Oxy-fuel/CO_2 Capture Technology for OTSGs

Phase II Report
Oxy-fuel Combustion Demonstration

Kelly Tian, Larry Bool,
Larry Cates, Stefan Laux

Praxair, Inc.

Final Report
5 October 2015

Business Confidential

Summary

This report describes the findings and results from the demonstration of oxy-fuel combustion on an Once Through Steam Generator (OTSG) boiler. It includes a description of the test boiler, the design and operation of the oxy-fuel combustion systems, as well as the results of the demonstration test.

This demonstration was Phase II of the CCP3 (CO_2 Capture Project Phase 3) project "Oxy-fuel/ CO_2 Capture Technology for OTSGs". The goal of this project is to evaluate the integration of oxy-fuel combustion and CO_2 capture technology with an OTSG boiler to enable CO_2 sequestration. The objective of Phase II was to safely demonstrate oxy-fuel combustion on an existing boiler and to quantify changes in operation and performance.

The tests were executed at the 50 MMBtu/hr (14.6MW) OTSG located at Cenovus's Christina Lake facility in Alberta, Canada. Oxygen was transported to the site by truck due to the short duration of the test (2 weeks). The boiler was retrofitted with additional ductwork to recirculate flue gas from the boiler outlet back to the burner and to mix oxygen into the flue gas recirculation. The mixture replaced the combustion air and almost eliminated nitrogen from the boiler exhaust. The flue gas contained high concentrations of CO2 and water vapor, which is desirable for carbon capture.

The demonstration test had the following goals.

- Identify changes in heat transfer pattern and flame length between air-fuel and oxy-fuel combustion
- Find the best combustion solution for oxy-fuel operation with respect to heat transfer, emissions, oxygen concentration and the flame stability of the existing burner.
- Determine the volumes of flue gas recirculation for the operation with oxy-fuel and
- Establish safe and reliable operating procedures, interlocks, and control methods

The above goals were achieved and the operation of an OTSG in Steam Assisted Gravity Drain (SAGD) service with oxy-fuel combustion and flue gas recirculation was safely demonstrated. Although the retrofit of the technology to this specific boiler showed a few minor limitations during testing, the demonstration clearly showed that there are no fundamental technology limitations for retrofitting a SAGD OTSG boiler for oxy-fuel combustion and operating it continuously. Boiler performance was nearly identical between air-fuel and oxy-fuel and the same steam quality and steam flow were achieved compared to loads under air operation due to a similar balance between the heat transfer to the boiler evaporator and the economizer. In addition, the fuel consumption was approximately 5% lower than air-fuel at the same boiler feed water flow and the same steam quality because of the higher efficiency with oxy-fuel combustion. The mass-based oxy-fuel NOx emissions were on average only 15% of those measured with air-fuel combustion and no CO emissions were measureable with air or oxygen.

The test boiler had a few limitations preventing it to reach full load in oxy-fuel operation due to the use of the existing air burner. The demonstration has shown that operation of the pre-mix low NOx air burner with oxygen and flue gas recirculation is not as stable at certain operational conditions even though the flame was quite stable during most of the test period. In general, high burner velocities proved to limit the load range and oxy-fuel required higher than expected minimum oxygen concentrations in the flue gas recirculation (FGR) of 21.2%. However, the technical team strongly believes that there is no general limitation for retrofitting OTSGs for oxy-fuel operation and that identified limitations can be overcome by appropriate design measures.

After initial commissioning challenges, the transitioning between air-fuel and oxy-fuel operation and back was optimized so well that the transition process was performed almost as a routine by Cenovus operators. These transitions are best performed at low boiler load and moderate flows for air and oxygen. The use of a small oxy-fuel pilot burner in the main burner center proved to be invaluable for the stabilization of the oxy-fuel flame during transitions and during oxy-fuel boiler operation. The heat from the burner resulted in improved combustion temperatures at the root of the flame on the main burner.

In summary, this demonstration of an oxy-fuel retrofit to an existing SAGD boiler was very successful. Although the demonstration boiler is much smaller (50 MMBtu/hr) compared to current full-scale SAGD boilers (250 to 300 MMBtu/hr), the findings can be applied to larger boilers. Lastly, there are no technical scale-up limitations noted in implementing oxy-fuel operation commercially for carbon capture and scale-up recommendations are provided at the end of the report.

Table of Content

Figures

Tables

1. Oxy-fuel Combustion Demonstration

1.1. Test Outline and Objective

This report describes the findings and results from the demonstration of oxy-fuel combustion on an OTSG test boiler. It includes a description of the test boiler, the design and operation of the oxy-fuel combustion systems, as well as the results of the demonstration test.

This demonstration was part of the CCP3 project "Oxy-fuel/ CO_2 Capture Technology for OTSGs". The goal of this project is to evaluate the integration of oxy-fuel combustion and CO_2 capture technology with an OTSG boiler to enable CO_2 sequestration. The project has the following three phases:

- Phase I– A study to establish the process design and costs of oxy-fuel operation and CO_2 capture was completed in December 2010 and had three main components:
  - Task 1 - Commercial-scale OTSG boiler with CO_2 capture, purification and compression [1]
  - Task 2 - Demonstration scale oxy-fuel boiler retrofit [2], and
  - Task 3 - Design/costs for demonstration of CO_2 compression and purification [3].
- Phase II – The demonstration of oxy-fuel combustion on a small OTSG. The test was completed in April 2015 and is the subject of this report.
- Phase III – A proposed future demonstration of capture and purification technology.

The objective of Phase II was to safely demonstrate oxy-fuel combustion on an existing boiler and to quantify changes in operation and performance. Process data were collected for comparison between air combustion and oxy-fuel combustion.

The demonstration was executed on a 50 MMBtu/hr (14.6MW) OTSG located at Cenovus's Christina Lake facility in Alberta, Canada. Due to the short duration of the test (2 weeks) oxygen was supplied to the test site as liquid transported by truck.

The demonstration test had the following goals.

- Identify changes in heat transfer pattern and flame characteristics between air combustion and oxy-fuel combustion
- Find the best combustion solution for oxy-fuel operation with respect to heat transfer, emissions, oxygen concentration in FGR and the flame stability of the existing burner.
- Determine the volumes of flue gas recirculation for the operation with oxy-fuel, and
- Establish safe and reliable operating procedures, interlocks, and control methods

1.2. Project Organization and Funding

Phase II was funded by the Climate Change Emissions Management Corporation (CCEMC) and an industry consortium consisting of the CO_2 Capture Project Phase 3 (CCP3) members and by Cenovus FCCL Ltd., Devon, Statoil, MEG Energy, and Praxair Inc.

Alberta Innovates – Energy and Environmental Solutions (AI-EES) served as a Project Advisor for CCEMC which is an Alberta Government Agency. CCP was formed in 2000 as a partnership of major energy companies working to advance CO_2 capture and storage (CCS) development for the oil & gas industry. CCP3 members companies and project funders are: BP, Chevron, Eni, Petrobras, Shell and Suncor.

Suncor Energy Inc served as the consortium lead and the project management for the consortium was provided by BP.

Three companies executed the Phase II demonstration project:

- Suncor Energy as the project administrator
- Cenovus Energy as the site host and
- Praxair Canada as the technology provider.

1.3. Introduction to the Oxy-fuel Combustion Process

OTSGs consist of a radiant section that utilizes a gas fired boiler to evaporate feedwater to steam of approximately 80% quality (i.e. 20% of the water leaves the boiler as liquid droplets). After the radiant section, the flue gas enters the convective section (economizer) where the feedwater is preheated. The sizes of the two sections were designed to optimize heat transfer with air combustion. For a typical OTSG, the duty split between the radiant section and the convective section (economizer) is determined by the heat transfer with air combustion and the overall mass and heat balance between the two. Equipment limitations often exist in both sections that occasionally prohibit the shift in the heat duties when modifying the process to adapt oxy-fuel combustions.

When oxygen is utilized for combustion, the nitrogen in the air is eliminated resulting in a significantly lower flue gas flow. With a conventional oxy-fuel burner high flame radiation and lower flue gas mass flow lead to increased heat transfer in the radiant section, reducing the heat that can be transferred in the economizer. High radiant heat fluxes are a concern for boiler operation due to the potential for boiler tube dry out and subsequent tube damage. While the design of the OTSG promotes relatively low heat flux and incomplete evaporation of the water for a certain margin of safety, it is critical to maintain similar heat flux when the boiler is converted to oxy-fuel firing. Recirculated flue gas was substituted for the nitrogen component of air in order to better match the operation of the boiler with air-fuel combustion.

Figure 1 shows a sketch of the major modifications for the oxy-fuel demonstration on the boiler. Part of the flue gas was taken from downstream of the economizer and recirculated back to the burner to balance the boiler heat transfer and be able to approximate the heat transfer pattern of the existing air-fuel combustion system. The flue gas recirculation (FGR) system was outfitted with dampers to isolate the flue gas recirculation when the boiler was operated in air-fuel operation and when the boiler was operated in oxy-fuel mode, an isolation damper at the air inlet shut off the supply of air. The forced draft (FD) fan of the boiler was used to move the FGR through the recirculation loop. Oxygen was mixed with the FGR to replace the air and a boiler retrofitted in this manner can operate either on air-fuel or oxy-fuel with seamless transition without boiler shutdown. For the test the oxygen for oxy-fuel operation was stored in a cryogenic tank in liquid form and evaporated into a gas for process use. Future, full-scale commercial installations would require an onsite air separation unit to reliably produce sufficient quantities of oxygen.

It is desirable to start up the oxy-fuel boiler as a conventional air fired boiler to avoid condensation of water due to the high water content in the flue gas from oxy-fuel combustion and the subsequently higher dew point. Once the boiler was at operating temperature, the air damper was closed and the FGR damper was gradually opened. At the same time oxygen was injected into the FGR stream to assure complete combustion of the fuel at the main boiler burner. The transition between air-fuel and oxy-fuel firing is discussed in detail in this report at a later section.

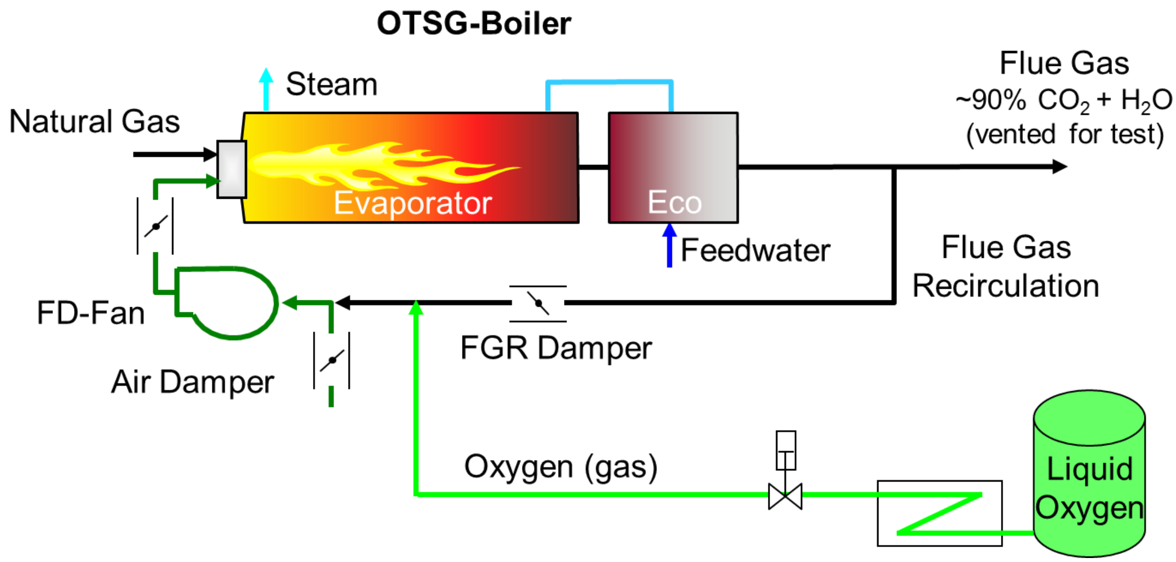

Figure 1: Sketch of Oxy-fuel Combustion Test System

The operation of ultra-low NOx burners designed for air combustion with oxy-fuel can be challenging due to the highly complex semi-premixed design used to meet low NOx emission requirements. The description of the air burner installed in the boiler can be found in Section 2.3. Some of the fuel in these burners is distributed into the combustion air to avoid local high flame temperatures that result in high NOx emissions. Given the higher heat capacity of the recirculated flue gas, this premixing strategy may create flame temperatures that are too low to promote stable combustion. Therefore, operating with a mixture of FGR and oxygen may result in a less stable flame, i.e. the ignition conditions at the root of the flame change significantly to result in the extinction of the flame or a “flame out”.

The major changes to the combustion process have resulted in maintaining the heat transfer profile in the unit, avoiding high heat flux in the radiant section, and maintaining stable ignition. For example, the mass flow through the boiler required maintaining the heat distribution between evaporator and economizer. The use of hot flue gas recirculation (approximately 200°C) in comparison to cold air resulted in an increase of the volumetric flow through the burner of approximately 50% during oxy-fuel combustion. In turn, the velocities through the burner also increased by 50%. It was observed during testing that high burner velocities jeopardize flame stability as the time for the combustion process to establish itself is shorter resulting in a unstable flame. In addition, the lower oxygen diffusivity in the recirculated flue gas slows down the combustion process and the higher heat capacity of CO_2 and water vapor in the FGR reduced local temperatures.

To provide a high degree of flame stability during the demonstration, the fuel distribution to the fuel nozzles of the existing air burner was changed and a small oxy-fuel burner (Praxair J-Burner) operated in the center of the air burner. This provided additional ignition energy at the root of the flame. Details of the equipment and the results are described in later sections.

1.4. Project Safety

Several safety reviews were completed prior to finalizing the design of the oxygen supply, completing the boiler modifications, installation of equipment and controls required for the test.

A Hazard and Operability Analysis (HAZOP) was conducted during February 2013 by a team consisting of representatives of Cenovus Energy, Cenovus's engineering provider, Cenovus's burner service company, Cenovus's control service company, and Praxair. The analysis was facilitated by a facilitating services provider.

The HAZOP method provides a means of systematically reviewing the design and operation of a system to identify potential hazards and/or operability problems. It focuses on how a process may deviate from the design intent, and draws on the expertise of the team members and their past experience with the design and/or operations of similar facilities.

A number of recommendations were developed as a result of this analysis and were subsequently addressed by various team members. In addition, a Layers of Protection Analysis (LOPA) study was completed during July 2013 to address some of the unresolved scenarios that have higher risk levels.

The LOPA study was undertaken to quantify the risk reduction required for the scenarios identified from the HAZOP; to verify the adequacy of existing safeguards for these scenarios; and to determine if Safety Instrumented Function (SIFs) would be required. The study also demonstrates due diligence and compliance to the functional safety lifecycle as per the IEC-61511 standards, which required risk assessment of the process and allocation of safety functions to protection layers. The LOPA study resulted in an additional 17 recommendations for further action. These were also subsequently addressed by team members.

All equipment and components involved in the storage and supply of oxygen were selected for compatibility for oxygen service. The liquid oxygen storage and vaporization equipment consisted of standard Praxair components designed for oxygen service. The piping transporting the gaseous oxygen from the supply skid to the flow control valve skid was made of stainless steel. The flow control valve skid, sparger and connecting piping were also constructed of stainless steel. All piping, equipment, and components that were in contact with oxygen were specially cleaned for oxygen service to remove any trace of hydrocarbons.

A Factory Acceptance Test (FAT) was performed in July 2013 at the Praxair vendor facilities for the oxygen flow control skid and electrical control panel. The purpose of this test was to demonstrate the functionality of the equipment, controls, and software supplied by Praxair. The equipment for this test included the programmable logic controller (PLC), human machine interface (HMI), as well as the flow control skid and electrical control panel. The control philosophy for the test was also simulated during the FAT.

A Software Acceptance Test (SAT) was conducted on site at Cenovus's Christian Lake facility in February 2014, with follow-up testing performed at later dates. The SAT consisted of the control equipment being installed and ready for service with all input/output (I/O) signals verified or "loop checked". During the SAT all interlocks based on the shutdown key and alarm list were tested and verified. The purpose of this test was to validate the operation of instrumentation, confirm the operation of interfaces between the PLC and DCS controllers, and test the operation of dampers, valves, and other control devices. The FD fan and all dampers were also confirmed for operability and the burner operation was simulated with oxygen flow. Problems with wiring and equipment were discovered and rectified by Cenovus personnel and later retested.

A major component of this test was the operation of the purge sequences. The addition of the FGR recirculation duct required modification to both pre-ignition purge and post-combustion purge procedures to ensure that the existing boiler purging requirements are preserved and the new FGR duct would be properly purged, even with the oxygen system not in operation.

Finally, an Emergency Response Plan (ERP) was developed to deal with the presence of oxygen on site. In June 2014, a scenario driven session was hosted by Cenovus to allow personnel to simulate responses to various emergency events.

2. Test Boiler Description

The tests were performed on a small natural gas fired OTSG located at Cenovus Energy's Christina Lake SAGD operation in Alberta. Figure 2 shows the 50 MMBtu/hr (14.6MW) test boiler (Boiler B-102) in oxy-fuel operation next to a larger 180 MMBtu/hr (52MW) boiler. Note the steam plume from the stack due to the high water vapor concentration and the high dewpoint of the flue gas. The test boiler full load CO2 emission rate using air combustion is approximately 85 t/d.

Figure 2: Picture of the Test Boiler (with permission from Cenovus FCCL Ltd.)

2.1. Boiler Design

The ITS/Thermotics OTSG consists of a cylindrical horizontal furnace section and a vertical economizer with a short stack (left in Figure 3). A single Coen QLN gas burner is installed in a windbox supplied with combustion air by a forced draft (FD) fan located on top of the windbox. The horizontal furnace/evaporator has 56 tubes arranged in a dual pass serpentine coil on the inner circumference of the boiler. The convection section is fabricated from both bare and finned type tubes and flue gas from the radiant section enters the convection section flowing across the bare tubes first. The flow then crosses the finned tube and ultimately exits through the stack above the economizer. The radiant tubes lining the chamber walls are spaced approximately two tube diameters apart (center to center) and one diameter away from the refractory lined wall. The radiant and convective coils are made of 3" SCH80 SA-106-GR.B seamless pipe.

The boiler is typically operated with mixture of natural gas and desulfurized produced gas. This is primarily done to meet SOx emission limits, but has also the advantage to limit the corrosion potential of any condensate present in the system. The investigation of potential corrosion issues due to oxy-fuel firing of the OTSG was not part of this study.

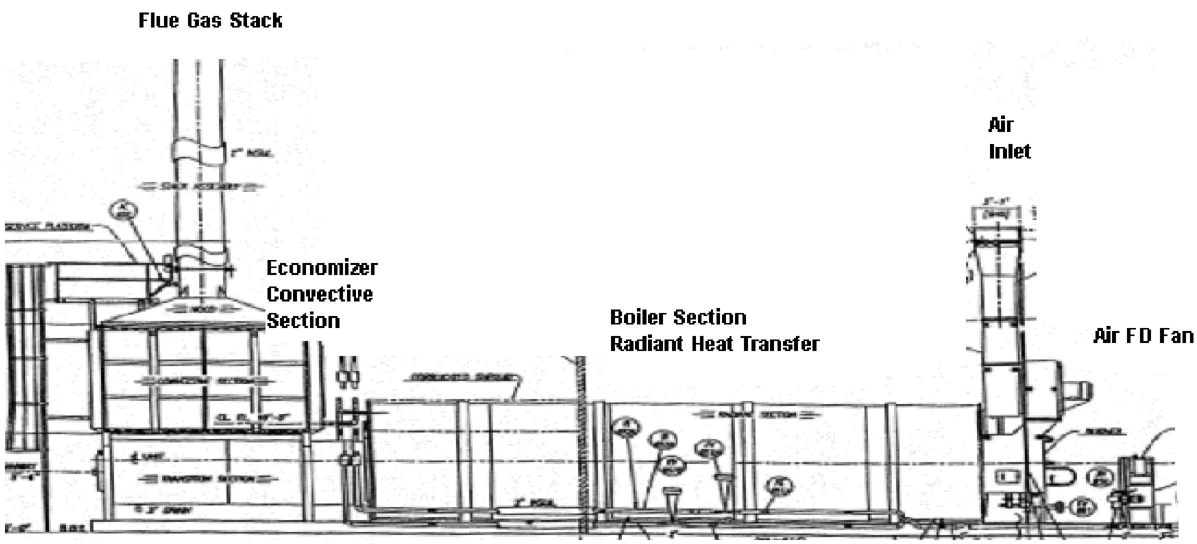

Figure 3: Test Boiler General Arrangement

2.2. Operational Data

The operational data for the test boiler is summarized in the Data Sheet in Table 1 below.

