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INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE

Waste Heat Recovery from Existing Simple Cycle Gas Turbine Plants
A Case Study

by

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Abstract

Waste heat recovery from the exhaust of existing simple cycle gas turbine plants is effective for powering new sources of electric generation without new sources of greenhouse gas emissions. This paper discusses two such projects in British Columbia, Canada. Discussed are the project conception, technology selection, regulatory considerations, and initial operation of these plants. Two 4.5 MW Enpower Green Energy Generation Limited Partnership plants are operating adjacent to Spectra Energy Corporation's natural gas transmission compression facilities at 150 Mile House, BC and Savona, BC. These plants are powered by the gas turbine exhaust heat of previously installed 18.5 MW ISO rated pipeline compressor drives taking an original simple cycle LHV net efficiency from 36.5% to 45.2% at the design point of the Energy Recovery Generation system.

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Acronyms

ERG	Energy Recovery Generation
WHOH	Waste Heat Oil Heater
HRSG	Heat Recovery Steam Generator
ORC	Organic Rankine Cycle
BCSA	British Columbia Safety Authority
NEB	National Energy Board

1. Background

In 2002, Chinook Engineering Ltd. began working with Pristine Power Inc, an Independent Power Producer (IPP), to evaluate the feasibility of installing Energy Recovery Generation (ERG®) facilities at various existing gas compressor stations in British Columbia. After initial site and technology reviews, five stations were identified on Spectra Energy's natural gas transmission system where gas turbine powered compressors were forecast to have the runtime and loading necessary to make the projects economic.

Two of these stations were submitted to BC Hydro under their 2002 Call for Green Energy. Even though ERG facilities have the benefit of using existing waste heat sources to generate electricity without incremental emissions, these projects did not meet the strict guidelines of BC Hydro's 2002 Call for Green Energy and were initially rejected. In 2005, the BC government established new BC Clean Electricity Guidelines that include waste heat recovery from gas turbine engines.

In 2006, Pristine Power Inc partnered with EnMax Green Power Inc, a wholly owned subsidiary of EnMax Corp. to form EnPower Green Energy Generation Limited Partnership to develop these projects. Enpower worked closely with Spectra Energy to establish host agreements that would govern the development and execution of ERG projects on Spectra Energy's compressor stations. The Host Agreements allowed for long term leasing of project lands and operation of the ERG facilities by Spectra Energy's operations team. ERG facilities at five compressor stations were then submitted as BC Clean Electricity Projects under BC Hydro's 2006 Open Call for Power and power purchase agreements were awarded for two of the proposed sites. These two facilities were constructed and have been in commercial operation since Q4 2008.

1.1. Site Selection and Evaluation

Upon initial review of Spectra Energy's gas transmission system, five sites were identified as having engines potentially suitable for ERG facilities using a bottoming cycle. The selected sites all had simple cycle gas turbines with a long remaining useful life, high forecast runtimes based on projected pipeline gas throughputs, and were all located close to tie-in locations on BC Hydro's electrical grid. In short, these sites were identified because they were expected to produce the most power at the lowest capital cost.

The five sites originally considered were Spectra Energy's;

- Summit Lake Compressor Station (CS-4A),
- Hixon Compressor Station (CS-4B),
- Australian Compressor Station (CS-5),

- 150 Mile House Compressor Station (CS-6A), and
- Savona Compressor Station (CS-7).

Figure 1 shows the locations of the five proposed sites.

