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Project Title: Hydrated Limestone Injection for SOx Control during
Staged Combustion
ICCI Project Number: 87/2.2A-7
Principal Investigator: Dr. William M. Swift, Argonne National
Laboratory
Other Investigators: Mr. F. Gale Teats, Argonne National Laboratory
Project Monitor: Dr. Mike Lin, CRSC

ABSTRACT

The primary objective of this project was to further evaluate the
potential of injecting hydrated lime into a two-stage slagging
combustor to meet federal and state environmental standards for SO2
emissions from coal-fired boilers. In previous tests at Argonne
National Laboratory (ANL), reductions in SO2 emissions of up to 80%
were obtained during the injection of hydrated lime into the first
stage of a nominal 2 MW slagging combustor. In the current
investigation, six tests provided data on SOx and NOx emissions at 21
different test conditions. Nominal test conditions were a coal feed
rate of 290 lb/h, an overall combustion stoichiometry of 1.2, Ca/S
ratios between 1.4 and 3.8, air preheat temperatures from 130 to
510°F, first stage combustion stoichiometries from 0.61 to 0.87, and
use of first or second stage sorbent injection. The measured
reductions in SO2 emissions based on flue gas analysis ranged from 0%
to 94%. The reduction in SO2 emissions increased with decreasing
first stage combustion stoichiometry, decreasing air preheat
temperature, and increasing Ca/S ratio. It also increased with use of
second stage sorbent injection. Although the results are very
encouraging, considerably more work is required to understand the
complicated phenomena associated with the high sulfur retentions
reported for this work and by other investigators under temperature
conditions where the thermodynamics are unfavorable.

In these tests, NOx emissions ranged from 0.46 to 0.75 lb NO2/10^6 Btu,
with emissions increasing with increasing first stage combustion
stoichiometry. Slag rejection was poor in all the tests due to
problems with keeping the slag tap open. Combustion efficiencies,
based on the analysis of carbon in the first stage slag and CO levels
in the flue gas, were estimated to be on the order of 99.7%.
EXECUTIVE SUMMARY

Although Illinois has the largest reported bituminous coal reserves of any state in the U.S., the utilization of Illinois coal has been hampered because of its generally high sulfur content (3 to 5%). The sulfur, if emitted to the atmosphere during combustion of the coal, can contribute to the formation of acid rain. Since such sulfurous emissions, in sufficient quantity, can pose an environmental problem, federal and state regulations have been imposed limiting them.

The objective of this work was to continue the effort previously funded by the Illinois Coal Industry Committee to evaluate limestone injection for controlling $SO_x$ emissions in coal combustion. Testing involved the injection of a highly activated limestone sorbent, pressure-hydrated lime, into a nominal 2-MWt staged slagging combustor (designed and fabricated at ANL) burning high-sulfur Illinois coals. In addition to the potential for achieving high sulfur retentions with the hydrated-lime sorbent, the two-stage slagging combustor has the added potential advantages of low $NO_x$ emissions, due to staged combustion, and high ash rejection rates, due to the formation and removal of slag by the cyclone design of the combustor.

Six combustion tests with a single Illinois No. 6 coal (3.28 % S, dry basis) were completed. Performance data on $SO_x$ and $NO_x$ emissions were obtained at 21 different test conditions. The main parameters varied during the tests were Ca/S ratio (1.4 to 3.8), air preheat temperature (130 to 510°F), first stage air/fuel stoichiometric ratio (0.61 to 0.87), and use of either first or second stage sorbent injection. The overall air/fuel stoichiometric ratio was maintained at 1.2 ± 0.1, and the coal feed rate was maintained at 290 ± 30 lb/h. The sorbent used was a commercially obtained pressure hydrated lime.

The $SO_2$ retention was determined by the reduction in $SO_2$ levels in the combustion gas during lime injection from baseline levels established without sorbent injection. These values varied from 0% to 94%. During first stage injection, $SO_2$ reductions were generally in the range of 40 to 60%. The reduction in $SO_2$ emissions increased with decreasing first stage stoichiometry, decreasing air preheat temperature, and increasing Ca/S ratio.

With second stage injection, first stage stoichiometry had no apparent effect on overall $SO_2$ removal, with retention increasing with increasing Ca/S ratio and decreasing air preheat temperature. The highest levels of $SO_2$ removal (94%) were observed with second stage injection of the sorbent at low air preheat temperatures (130 to 150°F).

Although the results are very encouraging with respect to the observed reductions in $SO_2$ emissions, considerably more work needs to be done to understand the complicated phenomena of combustion and fluid mechanics in the ANL slagging combustor. Of particular concern with respect to the current work (and results reported in the literature for other slagging combustors) are the high sulfur removals obtained
at thermodynamically unfavorable conditions. Possible explanations requiring further study are: (1) reaction of the sorbent with SO₂ at particle temperatures well below the gas temperature and (2) locally favorable temperature and air/fuel ratios in the complicated high swirl flows in the cyclone-type slagging combustor.

The NOₓ emissions from the slagging combustor ranged from 0.47 to 0.75 lb NO₂/10⁶ Btu, as compared with the U.S. New Source Performance Standard limit of 0.6 lb NO₂/10⁶ Btu. The emissions were found to increase with increasing first stage combustion stoichiometry. These NOₓ emission levels were somewhat higher than the results reported for other slagging combustors, possibly due to differences in combustion temperatures and gas residence times.

Data on slag rejection were not obtained during the test program due to persistent problems with keeping the slag tap open during combustion. Burners installed in the slag line between the combustor and slag receiver were not effective in preventing the slag tap from plugging with solidified slag shortly after each startup.

The poor slag rejection and the inability to sample the second stage flue gas for particulate also prevented an accurate assessment of the overall carbon conversion. Slag samples recovered from the first stage consistently contained less than 0.1% by weight of carbon. The flue gas CO emissions, another potential loss of carbon from the combustor, were generally between 150 and 400 ppm. Based on these results, carbon conversion was estimated to be on the order of 99.7%, which is consistent with the results reported for other slagging combustors.
OBJECTIVES

The general objective of this project was the successful demonstration of an advanced combustion technology with the potential for controlling sulfur dioxide emissions, even when burning high-sulfur Illinois coals. More specifically, the work was intended to continue the effort previously funded by the Illinois Coal Industry Committee through the CRSC to evaluate the injection of a highly activated form of limestone (pressure-hydrated lime) into a staged slagging combustor to achieve the direct burning of high-sulfur coals with low sulfur emissions. The current work was intended to provide a better understanding of the parameters that affect sulfur retention and NO\textsubscript{x} emissions during coal combustion in the 2-MW ANL slagging combustor with pressure-hydrated lime injection. The specific objectives of the work were (1) to determine the effect of the first stage air/fuel ratio, Ca/S molar ratio, and combustion air preheat temperature on the SO\textsubscript{2} and NO\textsubscript{x} emissions at an overall combustion stoichiometry of 1.2 and (2) to study the potential of second stage sorbent injection for improving the control of SO\textsubscript{2} emissions.

