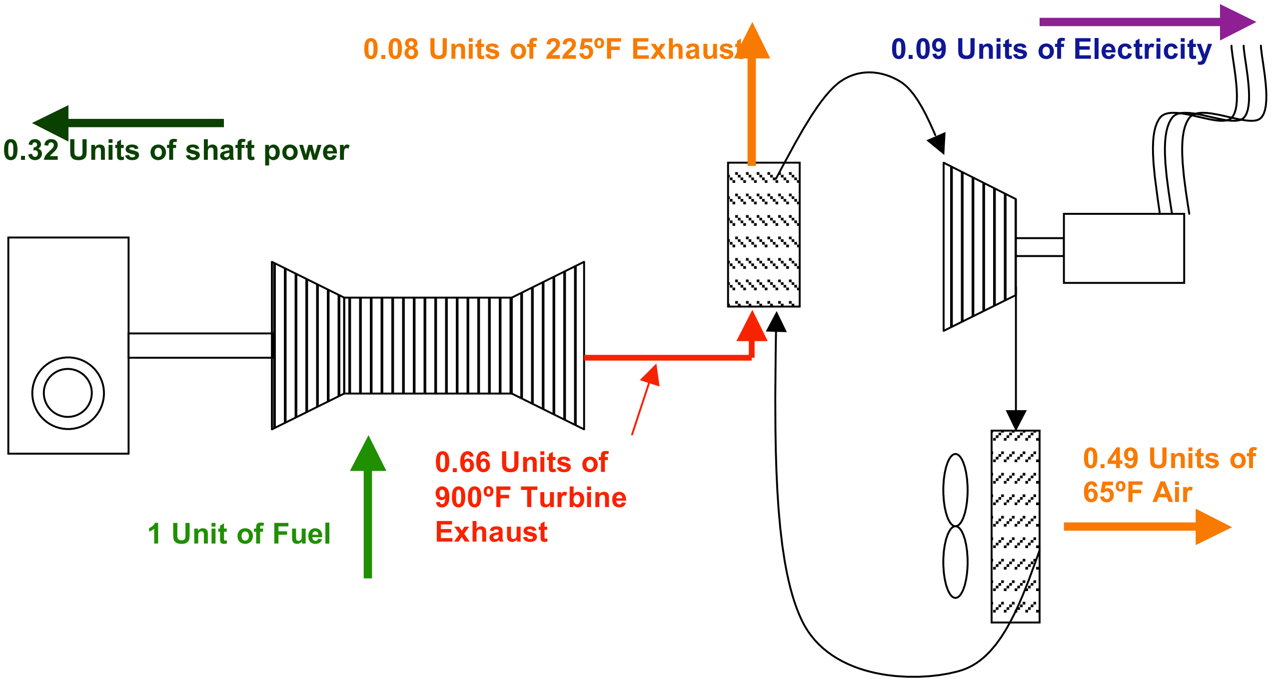

Figure 1. CHP System Delivers Electrical Energy from Waste Thermal Energy

Northern Border Pipeline Co. was formed in 1978 as a Texas general partnership and now is owned by ONEOK Partners LP and TC Pipe-Lines LP. Northern Border constructed a natural-gas pipeline that today extends from the Montana/Saskatchewan border near the Port of Morgan, MT, more than 1,200 miles to North Hayden, IN (the northern section of this pipeline is shown in Figure 2). The pipeline carries about one-fifth of the gas imported from Canada to the US (2.2 billion ft^3/day) and interconnects with many other pipelines serving Midwestern markets. The pipeline is well positioned to ship gas from the future Alaska gas pipeline.

The Northern Border pipeline system was initially constructed in 1982 and was expanded or extended in 1991, 1992 and 1998. The Chicago Project was completed in 1998 and increased the pipeline system's ability to receive natural gas by 42% to its current capacity of 2.4 billion ft^3/day. In 2001, Northern Border Pipeline completed construction of Project 2000, the 35-mile extension and expansion of its pipeline system into Indiana. Project 2000 strategically positions Northern Border Pipeline to move gas east of Chicago and affords its shippers access to the northern Indiana industrial zone.

Northern Border Pipeline transports natural gas for shippers under a tariff regulated by FERC. The tariff specifies the calculation of amounts to be paid by shippers and the general terms and conditions of transportation service on the pipeline system. Northern Border Pipeline derives revenue from agreements for the receipt and delivery of gas at points along the pipeline system as specified in each shipper's individual transportation contract. Northern Border Pipeline does not own the natural gas that it transports and therefore does not assume the related natural gas commodity risk. The Northern Border Pipeline system serves more than 50 shippers with diverse operating financial profiles.

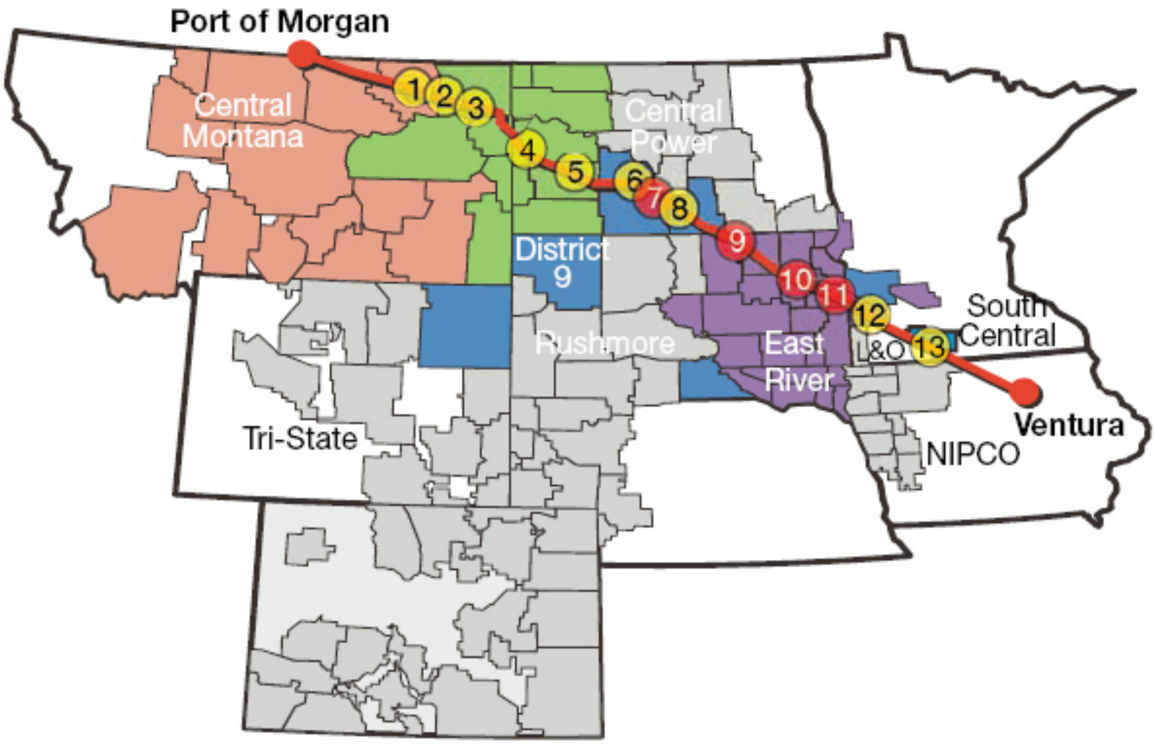

Figure 2. Northern Border Pipeline Compressor Stations

ORMAT Technologies, Inc, headquartered in Reno, Nevada, is the developer of the proprietary technology and owner/operator of the energy recovery/power generation system at all four compressor stations. ORMAT is a world leader in the geothermal power sector. The Company has four decades of experience in the development of state-of-the-art environmentally sound power solutions, primarily in geothermal and recovered energy generation with about 900 MW of its ORC systems delivered.

ORMAT is a vertically-integrated company whose primary business is to develop, build, own, and operate geothermal and recovered energy generation power plants utilizing in-house designed and manufactured equipment. In addition, ORMAT supplies geothermal and recovered energy power generating equipment of its own design and manufacture, and complete power plants incorporating its equipment on a turnkey basis, as well as small size power units for remote continuous unattended operation.

Basin Electric Power Cooperative, Bismarck, ND, a generation and transmission (G&T) co-op, was formed in 1961 by 67 distribution cooperatives located in eight Midwestern states. The organization currently has 125 owner/members that serve 2.5 million customers in nine states: Colorado, Iowa, Minnesota, Montana, Nebraska, New Mexico, North Dakota, South Dakota, and Wyoming. The regional areas are divided into 10 membership districts whose directors serve on Basin Electric's board (See Figure **3**).

Basin Electric's primary mission is to provide reliable, low-cost power to member companies. It produces electricity from a variety of generation resources and buys some from others; most of the power it generates comes from coal. The utility, which ranks among the top 10 co-ops nationwide in terms of generating capability, has a pooling agreement with the Western Area Power Administration to deliver its power to member companies across the federal transmission system. The co-op also is a member of the Mid-Continent Area Power Pool, which provides backup generation in the event Basin cannot meet demand on its own. Basin Electric has made a significant commitment to renewable energy resources. It currently owns or purchases the output of 136 MW of wind energy and 22 MW of green energy for a total of 158 MW green energy in its energy portfolio.

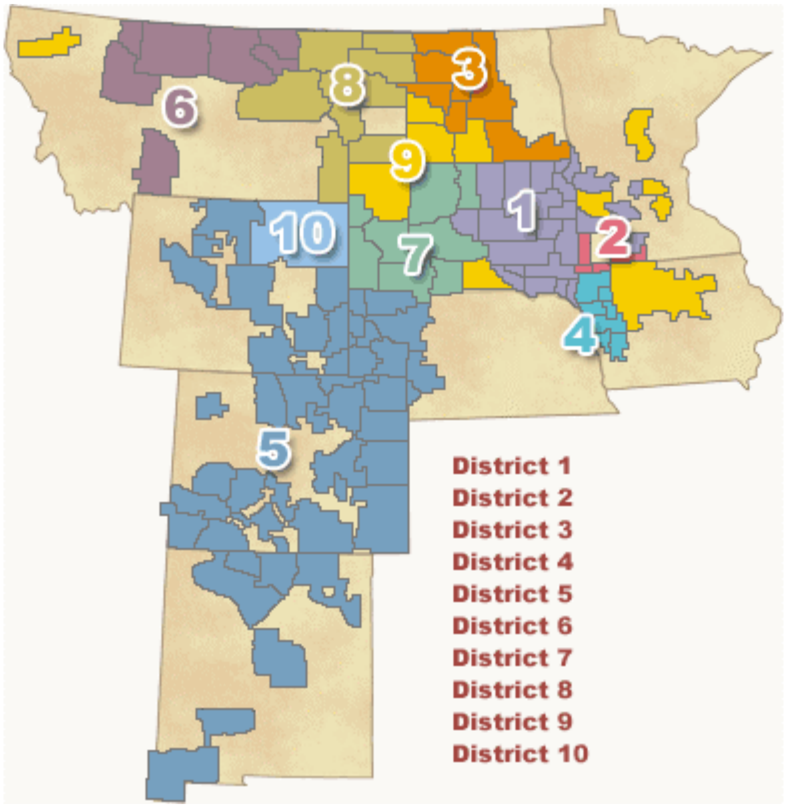

Figure 3. Basin Electric Cooperative Service Area Map

2. Project Description

2.1 Site Selection

The Northern Border Pipeline system uses 13 simple-cycle gas-turbine-powered compression stations (each ranging from 35,000 to 40,000 hp) to deliver natural gas to the upper Midwest. Four of these stations were selected by Basin Electric, ORMAT, and Northern Border Pipeline for waste heat recovery. CS#7, 9, 10, and 11 were retrofitted with heat recovery systems with a design electricity generation capacity of 5.5 MW at each site. CS#7, near St. Anthony, ND, is the site evaluated in this project. The other three stations are in South Dakota near Wetonka, Clark, and Estelline.

Site generation at CS#7 is interconnected to the MorGranSou Electric Cooperative grid through a Basin Electric grid interconnection. The recovered energy generation plant at CS#7 provides voltage and reactive power support for critical loads such as hospitals to help ensure high reliability and power quality. MorGranSou integrates the recovered energy generation plant power into its grid, firming the power supply to its consumers. Loads served by that grid include an Indian Nation with an important hospital load.

The natural gas pipeline compressor stations in the Northern Border Pipeline system typically consist of a Cooper-Rolls Coberra 6000 RB-211 gas turbine driving a natural gas compressor, which compresses the natural gas at periodic intervals along the pipeline. The exhaust temperature from the gas turbine is roughly 900ºF, making it suitable for either steam generation or ORC systems.

2.2 Organic Rankine Cycle for Recovered Energy Generation Plant

While steam technology used to recover residual heat from gas turbines in combined cycle electric utility plants is cost-effective, the same cannot be said of gas turbines installed in compressor stations. These gas turbines are about an order of magnitude smaller than their utility counterparts, leading to small steam bottoming plants whose capacity cost escalates rapidly as scale diminishes. Sufficient water supply is also a challenge. Compressor stations are often installed in remote areas where in-situ water sources normally do not exist. In addition, steam processes require licensed operators. Finally, managing water at a remote site in a very cold climate can be difficult and expensive. To avoid these issues, the team chose an ORC for this heat recovery power project.

