OXYGEN ENHANCED COMBUSTION FOR NOx CONTROL

QUARTERLY TECHNICAL PROGRESS REPORT

For Reporting Period Starting October 1, 2001 and Ending December 31, 2001

Principal Authors:

Program Manager and Business Officer: **David R. Thompson**
Principal Investigator, Combustion Development: **Lawrence E. Bool**
Principal Investigator, OTM Development: **Jack C. Chen**

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Submitted by:

Praxair, Inc.
175 East Park Drive
Tonawanda, NY 14150

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ABSTRACT:

This quarterly technical progress report will summarize work accomplished for the Program in the seventh quarter October-December 2001 in the following task areas: Task 1 - Oxygen Enhanced Combustion, Task 2 - Oxygen Transport Membranes, Task 3 - Economic Evaluation and Task 4 - Program Management.

Computational fluid dynamic (CFD) modeling of oxygen injection strategies was performed during the quarter resulting in data that suggest the oxygen injection reduces NOx emissions while reducing LOI.

Pilot-scale testing activities concluded at the University of Utah this quarter. Testing demonstrated that some experimental conditions can lead to NOx emissions well below the 0.15 lb/MMBtu limit.

Evaluation of alternative OTM materials with improved mechanical properties continued this quarter. Powder procedure optimization continued and sintering trial began on an element with a new design.

Several OTM elements were tested in Praxair's single tube high-pressure test facility under various conditions. A modified PSO1d element demonstrated stable oxygen product purity of >98% and oxygen flux of 68% of target.

Updated test results and projected economic performance have been reviewed with the Utility Industrial Advisors. The economic comparison remains very favorable for O_2 enhanced combustion.

Discussions regarding possible Beta sites have been held with three other utilities in addition to the industrial advisors. Proposals will be prepared after the completion of full scale burner testing. Beta test cost estimating work has been initiated.

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A. Executive Summary

The objective of this program is to demonstrate the use of oxygen enhanced combustion as a technical and economical method of meeting the EPA State Implementation Plan for NOx reduction to less than that of 0.15lb/MMBtu for boilers and coal. This program will develop both oxygen based low NOx technology and the new low cost oxygen transport membrane (OTM) oxygen production technology.

Computational fluid dynamic (CFD) modeling was performed at Reaction Engineering International (REI) to illustrate the benefit of oxygen addition to low NOx coal firing systems (Task 1.1.1). The effects of various O_2 injection strategies that have been tested in the L1500 were studied resulting in CFD modeling predictions that O_2 injection reduces NOx emissions while reducing LOI.

Final pilot-scale testing (Task 1.3) was conducted this quarter at the University of Utah's L1500 facility. Two bituminous coals were tested. The test results showed that some oxygen enhanced combustion conditions can lead to NOx emissions well below the 0.15 lb/MMBtu limit even under commercially viable staging conditions.

Efforts in the OTM materials development program (Task 2.1) this quarter continued to focus on the study of modified PSO1 compositions to improve mechanical properties in order to produce a more robust OTM element. Optimization of the thermo-mechanical properties of these modified compositions continued.

OTM element development (Task 2.2) efforts this quarter focused on binder burnout/sintering trials on an element with a new design fabricated last quarter[1]. PSO1d powder issues slightly delayed some process optimization. Dense PSO1d elements (60% of target length) were successfully fabricated.

OTM process development (Task 2.3) activities performed this quarter included three separate studies in Praxair's single tube high-pressure test facility on PSO1, modified PSO1, and modified PSO1d elements. An oxygen flux of 68% of target was demonstrated with a modified PSO1d element.

Economic evaluation (Task 3) continued this quarter. Updated estimates and projected economic performance were reviewed with the Utility Industrial Advisors. The economic comparison remains very favorable for oxygen enhanced combustion.

Discussions with three utilities and industrial advisors were held to identify potential Beta test sites. Beta test cost estimating work has been initiated.

Program management (Task 4) continued on track during the seventh quarter of this program. All required subcontracts have been negotiated and executed. Project documentation has been prepared and delivered to the US DOE in accordance with the cooperative agreement.

B. Experimental Methods

B.1. Combustion Modeling (Task 1.1.1) Experimental Methods

The objective of this task is to illustrate the benefit of oxygen addition to low NOx coal firing systems. Computational fluid dynamic (CFD) modeling simulations performed this quarter were designed to elucidate the impact of the oxygen injection method on the near burner flow pattern, coal

devolatilization and NOx formation. Two new simulations were performed which modified the origin of the replaced air. An Illinois # 6 coal was used for the simulations and the typical firing rate tested in the L1500, 4 MMBtu/hr, was assumed.