INTRODUCTION AND BACKGROUND

Illinois has the largest reported bituminous coal reserves of any state in the U.S. The consumption of Illinois coal in utility and industrial boilers has been hampered, however, because it generally contains three to five percent sulfur. The sulfur, if emitted to the atmosphere in sufficient quantity during combustion, can pose a major environmental problem. Hence, federal and state regulations have been imposed, severely limiting sulfur emissions from coal-fired boilers. Corresponding to the implementation of these regulations has been a general decline in the production of Illinois coal.

The market for Illinois coal would be improved significantly by the development and demonstration of cost-effective coal combustion technologies that could reduce emissions of both sulfur oxides and nitrogen oxides, the major acid-rain precursors. A promising control strategy currently under development combines low NO\textsubscript{x} burners with limestone injection to simultaneously control these pollutants. This technology is a potentially lower-cost alternative to present SO\textsubscript{x} control approaches, such as flue gas desulfurization, coal cleaning, and coal switching. This technology is particularly attractive when coal-fired boilers must be retrofitted to minimize emissions of NO\textsubscript{x} and SO\textsubscript{x}. A major drawback, however, to the technology has been the costly need for large quantities of limestone to meet the existing and proposed regulations for SO\textsubscript{x} emissions control.

The more recent studies related to limestone injection for SO\textsubscript{x} control have centered around obtaining an understanding of the important factors in sulfur capture by limestone sorbents. These studies have involved generic R&D, prototype testing, boiler demonstrations, and efforts at generalization of the technology to a wide range of boiler designs, coals, and sorbents. With respect to the use of limestone
sorbents, several factors have been identified as influencing sulfur capture, e.g., the chemical composition of the sorbent, the stoichiometric ratio of Ca to S, the gas/solids mixing in the combustor, the gas temperature at the location of the sorbent injection, and the subsequent gas temperature/time history.

Perhaps the most important factor in controlling the efficiency of the sulfur capture reaction is the morphology or the surface area of the sorbent. The failure of early limestone injection studies (such as the large-scale test at the Tennessee Valley Authority Shawnee Station, which required Ca/S ratios as high as 7 to achieve a sulfur capture of only 50%) was attributed, in part, to "dead burning" of the limestone. Dead burning is the phenomenon of heating the limestone to a temperature above which the fresh calcine (CaO) recrystallizes, causing a dramatic decrease in the surface area of the lime and, hence, the reactivity of the sorbent.

The U.S. Environmental Protection Agency (EPA) has concluded from a number of studies that the injection of limestone alone will not achieve the sulfur capture goals for many U.S. boiler applications [1]. Two types of materials have been identified, however, for substantially exceeding the goal of 50-60% sulfur capture: high-surface-area hydrated lime and relatively inexpensive and innocuous promoters that enhance the limestone sorbent activity.

Several years ago, researchers at ANL [2, 3, 4] discovered that the ratio of limestone to coal required for fluidized-bed coal combustors could be significantly reduced if the partially spent sorbent from the bed underflow (a mixture of CaSO₄ and CaO) was hydrated and recycled back into the bed. One cause of this improvement in limestone utilization by hydration was the formation of calcium hydroxide, which fractured the reaction-inhibiting outer layer of calcium sulfate on the limestone particles. The calcium hydroxide subsequently decomposed back to calcium oxide at the nominal temperatures within the fluidized-bed combustor. More importantly, the morphology of this calcium oxide was considerably different from that of the original calcined limestone: the grain size was much smaller and the surface area much larger.

More recently, researchers investigating limestone injection into boilers for controlling SOₓ emissions have reported that hydrated calcites (of limestones and dolomites) are superior sorbents as compared to the respective carbonates [5, 6, 7, 8]. In tests carried out at the Hoot Lake Power Station in Fergus Falls, Minnesota, 50% sulfur capture was reported for a Ca/S ratio of 2 with pressure-hydrated lime, as compared to a Ca/S ratio of almost 5 when untreated limestone was tested [5]. In pilot-scale tests of limestone, calcium hydroxide, and pressure-hydrated dolomitic lime injection into an experimental combustion facility, over 80% sulfur removal was achieved with the pressure-hydrated lime, as compared to only about 55% for a dolomite and about 40% for a dry limestone at a calcium-to-sulfur ratio of 2 [7].
Pressure-hydrated lime is prepared by first calcining the limestone. The calcine is mixed with water, and the mixture is then compressed up to 10-atm pressure at temperatures as high as 300°F. When decompressed, the resulting calcium hydroxide particles are extremely small with large surface area. As a result, pressure-hydrated lime has proven particularly effective in testing. Compared with slaked calcites [Ca(OH)₂ and Ca(OH)₂·Mg(OH)₂], which have also performed favorably in reactivity tests, pressure-hydrated calcites have the additional advantage of being produced as a dry product by the flashing off of the excess water during decompression.

The second major advance in technology relevant to the current work is the development of the staged slagging combustor. The initial effort to develop a slagging combustor was conducted at the Pittsburgh Energy Technology Center. The primary objective of that initial study was to obtain basic data with which to optimize slag rejection in a slagging gasifier-combustor under fuel-rich conditions. From that initial effort, slagging combustors were developed principally in support of magnetohydrodynamics (MHD) technology. More recently, staged slagging combustors have been developed and promoted for use as new boiler installations and retrofits of existing boilers to achieve reductions in SOₓ and NOₓ emissions. The staged slagging combustor with sorbent injection is also suitable for retrofitting existing costly gas- and oil-fired combustors without derating the boiler or causing extensive fouling of the heat transfer surfaces by fly ash. The slagging combustor is also being investigated for use in advanced coal-fired gas turbine systems.

