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U.S. DOE-CLEAN COAL PROGRAM

"THE DEMONSTRATION OF AN ADVANCED CYCLONE COAL COMBUSTOR, WITH INTERNAL SULFUR, NITROGEN, AND ASH CONTROL FOR THE CONVERSION OF A 23 MMBTU/HOUR OIL FIRED BOILER TO PULVERIZED COAL"

FINAL TECHNICAL REPORT

REPORTING PERIOD - March 9, 1987 to February 28, 1991

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GLOSSARY OF TERMS

SR1	First stage inverse equivalence ratio or fraction of theoretical combustion air.
SR2	Second stage inverse equivalence ratio.
HEATIN	Total fuel heat input in MMBtu/hr
PCTPC	Percent contribution of coal to HEATIN
SWIRLPR	Regenerative combustion air swirl pressure, inches water column ("WC)
CASRAT	Combustor calcium/sulfur mole ratio.
TSSCEFF	Combustion efficiency calculated from carbon in scrubber discharge, in % of fuel combustibles utilized.
SLAGCEFF	Combustion efficiency calculated from slag carbon content.
GASCEFF	Combustion efficiency calculated from measured fuel and combustion air flows and measured oxygen at the boiler outlet.
SLAGREJ	Slag rejected through the combustor slag tap as percent of total solids.
BOILREJ	Solids retained in the boiler, usually includes slag deposits in the exit nozzle and on the boiler front wall. Also as % of total solids.
SCRUBREJ	Solids captured by the scrubber as percent of total solids.
XSCHROM	Slag chrome (Cr_2O_3) content, weight percent, that is from refractory.
NORMNOX	Measured NOx at the boiler outlet in ppmv, dry basis. Normalized to 3% O_2 or 15% excess air.
ACTSLGS	Slag sulfur content as percent of total sulfur.
BOILSULF	Sulfur retained in the boiler as percent of total sulfur.
PCTSSCRB	Sulfur retained in the scrubber as percent of total sulfur.
ATMSULF	Sulfur emitted to atmosphere as SO_2, percent of total sulfur.
SREDBO	Reduction in measured SO_2 at the boiler outlet, as % of total sulfur.
SREDFS	Reduction in measured SO_2 at the scrubber fan stack, as % of total S.
AIRFLUX	Combustor wall heat transfer to the cooling air in $Btu/hr/ft^2$.
THSTEMP	Air cooling tube maximum (hot side) temperature, degrees F.
LINERTEM	Calculated combustor wall average temperature, degrees F.

Acknowledgments

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The authors also wish to especially express their appreciation to Mr. Baldwin for his efforts on behalf of the project in the programmatic area, in securing the assistance of other DOE laboratories for materials analyses and for special test equipment. The latter were instrumental in preventing premature shutdown of tests on several occasions during the course of the project.

Note on the Data Contained in this Report

Some of the data generated in this project relates to the performance of the combustor that utilizes proprietary design and procedures, some of which were developed independently of this Clean Coal project. As per the terms of the Cooperative Agreement between the Department of Energy and Coal Tech, this data has been supplied to DOE in a separate "Proprietary Document", concurrently with this Final Report. The authors have placed a footnote on each page in this Final Report which states that "Additional data is contained in the Proprietary Document". The pages as: 35, 36, 37, 47, 56, 57, 59, figures 8, 16, 20, 21, and 22. Also, Appendix II: Pages A-II-21, 22, 23, and 24, and figures S, S-2, T, and U.

The Proprietary Document also contains additional summary performance test data as well as raw test data from representative test runs PC 9 and PC 26. (See list of test runs at the end of Appendix "A").

Statement of Coal Tech's Approach to Energy Technology

In the course of several decades of R&D by Coal Tech's principals on a number of advanced power systems, it has been observed that in many cases capital and operating costs have a greater impact on energy costs than fuel costs and/or system efficiency. Therefore, Coal Tech's approach to the air cooled combustor has been to integrate the combustion and environmental performance inside the air cooled combustor, and to develop procedures that allow its fully automatic operation. It is anticipated that this approach will allow energy systems incorporating this combustor to fully benefit from the low cost of coal and related solid fuels.

1. SUMMARY

This Final Report presents the results of a three year demonstration test effort on a 30 MMBtu/hr combustor retrofitted to an oil designed package boiler. In May 1990, this project became the first U.S. Department of Energy (DOE) sponsored, Clean Coal Technology Program Project to complete its Phase III test effort. In addition to DOE, the $1 million project was supported by the Pennsylvania Energy Development Authority (PEDA) and the Pennsylvania Power & Light (PP&L) Company. Project test work was conducted at the Tampella/Keeler Co. plant in Williamsport, PA. The project objective was to demonstrate a technology which can be used to retrofit oil/gas designed boilers, and conventional pulverized coal fired boilers to direct coal firing, by using a patented air cooled coal combustor that is attached in place of oil/gas/coal burners. During the Clean Coal project, the combustor was operated for a total of 900 hours on oil, gas, and dry pulverized coal. This includes about 100 hours of tests under other projects. One-third of the operational time was on coal, with 125 tons consumed. Evaluation of test results indicates that most of the Clean Coal project goals have been met.

A significant part of the test effort was devoted to resolving operational issues related to uniform coal feeding, efficient combustion under very fuel rich conditions, maintenance of continuous slag flow and removal from the combustor, development of proper air cooling operating procedures, and determining component materials durability.

The second major focus of the test effort was on environmental control, especially control of SO2 emissions. By using staged combustion, the NOx emissions were reduced by around three-fourths to 184 ppmv, with further reductions to 160 ppmv in the stack particulate scrubber. By injection of calcium based sorbents into the combustor, stack SO2 emissions were reduced by a maximum of 58% depending on the Ca/S ratio and combustor operating conditions. In addition, a small but significant amount of the coal sulfur (maximum = 11%) was trapped in the calcium bearing slag. The test results suggest that further significant sulfur retention in the slag is attainable. With sorbent injection downstream of the combustor, tested in a preliminary fashion primarily under the fly ash vitrification projects (Ref.1.1, page 2A), a maximum of 82% SO2 reduction was achieved.

Slag retention in the combustor is a function of the combustor stoichiometry, decreasing with increasing fuel rich operation. As very fuel rich operation appears to increase sulfur reduction, a significant portion of the tests were performed under these conditions. Slag retention under fuel rich conditions is lower than that attainable under fuel lean combustion conditions. The magnitude of ash/slag retained in the combustor and boiler floor was obtained from the ash collected in the scrubber. It showed that on average 72% of the ash/reacted sorbent was retained in the combustor/boiler for all the test runs with a range of 55% to 90%. Under near stoichiometric conditions, the average value was 80%. Of the 72% value, about 55% was retrieved from the slag on the combustor wall, exit nozzle, and slag tank, with the other 17% being ash deposited on the floor of the furnace.