B.2. Pilot-Scale Testing (Task 1.3) Experimental Methods

The objective of this task is to demonstrate the effect of various oxygen injection strategies on NOx emissions from a typical wall fired burner. Testing this quarter continued at the L1500 facility at the University of Utah. This pilot-scale furnace was described in the previous quarterly report [2]. Further tests were conducted with three bituminous coals - Illinois No. 6, Illinois No. 5 and Utah.

B.3. OTM Materials Development (Task 2.1) Experimental Methods

The objective of this task is to determine a suitable material composition that can be fabricated into dense tubes capable of producing the target flux oxygen. Efforts to improve the mechanical properties in order to produce a more robust OTM element continued this quarter. Work focused on the further development of modified PSO1 compositions with improved strength and creep resistance.

B.4. OTM Element Development (Task 2.2) Experimental Methods

Powder characterization techniques and element manufacturing equipment were described in the first quarter technical progress report [3]. As a result of a surplus of elements in inventory, no elements were delivered this quarter for high-pressure single tube reactor tests. Binder burnout / sintering trials began on an element with a new design. Process optimization continued with fabrication of dense PSO1d elements in preparation of commercial scale-up.

B.5. OTM Process Development (Task 2.3) Experimental Methods

The operation and flux calculations of Praxair's single tube high-pressure permeation test facility are described in the third quarterly technical progress report [3]. Three separate studies were performed this quarter in the single tube high-pressure test facility. The first study was on an architecturally modified dense element of a modified PSO1 composition with a thin wall. The second study was on a dense PSO1 element that was thermal cycled two times. The third study was on two separate architecturally modified dense PSO1d elements.

C. Results and Discussion

C.1. Combustion Modeling (Task 1.1.1) Results and Discussion

This quarter's work built upon earlier modeling activities focused on near burner mixing and coal devolatilization issues in the University of Utah's 1500 kW pilot-scale test facility. The purpose of these modeling activities is to better understand the effects of various O_2 injection strategies that have been tested in the L1500, and to help optimize the O_2 injection design.

Two new simulations were performed which modified the origin of the replaced air. These two cases were compared with the two previous cases – Base case (no O_2 injection) and O_2 injection case described in the last quarterly report [1]. From the data, the cases with the modified O_2 injection strategy result in significant reduction in both NOx and total fixed nitrogen (TFN). These data also suggest the O_2 injection actually reduces NOx emissions while reducing LOI. In the next quarter REI will use one of their existing coal fired utility boiler models to explore the effect of O_2 injection on NOx formation and LOI.

C.2. Pilot-scale Testing (Task 1.3) Results and Discussion

The program coal, Illinois No. 6, and two other bituminous coals, Illinois No. 5 and Utah, were used in the University of Utah's final experiments to optimize the O_2 injection strategy in the L1500, a typical wall fired burner. These experiments demonstrated that oxygen enhanced combustion can lead to significantly lower NOx emissions, with some conditions leading to NOx emissions well below the 0.15 lb/MMBtu limit even under commercially viable staging conditions. Finally all of the experimental results are consistent with both the theory and the CFD modeling, enhancing the confidence in the results.

Pilot-scale testing of staged combustion was completed, thus achieving a program milestone. No additional testing is planned at the University of Utah for this program.

C.3. OTM Materials Development (Task 2.1) Results and Discussion

OTM material development work in the seventh quarter has concentrated on improving the mechanical properties of the OTM material in order to produce a more robust OTM element. Efforts have focused on the development and optimization of modified PSO1d compositions for improving the strength of the OTM material. The mechanical strength of one modified PSO1d composition at room temperature was determined to be 5% greater than that of PSO1d, however, the sample failed in the 4-point bend apparatus at high temperature. Investigation into this issue will continue next quarter.

Optimization of modified PSO1d compositions for improving the creep resistance continued this quarter. The modified PSO1d compositions showed up to 17% improvement in creep rate compared to PSO1d. Work next quarter will focus on optimization of mechanical properties and modeling of reliability.

C.4. OTM Element Development (Task 2.2) Results and Discussion

One new design for elements that may be more resistant to creep resulted in the successful fabrication of an element last quarter [1]. Binder burnout / sintering trials were initiated this quarter. A modified

binder burnout protocol from a previous Praxair program was conducted on various sections of the element with moderate success.

PSO1d powder issues caused a slight delay in process optimization, however with the latest PSO1d powder lot, dense elements 60% of target length were successfully fabricated. Another new element design was completed. Fabrication and sintering trials of this new design will be performed next quarter.