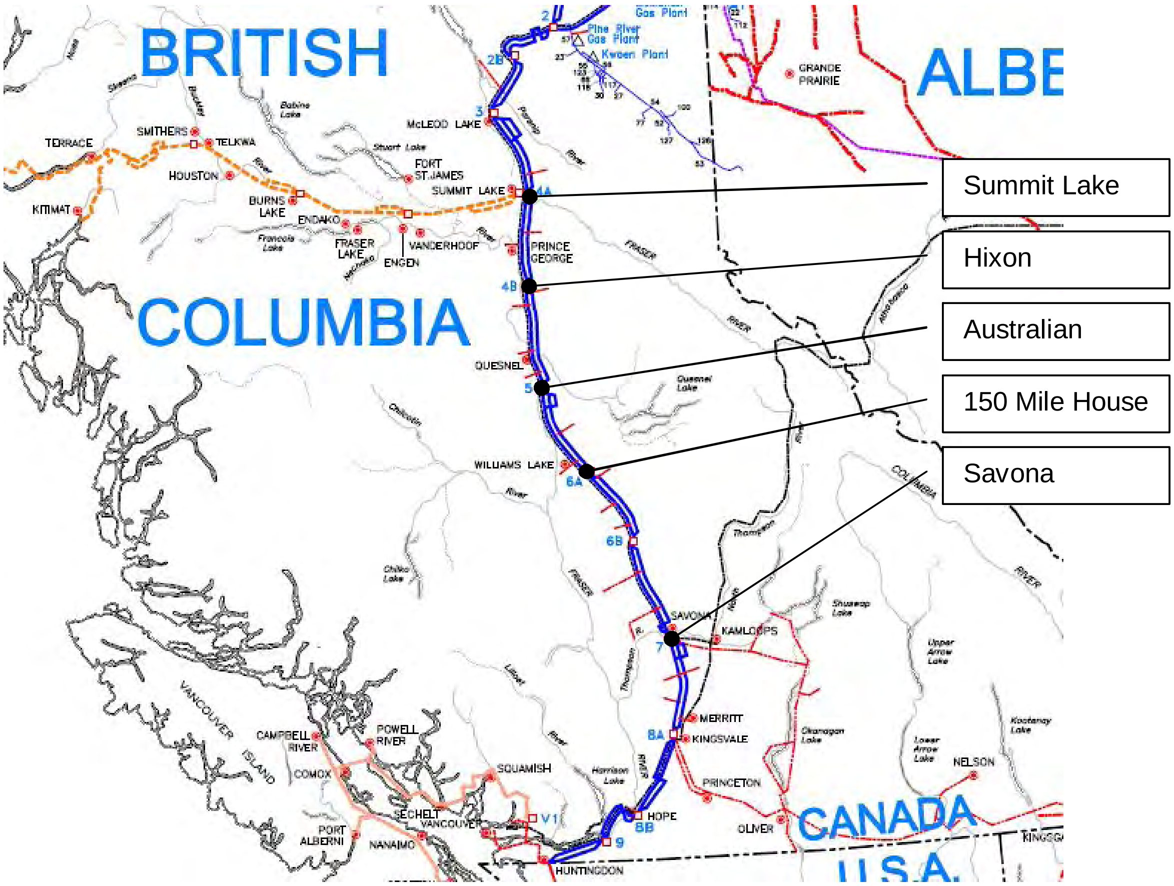

Figure 1 - Locations of Proposed Waste Heat Recovery Facilities

In the 2006 BC Hydro Call For Power, long term power purchase agreements were awarded for the facility at 150 Mile House (CS-6A) and at Savona (CS-7). These facilities had the most favourable economics due mainly to higher compressor utilization factors, lower grid interconnection costs and proximity to high demand markets for power.

1.2. Key Project Requirements

Although a number of viable technologies for Energy Recovery Generation were available, most of these technologies were not yet mature. In order to obtain favourable project financing terms for these projects it was imperative that the facility use only well proven technologies. This requirement played heavily into the technology selection process.

The ERG facilities had to be suitable for unmanned operation since the project economics would not support continuous supervision. As the Spectra Energy compressor stations are only manned for a limited number of hours per day and the ERG facilities are operated by the same staff as the Spectra facility, the operator manning requirements had to be comparable to Spectra's previous manning levels.

