OXYGEN ENHANCED COMBUSTION FOR NOx CONTROL

QUARTERLY TECHNICAL PROGRESS REPORT

For Reporting Period Starting January 1, 2003 and Ending March 31, 2003

Principal Authors:

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

Report Issue Date: April 2003

DOE AWARD NO. DE-FC26-00NT40756

Submitted by:

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

DISCLAIMER:

ABSTRACT:

This quarterly technical progress report will summarize work accomplished for the Program through the twelfth quarter, January-March 2003, in the following task areas: Task 1 - Oxygen Enhanced Combustion, Task 2 - Oxygen Transport Membranes, Task 3 - Economic Evaluation and Task 4 - Program Management.

The program is proceeding in accordance with the objectives for the third year. Pilot scale experiments conducted at the University of Utah explored both the effectiveness of oxygen addition and the best way to add oxygen with a scaled version of Riley Power's newest low NOx burner design. CFD modeling was done to compare the REI's modeling results for James River Unit 3 with the NOx and LOI results obtained during the demonstration program at that facility.

Investigation of an alternative method of fabrication of PSO1d elements was conducted. OTM process development work has concluded with the completion of a long-term test of a PSO1d element

Economic evaluation has confirmed the advantage of oxygen-enhanced combustion. Proposals have been submitted for two additional beta test sites. Commercial proposals have been submitted. Economic analysis of a beta site test performance was conducted.

TABLE OF CONTENTS

A. Executive Summary — Page 3

B. Experimental Methods — Page 4
- B.1. Task 1.1.1 Combustion Modeling — Page 4
- B.2. Task 1.3 Pilot-Scale Testing — Page 4
- B.3. Task 1.4 Full-Scale Testing — Page 4
- B.4. Task 2.2 OTM Element Development — Page 5
- B.5. Task 2.3 OTM Process Development — Page 5

C. Results and Discussion — Page 5
- C.1. Task 1.1.1 Combustion Modeling — Page 5
- C.2. Task 1.3 Pilot-Scale Testing — Page 7
- C.3. Task 1.4 Full-Scale Testing — Page 7
- C.4. Task 2.2 OTM Element Development — Page 8
- C.5. Task 2.3 OTM Process Development — Page 8
- C.6. Task 3 Economic Evaluation — Page 8
- C.7. Task 4 Program Management — Page 8

D. Conclusion — Page 9

E. References — Page 10

F. Appendix – Proprietary Data — Page A1

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.

The breakdown of the program work consists of the following four major tasks:

Task 1.0 Oxygen enhanced combustion
Task 2.0 Oxygen transport membranes
Task 3.0 Economic evaluation
Task 4.0 Program management

Task 1 work focused on two areas: CFD modeling results from Reaction Engineering International (REI) (Task 1.1.1) in general showed lower sensitivity of staging on LOI as compared to the measured results. The modeling also showed a lower sensitivity to oxygen addition on LOI as compared to the measured results. Preliminary pilot-scale testing (Task 1.3) at the University of Utah tests showed that the scaled version of Riley Power's newest low NOx burner design was significantly different than the full- scale burner, with NOx emissions much higher in the scaled burner than observed with the full-scale burner (Task 1.4).

Task 2 efforts focused on OTM element development (Task 2.2) of an alternative fabrication technique for PSO1d elements. A long-term test with a PSO1d element of alternative architecture was successfully completed under Task 2.3, OTM process development.

Task 3 work confirmed the economic advantages of oxygen enhancement based on beta site test results. Target boiler utilities were identified. Test proposals were submitted to one additional utility. Commercial proposals were also submitted.

Program management (Task 4) continued on track the throughout the year. All subcontracts and amendments to subcontracts have been negotiated and executed. Subcontracts with REI and the University of Utah have been extended through September 2003. Project documentation has been prepared and delivered to the US DOE in accordance with the cooperative agreement. The major objectives and accomplishments of the third year of the program are summarized in Table 1 below.