There are several projects underway in the United States to develop staged slagging combustors for SOₓ-NOₓ control. Three of the projects have been selected for demonstration testing as part of the U.S. Clean Coal Technology (CCT) program. The CCT projects include an industrial boiler retrofit (Coal Tech) and two utility boiler retrofits (TRW and Trans-Alta). Other slagging combustor concepts are also under development as part of the U.S. Heat Engines Program.

In staged combustion, lime (or limestone) injected into the fuel-rich first stage will react with the sulfur released from the coal to form CaS. Capture as CaS is preferable under the conditions found in a slagging combustor because CaS is stable to higher temperatures than CaSO₄ is [1]. Simons and Rawlins [9] reviewed the kinetics of the reactions of SO₂ and H₂S with limestone to form CaSO₄ and CaS, respectively, and concluded that the reaction of H₂S with CaO proceeds almost as fast as that of SO₂ with CaO. They further concluded that any procedure utilizing limestone to remove SO₂ from combustion gases is potentially capable of removing H₂S at approximately the same rate. Since the formation of CaS does not completely obstruct the porous structure of CaO, as does the formation of CaSO₄, higher limestone utilizations have been demonstrated in the reaction of CaO with H₂S as opposed to the reaction with SO₂. Hence, the potential benefits of improved sulfur retention with pressure-hydrated lime in conventional boiler tests can be expected to extend to staged combustion.
The thermodynamics of the sulfur retention process in a slagging combustor are illustrated in Fig. 1 for combustion of a typical medium sulfur (2.66 wt %) coal containing 2.34 wt % moisture. The figure presents the predicted retention of sulfur by a limestone sorbent (Ca/S = 2.5) as either CaS under fuel-rich conditions or as CaSO₄ under excess air conditions. Factors that strongly influence the thermodynamic calculations include system pressure, coal sulfur content, stoichiometry, and the reaction temperature. Figure 1 indicates that a temperature below 2600°F at a stoichiometric ratio of approximately 0.5 would be required to achieve 80% sulfur retention in

![Graph showing sulfur retention as a function of temperature for different stoichiometric ratios.](image)

**Legend**
- ■ Stoichiometric Ratio = 0.5
- □ Stoichiometric Ratio = 0.7
- ● Stoichiometric Ratio = 1.2

**Coal Sulfur** = 2.66 wt %
**Coal Moisture** = 2.34 wt %
**Ca/S Ratio** = 2.5

**Fig. 1.** Thermodynamically Calculated Sulfur Retention as a Function of Air/Fuel Stoichiometric Ratio and Temperature for the Combustion of a Coal Containing 2.66 wt % Sulfur.
the first stage of the slagging combustor. This maximum temperature for 80% sulfur retention decreases with increasing stoichiometric ratio.

At issue in slagging combustors is whether the temperatures required for good sulfur removal are consistent with the temperatures required for good carbon conversion and good slag rejection in the first stage -- performance characteristics that would be expected to improve at fairly high gas temperatures. As a result, the approach to achieving SO\textsubscript{X} control is being considered somewhat differently by each developer of the technology.

Although the exact details are not known in most cases (for proprietary reasons), some developers do not inject the limestone in the slagging first stage of the combustor. Others, such as Coal Tech [10] and AVCO [11], are continuing to pursue first stage sorbent injection for SO\textsubscript{X} control. AVCO maintains that sulfur retentions in excess of those thermodynamically possible based on the gas temperature can be achieved by introducing the sorbent near the exit of the slagging first stage and immediately removing the sorbent with the slag. This assumes that the particle temperature never reaches gas temperature and that mass transfer and reaction kinetics are relatively fast compared to heat transfer.

A similar argument was made by General Electric (GE) researchers in the early development of an advanced combustor for application to magneto-hydrodynamic power generation and conventional utility and industrial boilers. They took the view that some combination of operating conditions could result in substantial reduction of SO\textsubscript{2} emissions with limestone injection [12]. Factors considered favorable by GE were (1) the general reduction of bulk gas phase temperatures and gas/slag interface temperatures at low stoichiometric conditions and (2) stratification of coal/air mixing into combustion zones having local nonequilibrium temperatures and equivalence ratios.

The reported results in the development of advanced slagging combustors with respect to the control of SO\textsubscript{X}/NO\textsubscript{X} emissions have been promising [13,14]. Tests of a slagging combustor using a 2.1% sulfur coal and pulverized limestone have demonstrated 80% SO\textsubscript{2} removal (at 3% excess oxygen) at a Ca/S ratio of 3 [13]. In testing with predominantly low-sulfur western coals (0.2 to 0.4% S), 70% sulfur removal was achieved in a staged slagging combustor with Ca/S mole ratios as low as 2, where the only calcium added to the system was the calcium inherently present in the coal ash [14].

In another test, dry limestone was injected into the high temperature (3050-3320°F) combustion zone of a 7.3 MW staged combustor. A level of 75-90% reduction in the SO\textsubscript{2} emissions was reported with injected sorbent Ca/S ratios in the range of 2.7 to 3.0 [11].

The reported data on NO\textsubscript{X} emissions from staged slagging combustors have been equally encouraging -- with NO\textsubscript{X} levels as low as 100 ppm in low sulfur coal tests [14] to as high as 450 ppm in the tests with higher sulfur coals [13].
The nominal 2-MW staged slagging combustor located in the Fossil Energy Users Laboratory (FEUL) at ANL was used to determine whether the injection of pressure-hydrated limestone would yield low sulfur emissions during the combustion of Illinois coals [15]. Two Illinois No. 6 coals were tested, a 1.5% sulfur coal and a 3.0% sulfur coal. The limestone used was quarried in Michigan and pressure hydrated to approximately 95% Ca(OH)$_2$.

The preliminary testing of pressure-hydrated lime injection into a slagging combustor at ANL focused on the first-stage injection of the sorbent. This testing was done to determine the effects of Ca/S molar ratio, first stage and overall air/fuel ratios, and the two different coals on the control of SO$_2$ emissions. Sulfur retention (as determined by the reduction in SO$_2$ levels during the periods of limestone injection) varied from 17% to 80% at a calcium-to-sulfur mole ratio of 3.5. Conditions of first stage combustion with excess air (110 to 120% of stoichiometric) or low overall excess air (120% of stoichiometric) generally resulted in lower sulfur retention compared with the results of tests in which the first stage was operated fuel rich (60 to 70% of stoichiometric air) and the second stage was operated at high excess air conditions (170 to 180% of stoichiometric).