The ERG facilities also had to be designed and installed in a manner that had minimal impact on the availability of Spectra Energy's equipment. Spectra's foremost priority is to their shipper customers. It would be unacceptable for a third party power generation facility to interfere with Spectra Energy fulfilling their obligations to their customers. For this same reason, construction of the ERG facilities had to be performed in a manner that minimized disruptions to the existing Spectra Energy equipment.

The ERG facilities also had to have a high degree of operational flexibility to capture waste heat from an intermittent heat source. The host compressor stations run intermittently and do not always maintain steady or full loads.

1.3. Technologies Considered

At the onset of these projects, several technologies were considered for the ERG system. The three most promising technologies considered were the Steam Rankine Cycle, the Kalina Cycle and the Binary Organic Rankine Cycle (ORC). Each of these processes have their own benefits and drawbacks relating to their efficiencies, capital costs, proven reliability and regulated operator manning requirements.

<u>Steam Rankine Cycle</u>
The Steam Rankine Cycle is very commonly used in combined cycle plants as it has a high efficiency and is a proven technology with good reliability. The main drawback for this cycle is that it requires relatively high temperatures and pressures to achieve high system efficiencies and as a result, direct heating from the exhaust is required. Direct vaporization of water in a Heat Recovery Steam Generator (HRSG) has very significant implications on the regulated operator manning and certification requirements.

<u>Kalina Cycle</u>
The Kalina cycle is a newer process that uses an ammonia-water mixture as the working fluid. This process can offer higher efficiencies than the Steam Rankine cycle. The main drawback with this option is that it is a more complicated process with a limited track record in similar applications. The Kalina Cycle would also require direct vaporization of process fluid in a Heat Recovery Steam Generator (HRSG) which again

has significant implications on the regulated operator manning and certification requirements.

Binary Organic Rankine Cycle
The Organic Rankine Cycle (ORC) uses essentially the same process as the Steam Rankine Cycle, except that steam is replaced with an organic fluid with high molecular weight such as pentane. The main benefit of the ORC is that it maintains relatively high efficiencies at much lower temperatures and at lower operating pressures. As a result, it is not necessary to directly vaporize the working fluid in a HRSG. Rather, a Waste Heat Oil Heater (WHOH) is used to heat an intermediary thermal fluid system. The thermal fluid is then used as a heat source for the ORC. This thermal fluid system provides significant safety benefits and provides the means necessary for ERG facilities to be permitted for unmanned operation in many jurisdictions.

Over recent years there have been increasing numbers of binary ORC installations for heat recovery from gas turbine exhaust. The ORC has proven to be a mature technology ready for widespread application. The binary ORC has some unique characteristics that offer several benefits over the Steam Rankine Cycle. Specifically;

- The absence of water in the process reduces freeze-up risks in cold climates. The process fluids, pentane and thermal oil, do not freeze until extremely low temperature reducing the need for freeze protection in colder climates.
- Pentane has a dry fluid saturation curve so as it expands through the turbine, it becomes superheated. As there is no condensation or mixed flow in the turbine, potential erosion damage is reduced.
- No make-up or produced water in the facility makes for easier permitting.
- The binary ORC has greater potential to be approved for unmanned operation while requiring a lower level of operator certification.

1.4. Regulatory Considerations [1]

Within British Columbia, as in most provinces, systems involving fluid heaters or vaporizers typically fall under the jurisdiction of the provincial regulating authority. In this case the projects fell under the jurisdiction of the BC Safety Authority (BCSA) and had to abide by the requirements of the *BC Safety Standards Act*. By the direct application of the definitions and requirements in the *BC Safety Standards Act*, none of the technologies considered in Section 1.3 would be eligible for unmanned operation, hence they would require 24/7 supervision by a certified Power Engineer of the appropriate Class. As previously stated, facilities of this size can not support the financial burden of operators in continuous attendance.

[1] Italicized terms in this section are as per the definitions in the BC Safety Standards Act.

