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Final Report to Jupiter Oxygen Corporation On CRADA Phase I Activities

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Introduction

Summary of interaction activities

In January of 2004, a Cooperative Research and Development Agreement was signed with the Jupiter Oxygen Corporation; its term extends from January 2004 to January 1, 2009. The statement of work is attached as Appendix A. Under Phase I of this agreement, ARC was to provide technical expertise to develop computer models of existing power plants relative to retrofitting with oxy-fuel combustion; help design experiments to verify models and analyze data from experiments; help produce designs at larger scales; help design a new technology oxy-fuel power plant; and co-author technical papers on this work for presentation at appropriate conferences.

Computer modeling of oxy-fuel and oxy-fuel plus IPR systems has been completed at several scales using GateCycle® software, and was reported in several papers prepared for and presented at technical conferences¹⁻⁶. A bench-scale proof-of-concept system was designed and built to combine Jupiter's oxy-combustion technology with the Albany Research Center's integrated pollutant removal (IPR) technology; it was successfully operated in November, 2004, with capture of CO₂ and all other pollutants. ARC has worked with Jupiter Oxygen to generate economic data in order to enable cost comparison of oxy-fuel plus IPR with other proposed methods of CO₂ capture. Finally, ARC and Jupiter have submitted an application for a patent that describes a novel oxy-fuel power plant. These activities, which are individually discussed in more detail below, complete ARC's obligations under Phase I of the CRADA.

Background of interaction

The request to work with Jupiter Oxygen Corporation came during FY 2003 from a project managed by Don Bonk and led at ARC by Cindy Dogan. The interaction arose out of conversations at the Clearwater 2003 conference, at which Jupiter personnel presented a paper on oxy-fuel combustion in a saturated steam boiler. ARC personnel visited Jupiter during 2003.

In December 2003, Jupiter personnel visited ARC to discuss the potential for cooperative activities in computer modeling of oxy-fuel combustion boilers. At this time, they also visited with Paul King of ARC to talk about aluminum work. The CRADA describing Phase I of the interaction was emplaced shortly after this visit.

Patent application preparation

During the meetings in December 2003, discussions led to the concept of a new type of oxy-fuel, coal-fired boiler. It was agreed at the time that the concept was patentable and that ARC and Jupiter Oxygen would pursue a joint patent. During the next year, ARC personnel assisted with development of GateCycle models of the new boiler concept. The patent application, titled "Module-Based Oxy-Fuel Boiler" was submitted in early 2005. A paper detailing the conceptual boiler's features was prepared and presented at the Clearwater 2005 conference².

Modeling of New and Retrofit Oxy-Fuel and Oxy-Fuel/IPR Systems

ARC used GE GateCycle[®] software[°] to model the characteristics of power generation in retrofit oxy-fuel applications and for advanced, next-generation oxy-fuel systems.

Retrofit modeling activities included a simulated subcritical single reheat PC unit (2,400 psi (16.55 MPa), 1,004°F (540°C), 1,004°F) and a mildly supercritical double reheat PC unit (3,500 psi (24.13MPa), 1,050°F (566°C), 1,050°F, 1,050°F), both designed to a 400 MW capacity and using “wet flue gas recirculation.” The studies used consistent flow rates of oxygen and pulverized coal, and changed oxygen concentration by adding or subtracting recycled flue-gas from the combustion-supporting gas entering the boiler.

The following results and implications were reported:

