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**INTEGRATED EMISSIONS CONTROL SYSTEM
FOR RESIDENTIAL CWS FURNACE**

Annual Status Report Number 2

Report Period: October 1, 1990 to September 30, 1991

**By
J.C. Dalsavich, Jr.**

November 1991

**Work Performed Under Contract No. DE-AC22-89PC89804
September 20, 1989 to March 20, 1992**

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1. INTRODUCTION AND SUMMARY

One of the major obstacles to the successful development and commercialization of a coal-fired residential furnace is the need for a reliable, cost-effective emission control system. Ash, sulfur, and fuel-bound nitrogen make the control of NO_x , SO_x , and particulates much more difficult with coal-based fuels than with either natural gas or oil. While techniques for controlling these emissions in large utility power plants are well advanced, they generally would be too complex and costly to be applied directly to residential applications.

To meet the emission goals set by the Pittsburgh Energy Technology Center (PETC), Tecogen Inc. is developing a novel, integrated emission control system to control NO_x , SO_2 , and particulate emissions. At the heart of this system is a unique emissions control reactor for the control of SO_2 . This reactor provides high sorbent particle residence time within the reactor while doing so in a very compact geometry. In addition to controlling SO_2 emissions, the reactor provides a means of extracting a substantial amount of the particulates present in the combustion gases. Final cleanup of any fine particulates exiting the reactor, including respirable-sized particulates, is completed with the use of high efficiency bag filters.

With SO_2 and particulate emissions being dealt with by an emissions control reactor and bag filters, the control of NO_x emissions needs to be addressed. Under a previous contract with PETC (contract No. DE-AC22-87PC79650), Tecogen developed a residential-scale Coal Water Slurry (CWS) combustor. This combustor makes use of centrifugal forces, set up by a predominantly tangential flow field, to separate and confine larger unburned coal particles in the furnace upper chamber. Various partitions are used to retard the axial, downward flow of these particles, and thus maximize their residence time in the hottest section of the combustor. By operating this combustor under staged conditions, the local stoichiometry in the primary zone can be controlled in such a manner as to minimize NO_x emissions.

The development program for this project is divided into three facets, each having specific objectives with clear goals that would be met prior to proceeding to the next step. First, all system and component analyses would be completed, and the initial prototype component hardware would be tested and evaluated. Preliminary manufacturing and operating cost estimates would also be made. Second, final prototype hardware would be built and tested, and cost estimates updated. Finally, the entire furnace system would be tested to demonstrate that the emissions goals were met, and the high-volume production cost estimates would be finalized.

The entire program covers a period of 30 months. The first step requires 12 months, and the next two, 9 months each. This report summarizes work conducted during the second year of the program.

In work during the second year of the program, testing of the individual components was completed. As a result of this testing the CWS combustor achieved NO_x emissions as low as 0.14 lbm/MMBtu under staged conditions with the specified CWS for this program. This is less than the 0.2 lbm/MMBtu goal that was established for this program. Tests of the SO_2 reactor revealed emissions levels of 0.39 lbm/MMBtu. This represents over a 90-percent reduction in SO_2 and is less than the 0.4 lbm/MMBtu program goal.

2. PROGRAM OBJECTIVE

The objective of this program is to develop a combined particulate, SO₂, and NO_x integrated control system for flue gas cleanup of residential furnaces fueled by coal water fuel mixtures. Specific objectives for this program are:

- To reduce flue gas emissions from the furnace to the following levels:
 - SO₂: 0.4 lb/MMBtu
 - NO_x: 0.2 lb/MMBtu
 - Particulates: 0.02 lb/MMBtu
(99.9% capture of particles 0.5 to 10 microns)
- To achieve a high reliability and a service life of 20 years or more by utilizing a simple design concept with no critical moving parts.
- To keep scheduled maintenance to twice a year.
- To achieve efficient sorbent utilization in reducing SO₂ so that the volume of ash and spent sorbent collected before removal is acceptable.
- To use a simple design approach to keep manufacturing costs as low as possible.

In order to achieve these objectives, this program has been divided up into 8 individual tasks. These tasks, along with their various subtasks, provide the framework for this project and establish the various goals and milestones. The 8 main tasks for this program are:

- Task 1: Project Work Plan
- Task 2: System Definition
- Task 3: Prototype Component Analysis and Design
- Task 4: Prototype Component Fabrication and Assembly
- Task 5: Testing and Development
- Task 6: Integrated System Operation
- Task 7: Economic Evaluation
- Task 8: Reporting and Management

3. WORK PERFORMED DURING THE SECOND YEAR

During the second year of this program, work was completed on testing the individual components as a prelude to system integration. This work included operating the coal water slurry (CWS) combustor under staged and unstaged conditions in the NO_x reduction test facility as well as testing both 6-in.-diameter and 8-in.-diameter reactors with various sorbents in the SO_2 reduction test facility. For both the CWS combustor and the SO_2 reactor, the emissions goals that were established for this program - 0.2 lbm/MMBtu for NO_x and 0.4 lbm/MMBtu - were met. For the CWS combustor, which was operated with the specified CWS for this program, NO_x emissions as low as 0.14 lbm/MMBtu were achieved. For the 8-in.-diameter SO_2 reactor, emission levels as low as 0.39 lbm/MMBtu were achieved.

3.1 SO_2 REACTOR TESTING

Tests were conducted on both 6-in. and 8-in. nominal diameter reactors, both with and without axial recirculation, in the SO_2 Removal Test Facility. A photograph of the facility is shown in Figure 3.1 and a schematic diagram is shown in Figure 3.2. The SO_2 Removal Test Facility operates with the products of combustion produced by burning No. 2 home heating oil. In order to obtain the required reactor inlet concentration, a metered amount of SO_2 is injected into the combustion chamber. The reason for using an oil burner in this facility is that it is flexible enough to provide a range of input rates from 65,000 to over 400,000 Btu/hr.

The key component in the SO_2 Removal Test Facility is the SO_2 reactor. The SO_2 reactor is a vortical upflow device shown schematically in Figure 3.3. Both the products of combustion and sorbent enter tangentially at the base of the reactor and spiral upward toward the reactor outlet. Due to the strong vortex set up in the reactor, the pressure at the reactor wall is greater than at the centerline. By connecting one end of a tube tangentially from the reactor wall and the other to the reactor centerline, an axial recirculation path for both gas and particles is established that relies only on the natural pressure difference of the vortical flow field. The key feature of this recirculation effect is to improve the radial and axial distribution of particles within the reactor.