The selected ORC system is an ORMAT Energy Converter using a hot oil loop to recover heat from the gas turbine exhaust. The ORMAT Energy Converter operates as a modified ORC, the key element of the modification being the recuperator. The organic working fluid (pentane) is vaporized by the hot oil in an evaporator. The organic fluid vapor expands in the turbine and is then condensed using ambient air for cooling. The condensate is pumped back to the evaporator thus closing the thermodynamic cycle. Heating and cooling sources are not directly in contact with the working fluid or with the turbine. Figure 4 depicts the following six processes in the ORMAT Energy Converter, each changing the working fluid state:

- Process 5-6: First, the working fluid is pumped (ideally an isentropic process) from low to high pressure.
- Process 6-1: The working fluid is then heated in the recuperator and pre-heater.
- Process 1-2: The high pressure liquid enters a vaporizer where it is heated at constant pressure by an external heat source to become a saturated vapor.

- Process 2-3: The saturated vapor expands through a turbine to generate power output (ideally an isentropic process). This decreases the temperature and pressure of the vapor.
- Process 3-4: The vapor leaving the turbine enters a recuperator where it exchanges heat with the condensed pentane leaving the pentane pump.
- Process 4-5: The vapor then enters a condenser where it is cooled at constant pressure to become a saturated liquid. This liquid then re-enters the pump and the cycle repeats.

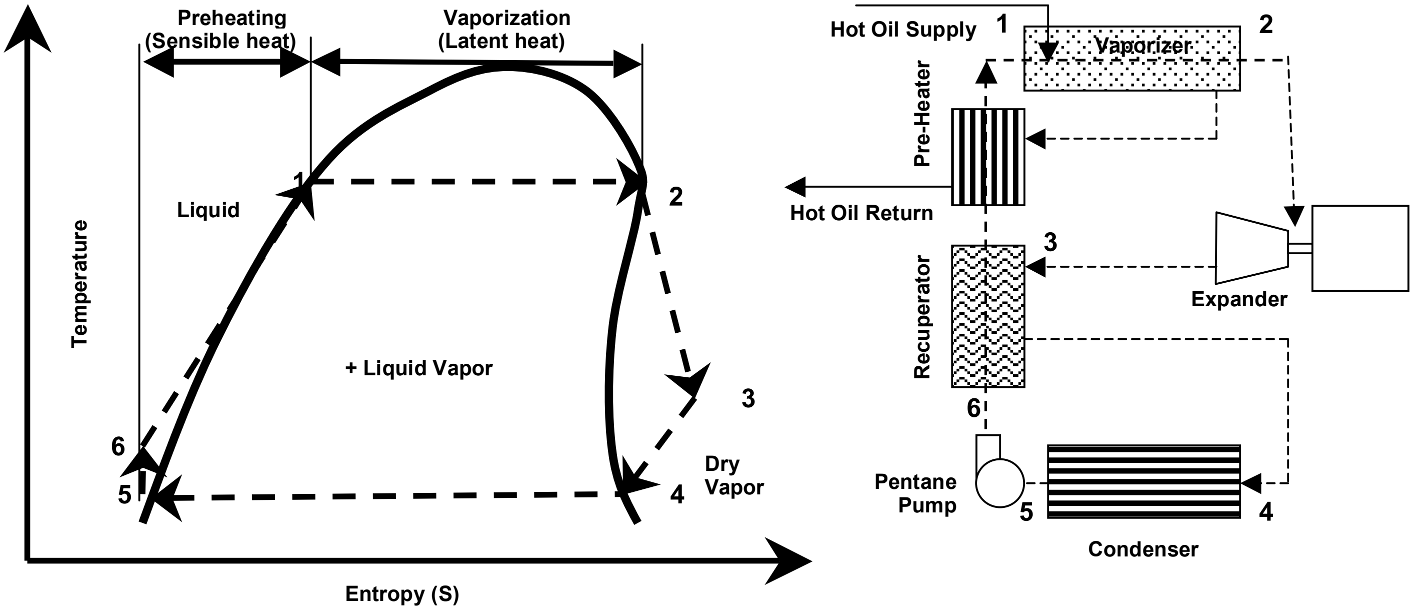

Figure 4. Ideal ORC Temperature Entropy Diagram

2.3 System Design and Installation

The Recovered Energy Generation plant uses an ORMAT Energy Converter intermediate oil heat exchange. Heat in the gas turbine exhaust is used to heat DowTherm^{TM} Q, a synthetic organic heat transfer fluid. The heat transfer fluid is then used to vaporize the organic working fluid, pentane, at high pressure, in a secondary heat exchanger. The pentane expands through a turbine-generator and condenses in an ambient air-cooled condenser and recuperator. This process requires a small amount of auxiliary electricity to operate fans and pumps, but produces more than six times the amount consumed by the ORMAT Energy Converter.

ORMAT uses an indirect method of energy recovery from the gas turbine exhaust rather than direct heating of the pentane. The enhanced system safety and improved control achieved by separating the gas turbine exhaust from the ORC were considered more critical than the reduction in efficiency from the additional heat exchange process. Figure 5 shows a simplified schematic of the recovered energy generation plant. Figure 6 shows the completed ORC system at CS#7. Figure 7 provides a view of the entire facility.

2.4 Sequence of Operation

The sequence of operation is relatively straightforward. Gas-turbine exhaust heat is transferred to thermal oil circulating through a waste heat recovery heat exchanger. The hot thermal oil boils organic fluid (pentane) in the vaporizer and then gives up additional heat to pentane in the preheater before returning to the recovery unit. Vaporized pentane expands through the turbine and flows to the recuperator where it warms the pentane returning from the air-cooled condenser. A storage/expansion tank accommodates any variations in oil volume and maintains a constant head on the system. A gas turbine exhaust bypass stack and oil pump flow controller balance the waste-heat-to-oil heat exchanger conditions to avoid condensation in the heat exchanger and turbine exhaust stack, and to control the maximum oil temperature.