Both the Steam Rankine Cycle and the Kalina Cycle for a plant this size would be classified as *1st Class Power Plants* since the boilers are considered as a fired boilers with heating surface areas in excess of 1000m^2. The maximum heating surface area for *Power Plants* to be eligible for *General Supervision Status* and consequently for unmanned operation is 30m^2. These facilities would not be approved for unmanned operation in British Columbia.

The binary ORC system is comprised of two separate plants, the ORC system and the Thermal Fluid system, each system with its own plant classification. The ORC system is a *5th Class Unfired Plant* with a boiler heating surface area less than 500m^2 and the Thermal Fluid System is a *3rd Class Low Pressure Thermal Fluid Plant* with a boiler heating surface area in excess of 1500m^2. Although the ORC system meets the requirements of *General Supervision Status*, the Thermal Fluid system has too much surface area to meet the requirements set forth in the current regulations.

It is, however, recognized by the BCSA that the current safety regulations are written to quantify the size and address the safety issues of typical fired thermal fluid heaters. They do not appropriately address heat recovery systems. Through early negotiations and ongoing cooperation with the BCSA, an agreement was reached that classified these facilities as *General Supervision Status* and consequently approved for unmanned operation through use of an *Equivalent Standards Agreement*.

As the regulation of power plants typically falls under the jurisdiction of provincial regulatory authorities, there are some differences as to how these facilities are treated from province to province. Whereas Alberta has very similar regulations to British Columbia, the Saskatchewan Boilers Branch has previously treated these facilities as pressure vessel systems without specifically regulating the operator certification and manning requirements. In some situations the facilities may fall under the jurisdiction of the National Energy Board (NEB). Regardless of who the regulating authority is, it is essential that they are consulted early and thoroughly on any ERG project to ensure that operator manning and certification levels are clearly and fairly established.

1.5. Safety Reviews and Considerations

Although the ERG facilities can and have been approved for unmanned operation by various regulatory authorities, there are many steps and considerations to insuring these facilities are built and operated safely. These projects underwent a thorough safety review that included a comprehensive HAZOP and dispersion modelling of catastrophic pentane releases. The safety reviews identified critical system components and design features as well as updates to Spectra's Emergency Response Plan.

The diverter valve is critical to the safe operation of the ERG facility. The diverter must be extremely reliable as it is the equivalent of the fuel shut-off valve on a typical boiler.

If there are any problems with the ERG facility, the diverter must be able to quickly and reliably divert the exhaust gas to the bypass stack to remove the heat source without interrupting the gas turbine operation.

The process and safety reviews addressed equipment, controls, shutdowns and also the policies that govern operations. Procedures and policies were developed to ensure that the facilities always receive the appropriate level of monitoring and that unexpected events are swiftly responded to during both manned and unmanned operation.

The operators have undergone extensive training by the equipment designers and process fluid suppliers and have gone through BC Safety Authority's certification process for Power Engineers. The operators are well trained in the operation of the facilities and can anticipate most problems before a shutdown is necessary.

2. System Description

The ERG facilities are configured around existing simple cycle 18.5 MW ISO General Electric PGT25 gas turbine engines driving gas compressors and are each designed to produce a minimum of 4.5 MW net electrical power at design conditions. The power rating of these engines is based on a de-rated model of the General Electric LM2500 gas generator.
Figure 2 shows a simplified Process Flow Diagram of the 150 Mile House ERG facility including design point temperatures and pressures.

At 150 Mile House, the turbine exhaust passes through a diverter that directs it to the Bypass Stack or to the Waste Heat Oil Heater (WHOH) to produce high temperature thermal oil. The thermal oil system delivers all useful heat from the turbine exhaust to the Organic Rankine Cycle (ORC) where the electricity is generated.