3.1.1 Six-Inch-Diameter Reactor Performance

The first reactor tested in the SO_2 Removal Test Facility was a nominal 6-in.-diameter reactor. This reactor had the following geometry:

Inside Diameter:	6.065 in.
Recirculation Line Diameter:	1.049 in.
Active Reactor Height:	45 in.
Inlet Area:	4 in. ²

Figure 3.1 SO_2 Test Facility

Figure 3.2 Schematic Diagram of SO₂ Removal Test Facility

Figure 3.3 Schematic Diagram of SO_2 Reactor

The calcium-based sorbent used in this testing was a dolomite from northwest Connecticut that is used primarily for residential lawn applications. This dolomite contained about 60 percent CaCO_3 with the balance being MgCO_3 . This sorbent was used in two forms that differed in particle size distribution. The first form was designated sorbent 1, and was the as-received form of the dolomite. This sorbent had a mean particle diameter of 194 microns. The second form of the sorbent was designated sorbent 1-A. This sorbent was obtained by sieving and then selectively mixing sorbent 1 to result in a mixture having a mean particle diameter of 117 microns, with a good percentage of fines. A comparison of particle size distributions for sorbents 1 and 1-A is shown in Figure 3.4 in the form of a Rosin and Rammler chart.

Numerous tests were conducted on the 6-in.-diameter SO_2 reactor to assess the performance of the reactor for various operating temperatures, Ca/S mole ratios, gas residence times, inlet SO_2 concentration, and sorbent particle diameter. The performance of the 6-in.-diameter reactor is shown in Figure 3.5 as the form of percent reduction in SO_2 plotted for various Ca/S mole ratios. Figure 3.5 shows that an asymptotic limit is reached in SO_2 reduction at a Ca/S mole ratio of approximately 4:1. Test conditions for the data shown in Figure 3.5 in terms of average gas temperature and gas residence time are shown in Table 3.1.

In obtaining the data shown in Figure 3.5, the following procedure was used. First the reactor was allowed to reach thermal steady state. At that point, a metered amount of SO_2 was injected well upstream of the reactor. Upon reaching steady state, a metered amount of sorbent was injected at the reactor inlet. Sorbent feed was continued until after the reactor had reached steady-state conditions. The percent reduction in SO_2 was then determined by using the average value of SO_2 from before sorbent was injected, and well after injection had stopped. During testing, important data were recorded via a microcomputer-based data acquisition system. A typical plot of SO_2 concentration as a function of time is shown in Figure 3.6.

The data shown in Figure 3.5 are reported as percent reduction in SO_2 concentration on a volume basis. The SO_2 test facility operates with the products of combustion produced by an oil burner. Since the composition of these products differs from that of coal water slurry (CWS), it becomes necessary to put these results on a coal equivalent basis, so that weight-based results, not volume-based results, can be reported. In order to establish this equivalent basis it was decided to equate the oxygen content in the products of combustion of heating oil with that of CWS. With an equivalent oxygen level for CWS combustion established, the stoichiometric ratio was determined and the volumetric measurements were converted to a weight basis. These results are shown in Figure 3.7.

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Figure 3.4 Comparison of Particle Size Distributions for Sorbents 1 and 1-A

Figure 3.5 6-Inch SO_2 Reactor Performance for Various Operating Conditions

TABLE 3.1
TEST CONDITIONS

Test No.	Average Gas Temperature (°F)	Gas Residence Time (ms)	Average Inlet SO ₂ Concentration (ppm)	Average Inlet SO ₂ Concentration (lbm/MMBtu)	Sorbent
SO ₂ _3	1,437	219	2,070	5.29	1
SO ₂ _5	1,579	244	2,280	5.27	1
SO ₂ _6	1,407	333	2,350	5.30	1
SO ₂ _8	1,514	314	1,570	3.22	1
SO ₂ _9	1,534	312	1,170	2.39	1
SO ₂ _10	1,548	312	1,900	3.88	1-A
SO ₂ _11	1,439	337	2,110	4.20	1-A
SO ₂ _12	1,544	329	2,260	4.58	1-A

TF26-291

Figure 3.6 SO₂ Concentration as a Function of Time for a Typical Test

Figure 3.7 SO₂ Reduction for Various Operating Conditions (6-Inch Reactor)

As an indication of the reduction level in SO_2 emissions required to meet the 0.4 lbm/MMBtu goal, consider the CWS specified for this program. The coal used to prepare this fuel contains 2.36 percent sulfur and has a heating value of 13,579 Btu/lbm, yielding a potential for the formation of 3.87 lbm/MMBtu of SO_2 . Therefore, in order to achieve the required emissions goal, an 89.7-percent reduction is required. Properties of the specified CWS for this program, IL6-248-MCW-G, are shown in Table 3.2.

In testing the 6-in. SO_2 reactor under conditions similar to the combustion of IL6-248-MCW-G, SO_2 reduction levels approaching 80 percent have been achieved at Ca/S ratios of 4:1, as shown in Figure 3.7. Though this reduction level does not reach the required 89.7-percent level, it comes fairly close and is quite good compared to the relatively short gas residence time associated with the 6-in. reactor. The interesting feature about the 80-percent reduction is that it was obtained with the external axial recirculation line blocked and the reactor operated with the smaller particle diameter sorbent 1-A.

3.1.2 Effect of Axial Recirculation on Reactor Performance

Operating the reactor with the external axial recirculation line blocked yielded high SO_2 reduction rates. In order to determine the effect of external axial recirculation on reactor performance, a test was conducted in which the reactor was operated under conditions similar to the combustion of IL6-248-MCW-G with the recirculation line both open and blocked. These tests were conducted with the smaller diameter sorbent, sorbent 1-A, and the results are shown in Figure 3.8.

The data shown in Figure 3.8 indicate that when the reactor is operated without axial recirculation, a higher percent reduction in SO_2 is achieved at lower Ca/S mole ratios than when the reactor is operated with recirculation. As the Ca/S mole ratio is increased, the reduction levels tend to approach one another both with axial recirculation and with the recirculation line blocked. This is also shown in Figure 3.9, in which outlet SO_2 concentration based on lbm/MMBtu is plotted against Ca/S mole ratio.