Table 1. Major Program Objectives for Year 3 - "Oxygen Enhanced Combustion for NOx Control"

ID	Task	Milestone	Accomplishments
12	1.4.3	Burner test at full scale complete	Burner testing at full scale complete. The results from the full-scale demonstration project at the James River Power Station indicated that oxygen enhanced combustion can substantially reduce NOx emissions from coal-fired power plants.
14	2.1.2	Optimization of OTM material complete	Optimization of OTM material PSO1 and PSO1d complete
34	3.5	Site specific economics complete	The economic advantage of oxygen enhancement was confirmed. Market segmentation was completed with target utilities and boilers identified. Discussions were held with utilities to confirm economics and identify issues limiting the commercialization of the technology. Additional beta site proposals and commercial proposals have been submitted.
35	4.1	Program review meetings	Annual program review meeting held on May 15, 2002 at the US DOE. Teleconferences conducted throughout the year for combustion review. Program was extended through September 30, 2003 to allow additional time for the final project report and program closeout.

B. Experimental Methods

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

Computational fluid dynamic (CFD) modeling activities were performed by Reaction Engineering International (REI) for Praxair's United States Department of Energy (US DOE) program entitled "Oxygen Enhanced Coal Combustion for NOx Control". The objective of this work was to illustrate the benefit of oxygen addition to low NOx coal firing systems. Modeling performed during the last quarter compared REI's modeling results for James River Unit 3 with the NOx and LOI results obtained during the demonstration program at that facility. The modeling took into account actual operating information during the testing.

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

The objective of this task is to explore the effect of various oxygen injection strategies on NOx emissions from a typical wall fired burner[2]. This quarter a scaled version of Riley Power's newest low NOx burner design was fabricated to explore both the effectiveness of oxygen addition with this design and the best way to add oxygen.

B.3. Full-Scale Testing (Task 1.4) Experimental Methods

Full-scale experiments were previously performed in ALSTOM Power's Industrial Scale Burner Facility (ISBF) in Windsor, CT using a 25 MMBtu/h commercially available Radially Stratified Flame Core (RSFC™) burner as discussed in the 8th quarterly Technical Progress Report[3]. A wide range of burner parameters were evaluated, as were the first stage stoichiometric ratio and residence time. Several methods were explored to introduce the oxygen into the first stage.

The main driver for the development of oxygen enhanced combustion for NOx control is to not only allow utility operators to control NOx emissions but to also avoid or minimize many of the detrimental side effects common to alternative control strategies. The successful demonstration of the concept at the pilot and full-scale single burner levels led to an agreement between Praxair and City Utilities of Springfield, Missouri to test oxygen enhanced combustion at full scale. The demonstration project (separately funded) utilized Unit 3 at the James River Power Station to evaluate the effect of O_2 addition during staged combustion on NOx emissions, residual carbon in ash, opacity and plant operation (Q4, 2002).

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

The objective of this task is to fabricate elements from OTM materials for testing. Powder characterization techniques and element manufacturing equipment were described in the first quarter technical progress report [4]. An alternative proprietary fabrication technique for PSO1d elements was further investigated. This fabrication method was developed outside this program.

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

The objective of this task is to design, build and operate a single tube reactor for high-pressure operation that can demonstrate at least 75% of the commercial target flux . Details of the design and operation of the single tube high-pressure permeation test facility can be found in the second[5] and third[1] quarterly reports.

This quarter long-term testing of a dense PSO1d element with alternative architecture in the single tube high-pressure permeation reactor was completed.

C. Results and Discussion

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

During the last quarter CFD modeling was done to compare the REI's modeling results for James River Unit 3 with the NOx and LOI results obtained during the demonstration program at that facility. The modeling took into account actual operating information during the testing. In general the modeling results showed lower sensitivity of staging on LOI as compared to the measured results, Figure 1. The modeling also showed a lower sensitivity to oxygen addition on LOI as compared to the measured results. For NOx the model predicted consistently higher NOx than was measured. However, when compared on a reduction from the baseline conditions, Figure 2, the predicted reductions were comparable to those measured during the testing.