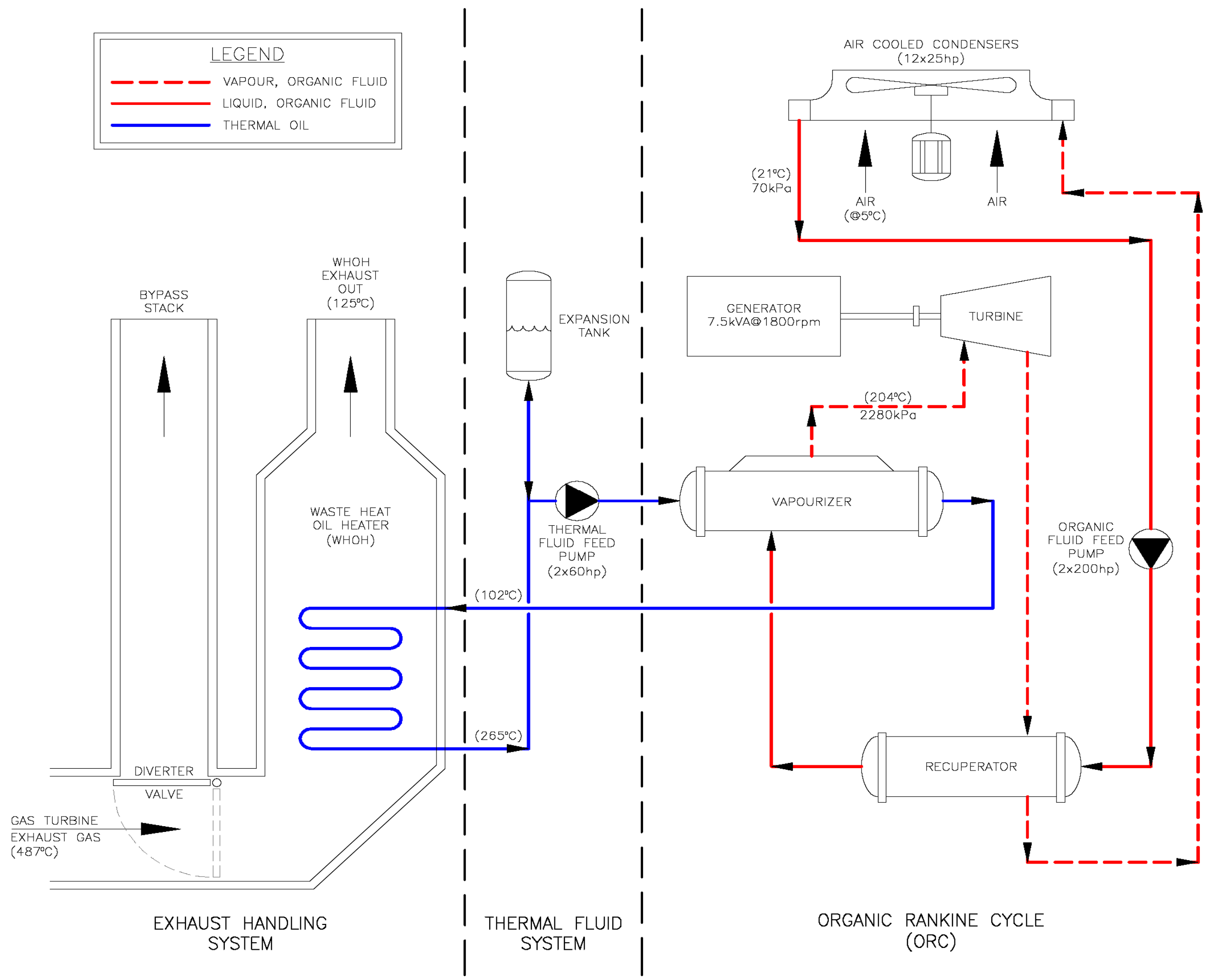

Figure 2 - Waste Heat Recovery Simplified Process Flow Diagram

The Savona facility is virtually identical, except that the exhausts from two PGT25 engines are ducted to share a common WHOH. The ERG facility is designed for one turbine running at 100% load, but may take exhaust from both turbines if they are running at reduced loads. The Savona thermal oil system and ORC are virtually identical to the 150 Mile House system.