Another comparison of the effect of particle size and the effect of axial recirculation is shown in Figure 3.10, in which outlet SO_2 concentration is plotted against inlet SO_2 concentration on a lbm/MMBtu basis, for various sorbent diameters and operating conditions. The results shown in Figure 3.10 were obtained by interpolating the collected data so that all results could be presented for a common Ca/S mole ratio of 3:1. Figure 3.10 shows the sharp difference with and without axial recirculation, where for a moderate Ca/S ratio of 3:1 there is quite a difference in performance. Figure 3.10 also clearly shows the difference in

TABLE 3.2
PROPERTIES OF IL6-248-MCW-G

Coal Analysis (Dry Basis)

Carbon	77.56%
Hydrogen	4.69%
Nitrogen	1.36%
Sulfur	2.63%
Ash	6.72%
Oxygen (Diff.)	7.04%
High Heating Value	13,579 Btu/lbm

Ash Fusion Temperatures

	Reducing	Oxidizing
Initial	2,380°F	2,610°F
Softening	2,460°F	2,690°F
Hemispherical	2,524°F	2,700°F +
Fluid	2,590°F	2,700°F +

CWS Properties

Shear Rate	Viscosity (Centipoise)
100 sec ⁻¹	230
500 sec ⁻¹	300
1000 sec ⁻¹	280
Mean Particle Diameter	6.4 microns
High Heating Value	7,100 Btu/lbm

Figure 3.8 6-Inch SO_2 Reactor Performance With and Without Axial Recirculation Sorbent 1-A

TF130-191

Figure 3.9 6-Inch SO₂ Reactor Performance With and Without Axial Recirculation
Sorbent 1-A, Weight Basis

TP84-101

Figure 3.10 Comparison of SO₂ Reactor Performance at a Ca/S = 3:1

reactor performance when the unit is operated under similar thermal conditions and residence time, but with a different sorbent particle diameter. Surprisingly, the larger diameter sorbent 1 exhibited better performance than the smaller diameter sorbent 1-A, which provides a greater surface-to-volume ratio.

Smaller sorbent particle diameters provide the potential for greater SO₂ reduction levels only if they can be detained within the reactor. Since external axial recirculation transports particles from the reactor periphery and introduces them as a jet at the reactor centerline, it is expected that some of the smaller entrained particles might be carried out by the action of this jet and as such decrease their residence time within the reactor. To determine the effect of axial recirculation on particle separation, a test was conducted on the 6-in.-diameter reactor to determine the actual particle size distribution within the reactor and compare it to what was injected. For this test, once the reactor reached steady-state conditions in terms of SO₂ reduction while using sorbent 1, the oil burner, the SO₂ and sorbent feed, and the I.D. fan were simultaneously shut off, and the particles within the reactor were removed and analyzed for their size distributions. These results are shown in Figure 3.11 along with the distribution for the injected sorbent. The spent sorbent left in the reactor was found to have a mean diameter of 260 microns compared to the 194-micron mean diameter sorbent particles that were injected.

In order to quantify the effect of axial recirculation on particle separation, tests were conducted on a plastic flow visualization model, shown in Figure 3.12. To avoid the difficulty of measuring the solids flow rate that exited the model under steady-state conditions, a transient approach was adopted. In this approach, a predetermined amount of particles was injected into the model in a very short period of time. When the solid feed was stopped, the inlet to the reactor was immediately blocked and the I.D. fan was turned off. The separation efficiency was then determined by comparing the weight of particles collected within the model with that which was injected. In addition to weighing both the injected and collected particles, a sieve analysis was also performed to determine the particle size distribution.

Three different test conditions were examined with the cold flow test facility. These conditions were with axial recirculation, with the recirculation line blocked at the inlet, and with a 2 3/8-in. diameter, 60° tapered cone situated 3 in. above the recirculation tube outlet. For all these tests, the feed material was the same sorbent used in the majority of the hot flow tests, sorbent 1. For these tests the highest separation efficiency, 93.8 percent, was obtained with the recirculation line blocked. With the recirculation line open, a separation efficiency of 87.1 percent was obtained, whereas with the recirculation line open and the deflector cone in place, a separation efficiency of 93.6 percent was obtained.

Figure 3.11 Particle Size Distribution of Injected Sorbent and Spent Sorbent

TF112-990

Figure 3.12 Plastic Flow Visualization Model

The purpose of external axial recirculation is to provide a more uniform distribution of particles within the reactor and thereby increase the effective particle surface area within the reactor, and not to aid in particle separation. Without axial recirculation, flow visualization indicates that there tends to be some particle stratification in the upper part of the reactor. With recirculation, these particles are more evenly distributed axially along the reactor; however, particle separation is decreased. Based on hot testing within the SO₂ reactor, it appears that the benefit of a more uniform distribution of particles provided with axial recirculation is offset by the decrease in separation efficiency. It appears that the high degree of mixing due to turbulence within the reactor offsets the effect of particle stratification, and as such there appears to be a benefit in not using axial recirculation in the configuration that was recently tested.

In addition to particle separation efficiency testing on the flow visualization model, particle size distribution comparisons were made between injected and collected particles. Figures 3.13 and 3.14 show the change in the weight of each sample, for each particle size interval, for the case where the recirculation line was blocked and the tapered cone was used. These figures show that a greater amount of fine particles was collected within the reactor than what was injected. This is due to particle fragmentation within the reactor resulting from high tangential velocities.

3.1.3 Eight-Inch-Diameter Reactor Test Results

Due to the relatively short residence time of the 6-in.-diameter reactor, it was difficult to obtain the 0.4 lbm/MMBtu emissions goal of this program when operating with an inlet concentration of 3.87 lbm/MMBtu. In order to meet the 0.4 lbm/MMBtu goal, an 8-in.-diameter reactor was constructed. For this reactor, external axial recirculation was not used, in an effort to maximize separation efficiency. This reactor had the following geometry:

Inside Diameter:	8.329 in.
Outlet Diameter:	1.5 in.
Active Reactor Height:	43 in.
Inlet Area:	4 in. ²
Recirculation Line Diameter:	External Axial Recirculation Not Used

Four different calcium-based sorbents were tested in the 8-in.-diameter reactor, and a summary of these sorbents in terms of specific calcium compound, weight percent, and mean particle diameter is shown in Table 3.3. The particle size distribution for these sorbents is shown in Figure 3.15 in the standard Rosin and Rammeler format. The sorbents used in this work represented a cross section of

Figure 3.13 Effect of Axial Recirculation on Particle Size Distribution

TP-65-301

Figure 3.14 Effect of Axial Recirculation on Particle Size Distribution with 60° Taper Cone

TF4-591

TABLE 3.3
SORBENTS USED IN TESTING THE 8-INCH-DIAMETER SO₂ REACTOR

Sorbent	Calcium Compound	Percentage	Mean Diameter (microns)
1-A	CaCO ₃	60	117
2	CaCO ₃	97.8	88.5
3	CaO	95.4	82.1
4	CaCO ₃	98.3	172

Figure 3.15 Particle Size Distribution for Various Sorbents Tested in the 8-Inch-Diameter Reactor

various products found throughout the United States. Sorbent 1-A was a dolomite from northwest Connecticut and was tested extensively in the 6-in. reactor. The as-received version of this sorbent, called sorbent 1, had a mean diameter of 194 microns. In order to obtain the as-tested size distribution, the as-received dolomite was sieved and then selectively blended. Sorbent 2 was a high-calcium limestone from Pennsylvania that was received in pulverized form. Sorbent 3 was a pulverized lime that was calcined from the same limestone used in sorbent 2, and sorbent 4 was an as-received limestone from Illinois.