The NO$_x$ emissions were significantly different for the two coals tested, averaging 0.9 lb NO$_2$/10$^6$ Btu with the higher nitrogen coal (1.4% N$_2$) and 0.47 lb NO$_2$/10$^6$ Btu with the lower nitrogen coal (1.2% N$_2$). Although it is unlikely that the rather small difference in fuel-bound nitrogen resulted in the fairly significant difference in the measured NO$_x$ emissions, the effects of other parameters were not apparent from the limited test data. The results did demonstrate, however, the ability of the combustor to meet the current New Source Performance Standard of 0.6 lb NO$_2$/10$^6$ Btu.

Although the number of test data from the initial test series was fairly limited, the potential of the staged slagging combustor with the injection of hydrated lime for controlling SO$_x$-NO$_x$ emissions was demonstrated. The tests did identify the need for further study, however, to obtain a better understanding of the parameters that influence sulfur retention and NO$_x$ emissions. Specifically, additional testing is necessary to investigate (1) the effects of first and second stage gas temperature and stoichiometry on SO$_x$ and NO$_x$ emissions, (2) the potential of second stage sorbent injection, (3) the addition of promoters to improve sorbent performance, (4) the use of conventional limestone sorbents (carbonates) to assess the potential economic benefit, if any, of the hydrated sorbent, and (5) the effect (if any) of coal nitrogen on NO$_x$ emissions.

The goals of this second phase of the ANL study on sulfur capture by hydrated-lime sorbents in the ANL two-stage slagging combustor are to:

1. Obtain additional performance data to determine the effects of air/fuel stoichiometric ratio, calcium-to-sulfur ratio, and combustion air preheat temperature on
sulfur capture by pressure-hydrated lime injected into the first stage of the combustor at low overall excess air conditions.

2. Determine whether second stage sorbent injection improves sulfur retention at low overall excess air conditions.

3. Determine NO\textsubscript{x} levels as a function of operating conditions.

4. Determine carbon burnup and slag rejection at selected test conditions.

EXPERIMENTAL

The ANL two-stage slagging combustor was used to test the injection of pressurized, hydrated lime to achieve low sulfur emissions with the direct burning of an Illinois high-sulfur coal. The following sections describe the coal and limestone sorbent tested, the experimental apparatus, and the test procedures.

Coal and Limestone Characteristics

Test Coal. The coal used in the combustion tests was a high sulfur (3.28 wt %, dry basis) Illinois No. 6 obtained from a mine in Perry County, Illinois. Results from the detailed analysis of the coal on a dry and as-fired basis are given in Table 1. In addition to the normal proximate and ultimate analyses, other properties related to the slagging and fouling characteristics of the coal ash are reported. All of the ash characteristics are typical of a slagging coal, including a T\textsubscript{250} temperature of 2360°F. The coal was pulverized off-site to a particle size of 90% -200 mesh and delivered to ANL in sealed metal containers.

Hydrated Limestone. The hydrated limestone originated from a quarry in Northern Michigan. The raw stone was pressure-hydrated by a commercial vendor in Wisconsin. The limestone was calcined, mixed with water, and pumped to a pressurized reaction vessel where the calcium oxide (and MgO, if present) was hydrated. The hydration liberates heat and pressures build within the reactor. Rotating flights promote intimate mixing of the reactants, and the resulting high temperatures and pressures drive the reaction to completion. The hydrated material is then expelled through an orifice in the vessel, and the hydrate, now a dry powder, is collected and sent to a tube mill that breaks up any agglomerates and creates additional surface area. The material is then screened to particle sizes of 99.1% -200 mesh. Results from a nominal analysis of the material are given in Table 2.
Table 1. Analytical Results for Coal Used in Hydrated Lime Injection Tests

<table>
<thead>
<tr>
<th>Proximate Analysis</th>
<th>Weight %</th>
<th>Dry Basis</th>
<th>Mineral Analysis</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>9.70</td>
<td>--</td>
<td>SiO₂</td>
<td>46.52</td>
</tr>
<tr>
<td>Ash</td>
<td>11.10</td>
<td>12.29</td>
<td>Al₂O₃</td>
<td>19.06</td>
</tr>
<tr>
<td>Volatile</td>
<td>34.16</td>
<td>37.83</td>
<td>TiO₂</td>
<td>0.94</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>45.04</td>
<td>49.88</td>
<td>Fe₂O₃</td>
<td>21.77</td>
</tr>
<tr>
<td></td>
<td>100.00</td>
<td>100.00</td>
<td>CaO</td>
<td>4.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MgO</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K₂O</td>
<td>2.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Na₂O</td>
<td>0.44</td>
</tr>
<tr>
<td>Ultimate Analysis</td>
<td></td>
<td></td>
<td>SO₃</td>
<td>3.54</td>
</tr>
<tr>
<td>Carbon</td>
<td>62.67</td>
<td>69.40</td>
<td>Fe₂O₃</td>
<td>1.8</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4.32</td>
<td>4.78</td>
<td>Mn₃O₄</td>
<td>0.03</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.23</td>
<td>1.36</td>
<td></td>
<td></td>
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<tr>
<td>Chlorine</td>
<td>0.05</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfur</td>
<td>2.96</td>
<td>3.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen (diff.)</td>
<td>7.97</td>
<td>8.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Btu/lb</td>
<td>11,289</td>
<td>12,502</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

T₂50 Temperature 2360 °F
Base:Acid Ratio 0.45
Silica Value 63.16

Fusion Temperature of Ash:
- Reducing
  - Initial Deformation 1990 °F 2325 °F
  - Softening (H=8) 2105 °F 2400 °F
- Oxidizing
  - Fluid 2325 °F 2540 °F

Fouling Index 0.20
Slagging Index 1.46

Experimental Apparatus

Test Facility. The experimental test program was conducted in the ANL Fossil Energy Users Laboratory (FEUL), which was constructed to accommodate a wide range of experiments related to coal and oil combustion and to commercial and utility boiler systems. The facility has two test legs: one test leg has a nominal 2 MW combustor capable of burning a variety of liquid fuels, including various types of slurry mixtures; the other test leg contains the nominal 2 MW, two-stage slugging coal combustor used in performing the tests described in this report. Each test leg has the necessary independent fuel feed, support, and control systems. The air compressors, combustion air preheater, effluent control equipment, recirculating water/ethylene glycol cooling system, and data acquisition system are shared by the two test legs. Instrumentation readout, data acquisition and processing, and facility control systems are located in a building adjacent to the test facility.
Table 2. Results from Nominal Analysis of Pressure-Hydrated Limestone