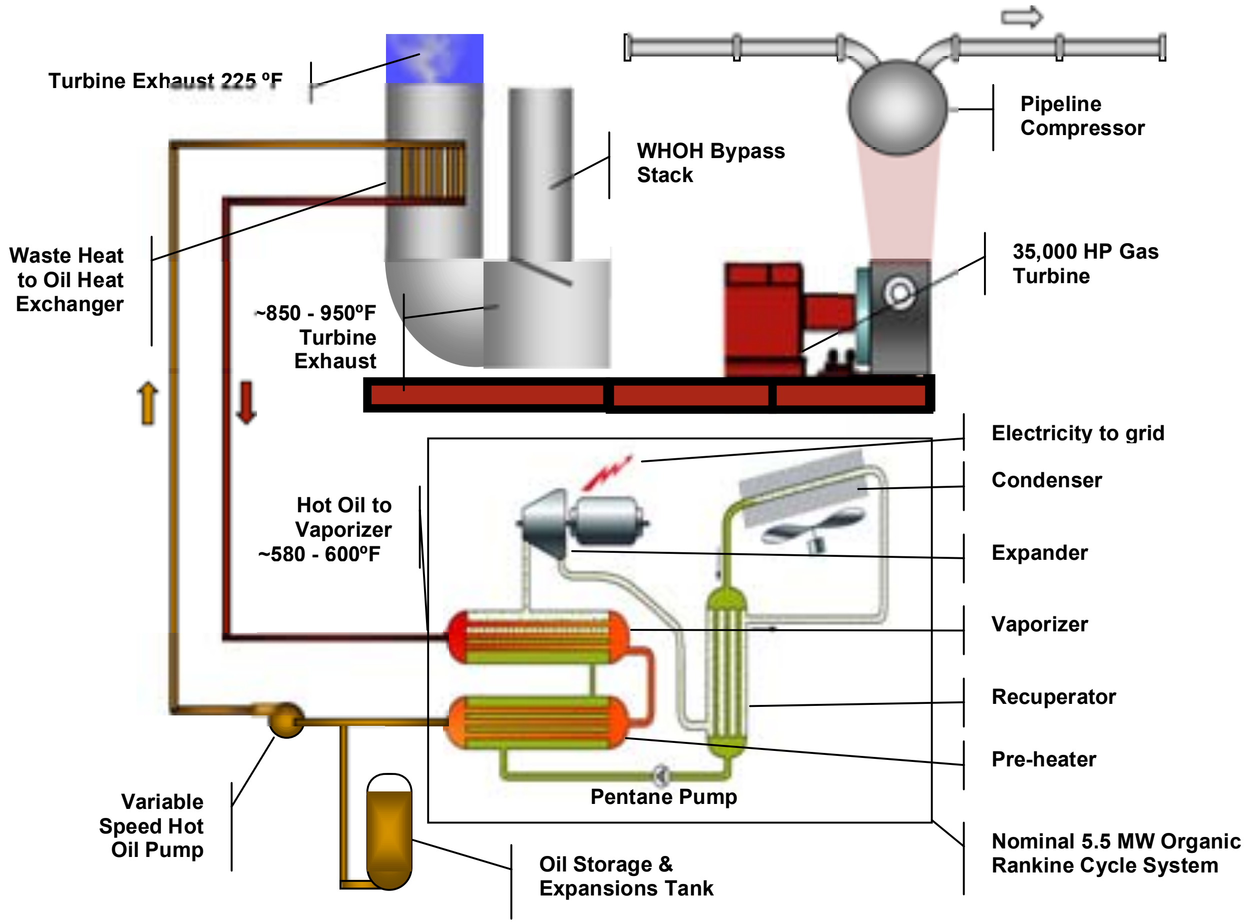

Figure 5. Schematic of the ORMAT Recovered Energy Generation Plant

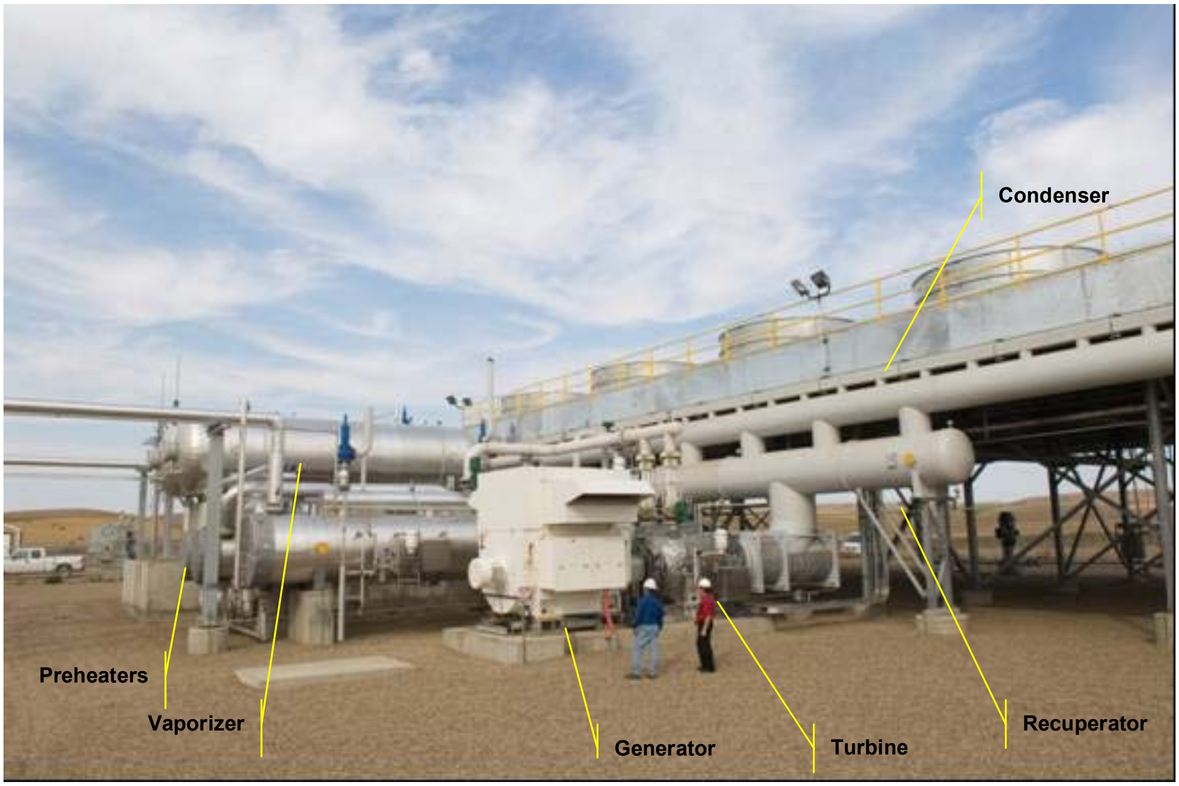

Figure 6. ORC Installation at CS#7

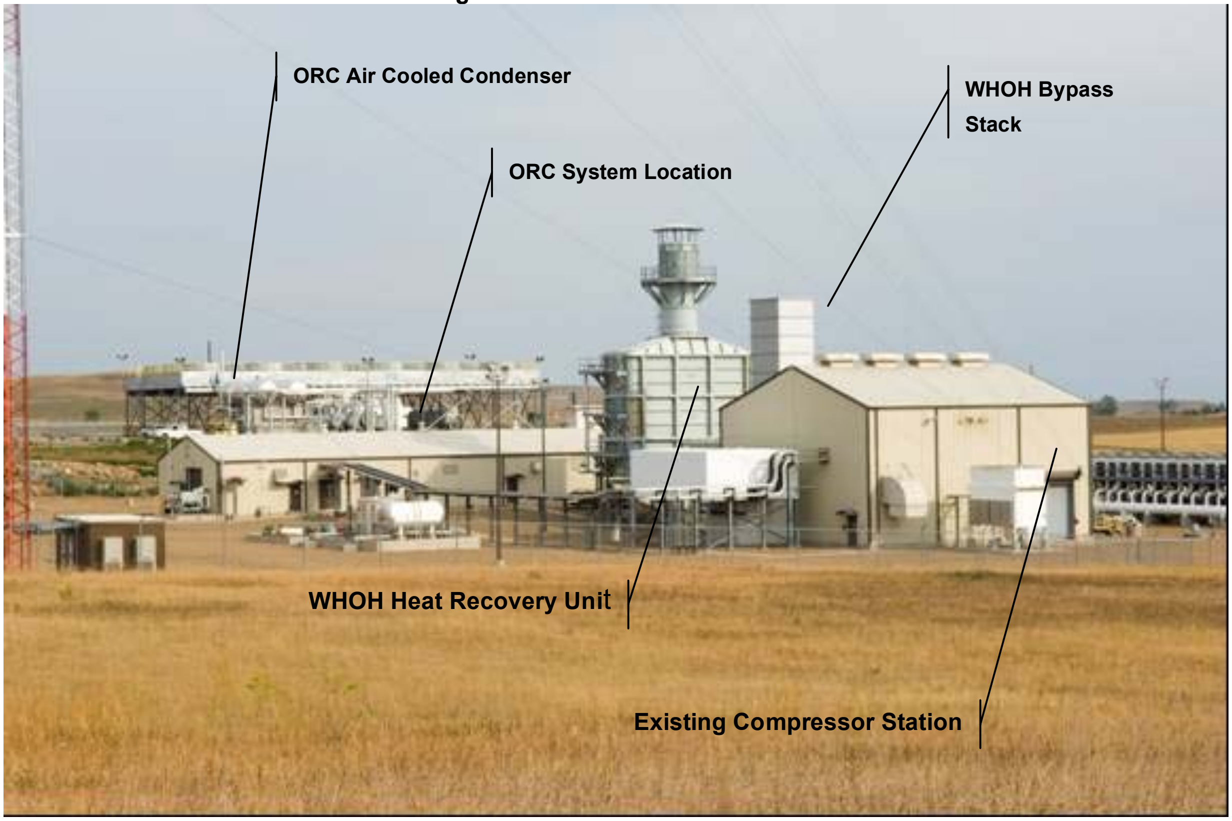

Figure 7. CS#7 with Completed Recovered Energy Generation Plant

3. System Performance

3.1 System Availability

The first year of recovered energy generation plant operation included three phases, each of which had a different impact on overall system availability and delivered power:

- System startup and commissioning (Summer/Autumn 2006)
- Component and controls shakedown (Autumn/Winter 2006-07)
- Stable plant operation (Spring/Summer 2007)

System Startup and Commissioning Phase – The ORMAT Energy Converter plant was the first-of-its-kind project on a pipeline compressor station in the US. It was expected that there would be numerous technical challenges during this project that would reduce system availability, especially immediately after construction was finished. During startup and commissioning from July to October 2006 there were several transition issues that reduced system availability. Most issues related to controls and instrumentation adjustments. In addition, the pipeline compressor was occasionally shut down due to pipeline demand fluctuations. Issues experienced during the commissioning period were managed and controls were optimized without undue difficulty.

Component and Controls Shakedown Phase – During the shakedown period in October 2006 through February 2007, availability suffered from several component and controls malfunctions and failures, some of which were related to low temperature freezing problems with sensors and valves. Faulty components and sensors were subsequently replaced (e.g., with components with lower ambient temperature ranges). Pentane pumps with long lead times were replaced in early spring 2007 to solve a performance deficiency discovered during commissioning. Availability was not affected, but peak output was reduced by about 1/3 when only one of the two parallel pentane pumps was running. Specific issues identified and resolved during the shakedown period included:

- Oil feed pump replacement
- Flawed diverter control logic
- Nitrogen leak through a valve
- Surge tank pressure relief valve failure
- Frozen flow transmitter
- Thermal oil freeze-up
- Low flow through flow transmitter
- Heat source valve transmitter failure
- Air compressor failure
- Pentane motive pump change-out

Stable Plant Operation Phase – From February through June 2007, the recovered energy generation plant was available nearly continuously, except when the pipeline compressor was shut down due to demand fluctuations. System peak output during this period was also affected by the pentane pump change-out period that continued into April 2007.

Figures 8 and 9 provide an overall picture of system performance versus the project goal of providing 5.5 MW base load power to the grid with at least 90% availability. Figures 10 through 13 provide quarterly data on system performance. Due to factors described above, the goal was met or exceeded often but not consistently during the first year of operation. However, increased projected pipeline sales and an improved understanding of system operating constraints obtained because of this project are expected to significantly improve long term performance. The recovered energy generation plant is expected to achieve the 5.5 MW

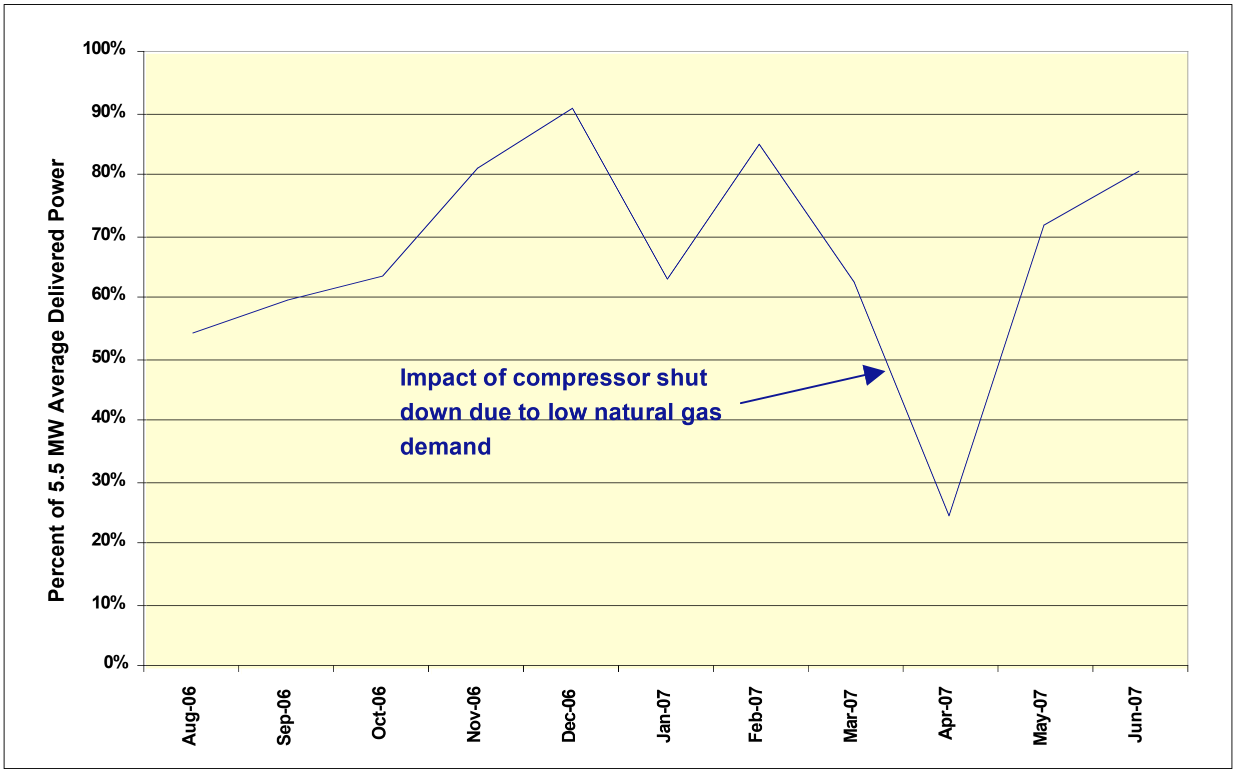

Figure 8. Monthly Average Output Relative to Project Goal of 5.5 MW

delivered power goal in the future and should consistently exceed 90% availability whenever the pipeline compressor is operating.

Figure 14 presents the data during the test period when the system was in operation. The average delivered power during ORC operation was 5.57 MW with a standard deviation of 0.95 MW. The average output shows that the system performed well with respect to the contracted performance goal of 5.5 MW. However, there was significant variation in the delivered power to the grid due to various factors described above. For energy efficiency calculations and system behavior relative to ambient temperature, a subset of the data that avoids confounding factors such as pipeline compressor shutdowns was selected for analysis.