Results of 8-in.-diameter reactor testing are shown in Figure 3.16 in terms of SO_2 content, lbm/MMBtu, as a function of Ca/S mole ratio along with lines that represent a least squares method fit of the data (exponential fit). Figure 3.16 shows that the SO_2 emissions goal for this program -- 0.4 lbm/MMBtu -- was reached at a Ca/S mole ratio of about 5:1 for sorbent 1-A.

The data shown in Figure 3.16 bring up an interesting feature about the reactor and the SO_2 capture process itself. Consider the results for sorbents 2 and 3, which have essentially the same mean particle diameter and distribution. Sorbent 3 is made from the calcination of the material used in sorbent 2, and since it is CaO that captures SO_2 directly and not CaCO_3 , it was expected that better SO_2 capture would be achieved with sorbent 3 since the calcination step within the reactor was eliminated. This was not the case. Sorbent 2, which undergoes the calcination process within the reactor, exhibited a much greater ability to capture SO_2 and at much lower Ca/S mole ratios than sorbent 3. In fact, sorbent 2 achieved an SO_2 emissions level of 0.54 lbm/MMBtu, an 88.3-percent reduction at a Ca/S mole ratio of 4.12 compared to 0.73 lbm/MMBtu, an 80-percent reduction, at a Ca/S mole ratio of 7.53.

In addition to reporting SO_2 reduction as a function of Ca/S mole ratio, it is also desirable to use as an independent variable the sorbent mass loading, i.e., the mass of sorbent injected into the reactor for each unit mass of SO_2 . These results are shown in Figure 3.17. The main difference between Figure 3.16 and Figure 3.17 is with respect to sorbent 1-A, which achieved 0.39 lbm/MMBtu at a Ca/S mole ratio of about 5:1. However, since sorbent 1-A is a dolomite that contains approximately 40-percent MgCO_3 , it takes considerably more sorbent on a mass basis to achieve a given Ca/S mole ratio compared to any of the other high-calcium-based sorbents. Therefore in order to achieve the required reduction in SO_2 , over 13 pounds of sorbent 1-A are required for every pound of SO_2 in the gas stream. For purposes of comparison, consider achieving a reduction in SO_2 to 0.6 lbm/MMBtu. For sorbent 1-A, this would require 12 pounds of sorbent for each pound of SO_2 ; however, for sorbent 2, less than 6 pounds of sorbent are required for each pound of SO_2 .

Figure 3.16 Effect of Ca/S Mole Ratio on 8-Inch-Diameter Reactor Performance

Figure 3.17 Effect of Sorbent Loading (Weight Basis) on the Performance of the 8-Inch Reactor

The results shown in Figures 3.16 and 3.17 are SO_2 content on a lbm/MMBtu basis versus Ca/S and sorbent loading ratio, respectively, which represent absolute values. In some instances, it is desirable to present the data on a relative basis, i.e., percent reduction in SO_2 . This is shown in Figure 3.18, in which percent reduction in SO_2 is plotted against Ca/S mole ratio. This plot shows in a very simple manner how each sorbent performs relative to the others. For example, at a Ca/S mole ratio of 1:1, sorbent 2 exhibits an almost 60-percent reduction in SO_2 , whereas sorbent 4 at this Ca/S mole ratio only exhibits about a 15-percent reduction.

3.1.4 Performance Comparison Between the 6- and 8-Inch-Diameter Reactors

The 8-in.-diameter reactor represents an increase in gas residence time of 1.78 times that of the 6-inch-diameter reactor previously tested. A comparison of the performance of the 8- and 6-inch-diameter reactors is shown in Figure 3.19. For these test results, the reactors were operated under the same operating conditions, and both used sorbent 1-A. A comparison of both reactors showed that the 8-inch-diameter reactor was capable of meeting the emissions goal of 0.4 lbm/MMBtu, whereas the 6-inch-diameter reactor was only capable of achieving an SO_2 emissions level of about 1 lbm/MMBtu.

Along with the data shown in Figure 3.19, solid lines, which represent the least square fit of the data using an exponential fit, are also shown. The purpose of using an exponential fit for the data was based on model predictions for the effect of Ca/S mole ratio on SO_2 reduction. Figure 3.19 shows that the exponential fit is quite good for the 8-inch-diameter reactor over the entire range of Ca/S mole ratio tested, and is a good fit for the 6-inch-diameter reactor only up to a Ca/S mole ratio of 3:1. Beyond a Ca/S mole ratio of 3:1, SO_2 reduction levels off in the 6-inch-diameter reactor, and at higher Ca/S mole ratios, SO_2 emissions levels start to rise. A possible explanation for this occurrence is the higher axial gas velocity present in the 6-inch-diameter reactor. During testing, the gas flow rate is held constant as sorbent particles are injected. As the sorbent flow rate is increased and a volume of particles accumulates within the reactor, the actual axial gas phase velocity increases and is capable of carrying more sorbent particles out of the reactor. This effect was not noted in the 8-inch-diameter reactor since due to its larger diameter the axial gas velocity is 1.78 times lower.

3.1.5 SO_2 Reactor Model Results and Comparison with Data

As part of this program, a simplified analytical model of the SO_2 reactor was developed.¹ This model treats the reactor's highly complex, vortical flow field in a very simple manner. By modeling the reactor as a cyclone separator, the

Figure 3.18 Effect of Ca/S Mole Ratio on 8-Inch-Diameter Reactor Performance

Figure 3.19 Performance Comparison Between 6- and 8-Inch-Diameter Reactor Operating with Sorbent 1-A

separation efficiency of a given size particle can be determined based on the reactor geometry and operating conditions. The separation efficiency of a given size particle determines the solids inventory within the reactor that is capable of participating in SO_2 capture. With an estimation of the solids inventory, the SO_2 reactor is treated as one dimensional (axial direction) with respect to species concentration, and the two coupled ordinary differential equations that describe the rate of change of CaO and SO_2 are solved numerically.