2.1. Exhaust Handling System

The exhaust handling system diverts the hot exhaust gasses to either the bypass stack or the Waste Heat Oil Heater (WHOH). The exhaust handling system consists of insulated ducting, diverter valves, bypass stacks and instrumentation. The diverter valves direct the exhaust gas to the bypass stacks whenever the generating facilities are not on-line and to the Waste Heat Oil Heater when the generating facilities are online. On loss of power, instrument signal or instrument air, the diverter will move to its failsafe position which is open to the Bypass Stack. In this manner, Spectra Energy's turbine compressors can run unaffected by the generating facilities.

The PGT25 engines are configured with the exhaust leaving the side of the compressor building and with the exhaust silencer located horizontally within the building. Installation of the diverter was relatively straight forward at these sites as the exhaust stack and its foundation could be re-used and the exhaust silencer left undisturbed. Photos of the 150 Mile House bypass stack and diverter are shown in Figure 3.

Original Exhaust Stack | *New Diverter and WHOH* | *Diverter Pneumatic Components*

Figure 3 - Photographs of the 150 Mile House Diverter Installation

The Savona Exhaust Handling System is more complicated as it is configured to accept exhaust from either of two gas turbines. Each turbine has its own diverter and bypass stack identical to the 150 Mile House design, followed by ducting to a shared WHOH. There are also guillotine dampers on each duct leg to provide secondary isolation for turbine maintenance. The photo in Figure 4 shows the Savona Exhaust Handling System.

Figure 4 - Photograph of the Savona Exhaust Handling System

The exhaust system was carefully sized in order to minimize the incremental backpressure on the PGT25 engines. Any increase in the gas turbine backpressure has a detrimental effect on the turbine heat rate.

The exhaust backpressure on each turbine was measured before and after the exhaust system modifications. Trend lines for these measurements are shown in Figure 5. There is no measurable increase in backpressure when flowing through the Bypass Stack. For typical site operating conditions (at approximately 80% gas turbine load), an average increase in engine backpressure of 76mm H_2O (750 Pa) is apparent, and consequently a 0.4% increase in the turbine heat rate is realized. Due to the configuration of the de-rated PGT25 gas turbine engine, there is no reduction in engine power available to Spectra's compressor drive.