- The models showed increases in both efficiency and plant capacity (above those of air) with increases in O₂ concentration to about 28%.
- The total radiant duty of all heat transfer surfaces in the boiler, and duty at the furnace walls, increased as flue gas recirculation rates decreased, which is expected as increased relative oxygen (lower fraction of other gases) increases the brightness and temperature of the burner flame. A larger amount of the fuel's finite chemical energy is released in the boiler's radiant zone, and less energy is available in the gas for convective transfer in the boiler's back pass. Optimal recirculation was determined to balance the radiative and convective portions so the boiler could run under normal steam conditions.
- With reduction of the flow of recycled flue gas to increase oxygen content of the combustion gas, the volumetric flow of exhaust gas decreased. Initial studies of the effect of reduced volumetric flow rate on the convective heat transfer in the boiler show the expected drop in heat transfer coefficient as oxygen content increases.
- Elevated rates of energy released in the radiant zone increase the rate of steam generation at this location. Steam flow increase is accompanied by a decrease in the superheat temperature. A minimum level of flue gas recirculation is required in order to maintain superheat temperature and flow rates, as was described earlier in the model.
- The supercritical model also examined the ramifications of changes in boiler heat transfer surface area in response to changes in relative oxygen content in the combustion gas. When the model was allowed to change boiler surface area, the concentration of oxygen that could be applied to the plant in a balanced model nearly doubled. Thermal efficiency and plant capacity improved as a function of increased oxygen fraction and decreased water-wall surface area. With the decrease in surface area to offset the increased heat transfer rate in the radiant zone of the boiler, concentrations of oxygen up to 38% were modeled to continuously increase plant efficiency and capacity to up to 42% and 417 MW, respectively.

For the advanced oxy-fuel boiler system model, comparisons were made between the operation of a typical 400 MW power plant and the oxy-fuel design. In the standard design, air was both primary and secondary air in a single fossil-fueled boiler. In the advanced-design, multistage oxy-fuel boiler system, multiple boiler sections take advantage of the

[°] The USDOE neither endorses nor recommends specific products. References to product names are for information purposes only and should not be interpreted as endorsement or recommendation.

higher flame temperatures found in an oxy-fuel flame. The characteristic lack of N_2 in the combustion gases of the oxy-fuel boiler greatly reduces the mass requiring treatment and changes the composition of the combustion products.

In the cases modeled, the mass flow through a 400 MW standard flue gas exhaust system using air as the combustion supporting gas is approximately 3,780,000 lb/hr while the flow of exhaust gas out of a comparable 400 MW oxy-fuel system is only about 913,000 lb/hr, a mass ratio of approximately 4 to 1. Thus the treatment facilities in an advanced oxy-fuel boiler will handle approximately one-quarter of the mass with an attendant decrease in costs.

Proof-of-concept experiments in Hammond, Indiana

Background overview

In August of 2004, ARC and Jupiter committed to designing, constructing, and operating a system that combined oxy-fuel coal combustion with an ARC integrated pollutant removal design for demonstrating that the oxy-fuel combustion gas could be cleaned with capture of CO_2 in liquid form. ARC personnel participated heavily in the design phase through computer modeling, helped with component selection, and took an active part in overseeing the construction of the combustion/gas cleanup system. Subsequently, they participated in testing and ultimately, in operation of the new system, data gathering, and interpretation of the data.

The goals of the testing were to build an operational system that generated a CO_2 -rich combustion gas from a coal-burning oxy-fuel boiler; cleaned it of particulates, sulfur oxides, and mercury; and produced a liquid CO_2 product. All of these goals were met by operations conducted in November, 2004.

Computer modeling

Computer models were generated by GateCycle® software. The system differed from one designed for a full-sized power plant in several ways. Recirculation of flue gas was simulated by CO_2 gas inputs to the combustor; neither steam nor electricity was produced; condensate was not recirculated to cool the flue gas in the direct-contact, wet heat exchangers. Input rates for coal, oxygen, CO_2 and cooling water were arrived at based on a desired 75 kW electrical production, along with output flows of product condensates and gases.

Design, construction, and operation

Design decisions were largely supply-dependant. Following the process flow and searching in the range of flow rates and pressure conditions identified in the computer modeling, equipment was purchased “off-the-shelf.” The system was reworked, both in modeling and during construction, to accommodate the specific capabilities of the equipment procured.

The interrelationship between process steps, especially during start-up or shutdown of the system, and the problems brought out by those interrelationships were captured in a quickly evolving operating procedure. For instance, evolution and dissolution of CO_2 in the water-based wet heat exchangers required shutdown procedures take into account the fact that CO_2 will come out of solution during depressurization. The resulting “fizzing” water was the

cause of more than one system flooding before procedures were developed. During steady running, the pressure balance at the low-pressure end of the system was found to be critical to prevent flooding of the system by allowing one of the wet heat exchange columns to fill completely with liquid.

Economic Analysis Studies

ARC personnel and Jupiter Oxygen personnel have worked together on economic analysis studies under the CRADA. Following the POC experimentation in November 2004, the major responsibility for these studies was turned over to Jupiter Oxygen.

