PROJECT RESPONSE TO ASME QUESTION FOR COMPARISON OF PURE OXY-FIRING TO DILUTED OXY-FIRING
(to be supplemented as the project proceeds)

TOPICAL REPORT

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ABSTRACT

High flame temperature oxy-combustion has significantly improved radiant heat transfer compared to low flame temperature oxy-combustion, but heat flux at the water walls can be controlled. High flame temperature oxy-combustion used with the NETL's Integrated Pollutant Removal System can capture 95%-100% of the CO_2 with heat recovery. These technologies create CO2 capture cost savings, and are applicable to new design and existing design boilers.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

High flame temperature oxy-combustion and low flame temperature oxy-combustion are the two primary types of oxy-combustion, which is the combustion of fossil fuel with oxygen instead of air. High flame temperature oxy-combustion results in increased radiant energy, but heat flux at the water walls has been demonstrated to be maintained within design parameters. Less fossil fuel is used, so less CO_2 is produced. Latent and sensible heat can be partially recovered from the compressors. CO_2 capture costs are decreased. Evenly distributed heat avoids creating hot spots. The NETL IPR capture system can capture 100% of the CO_2 when operating at steady state. New boiler designs for high flame temperature oxy-combustion can take advantage of the higher flame temperatures. High flame temperature oxy-combustion with IPR capture can be retrofitted on existing plants.

REPORT DETAILS

1. INTRODUCTION This project involves high temperature oxy-combustion with an Integrated Pollutant Removal System and Energy Recovery system.

2. TWO TYPES OF OXY-COMBUSTION - There are two types of oxy-combustion: high flame temperature oxy-combustion (pure oxy-firing) and low flame temperature oxy-combustion (diluted oxy-firing). The difference between the two is due to the (a) the use of recycled flue gas to mix with combusting oxygen and fuel in the low flame temperature burner and (b) the avoidance of mixing of recycled flue gas with the oxygen and fuel in the high temperature burner except a small volume to propel the coal.

The reduction in combustion product mass, by not mixing large volumes of diluting gases into the flame, allows the chemical potential energy in the fuel to heat the reduced mass (heat capacity) combustion products to a higher temperature. Both high and low temperature oxy-fuel boiler systems must avoid or minimize air in-leakage (leak identification and sealing is an important part of retrofitting a boiler), so that nitrogen from air is not present except for very small amounts. This reduces excess mass in the combustion products and reduces the production of thermal NOx. In an system that captures and sequesters the combustion products, the production of NOx is not as important as it would be in a system that released the combustion products to the atmosphere.

Oxy-combustion produces combustion products with high CO_2 and water vapor content. Both CO_2 and H_2O are strong absorbers and emitters in the infrared which changes the heat transfer characteristics of the oxy-combustion atmosphere away from that of air fired combustion products. High temperature oxy-combustion takes advantage of the emitting strength of CO_2 and H_2O by increasing the radiant output of the combustion products in accordance with the T^4 law (energy radiated is proportional to the fourth power of the absolute temperature). This increases radiant energy (both luminous and non-luminous) in high temperature oxy-coal flames.