2.3. Air Burner

The boiler uses a single Coen QLN 3.2 ultra-low NOx burner. The burner consists of a refractory quarl with a 32" (812 mm) inner diameter and a metal burner insert that is installed into a round windbox opening so that the raised part of the quarl is flush with the refractory front wall of the boiler. This pre-mixed burner design uses multiple fuel injection location to reduce the flame temperatures and minimize thermal NOx generation (Figure 4 and 5).

Approximately half of the natural gas is injected though six burner nozzles penetrating the outer ring of the refractory quarl. Roughly the other half of the fuel is injected through inner gas spuds into the combustion air flow that enters the furnace through rectangular slots oriented similar to spokes in the burner quarl. Each of the six injectors has four nozzles. Six nozzles in the burner center (core spuds, not shown in Figure 4) inject only about 5% of the total gas flow. A liquid fuel gun on the burner axis can be included in the burner, but no liquid fuel is used at the site. Instead, a small oxy-fuel burner as described below was inserted into the oil gun guise pipe. The pressure difference between the windbox and the furnace is used to drive the flow of air through the slots as well as past the outer natural gas nozzles. The gas flow can be biased between the outer, inner and core spuds to optimize the shape of the flame and NOx emissions.

Table 1: Test Boiler General Data

Test Boiler

Boiler Location	Christina Lake, Alberta, operated by Cenovus Energy
Manufacturer	ITS Engineered Systems, Inc.
Type/Model	ITS/Thermotics Steam Flooded

		Sweet Natural Gas		
Fuel	Methane	98.6	vol %	May also fire on mixed gas
	Ethane	0.1	vol %	
	Propane	0.05	vol %	
	C4H10	0.05	vol %	
	Nitrogen	0.9	vol %	
	CO2	0.3	vol %	
	HHV	982.3	Btu/1000ft^3	@ standard conditions
	Temperature	40	F	
	Specific Gravity	0.563		
	Fuel Flow	58,562	scfh	
Boiler	Steam flow	67,386	lb/hr	
	Feedwater pressure	1827	psig	minimum required at inlet
	Eco inlet pressure	1812	psig	
	Eco outlet pressure	1800	psig	
	Steam pressure	1737	psig	@ discharge to header
	No of parallel steam passes	1	-	
	steam quality boiler outlet	80	%	
	Feedwater temperature	325	°F	
	Eco inlet temperature	325	°F	
	Eco outlet temperature	580	°F	
	Steam temperature boiler outlet	617	°F	
	Air preheater inlet temperature	-	°F	
	Combustion air temperature	122	°F	
	Flue gas temperature furnace exit	1725	°F	
	Flue gas temperature eco exit	375	°F	
	Excess oxygen flue gas (eco outlet)	15	%	% excess air
Geometry	Furnace length	41.167	ft	
	Furance diameter, if circular	10.167	ft	tube center to tube center
	Diameter flue opening	5.896	ft	
	Diameter burner opening	5.083	in	
	evaporator tube OD	3.5	in	
	evaporator tube ID	2.9	in	
	tube center spacing from wall	4.46	in	
	tube center spacing on circumference	6.84	in	
FD fan	Design flow rate	63575	lb/hr	max
	Design pressure increase	15	in wg	

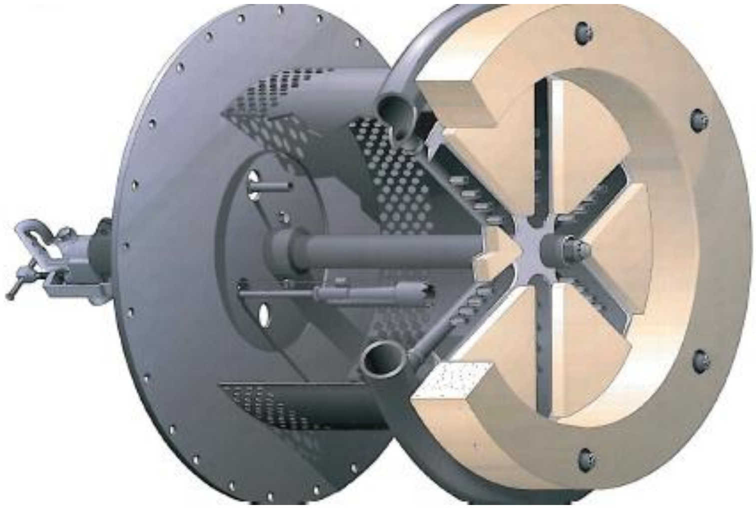

Figure 4: Coen QLN Air Burner (with permission from Coen)

Figure 5: Coen QLN Burner with Center Praxair J-Burner (with permission from Cenovus FCCL Ltd.)

3. Oxy-fuel Combustion System Design

3.1. Boiler Modifications

To enable oxy-fuel combustion with the existing air combustion system, a flue gas recirculation system was added to the boiler. The flue gas recirculation was taken from the economizer outlet with a new duct installation connecting to the windbox. Mixing oxygen into recirculated flue gas prior to the existing air-fuel burner is one of the simplest methods of enabling oxy-fuel combustion capability. Figure 6 shows a simplified process flow diagram.

Two louver-type air dampers were added at the inlet for the combustion air. One damper was designed as a low leakage damper to avoid air in-leakage into the system when the boiler was operated in full oxy-fuel operation. For future oxy-fuel retrofits it is essential to minimize the nitrogen content in the flue gas that is the result of air in leakage as higher nitrogen in the captured flue gas increases the cost of carbon capture operation. The other air damper was designed as an opposed blade damper to allow good control of the air flow during transitions. The original glycol air preheater had not been used with the exiting air-fuel operation and was hence removed to make space for the recirculation system.

The FD fan was located on top of the windbox and discharged the flow into the windbox below through flow control damper. For the demonstration, the fan was replaced with a larger model to handle the larger volumetric flow rates produced during oxy-fuel mode. When the boiler was operated with flue gas recirculation and oxygen the volumetric flow rate was increased due to the higher temperature of the mixture (approximately 180°C) in comparison to the air at ambient temperature. The fan was equipped with a Variable Frequency Drive (VFD) motor to allow better adjustment to the flow. During commissioning, it was found that the flow control with the control damper after the fan was entirely adequate and the VFD was set to 60% for all tests.

The recirculation duct was tied into the plenum above the economizer at the base of the stack. Similar to the air dampers, two FGR dampers were installed to control the flow in the duct. One damper was designed as a low leakage shut-off device and the other designed as a control device. The total oxidant flow, whether it was combustion air or oxygen mixed with recirculated flue gas, was controlled by the same damper installed downstream of the FD fan. For the use of oxygen with recirculated flue gas the two dampers in the recirculation duct were opened and the air dampers closed. A mixer for oxygen (sparger) was installed in the FGR duct to mix the oxygen into the flue gas (mostly CO_2 and water vapor). The oxygen concentration was measured and controlled to the target value by adjusting the amount of oxygen to the sparger via a flow control valve that was located on the Praxair flow control skid. The total oxidant flow was then controlled by the control damper downstream of the FD fan through the Cenovus DCS via a cross limiting network between fuel and oxidant flows.

Oxygen and moisture analyzers provided the oxygen concentration of the oxidant and the dewpoint temperature for control purposes. A stack gas analysis was added to collect emission performance data. The oxygen was supplied by a control skid described in Section 3.2.3 below. The existing burner fuel supply was used essentially unchanged. However, a small burner to support the flame stability (J-Burner) was installed in the center of the air burner and separately supplied with natural gas and oxygen. The J-burner is described in Section 3.3.2.

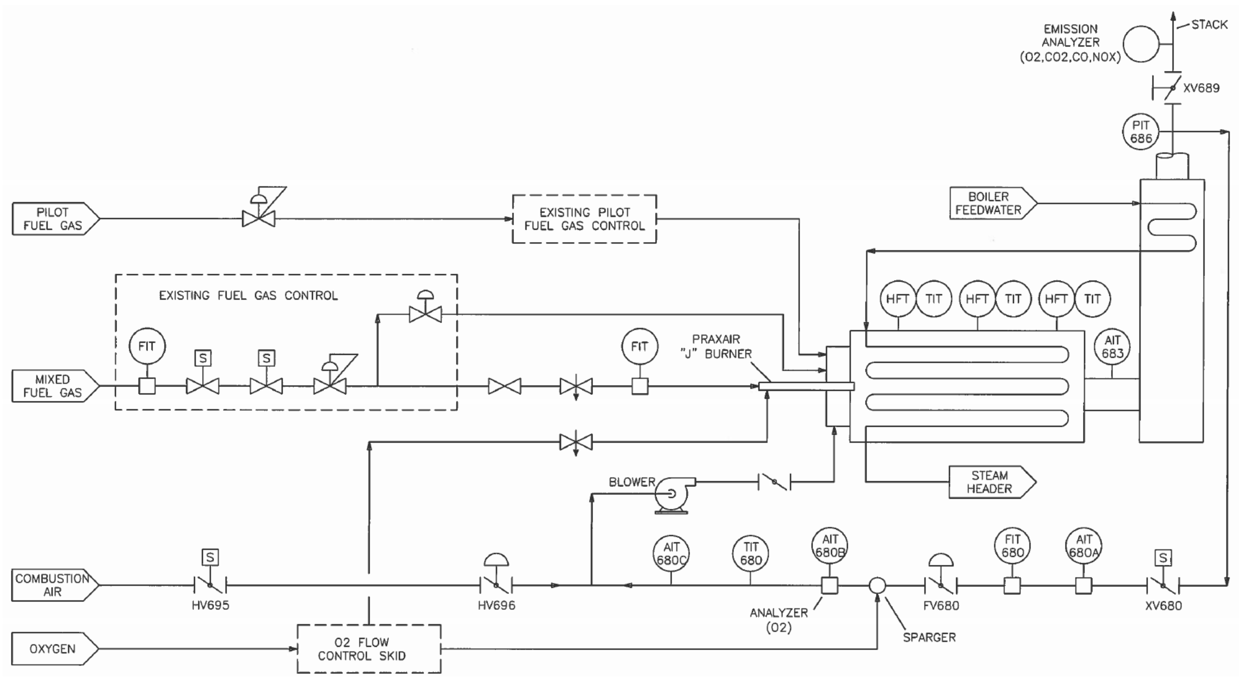

Figure 6: Simplified Process Flow Diagram for Demonstration System

3.2. Oxygen Supply System

3.2.1 Liquid Oxygen Supply

The oxygen was supplied from cryogenic tanks for the relatively short time of the demonstration. The liquid oxygen was trucked to the site in standard cryogenic tanker trucks.

The oxygen supply system (Figure 7) consisted of two cryogenic tanker trailers (so called “Queen” trailers), an electric transfer pump, a 13,000 gallon (49 m^3) high pressure vertical storage tank, three ambient vaporizers and one pressure regulating manifold (LTPP).

The liquid oxygen was delivered and stored in the two Queen trailers with each at an approximate capacity of 23,500 gallons (89 m^3) of liquid oxygen. The trailers discharge piping was combined into a single line which fed into a transfer pump. A double block and bleed valve design was installed ensuring the supply of liquid O2 was stopped, by pressing the e-stop terminal, to the transfer pump in case of an emergency. Two e-stop push buttons were installed, one near the pump and the other on opposite side of the pump at the trailer location.

Liquid O2 was periodically pumped from the low pressure trailers to the high pressure vertical storage tank. The transfer pump was operated manually by trained Praxair personnel to fill the vertical buffer tank. The pump required priming in cooling the pump down to -297°F (-183°C) which was done manually by introducing cold liquid O2 from the trailers and returning the gaseous O2 back to the trailer.

The storage tank maintained a set pressure of approximately 215 psig (15 bar) with a pressure control system consisting of pressure switches, actuated ball valves and an ambient pressure building vaporizer.

The pressure switches were activated when the pressure was too low or high and opened up the corresponding ball valve either for increasing tank pressure or decreasing tank pressure through venting.

After the vertical high pressure storage vessel, the liquid oxygen travels to the three ambient vaporizers, each rated for 75,000 scfh (2100 m^3_N/h), where the oxygen changes state from liquid to gaseous form. The vaporizers designed with a high surface area, use the heat in the surrounding ambient air to evaporate the oxygen. The design temperature of the product at the outlet of the vaporizers was approximately 20°F (11°C) less than the ambient temperature.

The gaseous oxygen continued its path to the pressure regulating manifold (LTPP) which has three functions; regulate pressure, stop the flow of low temperature gas and stop the flow during a potential downstream pipe break. The oxygen pressure was regulated by a Kay-Macdonald regulator and was set at 175 PSIG (12 bar). In the event of an extremely cold ambient temperature or a very heavy draw on the system the low temperature probe, set at -40°F (-22°C) , would shut the flow of gas to the regulator. This would protect potential devices that cannot withstand temperatures below design. Lastly, in the event of pipeline breakage, where there is a sudden drop in the downstream supply pipe, an additional regulator would dump the dome pressure of the main Kay-Macdonald regulator. In doing so, the Kay-Macdonald regulator would close and stop the flow of oxygen until the system is reset by closing a needle valve.

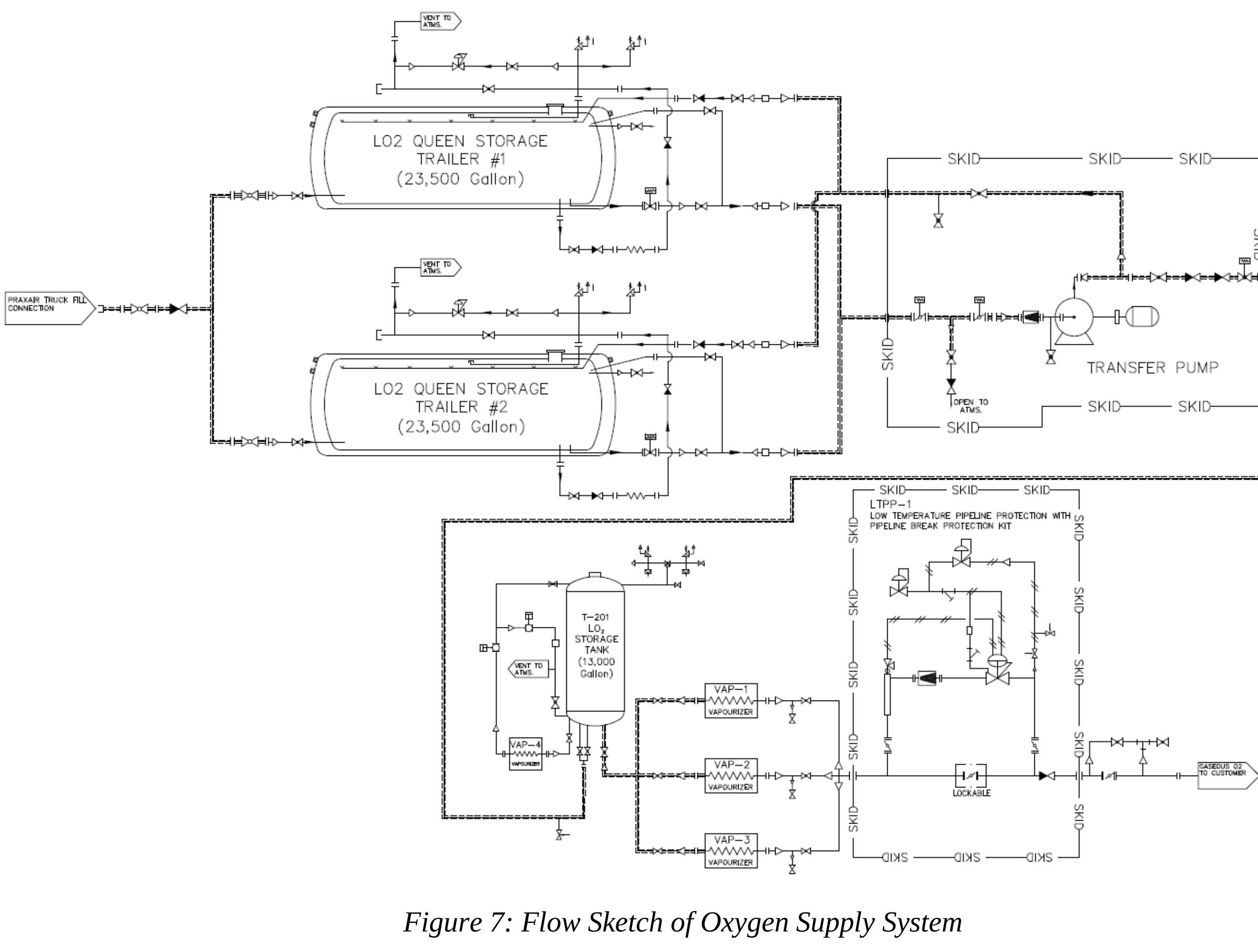

Figure 7: Flow Sketch of Oxygen Supply System

3.2.2 Oxygen Control Valve Skid

An oxygen control valve skid was supplied to measure and regulate oxygen flow, and to provide oxygen safety interlock and shutoff functions. This prefabricated skid was located in the boiler building close to the burner. The skid components were selected and cleaned for oxygen service and were designed for a maximum pressure of 300 psig (20.7 bar). Pressure at the inlet was maintained at approximately 150 psig (10.7 bar). The skid requires clean, dry compressed air at 80-120 psig (5.5 to 8.3 bar) for operation of the pneumatic valves.

The oxygen flow was measured with an orifice flow meter incorporating pressure and temperature compensation to measure flow in standard units. The skid included pressure switches and double blocking valves for safely shutting down oxygen flow. The automatic safety functions of the skid were controlled through hard wired interlocks and by the PLC that was interfaced with the boiler control DCS system to receive permissives and setpoints and communicate process data. In the event of power interruption, instrument air failure, or safety shutdown, all valves are designed to close automatically.

After the blocking valves the flow was split into the main flow to the sparger and a much smaller flow the stabilizing J-Burner. The main flow was controlled with an automatic flow control valve through the PLC. The oxygen flow to the stabilizing burner was manually controlled through a small valve. This flow was measured with a second orifice flow meter similar in design to the upstream flow meter mentioned above.

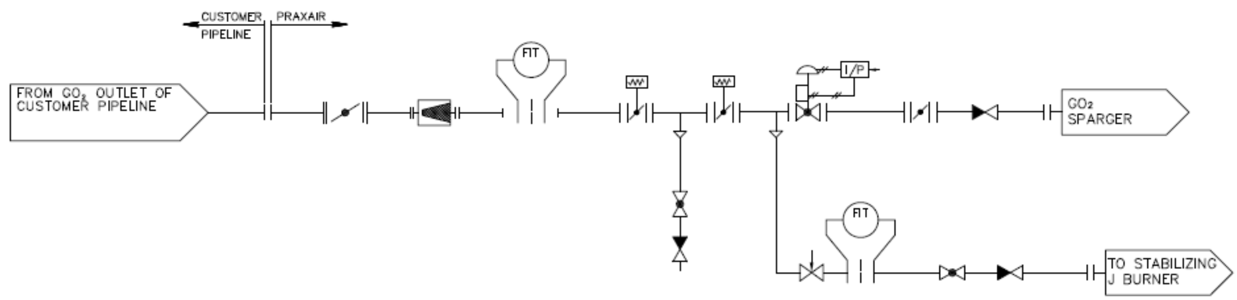

Figure 8: Process Flow Sketch of Oxygen Control System

3.3. Oxy-fuel Combustion System

3.3.1 Oxygen Mixer

The oxygen mixing device (sparger) was mounted in the new flue gas recirculation duct after the FGR damper. The sparger consisted of a 4" pipe with multiple holes drilled perpendicular to the FGR flow designed to distribute the oxygen evenly into the duct. Computational Fluid Dynamic (CFD) computer modelling was used to design the sparger to ensure complete mixing of the oxygen into the flue gas. The available length of straight duct immediately after the mixer was taken into account in the modelling of the mixing. In addition to the residual oxygen concentration in the recirculated flue gas, the injected oxygen provided the oxygen necessary for combustion. An oxygen concentration measurement after the sparger was used to control the oxygen concentration in the oxidant. This proved to be accurate and easy to implement.

3.3.2 J-Burner

The numerical study executed in the Phase I Task II has shown that the flame stability of the Coen burner may be affected with the FGR/oxidant mixture. The highly optimized NOx reduction technology of the premixed air burner may not be suitable to provide flame stability for oxy-fuel combustion. This is likely due to the higher heat capacity of the FGR/oxidant mixture in comparison to air. The numerical study also provided guidance that a small oxy-fuel burner in the burner center is a successful strategy to overcome this problem. A small Praxair J-Burner was inserted into the center guide pipe of the air burner to provide flame stability (see Figure 5). This patented solution is a simple method to improve flame stability by adding heat in the burner center [4]. The burner firing capacity was 700kW (3 MMBtu/hr), i.e. only a maximum of 6% of the heat input was provided by this burner.

The J-Burner is shown in Figure 9. It is a pipe-in-pipe design with the natural gas flowing in the center and the oxygen in the annulus. The flame length of this burner can be adjusted by changing the diameter of the nozzle at the end of the natural gas pipe. The specific burner used at Christina Lake was designed in two parts that were connected with a standard flange due to the limited extraction length between the windbox and a control cabinet in front of the windbox. The O-ring at the connection provides the seal for oxygen and fuel gas. Normally the burner is a one-piece design.