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca(OH)$_2$</td>
<td>94.9</td>
</tr>
<tr>
<td>Mg(OH)$_2$</td>
<td>1.1</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe$_2$O$_3$ + Al$_2$O$_3$</td>
<td>0.5</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0.5</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>0.5</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>0.6</td>
</tr>
<tr>
<td>Unhydrated Oxides</td>
<td>0.5</td>
</tr>
</tbody>
</table>

A schematic of the coal-fired test leg is shown in Fig. 2. Coal, prepared off-site and delivered to ANL in sealed containers, is loaded into a coal storage hopper. Coal is discharged from the hopper and conveyed pneumatically to the first stage of the coal combustor at the nominal rate of 300 to 400 lb/h (1.0 to 1.5 MW). Preheated air is injected into the first stage through a center line axial port and through a series of ports located around the circumference of the combustor. The first stage of the combustor was designed with a slag tap to remove the molten slag expected to form on the first stage combustor walls. The gases leaving the first stage of the combustor encounter additional combustion air injected radially into the second stage of the combustor. The flue gases then pass through a test section where the combustion gases are sampled continuously to provide on-line gas analysis. The gases are then quenched and sent to a venturi scrubber for cleaning before entering the stack. The combustor and the associated ancillary equipment are described in more detail in the following sections.

Coal Combustor. A cross section of the coal combustor, designed and fabricated by ANL, is illustrated in Fig. 3. The combustor consists of three flanged sections with a fourth section downstream of the combustor for instrumentation and gas sampling. The primary combustor consists of two sections: the first section accommodates the combustion air inlet header, coal feed injection nozzle, and a limestone feed port; the second section accommodates the slag tap (see Fig. 3). Both sections of the primary combustion stage are fabricated from 24-in. schedule 20 carbon-steel pipe (23.25-in. ID) and flanged at both ends. The coal and air inlet section has an overall length of 30
Fig. 2. Schematic of the ANL Slagging Coal Combustor Test Leg

in.; the slag tap section is 24 in. in length. There are numerous ports in both sections of the primary combustor that can be used for insertion of instrumentation or feeding additives, sampling, and visual observation.

The primary combustor is lined with a high-alumina castable refractory to protect the combustor walls and reduce heat losses. Hence, the nominal inside diameter of the first stage is approximately 21 in. Air to the first stage combustor enters through a header which is flanged and attached to the upstream flange of the combustor. The primary combustion air is split using flow control valves. Some of the air enters axially on the combustor centerline; the remaining primary combustion air enters radially through a plenum chamber that extends into the first stage of the combustor. The plenum chamber has six rectangular openings which admit air into the first stage.
Fig. 3. Cross-Section Schematic of the ANL Slagging Coal Combustor

Louvres placed over the plenum chamber openings provide a tangential component to the air entering the combustor.

Coal enters the first stage of the combustor through a nozzle that penetrates the primary combustion air header along the combustor centerline axis. The nozzle is illustrated schematically in Fig. 3 and in somewhat more detail in Fig. 4. A pintle with an angle of 45° is located at the end of the coal injection nozzle to radially disperse the incoming pulverized coal.

Two additional flanged ports penetrating the primary combustion air inlet header were used to accommodate the feeding of hydrated lime to the first stage, and a methane ignition system was used for startup.
Fig. 4. Details of the First Stage Coal Injection Nozzle

The feed line for the hydrated lime did not extend beyond the inlet to the combustor. If extended, however, the line of injection would have intersected the centerline of the combustor at a point approximately 16 in. downstream of the combustor inlet (approximately 10 in. downstream of the coal injection nozzle).

The second stage of the combustor is fabricated from 18-in. schedule 40 standard pipe with an inside diameter of 17.25 in. This section has flanges at both ends with a length of 36 in. Secondary air is injected radially through three 2.5-in. diameter ports located 120° apart on the combustor wall and in a plane perpendicular to the combustor axis. The secondary combustor also contains ports for sampling and visual observation. The second stage is also refractory lined, which reduces the inside diameter to approximately 15 in.
The first and second stage combustors are separated by a water cooled slag baffle, which is approximately 1-1/4-in. thick and has a combustor centerline opening with a diameter of 10.5 in. The purpose of the baffle is to prevent liquid slag formed during first stage combustion from flowing into the second stage.

Downstream of the second stage combustor is a test section where the flue gases can be sampled prior to quenching with water and being sent to a venturi scrubber. The test section is fabricated from 24-in. schedule 60 pipe, flanged at both ends with an overall length of 72 in. Refractory lining on the inside reduces the inside diameter to approximately 18 in.

Combustion Air Supply. Combustion air is supplied by two compressors with a total capacity of 2 lb/s (approximately 1500 scfm) at 25 psig. The air can be preheated up to a maximum temperature of approximately 1500°F by an electrical resistance heater, which has a maximum power output of 600 kW. The preheated air is then split, using high temperature diverter valves, into three parts: axially injected primary combustion air, radially (or tangentially) injected primary combustion air, and secondary combustion air. Total air flow is controlled by venting some of the compressor output directly to the atmosphere.

Coal Feed System. The coal is prepared off-site to the required size distribution and then shipped to ANL in sealed containers which hold approximately 1500 lb of coal. The bins are placed in an automated unloader that lifts and dumps the coal through a screen in a closed system. The coal passing the screen is lifted pneumatically (in dense phase transport) to the top of the coal storage hopper where it is separated from a nitrogen carrier gas by means of a cyclone, collected in a lock hopper, and then periodically transferred to the main storage vessel, which holds approximately 2500 lb of coal.

During coal feeding, the storage tank is pressurized by nitrogen to around 5 psig, and fluidizing nitrogen is introduced near the bottom of the hopper. Transport air flows through a venturi nozzle at the base of the coal bin in order to draw coal from the hopper. The venturi throat is adjustable so that the coal feed rate can be controlled by a remotely operated venturi positioner. The coal flow rate can also be controlled at a fixed venturi position by adjusting the hopper pressure to control the Δp across the venturi.

