Development of a Low NOx Burner for Combined Cycle Gas Turbine/Once-Through Steam Generator System

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Abstract

New Low NOx gaseous fuel burner designed to operate in co-generation systems for OTSG applications will be presented. Technology and process description, modes of operation, control strategy development, mechanical design features, comparison of greenhouse gas (GHG) production to other technology options, and key operating benefits will be discussed. Computational fluid dynamics (CFD) analysis will be presented comparing modes of operation including vessel heat flux profiles and flame shape. Data results from large scale combustion tests will be presented.
Introduction

At present, the most prevalent and effective method of bitumen crude oil collection in the province of Alberta, Canada uses Steam Assisted Gravity Drainage (SAGD) technology. In this process high pressure steam is injected into underground wells to mobilize highly viscous heavy bitumen crude located in oil sand deposits. Continuous steam injection is required to maintain well production. Intermittent steam supply, even temporary, have significant impact on production as the wells can rapidly cool and considerable time is required to bring well production back to capacity once steam is reintroduced.

Up to 90% of water used in the SAGD process is recycled. After well production, the condensed steam is separated from the bitumen and treated to remove dissolved solids and residual hydrocarbons. Treatment processes can be extensive but typically significant concentrations of impurities remain in the water. This recycled water is combined with fresh water as feedwater to the boiler. A specialized boiler design is required to avoid tube fouling due to the dissolved solid content [1]. The most common design is a horizontally fired once-through steam generator (OTSG). With this design, boiler tubes are arranged parallel to the furnace cavity and contain a single pass. This arrangement allows access to boiler tubes for periodic cleaning. Typical fuels fired in these boilers are natural gas and "produced" gas, which is a methane-rich hydrocarbon gas collected from the well. The standard OTSG boiler arrangement uses a large single burner typically in excess of 300 million Btu per hour (300 MMBH, LHV) [88 MW]. Further details on the SAGD process can be found on the Government of Alberta webpage [2].

Most SAGD plants have grid-based electrical power supply. Due to geographical isolation and cold weather, power outages are not uncommon. Additionally, the energy market is variable-rate. Energy prices during peak demand can increase in excess of ten (10) fold compared to normal rates [3]. Due to this, there is a strong interest in many SAGD facilities to produce power on-site.

Co-generation is a common, effective, and economic method of electrical power and steam generation. In the most common arrangement, a gas turbine (GT) is paired with a heat recovery steam generator (HRSG). The GT combusts natural gas with air and drives an electrical generator to produce electrical power. The exhaust from the turbine, known as turbine exhaust gas (TEG), has considerable residual oxygen and sensible heat. TEG is ducted to the HRSG to recover the sensible heat as steam. Increased steam production is typically achieved by auxiliary firing natural gas directly into the TEG stream with duct burners.
Alternative Technology Analysis

The GT/HRSG model has several drawbacks when applied to SAGD facilities. As a potential step to improve operational deficiencies and overall system efficiency, a new co-generation system that combined a gas turbine system paired directly with an OTSG was considered.

GT/HRSG co-generation systems produce a high electrical power to thermal (steam) ratio. SAGD facilities, however, require high thermal (steam) production but relatively low power production requirements. If a GT/HRSG system is sized to meet energy demand, the system would produce insufficient steam. Conversely, if the system is sized to meet steam demand, excess electrical energy is produced that must be exported. Figure 2 (GT/HRSG system) and Figure 3 (GT/OTSG system) provide a comparison of the typical operating range between co-generation methods, with relative units of steam production and fuel gas consumption. Both cases generate equivalent electrical power.

When no auxiliary fuel is fired (GT only), steam is produced through sensible heat recovery of the TEG. As Figure 2 depicts, when auxiliary fuel is fired through duct burners, oxygen is depleted and increased steam production is achievable. For most large GT/HRSG systems, auxiliary firing is limited to a stack O2 of 10% O2 (dry). The duct walls of large GT/HRSG systems are lined with insulation, and auxiliary firing is limited due to overheating concerns of insulating liner materials.
Since OTSG boilers contain heat transfer surfaces (boiler tubes) in the radiant combustion section, the oxygen content can be depleted much further. As Figure 3 depicts, an OTSG burner can fire gas fuel to deplete the oxygen to 3% (dry). To continue to generate additional steam flow and fire more gas fuel without further depleting the oxygen, auxiliary air can be added with a forced draft blower. With auxiliary air, a GT/OTSG system can generate more than two and a half times as much steam production compared to a GT/HRSG system with equivalent electrical energy production.