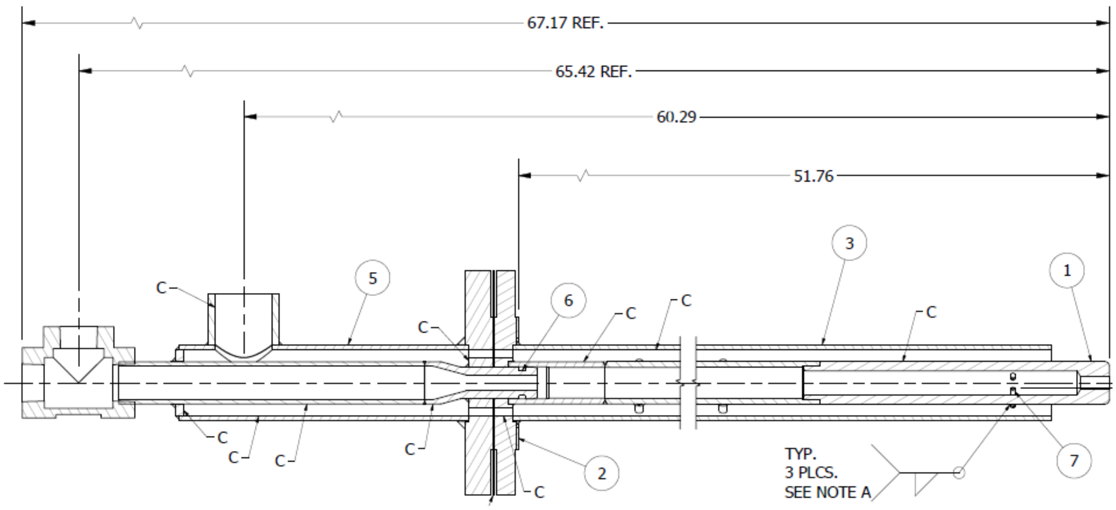

Figure 9: Praxair J-Burner

3.4. Measurements

3.4.1 Data Acquisition

Process measurements taken both from the dedicated PLC system, as well as the existing boiler control DCS system were recorded and they were extracted on a 15 second basis throughout the trial in the DCS database system. Data included:

- Boiler feedwater flow, pressure, and temperature
- Steam flow, temperature, pressure, and quality
- Stack oxygen, CO, and moisture concentration
- Fuel gas flow, temperature, and pressure

- Combustion air flow and temperature
- Flue gas flow, temperature, and pressure
- Flue gas oxygen concentration, before and after sparger
- Oxygen flow and pressure to sparger
- Oxygen flow to “J” burner
- Heat flux and boiler tube temperature

3.4.2 Emission Measurement

As part of the boiler test, emission measurements (O_2, CO_2, CO, NOx, SO2) at the top of the stack were to be performed by a subcontractor. The system also measured stack flow. The low flue gas flow during the oxy-fuel demonstration (only approximately 25% of the comparable flue gas flow during air combustion) resulted in very low stack velocities that were below the detection limit of the system. The flue gas amount during oxy-fuel tests was calculated from a boiler mass balance with the fuel and oxygen input and the excess oxygen. The samples contained a significant amount of moisture (>50 vol%) and have a dew point of more than 80°C (180°F) so proper flue gas handling and line insulation was necessary to measure reliably under these conditions. The system diluted the sample with a known amount of nitrogen at the stack to avoid water condensation. A heated sample line was used to convey the sample to a heated trailer with the analyzers. The sample gas was analyzed and the result corrected for the high dilution. Diluting the sample to a very low dewpoint allows measuring the wet gas directly in the analyzers without any drying, but requires accurate analyzers.

Throughout the test, daily calibration and proper maintenance to the emission equipment was be performed remotely to ensure that the systems were functioning properly.

3.4.3 Heat Flux Measurement

The heat flux probe used for the demonstration was a commercial Medtherm GTW Furnace Heat Flux Probe. The probe operates using a Schmidt-Boelter sensor, which measures total heat flux (convection and radiation) at the probe location. The operating principle of the sensor is measurement of a temperature difference across a material of known thickness and thermal conductivity, which is then readily interpreted as a heat flux. Water cooling is employed to prevent overheating and to provide a heat sink to allow heat to flow through the sensor. Calibration of the probe is accomplished at the manufacturer using blackbody radiation.

Three heat flux probes were installed in the boiler evaporator wall at 19, 44 and 63% of the relative evaporator length measured from the burner. The probes were installed through the 2” gap between two boiler steam pipes. The probes are sensitive to the environment and are not reliable for long-term operational measurements. Unfortunately, only the center probe at 44% of the length was available at the time of the demonstration. The other two probes had failed earlier due to the long exposure to the operation after installation.

3.4.4 Flame Camera

To be able to observe the flame and allow immediate assessment of the flame stability a furnace camera was installed in the boiler side wall. The camera was installed at an angle of 48° with respect to the axis of the boiler looking directly at the burner through two steam pipes. The field of vision was +- 30° from a point on the centerline of the boiler that was 1.2m (4') away from the burner. This allowed observation of approximately 2.3m (7.5') of the initial flame.

The camera was a LENOX assembly with a commercial CCD video camera in an air-cooled housing. A small lens at the end of a 600mm (24") long lens shaft purged and cooled with compressed air which introduces a small amount of nitrogen into the boiler. The images were displayed in the control room and recorded with a commercial digital video recorder. Note that the camera produces images in the NTSC format which have limited resolution.

3.5 Control Integration

This section summarizes the operation and controls for the integration of the oxy-fuel combustion system into the existing boiler controls. The chapter outlines the components for the control system, the key control loops and the safety equipment and interlocks. The full description of the controls is available as a separate document.

The control system for the oxy-fuel demonstration has three components:

1) Burner Management System (BMS) – this mandatory and code compliant safety component for any combustion system was upgraded for the demonstration to include more interlocks. The basic function is to monitor the flame and ensure safe boiler startup and operation.
2) Distributed Control System (DCS) – the operational control of all equipment at the plant is integrated in the DCS. The DCS system for the boiler was existing and additional communication with the oxy-fuel system controls added.
3) Programmable Logic Controller (PLC) – most of the additional components for the oxy-fuel demonstration and their controls were established in a PLC. A HMI system was also supplied for operating the PLC controlled components, with monitors located both in the remote control room and in a lab located near the boiler. The oxy-fuel PLC communicated with the DCS via the plant Ethernet network and through several direct wired I/O signals. Due to the temporary nature of the demonstration this solution was the most practical. In a commercial implementation these functions would be permanently incorporated in the existing DCS.

3.5.1 Description of the Control System

The boiler operation is primarily controlled by a DCS system that monitors and controls the boiler startup and shutdown, and all process variables (i.e. steam quality, steam generation rate, ramp up/down, etc.), while a local PLC managed the oxy-fuel system operation.

The boiler firing rate (fuel gas flow rate) was automatically adjusted by the DCS according to the feedwater rate through the boiler. The key target variable was the desired steam quality at the boiler outlet by adjusting the heat input in relation to the feedwater flowrate. The combustion air flowrate was controlled by the preset air to fuel ratio, cross limited to the fuel gas flow rate, and trimmed to maintain the desired excess O2% level in the exhaust stack. In order to provide a safety margin during transitions between air-fuel and oxy-fuel operation, the excess O2% trim control was used to slightly increase the oxygen to fuel ratio. This was to prevent the possibility of a fuel rich condition in the boiler. During transients cross-limiting of the combustion air and fuel flow ensured that the above stoichiometric operation was maintained.

Safety critical shutdowns such as interruptions to the fuel gas supply or a loss of flame due to flame instability would result in a shutdown of the boiler by the BMS. The BMS receives input from a flame sensor (flame scanner) that detects the presence of flame through UV radiation from the combustion process.

Prior to starting the burner and after a shutdown, code prescribed purge sequences had to be completed. These purge sequences and interlocks were coordinated through the BMS. The DCS controlled the operation of the forced draft fan, the downstream air flow control damper, and the upstream air isolation damper. The PLC controlled the operation of the flue gas dampers and the upstream air modulating damper.

When operating in oxy-fuel mode, the PLC controlled the oxygen concentration in the recirculated flue gas. The oxygen concentration was measured in the flue gas duct downstream of the sparger and controlled through a PID loop.

3.5.2 HMI Screens

The HMI system provided for the test was programmed with several screens to facilitate operation and monitoring of the process.

Operation Screen

The "Operation" screen includes faceplate controllers for:

- O2 Skid Start/Stop
- Sparger Oxygen Flow Control FIC-300
  - Cascade – Controller in Auto mode using setpoint from DCS
  - Auto – Controller in Auto mode using local entered setpoint
  - Manual – Control valve position may be controlled directly by entering percentage open
- Flue Gas Flow Control FIC-680
  - Manual – Control valve position may be controlled directly by entering percentage open
- Flue Gas Isolation Damper XV-680
  - Manual – Damper position set by operator
- Combustion Air Damper HY-696 (Air inlet damper)
  - Manual – Damper position may be controlled directly by entering percentage open

Below the controller are the following Process Variable Indicators, displayed both in metric and imperial units:

- J-Oxygen Flow (FT-301) – Oxygen flow to the stabilizing burner
- FIC-300 Actual SP – Oxygen flow setpoint from oxygen concentration controller AIC-300O2 Supply Pressure (PIT-300) – Oxygen pressure at inlet to flow control skid

- O2 Outlet Pressure (PIT-301) – Oxygen pressure delivered to outlet of flow control skid
- FGR O2% Setpoint – Desired percentage of oxygen in recirculated flue gas
- FGR O2% Calculated – Calculated percentage of oxygen in recirculated flue gas
- O2% Before Sparger (AIT-680A) – Measured oxygen percent in flue gas prior to sparger
- O2% After Sparger (AIT-680B) – Measured oxygen percent in flue gas after sparger
- O2% At Transition Duct (AIT-683) – Measured oxygen percent in flue gas at transition duct
- FGR Moisture (AIT-680C) – Measured moisture percentage in recirculated flue gas
- Stack Temperature (TIT-667) – Stack temperature
- Stack Pressure (PIT-668) – Stack pressure

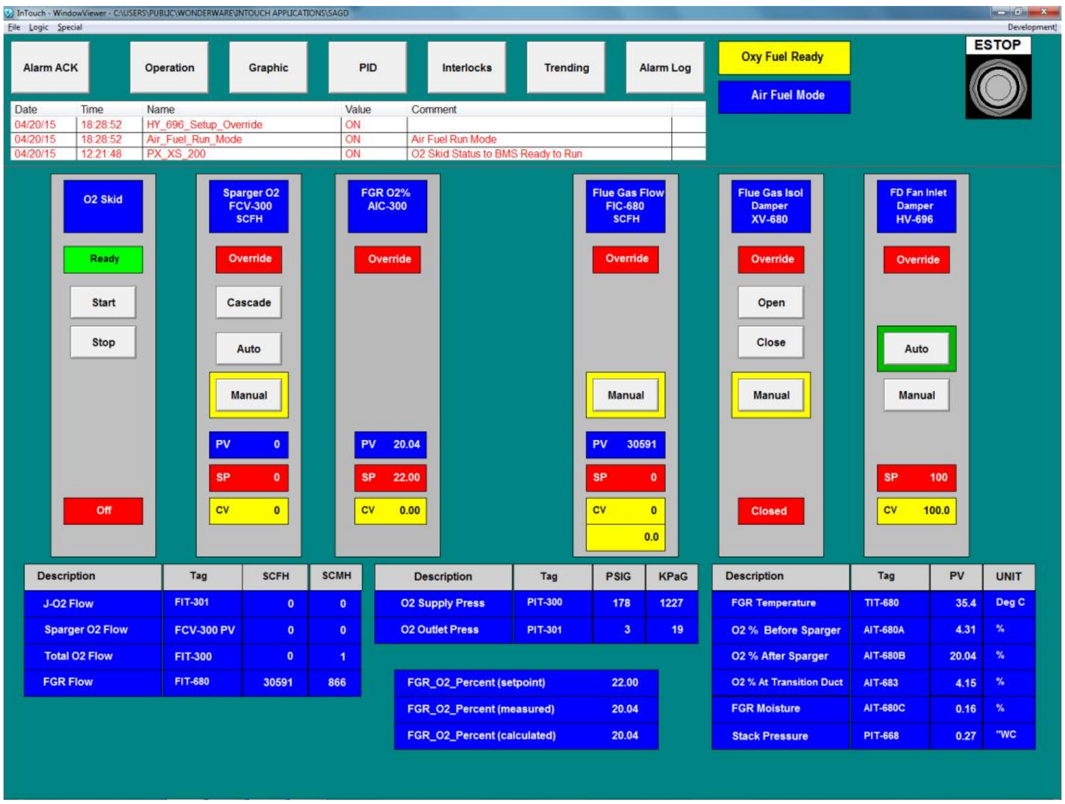

Figure 10: PLC Operation Screen for Oxy-Fuel System

Process Graphic

The Process Graphic screen in Figure 11 provided a status overview of the process for operation and troubleshooting. It showed the flue gas recirculation loop in the center with the shutoff dampers and the following instrumentation (in the direction of flow):

- O2% Before Sparger (AIT-680A) – Measured oxygen percent in flue gas prior to sparger
- Flow in FGR Duct (FIT-680) – Flow measured with a pitot grid

- O2% After Sparger (AIT-680B) – Measured oxygen percent in flue gas after sparger
- Temperature of Mixed Oxidant (TIT-680) – Temperature of mixture between FGR and O2
- FGR Moisture (AIT-680C) – Measured moisture percentage in recirculated flue gas

Below the FGR duct the oxygen train is shown with the following instrumentation (in the direction of flow):

- O2 Supply Pressure (PIT-300) – Pressure of oxygen from the supply system
- O2 Flow (FIT-300) – Total oxygen flow
- O2 Pressure at Sparger (PIT-301) – Pressure of oxygen after control skid
- O2 Flow (FIT-301) – Oxygen flow to J-Burner

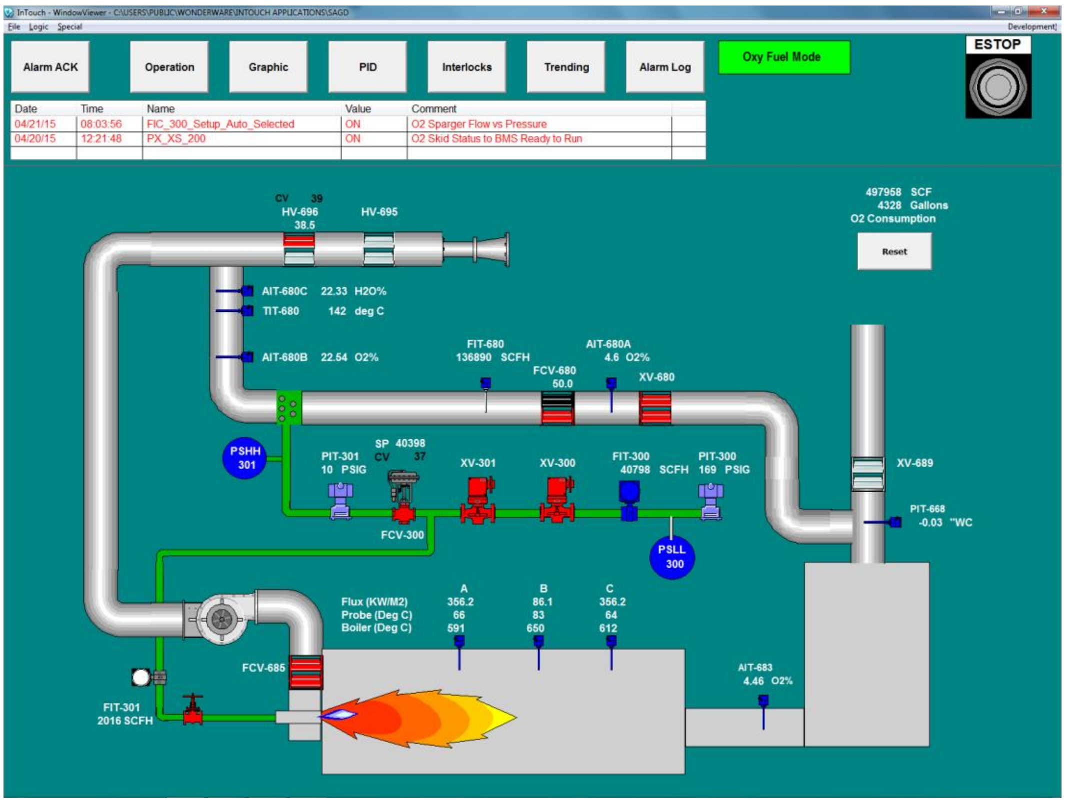

Figure 11: PLC Process Graphic Screen for Oxy-Fuel System

The steam evaporator at the bottom of the screen shows the heat flux measurement, temperatures in the heat flux probes to confirm cooling of the probes and the boiler thermocouples installed in the wall at the location of the tube circle. Two measurements are shown downstream of the evaporator section:

- O2% At Transition Duct (AIT-683) – Measured oxygen percent in flue gas between evaporator and economizer
- Stack Pressure (PIT-668) – Stack pressure

At the top of the screen a row of buttons allowed navigation between the screens and the most recent warnings, alarms and status messages were displayed in tabular form below.

Interlocks

Figure 12 shows the process interlocks that needed to be satisfied for the operation of the system. The interlocks were grouped in the following categories:

- Hard Wired Interlocks – These interlocks are through hardwired circuits that directly shut off power to the oxygen skid and to the BMS.
- Manual Transfer Warning Alarms – These interlocks do not directly shut off the oxygen skid. They signal the operator to initiate a manual transfer to air/fuel combustion.
- Warning Alarms – These are critical alarms that should be monitored closely by the operator, but do not require immediate shut down of the oxygen combustion system.
- Interlock Alarms – These are interlocks managed through software in the PLC that will shut off the oxygen combustion system.

Trip points are indicated for each interlock and may be adjusted by authorized personnel after "Logon" and entering the required password.

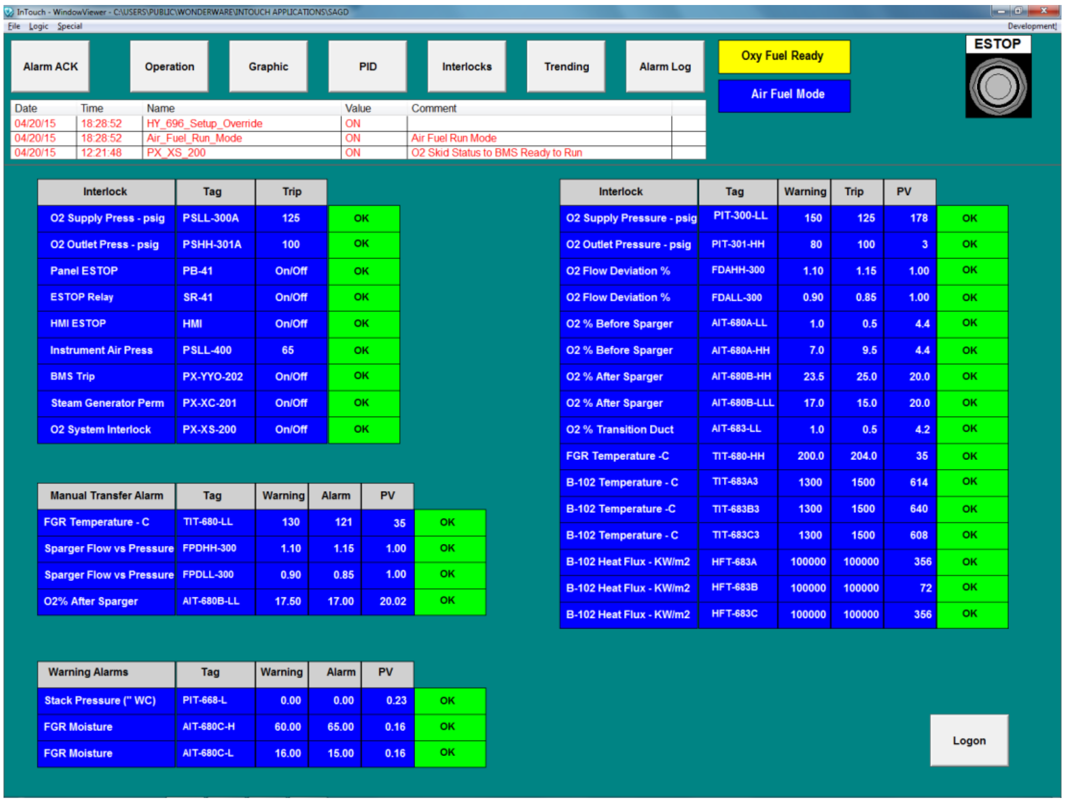

Figure 12: PLC Process Interlock Screen for Oxy-Fuel System

PID Faceplate

Standard PID faceplate controllers used for tuning PID parameters are shown in Figure 13. A "real time" trend and PID tuning parameters for each loop could be displayed by clicking the "Tuning" button to aid the tuning process.