Sorbent Feed System. A feed system consisting of a storage hopper and a rotary valve metering system injects the hydrated lime into the combustor at controlled rates. During feeding, fluidizing air is introduced into a cone at the base of the hopper to assist the flow of lime from the hopper. A manually regulated, variable-speed drive motor is used to control the speed of the rotary valve and, hence, the lime feed rate. The rotary valve is emptied into a tee, where the lime is entrained and pneumatically injected into the first or second stage of the combustor.
Coolant System. The walls of the combustor sections are fitted with panel-type cooling plates to prevent overheating of the walls. A thin layer of heat transfer cement between the panels and the combustor walls improves their thermal contact. Areas not well covered by the panels are fitted with windings of copper tubing, which are also bonded to the combustor walls with heat transfer cement. The cooling panels and copper windings are connected into a number of parallel cooling circuits. Each of the individually flanged sections (including the test section) has two main cooling circuits equipped with flow meters to measure coolant flow and thermocouples to determine the temperature rise of the coolant. The coolant used to remove heat from the combustor walls is a 50/50 solution of ethylene glycol and water. The coolant is recirculated in a closed loop system between the combustor and a finned-tube, fan-cooled heat exchanger.

Gas Quench and Effluent Handling. The hot combustion gases leaving the insulated test section are first quenched with a spray of clarified scrubber water. The cooled gases then flow through a wet venturi scrubber and are exhausted from a 115-ft high stack. The quench water and scrubber water are recirculated from a lined pond in which suspended solids settle out and are temporarily stored.

Instrumentation. The total air flow rate to the combustor was measured using a vortex shedding flow meter located between the air compressors and the electrical air preheater. The signal from the flow meter automatically compensates for changes in gas density, using locally measured values of gas temperature and pressure. After the total air flow is split, the axial, swirl, and secondary air flow rates are determined from Pitot tube Δp measurements and local measurements of gas temperature and pressure. All signals are transmitted to a data acquisition system, and the individual flow rates are displayed on an interactive display terminal.

The coal and hydrated lime feed hoppers and associated equipment are both supported on load cells. The output from the coal hopper load cells is transmitted to a dedicated microprocessor that calculates coal feed on the basis of 10-s and 100-s time averages. The output from the lime hopper load cells goes to a remote digital readout, and the data are as manually recorded as a function of time to determine the limestone feed rate.

Six ports can be used to sample the combustion gases in the first and second stages of the combustor. The capability exists to remotely select and change the sample point in service at any time during a test. Sample lines not in service can be back-purged with air or nitrogen while in the standby mode. The gas sampling tubes (uncooled) are inserted through ports located in the test sections and extended so that sampling occurs near the combustor wall.

Each sample line is fitted with a small, water-cooled heat exchanger to quench the sample gas leaving the combustor. The sample is then filtered free of particles and dried with a membrane-type dryer before being pumped to the gas analysis system. The gases are then analyzed.
on-line for CO (infrared), O₂ (electrochemical), SO₂ (infrared), CO₂ (infrared), and NO/NOₓ (chemiluminescent). The analyzers are calibrated using standard calibration gases at the beginning of each test.

Test Procedures

Start-up. Coolant flow to the combustor walls and quench water to the quench spray ring and venturi scrubber are established. The compressors are turned on, and the bypass valve is adjusted to provide the desired gas flow rate to the air preheater and combustor. The air preheater is then turned on, and the temperature controller is set to the desired preheat temperature. As the system is being preheated, the data acquisition system is activated, the gas analysis equipment is turned on and calibrated, and the coal hopper is pressurized to approximately 5 psig with nitrogen.

Once the combustor is at the desired air preheat temperature, approximately one to two hours from the beginning of the start-up procedure, the air and methane supply lines to the methane ignition system are opened and the correct supply pressures are established. As a matter of safety, the final ignition sequence is performed remotely from a control room.

From the control room, the flow of transport air is established, and the coal metering orifice at the base of the coal hopper is adjusted to the desired setting for start-up. The ignition sequence is initiated by a purge switch that requires a 30-s delay before proceeding. Once the delay is ended, an ignition switch that simultaneously opens a positive shut-off valve at the base of the coal hopper and establishes a methane flame in the combustor is activated. The methane flame is automatically shut off at the end of 10-s. At that point, if a flame is not detected by either of two flame detectors located in first- and second-stage combustor view ports, the ignition sequence aborts automatically. The purge switch must be reactivated, requiring another 30-s delay before making another attempt to ignite the combustor. Detection of a flame by either detector allows the coal feed valve to remain open. With ignition, the start-up sequence is completed.

Parametric Variation During Data Collection. After ignition, a period of one to two hours is generally required to adjust the air and coal feed rates and achieve the desired combustion stoichiometries in the first and second stages. The desired stoichiometries are confirmed by analysis of the first and second stage combustion gases.

The procedure generally followed during test periods was to collect baseline data at a given set of conditions without the injection of hydrated lime. The hydrated lime was then injected into the first or second stage of the combustor and the gas analysis in the second stage was observed for changes in SO₂ level until a new "steady-state" value of SO₂ was achieved. The limestone feed was then discontinued, and the SO₂ level in the combustion gas was allowed to "recover" to the baseline value.
After the operating parameters were changed, the above procedure was repeated at the new set of conditions. This procedure was repeated three to six times during each test period to collect data at several different conditions.

RESULTS AND DISCUSSION

Fifteen attempts were made to operate the ANL combustor with hydrated-lime injection. Six attempts were successfully completed, with data being obtained at a total of 21 different test conditions. The major operating difficulties encountered during the other nine attempts were (1) failure of the coal ignition and flame detection system, (2) moisture in the transport air that resulted in coal and hydrated lime feeding problems, and (3) occasional flameouts due to interruptions in the coal feed. One of the problems related to ignition and flame stability was corrected when it was discovered that the coal injection nozzle heat shields (see Fig. 4) had slipped into the axial air inlet. Problems related to sustaining ignition during start-up and flame stability during testing were improved considerably when the heat shields were located in the correct position shown in Fig. 4.

The main parameters varied during the tests were Ca/S ratio (1.4 to 3.8), air preheat temperature (130 to 510°F), first stage air/fuel stoichiometric ratio (0.61 to 0.87), and location of hydrated-lime injection (first or second stage). The overall air/fuel stoichiometric ratio was maintained at 1.2 ± 0.1. The coal feed rate during the tests varied from 260 to 320 lb/h.