By controlling auxiliary air, a stack O₂ of 3% (dry) is achievable over a design operating range. Additionally, as the oxygen contribution of TEG changes with GT load and ambient temperature, auxiliary air can be adjusted to maintain stack O₂.

Operation at high exhaust stack O₂ levels results in lost efficiency. Compared to GT/HRSG technology, increased thermal efficiency and corresponding reduction in greenhouse gases (carbon dioxide production) is achievable using alternative GT/OTSG technology. Table 1 shows calculated thermal efficiencies for typical GT/HRSG systems compared to the efficiency of a GT/OTSG system. A typical large-scale GT/HRSG system operates with an exit O₂ of 13% (dry, by volume) when un-fired, and 10% O₂ when auxiliary fired. If a GT/OTSG system could operate near the 3% nominal exhaust O₂ level of a fresh-air fired OTSG system, significant efficiency gain can be realized.
Table 1 – Thermal Efficiency Comparison of Typical GT/HRSG System to GT/OTSG System

<table>
<thead>
<tr>
<th>System</th>
<th>Exhaust O₂% (dry, vol)</th>
<th>% Thermal Efficiency, LHV*</th>
<th>%, Net Fuel/CO₂ Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT/HRSG Unfired</td>
<td>13</td>
<td>84.9</td>
<td>0</td>
</tr>
<tr>
<td>GT/HRSG Auxiliary Fired</td>
<td>10</td>
<td>88.6</td>
<td>4.18</td>
</tr>
<tr>
<td>GT/OTSG</td>
<td>3</td>
<td>92.4</td>
<td>8.12</td>
</tr>
</tbody>
</table>

* Assumes 350°F [180°C] stack temperature and no skin losses

Another issue is the adaptability of new GT/HRSG systems to existing SAGD facilities. Existing SAGD facilities have an installed base of OTSG equipment, and there are strong economic incentives to reuse this equipment rather than buying new GT/HRSG systems.

Finally, a drawback is the lack of redundancy inherent to a centralized GT/HRSG system. With such a system, a trip of a GT results in loss of both power production and steam production throughout the facility. As SAGD facilities prioritize steam production, the impact of such a failure on operations is significant.

For these reasons, the new GT/OTSG system was desired. This GT/OTSG system could provide a higher and more favorable thermal to electrical power generation ratio by adding auxiliary air to the TEG to allow for higher OTSG firing rates and more steam production. Design features could be included that allowed for continuous steam production following loss of a GT or during GT outages by using ambient fresh air.

**Procedure**

John Zink Hamworthy Combustion (JZHC) partnered with a major energy producer in Alberta for this development effort. The effort consisted of development of suitable burner technology and associated combustion controls. Based on market needs, primary development goals were established for the burner technology. These were:

- Burner operation with 100% ambient air (Fresh Air Mode)
- Burner operation with a combination of TEG and ambient air (TEG mode) at similar exit velocities and pressure drops compared to fresh air mode
- Design of combustion control logic and system components allowing for online transition between TEG and fresh air modes
- Design of fully metered control system that provides low OTSG stack O₂ levels with variable TEG (temperature, O₂ concentration, and mass flow) supply.
- Design system to provide continuous steam production following trip of GT.
- Meet NOx emissions targets of 26 g/GJ [4, 5].
- Generate favorable radiant section heat flux profiles.

The initial engineering assessment included analysis and selection of suitable burner technology. John Zink Hamworthy Combustion (JZHC) burner technology has been used on approximately two hundred (200) OTSG applications in Alberta. The majority of these applications use JZHC QLN™ burner technology. This technology uses multi-stage fuel injection with simulated pre-mix and staged combustion zones to produce low NOx emissions. The burner is designed to produce a uniform furnace heat flux profile, which is required by OTSG manufacturers to avoid tube fouling. As this technology has been very successful operating in OTSG applications and in meeting the performance requirements of
Alberta, this technology was used as the basis for GT/OTSG development and benchmark for combustion performance.

![Figure 4 - OTSG Furnace Firing End with QLN™ Burner Installed](image)

The development project was executed in three (3) phases as follows:

**Phase 1:** 31 million Btu per hour (LHV) [9.1 MW] Test Burner development at JZHC test facility. This served as a proof of concept prototype system to demonstrate TEG and fresh air firing capabilities.

**Phase 2:** 50 million Btu per hour (LHV) [14.7 MW] Pilot Burner as a small scale beta demonstration in an OTSG at the energy producer’s facility in Alberta.