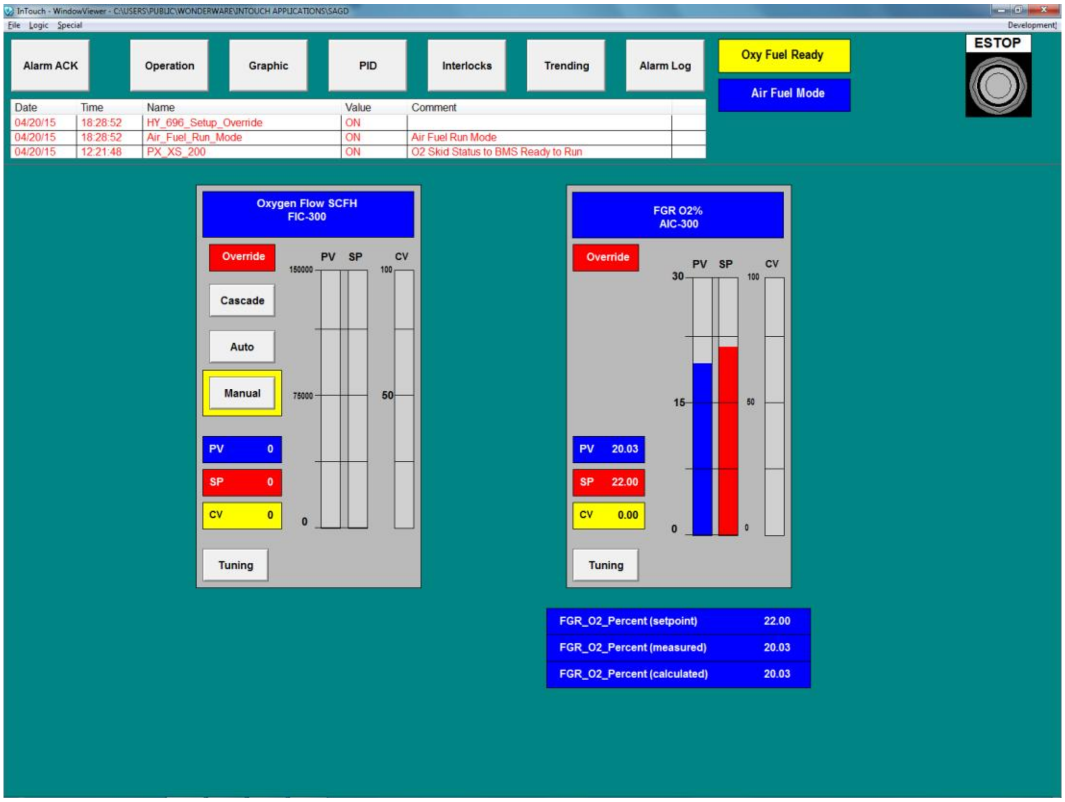

Figure 13: PLC Controller Screen for Oxy-Fuel System

Alarm Summary

The summary screen of alarms is shown in Figure 14. Alarms that were not active and acknowledged were cleared from the log.

Trending

The trend screens (Figure 15 shows oxygen flow as an example) proved useful for system optimization and transitions.

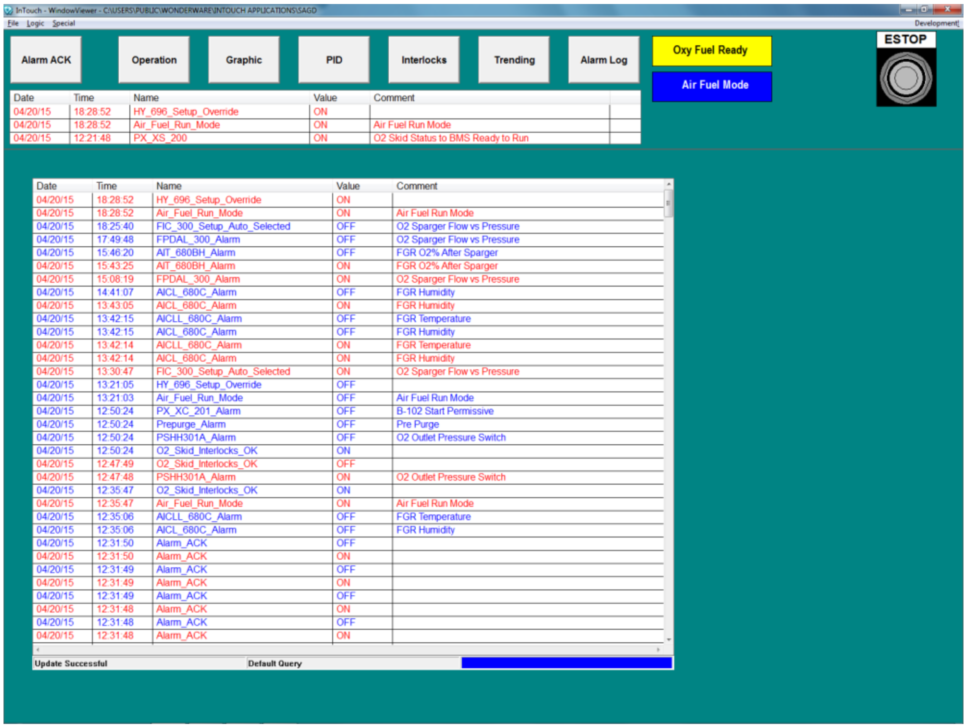

Figure 14: PLC Alarm Screen for Oxy-Fuel System

Figure 15: PLC Trending for Oxy-Fuel System

4. Results

The testing of the modified boiler began on 15 April 2015 with optimizing the transition from air to oxy-fuel. After losing the flame several times and learning how to best adjust the air and flue gas recirculation dampers the first successful transition was completed on 17 April 2015 at 10:15h. Oxy-fuel data collection started after this. When the oxy-fuel system was not in service, comparison data was collected during air-fuel operation. The contributing consortium members visited on 23 April and witnessed a successful transition from oxy-fuel to air-fuel and back which is discussed in Section 4.1.2.

Table 2 shows a summary of the test conditions for air-fuel and oxy-fuel. The boiler steam flow load range for the testing was 53 to 82% for the air-fuel tests and 54 to 78% for the oxy-fuel tests. The upper range for the load on oxy-fuel was restricted due to several operational issues discussed below. Typical operation for this boiler is at approximately 80% of theoretical design steam flow. As discussed in detail below the tests at high oxy-fuel loads were limited by increased burner velocities. The operation with oxy-fuel requires less fuel flow at the same boiler feedwater flow due to the higher efficiency of oxy-fuel combustion. Therefore, the flue flow range for oxy-fuel is slightly lower. The maximum possible fuel flow for this boiler is 28 t/d which corresponds to 93% of theoretical design steam flow.

Testing was performed at approximate levels of 70% and 80% of steam quality for both air-fuel and oxy-fuel to allow easier comparison of the data. Excess oxygen in the flue gas was about 1% higher during oxy-fuel tests compared to air-fuel. This is primarily due to the control system tuning for the equivalent air to fuel ratio during oxy-fuel operation. There is no question that the control system could be further optimized to match to the air-fuel operation excess O2 for a permanent installation.

Table 2: Range of Test Conditions

	Air-Fuel	**Oxy-Fuel**
Test Period	14 to 26 April 2015	17 to 23 April 2015
Feedwater Flow, t/d	390 - 601	395- 571
Boiler Load, % (see note)	53 - 82%	54 - 72%
Boiler Fuel Flow, t/d	14.1 - 24.6	13.6 -20.3
Steam Quality, %	68.2 – 69.1% and 77.6 – 78.7%	68.0 – 69.9% and 77.9 – 78.4%
Excess O2, %	2.8 – 4.4%	3.8 - 5.9%
CO_2 Emission Rate	40.0 – 69.9 t/d	38.5 – 57.7t/d

Note: The boiler load is expressed as percentage of design steam flow (733t/d). See text for details.

Typical composition for the flue gas concentrations at high boiler load are shown in Table 3. Theoretically, oxy-fuel eliminates all nitrogen in the flue gas. However, due to air damper leakage a small amount (~4-6%) of air entered the boiler and the camera and other instruments use cooling air which introduced additional nitrogen. The nitrogen concentration that was achieved at full load was approximately 16%. This concentration is subject to the internal boiler pressure and the quality of the air dampers. For a commercial system it will be important to minimize air leakage. Since the nitrogen in the flue gas was significantly reduced the concentrations for CO_2 and water vapor in flue gas are much higher. For example, the CO_2 concentration had increased from 8.2 to 27.5% when the boiler operation is switched to oxy-fuel.

With oxy-fuel combustion nearly half of the flue gas is water vapor. This has a significant impact on the water dewpoint. Using the flue gas concentration of air-fuel combustion in Table 3 the dewpoint is calculated as approximately 55°C, i.e. the flue gas starts to condense on surfaces with a temperature of less than this temperature. When the boiler was on oxy-fuel the calculated dewpoint is much higher and condensation occurred at temperatures below approximately 83°C. This has consequences for the design and cold startup of oxy-fuel flue gas system. The duct system needs to be designed with appropriate drain points, the system cold spots must be avoided by adding insulation and boiler access door seals and the insulation system must be appropriately designed to minimize the presence of liquid water.

Table 3: Typical Flue Gas Composition for High Boiler Load

	Air-Fuel		**Oxy-Fuel**	
	wet	dry	wet	dry
Carbon Dioxide, CO2	8.2%	9.7%	27.6%	57.5%
Water Vapor, H2O	15.5%	0.0%	52.0%	0.0%
Nitrogen, N2	72.9%	86.3%	16.2%	33.8%
Oxygen, O2	3.4%	4.0%	4.2%	8.8%
Sulfur Dioxide, SO2	0.0%	0.0%	0.0%	0.0%
Molecular Weight of Mixture	27.0	29.7	27.4	37.6
Dewpoint of Mixture	55°C	-	83°C	-

4.1. Operating Results

4.1.1 Boiler Load and Steam Quality

The following results for the boiler performance are expressed versus the feedwater flow as the measure for boiler load. Figure 16 and Figure 17 show the fuel flow and steam quality for air-fuel and oxy-fuel versus the boiler load for a steam quality level of approximately 70 and 80%, respectively. Note that the higher steam quality requires higher heat input to evaporate the additional water.

It can be seen that there is no steam quality difference between air-fuel and oxy-fuel combustion. Once the operator sets the steam quality target from the HMI, the boiler reacts the same regardless of the method of combustion and the trends for air-fuel and oxy-fuel are identical.

As both Figures show, the fuel flow for a given load is lower for oxy-fuel combustion. This is expected as oxy-fuel combustion is fundamentally more efficient than air fuel combustion. Air contains 78% nitrogen which is entering the boiler at ambient temperatures (~15°C at the time of testing) and leaves at the stack temperature (~200°C). This heating of nitrogen is an efficiency loss. The test boiler was not equipped with an air heater due to space constraints. The combustion with oxygen does not introduce nitrogen to the process, which reduces the flue gas amount by approximately 75% and the stack loss is significantly lower. During the demonstration the nitrogen concentration in the test boiler was approximately 16% due to a small amount of air leakage through the air dampers and the use of cooling air for the instruments.

Both figures suggest that oxy-fuel reduces the fuel consumption by approximately 1 t/d or 5%. The theoretical value can be calculated with an energy balance as 7% for a stack temperature of 200°C and an air temperature of 60°C.

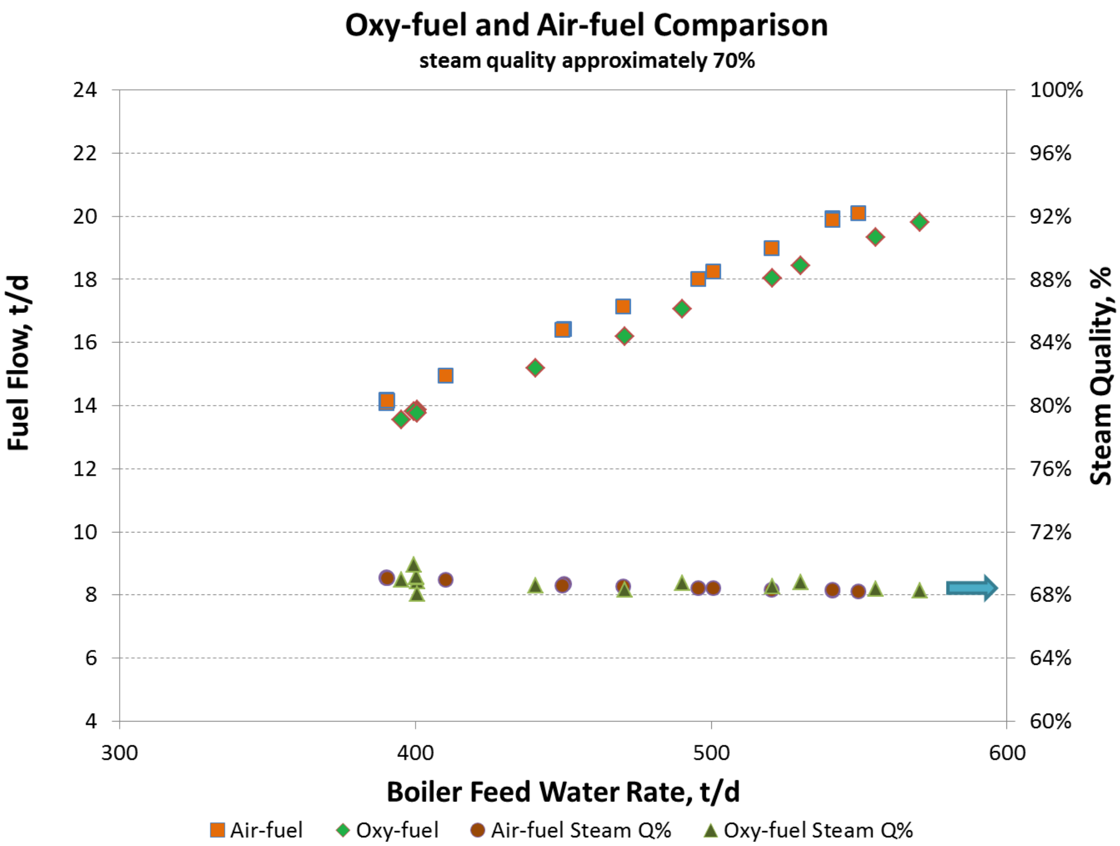

Figure 16: Fuel Flow at 70% Steam Quality versus Boiler Feedwater Flow

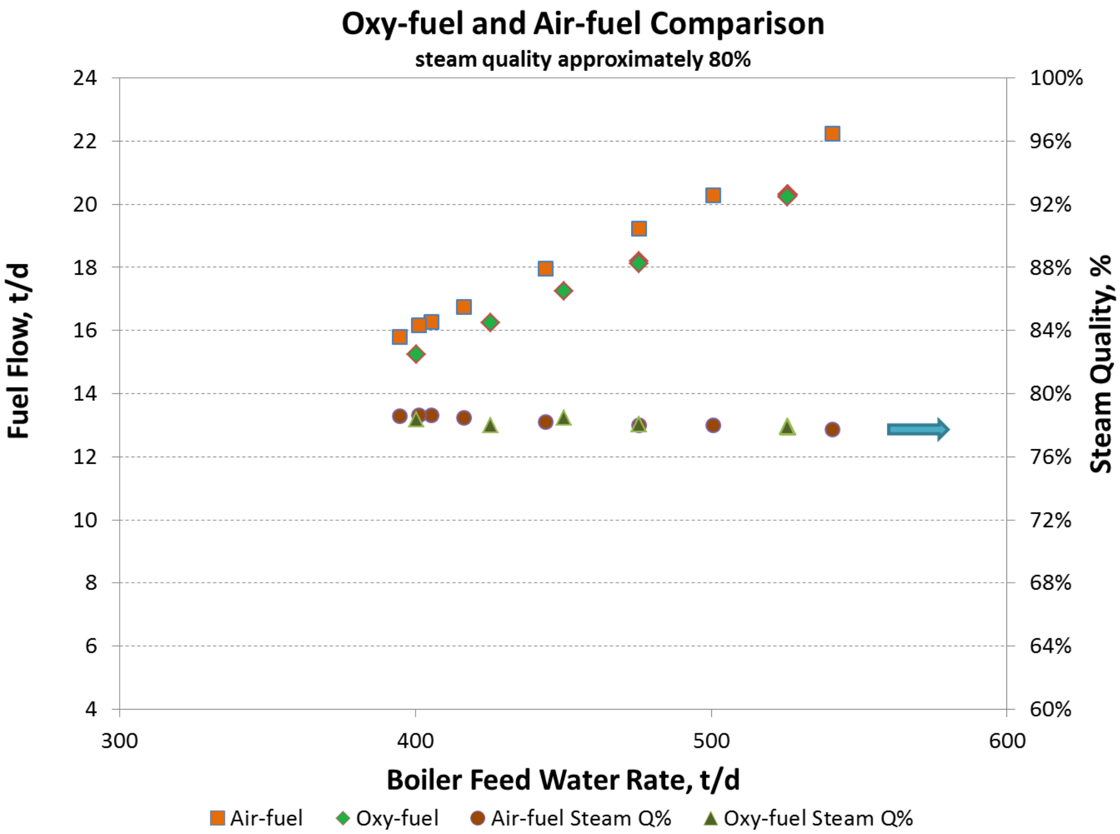

Figure 17: Fuel Flow at 80% Steam Quality versus Boiler Feedwater Flow

The variation of excess oxygen in the flue gas is shown in Figure 18. With air-fuel combustion the average excess oxygen was varied between approximately 4% at low load and 3% at maximum test load. The variation was larger with oxy-fuel testing mainly due to deliberate variations and the fact that there was no excess oxygen trim correction for the oxygen flow implemented for the short demonstration test. There is no technical reason that excess oxygen cannot be controlled to a tighter band and to a lower level than with air-fuel combustion.

In a commercial implementation of oxy-fuel combustion on a boiler for the purpose of carbon capture it is desirable to minimize excess oxygen. Like nitrogen, oxygen is a non-condensable gas and needs to be separated from the CO2 in the CO2 Processing Unit (CPU) prior to separation. With the appropriate controls oxy-fuel combustion will allow for stack excess O2 to be maintained near 1%. The reduction versus air combustion results in lower ASU and CPU power as less total O2 is required and fewer impurities will be sent to the CPU. Details are discussed in the Phase I - Task 2 Report [2].

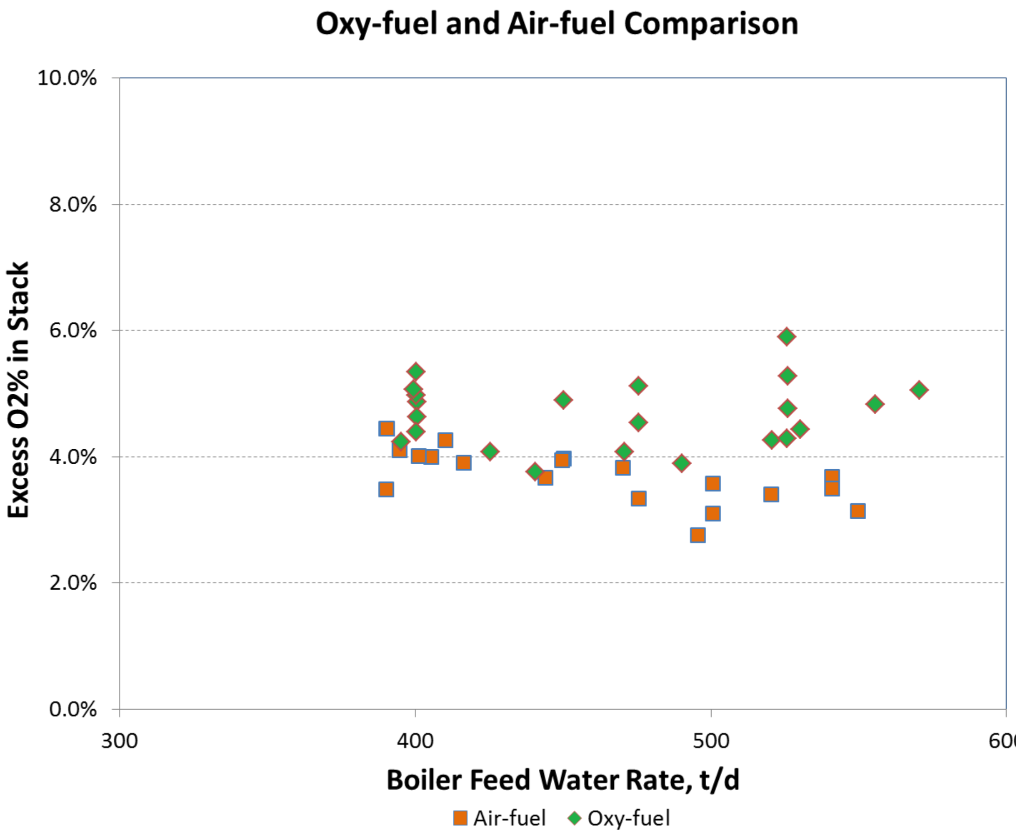

Figure 18: Boiler Excess Oxygen versus Boiler Load

Figure 19 shows experiments at 70% steam quality. The mass flow of flue gas through the evaporator and economizer is shown in the left vertical axis versus the boiler feedwater, i.e. the boiler load. On the right vertical axis the concentration of oxygen in the flue gas recirculation is shown. Most of the experiments were conducted with an FGR oxygen concentration of 23%. This oxygen concentration was chosen for these experiments as it produced stable combustion while keeping burner temperatures acceptably low.