The nominal operating conditions and test results are presented in Table 3. Tests 5D, 5E, 6D and 7 investigated the effects of Ca/S ratio, first stage air/fuel ratio, and air preheat temperature on combustor performance with first stage sorbent injection. Tests 8 and 9 concentrated on second stage sorbent injection. The results of the tests are discussed in the following sections.

Sulfur Retention. Sulfur retention was determined as the percent reduction in SO₂ emissions (as determined by the on-line analysis of SO₂ in the combustion gas leaving the second stage of the slagging combustor) from the baseline value at the start of a test period of hydrated-lime injection. A total sulfur balance for the system could not be made because slag rejection was poor (discussed below) and representative samples of the fly ash could not be obtained from the combustor (the hot combustion gas is quenched with a water spray that flows to a retention pond).

The observed reduction in SO₂ emissions at several of the test conditions is illustrated in Fig. 5. As indicated by the data, the initial reduction in SO₂ generally occurred within two to four minutes. This delay can be largely attributed to the gas sampling, conditioning, and analysis system, since the average gas residence times in the slagging combustor are very short (about 150 ms in the
Table 3. Slagging Combustor Operating Conditions and Test Results

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N.D. = Not Determined
first stage and 250 ms in the combined second stage and downstream test section).

Also indicated by Fig. 5 is the relatively short duration of the limestone injection test periods. This time was generally sufficient due to the rapid response of the SO\textsubscript{2} emissions to limestone injection. The short limestone injection periods were also helpful in minimizing the need to recharge the relatively small capacity sorbent feed hopper during the combustion tests, a difficult and time-consuming task.

The data for Test 8A-5 in Fig. 5a also illustrate the response of the system when the sorbent feed was discontinued (unshaded square symbols). As can be seen, the SO\textsubscript{2} emissions quickly returned to the baseline level. The data in Fig. 5b show some fairly large swings in the SO\textsubscript{2} data with time. This probably resulted, in part, from fluctuations in the coal and hydrated lime feed rates. The fluctuations may also be indicative of instabilities in the fluid dynamics of the slagging combustor. The buildup of slag deposits on the combustor walls has resulted in a non-uniform flow geometry that may have created a nonstable flow field within high swirl regions. This could affect the time-temperature history of the sorbent particles and result in variations in sulfur removal even under uniform feed rate conditions.

As shown in Table 3, the observed sulfur retentions over the range of test conditions varied from 0% to 94%. An attempt was made to correlate the fairly limited data as a function of Ca/S ratio, air preheat temperature, and first stage stoichiometry for both the first and second stage lime injection tests. The results are shown in Figs. 6 and 7.

Figure 6a presents the data for first stage injection tests with a low air/fuel stoichiometric ratio (0.61-0.74). The data indicate a small effect of Ca/S ratio and air preheat temperature. These data suggest that low first stage stoichiometry is the controlling factor in determining first stage gas temperature, and that the effect of increasing the air preheat temperature by 350°F has a marginal effect in reducing the measured sulfur retention. Previous tests in the ANL combustor had indicated carbon conversion in the first stage under reducing conditions (stoichiometry of 0.66-0.7) to be on the order of 60 to 80 percent of theoretical based on the air-to-coal flow rates [16]. Hence, at this low stoichiometric ratio, the reduction in first stage gas temperature may be quite high.

Figure 6b presents the measured effect of first stage hydrated-lime injection on sulfur retention for higher air/fuel stoichiometric ratios (0.75 to 0.87). In this case, where carbon conversion in the first stage is probably closer to theoretical (on the order of 85 to 95 percent [16]), the effect of the first stage air preheat temperature is much more pronounced. Comparing Figs. 6a and 6b indicates that, at the low air preheat temperatures of 135 to 165°F, sulfur retention was not significantly influenced by the first stage
Fig. 5. Observed Reductions in SO$_2$ Emissions during the Injection of Hydrated Lime in (a) test 8a and (b) Test 9. (The SO$_x$ concentration is in ppm normalized to 3% O$_2$ in the Combustion (gas).
Fig. 6. Effect of Ca/S Molar Ratio and Combustion Air Preheat Temperature on Sulfur Retention for First Stage Sorbent Injection at First Stage Air/Fuel Stoichiometric Ratios of (a) 0.61 to 0.74 and (b) 0.75 to 0.87.
stoichiometry. However, sulfur retention is significantly lower at the combined higher air preheat temperature and higher air/fuel ratio.

For tests 8 and 9 (second stage injection), the data did not indicate a strong influence of first stage stoichiometry. The only observed influence on sulfur retention was Ca/S ratio and air preheat temperature (see Fig. 7). This finding is not unreasonable; since carbon conversion in the second stage approaches 100 percent under excess air conditions, the first stage air/fuel ratio should not strongly influence the second stage gas temperature. Gas temperature would, however, still be influenced by the combustion air preheat temperature.

An unexpected result is that the highest sulfur retentions (85 to 95%) were observed at the low air preheat conditions and second stage sorbent injection. The previous tests in this series [5] had indicated that, at the low overall stoichiometry of 1.2, sulfur retention was generally in the range of 30 to 60% with first stage sorbent injection under reducing conditions and 500 to 700°F air preheat temperature (results consistent with the current findings). It had been expected, however, that improvement over these previous results would occur with first stage sorbent injection at low air preheat temperatures but not with second stage injection, where the theoretical gas temperatures are higher and the conditions are oxidizing.

![Graph](image.png)

Fig. 7. Effect of Ca/S Molar Ratio and Combustion Air Preheat Temperature on Sulfur Retention for Second Stage Sorbent Injection.
However, since most of the first stage injected material (lime and coal ash) is being carried as fly ash into the second stage due to the poor slag rejection of the ANL combustor, the distinction between first and second stage injection of the hydrated lime in the current study is not clearly delineated. In fact, second stage injection may be advantageous in reducing the residence time of the sorbent particles in the high temperature combustion gas.

Theoretical gas temperatures in the first and second stages of the combustor were calculated for representative conditions of first stage stoichiometry, air preheat temperature, and wall heat losses. The data are given in Table 3. The temperatures were determined by assuming adiabatic equilibrium carbon conversion in each stage for the measured air/fuel ratios and then adjusting for the measured transfer of heat to the combustor walls. Actual temperatures were probably several hundred degrees below the theoretical "flame" temperatures due to incomplete carbon conversion, particularly in the first stage where, as indicated above, carbon conversion was only 60 to 95% of theoretical under reducing conditions [16].