As a benefit to the present project, in terms of extended durability and operational testing, as well as evaluation of the range of alternate combustor applications, Coal Tech conducted tests under other projects, interspersed with Clean Coal project testing. These other projects dealt primarily with the conversion of utility flyash or municipal solid waste incinerator ash to slag. Pertinent results of these tests are mentioned in this report where appropriate. Detailed information on these projects may be found in the Coal Tech reports cited on page 2A, references 1.1,1.2, and 1.3.

The data base for continuous and long duration operation of this combustor has been established. Near the end of the project, this data base was incorporated under other projects into a micro-computer process control system that will allow complete automation of the combustor's operation. The data base now exists to scale up the combustor to a 100 MMBtu/hr thermal input. Using the above SOx/NOx data, Coal Tech's economic analysis of the application of this combustor for emission control in coal fired utility boilers indicates that it may be lower in cost than other furnace sorbent injection processes. The combustor may also be economically attractive in certain industrial boiler applications, e.g. vitrification of fly ash to slag, and incineration of refuse derived fuels (RDF).

References to Section 1.

1.1. "Use of a Cyclone Combustor to Convert Municipal Incinerator Fly Ash to Inert Slag", US EPA-SBIR Phase I Project Final Report, EPA Contract No. 68D90117, Period of Performance: Sept. 11, 1989 to April 30, 1990.

1.2. "Use of an Air Cooled Cyclone Coal Combustor to Convert Ash to Inert Slag", DOE-SBIR Phase I Project Final Report, DOE Comtract No:DE-AC01-88ER80568.

1.3. "Use of an Air Cooled Cyclone Coal Combustor to Convert Ash to Inert Slag", DOE-SBIR Phase II Project Quarterly Reports, DOE Contract No. DE-AC01-88ER-80568, May, 1989.

2. BRIEF OVERVIEW OF PROJECT

2.1. Project Description

The Coal Tech Clean Coal I project was conducted in three phases. Phase I consisted primarily of activities involving design and specification of equipment peripheral to the combustor and boiler, including coal and limestone dry feed systems, the stack particulate scrubber, several air blowers as well as the various equipment required for flow stream measurement and control. In addition, efforts were initiated to acquire the necessary environmental regulatory operating permits.

During Phase II, Coal Tech installed the equipment designed in Phase I and also conducted several one-day shakedown tests on the newly installed equipment to determine its operability.

During Phase III the initial aim was to develop a data base associated with combustor operation and to identify and resolve materials and hardware issues related to actual retrofit. The ultimate aim of Phase III was to conduct multi-day tests demonstrating continuous operation.

The following test objectives were specified to implement the joint objectives in the Clean Coal project cooperative agreement:

1. Combustor operation with coals having a wide range of sulfur contents.

2. 70 to 90% reduction in sulfur oxides in the stack, with maximum sulfur retention in the slag.

3. NOx reductions to 100 ppm or less.

4. The solid products from the combustor, i.e. slag/sorbent/sulfur compounds, are environmentally inert or can be readily converted to an inert form.

5. Achieve high combustor slag retention and removal, with the goal being 90% - 95%, as well as compliance with local particulate emission standards.

6. Achieve efficient combustion under reducing conditions.

7. Determine combustor turndown, with a 3 to 1 objective.

8. Evaluate materials compatibility and durability.

9. Operate the combustor for about 900 hours of steady state operation on coal with frequent start-ups and shutdowns.

10. Develop safe and reliable combustor operating procedures.

2.2. Project Activities

Appendix III contains a photographic record of the project. The photographs were selected to show the various stages of the project, including the original installation of the equipment; various features of its operation, such as slag removal, exit nozzle luminosity, steam blowoff plume, etc. Also, the combustor-boiler internals after operation; wall damage and repairs of the combustor-exit nozzle wall; and modifications to the original equipment as a result of the test activities. The photographs were selected to give a visual chronological record of the project, with emphasis on the features of the combustor installation, the type of operational problems encountered and solved, and the operational features of the combustor. The selections do not reflect on their relative importance to the success of the project.

The following sections briefly summarize the effort in the three project phases. The accomplishments will be presented in more detail in the next subsection.

2.2.1. Phase 1: Design & Permitting

In work pre-dating the Clean Coal Technology I project, the Coal Tech air cooled cyclone coal combustor was designed, fabricated, and retrofitted to a 23 MMBtu/hr oil designed package boiler at the Tampella facility in Williamsport, PA. The combustor design effort began in 1984. Combustor fabrication required a one year period during 1985-6. Installation began in late 1986 and it was completed in early 1987. The original installation was for use with low ash, low sulfur, coal-water slurry fuels. No particulate stack scrubber or sulfur control system was included in this original system. That effort culminated with initial tests on the combustor in the Spring of 1987, using a coal water slurry. The combustor was operated for a period of 40 hours on coal-water slurry fuels at about 17 MMBtu/hr. Combustor operation was as per design. An important result was that combustor pre-heat to operating temperature was accomplished with the slurry fuel. This initial operating experience was a major factor in the preparation of the test plan for the DOE Clean Coal project.

The Clean Coal project began in March 1987. In Phase I, the auxiliary equipment necessary to allow dry pulverized coal firing was designed. This included a 4 ton, on-site pulverized coal storage system, a pneumatic coal delivery system to the combustor, a 1/2 ton dry pulverized limestone storage and pneumatic feed system, and a wet stack particulate scrubber. Coal pulverization was off-site with regular fuel delivery by pneumatic tanker truck. Commercial designs were used for each system, and it was planned to purchase the equipment in Phase 2.

The second part of Phase 1 consisted of preparation of the required project environmental reports, and initiation of process to obtain the various environmental permits for operating the combustor on pulverized coal. These permits included an operating permit from the PA Department of Environmental Resources (DER), which included an initial approval of the operating plan, followed by an air quality emission permit. Both permits were obtained in Phase 2. The second permit was for the discharge of the scrubber waste water into the Williamsport Sanitary system, which had been obtained prior to the start of the Clean Coal project. The third permit was for the disposal of the solid waste produced during combustor operation in an approved landfill. This application was delayed until the start of Phase 3, as a profile of the solid waste stream was required to file for the permit.

Phase 1 was completed on schedule in May 1987. During the transition to Phase 2, procurement of the long lead items required for the coal conversion began.