3. HIGH FLAME TEMPERATURE OXY-COMBUSTION - Jupiter Oxygen's high flame temperature oxy-combustion is produced by the use of relatively pure oxygen (95% or greater) mixed with a fossil fuel while excluding other gases. Oxygen is mixed with the fossil fuel in specially designed burners. Further testing will determine the lowest excess oxygen levels that can be used in the high temperature flame in an attempt to approach stoichiometry. A small volume of re-circulated flue gas is used to propel the coal, so there is only a small volume of CO_2 and water vapor at combustion when coal is the fuel. Jupiter's approach is to maintain the purity of the oxidant in order to have a flame with a high concentration of oxygen at the burner tip, thereby producing a very stable flame. The resulting flame temperature can exceed 5000 °F compared to air-fossil fuel flame temperatures in the low 3000 °F range. With the high effective flame temperatures of high-oxygen-concentration oxy-fuel firing, radiant heat transfer from the flame to boiler surfaces is increased due to the T^4 relationship of radiant transfer. The T^4 effect of the higher temperature difference in coal fired flames produces more visible light and near infrared radiant energy (due to more black body radiation from particles) than oxy-natural gas or oxy-oil flames which is not strongly absorbed by CO_2 H_2O, resulting in significantly increased radiant heat transfer to the radiant section of the boiler. This increased radiant heat transfer is controlled to maintain boiler design wall heat transfer rate, and water tube temperatures. In comparison with air firing the oxy-combustion system lowers the fuel input for a given amount of steam output improving overall boiler efficiency through the elimination of the nitrogen. The effective temperature of the flame determines the radiative heat transfer from the flame to the boiler wall. As long as the careful engineering design keeps the heat flux within design parameters and the flame (or extremely hot gases from the flame) do not come in contact with the walls, the boiler interior materials will function as designed without damage or excess degradation. Moreover, the final flue gas flow is only 20% to 25% of the flow realized with air as the oxidant in a conventional facility. Capital emission control and CO_2 capture costs are reduced nearly proportionally to the flue gas flow reduction. In addition, the engineered even heat distribution with improved radiant heat transfer avoids creating hot spots, slagging and fouling beyond that found with air firing, or accelerated corrosion. Furthermore:

* Thermal NOx levels are low without SCR type emissions control systems. Any NOx emission lowering beyond combustion can be accomplished with the IPR system described below.

* Jupiter's technology approach allows for precise burner optimization, including flame control which reduces corrosion concerns

and enhances boiler efficiency through complete combustion and reduced sensible heat losses, when compared with higher flue gas volumes through the burners.

* Cost savings include capital costs savings because the associated pollution control and carbon capture equipment can be considerably smaller due to reduced exit gas flows (approximately one-fourth of air firing), and the changed composition of the exit gases (concentrated CO_2, low excess oxygen levels, low thermal NOx, and lowered minor pollutants due to the fuel input reduction). This non-diluted gas stream is now easier and less expensive to clean, as defined by the amount of work (capital and operating costs of flue gas cleanup equipment) required to remove remaining pollutants such as SOx if required by either air emission standards in the absence of carbon capture or captured CO_2 purity requirements.

* Smaller burners are used due to less flow with lowered excess oxygen [with testing to determine optimal levels], less fossil fuel and, with CO_2 to propel the coal.

* Four key factors [reduction of nitrogen in comburent, greater radiant heat transfer, the oxygen-fossil fuel ratio and in some instances longer residence time] mean that Jupiter Oxygen's technology makes boiler combustion become much more efficient and use significantly less fuel to create the desired megawatts.

* Jupiter’s high flame oxy-combustion process avoids the question about potential explosion concerns by mixing oxygen with flue gas containing coal particles in a pipe before ignition since the coal particles may cause a very small spark hitting the pipe as the flue gas travels through the pipe. Jupiter has the oxygen travel in a separate pipe and meet the coal being propelled by a small volume of re-circulated flue gas only at ignition.

4. LOW FLAME TEMPERATURE OXY-COMBUSTION - Unlike high flame temperature oxy-combustion, low temperature oxy-combustion seeks to mimic air with fossil fuel flame temperatures and gas volumes by using re-circulated flue gas to cool the flame to the low 3000 ℉ range and result in the same gas volume flow through the burner as air firing. This is commonly done by mixing oxygen with re-circulated flue gas to create the same volume of gases through the burner as with air firing, using the same burners as air firing. However, the gases through the burner substitute CO_2 and H_2O for nitrogen, thereby causing a change in the properties of the combustion products. This change in combustion product properties makes it difficult to match heat transfer at each surface in the

boiler. Jupiter Oxygen's high flame temperature process avoids issues of flame stability and flame out by only having a low volume of CO_2/H_2O coming through or near the burner at combustion, as explained above. Low temperature oxy-combustion normally mixes the oxygen with a large volume of flue gas containing coal particles in a pipe before ignition in order to cool the flame temperature to air-fired levels.