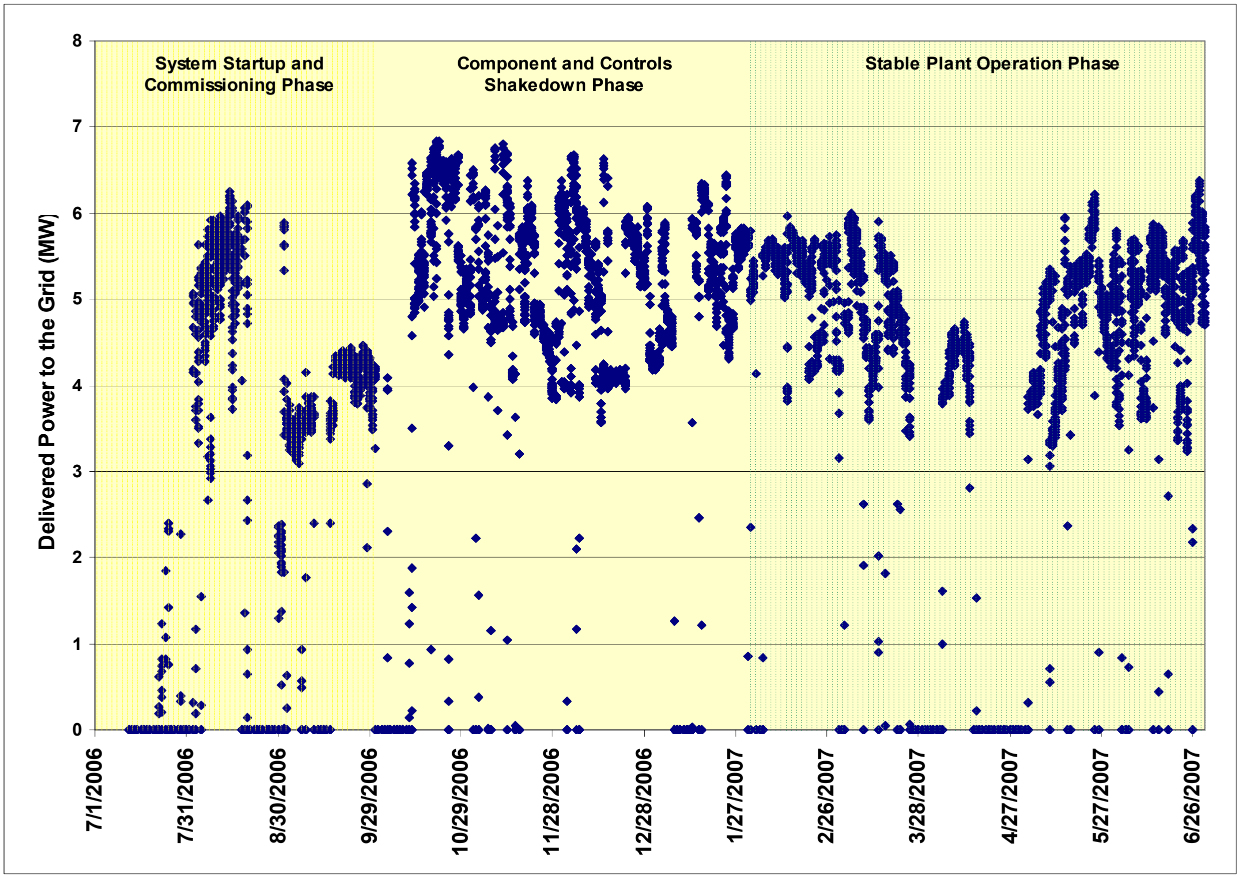

Figure 9. Hourly Delivered Power from the ORC Recovered Energy Generation Plant

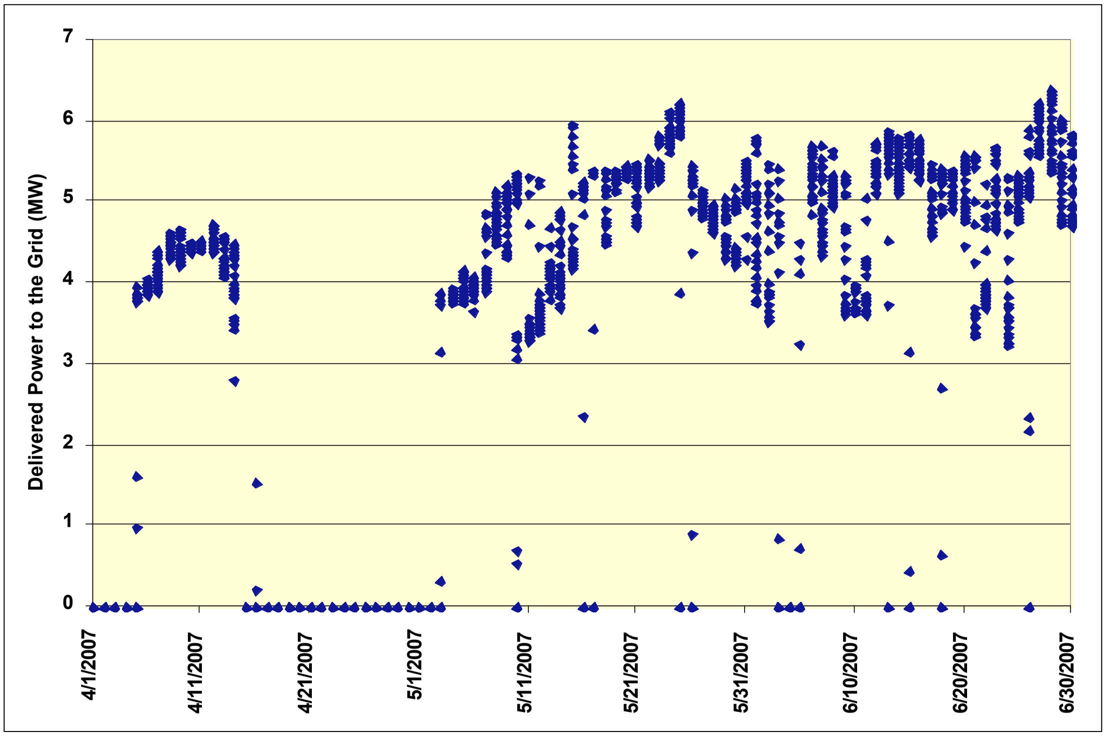

Figure 10. Second Quarter 2007 Hourly Delivered Power

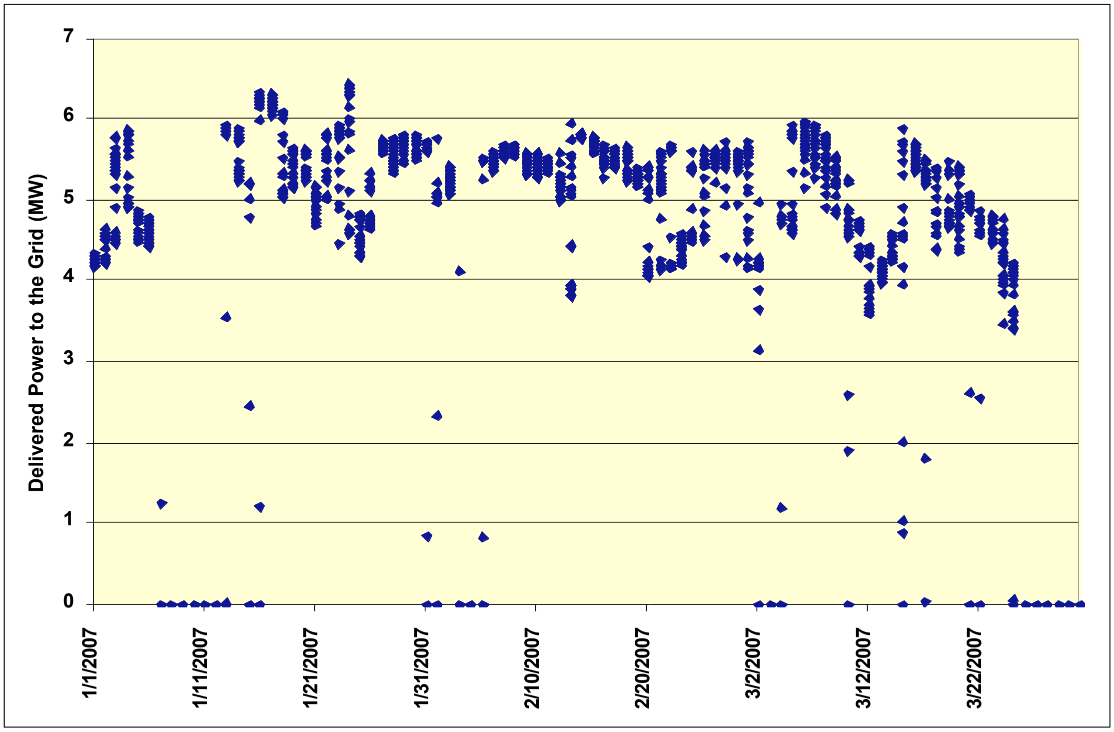

Figure 11. First Quarter 2007 Hourly Delivered Power

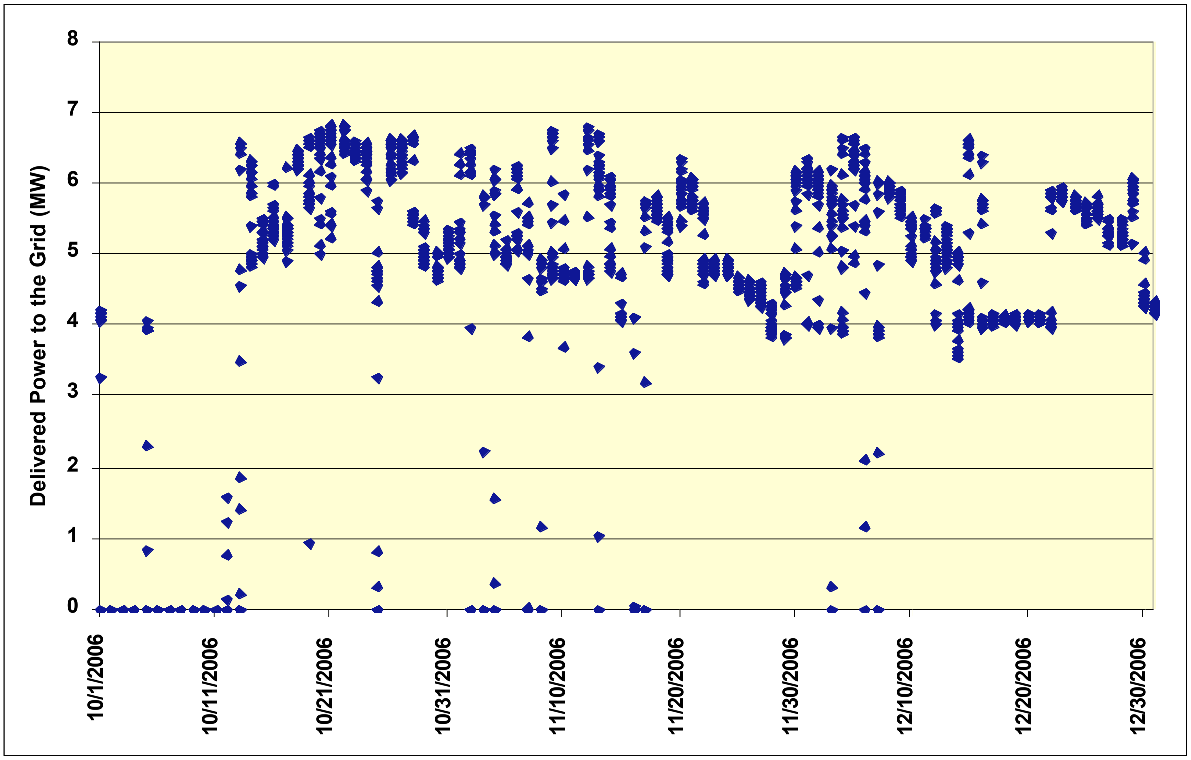

Figure 12. Fourth Quarter 2006 Hourly Delivered Power

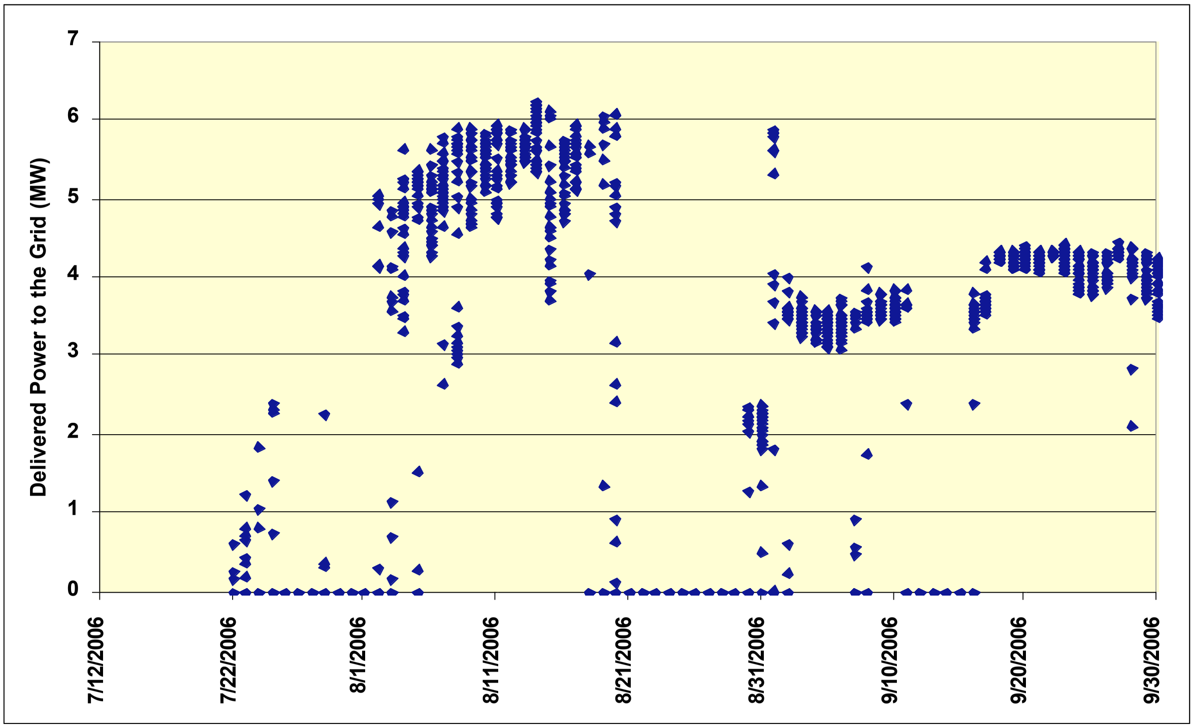

Figure 13. Third Quarter 2006 Hourly Delivered Power

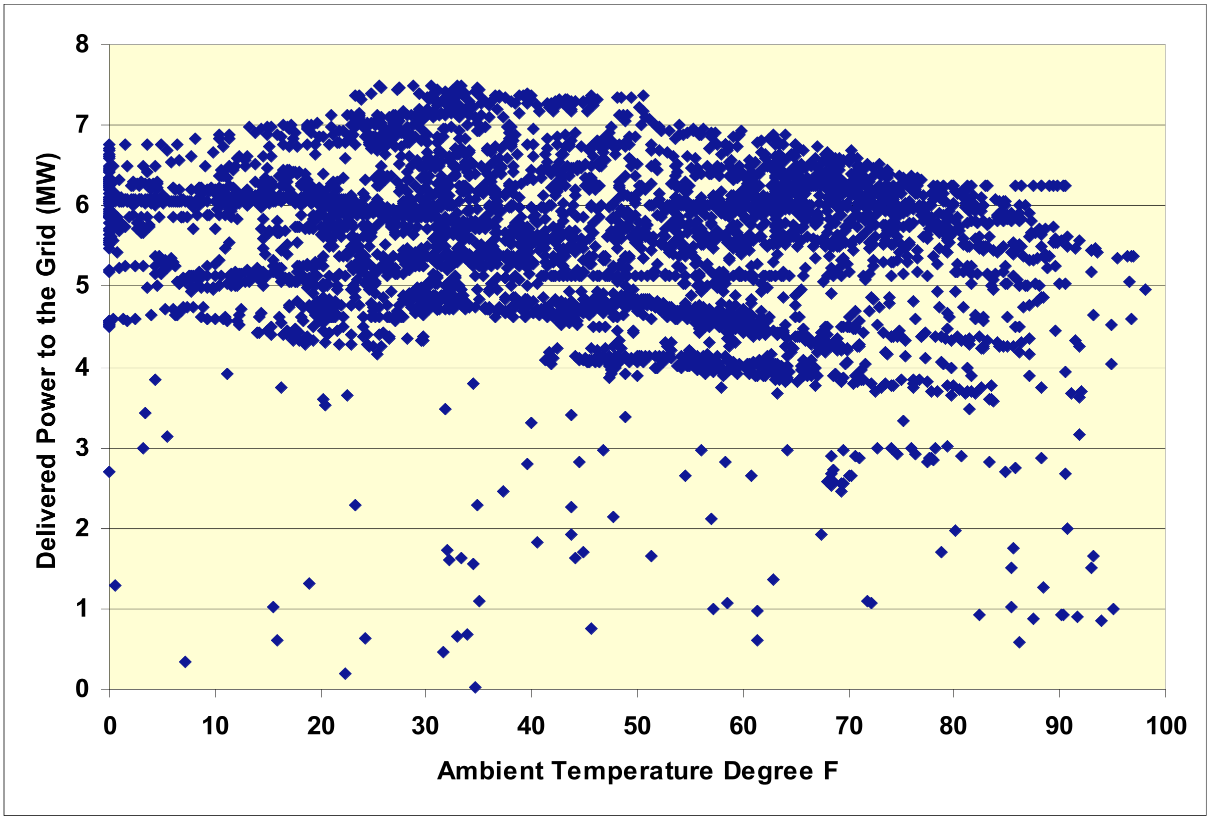

Figure 14. ORC Recovered Energy Generation Performance during Operation

3.2 Energy Efficiency

Recovered energy generation plant performance and economic viability are directly related to the overall energy efficiency of the system. In the case of recovered waste heat, energy efficiency has two major components: gas turbine exhaust to oil heat exchange efficiency, and oil heat to electricity conversion efficiency. The first component of efficiency affects the overall capacity of the system for a given size heat source. The second component measures the efficiency of the ORC heat conversion system. Optimizing both components is critical for economic viability.