The computer model was used as part of a parametric study to determine the effect of such parameters as reactor diameter, Ca/S , and particle diameter on SO_2 capture. For this analysis, the reactor model was operated with the combustion products of the CWS (IL6-248-MCW-G) specified for this program and under conditions that the SO_2 reactor would operate under in the integrated system. The parent coal in this CWS is an Illinois No. 6 coal, which contains 2.63-percent sulfur and has a higher heating value of 13,579 Btu/lbm. This provides the potential of 3.87 lbm/MMBtu of SO_2 . When this CWS is burned with 20-percent excess air, this SO_2 potential translates into a concentration of 1,950 ppm on a dry basis.

Borgwardt's² model was used to account for the effect of chemical kinetics on the stone sulfination process. In Borgwardt's model the reaction rate time delay phenomenon caused by pore plugging is treated by modifying the conventional Arrhenius frequency factor with an exponential decay coefficient. This decay factor is characterized by a stone dependent, pore plugging constant, β . Due to this additional feature, three empirically determined constants must be supplied to the model in order to characterize the kinetics of the SO_2 capture process. The kinetics constants used in this analysis were obtained from Borgwardt's paper. The parameters used in this analysis are shown in Table 3.4.

3.1.5.1 Effect of Sorbent Particle Diameter on Reactor Performance

The effect of sorbent particle diameter on reactor performance is shown in Figure 3.20 for reactor diameters of 4, 6, and 8 in., operating with a Ca/S mole ratio of 3:1. The interesting feature of Figure 3.20 is that for each reactor diameter, there is an optimum particle diameter for SO_2 capture. This optimum diameter is based on the reactor's ability to capture particles of a given size. Particles smaller than the optimum diameter cannot be detained in the reactor and pass through without participating in the SO_2 capture process. Particles that are larger than the optimum diameter are able to be detained in the reactor; however, since the sorbent particle surface area to volume ratio decreases as the diameter increases, there is less available surface area in the reactor to participate in the SO_2 capture process compared to the optimum.

TABLE 3.4
MODELING PARAMETERS

Fuel:	IL6-248-MCW-G (Specified fuel for the program)
Coal Content (weight %)	53.22
Higher Heating Value (Btu/lbm)	7,227
Sulfur Content (coal)	2.63
Input Rate (Btu/hr):	120,000 (nominal)
Excess Air (%)	20
SO ₂ (ppm dry basis)	1,950
Reactor Operating Temperature (F)	1,600
Reactor Diameter (in.)	4, 6, 8
Reactor Height (in.)	45 (nominal)
Sorbent Properties:	
Activation Energy (cal/g-mole)	10,000
Frequency Factor (1/s)	335,000
Beta (g/g-mole)	333.3
Density (lbm/ft ³)	150

Figure 3.20 Effect of Particle Diameter on Reactor Performance
(Operating with a Ca/S Ratio of 3:1)

Another interesting feature of Figure 3.20 is that the ability of the reactor to capture SO_2 increases as the reactor diameter is increased. This is due to the lower axial gas velocity associated with the larger diameter reactor. As the axial velocity decreases, the gas phase residence time increase inversely, providing more time for the SO_2 capture process.

3.1.5.2 Effect of Ca/S Mole Ratio on Reactor Performance

The effect of Ca/S mole ratio on reactor performance is shown in Figure 3.21 for reactor diameters of 4, 6, and 8 in. For each of these cases the model used the optimum particle diameter for these operating conditions, as shown in Figure 3.20. For the sorbent properties used in this analysis, the required 90-percent reduction in SO_2 emissions is achieved at a Ca/S mole ratio of about 4.5 for the 8-in.-diameter reactor.

The effect of gas phase residence time, i.e., reactor diameter on performance, is also shown in Figure 3.21. Reactor performance strongly decreases as the reactor diameter is decreased. For example, at a Ca/S mole ratio of 5:1, the 8-in. reactor achieves a 93-percent reduction in SO_2 , but the 6-in.-diameter and 4-in.-diameter reactors achieve reductions of 77 and 50 percent, respectively.

3.1.5.3 Effect of Reactor Height on Reactor Performance

For given operating conditions, reactor height is directly proportional to gas phase residence time, and as such, as the reactor height is increased, reactor performance also increases. This is shown in Figure 3.22 for reactor diameters of 4, 6, and 8 in., each operating with the optimum particle diameter for these conditions (as shown in Figure 3.20), and with the reactor operating at a Ca/S mole ratio of 3:1. Figure 3.22 clearly shows the negative exponential dependence of reactor performance on height, with reactor performance increasing with reactor height and diameter.

Due to the nature of the species continuity equations, which are first order, reactor performance can be described by an exponentially decaying solution, provided the coupling between the equations for CaO and SO_2 is relatively weak (i.e., low value of beta). For a system that exhibits exponentially decaying behavior, it is desirable to characterize the response of the system in terms of a time constant. Since reactor height is directly related to residence time, the characteristic time constant for the reactor operating under specific conditions can be treated as a characteristic length. This is shown in Figure 3.22, in which the 8-in. diameter reactor, under these operating conditions, has a time constant equivalent to a reactor length of 23 in.

Figure 3.21 Effect of Ca/S Mole Ratio on Reactor Performance

Figure 3.22 Effect of Reactor Height on Performance
(Operating at a Ca/S Ratio of 3:1)

The idea of equating a reactor length scale with an equivalent time constant provides a convenient way of expressing reactor length with a desired level of performance. By normalizing reactor height with respect to the length equivalent time constant, the required number of time constants to achieve a given reduction in SO_2 can be determined by definition since 1 time constant represents a 63.2-percent reduction, 2 time constants represent an 86.5-percent reduction, 3 time constants represent a 95-percent reduction, 4 time constants represent a 98.2-percent reduction, and so forth.

3.1.5.4 Effect of Input Rate on Reactor Performance

The effect of input rate on reactor performance is shown in Figure 3.23 as a function of particle diameter. For this case, only an 8-in.-diameter reactor is considered since at the higher flow rates, the pressure drop becomes excessive in the smaller units. Figure 3.23 shows that as the input rate is increased, reactor performance decreases. This is due to the reduction in gas phase residence time associated with the fixed reactor height.

An interesting feature of Figure 3.23 is that as the input rate is increased, the optimum particle diameter for SO_2 capture decreases. This is due to the fact that at the higher tangential velocities associated with the increased flow rates, the reactor has a greater ability of capturing smaller sized particles. This provides a greater surface area concentration within the reactor.