5. LOWER OXYGEN COSTS

> * Both high temperature and low temperature oxy-combustion can use on-site oxygen plants to lower oxygen production costs below those commonly reported in oxy-combustion studies, since the transport pressure is lower due to the short on-site transport distances, thereby saving on compression capital and operating costs
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> * On-going testing is evaluating the approach of high temperature oxy-coal combustion to stochiometry. Theoretically, the high oxygen concentration makes oxygen more readily available to the coal particles during combustion and less oxygen is likely to not meet combustible components. That, coupled with the high temperature should allow less excess oxygen to be used for complete combustion. As the lowest excess oxygen levels are determined in the testing for high flame temperature oxy-combustion, a determination will be made about the effect of high-flame temperature oxy-coal combustion on lowering oxygen costs so that the oxygen plant can produce less oxygen to achieve the same steam output.

6. IPR – Jupiter's high flame temperature oxy-combustion process results in low thermal NOx at combustion to be addressed by the IPR system. This lowers capital and operating costs, and simplifies capture for 95% or higher capture rates. In the IPR CO_2 capture approach, the sensible and latent heat of the flue gas is partially recovered and can be used to heat the boiler condensate. In like manner, heat of compression can be partially recovered by using boiler feedwater to intercool the stages of compression. The decreased volume of flue gasses which need to be processed (roughly 25% of a comparable air firing boiler) by IPR uses a series of staged flue gas stream compression and cooling to condense water and to capture soluble pollutants from the flue gas while recovering sensible and latent heat. The IPR can return recovered thermal energy to the steam cycle to improve the power cycle efficiency. In addition, the IPR operates either on only the net flue gas flow, which can exclude the recycle stream or on all or part of the recycle stream if SOx is a problem. Specifically, the heat of compression of the combustion product feed stream can be returned to the steam cycle of the power plant. The NETL's Integrated Pollutant Removal

System (IPR) refers to an integrated system of particulate removal, wet heat exchangers, filtering, water removal and compression. Since there is little nitrogen from the air, there is no need for an SCR or similar equipment when combined with Jupiter Oxygen high flame oxy-combustion. In modeling and tests with Jupiter Oxygen's high flame temperature oxy-combustion, the IPR has been shown to be able to capture 100% of the combustion products. Furthermore, to the extent the capture system is added prior to a CO_2 transport system with high temperature oxy-combustion firing, air emissions are at ultra-low levels:

* Coal as fuel: removes >99% of NOx, S0x, and particulate, as well as >90% capture of mercury

* Natural gas as fuel: capture of 99% of NOx

* The purpose of the IPR process is to minimize energy usage and costs (both capital and operational) of CO_2 capture and preparation for transportation. IPR is a staged approach to CO_2 capture that recovers heat from combustion products and uses that heat in the power plant. The integration of this low grade heat back into the cycle minimizes the energy penalty to operate these systems. The recovered heat can be applied to the steam cycle in the feedwater or used as a source of process heat. Capture and preparation include cooling, dewatering, reacting, and compressing the combustion products to produce a dry, supercritical stream comprising CO_2 and tramp gases. Energy costs are reduced through recovery of sensible heat and latent heat of water condensation from the flue-gas at each IPR compression/cooling step.

* Jupiter Oxygen's high flame temperature oxy-combustion with IPR results in ultra-low pollution emissions whether released to the air without carbon capture or with carbon capture for sequestration/EOR/food processing

7. CO_2 AVOIDANCE AND OTHER SAVINGS - Lower fuel usage reduces CO_2 produced per MW, thereby lowering capture, transport and sequestration costs. Further favorable economies can be provided by partial heat recovery from the oxygen plant and IPR compressors. In addition, IPR water recovery is greater than boiler feedwater requirements for most fuels.

8. COMMERCIALLY AVAILABLE EQUIPMENT - Both the high flame temperature oxy-combustion and the Integrated Pollutant Removal System use commercially operational equipment. Only the burners are specially manufactured using standard materials, and are smaller than low temperature oxy-coal burners due to the reduced gas volume, and are approximately one-fourth of the size of air fired burners with the same mmbtu capacity.

9. OPERATING COSTS – Testing and modeling show Operating costs with carbon capture are projected to be approximately the same as air fired plants with an air emissions control system but no carbon capture.