Figure 15 provides the key heat input and power output state points used to determine system performance and energy efficiency for the recovered energy generation plant.

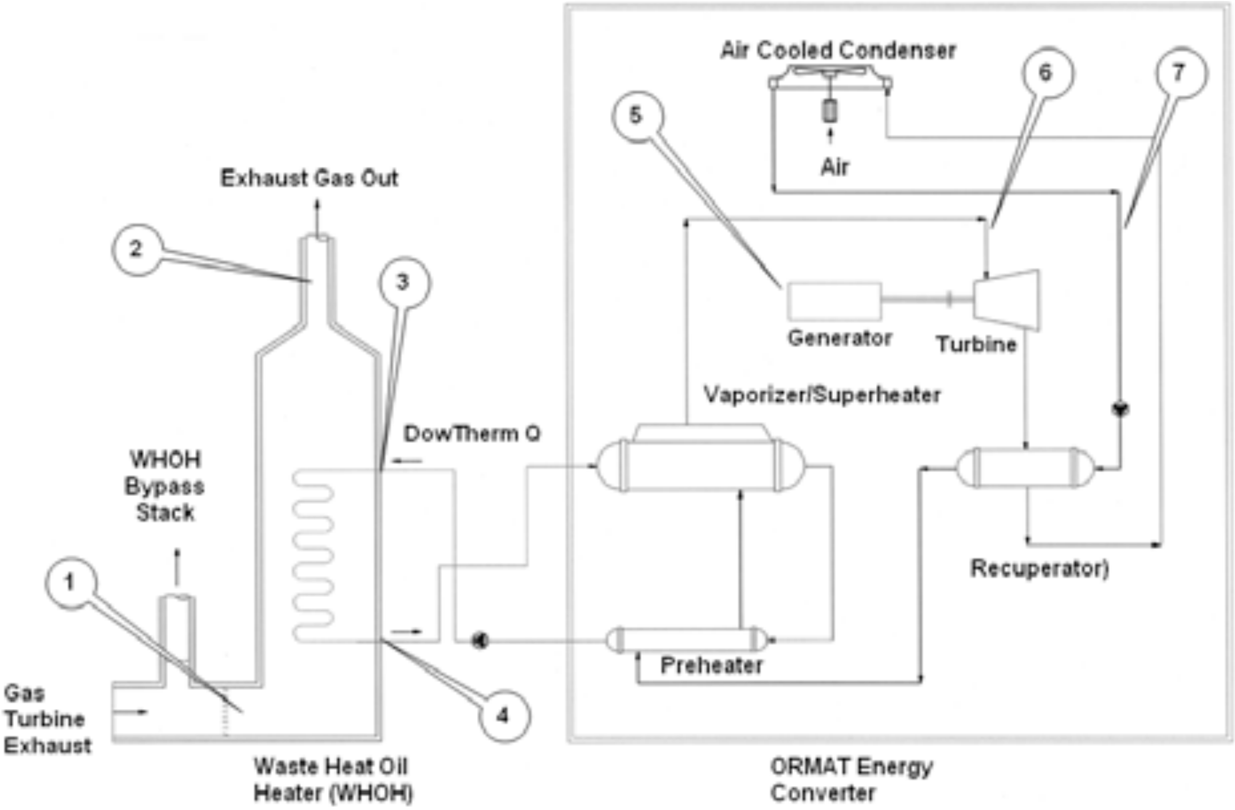

Figure 15. State Points for Energy Efficiency Calculations

Table 1 state point locations are identified in Figure 15.

Table 1. Data Point Measurement Locations

State Point	Measurement
1	Waste Heat Oil Heater (WHOH) Entering Gas Temperature
2	WHOH Exhaust Gas Temperature
3	WHOH Entering Oil Temperature and flow
4	WHOH Leaving Oil Temperature
5	Electric Power Generated
6	Pentane Vapor Temperature
7	Condensed Pentane Temperature

Gas Turbine Exhaust to Oil Heat Exchange Efficiency – The effectiveness of the waste-heat-to-oil heat exchanger is a critical element in the overall system performance. Because of the desire to avoid condensation conditions within the waste heat gas stream, the maximum amount of heat that could be harvested from the waste heat stream is about 90%.[1] To maintain an adequate margin of safety and to reduce maintenance costs, a slightly lower design limit (e.g., 88%) may be appropriate.

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[1] The proportion that can be harvested is stated relative to the ambient temperature and therefore includes the enthalpy that would be released as the water vapor present in the exhaust gases condenses. This convention is used to maintain consistency with the fuel input characterized by the higher heating value (HHV).

Ideally, the heat exchanger effectiveness would be calculated by comparing the heat available within the hot gas stream to the heat absorbed within the hot oil. However, the mass flow rate of the hot gas was not measured, so this calculation was not possible. In the absence of hot gas flow data, the amount of heat available from the turbine exhaust can be estimated for those times when there is no flow through the waste-heat-to-oil heat exchanger bypass stack. For this system, there were periods with no bypass at approximately 30 ° F ambient temperatures, so data for operation at this temperature were used in the analysis.

State points #1 and #2 in Figure 15 are the exhaust gas stream from the gas turbine. Because the actual exhaust gas composition and mass flow were not measured, the energy content was estimated from the combustion turbine heat rate and delivered power. CS#7 uses a Coberra 6000 coupled turbine, which incorporates a Rolls-Royce RB211-24G aircraft-derivative gas turbine and a Cooper-Bessemer power turbine. For this turbine, the power and heat rate at ISO standard conditions (59ºF, sea level) are 35,000 shaft horsepower (26,100 kW) and 9,534 Btu/kWh LHV (10,559 Btu/kWh HHV). Turbine efficiency increases by about 0.3% at 30ºF compared to ISO conditions, and its output increases by about 7%[2]. The resulting turbine efficiency for design heat exchange efficiency calculations is estimated at 32.6% (HHV), and its output increases to about 27,900 kW. Assuming 2% jacket heat losses, the following analysis estimates the design heat exchange efficiency for the waste-heat-to-oil heat exchanger.

Fuel at 30ºF Ambient Conditions = 291 Million Btu/h (Higher Heating Value)
Fuel to power = 95 Million Btu/h
Jacket losses = 5 Million Btu/h
Total Heat in Exhaust Gas = 191 Million Btu/h

Based on measured flow rates and heat content of oil (state points 3 and 4 shown in Figure 15 and data from Table 2), the energy transferred into the oil at a measured recovered energy generation plant output of 7.3 MW was 167 million Btu/h. This yields an estimated waste-heat-to-oil heat exchanger efficiency of 87%. The calculated heat exchanger efficiency is within acceptable tolerances for a tightly controlled system to avoid condensation while maximizing efficiency.

It should also be recognized that the heat exchanger effectiveness will vary as both the hot gas and oil flow rates are controlled by the use of stack bypass or oil pump modulation. The measured hot oil heat transfer rates varied significantly when oil pump flow control and stack bypass were used to maintain safe waste-heat-to-oil heat exchanger operation across a wide range of ambient temperatures. The net effect was a heat exchanger effectiveness that ranged from 87% at 30ºF to about 65% at extreme ambient temperatures.

Oil Heat to Electricity Conversion Efficiency – There was typically a large oil temperature rise in the waste-heat-to-oil heat exchanger (e.g., 177ºF inlet to 568ºF outlet). Since DowTherm Q specific heat varies significantly as a function of temperature, the heat content calculation uses a variable specific heat value derived from manufacturer's data in Table 2 at the inlet and outlet waste-heat-to-oil heat exchanger temperatures. Heat delivered to the hot oil within the

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[2] Energy Nexus Group. 2002. Technology Characterization: Gas Turbines. Environmental Protection Agency, Climate Protection Partnership Division. Washington, DC.

waste-heat-to-oil heat exchanger can be calculated from the manufacturer's data coupled with field data using Equation 1.

$$\dot{Q}_{\text{in}} = \dot{m} \times \Delta(c_p T) \qquad (1)$$

Where:

$\dot{Q}_{\text{in}}$ = hot oil input rate to the vaporizer
$\dot{m}$ = hot oil flow rate
Δ = change, outlet minus inlet of haste-heat-to-oil heat exchanger
c_p = specific heat (Btu/Lb-F) of DowTherm Q
T = hot oil temperature, F

The plant conversion efficiency of the ORC system is calculated by dividing the delivered electricity by the oil heat content as shown in Equation 2.

$$\eta_{\text{ORC}} = \frac{\dot{W}_{\text{turbine}} - \dot{W}_{\text{auxiliary electricity}}}{\dot{Q}_{\text{in}}} \qquad (2)$$

Where:

η_{ORC} = ORC system plant conversion efficiency
$\dot{W}_{\text{turbine}}$ = total power generated by the ORC expander turbine
$\dot{W}_{\text{auxiliary electricity}}$ = auxiliary power required by the ORC system including controls, pumps and fans

Table 2. Heat Content Properties of DowTherm Q

Temp. °F	Specific Heat Btu/lb°F	Density lb/ft3	Therm. Cond. Btu/hr ft^2 (°F/ft)	Viscosity cP	Vapor Pressure psia
-30	0.353	62.84	0.0741	29.0	
0	0.366	62.05	0.0730	14.7	
50	0.387	60.74	0.0712	5.42	
100	0.409	59.43	0.0693	2.50	
150	0.429	58.12	0.0672	1.38	0.01
200	0.450	56.81	0.0650	0.88	0.03
250	0.471	55.50	0.0627	0.61	0.14
300	0.491	54.18	0.0604	0.46	0.45
350	0.511	52.87	0.0580	0.36	1.22
400	0.531	51.56	0.0555	0.30	2.88
450	0.551	50.25	0.0530	0.25	6.09
500	0.570	48.94	0.0505	0.22	11.73
550	0.589	47.63	0.0480	0.20	20.93
600	0.609	46.32	0.0455	0.18	35.05
630	0.620	45.53	0.0440	0.17	46.51

ORC Performance Dataset for Figures 16 to 19 – During the data collection period, the natural gas pipeline flow, and therefore compressor station waste heat availability, was highly variable. In order to remove that and other confounding factors from the evaluation of the recovered energy generation system, the dataset presented in Figures 16 – 19 is a subset of the complete test period data presented in Figure 14. Because the compressor operation itself was not monitored, and the impact of other factors was highly variable, proxy criteria were defined to delete those data observations that corresponded to low or no waste heat availability. The criteria that were used to indicate adequate waste heat availability were: hot oil supply temperature to the vaporizer greater than 515ºF, and minimum heat available in the hot oil greater than 112 MMBtu/h.

Effect of Ambient Temperature on System Performance – Ambient temperature had a noticeable impact on overall ORC performance and recovered energy generation plant output. As shown in Figure 16, the ORC system consistently performed between 13 and 15 percent thermal efficiency when the ORC was operating at full power during the test period, with peak efficiency occurring between 20ºF and 50ºF ambient conditions.