The flue gas mass flow from oxy-fuel is generally lower than for air-fuel at comparable load and similar boiler performance (compare steam quality graph above), which means that the boiler heat transfer is similar under these conditions although less flue gas mass is flowing through the boiler. It should be noted that on oxy-fuel the mass flow of gas through the boiler is significantly higher than the stack mass flow as most of the gas flowing through the boiler is flue gas recirculation. The differences in heat transfer characteristics for oxy-fuel will be discussed in subsequent sections.

The graph also contains a variation of the oxygen concentration in the flue gas recirculation from 23% down to 21.2% at low load. The operation at 21.2% at the lower boiler load was at the burner stability limit and any further reduction in oxygen concentrations would have resulted in a loss of the flame. For the same boiler load the amount of oxygen required for combustion is the same, so the lower oxygen concentration could only be achieved by increasing the FGR which results in a higher mass flow through the boiler. The variation of the oxygen concentration in the FGR by approximately 2% leads to an increase of the boiler flue gas mass flow to the level of the air combustion. The same increase can be achieved by an increase of excess oxygen of approximately 2%, which increases the gas mass flow in a similar fashion. In summary the boiler mass flow reacts as to be expected and as shown later, the increased gas mass flow shifts the heat transfer from the radiant section to the economizer.

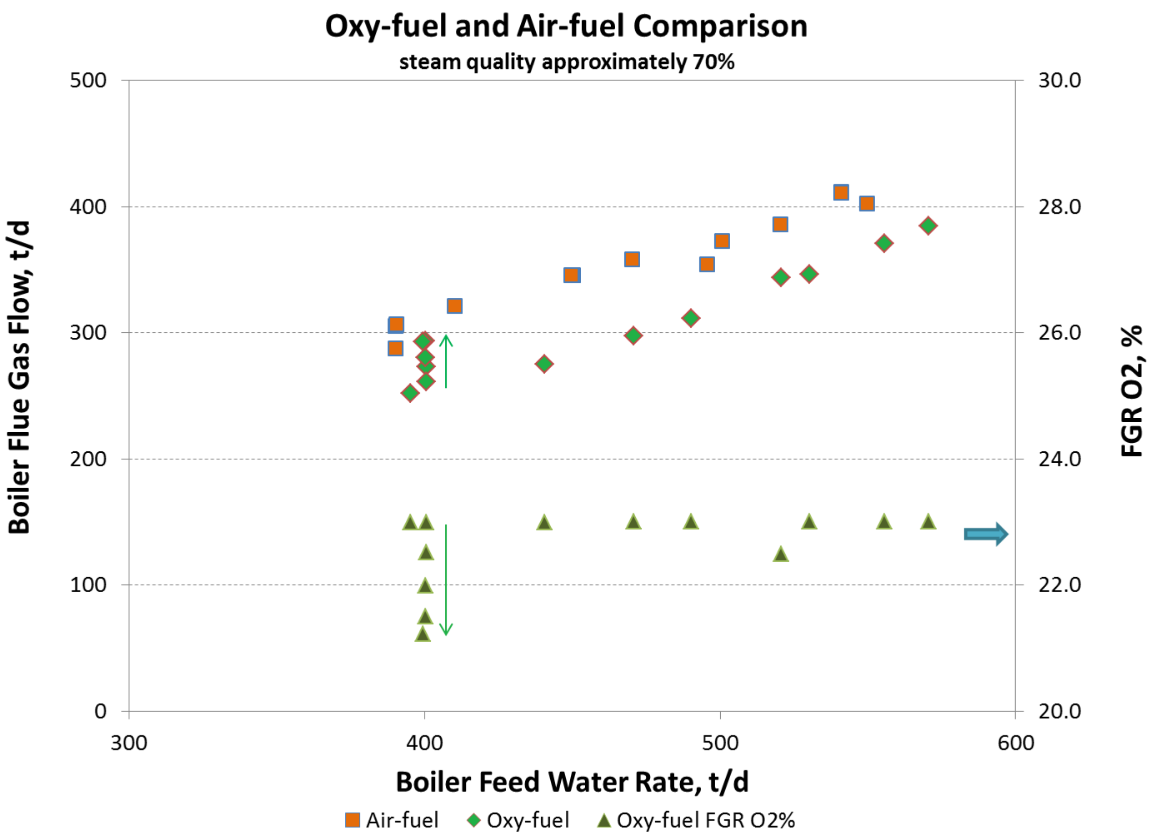

Figure 19: Calculated Flue Gas Flow versus Boiler Feedwater Flow

4.1.2 Transition

Transitioning between air-fuel and oxy-fuel was accomplished by first slowly opening the FGR dampers to introduce a mixture of FGR and oxygen then followed by slowly reducing the air flow to the boiler with the air dampers until the two air dampers were completely closed. The detailed procedure is listed in Section "Transition Air to Oxy-Fuel" of Cenovus Energy's Christina Lake Procedure B-102 COLD START-UP FOR OXY-FUEL in Appendix A. It proved essential to put the J-Burner in the center of the air burner into service for the transitions in and out of oxy-fuel as well as during full oxy-fuel operation. The energy from the small oxy-fuel burner increased the local temperatures at the flame root and provided stable ignition conditions for the fuel of the main burner. Transition back to air-fuel would take place in a similar fashion but in reversed steps.

Transitions were attempted at 70% and 50% boiler load, but changing the dampers induced pulsations of the flow during the transition that made transition attempts at 70% load unsuccessful. It is in the nature of systems with a recirculation loop that combustion disturbances are fed back to the burner inlet after the gas has traveled through the system. In the case of oxy-fuel combustion with flue gas recirculation approximately 75% of the combustion gas is recirculated. For example, if the burner starts to become unstable and the flame starts pulsing the resulting pressure and flue gas composition fluctuations are fed back to the burner inlet where they further disturb the combustion. Eventually the flame is lost.

However, after several initial flame failures and boiler shutdowns the procedure was optimized at a fuel input of 14 t/h (50% load) and transitioning became somewhat routine. The first successful transition took approximately two hours while at the end of the demonstration test a transition to oxy-fuel was completed in less than 30 minutes. The transition back to air-fuel was accomplished in a similar time frame. Figure 20 shows several boiler parameters versus time for the transitions from oxy-fuel to air-fuel combustion and back on 23 April 2015. The oxygen concentration in the flue gas recirculation was 22% during the transition and on oxy-fuel. The left vertical axis has the scale for the flows of air, oxygen and fuel gas mass flow. The brown line at the top shows the "Total Air", which accounts for both actual combustion air flow and the equivalent air amount that is calculated based on the oxygen flow rate from the oxy-fuel skid. The black line displays the fuel flow magnified by a factor of 10 to fit the common scale. The oxygen flow from oxy-fuel skid is shown in green and the actual combustion air flow in orange. The right axis shows the scale for the gray line, the excess oxygen in the flue gas.

The boiler is in stable oxy-fuel mode at the beginning of the time period. Note that the air flow measurement (orange) is not zero due to the measurement location and an offset of the flow transmitter at low or zero flows. However, the flow of air was reduced to some small air inleakage through the closed air dampers. To initiate the transition, the boiler fuel input was reduced to approximately15 t/h and the flow of oxygen and FGR with oxygen followed suit. At 12:27h the air dampers were opened and the flow of air started to increase while the oxygen flow is reduced. At 13:02h the transition to air-fuel was completed and the air flow measurement matched the total air flow. The boiler was held at a constant low load for approximately 2 hours before the transition from air-fuel to oxy-fuel was started at 14:52h. Here the process is reversed and initiated by opening the FGR dampers and starting FGR flow. The control system starts to increase the oxygen flow as needed to maintain appropriate oxygen concentration in FGR. When the FGR dampers were open the combustion air damper started to close further reducing air flow. The control system increases FGR and oxygen flows to maintain required combustion stoichiometry. The transition was completed at 15:20h and load was increased.

Although the excess oxygen in the flue gas (grey) showed stronger fluctuations during the transitions, which was due to how the control system was set up for the targeted air to fuel ratio, the maximum and minimum values are within an acceptable range. The main reason for the spikes was a fairly large air flow change when the air dampers are almost closed and that the timing of the control loops could have been further optimized. Note that most of the transition was performed manually and an automated process could have further improved the excess oxygen control. However, the operating team felt that the transitions were successfully optimized relatively quickly to a very good control quality and that further optimization would require longer commissioning time and hardware changes to the air dampers.

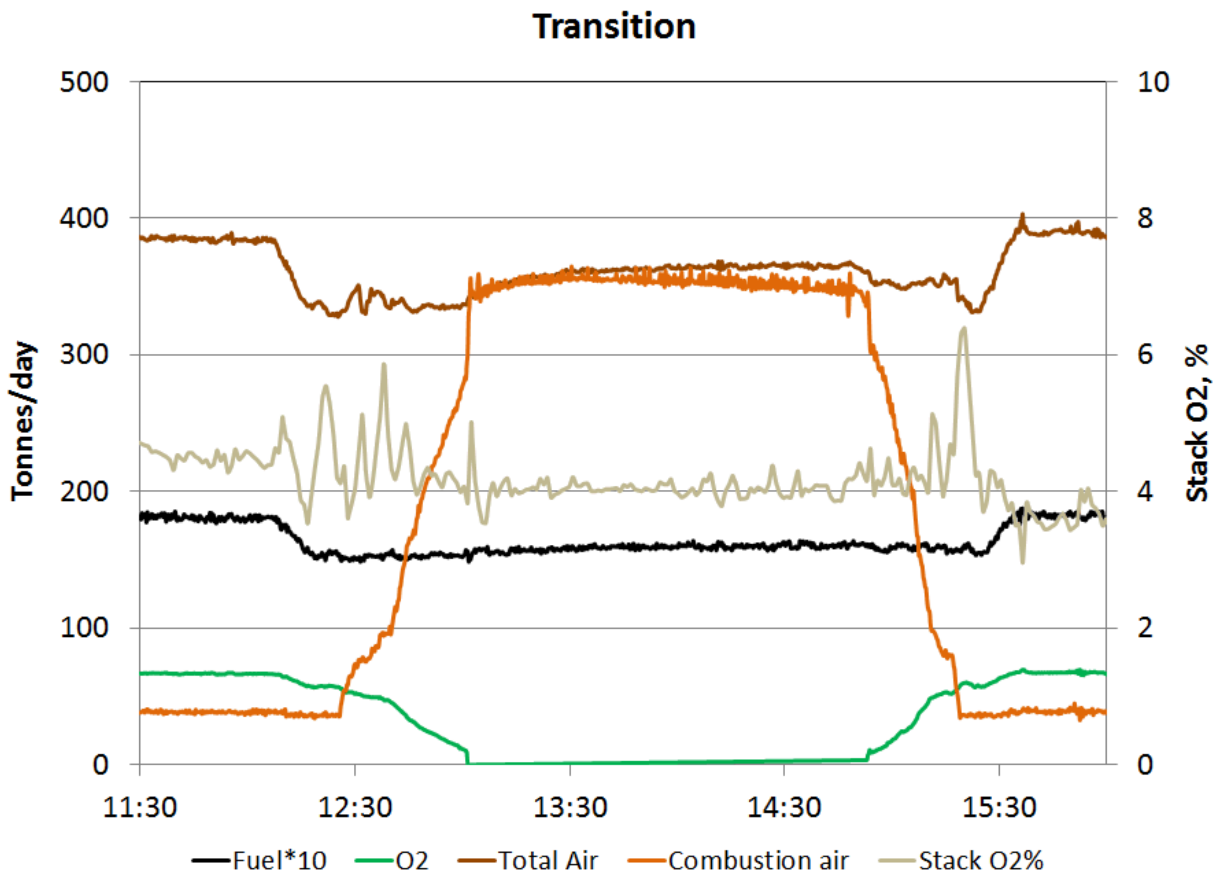

Figure 20: Transition from Oxy-fuel to Air-fuel and back

Some miscellaneous trends for the transition are shown in Figure 21 to further illustrate the process. The oxygen flow in green is used as a reference for oxy-fuel operation. At the beginning of the time period the boiler is on oxy-fuel. The mixture of FGR and oxygen is at a temperature of 162°C and the humidity of this mixture is approximately 40%. The on-line steam quality measurement shows values just below 80%.

When the boiler is transitioning to air-fuel, the temperature and humidity of the oxidant flowing to the burner drops as the oxidant is gradually changed to air. As mentioned above the air preheater was removed from the boiler for the demonstration to make room for the installation. The humidity drops due to the low humidity of the air mixing into the FGR.

The transition of the boiler from air-fuel to oxy-fuel reverses the trends. Although there are a few larger fluctuations of the steam quality during the entire transition, the quality is essentially unchanged by switching the boiler from oxygen to air and back. The transition trends show that there are very little operational changes in boiler behavior when oxy-fuel combustion with flue gas recirculation is retrofitted.

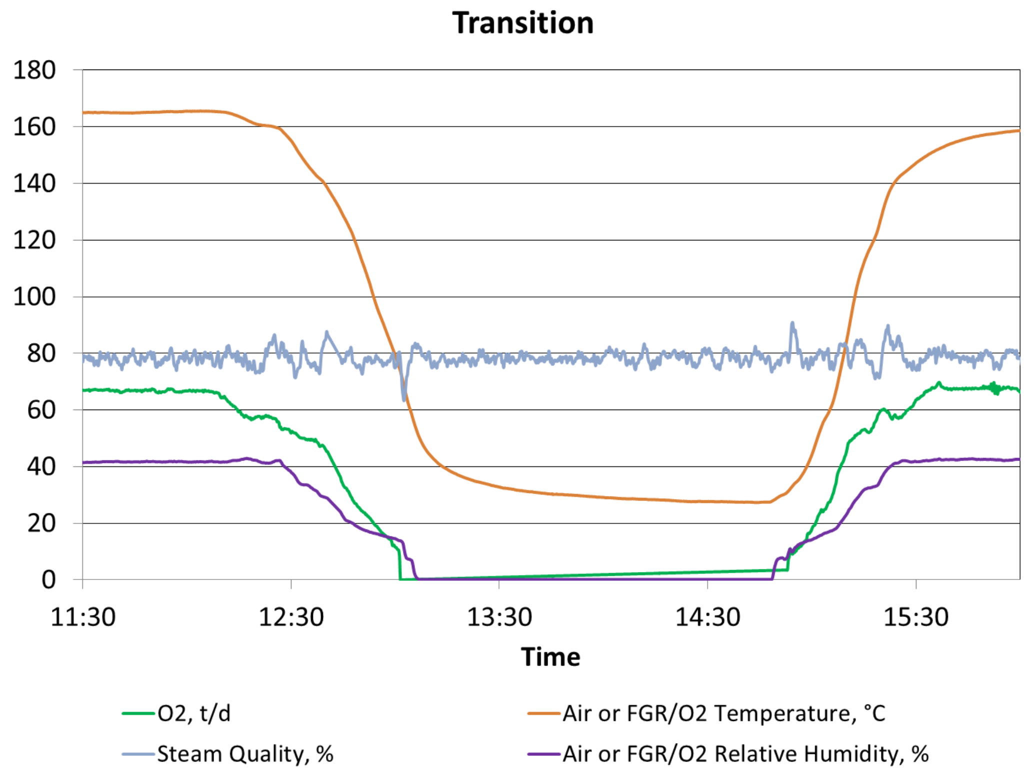

Figure 21: Miscellaneous Data during Transition

Figure 22 shows four flame images taken during the transition from air-fuel to oxy-fuel. The air-fuel flame shows bright flames near the pie-shaped burner refractory tiles. The fuel injected through the core fuel nozzles of the burner burns in the recirculation zone of the tiles that develops due to the air from the windbox that is coming from the slots between the tiles. The tiles glow orange and the increased temperature in this area provides appropriate ignition conditions. However, the bulk of the premixed fuel is burning with a blue flame which fills nearly the entire image. The tips of this flame are brighter from small amounts of soot that burn out in this region. This soot combustion illuminates the boiler internally.

The image at the top right shows the oxy-fuel J-Burner installed in the burner center lit. The heat input of this small support burner is only 3% of the total combustion heat input. The very luminous oxy-fuel flame illuminates the outer burner parts and the ring of the outer fuel nozzles becomes visible which makes the burner appear to be larger. Due to the auto-gain setting of the camera the increased brightness reduces the visibility of the air-fuel flame. The brightness of the burner tiles appear less for the same reasons.

During the transition (bottom left image) the flame above the tiles has nearly disappeared and the J-Burner flame is shorter. The mixture of air, oxygen, flue gas recirculation and natural gas burns with a dark blue flame. The shorter J-Burner flame is a result of higher overall burner velocities due to the increased temperature of the mixture and the flue gas recirculation. The forward momentum of the small J-Burner competes with the local recirculation near the burner axis which provides a backwards flow near the burner. At very high burner loads this resulted in a very short flame from the J-Burner.

The oxy-fuel flame after the transition is complete is shown in the bottom right image. The burner tiles glow orange with the exception of the immediate vicinity of the core gas nozzles which are very bright. The J-Burner flame has further shortened and is more slender. As a result the burner is less illuminated and the outer refractory ring is less visible. The premixed fuel burns with the oxygen in the flue gas recirculation with a dark blue flame. The overall brightness in the boiler was decreased. However, the brightness or visible light emissions are not necessarily related to the local heat flux (see below).

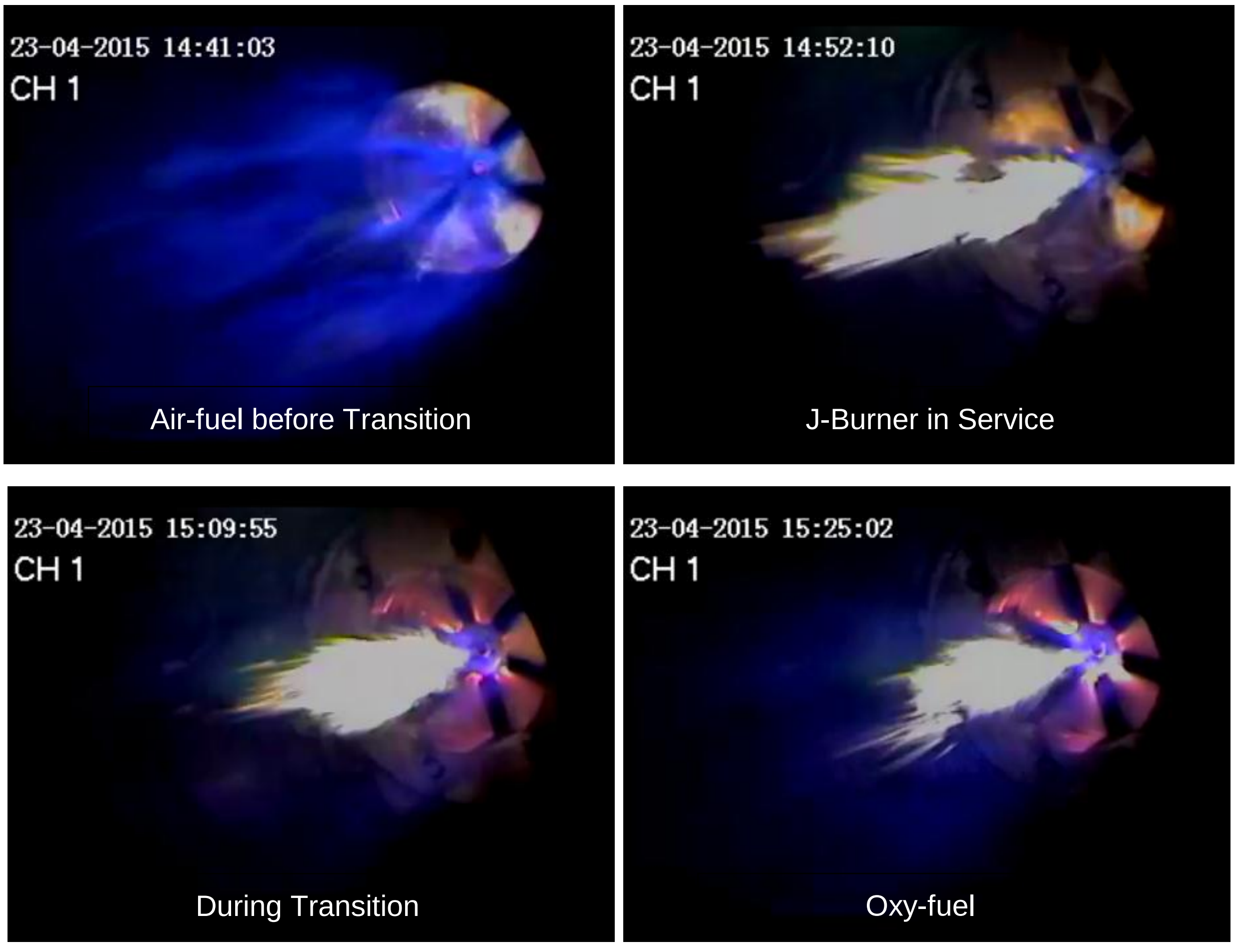

Figure 22: Flame Images for the Transition from Air-fuel to Oxy-fuel

4.1.3 Flame Appearance

The video camera allowed constant flame monitoring and was invaluable for the conduction of the tests. The changes in flame shape, potential localized overheating and beginning of flame instability could be easily detected and corrective action taken. The images were recorded on a DVR and screen snapshots taken for comparison.

