This report describes the work and results obtained using oxygen enrichment technologies in a pilot boiler. The State of Illinois-sponsored project has been led by Air Liquide in collaboration with McDermott Technology and the Illinois Geological Survey. The main goals of the project were to test several oxygen-enrichment technologies in a pilot boiler using Illinois coal. By replacing significant amounts of air with pure oxygen, the flue gas released in the atmosphere is reduced (up to around 80% when all air is replaced), and thus the cost of flue gas post-treatment can be lowered significantly.

Several different technologies have been tested, and the results are presented in the report. Notably, the NO\textsubscript{x} levels have been reduced below the 0.15 lb/MMBTU, a target for future coal-fired utility boilers. At the same time, the optimal oxygen injection into the boiler has led to significant reductions in the amount of unburnt carbon in the ash, thus increasing the boiler efficiency. The impact of oxygen enrichment on sulfur and mercury removal from the flue gases has been investigated. The results showed that the oxygen-enriched operation has led to significant reduction in both pollutant compounds from the flue gases.

A preliminary economical feasibility study has also been performed during the course of the project. The results showed that the air-fired and the oxygen-rich cases are relatively identical from a capital cost standpoint, and within the uncertainty range in terms of operating costs. When carbon dioxide capture was included in the calculation, the oxygen-fired case ranked significantly better than the air case coupled with an amine scrubbing system.

While future work is required to refine the tested technologies, this first demonstration of oxygen-enriched combustion in high sulfur coal-fired boilers clearly shows the great potential of the technology.
EXECUTIVE SUMMARY

Environmental concerns have changed many industries in the recent past. For instance, ozone depletion in the atmosphere has led to the retirement of long-used refrigerants, and the development of other, more environmentally friendly alternatives. In the same spirit, strong environmental restrictions have been applied to sulfur oxide emissions. As a consequence, high-sulfur coal consumption has been significantly reduced in the past few years, due to the high costs of sulfur oxide removal from flue gas. In order to make the high-quality, high-sulfur Illinois coal more competitive, it is imperative to reduce the costs of the flue gas post-treatment, particularly of desulfurization. This goal motivated the State of Illinois to award funds for a project led by Air Liquide, aimed at developing and testing oxy-combustion technologies using Illinois coal in boilers. The team assessing these technologies included McDermott Technologies and the Illinois Geological Survey.

Oxygen enrichment is a well-known technology, used in a variety of industrial applications. Oxygen enriched, as well as oxygen-fired combustion systems have certain advantages over traditional air-fired technologies, such as lowered emissions, higher combustion and thermal efficiency, higher productivity, improved control, etc. In addition, oxygen enrichment, by removing nitrogen from the process, represents an efficient method to significantly reduce the flue gas flow rate up to around 80% from the traditional air-fired technologies. The very significant reduction will require greatly reduced flue gas post-treatment equipment, such as the wet flue gas desulfurization unit. Finally, by reducing the amount of nitrogen in the process, the carbon dioxide in the flue gas is concentrated, facilitating its capture and sequestration, and thus reducing the emissions of this greenhouse gas in the atmosphere.

All the above-expected results have motivated the partners in this project to perform detailed tests of the oxygen enrichment techniques on a 5 MMBTU coal-fired pilot boiler unit of McDermott Technologies in Alliance Ohio. For this purpose, Air Liquide has provided the oxygen, oxygen delivery and injection system, as well as extensive oxy-combustion expertise, complementing McDermott’s extensive boiler operation and design expertise. Illinois Geological Survey has carried out ash tests, as well as a preliminary, yet detailed economical feasibility study. Detailed modeling of the pilot boiler in various operating conditions has been performed, removing some of the test uncertainties, and allowing for the selection of the optimal oxygen injection hardware and characteristics (location, velocities, direction, etc.).