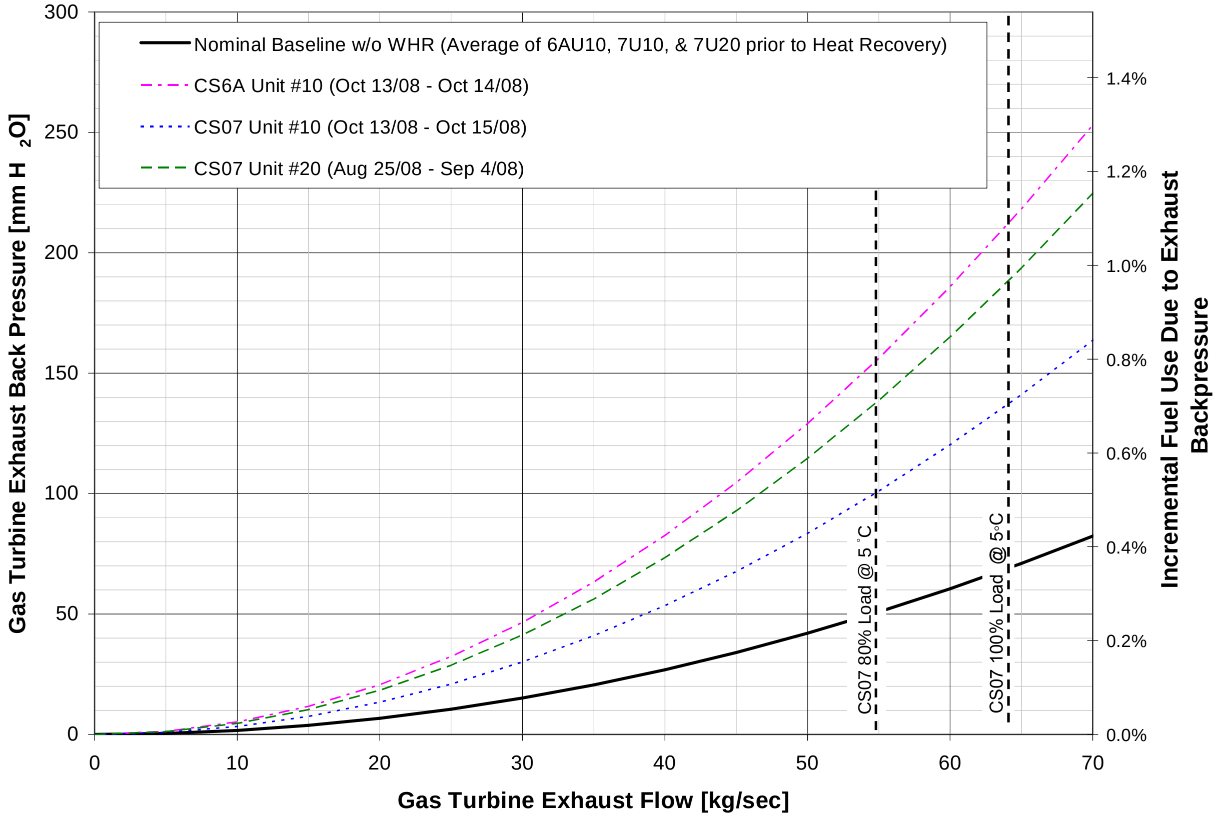

Figure 5 - GT Exhaust Backpressure Measurements Graph

2.2. Thermal Fluid System

The thermal fluid system captures the heat from the exhaust gases in the Waste Heat Oil Heater (WHOH) and transfers it to the Organic Rankin Cycle at 265˚C where it is used to vaporize the ORC working fluid. The thermal fluid returns from the ORC cooled to 102˚C. It is a simple system comprised primarily of the WHOH, pumps, control valves and expansion tank.

To qualify for unmanned operation, the thermal fluid system was required to be designed as a *Low Pressure Thermal Fluid Plant* as defined by the *BC Safety Standards Act.* As such the WHOH is fully vented to atmosphere to prevent the possibility of the system being over-pressured. Consequently, the fluid is pumped on the high temperature side of the system. Thorough diligence was required to ensure that all reliability and safety issues were fully addressed in this demanding application. The 150 Mile House diverter, WHOH, thermal fluid pumps, expansion tank and overflow tank can be seen in Figure 6.

Figure 6 – Photograph of the 150 Mile House Thermal Fluid System

2.3. Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is very similar to the Steam Rankine Cycle except steam is substituted with a high molecular weight organic fluid, in this case pentane. The pentane is pressurized by feed pumps into the preheater and vaporizer where the heat from the thermal oil vaporizes and slightly superheats it. The pentane vapour is expanded through a dry, multi-stage, axial flow, impulse style turbine that is directly coupled to the generator. Since the pentane is still superheated at the turbine outlet, it flows through a recuperator prior to being re-condensed in aerial coolers.

The ORC system used in these projects is a pre-engineered package supplied by Ormat Technologies. The ORC system was designed with a guaranteed electrical capacity of 4.5 MW net when operated at 5°C ambient temperature and at the gas turbine's rated power output. This improves the overall LHV net efficiency from 36.5% to 45.2% for the combined cycle system at this design point. However, the ORC performance is very sensitive to ambient temperature and to gas turbine loading. On colder days the ORC will exceed its rated output whereas on hotter days or when the gas turbine is running at reduced loads, the ORC output will drop significantly. It is important to thoroughly review the historical and forecast seasonal gas turbine usage when developing ERG power generation forecasts.