2.2.2. Phase 2: Fabrication, Installation & Shakedown Tests

Phase II commenced in July 1987. A commercial 4 ton pulverized coal storage and delivery system was procured. As no commercial pneumatic coal and limestone feed systems were available, they were fabricated and assembled to Coal Tech's designs. The original plan to purchase a recirculating particulate scrubber system and install it inside the boiler house was altered to a roof mounted once-through system. The former design approach had been selected due to concern over waterline freezing and boiler roof weight bearing capability. However, its cost was considerably beyond project resources, and Coal Tech redesigned and procured the once-through roof mounted system on a piecemeal basis. The installation of this equipment was completed in November 1987, and the two planned, one-day, shakedown tests were performed to evaluate the new equipment performance. One test was performed with coal water slurry and the second test was performed with dry pulverized coal.

The first test revealed a design flaw in the secondary air fan which provides the combustor cooling air and most of the combustion air. The fan operated on the wrong side of the fan curve which caused damaging vibrations and extremely high noise levels. Coal Tech found temporary solution to this problem by modifying the fan inlet. However, during the combustor overhaul in the Spring of 1988, the fan was returned to the manufacturer for rebuilding and it has operated quietly and without problems since that time.

The second shakedown test was the first one with dry pulverized coal. This test revealed that all the new equipment was functional. The test was performed with a low volatile, (<20% volatile matter), refractory ash (T250 > 2800°F) PA bituminous coal. The test showed that the air cooled refractory liner was considerably outside the optimum wall heat transfer range for this coal. In addition, it was found that the coal feed system produced up to 17% feed fluctuations of several minutes frequency. Finally, it was determined that dry pulverized coal could not be used effectively to pre-heat the combustor walls to operating temperatures. However, as the entire combustor-boiler system operated within an acceptable dry pulverized coal firing envelope, it was decided to proceed to Phase 3, with initial focus on the coal feed and combustor wall pre-heat.

2.2.2. Phase 3: Parametric & Long Duration Testing

Phase 3 began in November 1987. In the period between 12/87 and 5/90, 26 Phase III combustor tests were performed for a total operating time of around 800 hours, consuming about 125 tons of coal. All but the last seven tests were nominally 24 hrs in duration, including heatup and cooldown on auxiliary fuels. After December 1988, the balance of the tests were of multi-day duration.

The tests can be divided into the following groups, with major overlap among the various groups:

A- The initial group of tests was aimed at improving the combustion efficiency from the 80% level measured in the first tests, and to reduce the coal feed fluctuations. The latter goal was achieved by a series of incremental changes to the coal delivery and pneumatic feed system, which eventually reduced the feed fluctuations from 17% to a little over 1%.

The combustion efficiency was gradually improved to the 95-99% range by using an oil burner to preheat the combustor walls to operating temperature, instead of the planned use of coal. Incidentally, this change in the pre-heat from coal to oil was a major reason for the discrepancy between the originally planned 900 hours of coal fired operation, and the actual value which was about 1/3 of that. In addition, higher volatile and less refractory ash coals were used, and limestone fluxing was added to improve slagging performance. However, the mismatch in thermal properties of the combustor refractory wall with the combustion gas heat transfer resulted in operation of the combustor wall beyond its safe operating envelope. This caused refractory wall failure in several sections of the combustor roof in February 1988, which necessitated a complete disassembly of the combustor. A new refractory liner was installed having thermal properties consistent with the wall heat transfer. Also, the wall temperature diagnostics as well as the air cooling operating procedures were revised in light of the prior test experience. The combustor was reassembled and one day duration testing resumed in May 1988. Since that time the combustor wall has operated for almost 800 hours with only occasional minor patching required. Since the introduction of computer control of the combustor's operation, and a redesign of the combustor-exit nozzle interface in the Spring of 1990, no combustor wall patching has been necessary.

The second set of tests was primarily aimed at solving the slag tap plugging problem in the combustor. Very early in the test effort, operation was continued for a number of hours after the slag tap plugged and a nearly 1 foot thick layer of frozen slag formed on the floor of the combustor, which had to be removed manually by chisel and hammer. After that time, all tests were terminated when the slag tap plugged. By a series of trial and error methods, a combination thermal and mechanical slag breaker procedure was developed in the course of the project so that by the beginning of 1989, very few test were terminated due to slag tap plugging. Only one of the seven multi-day tests was terminated several hours early on the last day of the test due to a human error related to the operation of the slag breaker.

The third group of tests was related to durability of the combustor wall materials. The air cooled liner test results were noted above. The second materials area related to the combustor exit nozzle, which operated under near adiabatic conditions. The material used in the the exit nozzle withstood the aggressive slag environment throughout the test effort. However, the nozzle-combustor interface, as well as the nozzle-boiler wall interface suffered materials breakdowns due to differential expansion or selection of ceramics with poor slag or thermal resistance. The boiler front wall was redesigned in mid-1988. The combustor-exit nozzle interface was redesigned this year. These changes have resulted in a design suitable for long term operation. However, the present design requires a small amount of additional wall cooling to allow round-the-clock coal fired operation at fully rated coal fired thermal input. The combustor wall, on the other hand, is currently capable of operating continuously at full rated thermal input.

The fourth group of tests were focussed on environmental control of NO_x, SO_2 and particulate emissions. The results will be summarized in the next subsection. For present purposes, the item of major interest is that the gas emission controls require very fuel rich operation. Therefore, a major aspect of the test effort was to achieve efficient combustion under fuel rich conditions. During the course of the test effort, the combustor air flows were re-arranged a number of times until conditions at which air cooling, wall temperature, slagging, and combustion efficiency were optimized at fuel rich conditions. This result was achieved in mid-1989, and nearly all subsequent tests were performed at fuel rich conditions. However, fuel rich operation resulted in reduction of slag retention. At the end of the test effort, considerable progress in SO2 reduction had been made. However, a major project objective of high sulfur capture in the combustor and retention in the slag removed from the combustor had not yet been achieved. In subsequent post Clean Coal project tests, it was discovered that a high frequency coal feed fluctuation existed throughout the test effort. It is suspected that this may have adversely affected the sulfur capture process. Very recently this fluctuation has been dampened, and it is planned to perform future sulfur capture experiments under fuel rich operating conditions.

The next group of tests were to integrate all the operating data base gained in the project into a computer controlled operating system. The necessary equipment was installed prior to the last test of the Clean Coal project. However, it was only after the project tests ended that this computer system has been placed in operation. The process control software incorporates the operational data base. Its use in a series of tests since the completion of the Clean Coal project tests in May 1990, has resulted in a major improvement in the controllability of the combustor. It is anticipated that with a number of additional controls related to slag tap operation, and combustor start-up and shutdown, it will be possible to operate the combustor completely automatically.