The comparison of the oxy-fuel flame to air combustion at higher load (Figure 23) shows that the air flame has a large bulb-shaped area of blue flame close to the burner. The tips of this part of the flame are sometimes more luminous due to combustion of small amounts of soot. The tiles are glowing orange indicating that there are high combustion temperatures present in the ignition zone. Adjacent to some tiles more luminous flame can be seen. In the video this luminous flame is not stationary and jumps from tile to tile. In the center of the burner the tip of the J-Burner is glowing orange due to the high temperatures in this area. The J-Burner was designed for these conditions and there was no damage noticed on the burner after the demonstration.

The oxy-fuel flame image on the right shows a much darker main flame which appears to be more slender. This lower luminosity of the main flame resulted in lower light inside the boiler evaporator that made the observation through inspection doors a bit more challenging. However, the lower light conditions should not be confused with the radiative heat flux that the boiler tubes receive. This heat flux is generally higher with oxy-fuel combustion, because the products of combustion water vapor and CO_2 are radiating gases with much more effective heat transfer. Details are discussed in Section 4.2 below. The center of the oxy-fuel flame is illuminated by the flame of the J-Burner. The heat from this burner and the fuel injected close to the center through the core spuds results in a very bright burner center with high temperatures. The rest of the burner tiles are glowing orange in a similar fashion than with air combustion.

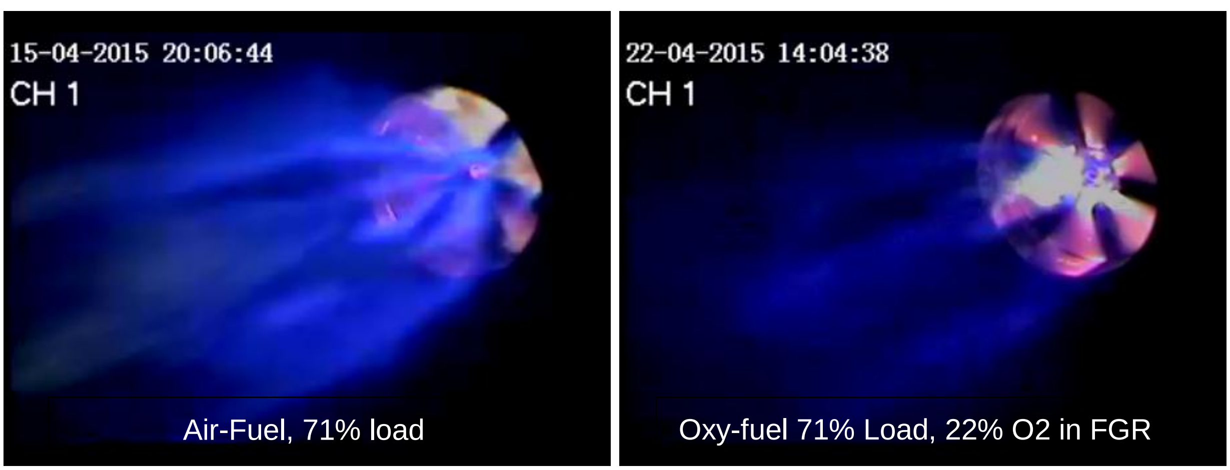

Figure 23: Air-fuel and Oxy-fuel Flame Images for High Load

Figure 24 compares images of oxy-fuel at different load with an oxygen concentration of 22% oxygen in the FGR. At low load the J-Burner flame is noticeable longer. As discussed in the description of the transition above, the forward momentum of the small J-Burner is not strong enough to compete with the internal recirculation flows of the larger flame. This “pulls” the small oxy-fuel flame towards the burner. The burner tile appeared hotter at high loads and the temperatures at the center of the burner increased considerably. This was confirmed by inspection of the tile steel backing plates during the experiments. Due to concern for the burner integrity further load increases were not attempted. With relatively simple burner design changes this limitation can be easily overcome. The darker blue flame parts of the main flame are brighter at high load and the flame is longer and more slender.

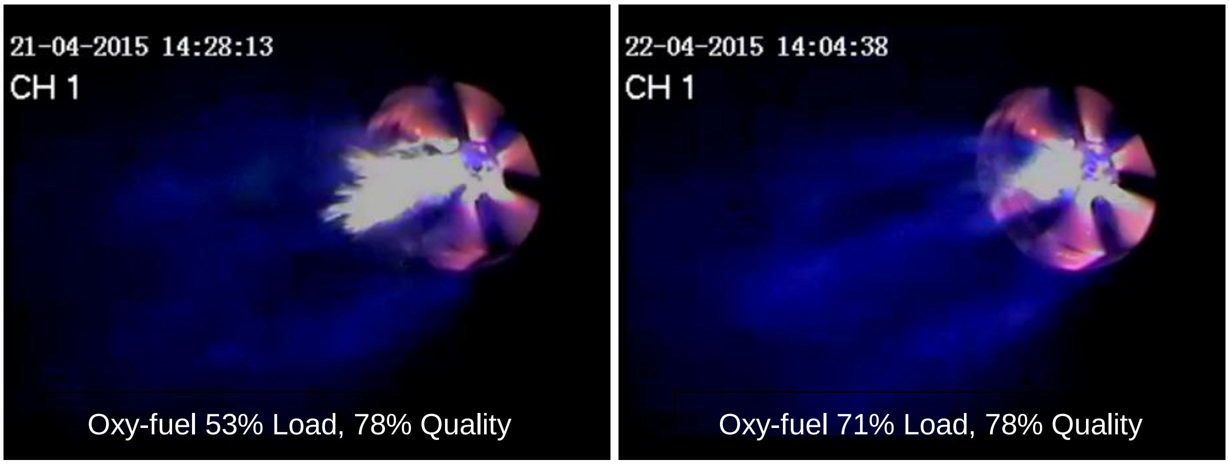

Figure 24: Oxy-fuel Flame Images for Low and High Load

4.1.4 Flame Stability

Figure 25 shows a comparison of two oxy-fuel images with different concentration of oxygen in the flue gas recirculation at low boiler load (53%). On the left the image shows combustion with a low oxygen concentration, i.e. higher FGR flow at the same oxygen flow. This image shows combustion at the stability limit. It was not possible to operate the burner below a concentration of 21% oxygen in the FGR. The video shows that the flame is noticeable flickering. The blue section of the flame is not well shaped and “pumping” with larger dark parts. The burner tiles are not very bright. The burner produced significantly higher CO emissions when it was close to the stability limit which is an indication that parts of the flame are getting too cold to completely combust the fuel. The flame was lost several times when it was attempted to determine the lowest possible oxygen concentration in the FGR.

In contrast, the image at 23% oxygen in the FGR shows that the tile is hotter and the flame is well shaped. There were no noticeable stability issues in the video and the blue part of the flame is well developed.

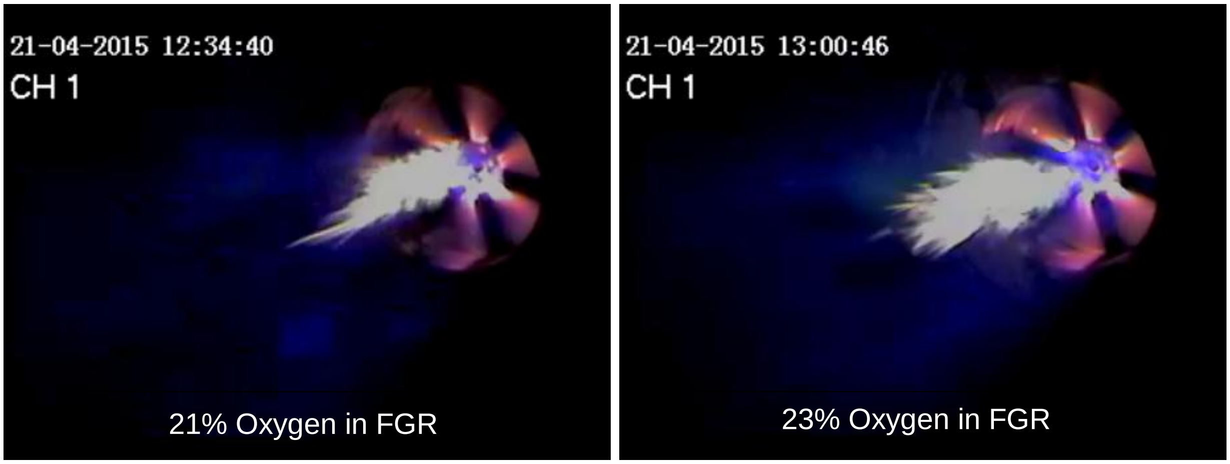

Figure 25: Flame Images for Different Oxygen Concentrations in FGR

The video images showed increased disturbance of the flame prior to loss of flame event. At that point is was usually too late to intervene by increasing the concentration of oxygen in the FGR. Due to the feedback of the recirculation loop to the windbox inlet any pressure fluctuations further negatively impacted the flame stability and the loss of flame occurred rapidly thereafter.

It is difficult to define a single parameter that affects flame stability. It is a function of burner velocity and local recirculation of hot combustion gas back to the flame root where sufficiently high local temperatures at the ignition point near the tile are necessary. These local temperatures are influenced by many factors such as firing rate, burner fuel distribution and O2 concentration in oxidant as well as the heat capacity of the gas. Higher velocities through the burner negatively influence the ignition process, because local velocities at the ignition point must be below the flame speed, so that the ignition front can propagate back.

The design of the ultra-low NOx burners premixes the majority of the flue with the air (or the oxygen/FGR mixture) that is flowing through the burner. This results in very low combustion temperatures and therefore low NOx. However, this air is intentionally fast to avoid early combustion behind the burner tiles and the operation of the burner is close to the stability limit.

The mixture of oxygen and hot flue gas recirculation had a temperature at the windbox in the range of 160 to 180°C. In contrast, the combustion air temperature was not preheated because the air preheater had to be removed due to space constraints. The differences in mass flow and the resulting combustion oxidant density difference resulted in the velocities displayed in Figure 26. At the same fuel input to the burner the velocities during oxy-fuel combustion were approximately 33% to 40% higher. This appreciable increase in velocities could be part of the reason why the burner is less stable with oxy-fuel combustion for certain operational conditions. However, it should be noted that for most conditions the oxy-fuel combustion showed a stable flame and that the demonstration of oxy-fuel combustion with this burner was quite successful.

The increase of burner velocities was also experienced when large OTSG boilers in commercial operation were retrofitted with flue gas recirculation systems for NOx reduction. Mixing flue gas recirculation (approximately 15%) into the combustion air lowers local flame temperatures and reduces NOx, but it also increases the gas mass flow through the burner. The latest generation of SAGD boilers with FGR for NOx control has relatively larger burners compared to similar boilers without this control method.

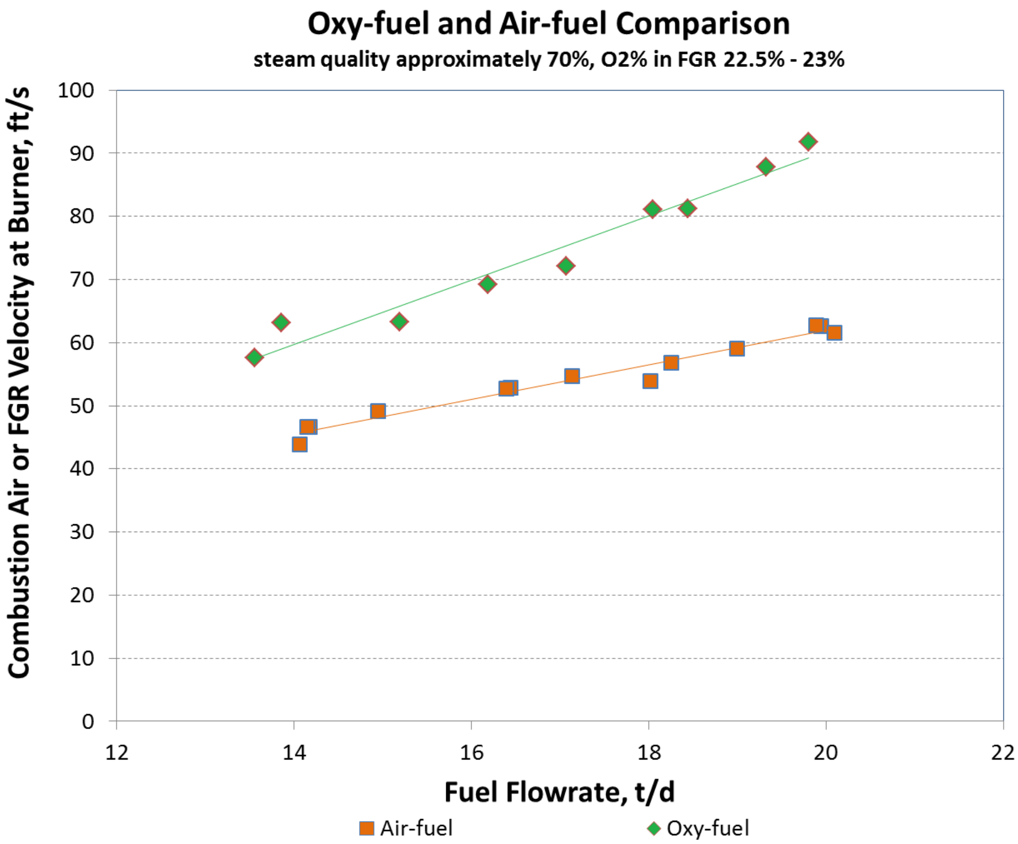

Figure 26: Calculated Burner Velocities versus Fuel Input

Data for low boiler feed water flow and targeted 70% steam quality which result in the lowest fuel flow to the burner are shown in Figure 27. The increased oxygen concentration in the FGR reduces the mass flow through the boiler and as a result the velocities at the burner are reduced as well. As mentioned above, operation at a concentration of 21.2% oxygen in the FGR is at the limit of stability and believed to be unsustainable over a longer time. The graph shows this data point in blue. Compared to the O_2 concentration of 21.5% the calculated velocity could not be significantly differentiated since the data collected for this condition was very short and other operational parameters might not have reached steady state. However, the trend is fairly clear that while holding other conditions the same higher burner velocity and lower O_2 concentration in oxidant would negatively affect flame stability. Further experiments on flame stability limit at other boiler load were not possible due to the limited time available for the demonstration.

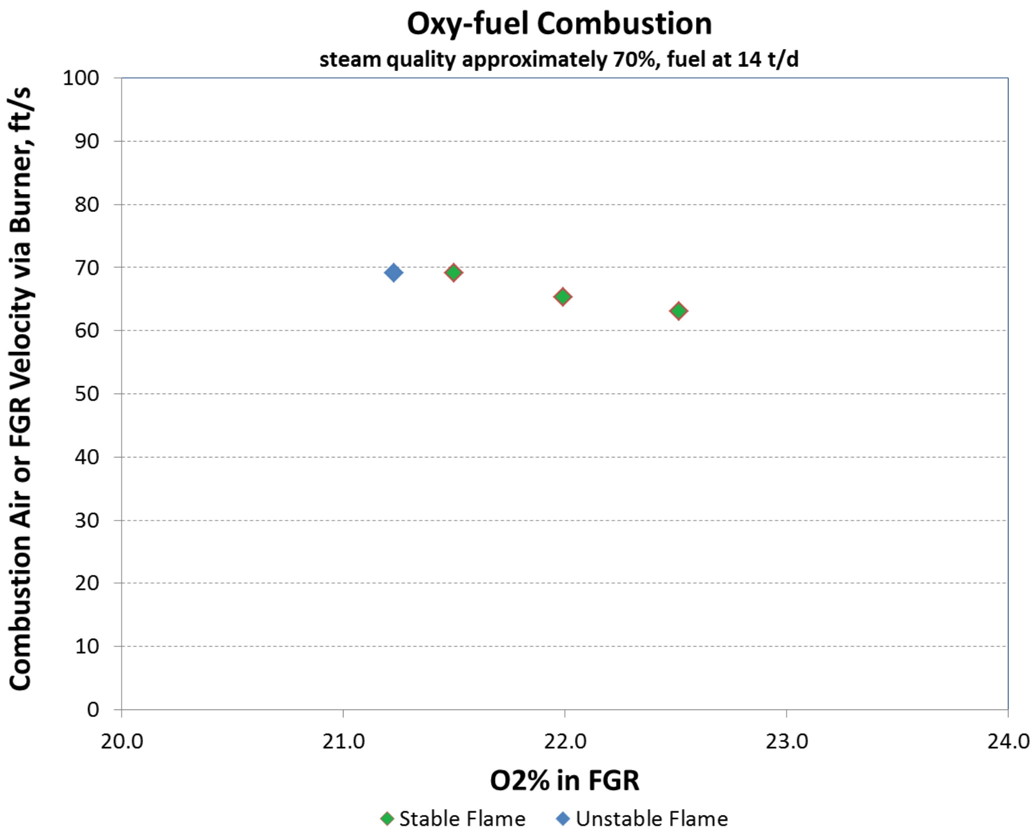

Figure 27: Burner Velocity versus Oxygen Concentration in the Flue Gas Recirculation

4.2. Heat Flux and Boiler Performance

It is well known that oxy-fuel combustion can increase furnace and boiler efficiencies due to reduced sensible heat loss (no nitrogen) and improved radiative heat transfer. This increase in efficiency allows the boiler operator to reduce the firing rate while maintaining the same steam output and quality. As described in section 4.1.1. , data from the demonstration showed that the fuel consumption rates were reduced by ~ 5% for all oxy-fuel conditions tested while keeping the steam flow rate and quality constant.

Another critical performance parameter is the heat duty split between the radiant section and the convective section. Even though the common design practice for OTSG is based on low radiative heat flux and incomplete evaporation of the boiler feed water in the radiant section, it is still ideal to keep the split similar to that of the air-fuel operation as well as to keep the heat transfer in the radiant section below the design limit in order to avoid added maintenance and operational issues with oxy-fuel firing. For example, if the heat transfer to the boiler tubes is higher than the design limit it could cause the coils to dry out leading to deposit of feedwater solids that inhibit the inner tube wall heat transfer and results in higher tube temperatures. This could cause tube failures leading to boiler damage and loss of production. On the other hand, if more heat is transferred to the convective tubes, which are designed to handle liquid phase boiler feed water, it could cause steaming in those tubes and exceed the design safety limit.

Since nitrogen from the air is eliminated with oxy-fuel combustion the flue gas flow is significantly lower than for air-fuel. The emissivity of the oxy-fuel flue gas is significantly higher than that from air-fuel combustion which results in higher heat transfer in the radiant section. Therefore, in order to better match the operation of the boiler with air-fuel combustion, flue gas recirculation is used to, create additional gas mass flow through the boiler to transport more heat to the convective section. This flue gas recirculation mixed with oxygen serves as a “pseudo air” for operation.

Data for heat duty splits that compares oxy-fuel combustion to the air-fuel combustion for the various of test conditions is plotted against boiler fuel load in Figure 28. The duty split is calculated by a heat and mass balance of the boiler feed water / steam side. A slight increase in heat transfer in the boiler evaporative section was noticed with oxy-fuel operation as compared to that of air-fuel, however, in general there is very good agreement between the heat transfer. The higher heat transfer in the evaporator is consistent with the fact that the oxygen concentration in FGR is higher than originally designed which led to slightly less flue gas flow. Also, the FGR oxygen concentration could not be further reduced in order to ensure flame stability at low boiler load. The heat duty split between the radiant and convective section is load dependent and at lower firing rates more heat is transferred in the radiant section. This could be seen in the same plot by the slight trending down in the duty split as firing rate is increased.