References / Technology Transfer

1. "Oxy-fuel Combustion Systems for Pollution Free Coal Fired Power Generation," Tom Ochs, Danylo Oryshchyn, Dietrich Gross, Brian Patrick, Alex Gross, Cindy Dogan, Cathy Summers, William Simmons, and Mark Schoenfield. Proceedings of the 29th International Technical Conference on Coal Utilization and Fuel Systems, April, 2004, Clearwater, FL.
2. "The Next Generation of Oxy-Fuel Boiler Systems," Tom Ochs, Alex Gross, Brian Patrick, Danylo Oryshchyn, Cathy Summers. Proceedings of the 30th International Technical Conference on Coal Utilization and Fuel Systems, April, 2005, Clearwater, FL.
3. "Proof of Concept for Integrating Oxy-Fuel Combustion and the Removal of All Pollutants from a Coal Fired Flame," Tom Ochs, Brian Patrick, Alex Gross, Danylo Oryshchyn, Larry Penner, Cathy Summers, Mark Schoenfield, and Paul Turner. Proceedings of the 30th International Technical Conference on Coal Utilization and Fuel Systems, April, 2005, Clearwater, FL.
4. "The Potential for Clean Energy Production using Oxy-Fuel Combustion and Integrated Pollutant Removal," T.L. Ochs, Danylo Oryshchyn, Thomas Weber, Cathy Summers. Presented at the Fourth Annual Conference on Carbon Capture & Sequestration, May 2-5, 2005, Alexandria VA.
5. "Developments in Integrated Pollutant Removal for Low-Emission Oxy-Fuel Combustion," D. Oryshchyn, T. Ochs, B. Patrick, C. Summers. To be presented at the Pittsburgh Coal Conference, September, 2005.
6. "Integrated Pollutant Removal and Oxy-fuel Combustion: A Proven Path for Removal of All Pollutants and CO₂ in Power Generation," Thomas L. Ochs, Danylo B. Oryshchyn, Brian Patrick, Cathy A. Summers. To be presented at PowerGen International, December, 2005.

Appendix A
Statement of Work – January 1, 2004 to January 1, 2009
Cooperative Research and Development Agreement Between the
United States Department of Energy (Albany Research Center) and
Jupiter Oxygen Corporation

ARC Project Manager: Cynthia Powell Dogan, 541-967-5803, dogan@alrc.doe.gov

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Jupiter Technical Representative: Alex Gross, AGross@jupitaluminum.com

Objective: To share expertise in the fields of fossil-fuel power plants and fossil fuel-fired burners.

Phase 1

ARC Contribution:

1. Develop models of existing power plants for retrofit of oxy-fuel combustion.
2. Assist with the design of experimental setups to verify the models and subsequent analyses of the resulting data.
3. Assist in translating the design from smaller systems to a larger (400 - 500 MW) system using modeling and experimentation.
4. Work on design of a new technology power plant using oxy-fuel.
5. With Jupiter Oxygen Corporation, co-author a paper for the 29th International Technical Conference on Coal Utilization and Fuel Systems (2004 Clearwater Conference) discussing the use of oxy-fuel combustion in coal-burning retrofit applications and other issues as agreed to by Jupiter and ARC.
6. Determine if further cooperation (Phase II) is needed.

Jupiter Contribution:

1. Work with ARC scientists and engineers to develop models of existing power plants.
2. Develop a staged design leading progressively from oxygen enriched combustion to full recirculation with varying oxygen content.
3. Design experimental setups to verify the models.
4. With ARC, co-author a paper for the 29th International Technical Conference on Coal Utilization and Fuel Systems (2004 Clearwater Conference) discussing the use of oxy-fuel combustion in coal-burning retrofit applications and other issues as agreed to by Jupiter and ARC.
5. Determine if further cooperation (Phase II) is needed.

Phase II

If funding becomes available to Jupiter Oxygen Corporation, the parties will modify this statement of work to encompass cooperation in developing one or more full-scale demonstration projects to show the commercial feasibility of Jupiter's oxy-fuel technology in combination with ARC's compression and condensation technology for integrated removal of particulates, NO_x, SO_x, and other pollutants from flue gas.