Beginning in the Fall of 1988, the Clean Coal Phase 3 test effort was focussed primarily on longer duration operation. In December 1988, the first three day duration test with overnight shutdown was implemented. Overnight shutdown was necessary because the combustor-boiler controls were manual, and required continuous operator supervision. To allow longer daytime periods of coal fired operation, and more rapid heatup to operating conditions, the combustor-boiler controls were converted to automatic, unattended, overnight operation on pilot gas fuel in early 1989.

Beginning in March 1989, a series of five 4 day tests with round-the-clock operation were implemented. Nighttime operation was on pilot natural gas, and daytime operation was on oil, for heatup and cooldown, and coal. These tests were interspersed with one to two day tests on the combustor for other projects. As a result by the end of the Clean Coal project in May 1990, a total of 900 hours of operation had been completed, of which 100 hours were on two other DOE and EPA R&D projects on fly ash vitrification. As of the date of this report, the combustor has operated an additional 100 hours of daytime coal fired operation. Most of the test goals were directed at optimization of combustor and support equipment operation as well as developing the operational database associated with environmentally acceptable performance.

For the tests, eight different Pennsylvania coals having different sulfur contents were used. Parametric testing of combustor operation was evaluated with regard to environmental and process effects. Parameters tested included first and second stage stoichiometries, coal type, coal firing rate, calcium/sulfur mole ratio, and so forth. In May 1990, Coal Tech completed the planned test effort on its DOE Clean Coal demonstration project. The final effort on this project has been analyzing and evaluating test results, and preparing the Final Report.

2.3. Project Accomplishments

The Clean Coal project Cooperative Agreement specified five technical objectives. To implement these objectives, the following 10 sub-objectives were defined. The following is a summary of the accomplishments as compared to the sub-objectives listed in section 2.1.

The first objective was to use Pennsylvania coals with up to 4% sulfur content. About eight different PA. bituminous coals with sulfur contents ranging from 1 to 3.3%, and volatile matter contents ranging from 19% to 37%, were tested.

The second objective was to achieve 70 to 90% SO2 reduction at the stack, with maximum sulfur encapsulation in the slag. With regard to the first part of the objective, a maximum of over 80% SO2 reduction measured at the boiler outlet stack, using sorbent injection in the furnace at various Ca/S ratios. However, this result is based on limited data from work mainly conducted under the ash melting projects. It should be emphasized that these results were obtained during preliminary trial runs which made no effort at parametric optimization. Until further testing can be performed, a full analysis of the results is not possible. Good progress was being made at the end of the test effort toward meeting the second part of this objective, which requires sorbent injection into the combustor. A maximum SO_2 reduction of 58% was measured at the stack with limestone injection into the combustor at a Ca/S of 2. A maximum of one-third of the coal sulfur was retained in dry ash removed from the combustor and furnace hearths, and a high of 11% of the coal sulfur was retained in the slag rejected through the slag tap. Further slag sulfur retention is definitely possible by increasing the slag flow rate, by further improvements in fuel rich combustion, and by further improvements in sorbent-gas mixing.

The third objective was to achieve NOx reductions to 100 ppm or less. With fuel rich operation of the combustor, a three-fourths reduction in measured boiler outlet stack NOx was obtained, corresponding to 184 ppm. An additional 5 to 10% reduction was obtained by the action of the wet particulate scrubber, resulting in atmospheric NOx emissions as low as 160 ppm.

The fourth objective was to produce an inert solid waste. All the slag removed from the combustor has produced trace metal leachates well below the EPA Drinking Water Standard when subjected to the EP TOX test, and has yielded sulfide and cyanide reactivities within the regulatory limit.

The fifth objective was to achieve 90%-95% slag/sorbent retention in the combustor, and meeting local stack particulate emission standards. The second part of this objective was met with the wet venturi particulate scrubber. Total slag/sorbent retention under efficient combustion operating conditions averaged 72% with a range of 55% to 90%. Under more fuel lean conditions, the slag retention averaged 80%. In post Clean Coal project tests on fly ash vitrification in the combustor, modifications to the solids injection method and increases in the slag flow rate produced substantial increases in the slag retention rate.

The sixth objective was to achieve efficient combustion under fuel rich conditions, was met. Combustion efficiencies exceeding 99% were obtained after proper operating procedures were achieved.

The seventh objective was to achieve a 3 to 1 combustor turndown. Turndown to 6 MMBtu/hr from a peak of 19 MMBtu/hr was achieved. The maximum heat input during the tests was around 20 MMBtu/hr, even though the combustor was designed for 30 MMBtu/hr and the boiler was thermally rated at around 25 MMBtu/hr. This situation was due to facility limits on water availability for the boiler and for cooling the combustor. In fact, even 20 MMBtu/hr was borderline, so that most of the testing was conducted at lower rates.

The eighth objective was to evaluate materials compatibility and durability. Different sections of the combustor have different materials requirements. Suitable materials for each section have been identified. Also, the test effort has shown that operational procedures are closely coupled with materials durability. In other words by implementing certain procedures, such as changing the combustor wall temperature, it has been possible to replenish the combustor refractory wall thickness with slag.

The ninth objective was to operate the combustor on coal for approximately 900 hours of steady state operations with frequent start-up and shutdowns. The combustor's total operating time during the life of the Clean Coal project was about 900 hours. This included about 100 hours operation in two other fly ash vitrification test projects. Of the total time about one-third was with coal. About 125 tons of coal were consumed.

The tenth and most important objective was to develop proper combustor operating procedures. Not only were procedures for properly operating an air cooled combustor developed, but the entire operating data base was incorporated into a computer controlled system for automatic combustor operation.

In conclusion, Coal Tech's goal for this project was to validate the air cooled combustor at a commercial scale. This was accomplished. While the combustor is not yet fully ready for sale with commercial guaranties, it is ready for further major scaleup for application to commercial projects such as waste solid fuels, limited sulfur control in coal fired boilers, and ash to slag conversion.

3. DETAILED DESCRIPTION OF PROJECT WORK

The discussion in this section will highlight those aspects of the project effort that are significant in evaluating the project accomplishments and directions for future work. The material is not a reproduction of the discussion contained in the various project technical reports, which have been previously submitted to DOE.

3.1. Phase I-Design & Permitting

In work pre-dating the Clean Coal project, the Coal Tech air cooled cyclone coal combustor was designed, fabricated, and retrofitted to a 23 MMBtu/hr oil designed, package boiler at the Tampella/Keeler facility in Williamsport, PA. The combustor design effort began in late 1984, combustor fabrication required a one year period in 1985-6, and installation began in late 1986 and it was completed in early 1987. The original installation was for use with low ash, low sulfur, coal-water slurry fuels. No particulate stack scrubber or sulfur control system was included in this original system. That effort culminated with initial tests on the combustor in the Spring of 1987, using a coal water slurry. The combustor was operated for a period of 40 hours on coal-water slurry fuels at about 17 MMBtu/hr. Combustor operation was as per design. An important result was that combustor pre-heat to operating temperature was accomplished with the slurry fuel. This initial operating experience was a major factor in the preparation of the test plan for the Clean Coal project.