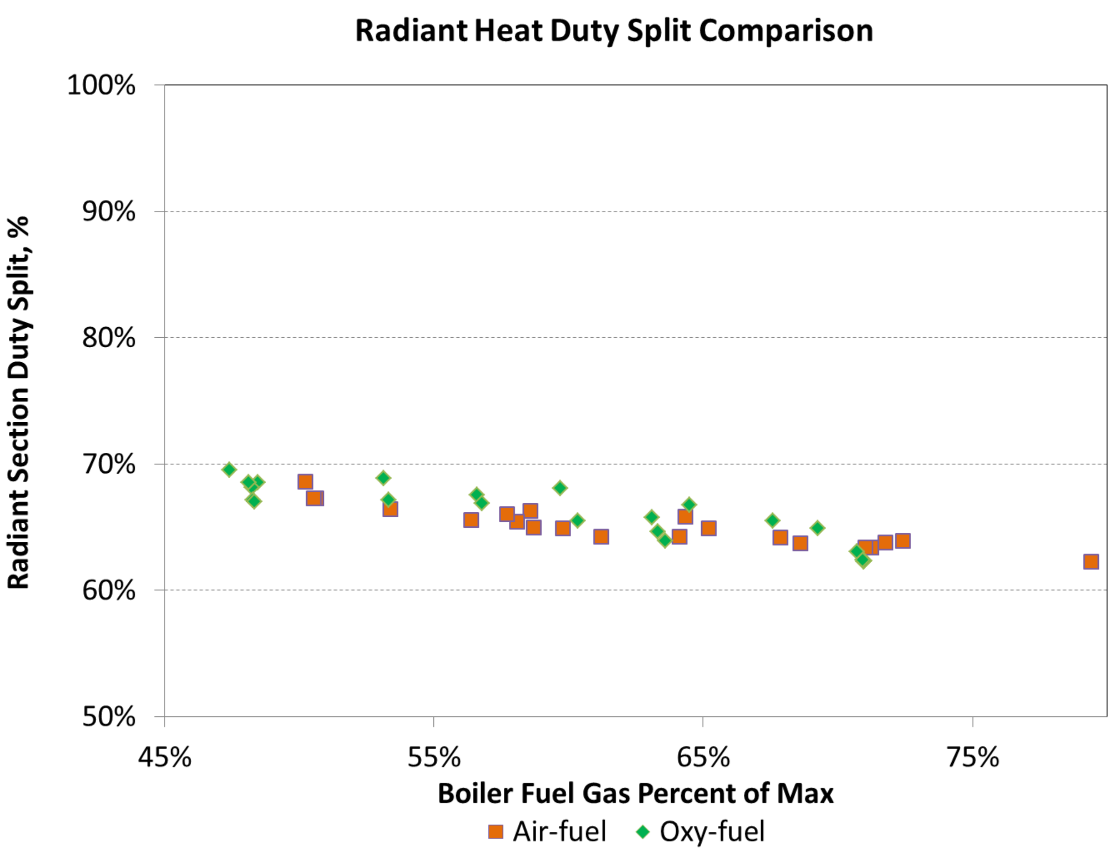

Figure 28: Comparison of Radiant Heat Transfer in Boiler

The higher heat transfer in the radiant section during oxy-fuel combustion is also shown by the results of the heat flux measurements at 44% of the relative evaporator length, in Figure 29. Normally, the standard OTSG design limits the maximum heat flux in the radiant to 39,000 to 40,000 Btu/ft^2-hr, or 123 KW/m^2. As can be seen in this Figure, the heat flux of the oxy-fuel case is slightly higher than that of the base air-firing case. This is due largely to the increase in the gas emissivity from ~ 0.30 (air-fuel) to ~0.52 (oxy-fuel). Therefore, even if the gas temperature profile is similar between the two combustion environments, the heat flux will be larger with oxy-firing.

When the boiler tubes were inspected at high oxy-fuel load a more visible glow of the tube hangers in evaporator center were noticed in this area. This was likely a combination of these hangers being more noticeable due to the generally "darker" boiler under oxy-fuel conditions and due to the increase of the heat flux in the center by approximately 10-15%. The operations team felt that this glowing was still acceptable. More FGR flow would have reduced the radiant flux in this area, but would have also lowered the oxygen concentration in the FGR, which has the aforementioned negative stability impact.

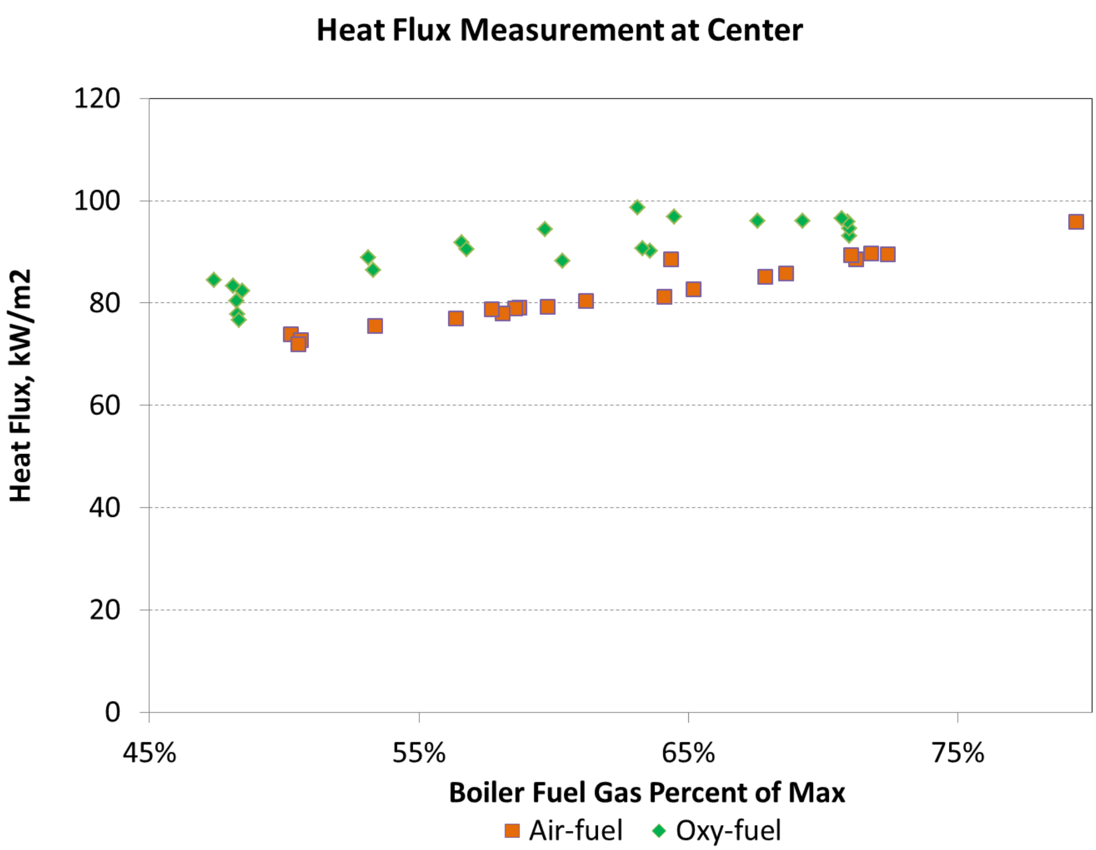

Figure 29: Total Heat Flux at Center Probe

One of the best ways to control the heat absorption balance is to optimize the flue gas recirculation rate. Since the flow of oxygen is fixed at a given fuel consumption, the flue gas recirculation rate also defines the oxygen concentration in the oxidant used to fire the boiler.

Our calculations show that in addition to the oxygen concentration in FGR the excess oxygen in the exhaust stack also has strong impact on the radiant/convective duty balance. This is explained in Figure 30 which shows the oxygen concentration in the FGR required to match the air-fuel combustion heat transfer as a function of excess oxygen in flue gas. During Phase I of the project the boiler operation was simulated with CFD modeling. It was concluded that the oxygen concentration in the FGR has to be 19% to match the heat transfer balance between the radiant and convective section. The model, however, assumed 1% excess oxygen in flue gas. As one can see from the calculation, at 1% excess oxygen the oxygen concentration in the FGR must be between 17-18% to balance the heat transfer in the two sections, which is consistent with the CFD model. During the oxy-fuel tests the excess O2% was at 4-5%, which means that the FGR oxygen concentration would have to be 21 to 23%, which is consistent with the experimental observations.

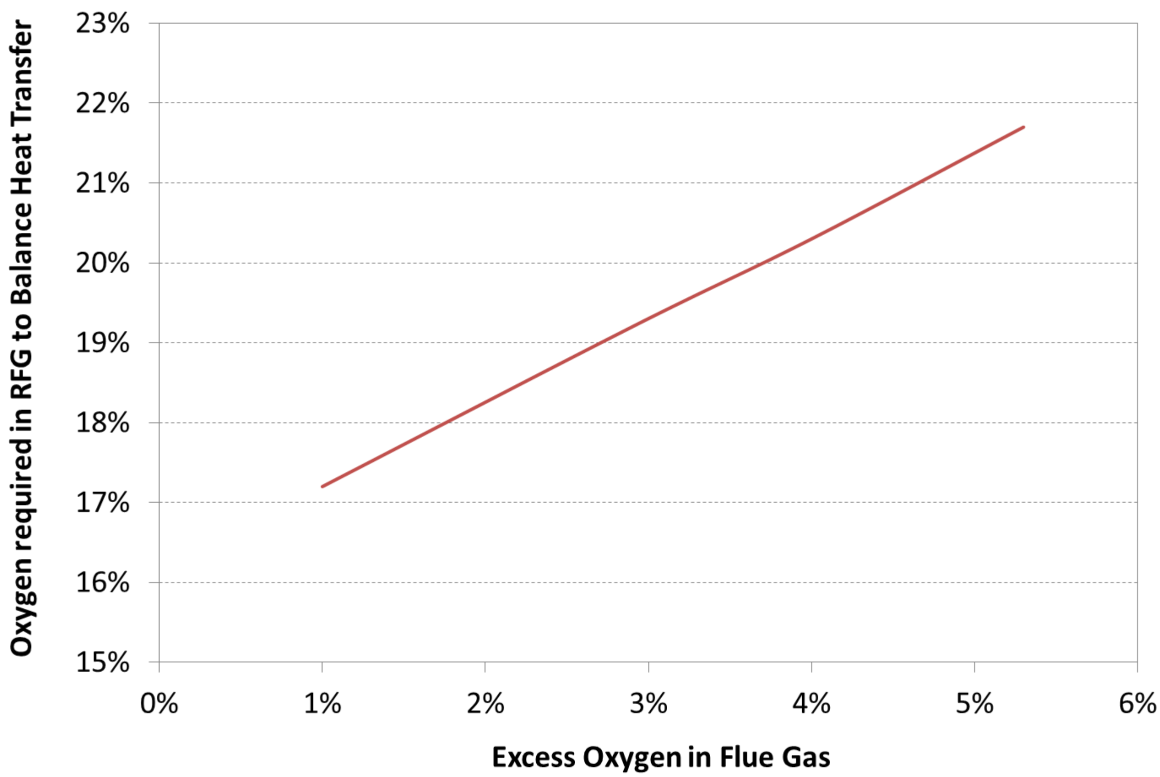

Figure 30: O2% in FGR as a Function of Excess O2% to Match Heat Transfer

4.3. Emissions

The emissions were measured during the demonstration with automated analyzers that were housed in a test trailer. The measurement sample was taken at the flue gas stack. Please refer to Section 3.4.2 for details.

The NOx emissions for all tests regardless of parametric variations are shown in Figure 31. The volumetric concentration was converted to the mass-based unit commonly used in North America, lb/MMBtu on a higher heating value basis. Reporting emissions with a mass-based unit makes more sense for oxy-fuel, because the amount of flue gas is much less and there is no nitrogen that acts as a dilutant as it is the case for air-fuel combustion.

In general, the oxy-fuel data shown in the graph are at a much lower level of approximately 15% of those measured on air combustion. The variation of the emissions on both air-fuel and oxy-fuel operation are surprisingly small.

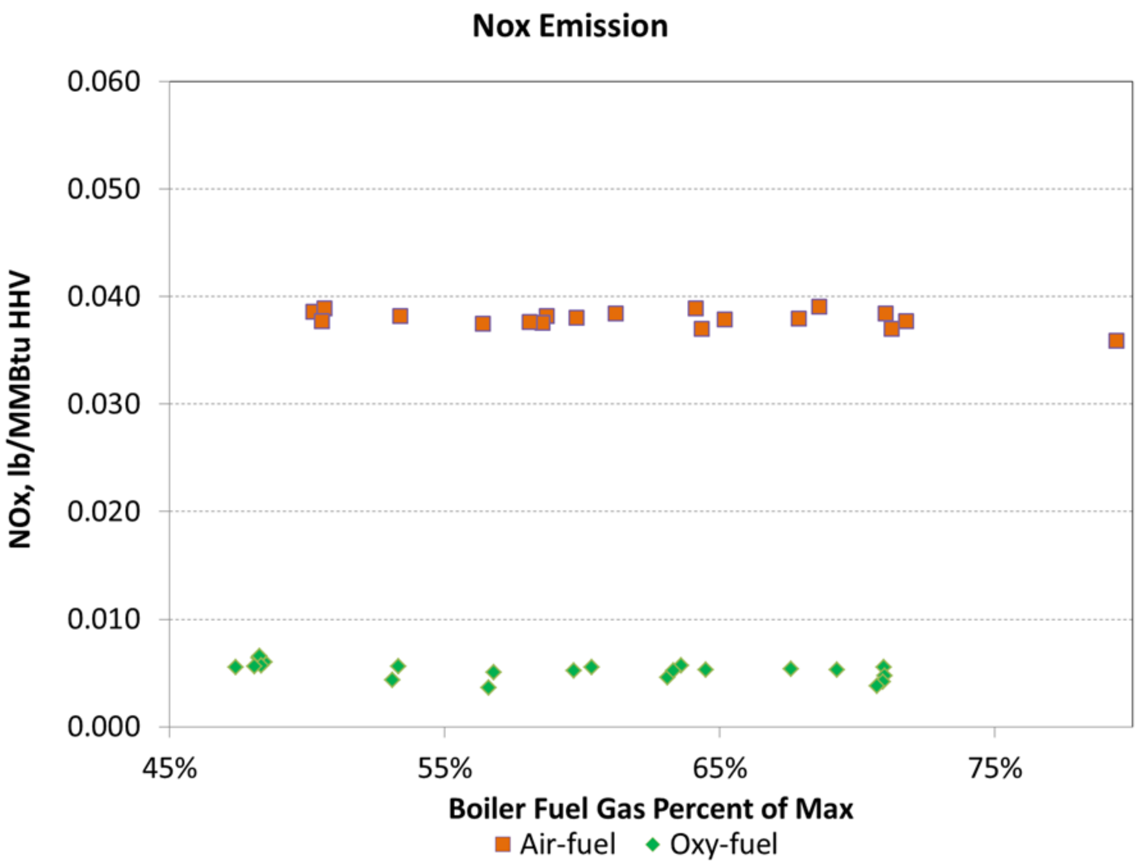

Figure 31: NOx Emissions Measured at the Stack

The CO emissions measured at the stack were zero for air-fuel and oxy-fuel operation. Significant CO emissions were only briefly measured when the burner was close to losing flame or immediately after flame was lost. Unburned fuel in the flue gas is expected when flame stability is compromised.

Figure 32 shows the NOx emission, CO_2 concentration and the stack temperature measured at the stack during the transition discussed in Chapter 4.1.2. The stack temperature dropped slightly during the transition from oxy-fuel to air-fuel, but it is relatively constant during the entire timeframe. Since the fuel flow changes only a few percent between oxy-fuel and air-fuel operation, the CO_2 mass flow stayed essentially the same. However, as expected, the CO_2 concentration dropped during air-fuel combustion as more nitrogen diluted the CO_2 generated by combustion. Twice the data for the stack emission was not available when the analyzers were automatically zeroed.

The trend for NOx is interesting. From the low level of oxy-fuel combustion the NOx emissions increase as the air damper is opened. With the air more nitrogen enters the flame which leads to an increase of NOx generation in the high temperature areas of the flame. The NOx production continues to increase in the highly enriched FGR until the flow of oxygen to the J-Burner stops. This process is shown in reversed order when the boiler was transitioned back to oxy-fuel operation. The J-Burner in the center of the main burner has a relatively high flame temperature which is desired to support ignition in this area. However, this also results in relatively high NOx emissions during the transition process when additional nitrogen from air increases NOx production.

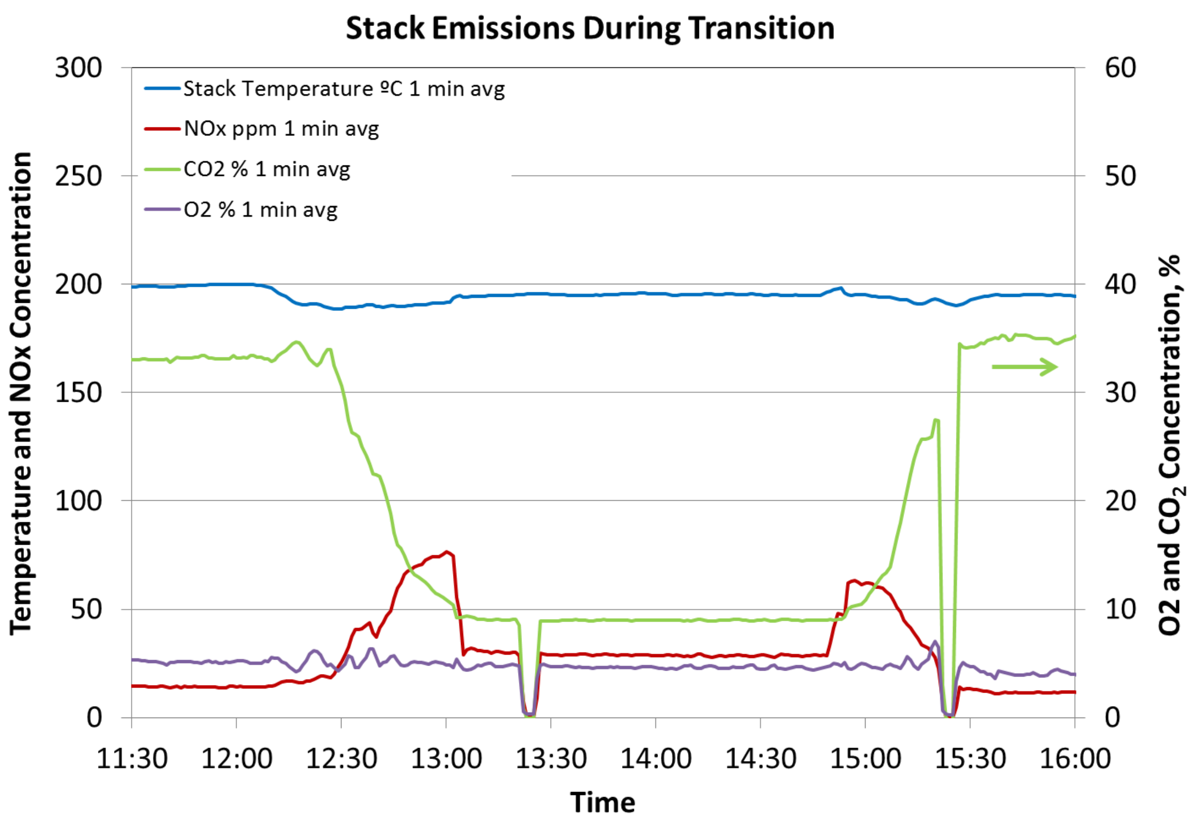

Figure 32: NOx Emissions, Oxygen and CO_2-Concentration and Stack Temperature during Transition

5. Conclusions

This chapter briefly summarizes the key results and limitations of the demonstration at Christina Lake. The demonstration test resulted in a number of recommendations for a full scale commercial implementation of oxy-fuel on a OTSG boiler that are listed in Chapter 5.3

5.1. Successes

1. The operation of an OTSG in SAGD service with oxy-fuel combustion and flue gas recirculation was safely demonstrated.
2. The demonstration clearly showed that there is no fundamental technology limitation for retrofitting a SAGD OTSG boiler for oxy-fuel combustion and operate it continuously. Boiler performance was nearly identical with air-fuel and oxy-fuel. However, the boiler could not be operated at full load due to size limitations of the burner. These can be corrected in future applications and should be subject to a separate design study.
3. There were no operational issues with oxy-fuel combustion. The boiler achieved the same steam quality and steam flow compared to loads under air operation. Some limitations due to the increased flue gas amount are discussed below under “Limitations”.
4. On average the fuel flow was reduced with oxy-fuel combustion by approximately 5% compared to air-fuel combustion at the same load and steam quality. This is an inherent advantage of oxy-fuel combustion.
5. The use of a small oxy-fuel pilot burner in the main burner center proved to be invaluable for the stabilization of the oxy-fuel flame. The heat from this burner resulted in improved combustion temperatures at the main burner flame root.
6. After initial challenges the transitions were optimized very well so that the transition process was performed almost routinely.
7. Transitions are best performed at low boiler load at moderate flows for air and oxygen. This minimizes the potential that pulsations develop that could result in the loss of the flame.
8. The retrofit of the boiler used common components that are available to the industry. The cost of the boiler retrofit is small compared to the cost of the entire carbon capture system [1].
9. The mass-based oxy-fuel NOx emissions were on average only 15% of those measured with air-fuel combustion. No CO emissions were measureable with air or oxygen. However, in a future oxy-fuel application for carbon sequestration the flue gas is fed to the CO2 Processing Unit that will remove NOx, SOx and CO. In other words, the “classic” hazardous air pollutants are not as relevant as they are today. Please refer to the Phase I Task 1 report for details [1].
10. A comprehensive safety process was executed using the HAZOP format. The technical and operations team worked very well together to implement the oxygen supply and oxy-fuel process safely at a site that processes hydrocarbons. The demonstration resulted in an increased comfort level with oxygen storage and use at such a site.