Figure 3.23 indicates that if operation at higher input rates is required and comparable performance with lower input rate operation is required, provisions must be made to compensate for the reduction in gas phase residence time. This can be accomplished by increasing either the reactor length or diameter.

3.1.5.5 Effect of SO_2 Concentration on Reactor Performance

The specified coal for this program, when burned with 20-percent excess air, has the potential to produce 1,950 ppm of SO_2 on a dry basis. Operation of the reactor with the products of combustion of other slurries yields the potential for different SO_2 inlet concentrations. The performance of the reactor as a function of inlet SO_2 concentration is shown in Figure 3.24 for a Ca/S mole ratio of 3:1 and reactor diameters of 4, 6, and 8 in. Figure 3.24 shows that the percent reduction in SO_2 increases as an exponential function of inlet concentration, approaching a limiting value of close to 100-percent reduction.

The fact that the percent reduction in SO_2 approaches an exponential limit at near 100 percent as inlet concentration is increased indicates that in absolute

Figure 3.23 Effect of Input Rate on Reactor Performance
(For an 8-in.-Diameter Reactor Operating
with a Ca/S Ratio of 3:1)

Figure 3.24 Effect of SO_2 Concentration on Reactor Performance
(Operating at a Ca/S Ratio of 3:1)

terms, i.e., with respect to the actual outlet concentration (ppm), the reactor would have a lower outlet SO_2 concentration when operated with higher sulfur coals. To illustrate this, the percent reduction results shown in Figure 3.24 are plotted in Figure 3.25 in terms of the actual outlet concentration of SO_2 (ppm on a dry basis). Figure 3.25 shows that particularly for the 6-in.-diameter and 8-in.-diameter reactors, as the inlet concentration is increased, for a fixed Ca/S ratio, there is more sorbent within the reactor and the outlet SO_2 concentration decreases. For example, consider the 8-in.-diameter reactor. Using this particular sorbent, an outlet concentration of about 400 ppm would be expected with the reactor operating at the 1,950 ppm expected for this coal. This result is about 200 ppm higher than the level required to meet the 0.4 lbm/MMBtu program goal. However, if the reactor was operated with a coal that produced about 3,500 ppm of SO_2 , the outlet concentration would meet the goal of 0.4 lbm/MMBtu (200 ppm).

3.1.5.6 Comparison of Reactor Performance with Computer Model Predictions

In order to describe the reaction kinetics used in this model, three constants need to be determined in order to characterize the sorbent. These constants are the activation energy, E ; the frequency factor, A_0 ; and the pore plugging parameter, β . Based on test results obtained with sorbent 3, a high-CaO lime product taken at three temperatures, these constants were determined to be:

Activation Energy:	11,750 cal/gmole
Frequency Factor:	243,100 1/s
beta:	0

which are well within agreement of published data.²

With an estimation of the sorbent properties, a computer model comparison was performed for two different cases. These results are shown in Figure 3.26, in which percent reduction in SO_2 is plotted against Ca/S mole ratio. Figure 3.26 shows that a fairly good agreement exists between the computer model and data.

3.2 NO_x REDUCTION TEST RESULTS

One of the goals of this program is to obtain NO_x emissions of 0.2 lbm/MMBtu or less from the combustor. During this year, work was continued in the NO_x reduction test facility with emphasis on testing various configurations. A photograph of the NO_x reduction test facility is shown in Figure 3.27, and a schematic diagram of the facility is shown Figure 3.28.

Figure 3.25 Effect of Inlet SO₂ Concentration on Reactor Outlet Concentration (Operating with a Ca/S Ratio of 3:1)

Figure 3.26 Comparison of Model Prediction and Reactor Data for the 8-Inch-Diameter Reactor Operating with Sorbent 3

TF41-590

Figure 3.27 Photograph of NO_x Test Facility

In work to date, the combustor was operated under staged conditions, using two different fuels. The first CWS tested was made from Upper Elkhorn Number 3 coal that was deeply cleaned and contained 1.32-percent ash and 0.66-percent sulfur. This CWS was used extensively in the development of the combustor under a previous program (contract number DE-AC22-87PC79650), and contained 65.16-percent coal by weight. This CWS was called UE3-224-MCW-F by the CWS supplier (Energy International Inc.) and for identification purposes in this program was called CWS number 1. The second CWS tested was made from Illinois Number 6 coal and contained 6.72-percent ash and 2.63-percent sulfur. This CWS contained 53.22-percent coal and was identified by the manufacturer (AMAX) as IL6-248-MCW-G, and in this program was called CWS number 2. CWS number 2 was the fuel specified to meet the emissions goals of this program. Properties of CWS number 1 and CWS number 2 are shown in Table 3.5.

In comparing CWS number 1 and CWS number 2 with respect to potential NO_x emissions, two facts are evident from Table 3.5. First, CWS number 2 contains more water than CWS number 1 (46.78 percent compared to 34.84 percent). Second, CWS number 2 contains less fuel-bound nitrogen than CWS number 1. On a normalized basis to the heating value of the coal, CWS number 2 has 1.002 pounds of molecular nitrogen contained in the equivalent of 1 million Btu and CWS number 1 has 1.043 lbm/MMBtu of nitrogen in the coal.

3.2.1 Combustor Configurations for Staged Combustion Operation

In work to date, the combustor operated for prolonged periods under four different staged combustion configurations. A schematic diagram detailing these configurations is shown in Figure 3.29. The first configuration that was tested was configuration 1 and was only used in tests with CWS number 1. In this configuration, the primary air inlet extended the entire length of the primary chamber, that is, 7.69 in. This long air inlet places a limit on the degree to which the primary chamber stoichiometric ratio could be reduced and provide stable combustion.

In configuration 2, the combustor upper primary chamber was extended in length to 12.5 in. in an effort to provide longer residence time. In this configuration, the primary air inlet was only 2.5 in. long. This provided higher air inlet velocities, which allowed for lower primary chamber stoichiometric ratios. This configuration was used with both CWS number 1 and CWS number 2. As a variation on configuration 2, the primary air inlet width was reduced 15 percent to provide higher tangential velocities. This variation in configuration 2 was called configuration 2A and was used in tests with CWS number 2.