**Phase 3:** 274 million Btu per hour (LHV) [80.3 MW] full scale burner for demonstration in a full size OTSG at the energy producer’s facility in Alberta.

**Burner Design Features**

Development of burner technology flexible enough to operate with both fresh air and a blend of TEG and air presented significant design challenges.

**Volumetric Flow Considerations**

Typical TEG has a volumetric oxygen concentration of 13% by volume or lower (balance is mix of mostly Nitrogen, Carbon Dioxide, and Water) with a temperature of approximately 1000°F [540°C]. This is compared to 21% volumetric oxygen concentration in ambient air. To supply an equivalent mass flow of oxygen, the volumetric flow rate of TEG is roughly twice that of ambient air.

Burner exit velocity is an important design criterion for OTSG applications. With low exit velocity, fuel and air can mix poorly causing a buoyant flame, non-uniform heat flux, and excessive CO emissions [6]. However, excessively high exit velocity results in high burner pressure drop which limits the power output of the gas turbine and causes efficiency loss. Consequently, the burner design had to operate both with ambient air or a blend of TEG and ambient air. As such, the burner equipment included mechanical devices designed to provide variable burner geometry.
In Figure 5, a picture of the burner is shown. Staged ports were designed to provide an additional injection path of TEG. An internal isolation damper actuates to isolate the staged ports during fresh air operation.

**High Temperature Design Considerations**

Another consideration was the mechanical design of the burner itself. Reliable operation was required with high temperature TEG and ambient air. Typical metallurgy selections used for burner components needed to be upgraded. Due to the high temperature differential between operating modes, significant thermal expansion of metal surfaces and structures must be considered. Design techniques such as slip connections and expansion joints were employed to address these issues.
CFD Modeling
Computational Fluid Dynamics (CFD) analysis was used to provide predictions of performance metrics and to evaluate key aerodynamic design features. A model of the improved QLN™ burner and OTSG furnace were generated in order to evaluate, predict, and optimize the mixing of air with TEG, staged TEG port design, fuel distribution between the three burner fuel zones, the furnace heat flux for both TEG and Fresh-Air firing cases, CO emissions, flame shape, and temperature profiles inside the furnace. In the CFD model, the furnace shell was modeled as a constant temperature wall in order to simulate the water-cooled heat transfer surfaces of the radiant furnace. The furnace front wall, rear wall, and all refractory portions of the burner were designated as adiabatic, allowing no heat transfer. Figure 6 depicts the geometry of the burner used for one of the simulations.

![Figure 6 – CFD View of Modified QLN™ Burner Face](image)

ANSYS/FLUENT CFD software was used for the simulation. For each of the computational cells, the code simultaneously solved the governing fluid dynamic equations of mass continuity, momentum (Navier-Stokes equations), and turbulent quantities to obtain a steady-state solution. Velocity and pressure coupling was resolved via the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm. Turbulence closure was obtained using the realizable k-Epsilon turbulence model. The turbulent boundary layer conditions for the momentum in the near-wall region follow the logarithmic law of the wall. Chemical reactions were modeled using a hybrid Finite Rate/Eddy Dissipation model with proprietary reaction kinetics. The radiation model used is the discrete ordinates model, and furnace gases absorption coefficient was calculated using the weighted sum of gray gases model. [7, 8]
Scaling
The three phases of the project included burners designed for 31 MMBH [9.1 MW], 50 MMBH [14.7 MW], and 274 MMBH [80.3 MW]. A combination of proprietary analytical algorithms and CFD analysis were used to determine scaling factors for the burner designs needed for each phase of the project. Final design considerations included exit velocity and combustion residence time [9].

The standard Alberta OTSG application uses very large burners which approach the largest size range of single industrial burners. With the increased volumetric flow and temperature of TEG, burner air plenums had to further increase in size. Increased structural analysis was required to evaluate static and dynamic forces on such large components. Finite element analysis (FEA) was used to finalize mechanical design features.

Control System Design Features

TEG Mode Metering System
Most industrial burner/boiler systems - including OTSG applications - use a “fully metered” control system. The primary components of this system are flow measurement and flow control devices that measure and control both fuel and air. Through a logic step known as cross-limiting the flow signals are compared and adjusted to maintain fuel to air ratio within a defined operating window.