C.5. OTM Process Development (Task 2.3) Results and Discussion

Three separate studies were performed this quarter in the single tube high-pressure test facility. The first study was on an architecturally modified dense element of a modified PSO1 composition with a thin wall. The oxygen flux observed with this element was 2.85 times higher than the flux of the element reported in last quarter's report [1] which was identical in composition with the target wall thickness.

The second study was on a dense PSO1 element that was thermal cycled two times. During the second thermal cycle no oxygen transport was observed at 900^{o}C . Consequently the reactor was heated to 950^{o}C so flux measurements could be taken. The reactor was then cooled to 900^{o}C and the flux observed in this second thermal cycle was comparable to the flux observed in the first thermal cycle. The element failed during the heatup of the third thermal cycle.

The third study was on two architecturally modified dense PSO1d elements. Both samples demonstrated oxygen flux of 61% of target flux. One sample failed during the cooldown process. The other sample was tested at 950^{o}C and demonstrated oxygen flux of 68% of target. The oxygen purity was as high as 99.999% and remained above 98% for the duration of the test.

Multiple thermal cycle experiments with architecturally modified PSO1 and PSO1d elements will be conducted next quarter.

C.6. Economic Evaluation (Task 3) Results and Discussion

Updated test results and projected economic performance have been reviewed with the Utility Industrial Advisors (NIPSCO, AEP and Alcoa). Estimates have been updated to reflect changes in projected SCR costs and performance and sensitivities around the O_2 technology performance. The economic comparison remains very favorable for oxygen enhanced combustion.

Discussions regarding possible Beta sites have been held with three other utilities in addition to the industrial advisors. Proposals will be prepared after the completion of full scale burner testing. Beta test cost estimating work has been initiated.

C.7. Program Management (Task 4) Results and Discussion

The Program Management highlights for the seventh quarter of the US DOE NO_x program are as follows:

- All required sub-contracts have been executed.

- Project documentation has been prepared and delivered to the US DOE in accordance with the cooperative agreement.
- Labor hours and costs continued to be monitored via accounts established within the Praxair accounting system.
- An updated statement of work will be prepared in the next quarter.

D. Conclusion

In the seventh quarter of this program, oxygen enhanced combustion work continued. The final planned test campaign at the University of Utah provided a great deal of valuable insight on the effect of oxygen addition NOx emissions. The experiments demonstrated that oxygen enhanced combustion can lead to significantly lower NOx emissions, with some conditions leading to NOx emissions well below the 0.15 lb/MMBtu limit even under commercially viable staging conditions. Various O_2 injection strategies were tested in the L1500, and unlike current low NOx burners, oxygen enhanced low NOx systems actually reduce LOI. Finally, all of the experimental results are consistent with both the theory and the CFD modeling, enhancing the confidence in the results.

No additional testing is planned at the University of Utah for this program. A program milestone, completion of pilot-scale testing of staged combustion, was achieved.

Efforts in the OTM development program this quarter continued to focus on the study of modified PSO1 and PSO1d compositions to improve mechanical properties in order to produce a more robust OTM element. Creep and strength properties were investigated. Small sections of a newly designed element were successfully sintered. Another new element design to improve creep resistance will be fabricated and sintered next quarter. Dense PSO1d elements (60% of target length) were successfully fabricated.

Three separate OTM process development studies were performed this quarter in Praxair's single tube high-pressure test facility on PSO1, modified PSO1, and modified PSO1d elements. An oxygen flux of 68% of target and stable oxygen product purity of >98% was demonstrated with a modified PSO1d element.

Economic evaluation activities are on schedule. Updated test results and projected economic performance were reviewed with the Utility Industrial Advisors. The economic comparison remains very favorable for oxygen enhanced combustion. Beta test cost estimating work has been initiated. Discussions regarding possible Beta sites have been held with three other utilities in addition to the industrial advisors.

An updated statement of work will be prepared in the next quarter.

E. References

1. Thompson et. al, “Oxygen Enhanced Combustion for NOx Control”, Quarterly Technical Progress Report for Reporting Period Ending September 30, 2001, US DOE Award No. DE-FC26-00NT40756, October 2001

2. Thompson et. al, “Oxygen Enhanced Combustion for NOx Control”, Quarterly Technical Progress Report for Reporting Period Ending June 30, 2001, US DOE Award No. DE-FC26-00NT40756, July 2001

3. Thompson et. al, “Oxygen Enhanced Combustion for NOx Control”, Quarterly Technical Progress Report for Reporting Period Ending June 30, 2000, US DOE Award No. DE-FC26-00NT40756, July 2000