TABLE 3.5
PROPERTIES OF COAL WATER FUELS TESTED

	CWS Number 1	CWS Number 2
Coal Identification	Upper Elkhorn Number 3	Illinois Number 6
Heating Value (Btu/lbm)	15,251	13,579
Ash	1.32%	6.72%
Sulfur	0.66%	2.63%
Ultimate Analysis:		
Carbon	85.40%	77.56%
Hydrogen	5.40%	4.69%
Nitrogen	1.59%	1.36%
Solids Content	65.16%	53.22%
Mean Particle Diameter (microns)	14	9
Viscosity (cps @ 100/s)	301	230

Configuration 1

Configuration 2 - 2A (*)

Configuration 4

* Note: The main difference between configurations 2 and 2A is that configuration 2A had a smaller air inlet so as to provide higher tangential velocities.

Figure 3.29 Combustor Configurations Used During Staged Operation

In configuration 4, the combustor upper primary chamber was extended to 18.5 in. in length to provide even longer primary chamber residence time. This configuration had the same air inlet geometry as did configuration 2A; however, the combustion chamber diameter was decreased from 8.5 to 8 in. in the upper section of the primary chamber. This was done to decrease heat loss in this section of the combustor where the CWS is introduced and to therefore aid in evaporation. Because the primary chamber in configuration 4 is lengthened, the surface area available for heat loss is increased, and this, coupled with the high water content of CWS number 2, made combustion difficult without the additional insulation. In fact, the original version of this configuration (called configuration 3) did not have the extra 1/2 in. of insulation, and in this configuration it was not possible to initiate or maintain stable CWS combustion with CWS number 2.

3.2.2 Effect of Excess Air on NO_x for Staged Combustion of CWS Number 2

Data obtained during testing in the NO_x reduction test facility were recorded every 15 seconds by a computerized data acquisition system. For each configuration, typically three tests were conducted, and these tests lasted for several hours. This resulted in each configuration generating large amounts of data that needed to be reduced. Typical results for two test runs are shown in Figure 3.30 in terms of NO_x as a function of excess air. In order to reduce the data to a more useful form, a statistical averaging procedure was used. First, the data for each configuration were sorted in ascending order with respect to stoichiometric ratio. Then the data were averaged in increments of 0.03 (3-percent excess air) of stoichiometric ratio.

The effect of excess air on NO_x emissions for staged combustion operation with CWS number 2, tested in configurations 2, 2A, and 4, is shown in Figure 3.31. These results represent the averaged values of over 1,000 data points. The results shown in Figure 3.31 indicate that NO_x is essentially a linearly increasing function of excess air for each of the configurations tested. The data also indicate that of the three configurations tested, configuration 4 has the lowest NO_x through the operating range. Configuration 2A had the next lowest NO_x levels, followed by configuration 2, which exhibited the highest NO_x levels of the configurations tested.

In comparing the results shown in Figure 3.31, the differences between the three configurations must be considered. Configurations 2 and 2A differ only in the air inlet geometry, with configuration 2A capable of operating at higher tangential velocities which prevent agglomeration of coal particles on the combustor wall. Due to this difference, it was possible to operate configuration 2A at lower primary/stoichiometric ratios than configuration 2. Both configurations 2A and 4 have the same air inlet geometry and therefore provide the same tangential velocity

Figure 3.30 Effect of Excess Air on NO_x Emissions for Typical Test Runs (Configurations 2 and 2A)

Figure 3.31 Effect of Stoichiometric Ratio on NO_x for Various Combustor Configurations Burning CWS Number 2

when operated at comparable conditions. However, since configuration 4 was 6 in. longer than configuration 2A it provided longer primary chamber residence time, which further lowered NO_x emissions.

The results shown in Figure 3.31 with the combustor operated in configuration 4 show that emissions levels as low as 0.14 lbm/MMBtu were achieved when the combustor was operated with 5-percent excess air. The emissions goal for this program was 0.2 lbm/MMBtu, and in order to operate at this level, the combustor can be operated with up to 12-percent excess air in configuration 4.

3.2.3 Effect of Primary/Stoichiometric Ratio on NO_x for Staged Combustion of CWS Number 2

The main difference between configurations 2 and 2A is that the primary air inlet in configuration 2A is smaller than in configuration 2. This difference allowed configuration 2A to operate at lower primary/stoichiometric ratios than configuration 2 while still maintaining tangential velocities high enough to provide stable combustion. The effect of primary/stoichiometric ratio on NO_x emissions is shown in Figure 3.32 for combustor configurations 2, 2A, and 4.

The results shown in Figure 3.32 indicate that for each configuration, NO_x emissions are essentially a linear function of primary/stoichiometric ratio. Figure 3.32 also shows the key difference between configurations 2 and 2A. Configuration 2 could only be operated at a minimum primary/stoichiometric ratio of 0.89 while still maintaining stable combustion and obtained NO_x emission levels of 0.36 lbm/MMBtu. In configuration 2A, the higher tangential velocities allowed the combustor to maintain stable combustion at a minimum primary/stoichiometric ratio of 0.69, and at this ratio achieved NO_x emissions of 0.26 lbm/MMBtu.

Figure 3.32 also shows in an indirect manner the effect of primary chamber residence time on NO_x emissions. Both configurations 2A and 4 were operated over the same range of primary/stoichiometric ratio; however, configuration 4 achieved consistently lower NO_x emissions over this range of operation. This is a result of the fact that configuration 4 has a longer primary chamber than configuration 2A and thereby provides longer residence time for the products of combustion in this fuel-rich zone.

Figure 3.32 Effect of Primary/Stoichiometric Ratio on NO_x for Various Combustor Configurations (Fuel: IL6-248-MCW-G)

3.2.4 Effect of Primary Chamber Residence Time on NO_x Emissions

The results shown in Figures 3.31 and 3.32 present NO_x emissions as a function of excess air and primary/stoichiometric ratio, respectively, and have implicitly shown the effect of primary chamber residence time. In order to observe this effect directly, Figure 3.33 shows NO_x emissions as a function of primary chamber residence time for operation with CWS number 2 in configurations 2, 2A, and 4 as well as test results obtained while burning CWS number 1 in configurations 1 and 2.

The interesting feature of Figure 3.33 is that if the test results from configuration 2 are ignored, all the results for both slurries operating under different configurations fall essentially on the same curve. This indicates that for this combustor, primary chamber residence time is the dominant parameter in NO_x emissions. This is a significant result since both slurries were made from different parent coals that had vastly different solids loading. The deviation of the results from configuration 2 on the effect of primary chamber residence time is assumed to be due to the fact that configuration 2 could only be operated at higher primary/stoichiometric ratios, and as such, the benefits of deeper air staging could not be realized.