Measured system performance data and calculated ORC efficiency values were used to determine the major constraints that impact peak recovered energy generation plant output at different ambient temperatures. Figure 17 illustrates the effect of ambient temperature on peak power delivered to the grid. The polynomial curve fit in Equation 3 provides a good prediction of forward going performance.

$$\dot{W}_{\text{turbine}} - \dot{W}_{\text{auxiliary electricity}} = -0.0005(T_{\text{ambient}})^2 + 0.035T_{\text{ambient}} + 6.48 \qquad (3)$$

where:
Tambient = ambient temperature, °F

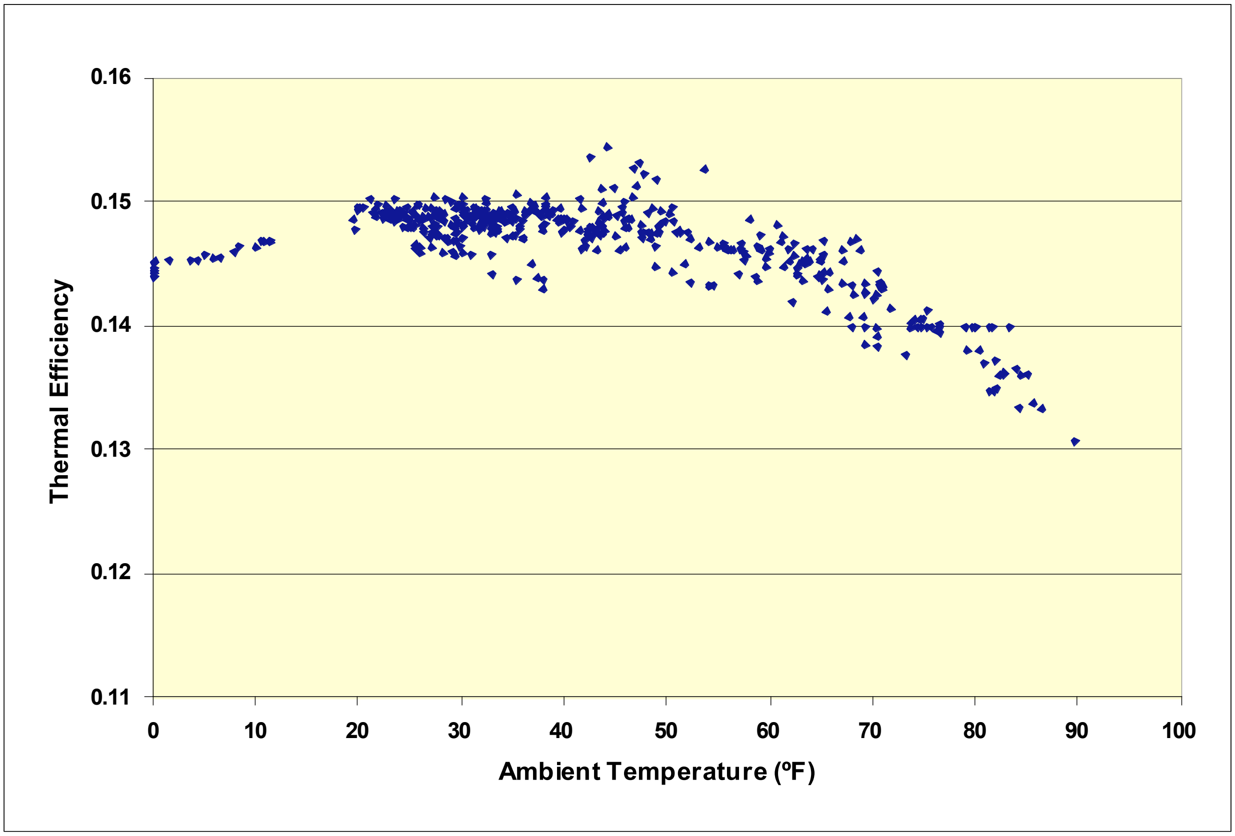

Figure 16. ORC Conversion Efficiency with Respect to Ambient Temperature

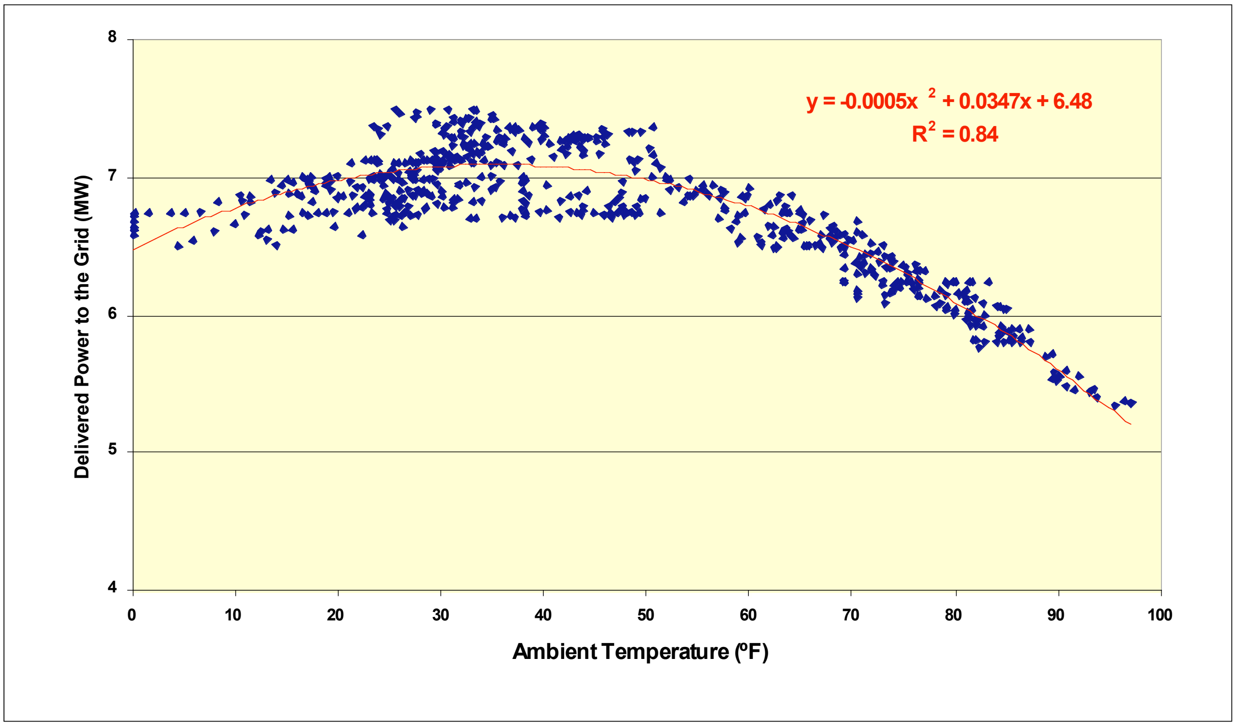

Figure 17. Recovered Energy Generation Plant Output with Respect to Ambient Temperature

Figure 18 tracks gas turbine exhaust temperatures, hot oil temperatures, condensed pentane temperature, and peak power relative to ambient temperature. As expected, the power output dropped as the condensed pentane temperature increased at higher ambient temperatures. The gas turbine exhaust temperature increased at higher ambient temperatures, which normally would translate into increased power output. However, system controls limited the waste heat recovery to avoid overheating the oil at warm ambient temperatures.

The effect of ambient temperature on pentane condenser performance can be assessed by examining the temperature differential between the pentane gas entering the condenser and the subcooled liquid leaving the condenser at a given ambient condition. The pentane gas-to-liquid temperature difference was 257ºF at 90ºF ambient and 300ºF at 0ºF. This yields a high/low temperature difference ratio of 85.6%. Examining the air side of the heat exchanger, one can infer performance directly from air density. At 0ºF, the air's density is .085 lb/ft^3, and at 90ºF it is .072 lb/ft^3, or a ratio of 89.5%. The 4.5% differential is well within field measurement tolerance.

Figure 19 plots the temperature drops for the ORC system. There is an important constraint on the gas turbine exhaust temperature exiting the exhaust stack. To reduce the capital cost of

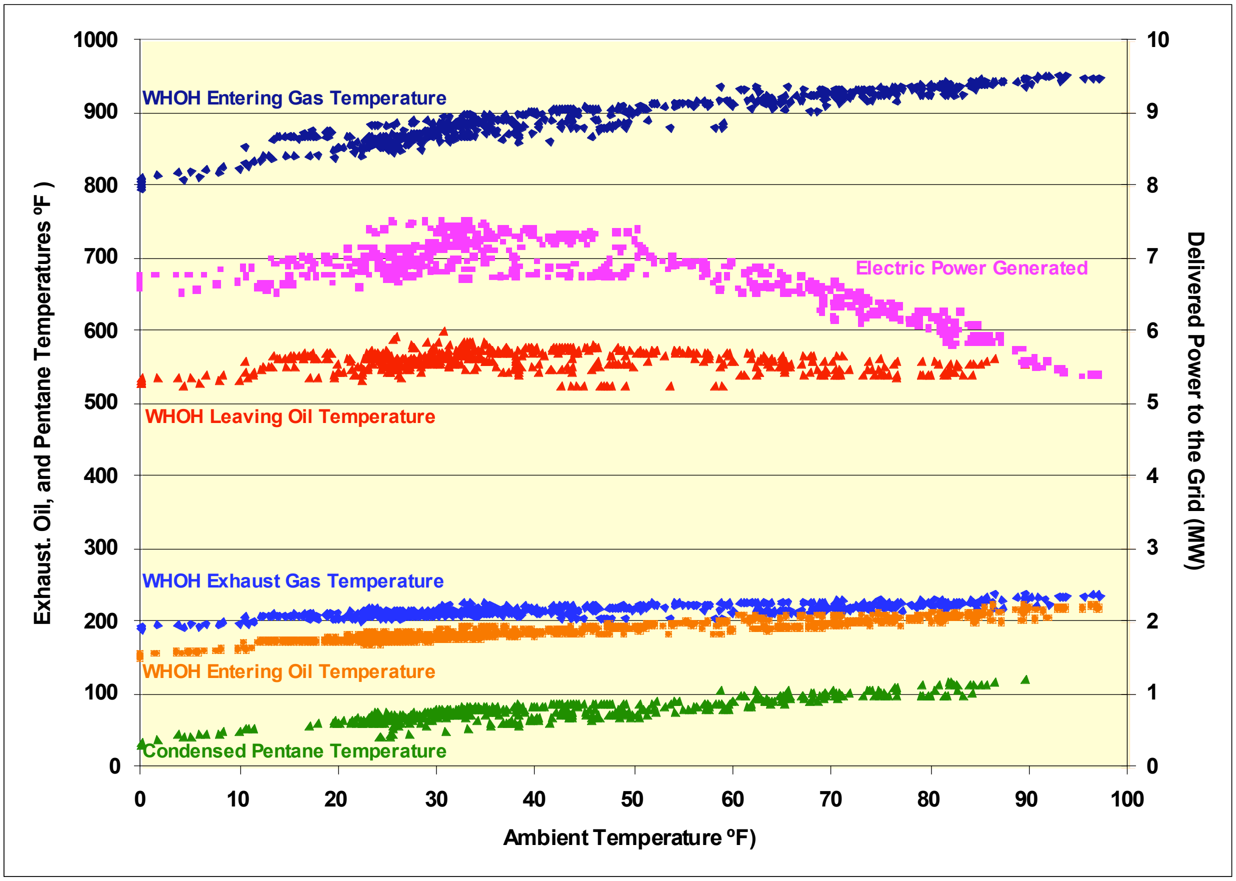

Figure 18. ORC Temperatures and Delivered Power with Respect to Ambient Temperature

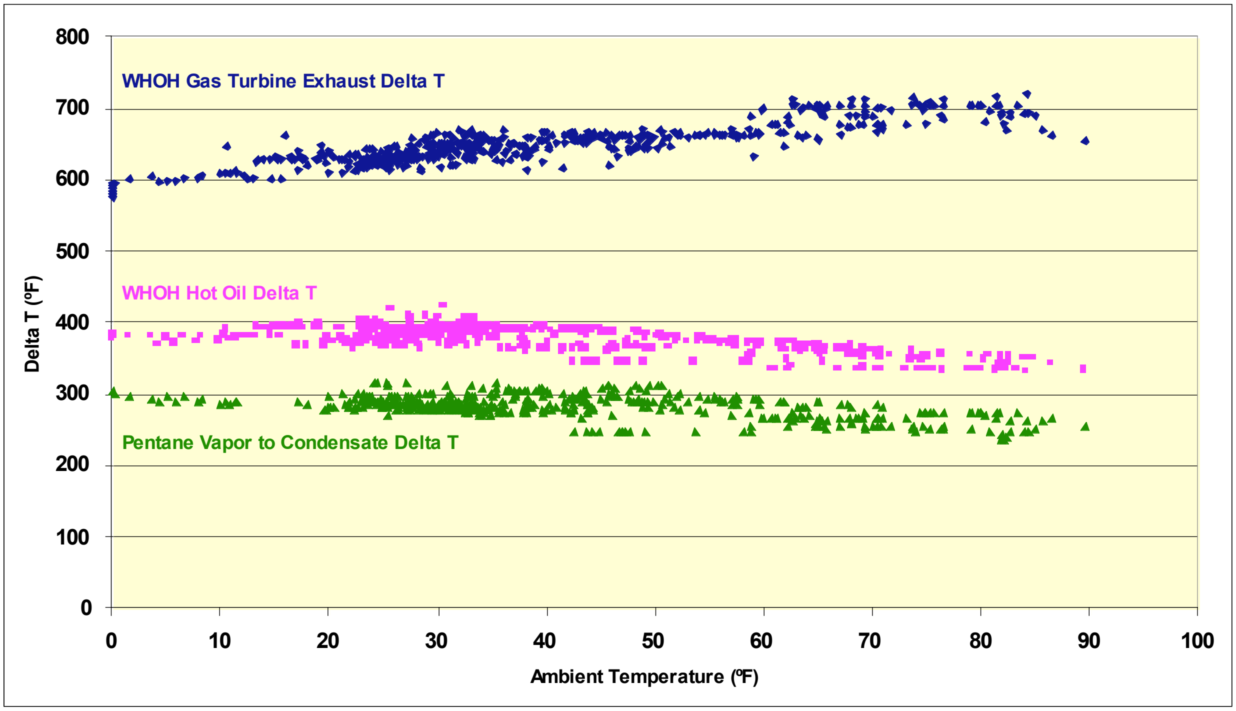

Figure 19. ORC Temperature Differences with Respect to Ambient Temperature

the system, the waste-heat-to-oil heat exchanger and exhaust stack were made from carbon steel. This limited the minimum gas turbine exhaust temperature to 200°F to 225°F depending on ambient conditions to avoid condensing water vapor and associated acid-based corrosion. The minimum exhaust gas temperature constraint had a limiting effect on system capacity and efficiency. The waste-heat-to-oil heat exchanger exhaust at 90°F was 240°F and at 0°F was 200°F (a reduction of 40°F) while the gas turbine exhaust gas at 90°F ambient was 950°F and at 0°F was 800°F (a reduction of 150°F).