The calculated flame temperatures are well in excess of temperatures where sulfur retention should theoretically occur. These results are similar, however, to the results of other tests of limestone injection into the first and/or second stages of slagging combustors in which sulfur retention exceeded the levels expected based on thermodynamic equilibrium calculations [10-12]. AVCO postulated the existence of "super-equilibrium" conditions in the combustor due to sulfur retention occurring before the sorbent particles reach gas temperature. Hence, the AVCO design is based on injection of the sorbent near the exit of the substoichiometric first stage and removal of the sorbent with the rejected slag before the particles achieve gas temperature. General Electric also postulated that nonuniform temperature and flow fields could lead to results not consistent with theory based on average temperature conditions [12]. The current results, although encouraging, emphasize the need for additional study to understand the complete phenomena occurring in a slagging combustor with respect to sulfur retention by a limestone sorbent.

$\text{NO}_x$ Emissions. A secondary objective of the test program was to monitor $\text{NO}_x$ emissions at each test condition. These results are also presented in Table 3 and correlated as a function of the first stage air/fuel stoichiometric ratio in Fig. 8. The emissions ranged from 300 ppm to 480 ppm (at 3% $\text{O}_2$) over the range of conditions tested. These values correspond to emissions of 0.46 to 0.75 lb $\text{NO}_2/10^6$ Btu, which is comparable with the New Source Performance Standard (NSPS) of 0.6 lb $\text{NO}_2/10^6$ Btu.

Although there is considerable scatter in the data, a least squares fit indicates an increasing trend in $\text{NO}_x$ emissions with increasing first stage air/fuel ratio. This result is consistent with the observed trends in $\text{NO}_x$ emissions for other slagging combustors [17,18]. The cited results show a minimum in $\text{NO}_x$ emissions at an air/fuel ratio of approximately 0.7 in the first stage, with the absolute $\text{NO}_x$ emissions at the minimum in the range of 75 to 250 ppm.
These levels of NO\textsubscript{x} emissions are well below those obtained during the current study with the ANL slagging combustor. This may be the result of a number of factors, such as differences in heat losses and first stage gas residence times.

The ANL results do confirm, however, that NO\textsubscript{x} emissions below the NSPS of 0.6 lb NO\textsubscript{2}/10\textsuperscript{6} Btu can be achieved in a staged slagging combustor when burning a typical Illinois No. 6 coal.

Slag Rejection. No meaningful data on slag rejection were obtained during the tests due to a persistent problem of slag drain blockages. Prior to the tests, burners were installed in the slag drain in an attempt to prevent the slag from "freezing" and plugging the slag tap during testing. Some bypassing of the first stage combustion gas
through the slag tap was also attempted to maintain the slag in a free-flowing condition. These efforts were unsuccessful, however. Slag rejections of only 5-10 percent were achieved (based on the overall period of testing) due to blockage of the tap shortly after each start-up of the combustor.

Combustion Efficiency. Because of failure of the slag tap and the inability to obtain samples of fly ash from the second stage of the combustor, we could not make the carbon mass balance calculations required to accurately determine combustion efficiency. Samples of slag recovered from the slag receiver before the slag tap blocked during each test were analyzed for carbon. The results are shown in Table 4. As can be seen, carbon levels in the slag were consistently below 0.1 wt%, indicating essentially complete burnout of the carbon in the ash that formed a slag. Emissions of CO from the second stage of the combustor were also generally quite low. The CO levels were typically in the range of 150 to 400 ppm, except during periods of start-up and transient conditions where the O2 level in the second stage was low (<0.6% by volume). This range of CO emissions corresponds to carbon levels of less than 0.3% of the carbon in the coal not being burned. The combined levels of carbon in the slag and CO emissions indicate carbon conversions on the order of 99.7%. This level of conversion is similar to the reported result of 99.5% in a 4000-h test of a slagging combustor by TRW [18]. This result needs to be confirmed for the ANL combustor, however, by sampling the fly ash to confirm low carbon levels in the fly ash, as well as sampling the combustion gas (as CO) and slag.

Table 4. Results from Analysis of Selected Slag Samples for Carbon Content

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Slag Carbon Content, % Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>5E</td>
<td>&lt;0.07</td>
</tr>
<tr>
<td>6D</td>
<td>0.09 ± 0.02</td>
</tr>
<tr>
<td>7</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td>8</td>
<td>&lt;0.07</td>
</tr>
<tr>
<td>9</td>
<td>0.04 ± 0.02</td>
</tr>
</tbody>
</table>

CONCLUSIONS AND RECOMMENDATIONS

A series of combustion tests was completed in the ANL 2 MW slagging combustor to assess the potential of injecting a limestone sorbent (hydrated lime) to achieve low SOx and NOx emissions during the
combustion of high-sulfur Illinois coals. The results are very encouraging. Measured sulfur retentions in excess of 90% were obtained during the injection of hydrated lime into the second stage of the combustor at a Ca/S ratio of 1.7 to 2.3. The results indicated that sulfur retention improved with decreasing first stage stoichiometry and air preheat temperature and with use of second stage injection of the sorbent.

NO\textsubscript{X} emissions below the NSPS were also achieved. These emissions increased with increasing first stage stoichiometry. Although not confirmed by analysis of the fly ash from the second stage of the combustor, carbon conversion based on carbon levels in slag samples from the first stage of the combustor and the CO levels in the combustion gas is estimated to be in excess of 99.7%.

Additional work needs to be done to understand the phenomena controlling sulfur removal by limestone-based sorbents in slagging combustors. Data from a number of combustors under development, including the results reported here, indicate sulfur removals in excess of thermodynamically calculated limits based on the average gas temperatures in the slagging combustor. Possible explanations that need to be investigated include (1) sulfur retention at temperatures below the bulk gas temperature as the injected limestone particles are heating up and (2) the existence of temperature and flow fields in the slagging combustor conducive to the lime-SO\textsubscript{2} reaction.

Additional work also needs to be done to improve the performance of the slag tap and second stage fly ash sampling to confirm (by material balance) the indicated sulfur retentions and carbon conversions based on gas analysis.

REFERENCES


17. B. Zauderer and K. S. Fuji, "NO\textsubscript{X} Control in an Air Cooled Cyclone Coal Combustor," Proceedings of the 1985 Joint Symposium on Stationary NO\textsubscript{X} Control, Boston, MA, EPRI Report EPRI CS-4360 (1986).