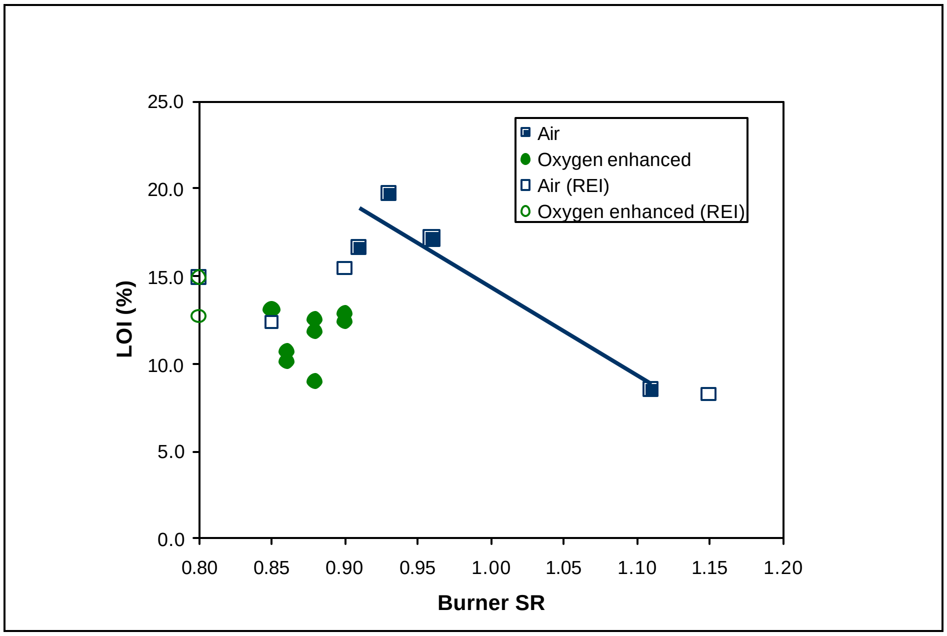

Figure 1. Comparison of REI and measured LOI results

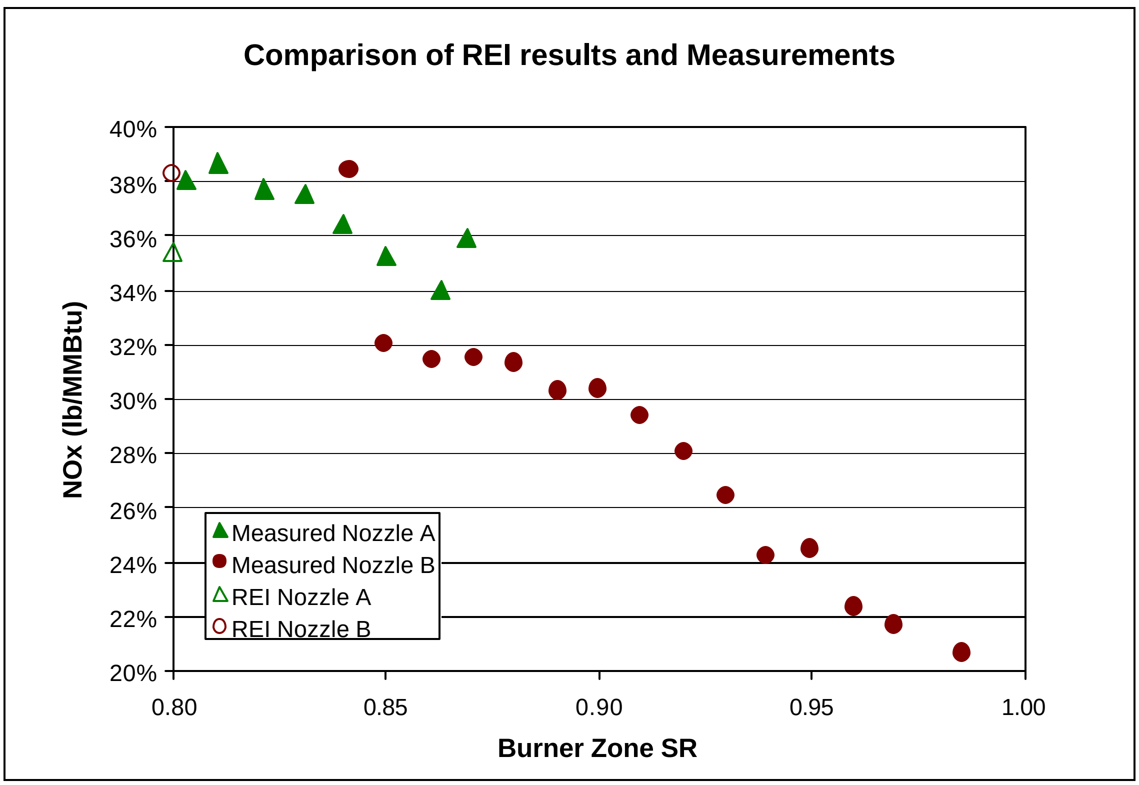

Figure 2. Comparison of NOx REI results and measurements

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

During the last quarter a scaled version of Riley Power's newest low NOx burner design was fabricated to explore both the effectiveness of oxygen addition with this design and the best way to add oxygen. However, several preliminary tests showed that the scaled design was significantly different than the full- scale burner, with NOx emissions much higher in the scaled burner than observed with the full-scale burner. Work is ongoing to determine what is causing the observed differences and to design a scaled burner with characteristics similar to the full-scale for further testing.