To further understand system performance constraints at different ambient conditions, the data set was split into different performance regions. The trend line of recovered energy generation plant output relative to ambient temperature in Figure 17 shows three distinct performance regions: 1) 0°F to 25°F low temperature; 2) 25°F to 50°F peak performance; and 3) above 50°F high temperature. Each region is discussed in more detail below.

1) 0°F to 25°F Low Temperature - There is a distinct negative change of slope in power output as ambient temperature falls below 25°F. The dominant factor in this reduction appears to be the reduction in absolute gas turbine exhaust temperature that is related to lower ambient temperature as shown in Figure 18. The pentane condenser categorically improved performance at lower ambient temperatures. Pentane condensate temperatures fell from 100°F at 80°F ambient temperature to 34°F at 0°F ambient temperature. The waste-heat-to-oil heat exchanger performance was a function of higher gas turbine exhaust gas mass flow and lower exhaust gas temperature, with an apparent negative slope change as the exhaust temperature went below about 875°F. The lower gas turbine exhaust gas temperature difference started to dominate the higher mass flow rate at ambient temperatures below 25°F, which can be seen in the change of slope of the exhaust gas and hot oil temperature differences in Figure 19. In this region, variable oil flow to the waste-heat-to-oil heat exchanger maintained exhaust gas temperature above 200ºF to avoid condensation in the heat exchanger.

2) 25ºF to 50ºF Peak Performance – The system reached its peak performance at ambient temperatures between 25ºF and 50ºF. The balanced plant operation limited the need for stack bypass and hot oil flow rate modulation in this region. The DowTherm Q was 580ºF to 600°F leaving the waste-heat-to-oil heat exchanger over much of this ambient temperature range, while the exhaust gas temperature was 210ºF to 225ºF.

3) Above 50ºF High Temperature - Above 50ºF the drop-off in power was roughly 370 kW for every degree F increase in ambient temperature. The major constraint in this region was the DowTherm Q recommended maximum operating temperature of 625°F. This was a function of two factors. The first factor was the condensed pentane temperature, which ranged from 87ºF at 50ºF ambient temperature to 119ºF at 90ºF ambient temperature. The increased condensed pentane temperature was caused by the air-cooled pentane condenser capacity reduction as ambient temperature increased. The increased condensed pentane temperature reduced the waste-heat-to-oil heat exchanger's ability to capture heat from the gas turbine exhaust gas due to the oil temperature limit, thereby limiting the power derived from the ORC's turbine.

The second factor was the increased gas turbine exhaust temperature. Hot gas flow through the waste-heat-to-oil heat exchanger was controlled using the bypass stack as the exhaust gas temperature increased to avoid overheating the oil as the pentane temperature increased. The heat gain by the hot oil at 50ºF was 160 million Btu/h and at 90ºF was reduced to 145 million Btu/h (a 9 percent reduction). The gas turbine mass flow reduction (6% over the temperature range) essentially balanced the 6% increase in exhaust gas temperature. However, the 20% loss in power over the range (7.0 to 5.6 MW) was related to the increased pentane temperature and 625ºF oil temperature limit. The pentane temperature exiting the vaporizer was relatively constant in this region, increasing slightly from 365ºF to 372ºF (2%). With this fixed upper limit, the temperature difference across the turbo-expander fell from 277ºF at 50ºF to 253ºF at 90ºF (a 9% drop across the turbo-expander). Combining the drop in thermal input (9%) and the drop in expander temperature difference (9%) there appears to be reasonable correlation with the 20% loss in power output over this temperature range. The exhaust gas temperature in this region ranged from 225ºF to 240ºF, consistent with controlled bypass stack operation at constant oil flowrate.

4. Economic Performance

Green energy production using ORC must be profitable for Northern Border Pipeline, ORMAT, and Basin Electric if it is to be rolled out in other areas. The following describes the overall project economics.

4.1 Benefits to the System Owner

The capital cost for the installed ORC system at CS#7 was about $13.75 million, which results in a rated (5.5 MW) installed cost of $2,500 / kW.

The plant component issues that caused a significant amount of nuisance problems were resolved. These issues can be categorized into three areas: Valves that did not perform in cold weather; instrumentation that did not perform in cold weather; and defective pentane pumps that required change-out in spring 2007.

The second performance issue was the low contracted capacity for the pipeline, which caused unexpected shutdowns in winter and spring 2007. Future contracts for the pipeline indicate this will also not be a problem.

Therefore, it is reasonable to assume, based on the operating history of the first year, that a 90% design load factor can be predicted, which would allow for routine maintenance. Operating and maintenance costs for the plant are $250,000 per year, and the design delivered annual capacity is 5.5 MW. This would yield 43 million kWh per year at 90% load factor of the 5.5 MW capacity. ORMAT estimates that future projects would require a purchase price of 5¢ / kWh for their business model to work.

Working with the above economics, a simple breakeven point can be calculated at about seven years (see Figure 20).

The Net Present Value (NPV) of this project with various contract terms (15 to 25 years in duration) with cost of capital of 6% to 10% for clean energy projects, ranged from $2 million to $12 million (see Figure 21).

Figure 22 shows the Internal Rate of Return that ranged from 4% to 14% for the project depending on contract length.

4.2 Benefits to the Utility

In addition to the economic benefits to the utility of receiving low cost green power as classified by the state, the utility grid receives volt-amperes reactive (VAR) support in a grid sector where voltage support is important for critical loads such as hospitals. In alternating-current power transmission and distribution, VARs are the product of the rms voltage and current, or the apparent power, multiplied by the sine of the phase angle between the voltage and the current. In mathematical terms, the reactive power Q, (measured in units of volt-amperes reactive or VARs), is given by Eq. 4.

$$Q = V_{\mathrm{RMS}} \times I_{\mathrm{RMS}} \times \sin(\varphi) \tag{4}$$

Where:
Q = Reactive power, VAR
V_{RMS} = Root mean square Voltage
I_{RMS} = Root mean square current,
φ = phase angle between the voltage and current.

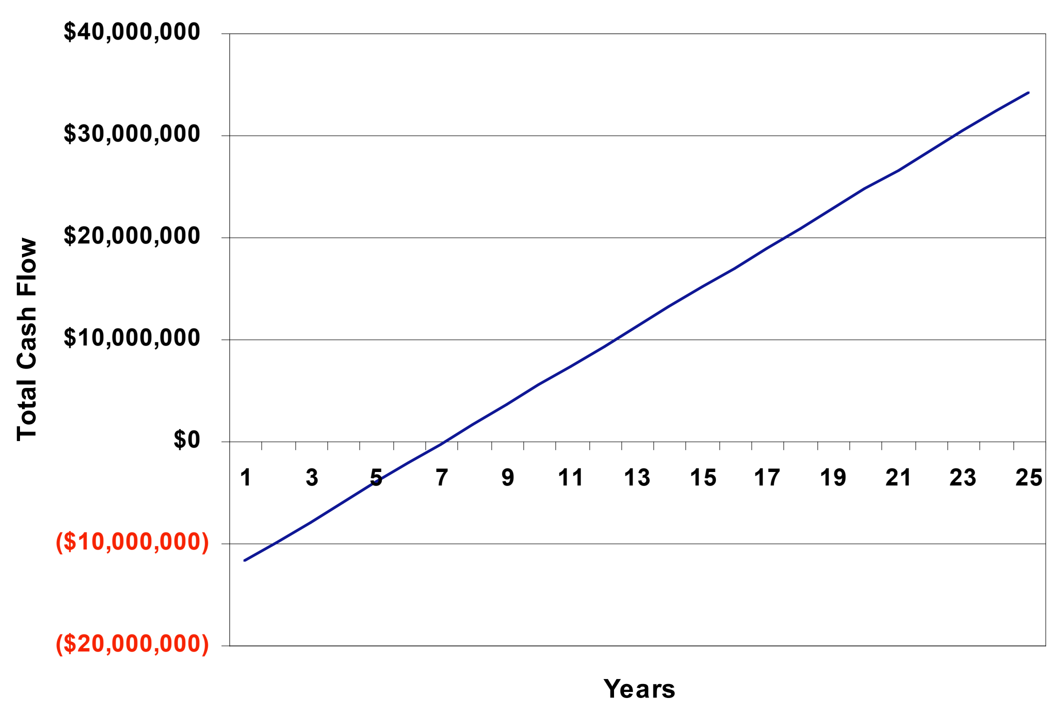

Figure 20. Breakeven Analysis

Figure 21. Net Present Value (NPV) Analysis

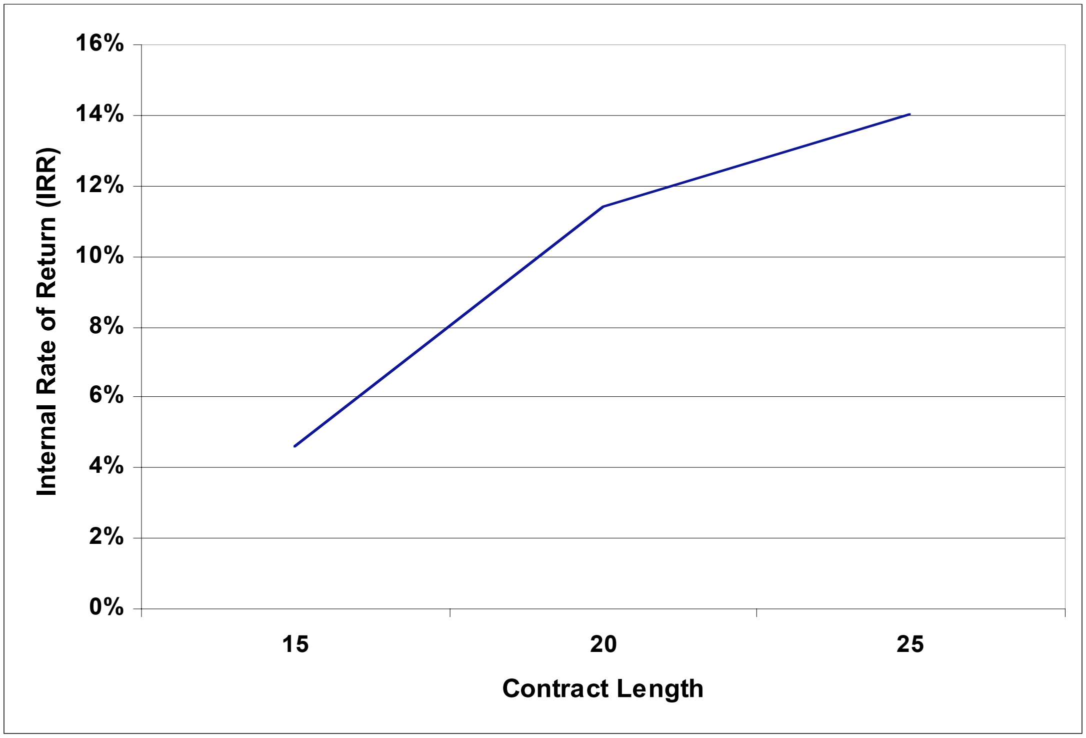

Figure 22. Internal Rate of Return (IRR) Analysis

To maximize transmission efficiency, VARs must be minimized by balancing capacitive and inductive loads, or by addition of an appropriate (off-setting) capacitive or inductive reactance to the load. The ORC system does this with system voltage stabilization.

System Voltage Stabilization – The electric generator is operated in a constant voltage output mode. Operation in this mode results in adjustment of the VARs produced or consumed by the generator as part of the process to regulate the voltage at the generator terminals.

These VAR adjustments and the regulated voltage output resulting from constant voltage control provide similar benefits on the electric system by moderating its voltage variations as well. It is this voltage stabilization that helps power sensitive users like hospitals.
The VAR variations at utility peak times are shown in Table 3:

- kVAR-ORMAT is kVAR at the generator terminals.
- kVAR-Grid is the kVAR at the generator step-up transformer high-side bushings, the point of interconnection to the grid.

Loss Reduction – At the St. Anthony site, the utility is served via a transmission source which assesses a transmission access fee on kWh delivered from that system. The utility benefits from this installation, as this fee does not apply to the energy that is generated from the distributed generation site and delivered directly to their system. Local delivery of the generated energy at a point closer to the load reduces electric system losses as well.