Additional control system complexity was required with combined operation of TEG and auxiliary air. First, this mode delivers two sources of oxygen to the OTSG. Second, the GT exhaust flow rate and O₂ concentration is dependent on the operating load of the GT as well as ambient air conditions. This results in significant variation in mass flow of oxygen in the TEG. To provide a control system that operates with low OSTG exhaust stack O₂, propriety control logic was developed. This system meters the mass flow of oxygen in the TEG. The fast acting signal is compared with the measured fresh air supplied by the combustion air fan to provide total airflow signal. To maintain the total required airflow needed for combustion, fresh air flow is adjusted through control devices on the combustion air fan.

Unique Combustion Control Logic
A unique design challenge faced was addressing the transition from fresh air firing operation to TEG firing operation. The most simplistic control logic for transition between fresh-air and TEG mode would require shutdown and restart of the OTSG. However, this method would be deficient in that the loss of steam due to the OTSG restart could significantly impact well production.

A control system was developed to provide operator initiated online transfer. After transfer is initiated, a control sequence executes. In this sequence, control devices move in concert so that the TEG flow is diverted from the OTSG to a vent stack, while total airflow to the OTSG is maintained within design operating range. The sequence involves actuation of TEG control dampers, fresh air control dampers, fuel gas flow control valves, and the internal burner isolation damper. During transition, the fuel firing rate is held constant. Once the sequence completes the system returns to automatic operation.

Another challenge faced was the loss (trip) of the gas turbine (GT). For a standard GT/HRSG system loss of a GT would cause a full system trip. Control logic was developed for the GT/OTSG system to quickly transition the OTSG to fresh-air firing mode following a GT fault without losing steam production. After a Gas Turbine fault, the TEG flow rapidly diminished as the turbine slowed. To safely transition while firing, a rapid response of the control system and control devices was critical.

To meet this requirement, logic monitored the “Run” contact of the GT. After a fault, the control system executed a system transition using a similar sequence as developed for transition logic. Control devices
actuated so that the OTSG airflow was continuously maintained within design range. Following this sequence, the burner system returned to automatic operation in fresh-air mode.

Results and Discussion

The following is the current project status for the three phases of development for the GT/OTSG project.

1. Test Burner – 31 MMBH (9.1 MW): Designed, built, and tested at John Zink Hamworthy Combustion Test Center in Tulsa, OK.
3. Full Scale Burner – 274 MMBH (80.3 MW): Designed, built, yet to be commissioned.

Phase 1 – Test Burner

The intent of this phase was to validate the mechanical design features and combustion reliability as well as determine combustion emission performance of the modified burner technology. This testing established the viability of the technology to meet all original process design goals that were not related to the control system or automation.

Three (3) TEG cases where established as best representing TEG variation of a standard GT as shown in Table 2.

<table>
<thead>
<tr>
<th>Table 2 – TEG Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case</strong></td>
</tr>
<tr>
<td>Description/Basis:</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>%O₂, volume wet</td>
</tr>
</tbody>
</table>

CFD Analysis Results

Prior to field tests, combustion performance was modeled with CFD. This kinetic CFD model predicted flame shape, heat flux, and species profile of the unit. Simulation cases were performed for the baseline fresh-air case as well as a TEG case (Case A). The full results of this CFD analysis can be found in Appendix A. Key performance criteria for each mode are depicted by 2D horizontal profiles.

To summarize the results qualitatively: the velocity, jet penetration, temperature profiles, and exit O₂ concentrations were nearly identical between operating modes. Flame length, as visualized by a 5000 ppm CO iso-surface, was predicted to be shorter with TEG firing mode compared to fresh-air firing mode. Heat flux profiles were similar, showing slightly more favorable heat flux intensity for the TEG firing mode.
Combustion Testing
Phase 1 testing occurred at the John Zink Hamworthy Combustion (JZHC) test center in Tulsa, Oklahoma. A thermal oxidizer coupled with an exit heat exchanger was used to simulate the TEG for the TEG firing cases. The goal of phase 1 testing was to validate mechanical design features and combustion reliability with fixed TEG modes. All TEG Cases were successfully tested on a modified burner assembly. Figure 7 shows the final installed test burner assembly.
**Stack Exhaust O<sub>2</sub> Operation**

Using the thermal oxidizer system, the mass flow, O<sub>2</sub> concentration, and temperature of the simulated TEG was set for each TEG firing case. Fresh-air was adjusted to maintain 3% stack O<sub>2</sub> at higher firing rates and set to a minimum flow rate at lower rates.