C.3. Full-ScaleTesting (Task 1.4) Results and Discussion

Full-scale single burner testing at Alstom was completed. Figure 3 shows the effect of oxygen replacement under deeply staged conditions. These data further support that under fuel rich conditions oxygen enhanced combustion can significantly reduce NOx formation even with very low oxygen replacement rates[6]. Similar data demonstrated that oxygen can enhance staging for NOx control over a wide range of conditions, and that the method for oxygen introduction is critical to the NOx reduction achieved[6].

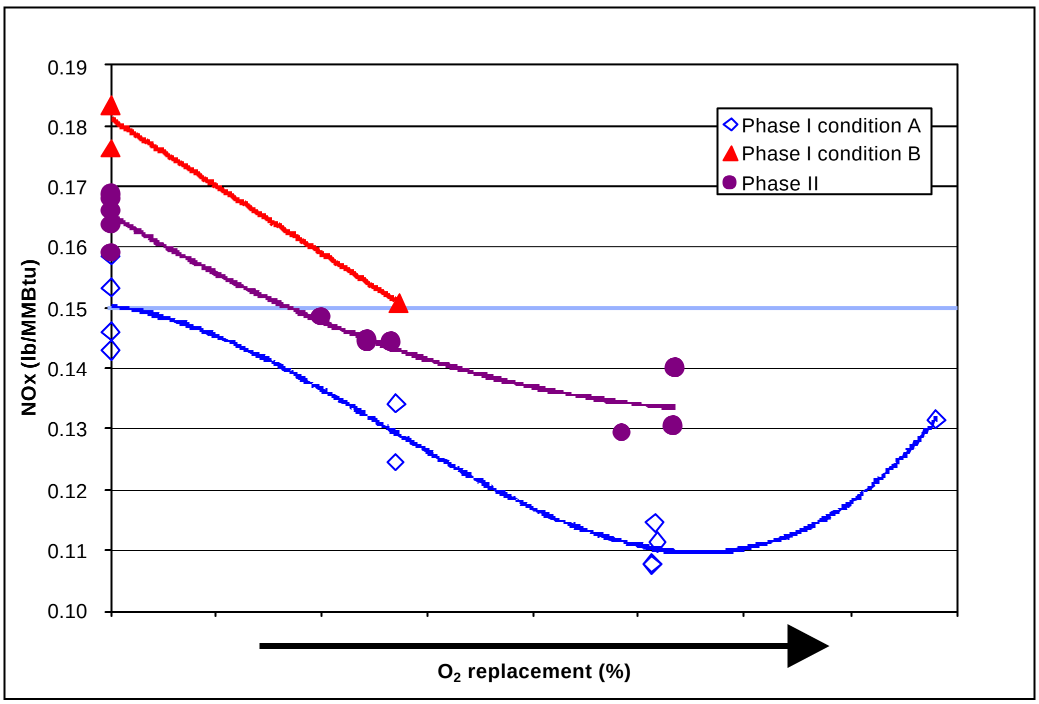

Figure 3. Full-scale single burner results – Alstom Power

This single burner work demonstrated that oxygen enhanced combustion can substantially reduce NOx emissions from coal-fired power plants.

Data analysis of the demonstration project at James River Unit 3 also indicated that oxygen enhanced combustion can substantially reduce NOx emissions from coal-fired power plants. The burner observations indicate that flame stability was dramatically improved with oxygen addition. The use of oxygen also *reduced* LOI and opacity as compared to the air- alone staging, with measured LOI and opacity being comparable or only slightly higher than the unstaged air-only condition. Therefore, this project demonstrated that oxygen enhanced combustion leads to significant reductions in NOx emissions *without* many of the problems typically associated with staged combustion systems.

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

An alternative proprietary element fabrication method, which may result in lower processing costs, was further investigated using PSO1d composition. Straight green and sintered elements were successfully prepared.

The OTM element development task of this program was completed this year.

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

A long-term alternative architecture PSO1d element test in the NOx reactor was completed. The element did not experience any dimensional changes after >600 hours of continuous operation. This lack of deformation is an important milestone in the long-term development of this technology.

The OTM process development task of this program was completed this year.