5.2. Limitations

1. The air preheater had to be removed for the demonstration to make room. This changed the temperatures at the windbox for air-fuel vs oxy-fuel operation.

2. Pre-mix low NOx burners are operating close to the stability limit to combust with low flame temperature for NOx reduction. The demonstration has shown that operation with oxygen and flue gas recirculation is not very stable and required higher than expected oxygen concentrations in the FGR of 21.2% minimum. Due to material compatibility issues in gas flows enriched with oxygen, the upper range of testing was 23.5% oxygen in FGR. This narrowed the range of oxygen concentration in the flue gas recirculation that could be tested.

3. The gas volumes through the burner with oxy-fuel operation were higher than with air-fuel operation due to higher oxidant temperatures. The burner ended up to be undersized for this application. This made it impossible to reach full boiler load under oxy-fuel in this test. However, this is a demonstration test limitation and not a technology problem. It can be mitigated with relatively simple design changes to the burner. For example, in future retrofits part of the flue gas recirculation can be added to the boiler outside of the burner to lower the gas velocities through the burner.

4. The main burner was not stable in oxy-fuel mode without operating the J-Burner serving as a pilot burner in the burner center. However, the relatively small pilot burner competes against the local flow of the main flame recirculation and is shortened substantially at higher loads. Localized overheating of the main burner at high loads was an operational concern. A more integrated design of the pilot burner with the main burner needs to be developed for a full scale commercial burner. Although this work is envisioned to be relatively easy for experts in combustion equipment design, it was not part of the demonstration test.

5. There was no limitation operating the boiler with flue gas recirculation, but it made robust controls more challenging. FGR adds an internal process feedback loop for concentration and pressure fluctuations that negatively impacted burner stability.

6. The tested boiler did not have a modulating stack damper to adjust the boiler pressure during operation (it was possible manually). The very low oxy-fuel flue stack flows resulted in a load limitation as the duct pressure at the air inlet damper increased with higher load over the local ambient pressure. The load could not be further increased when FGR started leaking out of the air inlet damper due to a positive pressure inside the duct at that location. Leaking FGR into the boiler house is an asphyxiation hazard.

7. Due to leakage mainly at the air intake damper, the air inleakage was relatively high. Thus, the nitrogen concentration in the flue gas was higher than expected.

8. High dewpoint poses a condensation challenge and dripping of water was noticed from inspection doors at economizer. Luckily the test was in April, so that no safety issue was created by ice buildup.

9. Two of three heat flux probes failed before the demonstration test which made the intended comparison of the heat flux profiles for air-fuel and oxy-fuel impossible. The data from the center probe indicated the expected increase in local heat flux at this location.

10. The retrofit installation and duct arrangement was a compromise which resulted in a few limitations in how the system could be operated, but the team learned quickly to understand the system response.
11. The flue gas amount with oxyfuel is only approximately 25% of the air combustion flue gas. This resulted in a plume exiting the stack with very low velocity and poor dispersion. In future technology implementations a smaller bypass stack should be considered that is used when the boiler is transitioned to oxy-fuel combustion before the CO_2 processing is ready to accept the flue gas.

5.3. Scale-up Considerations

Although the demonstration boiler is smaller (50 MMBtu/hr) compared to current full-scale OTSG boilers (250 to 300 MMBtu/hr), the findings can be applied to larger boilers. There are no technical scale-up barriers towards implementing oxy-fuel combustion commercially for carbon capture.

1. Air inleakage needs to be minimized eliminate nitrogen in the flue gas as much as possible to increase CO_2 concentration for carbon capture. This requires tight shutoff dampers for the air inlet (gate dampers). Condensation in the dead space of the air inlet behind the damper must be managed. Cleaned and dry CO_2 gas from the outlet of the CO_2 processing plant may be a suitable purge gas.
2. There are no limitations to fully automate the transition process in the future. The demonstration test did not have this goal. Dual combustion capability (air and oxygen) is simple to implement and provides maximum operational flexibility. Steam production would not be in jeopardy if any components of a future carbon capture system were unavailable.
   To be able to automate the transition procedure and achieve a smooth transition the flue gas recirculation and air control dampers require precise positioners. The control dampers should be opposed blade dampers with a low leakage and a nearly linear flow characteristic.
3. Differential pressure based flue gas flow meters are not ideal during the low flow conditions of the transitions, especially if the transition process is automated. High turndown instrumentation such as thermal dispersion mass flow meters should be investigated.
4. The burner design should be modified to manage higher velocities during oxy-fuel combustion with FGR. An alternative could be to introduce some of the recirculation gas through the boiler front wall outside of the burner at high flow conditions. In addition, the integration of a pilot burner or other means of stabilizing the main burner under oxy-fuel combustion should be investigated.
5. The stack damper should be retrofitted with a modulating damper to easily control boiler internal pressure over the entire load range.
6. Condensation management because of high oxy-fuel flue gas dewpoint is essential. The duct system needs to be designed with appropriate drain points, system cold spots must be avoided by adding insulation and boiler access door seals must be appropriately designed for the presence of liquid water. The stack design should also consider the potential for ice formation during winter operation due to higher water content in flue gas.

7. Liquid water corrosion or weak acid corrosion due to high CO_2 or residual SOx content of the flue gas was not part of the demonstration study. The technical team believes that these issues can be managed very well through appropriate design measures such as “warm” casing, avoiding standing water, appropriate insulation and material choices. However, a separate design study is recommended before the oxy-fuel combustion technology is used on a more widespread basis on SAGD boilers. Studies and experience with coal-fired oxy-fuel demonstrations projects may provide good guidance.

8. The oxygen piping and skid for the demonstration were designed with stainless steel. This choice was made because of the presence of sour gas in the facility. However, copper and carbon steel piping are viable choices for oxygen systems if certain safe design parameters are observed. They may be more economical for a full scale installation and could be kept in mind.

6. References

1 “Oxy-fuel/ CO_2 Capture Technology for OTSGs”, Phase I Report, Task I – Commercial System, Praxair, Inc., Final Report under PX-CCP3 Collaboration Agreement November 22, 2010

2 “Oxy-fuel/ CO_2 Capture Technology for OTSGs”, Phase I Report, Task II – Oxy-fuel Combustion Test, Praxair, Inc., Final Report under PX-CCP3 Collaboration Agreement November 22, 2010

3 “Oxy-fuel/CO2 Capture Technology for OTSGs”, Phase I Report, Task III – Design/Costs for Phase III Demonstration of CO_2 Compression and Purification, Praxair, Inc., Final Report under PX-CCP3 Collaboration Agreement November 22, 2010

4 US Patent 9,091,430 B2, “Stabilizing combustion of oxygen and flue gas “, July 28, 2015

Appendix A – Boiler Startup and Oxy-fuel Transition Procedure

This section summarizes the transition procedure that was developed during the demonstration. It was determined experimentally that the transition is best done at 50% boiler load.

1. OBJECTIVE

1.1. To initiate a start-up sequence and main burner ignition after steam generator has been shutdown long enough that the furnace has cooled off significantly; Has been locked out for maintenance or repair.

1.2 To transition between air-fire and oxyfiring mode safely, including lighting/shutting down the newly installed J-Burner in either operating mode (air-fire or oxyfired)

2. PREPARATION

2.1. Ensure that the B-102 commissioning checklist (Air fire, pre oxy test) is complete.

2.2. Cooling air is turned on for Oxy-fuel Thermal camera as well as the cooling water for the flux probes. Flue Gas Recirculation (FGR) ducts are closed for air fire. Praxair skid and PLC should be energized and started. Ensure manual valves are closed on oxygen lines to sparger (ISOLATION VALVE) & J burner (J-BURNER OXYGEN NEEDLE VALVE and HV-304X) & the fuel gas line to J burner (1" manual ball and globe valves). Ensure that the O2 ESD automatic safety block valves XV-300 and XV-301 are closed. Make sure MAIN FUEL GAS FLOW METER & J BURNER FUEL GAS have the same flow units, or, that there is a readily available conversion chart between the flow units.

2.3. Permissives are met and valves are in the correct position.

5 PROCEDURE

Legend

PX PLC Op – Praxair PLC Operator (located in lab inside boiler house)	**Boiler Op** –Boiler operator
PX CS Op – Praxair Control Skid Operator (boots on the ground by Praxair oxygen control skid and Cenovus boiler)	**CRO –** Control room/DCS operator
PX Out Op – Praxair oxygen delivery skid operator (outside by the delivery skid)	**All Ops –** All of the operators

✓	ACTION	NOTES
❑	1. **All Ops** follow the Praxair Oxy-fuel Test Plan. Record Air-fuel Baseline data for the test if it has not yet been recorded.	*Before transitioning to Oxy Fuel, there will be a period of Air Combustion Baseline operation.*

Preparing the Praxair PLC for Oxyfuel operation

✓	ACTION	NOTES
❑	2. **PX PLC Op** Set O2 FLOW CONTROLLER to "Manual", and its CV to "0". Set FGR MODULATING DAMPER to "Manual", and its CV to "0". Set	*In preparation to start the Praxair skid*

	FGR O2% set-point to 22.0%.	
❑	3. **PX PLC Op** Ensure all interlocks are OK, then press the "Start" button on the PLC panel on the "Operation" screen.	*The DCS sends a release for modulation signal as soon as it is in run mode after light off.* *O2 safety and block valves will open when the "Start" button on the PLC is pressed*
❑	4. **PX & Boiler Op** Verify safety and block valves have opened.	

Lighting the J Burner in preparation of Oxyfuel transition

❑	5. **PX CS Op** Look at main fuel gas flow meter to determine total fuel flow(T/d). Determine what 2.5% of the total flow is – this is the initial set-point for the fuel flow to the J-Burner Calculate the required oxygen flow to the J-Burner (oxygen flow shall be twice the fuel flow), then start oxygen to the J Burner by slowly throttling open the needle valve. Give an oxygen flow on O2 Skid J-BURNER OXYGEN CONTROL VALVE of 2 times the fuel flow on the J Burner fuel gas local in the same units.	****Do step 7 concurrently with step 8*** *Oxygen is started first to avoid a fuel rich atmosphere. Monitor flame through the furnace view ports.* **Use the unit conversion chart to convert between T/d, Sm/h, and SCFH* *The target ratio for oxygen to fuel gas is 2 units of oxygen to 1 unit of fuel gas.* *Monitor flame through furnace view points and flame camera*
❑	6. **Boiler Op** Start-up fuel gas to the J Burner, use LOCAL J-BURNER FUEL FLOW INDICATOR and slowly throttle open the globe valve to give a fuel flow of 2.5% of total fuel flow.	
❑	7. **CRO** Wait until combustion conditions and flows stabilize at O2 ANALYZER ON STACK and AIT 680B downstream of the O2 sparger when in Oxyfuel mode & notify All Ops.	*To allow time for the combustion controls to respond to the change.*
❑	8. **CVE & PX CS Ops** Ensure the burner is stable and there is no sign of flame lift off from the burner spuds	*Monitor through viewports and flame camera* *J-Burner may need to be increased as load is increased*

NOTE: The J Burner is now in service

Warning: **FGR oxygen concentration interlocks are not active until FGR flow is greater than 15000 scfh in order to prove initial circulation and oxygen flow through the FGR duct.**

Transition Air to Oxy-Fuel

Increasing Excess O2 in boiler

❑	1. **CRO** Ensure Combustion air controls are in Auto (external)	*This will compensate for any changes due to redistributed fuel and added oxygen or redistributed fuel and redistributed oxygen if lighting in oxyfuel mode*
❑	2. **Boiler Op & CRO** Ramp Boiler to 50% load (14t/day gas flow). Ensure quality is suitable to go into the steam header.	
❑	3. **CRO** - Ensure stack O2 trim is in Auto - Gradually & carefully, in steps of 0.5% to a total of 1.5%, raise the EXCESS O2 SET POINT ON STACK ANALYZER to ~5.0%.	Confirm with CRO & PX CS Ops at each step to ensure the flame is stable

Establishing initial Flue Gas Recirculation and Oxygen Flows

❑	4. **PX CS Op** Ensure FLOW CONTROL VALVE FOR OXYGEN TO THE SPARGER is fully closed, in manual mode, and the O2 set-point/concentration on the OXYGEN CONCENTRATION CONTROLLER in the FGR duct is set at 22.0% . Open manual ISOLATION VALVE on the main oxygen line to the sparger. Inform PX Out Op that sparger will be started, and wait for their confirmation that the sparger can be started.	*With FGR flow established oxygen can be introduced*
❑	5. **PX PLC OP** Open FGR ISOLATION DAMPER	*Opens when PX Control Skid is started*
❑	6. **PX PLC OP** -Gradually open FGR MODULATING DAMPER until a minimum stable FGR flow is established (17% open)	When around ~21%, set O2 controller to Cascade

	- Set O2 controller to Auto and ramp it to be about 7500scfh	
❑	7. **Boiler Op & CRO** Confirm that STACK O_2 MEASUREMENT levels are stable and flame is stable. Communicate with the PX CS Op as they observe the flame. Monitor air/fuel ratio – combustion air damper COMBUSTION AIR MODULATING DAMPER will automatically adjust to maintain overall boiler firing rate. Monitor VFD amps. **PX CS Op** Monitor combustion conditions through viewports to verify flame stability.	*Wait for stack oxygen reading to stabilize after each increment to allow for the delay between FGR/oxygen flow & stack oxygen changes. Will start to see changes after 30 sec, but may take up to 3min for conditions to fully stabilize. Throughout the test, this timing for condition changes will become more defined.*

NOTE: Combustion Air controls must be in auto (external) mode during this time. As FGR is introduced it will displace combustion air and the controls will adjust automatically to restore the excess O2 set point and maintain a stable firing rate

Ramping up the O2 enriched FGR recycle flow

❑	8. **PX PLC Op** Slowly increase the FGR flow by setting FGR MODULATING DAMPER CV to 50% (ramp rate will slowly open the damper) At each step, observe the following: • Air/fuel ratio is constant and within range • FGR flow has stabilized • Combustion conditions have stabilized (stack O_2 EXCESS O2 SET POINT ON STACK ANALYZER has stabilized, flame is stable etc.) • Furnace pressure • amp draw is stable **CVE & PX CS Ops** Observe flame stability throughout transition, and be aware of what is happening to the all dampers (stack, FGR, combustion air, etc) and the VFD fan. Understand how to modulate the stack damper if necessary.	*Combustion air flow through the air duct should decrease naturally as FGR is pulled through the ducting. The overall oxygen flow to the boiler should remain constant, as it will be regulated by COMBUSTION AIR MODULATING DAMPER to maintain the air-fuel ratio.* *the stack damper may need to be *modulated closed to encourage adequate FGR flow. This closure may also cause an increase of back pressure to the boiler. Furnace PRESSURE must be closely monitored.* **Note that modulating the stack damper refers to a procedure where Boiler Operations will climb to the stack platform and use wrenches to adjust the open stop screw on the damper actuator so as to partially close the damper.*

❑	9. **All Ops** Leave FGR MODULATING DAMPER at 50% open during transition and operation.	*This point was confirmed during commissioning due to flow reveral of FGR out through fresh air inlet.*

Ramping out the Combustion Air

❑	10. **PX PLC Op** Start to close COMBUSTION AIR MODULATING DAMPER from 100% to 40%	*COMBUSTION AIR MODULATING DAMPER has a ramp rate to slowly close damper*
	11. **PX PLC Op** Increase Oxygen Concentration Controller from 22% to 22.5% Continue to close COMBUSTION AIR MODULATING DAMPER from 40% to 20%	*COMBUSTION AIR MODULATING DAMPER will not close less 20% open due to clamped limit*
❑	12. **CRO** Start closing COMBUSTION AIR ISOLATION DAMPER, critical point is at 13% to 12% at which combustion air flow will be calculated **CRO and PX PLC Op** When COMBUSTION AIR ISOLATION DAMPER is at 6% increase O2 set point to 23%	*Close COMBUSTION AIR ISOLATION DAMPER from* *100% to 40% in 10% steps* *40% to 20% in 5% steps* *20% to 0% in 1% steps* *Take stack O2 trim controller to manual if necessary* *Maintain excess O2 between 3.5% to 6.5%*
	13. **PX R&D/PX CS Op & CVE & CRO** Observe Combustion Air, Oxygen, Fuel gas & FGR flows, and maintain communication with CRO.	*Set O2 trim controller in Auto and bias to 1% once stable*

NOTE: B-102 is now in Oxy-Fuel.

Transition Oxy-fuel to Air

✓	ACTION	NOTES
❑	14. **CRO Op** Ramp boiler down to a fuel rate of 14t/day	
❑	15. **PX PLC Op & CRO** Ensure COMBUSTION AIR ISOLATION DAMPER is in manual mode.	
❑	16. **PX PLC Op** Ensure that O2 FLOW CONTROLLER is in cascade mode.	*Oxygen flow will adjust automatically based on the changing FGR flow rate as Combustion Air is ramped up*

❑	17. **CRO** Increase stack O2 bias to 1.5%	*Target a stack O2 setpoint of ~5%.*
❑	18. **CRO** Gradually & carefully open COMBUSTION AIR ISOLATION DAMPER to 20%	*Ensure Air/fuel ratio is constant and within range, put in manual if needed to get within range* *Open COMBUSTION AIR ISOLATION DAMPER from* *0% to 20% in 1% steps* *20% to 40% in 5% steps* 40% to 100% in 10% steps
❑	19. **CRO** Decrease OXYGEN CONCENTRATION CONTROLLER to 22% when COMBUSTION AIR ISOLATION DAMPER is at 100% open	*Once at 60% open on COMBUSTION AIR ISOLATION DAMPER PX can start to open COMBUSTION AIR MODULATING DAMPER*
❑	20. **PX PLC Op** Open COMBUSTION AIR MODULATING DAMPER to 40% and set to 100% if stable.	*Put stack bias back 1%*
❑	21. **PX PLC Op** Close FGR MODULATING DAMPER to 17%.	*When COMBUSTION AIR MODULATING DAMPER is at 70%-80% opening*. Can be done when COMBUSTION AIR MODULATING DAMPER is at 100% if preferred
❑	22. **PX PLC Op** Take O2 flow out of cascade, put into Auto and ramp down its setpoint to 0	*Once at 0 setpoint on O2, put OXYGEN CONCENTRATION CONTROLLER in manual with 0% setpoint*
❑	23. **PX PLC Op** Close FGR MODULATING DAMPER	
❑	24. **PX CS Op** Manually close the ISOLATION VALVE to prevent oxygen flow to the sparger.	*To positively isolate Oxygen as Flow Control Valve may pass oxygen.*

Shutting down the J-Burner

❑	25. **Boiler Op** Gradually reduce the fuel flow to the "J" Burner fuel gas local meter, by a corresponding amount so that at the end of adjustment the Oxygen to Fuel Gas ratio is about 2 to 1.	*Reduce fuel gas first to avoid a fuel rich condition*
❑	26. **PX CS Op** Gradually reduce the oxygen flow through J-BURNER OXYGEN CONTROL VALVE until closed	*The target ratio for oxygen to fuel gas is 2 units of oxygen to 1 unit of fuel gas.*
❑	27. **CVE & PX CS Op**	*To gradually ramp out "J" Burner flows & allow*

	Repeat steps 1 through 2 until the flows are zero and the globe valves are closed	*time for the combustion controls to compensate for the changes.*
❑	28. **PX CS Op** Close the manual gate valves on the Oxygen & Fuel Gas to the "J" Burner.	*To positively isolate the flows & prevent inadvertent introduction of either service.*
❑	29. **PX PLC Op** If there are no further plans to conduct oxyfuel testing, press the "Stop" button on the PLC to close the two safety block valves.	
❑	30. **CVE & PX CS Op** Verify that the safety block valves have fully closed.	

Post-Purge Procedure if tripped

For all modes of operation (air-fuel, oxyfuel, transition, with or without the blower running):

1. System shutdown is initiated
2. Main fuel gas valves close, oxygen safety and block valves close
3. Blower is tripped. This initiates the five minute post-purge timer/fan lock-out.
4. All dampers go 100% open over a duration of 60 seconds. These include:
    a. Stack damper should be open to 100%
    b. FGR isolation damper
    c. FGR modulating damper
    d. Combustion air modulating damper located upstream of the FD fan.
    e. Combustion air modulating damper located downstream of fan to high fire position
    f. Combustion air isolation damper, located upstream of the FD fan
5. Hold all damper positions at 100% for the remainder of the post-purge timer (four minutes) to allow natural draft to purge the boiler
6. At the end of 5 minutes, the fan and dampers are released for operator control
7. The unit is now in "Standby Mode". Verify that all O_2 analyzers are reading above 20% oxygen, and there is no CO reading before attempting to restart the boiler.