Figure 8 depicts stack O<sub>2</sub> measured for each of the firing cases. Since the mass flow of TEG was set to a fixed value in the design specifications, low O<sub>2</sub> operation is only possible when the TEG oxygen mass flow is equal or less to the stoichiometric oxygen requirement based on fuel flow. This limits low stack O<sub>2</sub> operation to higher firing rates, and causes rapidly increasing O<sub>2</sub> levels at lower firing rates.

Though 3% O<sub>2</sub> was set as a target set point, exhaust O<sub>2</sub> values down to 1.0% were achieved with low CO emissions.

The design firing rate of the combustion tests was 31 MMBH (LHV) [9.1 MW]. For some TEG cases, fired tests were conducted in excess of 35 MMBH (LHV) [10.3 MW] for expanded data collection.

*Figure 8—Stack O<sub>2</sub> Operating Curve*
Combustion Reliability
For each TEG test case, the ratio of TEG to fresh-air was varied while holding 3\% stack O\textsubscript{2}. Figure 9 shows the tested range of TEG/air split for each TEG case. No deleterious effects on combustion reliability were observed during burner tests. Exhaust CO emissions were less than 10ppm for all cases. This testing provided high confidence for full-scale combustion operation with normal GT operating variance.

![Figure 9 - Mass Fraction of TEG with 3\% Stack O\textsubscript{2}](image_url)
**NOx Performance**

Figure 10 shows NOx emissions measured for each of the firing modes. Testing data showed a significant NOx reduction in burner-generated NOx with TEG firing modes compared to fresh-air firing operation. The relatively low NOx emissions observed with the TEG firing modes was significantly less than the burner NOx emission target of 26 g/GJ. This reduction was expected, and was attributed to a reduction in peak flame temperature. The majority of burner generated NOx was believed to be thermal NOx caused by the dissociation of diatomic nitrogen in air. Thermal NOx formation is highly dependent on peak flame temperature. Since TEG contains a significant concentration of inert species such as N₂, CO₂, and H₂O, the peak flame temperatures for the TEG fired modes were reduced compared to fresh-air firing performance.

*Figure 10 – Relative NOx Emissions at 3% O₂ (Corrected for TEG NOx)*
Burner Pressure Drop

Figure 11 shows the burner air side pressure drop for each of the firing cases. As discussed, firing cases with TEG contain significantly more volumetric flow compared to fresh air due to the high TEG temperature and high fraction of inert species. As described previously, to accommodate this flow deviation the combination of TEG ports and an internal isolation damper were used to create variable exit geometry. As the data graph below demonstrates, operation with similar and quite reasonable burner pressure drop was achieved for all firing modes.

Figure 11 - Burner Pressure Drop

**Figure 11 - Burner Pressure Drop**

- **TEG Case A**
- **TEG Case B**
- **TEG Case C**
- **Fresh Air**

Heat Input, (3% O$_2$) MMBH (LHV) 
[MW = MMBH x 0.293]

Burner Pressure Drop, “w.c.”
[Pa = w.c. x 248]
Furnace Heat Flux
For OTSG applications, high heat flux can negatively impact tube life through increased fouling from poor feedwater quality. An important performance metric of the burner assembly in TEG mode was ensuring peak heat flux did not exceed fresh-air mode, and maintaining an overall uniform heat flux profile.

Heat flux was measured through a probe placed at points across the furnace width at varying firing depths. Figure 12 depicts heat flux intensity measured along the length of the furnace for each of the firing modes. As the data demonstrates, heat flux profiles were uniform in both modes, and absolute values of heat flux were consistently lower for TEG mode compared to Fresh Air mode.

Comparing this data to the CFD results:

<table>
<thead>
<tr>
<th>Case</th>
<th>TEG Case A</th>
<th>Fresh Air</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Btu/ft²-hr</td>
<td>MW/m²</td>
</tr>
<tr>
<td>Peak Heat Flux, Test Data</td>
<td>29,240</td>
<td>92.2</td>
</tr>
<tr>
<td>Peak Heat Flux, CFD</td>
<td>32,416</td>
<td>102.3</td>
</tr>
</tbody>
</table>

CFD prediction results and testing data show radiant heat flux does not significantly increase for TEG mode compared to Fresh Air operation. Note the CFD predicted peak heat flux for Fresh Air mode is closer to test data compared to the TEG prediction. This was expected as the operating characteristics and tuning adjustments for this burner technology in fresh-air mode was well known. For TEG mode, approximations were present in the CFD calculation method and final tuning adjustments differed from CFD predictions. Burner tuning factors such as fuel split and exit velocity have a large impact on heat flux.
Phase 2 – Pilot Plant

A modified QLN™ burner was designed for a heat input of 50 MMBH (LHV) [14.7 MW] operating in a pilot plant of the partner energy producer. This burner design tested full online operation with a small gas turbine. The goal of Phase 2 testing was to validate the control system technology for continuous operation with a commercially available GT operating with site conditions and normal GT load variation. Equipment was installed and successfully commissioned. Figure 13 shows the installation at the partner’s facility.