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

Oxygen enhancement advantage versus SCR/SNCR was confirmed with utilities. Based on pilot-scales tests, commercial burner performance tests, and the beta site test results, the economic advantage of oxygen enhancement was confirmed.

The market segmentation was completed with target boiler utilities identified. Test and commercial proposals have been submitted.

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

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

- Annual project review meeting was held May 15, 2002 at the US DOE.
- An update meeting was held on December 18, 2002 at the US DOE.
- Teleconferences were held among combustion team members throughout the year.
- Monitoring of accounts established within the Praxair accounting system to track labor hours and costs was ongoing.
- Project documentation has been prepared and delivered to the US DOE in accordance with the cooperative agreement including quarterly technical progress reports and financial status reports.
- A paper entitled "O_2 Enhanced Combustion for NOx Control" was presented by Dr. Lawrence Bool of Praxair at the 2002 Conference on SCR and SNCR for NOx Control, Pittsburgh, PA, May 15-16, 2002.

- A paper entitled “Oxygen for NOx Control – A Step Change Technology?” was presented by Dr. Lawrence Bool of Praxair at the Nineteenth Annual Pittsburgh Coal Conference, Pittsburgh, PA, September 24-26, 2002.
- A presentation entitled “CFD Evaluation of Oxygen Enhanced Combustion in Coal Fired Boilers: Impacts on NOx, Carbon in Ash and Waterwall Corrosion” was co-authored by REI and Praxair and presented by Dr. Brad Adams of REI at the Electric Utilities Environmental Conference, Tucson, AZ, January 27-30, 2003.
- A paper entitled “NOx Reduction from a 44MW Wall-Fired Boiler Utilizing Oxygen Enhanced Combustion” was presented by Dr. Lawrence Bool of Praxair at the 28th International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, FL, March 10-13, 2003.
- A paper entitled “CFD Evaluation of Oxygen Enhanced Combustion in Coal Fired Boilers: Impacts on NOx, Carbon in Ash and Waterwall Corrosion” was co-authored by REI and Praxair and presented by Dr. Marc Cremer of REI at the 28th International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, FL, March 10-13, 2003.

D. Conclusion

Progress was made in all tasks toward achieving the DOE NOx program objectives.

Oxygen Enhanced Combustion Tasks:

CFD modeling experiments compared REI’s modeling results for James River Unit 3 with the NOx and LOI results obtained during the demonstration program at that facility. Results showed lower sensitivity of staging on LOI as compared to the measured results. The modeling also showed a lower sensitivity to oxygen addition on LOI as compared to the measured results. A scaled version of Riley Power’s newest low NOx burner design was fabricated at the University of Utah to explore both the effectiveness of oxygen addition with this design and the best way to add oxygen. Preliminary tests indicated that NOx emissions were much higher in the scaled burner than observed with the full-scale burner. Investigation will continue next quarter. The successful demonstration of oxygen enhanced combustion for NOx control at the pilot and full-scale single burner levels led to an agreement between Praxair and City Utilities of Springfield, Missouri to test oxygen enhanced combustion at full scale (separately funded). The results from the full-scale demonstration project at the James River Power Station indicated that oxygen enhanced combustion can substantially reduce NOx emissions from coal-fired power plants.

Oxygen Transport Membrane Tasks:

Straight PSO1d elements were successfully prepared and sintered using an alternative fabrication method. A long-term test (>600 hours) of a dense PSO1d element with alternative architecture in the single tube high-pressure permeation reactor was completed, resulting in no element deformation.

Economic Evaluation:

The advantage of oxygen enhancement versus SCR/SNCR was confirmed with utilities. Based on pilot-scales tests, commercial burner and beta site performance tests, the economic advantage of oxygen enhancement was confirmed. Also, market segmentation was completed with target utilities and boilers identified. Discussions were held during this quarter with utilities to confirm economics and identify issues limiting the commercialization of the technology. Additional beta site proposals and commercial proposals have been submitted. Commercialization activity further accelerated during this quarter.

E. References

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

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

3. Thompson et. al, “Oxygen Enhanced Combustion for NOx Control”, Quarterly Technical Progress Report for US DOE Award No. DE-FC26-00NT40756, April 2002.

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

5. Thompson et. al, “Oxygen Enhanced Combustion for NOx Control”, Quarterly Technical Progress Report for US DOE Award No. DE-FC26-00NT40756, October 2000.

6. Patents pending