The combustor and the test facility will be described below. Here relevant drawings and photographs will be introduced to clarify the subsequent discussion of the Phase 1 design effort. Figure 1 is a schematic diagram of Coal Tech's Advanced Air Cooled Cyclone Coal Combustor. The combustor is attached to a 17,500 lb/hr of saturated steam (23 MMBtu/hr) D frame, oil designed, package boiler in the boiler house of the Tampella/Keeler Company in Williamsport, PA. The latter is shown in figure 2. Figure 3 is a side view photograph of the combustor as it is currently attached to the boiler while figure 4 is a plot plan of the installation. Figure 5 is a process flow block diagram of the coal fired combustor-boiler system. Figure 6 is a photograph of the stack scrubber on the roof of the boilerhouse.

The Clean Coal project began in March 1987. In Phase I, the auxiliary equipment necessary to allow dry pulverized coal firing was designed. This included a 4 ton on-site pulverized coal storage system, a pneumatic coal delivery system to the combustor, a 1/2 ton dry pulverized limestone storage and pneumatic feed system, and a wet stack particulate scrubber. Coal pulverization was to be off-site with regular fuel delivery by pneumatic tanker truck. Commercial designs were used, and the entire system was planned for Phase 2 purchase. The basic design consisted of an upper (4 ton capacity) bin which discharged automatically into a small lower bin that was integrated with a screw feeder. The latter discharged the coal into a pneumatic air line that delivered the coal to the combustor. Injection was either axially though a pintle, or off-axis, downstream of a pneumatic coal flow splitter.

A limestone bin, with a 1/2 ton capacity was placed alongside the combustor, and it delivered the powder to the combustor in a manner similar to the coal feed.

To control stack particulate emission a wet particle scrubber was designed, with a recirculating water loop. The design called for placement of the scrubber inside the boilerhouse due to concern of winter freezing of the water loop, as well as concern over inadequate roof load capability of the boilerhouse.

The slag removal system design consisted of a simple drag conveyor which removed slag dropped into the slag tank located underneath the combustor.

It was planned to purchase all this equipment commercially. In fact, certain components were not available or they performed poorly, and Coal tech had to modify them extensively.

An existing sophisticated CO_2, CO, NO_x, SO_2, HC stack gas sampling system in a Keeler test facility adjacent to the combustor facility was made available for use in the combustor project.

A second major activity of Phase I was the permitting necessary to implement the Phase II and III test efforts. The water discharge permit was obtained from the Williamsport Sanitary Authority, while the application for the air emission permit was filed with the Pennsylvania Department of Environmental Resources (PA DER), Bureau of Air Quality Control, with subsequent approval of both the Test Plan and Operating Permit in Phase II.

Finally, the procedure for obtaining a solid waste disposal permit was initiated with the PA DER, Bureau of Solid Waste Management, including provision to accumulate and store slag samples on site for subsequent representative sampling and analysis as per the required Module 1 in Phase 2 & Phase 3 testing. However, it was discovered later in the project that the slag was covered under the Pennsylvania Coal Waste Product Recycling Act and, as such, did not require extensive testing/analysis to obtain disposal permits. In view of this, plus the fact that the Module 1 testing had already been performed, showing no hazardous solid waste characteristics, disposal of most of the slag and bottom ash produced in the tests was at the PP&L Montour solid waste facility. However, solid waste characterization testing of the slag was still deemed important in overall development and demonstration of the combustor and we therefore continued to monitor this substance. Late in the Phase 3 tests, PP&L could not accept the slag because a significant quantity of material consisted of large slag blocks. In addition, it was necessary to dispose of refractory removed from the combustor. As a result a Module 1 application is now being processed by a local landfill. Due to the lengthy filing period, it is planned to dispose of the remaining material at a secure private landfill.

Another activity of Phase I was the compilation and preparation of the necessary documentation as specified in the Cooperative Agreement and the preparation of the appropriate reports, including an Environmental Plan Outline and the Environmental Plan itself. These documents are on file at DOE and will not be reproduced here.

3.2. Phase II-Fabrication, Installation, and Shakedown Testing

In Phase II, the equipment designed and selected in Phase I was installed at the Tampella/Keeler facility. During installation the stack scrubber design was modified for placement on the roof of the boilerhouse, as opposed to inside the building, as in the original design. It was determined that the installation cost inside the building was much greater than the roof installation. The original contractor that erected the boilerhouse was able to ascertain that the roof bearing load was sufficient for this purpose. A second design change was to use a once through plain steel scrubber vessel instead of a stainless steel scrubber vessel with a recirculating water system. This reduced the cost of the scrubber system by a factor of 5. The decision to proceed with this approach was based on Coal Tech's assumption that the use of lime injection in the combustor would result in a basic water flow in the scrubber, which would reduce the corrosion rate substantially. This proved to be the case. The pH of the scrubber water ranged up to 12. The duct work and the scrubber fan were redesigned and procured separately.

In nearly 3 years of operation the scrubber operated very statisfactorily, even in the winter, with air temperatures as low as $5^{O}F$. To prevent freezing, the water lines were drained after each test. It was necessary to rearrange the water discharge to assure proper gravity flow for drainage purposes. The only problems encountered were erosion of the scrubber vessel inlet scroll which was caused by the fact that the wall thickness was too thin at that location. This section was replaced with a section of thicker, erosion resistant steel. In addition, the scrubber inlet duct was not properly supported which caused a shear tear in one wall of the inlet vessel. This was also readily corrected. The final problem with the scrubber system was damage to the fan wheel, which had to be replaced. It was not certain whether this was caused by inadequate maintenance, e.g. regular fan wheel cleaning and fan shaft bolt tightening, or whether it was caused by residual debris that had not been removed from the scrubber vessel after its repair. These three problems occurred in December 1989, and it is suspected that the fan problem was caused by flying debris.

A commercial, 4 ton capacity, dry pulverized coal storage and delivery system was procured. The original plan had been to purchase the pneumatic conveying system as part of the coal system. However, the high cost and limited commercial availability of a complete system resulted in the decision to design our own system. Various size eductors were tested with Coal Tech designed flow splitters to determine the appropriate component sizes. The final design selected allowed coal feed of up to 3/4 ton per hour with multi-point off axis injection in the combustor. The limestone feed system was limited to only about 200 lb/hr capacity due to the small size of the limestone injection tubes in the combustor. This proved to be a significant drawback in sulfur capture tests in the Phase 3 effort. To partially correct this problem, one of the coal ports was used for limestone injection. However, this was not a satisfactory solution as sorbent-gas mixing was not as uniform. (It should be noted that Coal Tech has recently installed a new solids injection system that would allow limestone injection rates in excess of 1000 lb/hr at off-axis locations.)