Table 3. St. Anthony Site CS#7 - Data at Time of Electric System Peak

Monthly Peak Day	Peak Time Hr. Ending	On-Peak kW-ORMAT	On-Peak kW-Grid	+ = Supplies VARS - = Draws VARS On-Peak kVAR-ORMAT	On-Peak kVAR-Grid	Point Of Interconnection Power Factor @ Peak
7/30/06	19:00	0	0	-14	-22	0
8/4/06	18:00	4910	4882	+202	+58	100.0%
9/6/06	21:00	3694	3679	-209	-374	99.5%
10/30/06	20:00	5047	5033	-403	-691	99.1%
11/29/06	19:00	4738	4723	-7	+29	100.0%
12/7/06	8:00	0	0	-22	-36	0.0%
1/30/07	8:00	5789	5760	-310	-684	99.3%
2/15/07	8:00	5810	5782	-425	-806	99.1%
3/2/07	20:00	4226	4212	-202	-418	99.5%
4/4/07	8:00	0	0	-22	-36	0.0%
5/13/07	22:00	4097	4090	-302	-504	99.3%
6/25/07	18:00	4788	4766	+1130	+850	98.5%

Coincidence with Electric System Peaks – Another important value-adding factor is the coincidence of power production with Basin's electric system peak. As shown in Table 3, there is a high coincidence of power production concurrent with electric system peak. The ORC system was off-line during July 2006 and December 2006 at peak due to project startup and shakedown problems.

4.3 Benefits to the Pipeline Owner/Operator

Operating and maintenance costs for the plant are $250,000 per year, which includes financial payment for use of its waste heat. However, this remuneration is only one factor in the pipeline's decision to permit installation of this energy recovery plant. The first issue for the pipeline is doing no harm to the pipeline operation, such as increased plant costs or reduced gas turbine efficiency. The ORMAT energy recovery plant is designed to avoid any deleterious effect on the pipeline's operation.

The other major consideration for the installation of energy recovery on pipelines is the overall energy efficiency benefit. This position may be more clearly understood by examining recent FERC deliberations over the proposed Rockies Express Pipeline.

FERC Commissioner Wellinghoff's statement on Rockies Express Pipeline LLC[3], with respect to pipeline design and energy efficiency, recommends using waste heat from combustion turbines or reciprocating engines that drive station compressors: 1) To generate electricity for use at compressor stations, or generate electricity for sale, 2) To operate a secondary steam or Rankine cycle turbine to partially drive the compressor, or 3) To produce absorption cooling to either reduce combustion turbine inlet temperatures to improve turbine efficiency or to provide a cooler and denser gas that is more efficient to transport.

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[3] Statement: April 19, 2007 Docket No: CP06-354-000 et al.

The FERC position provides significant encouragement to pipelines to undertake energy efficiency initiatives that are in the nation’s best interest.

5. Lessons Learned

Lessons learned that may be useful for evaluating future recovered energy generation plant opportunities include:

- There is an economic model that makes existing ORC technology applied to pipeline compressor stations cost-competitive with coal generation.
- Remote pipeline-based ORC systems can provide baseload power.
- Cold ambient operation provided challenges, including the need to replace frozen flow transmitters and change certain valve designs that were prone to freezing.
- There was minimal environmental impact, minimal permitting, and virtually zero incremental emissions related to this project.
- The pipeline compressor was shut down several times during the test period due to market demand fluctuations. Since compressor downtime affects annual waste heat availability and baseload power output, it is important to obtain good estimates of annual compressor run hours from the pipeline when selecting project locations. Fortunately for this project, the projected pipeline demand is expected to be high in the foreseeable future due to increased sales, which should significantly reduce annual compressor shutdown periods.
- The significant operating constraints identified were: heat input (temperature and mass flow) that was dictated by the gas turbine's operation; the selection of pentane over steam for the Rankine cycle; the material selection for the waste-heat-to-oil heater, which limited the minimum heat exchanger exhaust gas temperature to prevent condensation; the DowTherm Q maximum operating temperature of 625ºF, which required a control limit between 580ºF and 600ºF for safe operation; and pentane condenser surface area.
- Areas for potential improvement in performance that should not negatively impact capital cost (and may reduce capital cost) are to consider other working fluids and consider eliminating the oil loop. Care must be taken on both instances – particularly eliminating the hot oil loop. Risks of alternative approaches to pentane and hot oil must be carefully analyzed before making any recommendation.

Based on the successful results of this project, Basin Electric plans to purchase power from four of six new recovered energy generation plants that ORMAT will develop along the Northern Border Pipeline in Montana, North Dakota, and Minnesota. The new power plants are in addition to the existing four facilities in North and South Dakota that have been in commercial operation since autumn 2006. Under terms of the deal, 22 additional megawatts of electricity from the four new power plants will be sold to Basin Electric under a long-term power purchase agreement, expected to add up to approximately $6.4 million in yearly revenues to ORMAT's electricity segment. Eleven MW of power from the other two sites will be contracted to two other utilities. Development of the additional six sites will increase the capacity of ORMAT's portfolio of owned and operated recovered energy generation power plants to approximately 55 MW.

ORMAT has already secured the rights to the waste heat for two of the new power plants and is in the process of obtaining the rights to the remaining four new power plants. The projected completion date of all six new sites is 2009.

Appendix – Pipeline Compressor Station Photos

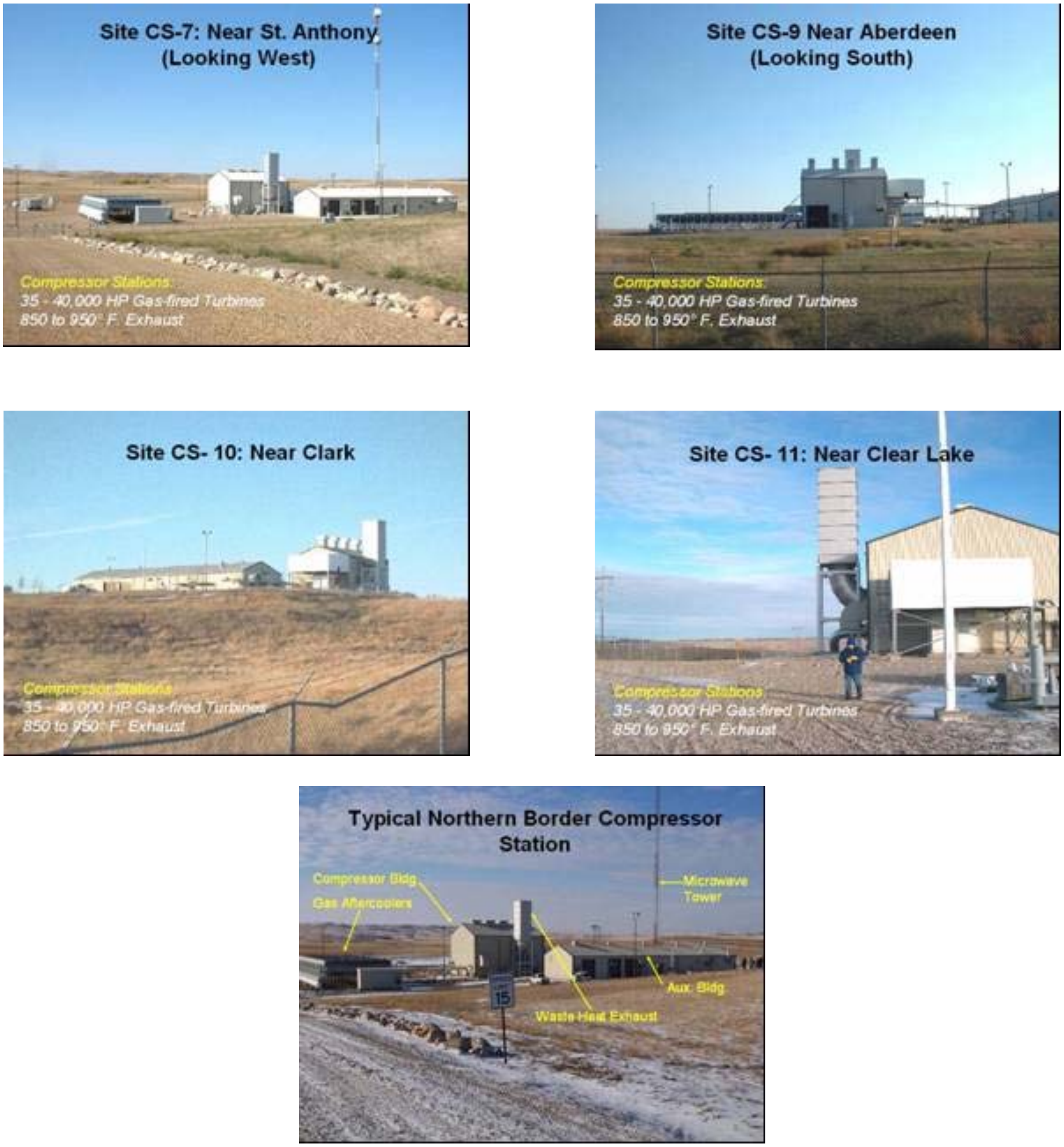

Figure 23. Compressor Station Overview Pictures

Figure 24. Feeder line from ORC to the Grid

Figure 25. Transporting Part of Waste-Heat-to-Oil heater Assembly during Spring Load Limit Restrictions. (Transport device uses 18 double-axles)

Figure 26. Transporting Assembly across County Bridge

(Shows spanning bridge with rigid support and illustrates hydraulically equalized axle loading.)

Figure 27. 225 kW Standby Generator On-Site For Emergency Backup

ORMAT Modular Switchgear and Control Building in Background.

Figure 28. Panoramic View of St. Anthony Site – Late May 2006.

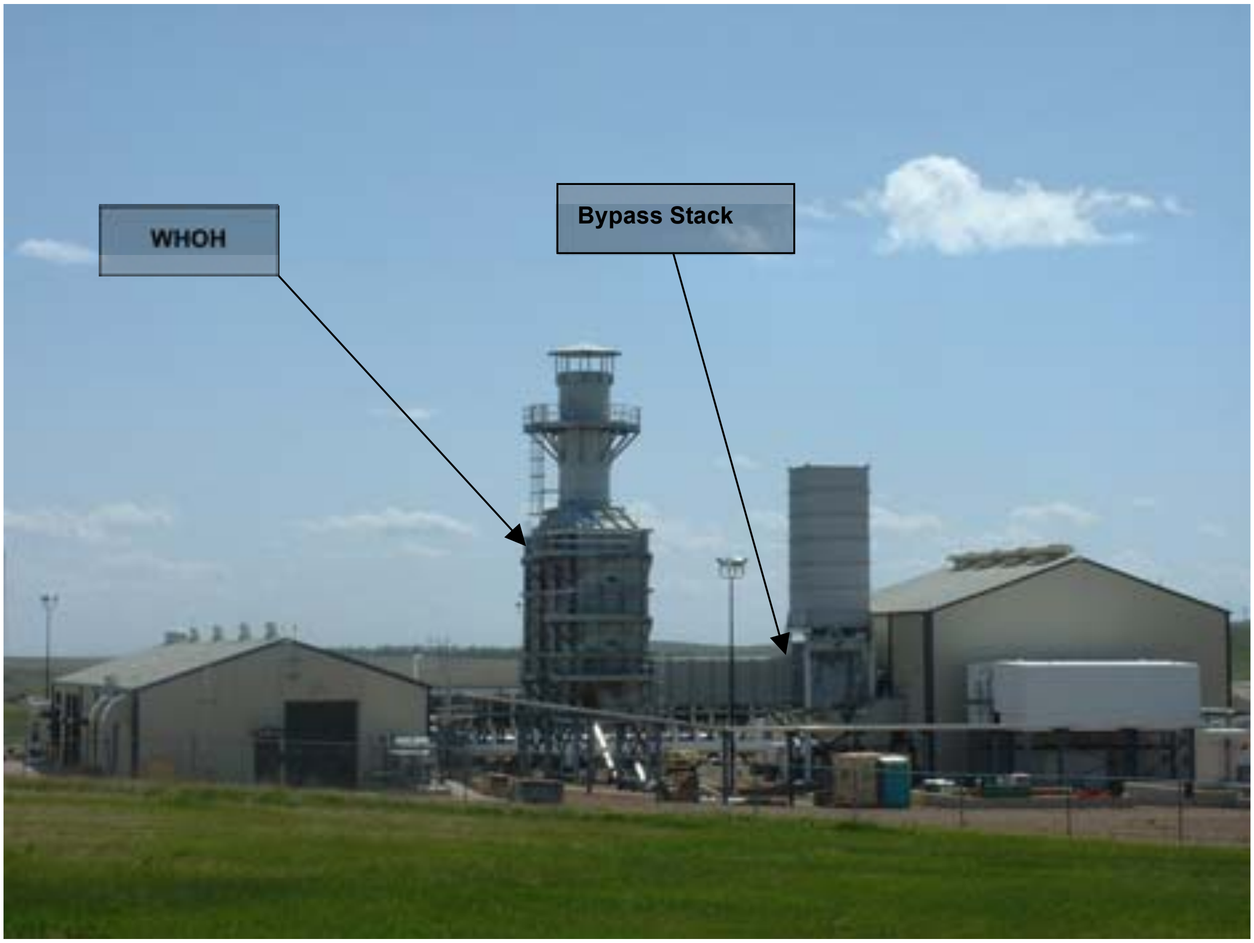

Figure 29. Waste-Heat-to-Oil Heater and Diverter Valve – St. Anthony Site – Late May, 2006

Figure 30. Completed Project

Figure 31. ORC System