Figure 7 - Photograph of the Savona ORC System

2.4. Monitoring and Operation

The ERG Facilities each have a dedicated control system independent from the host compressor stations. The PLC's, control terminals, and Motor Control Centres are all located in dedicated control buildings next to the ORC systems. Additional control terminals are also located in the host compressor stations' main control rooms to simplify daily monitoring and control operations. The existing Spectra Energy Station Operators are trained and responsible for all aspects of the daily operation and minor maintenance activities associated with the ERG Facilities.

Certain process parameters are tied into to Spectra's SCADA system so that the ERG Facility may be monitored remotely by Spectra's Gas Control Group while the facility is operating unattended. Only critical information, including overall status and critical alarms, are transmitted through the SCADA system such that if an alarm is sounded, an automatic callout to the on-call Station Operator is made. If the Station Operator is unable to respond to the alarm, the Gas Control Operator can safely shutdown the ERG Facility remotely.

3. Construction and Start-up

The total construction duration for both sites was approximately 6 months with the Savona construction schedule leading the 150 Mile House construction schedule by approximately one and a half months. This staggered approach allowed the contractor to save time and costs by using the same crew to repeat the same tasks at each site. All tie-ins were performed during planned compressor outages and required no more than 4 days outage per diverter. Other than the tie-ins, construction was performed with minimal impact on site operations.

Since the facilities have been in operation, there have been two issues that have resulted in downtime:

1. A leak developed within the preheater at the Savona facility. As a result, pentane began leaking into the thermal oil system and venting through the expansion tank and overflow tank. The Savona ERG facility was shutdown for several weeks to isolate, identify and repair the leaking heat exchanger. The leak was found to be the result of faulty tube-tubesheet connection. Once repairs were made, the ERG facility was put back in operation. This outage did not in any way affect the operations of the compressor station. Further inspections are scheduled to occur in Q3 2009, to ensure all other heat exchangers are leak free.

2. Through the first winter of operation freezing occurred in the ORC system. Although the process is designed to be water free, some residual water was found in the system from piping and heat exchanger hydrotests. The residual water resulted in the generation of ice and rust scale and resulted in the failure of several feed pump seals. A separator was installed on the ORC system to remove the residual water. No further related problems have been encountered since the installation of the water separator.

Since these issues were addressed in February 2009, both ERG facilities have achieved nearly 100% availability and have been subject only to the utilization levels of the host compressors.

4. Conclusions

The Energy Recovery Generation facilities at Spectra Energy's Savona and 150 Mile House compressor stations have demonstrated a very practical way to showcase environmental stewardship and capitalize on existing assets. These two facilities generate enough electricity to power 7,000 homes and offset over 25,000 tons of CO2 annually.

While historically, steam turbines have most commonly been used for bottoming cycles in combine cycle plants, these projects used a binary process with an Organic Rankine Cycle. Advantages of the binary ORC process include; It can be designed and approved for reduced manning requirements, it can reduce the potential of cold climate freeze-up and it can improve system reliability by eliminating condensation in the turbine. The main downfall of the binary ORC process is its lower thermal efficiency of 18-22% versus the 30-34% that can be achieved with a steam system. Binary ORC systems are most suited for smaller facilities where the efficiency benefits of steam are insufficient to offset its high operating costs.

New ERG projects should also explore the possibility of utilizing the heat rejected by the ORC system. Even after the bottoming cycle, over 50% of the fuel energy is rejected to atmosphere through the air cooled condensers. If this energy can be used by a process that takes advantage of low grade heat, such as district heating, the overall system efficiency could be increased to over 75%. As air cooled condensers would no longer be required, the system de-rating at high ambient temperatures might also be reduced.

These projects have shown that waste heat recovery can be economic on small scales as well as large when undertaken with long term power purchase agreements and appropriate financing. Managing the regulatory, environmental, technological and business aspects of heat recovery power generation projects can sometimes be outside of the core expertise of compressor station and pipeline owner-operators. Partnerships with third party independent power producers provide a means to share operating costs and provide a waste heat fee revenue stream. Such partnerships also bring the necessary expertise to the table to ensure project success.