In addition, a 1000 lb capacity limestone storage and feed system was fabricated and installed alongside the combustor.

As noted in the Phase I section, an existing gas sampling system in an adjacent building was made available for our use during this project. In Phase II, sampling lines were installed to allow extractive combustion gas sampling from either the boiler outlet, upstream of the scrubber, or from the scrubber fan stack exhausting to atmosphere.

Although a slag removal system had been designed prior to Phase I, it was decided to delay installation of a continuous slag removal system until the results of early testing could provide a determination of the nature of the slag. Owing to slag tap operation problems in the early Phase III tests, a continuous slag conveying system was not procured until later in Phase III. This conveyor, which is shown in several photographs in Appendix III proved to be of very poor design, as it was very prone to jamming. After one modification by the original manufacturer, Coal Tech made a number of incremental improvements to this conveyor. However, even at this date the unit is still prone to jamming, and for future multi-day tests, Coal Tech will use the experience gained to-date to design a new slag conveyor.

Two combustor shakedown tests were implemented in Phase II. The originally planned tests were to consist of two, one day tests with dry pulverized coal (PC) to establish the performance of the scrubber and the PC feed system. This plan was modified to a new test sequence in which the bulk of the first test was to be performed with coal water slurry fuel, with a brief operating period on dry PC. The second test was to remain unchanged with dry PC operation. The change in plans was motivated by the fact that both the scrubber and pneumatic feed systems for coal and limestone were purchased as individual components from multiple suppliers. Therefore, a prudent approach to test the scrubber first, using the proven slurry fuel, was followed.

The first test, which achieved 10 MMBtu/hr slurry firing, showed good scrubber performance but identified excessive noise and vibration of the combustion air fan as a problem. The details of this problem and its resolution are presented in section 3.3.3. Briefly, it was determined that the fan had a design defect and that it was operating on the wrong side of the fan curve. Coal Tech determined that by increasing the inlet opening to the fan the vibration could be eliminated. However, the fan noise was still unacceptably high. As a result, when the combustor was rebuilt in March 1988, the fan was returned to the manufacturer for installation of a new fan wheel. Since that time the fan has operated quietly and trouble free.

In the second test, 17 MMBtu/hr of dry PC was fired under fuel rich conditions. The coal storage and delivery system performed well, as did the scrubber. However, combustion efficiency was determined to be only around 80%. This problem and its resolution are also discussed in section 3.3.3. Briefly, the problem was caused by poor slagging on the combustor wall and very high coal feed fluctuations. Phase 2 was completed in November 1987.

3.3. Phase 3- Parametric & Long Duration Testing

3.3.1. Test Plan

The original Phase III test plan for the dry pulverized coal tests was developed on the basis of experience gained in earlier tests on this combustor with coal water slurries (1). It was assumed that after a brief checkout of the new dry pulverized coal storage and pneumatic feed systems, and the stack gas scrubber, that coal tests of increasingly longer duration could be implemented. However, as more operating time on PC was accumulated, the original test plan was modified to focus on technical issues which were discovered during testing that required additional work. For example, more extensive parametric tests were necessary to deal with the refractory ash properties of the test coal which made effective slag flow very difficult. This was not totally unexpected since in reviewing the literature on commercial and advanced cyclone combustors, it was noted that considerably lower ash fusion temperature coals have been used. While good combustion efficiency and slag flow were eventually achieved, it required considerable development work, including the refurbishment of the ceramic combustor liner when the combustor was inadvertently operated outside its designed thermal envelope. Another factor which impacted the test plan was the difficulty encountered in the operation of the dry PC storage and feed system. This commercial system required extensive modifications before reliable and steady coal flow to the combustor was achieved.

Another major factor that influenced the total operating time on coal was the finding that dry pulverized coal could not be used to pre-heat the combustor to operating temperatures. This statement requires clarification. Coal could be used to pre-heat the combustor. However, if the walls were too cold to slag the coal ash, a large fraction of the coal particles would blow out of the combustor. The furnace section of the package boiler is not designed to burn coal. Therefore, significant unburnt coal would entrain in the stack exhaust and overload the scrubber. For this reason, oil firing was used to pre-heat the combustor wall. Since we had planned frequent startups and shutdowns at least one-half of the scheduled hours of coal fired operation were eliminated. This is the major reason why only about 1/3 of the 800 hours of combustor operation in this project were on coal.

In the process of resolving these issues, the test effort was focused on the following areas of the combustor system:

-Use of a wider range of coals than had been originally planned.

-Extensive development of the coal storage and feed system.

-Debugging of the auxiliary components of the facility, such as the high pressure fan, combustor diagnostics and controls.

-Development of efficient combustor operation with the refractory coals under fuel rich and fuel lean conditions.

-Development of effective and continuous slag rejection.

-Development of efficient SO2 and NOx control techniques.

It should be emphasized that while the experience gained in the past decade of cyclone combustor R&D in pilot scale units has been extremely valuable in the present test activities, the operation of this commercial scale combustor is very different from the smaller units tested previously. Thus, during Phase III, the general aim was to develop a data base associated with combustor operation as well as to evaluate the performance of various system hardware and combustor components and upgrade where necessary.

This type of operational evaluation was necessary since the simultaneous optimization of key performance characteristics such as SOx and NOx control, combustion efficiency, and slag retention/rejection was not straightforward owing to coupling effects of operational parameters. In addition, "mapping" of this kind occasionally required running the unit at non-ideal conditions in order to identify the boundaries associated with good environmental control as well as satisfactory combustion and thermal performance. Another constraint was to operate the combustor in a manner which would not result in severe deterioration or failure of the combustor or any of its components. It was impossible to avoid this generation of a combustor operating data base since the available literature on commercial sized units is vague. Furthermore, the data available from pilot scale combustors, though useful globally, does not usually address materials issues such as compatibility and durability. Thus a major goal of the Phase III test work was to address durability and related technical issues.

3.3.2. Facility Description

Figure 1 is a schematic diagram of Coal Tech's Advanced Air Cooled, Cyclone, Coal Combustor. The cyclone combustor is a high temperature (>3000 F) device in which a high velocity swirling gas is used to burn crushed or pulverized coal. The ash is separated from the coal in liquid form on the cyclone combustor walls, from which it flows by gravity toward a port located at the downstream end of the device. Coal Tech's cyclone combustor is an advanced version of commercial cyclones used in large utility boilers in the 1950's and 60's (2). The use of these cyclones was reduced due to the high NOx emissions resulting from their mode of operation.