10. NEW BUILD POWER PLANTS - Cost projections for new build power plants with capture systems indicate that new high flame temperature oxy-combustion plants with IPR systems can be built for about the same costs as air fired power plants using traditional air emission technology without CO_2 capture . This is in part because the plants can be smaller due to improved heat transfer, with the degree of size decrease in part dependent on the use of higher temperature boiler roof, wall and water tube materials, as well as the smaller exhaust flow rate and the right choice of fuel. If desired, boilers can be designed for longer residence times with lower flows through the boiler as long as there still is sufficient flow for ash carry. In addition:

* As boilers are built with more advantageous steam cycles (Supercritical and Ultra Supercritical) firing systems capable of delivering high energy efficiently while limiting materials affects will be an advantage over similar systems which rely on older technology (Air firing) for thermal delivery of the the coal energy.

* An advanced design multistage high flame temperature oxy-combustion boiler may consist of multiple boiler sections to take advantage of the higher flame temperatures. There will be three boiler sections, each with its own high flame temperature oxy-combustion burners. The first boiler section will serve to boil the water to saturated steam. The second boiler section will superheat the steam generated in the first section. The third boiler section then will raise cooled steam that has passed through the high-temperature turbine to superheat temperatures for a reheat cycle. All of this will create additional efficiencies and decrease costs. The same approach can be applied to supercritical systems with the multiple boiler units incrementally increasing the temperature of the supercritical fluid.

11. BOILER RETROFIT APPLICATIONS - High flame temperature oxy-combustion retrofit applications have shown to be feasible without major boiler modifications or rebuilding. High flame temperature oxy-combustion burners are added with oxygen and fossil fuel piping and located to best spread the increased radiative power over the radiant zone, thereby maintaining heat flux and eliminating hot spots. Ductwork changes are made so that boiler gas flows are as desired. Recirculated flue gas is used to propel coal to avoid air. Additional recirculated flue gas can be used as necessary to balance heat transfer between the radiant, transition and convective zones as well as to carry coal ash. Wall, water tube and steam temperatures are maintained at air fired levels if desired, so that the temperature profile of the boiler can be maintained while using a high flame temperature oxy-combustion for improved heat transfer

boiler efficiency and fuel savings. Based in part on the boiler retrofits performed for the two test boilers used to test Jupiter Oxygen's high flame temperature oxy-combustion technology, the basic boiler retrofit steps for efficiency and fuel savings benefits are:

- An oxygen plant or pipeline source is added on the property, unless
- already present. Power plant operations are not disturbed during this step.

- CO_2 capture system [Integrated Pollutant Removal; or other compression system with flue gas clean-up as needed unless already present. Power plant operations are not disturbed during this step. This can be done before, after or at the same time as step one.

- High flame temperature oxyfuel burners and a control system, designed for Jupiter's particular oxyfuel process, are installed, allowing lower fuel usage and low excess oxygen combustion. Water wall and steam temperatures remain the same as with air firing unless otherwise desired, although the oxyfuel flame is at a much higher temperature and undiluted. This step can be done during approximately the same period as for air fired burner change-overs.

- During step 3, fans and ductwork can be modified for recirculation of flue gases for [a] feeding the coal without air and [b] balancing heat transfer in the radiant and convective regions based on pre-existing conditions if desired. Step 4 is considered because there is [i] far greater radiant heat transfer per kg of fuel than with air firing due to the much higher flame temperature and [ii] only approximately 25% of the gases created at combustion since oxygen is used instead of air. Recirculation occurs at a sufficient distance and direction from the flame to maintain the high flame temperature process.

- Also during step 3, the boiler is made relatively airtight to minimize the introduction of nitrogen, thereby avoiding higher thermal NOx levels and minimizing efficiency losses which occur when nitrogen is heated. This is done employing practical measures, such as ductwork and boiler casing inspections, and leak detectors, with repairs and sealing done as needed. Step 5 also can be important for some CO_2 product specifications, in order to avoid unnecessary CO_2 clean-up.

REFERENCES:

Ochs (NETL), Oryshchyn (NETL), Summer (NETL) Patrick (JOC) et. al., "The Next Generation of Oxy-Fuel Boiler Systems," 30th International Technical Conference on Coal Utilization & Fuel Systems (2005)

LIST OF ACRONYMS AND ABBREVATIONS

NETL - National Energy Technology Laboratory

IPR – Integrated Pollutant Removal technology of the NETL