During staged operation of the combustor with CWS number 2 in configuration 2, ash samples were collected for analysis in order to determine the effect of primary/stoichiometric ratio on combustion efficiency. These results are shown in Figure 3.34, which shows an increase in combustion efficiency with decreasing primary/stoichiometric ratio. In fact, at the lowest primary/stoichiometric ratio tested, the highest combustion efficiency of 97.3 percent was obtained.

3.3 PARTICULATE EMISSIONS CONTROL

The control of particulate emissions from the furnace is accomplished through the use of bag filters located downstream of the heat exchanger. In testing both the combustor and the SO₂ reactor, this baghouse has been used extensively; however, measurement of particulates downstream of the bag filters has not yet been performed. The reason for this is that up until now, only testing of the individual components has been performed. A large difference exists between both the particle size distribution of the flyash and the spent sorbent as well as the grain loading for each of these components in an integrated system. This indicates that meaningful particulate measurements can only be made when the system components are integrated into a complete furnace system.

Figure 3.33 Effect of Primary Chamber Residence Time on NO_x Emissions for CWS Numbers 1 and 2

Figure 3.3# Effect of Staged Combustion Operation on Combustion Efficiency for CWS Number 2

In order to gain an understanding as to the relative difference between the flyash and spent sorbent, consider the size distributions of the micronized coal and the pulverized sorbent used to capture SO_2 . These distributions are shown in a Rosin and Rammler format in Figure 3.35, in which the mean particle diameter for the coal is 9 microns and for the sorbent is 88 microns. Microtrac analysis of flyash collected on the bag filters has shown its distribution to be just slightly larger than that of the micronized coal, having a mean diameter of 14.2 microns, as shown in Figure 3.36. Though the sorbent undergoes a change in particle diameter due to calcination and particle fragmentation, it is not expected that the distribution will shift to one that is representative of the flyash. Therefore, when the baghouse must operate with both flyash and sorbent, the particle size distribution that the bag filters must deal with can span over two orders of magnitude compared to the one order of magnitude span that each individual component covers.

Now consider the amount of both sorbent and flyash that the baghouse must deal with. In order to perform this analysis consider a house in the Pittsburgh, Pennsylvania, area (5,931 degree days) that has an overall heat transfer coefficient, surface area product (UA) of 700 Btu/hr-°F, typical of a moderate-size home of new construction. Also, assume that the heating system for this home has an annual fuel utilization efficiency (AFUE) of 85 percent, the system burns CWS number 2 or equivalent, and high-calcium-carbonate limestone is used as the SO_2 sorbent. This house would require 1,690 gallons of slurry to meet its heat requirement of 117.2 MMBtu per year, and would emit to the atmosphere each year 23.4 pounds of NO_x , 46.9 pounds of SO_2 and 2.34 pounds of particulates, assuming the system met the required emissions goals.

With respect to particulates, the bag filters must annually remove from the combustion products 86.3 pounds of combustible matter (assuming a 99-percent combustion efficiency), 574.3 pounds of ash, 865.3 pounds of calcium sulfate, and unutilized sorbent ranging from 41 pounds for a Ca/S mole ratio of 1:1 to 2,028 pounds for a Ca/S mole ratio of 6:1. Results of this analysis are shown in Figure 3.37. This analysis indicates that due to the large amount of collected calcium sulfate and unutilized sorbent relative to flyash and unburned carbon, realistic measurements of both the quantity and size distribution that pass through the bag filter can only be made when the system is totally integrated.

3.4 INTEGRATED SYSTEM DESIGN

Since both the CWS combustor and SO_2 reactor are achieving the NO_x and SO_2 emissions goals established for this program, and because all the system components must be integrated in order to obtain meaningful particulate emissions

Figure 3.35 Size Distribution Comparison Between Micronized Coal and SO₂ Capture Sorbent

Figure 3.36 Comparison of Particle Size Distribution of the Collected Ash in the Baghouse and the Micronized Coal Used in the Slurry for CWS Number 2

Figure 3.37 Collected Material Breakdown at Varying Sorbent Utilizations
In Order to Meet the Emissions Goal
(For a Typical Home in the Pittsburgh Area)

data, an integrated emissions control system was designed. A schematic diagram of the integrated system is shown in Figure 3.38, and a photograph of the system is shown in Figure 3.39.

The main emphasis in designing the integrated emissions control system was to minimize the floor space that the system occupies. As part of this effort, the SO₂ emissions control reactor was integrated with the furnace heat exchanger. Also in this approach, the secondary stage of the combustor was integrated into the emissions control reactor. A detailed assembly drawing of the integrated reactor/heat exchanger is shown in Figure 3.40.

Figure 3.38 Schematic Diagram of Integrated Emission Control System

TF36-1191

Figure 3.39 Photograph of Integrated Emissions Control System

TF99-791

Figure 3.40 Assembly Drawing of Integrated Reactor/Heat Exchanger

4. SUMMARY STATUS ASSESSMENT AND FORECAST

During the second year of this program, work was completed on testing the individual system components. As a result of this testing, the CWS combustor and SO₂ reactor met the emissions goals established for this program; that is, NO_x emissions of less than 0.2 lbm/MMBtu and SO₂ emissions of less than 0.4 lbm/MMBtu. The CWS combustor operating under staged conditions achieved NO_x emissions as low as 0.14 lbm/MMBtu. Primary chamber residence time was found to be one of the most dominant parameters in NO_x emissions.

The SO₂ reactor achieved obtained over a 90-percent reduction in SO₂ emissions, achieving levels as low as 0.39 lbm/MMBtu. Both sorbent type and particle diameter were found to be the dominant parameters governing reactor performance. As a result of the data obtained with the SO₂ reactor, the simplified computer model that was developed in the first year of this program was experimentally verified.

With respect to particulate emissions, meaningful data cannot be obtained until the emissions control system is fully integrated and the baghouse is handling both fly ash and spent sorbent. This is due to the vastly different particle size distribution and grain loadings present in the NO_x and SO₂ removal test facilities. Towards this end, integration of the individual components into a complete emissions control system began this year.

The integrated emissions control system was designed to minimize the floor space that the furnace occupies; therefore both the SO₂ reactor and the system heat exchanger were integrated into a single unit. In the integrated system, the reactor/heat exchanger also serves as the secondary combustion chamber in an effort to minimize both floor space and furnace height.

In work to be conducted for the duration of the program, the integrated emissions control system will be extensively tested. These tests will include obtaining data on NO_x, SO₂, combustion efficiency, and particulate emissions, while burning the CWS specified for this program. In addition to testing, a manufacturing cost estimate for the entire system will be made and an economic evaluation will be performed.

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