A brief description of the operation of the air cooled combustor is as follows: a gas burner, located at the center of the closed end of the unit, is used as a pilot. A light oil gun, similarly located, is then used to pre-heat the ceramic lined combustor wall and to start coal combustion. Dry pulverized coal (70% minus 200 mesh or finer) is transported by primary air (= or < 2/1 coal to air mass ratio) and injected into the combustor through tubes in an annular region enclosing the gas and oil burners. In a similar way, limestone or calcium hydrate powder for slag viscosity and/or SO2 control is conveyed and injected into the combustor. The combustor can simultaneously or separately fire all three fuels noted above; in addition coal water slurries can be fired if a slurry gun is installed in place of the oil gun.

Secondary air (SA) is used to adjust the overall combustor stoichiometry for SO2 and NOx control. Final or tertiary combustion air is injected directly into the boiler to establish overall stoichiometry. The key novel feature of this combustor is the use of air cooling. This is accomplished by using a ceramic liner, which is cooled by the SA and maintained at a temperature high enough to keep the slag in a liquid, free flowing state. The SA tangential injection velocity and the off-axis coal injection are designed to ensure quick and complete mixing of fuel and air, resulting in suspension burning of the coal particles near the cyclone wall with high combustion efficiency.

This arrangement also promotes slag retention, and values in excess of 90% were achieved (3, 4) in the pilot scale unit while maximum values of 90% are obtained on PC with the present unit. This liquid slag is drained into a water quench tank where the solidified material is removed by a belt conveyor to a drum for subsequent disposal, as shown in figure 13. The balance of the slag/spent sorbent particulates, which are not retained in the combustor or deposited in the boiler, are conveyed by the flue gases to a venturi type wet scrubber which removes sufficient particulates to meet emission requirements. This device is shown in figure 6.

Although the combustor is mostly air cooled, some internal members are water cooled. This cooling water, as well as the slag quench water and the water discharged by the scrubber are all collected and discharged to the sanitary drains at the test site. This water discharge is routinely sampled and analyzed for compliance with the thermal, suspended solids, and heavy metal trace element standards and regulations of the Williamsport Sanitary Authority.

Tests on the combustor were performed in the boiler house of the Tampella/ Keeler Company in Williamsport, PA. and shown in figure 2. Installation work began in the Fall of 1986, and it was completed in March 1987. Figure 3 is a side view photograph of the combustor as it is currently attached to the boiler while figure 4 is a plot plan of the installation. Figure 5 is a process flow block diagram.

To contain the capital equipment costs at the combustor site, it was decided to sub-contract the pulverization of the coal to a local vendor, who would deliver the coal to the site in a tanker truck. The latter acts as the primary on-site storage system, and it has sufficient capacity for about 24 hr operation at full boiler load. To allow shorter duration testing, and to allow replacement of the empty trailer without combustor shutdown, a smaller 5 ton coal storage bin was installed at the site, to which coal is transferred from the trailer, and from which it is metered to the combustor by a pneumatic line.

As noted in the Phase I section, an existing gas sampling system in an adjacent building was made available for our use in this project. This system, which is pictured in figure 14, consisted of Beckman analyzers for O_2, CO, CO_2, NOx, and SO_2. In Phase II, sampling lines were installed to allow extractive combustion gas sampling from either the boiler outlet, upstream of the scrubber, or from the scrubber fan stack exhausting to atmosphere.

3.3.3. Topical Description of Tests

In the period between 12/87 and 5/90, 26 Phase III combustor tests were performed for a total operating time of around 800 hours, consuming about 125 tons of coal. All but the last seven tests were nominally 24 hrs in duration, including heatup and cooldown on auxiliary fuels. The final series of tests was multi-day with overnight firing on pilot natural gas. The final four tests involved three and four consecutive day operation. Most of the test goals were directed at optimization of combustor and support equipment operation as well as developing the operational database associated with environmentally acceptable performance. The following sub-sections discuss these key issues on a topical basis. A chronological description of the tests is presented in Appendix I, while the compositions and properties of the coals and sorbents used are presented in Appendix V.

3.3.3.1. Solids Feeding & Air/Fuel Mixing

Problems encountered with solids feeding were either a total or partial loss of feed, or too much variability in the flow. Feed loss was usually associated with hang-up of the pulverized coal or limestone (LS) in the feed hopper or screw, while diminished flow resulted from partial blockage of downstream flow components. In addition, the presence of oversized "tramp" material, such as rocks, can lead not only to flow problems but also to equipment damage, which occurred on one occasion. The hang-up problem was overcome by adding vibrators on the hoppers and by rearranging the pneumatic piping. The first occurrence of the "tramp" material problem was associated with improper quality control at the subcontractor's pulverization site. The second occurrence involved metal nodules, which were attributable to inadequate quality control at the pulverization company.

Variability or oscillation in solids flow, which for coal had a sine wave period on the order of several minutes, usually resulted from excessive interaction between the coal feed and pneumatic conveying system. The problem was greatly reduced by testing various arrangements of the pneumatic lines. By early 1989, the oscillations in the coal flow were reduced from a high of 17% to 1 to 3%. Fuel rich operation below 90% of theoretical combustion air (SR <0.9), which is necessary for both NOx and SO2 control, only became possible when these fluctuations had been essentially eliminated. Since the boiler acts as a calorimeter low frequency coal feed fluctuations can be seen on the steam flow chart records. Figure 7 shows the steam flow charts for two coal fired tests. Figure 7a was obtained during a test early in the project, while the figure 7b was taken later in the project after the feed fluctuation problem had been solved. Note that strong fluctuations in the steam flow rate in the top chart compared to the smooth steam flow in the bottom chart.

Air/coal mixing is critical to proper combustion. It was determined that central pintle injection of the coal resulted in poorer mixing than off-axis injection. However, even with off-axis injection, non-uniform or irregular coal flow can result in flame pulsation with fluctuations in flame length of several feet and frequencies in the seconds range. In this situation, efficient combustion within the combustor is not achieved.

However, even with uniform off-axis coal injection, initial dry PC testing yielded combustion efficiencies of 80% or less. This problem was solved by providing sufficient combustor heatup prior to coal injection. This was accomplished by the addition of a high thermal input oil gun which was used to heat the walls to temperatures at which the nominal slag viscosity was 250 poise or less. Due to the refractory nature of the ash for most of the Pennsylvania bituminous coals used in the project, it was necessary to flux the ash with the injection of limestone or calcium hydrate. These measures also improved combustion efficiency, resulting in efficiencies averaging 97% and 94%, based on slag carbon and stack gas/particulate analysis, respectively, since test 9 of May, 1988.