Several oxygen enrichment tests have been performed, and the results have been analyzed and discussed in the report. These tests include:

1. Enriching the secondary air stream with oxygen. These tests, performed with the specific purpose to test the oxygen delivery system, have led to significant reductions in the NOx levels, attributed primarily to the modified mixing patterns at the burner level. The tests also showed the smooth transition between air and oxygen-enriched fired conditions, as well as the ease to control the oxy-fired process, increasing the confidence in the technique.
2. Enriching the tertiary air streams with oxygen. These tests showed that by increasing the oxygen content in the final stages of the combustion process maintains low NO\textsubscript{x} levels, similar to the air-fired operation, and decreases significantly the amount of unburnt fuel in the ash. This leads to a more efficient overall process, and allows the operators to valorize the low-carbon ash.

3. Recirculating parts of the flue gas back into the boiler, and replacing a large portion of the air-based oxidant with oxygen. The recirculated flue gas plays the role of the nitrogen in the process, thus cooling the high-temperature fuel-oxygen flame. This solution is key to an oxygen enrichment retrofit boiler operation, maintaining the original heat and mass patterns as the air operation. The recirculated flue gas operation included secondary and/or tertiary oxidant enrichment, thus allowing a thorough analysis. The results show extremely promising trends. Thus, the operation of the boiler was very safe, with no hot spots or upsets. The oxygen control is much more versatile when compared to the air control, due to the reduced flowrate of oxidant and the easy-to-operate delivery system. The results showed extremely low NO\textsubscript{x} levels in the flue gas, well below future regulations of 0.15 lbs NO\textsubscript{x}/MMBTU. At the same time, the unburnt carbon in ash (LOI) levels have been reduced dramatically when compared to air operation, indicating a better efficiency and a high-quality ash by-product.

In addition to the above tests, detailed flue gas post-treatment has been conducted, and the results have been analyzed and discussed in this report. These tests included wet flue gas desulfurization measurements, for both air- and oxy-fired cases. The results showed that the SO\textsubscript{3} removal was significantly improved for the oxygen-enriched operation, when compared to the baseline air operation. The improvement, attributed in part to increased gas residence time, indicates that smaller desulfurization units can be used in association to the oxygen-enhanced operation.

Mercury speciation measurements have also been conducted for the air- and oxy-fired cases. The results of the tests have shown that the oxygen fired operation leads to a very significant reduction in the amount of elemental mercury in the flue gas. This result is extremely important in the development of the costly mercury removal technologies.

Finally, a preliminary, yet detailed economical feasibility study for the oxygen-enhanced technology has been performed. The results for a 500MWe utility power plant show that oxygen enriched operation requires a relatively similar capital as an air fired plant – in both cases the multi-pollutant post treatment equipment has been included as required. In addition, the oxy-fired operation costs are slightly higher than the air-fired operation, well within the estimation uncertainty. It is noted that, for lower plant outputs, due to the favorable economies of scale, oxygen operation is more favorable than the air operation.

The economical analysis also concludes that, when oxygen enrichment operation is compared to the air operation PLUS the amine-based carbon capture, the oxygen operation is significantly more economical from a capital and operational standpoint than the air operation. This shows the great potential of the proposed technology for an
economical zero-emission power generation operation. Given the DOE interest in carbon capture and sequestration, the proposed and tested oxy-fired technology provides a great opportunity for coal-fired boilers in general, and for high-sulfur coal in particular.

The tests described here obtained very encouraging results in conditions where the oxygen enrichment has only been partial, due to system limitations. Future tests will remove all remaining air sources in the system, in order to test and assess the impact of the full oxygen technology.

It is concluded that the oxygen-enriched technology has been successfully tested during the course of this project. The results show that the oxygen firing leads to important process improvements, reduction of the most tightly regulated pollutants, and important potential reductions in flue gas post-treatment effort. Oxygen-enriched operation is comparable to clean-coal air operation from an economical standpoint, and it is significantly more economical when carbon dioxide capture is included. Future tests and industrial demonstrations are required to fully assess the impact of oxygen enrichment on the superior utilization of Illinois coal.

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