![Phase 2 installed burner assembly](image)

Burner performance tests were representative of the Phase 1 testing. Figures 14 and 15 show the results from the tests. Burner contributed NOx was significantly less compared to fresh air mode. Due to OTSG feedwater flow limitations, the operating firing rate was limited to 40 MMBH (LHV) [11.7 MW].

During final unit commissioning, logic tests were performed to confirm control logic met design goals. The GT was rapidly ramped to test the fully metered system control logic. During the test, the OTSG exit $O_2$ varied less than 1% in both TEG and Fresh-Air modes. This showed the system could operate on a continuous basis during normal GT operation at design excess air levels.
Figure 14 - Phase 2 Commissioned Stack O$_2$ Data

Figure 15 - Phase 2 Commissioned NOx Data
Transition logic switching between TEG and Fresh air modes was tested. This was both by manual operator initiation, as well as an automatic transfer through forcing a GT trip. Transition logic successfully transferred operating modes while keeping the OTSG system online.

The unit ran continuously and reliably for nearly a year of operation during the test period. During continuous operation, the unit maintained NOx emissions well below the 26 g/GJ permit level. Stack O₂ remained at design levels with only trace CO emissions.

GT faults occurred on average of once to twice a month during the testing period. During early operation, system logic did not successfully recover on all faults; however, following further investigation it was determined this was due to incorrect commissioning setpoints rather than failure of the control algorithm. After tuning parameters were adjusted, the system recovered to fresh-air mode on all GT system faults.

Phase 3 – Full Scale

The full scale 274 MMBH [80.3 MW] unit was fabricated and delivered to the partner energy producer. Figure 16 shows the full scale after fabrication was completed. Due to market conditions and energy prices, the energy partner has not yet scheduled the unit for commissioning.
Conclusions

Burner and control system technology was successfully developed to meet a co-generation market demand of Alberta based energy producers. The new system allows onsite electrical energy production while maintaining the installed base of OTSG boiler equipment. Successful fired tests at the JZHC test facility in Tulsa, OK and at a partner energy producer’s facility confirmed suitability of the technology to meet real-world operating requirements. The system provides increased thermal efficiency and corresponding reduction in greenhouse gases compared to traditional co-generation methods.

The performance of the burner technology met or exceeded project design goals. Through control logic and the use of auxiliary air from a dedicated combustion fan, the exhaust O$_2$ of an OTSG can be held at design levels, even with variable flow, composition, and temperature from a TEG source. With TEG firing modes, flame shaping and heat flux profiles were comparable to the fresh-air firing mode indicating boiler heat transfer and tube fouling will not be negatively impacted. Burner contributed NOx production was significantly reduced while operating in TEG mode. Complex control system sensing and recovery logic provides increased reliability of the OTSG system such that steam production is maintained during severe upset conditions. Even with the loss of a key component of the system, the GT, continuous operation without full system trip is possible.

While the full scale system has not been commissioned at this time, the combination of successful test results from two facilities and the completed mechanical design of a full scale burner bring strong confidence to commercial readiness of the technology.
Bibliography


Appendix A

Figure 17: Contours of Velocity – Fresh Air Firing

Figure 18: Contours of Velocity – TEG Firing
Figure 19: Contours of Static Temperature, °F – Fresh Air Firing

Figure 20: Contours of Static Temperature, °F – TEG Firing
Figure 21: Contours of Mole Fraction O₂ – Fresh Air Firing

Figure 22: Contours of Mole Fraction O₂ – TEG Firing
Figure 23: Combined Iso-surface of 5000 ppm CO and 2500°F – Fresh Air Firing

Figure 24: Combined Iso-surface of 5000 ppm CO and 2500°F – TEG Firing
Figure 25: Contours of Total Surface Heat Flux (Btu/hr-ft²) – Fresh Air Firing

Figure 26: Contours of Total Surface Heat Flux (Btu/hr-ft²) – TEG Firing