As can be seen from Appendix V, coal particle size was not varied greatly and therefore had little impact on test observables. However, work performed under other projects suggests that overall combustion efficiency is enhanced by having a finer sized coal.

3.3.3.2. <u>Air Cooled Combustor Liner Operation</u>

The original liner material installed in the combustor was determined to have thermal properties that were inconsistent with the highly refractory coal ashes, and correspondingly high slag fluid temperatures, employed in the early tests. In addition, chemical analysis of slag samples obtained during this testing period showed evidence of slag/liner chemical interaction. Initial attempts to achieve good slagging conditions with this liner resulted in overheating of the liner and partial refractory failure. This occurred early in Phase III, and the combustor was disassembled and a new liner material, which was more compatible with the specific test coals, was selected and installed. As part of this redesign effort, sections of the ceramic and metal wall material was submitted by DOE/PETC to the Oak Ridge National Materials Laboratory and by Coal Tech to Professor D. Simpson of the Lehigh University Geology Department for electron microprobe and X-ray probe analysis. The results showed that while slag attack of the wall materials was taking place, this was not the probable cause of the wall failure. Instead it appeared to have been caused by failure of the support structure of the ceramic wall. This hypothesis was strengthened by a stress analysis of the combustor wall performed by Professor P.V. McLaughlin of Villanova's Mechanical Engineering Department. It showed that the support structure was subject to high thermal stresses. These results were incorporated in a modified support structure for the combustor wall.

In addition, an upgraded combustor operating procedure, which relied on improved process temperature measurement and control, was implemented. This procedure was designed to limit thermal shock of the refractory as well as to minimize slag corrosion. The new liner and control strategy were implemented during tests 8 and 9 in May of 1988, and have proved to be very satisfactory. Between 800 and 850 of the nearly 1000 hours of combustor operation, since the start of the Clean Coal tests, have been performed with the new liner, without having to replace it. Figure 8 shows the different nature of the wall heat transfer in the new liner compared to the old liner. The new liner is much less dependent on total thermal input to the combustor.

However, it should be noted that the present combustor was operated under a harsher thermal environment than commercial slagging combustors due to daily thermal cycling, and due to the wide range of operating conditions experienced during the parametric test effort. In commercial units, the combustor is only shutdown for maintenance after a relatively long campaign, at which time the refractory is generally replaced. As a result, in the present combustor, localized refractory losses were experienced from time to time but were quickly repaired with chemically identical cement. As cyclic operation generally occurs

occurs in smaller industrial and commercial boilers, a means had to be developed to replenish the refractory wall during combustor operation. A procedure to accomplish this, which involved adjusting process temperature and slag layer thickness, was developed late in Phase III testing. This procedure had been further refined in post Clean Coal project tests, and no patching of the combustor wall has been necessary since the early Spring of 1990.

3.3.3.3. Combustor/Boiler Thermal Interface

A major operational difficulty encountered during the Phase III testing was refractory failure in the exit nozzle section, at its attachment point to the boiler. The exit nozzle section connects the combustor to the boiler. In September of 1988, during test 14, hot combustion gases vented out of the boiler through small openings in the boiler access door. Post test inspection revealed extensive damage to the boiler front wall. However, the refractory in the exit nozzle was not damaged, and it indeed survived the entire 900 hours of operation. Detailed mechanical and heat transfer analysis led to the conclusion that the failure occurred mainly due to inadequate insulation at the nozzle/boiler interface. A different installation design, using different refractory materials, was implemented and has performed satisfactorily.

A second area of difficulty was overheating at the combustor/exit nozzle thermal interface. While temporary solutions controlled the problem initially, it was decided in the Summer of 1989 to design and install a modified interface refractory the next time the problem reappeared. This did not occur until February 1990, after about 250 to 300 hours of operation. Since the combustor was being used for testing under other projects, the modification was implemented in two steps in March and June 1990. In recent tests, the modification has performed as per design. Nevertheless, thermal data show that a modest degree of additional cooling is required at the boiler front wall in order to allow round-the-clock operation at full thermal combustor load.

One final point of importance regarding the operation of this combustor is slag flow into the boiler. Depending on the combustor's operating conditions, and on the geometry and contour of the exit nozzle, it is possible to either close a major part of the exit nozzle with slag, or to alternatively produce significant slag flow onto the boiler furnace floor. This complex issue was investigated in detail during the test effort, and procedures to prevent exit nozzle closing or slag flow into the boiler were developed.

3.3.3.4. Slag Retention/Rejection & Slag Tap Operation

As noted in a previous section, initial testing on dry PC resulted in poor combustion efficiency and slagging due to the high viscosity of the slag. It was not until LS injection was routinely implemented that both combustion efficiency and slag retention/rejection were greatly improved. In addition, plugging of the slag tap was the primary cause of premature termination of coal fired operation early in the Phase III testing. On one occasion, operation continued with a closed tap. After the test, a one foot thick layer of frozen slag covered the combustor floor. After many modifications to the slag tap operation, a combined mechanical and tap heating procedure was developed to keep the slag tap open. This procedure was introduced in mid 1989, and since that time only one test was terminated due to slag tap plugging. After the modifications were finalized, slag retention in the combustor, exit nozzle, and rejection to the slag quench tank averaged 72% with a range of 55% to 90%. Under near stoichiometric conditions, the combustor/boiler retention was better, averaging about 80% with a range of 65% to 90%. The slag retention is very sensitive to the injection location. After the completion of the Clean Coal project a new and improved solids injection procedure was used for fly ash injection. In one test better that 80% slag retention in the combustor was measured from the slag passing through the slag tap in the combustor.

3.3.3.5. Automated & Computer Controlled Operation

The combustor was controlled manually for virtually all of the coal fired Clean Coal Technology testing. The original test plan called for overnight shutdown of the combustor with daytime coal fired operation. This was dictated by project resource limitations. However, as it became clear that heatup and cooldown of the combustor could not be implemented with coal firing, and that cold-start daytime heatup and cooldown wasted too much operating time, the control system was converted to automatic overnight operation on low fire with pilot natural gas at the beginning of 1989. This operational and safety interlock system was devised and implemented to permit unattended overnight firing. This allowed a more rapid start-up the next day, which resulted in more test time on coal, and also allowed round-the-clock operation. This procedure has worked well, and five four-day tests with round-the-clock operation were logged since that time.

During the Spring of 1990, sufficient operational data had been accumulated to implement computer controlled operation. Under another project, a commercial process control software package was customized for control of the air cooled combustor using the control strategy developed during Phase III. This system was installed prior to the final four-day Clean Coal test in May of 1990. It is currently undergoing shakedown as part of other test efforts. This system is very important to the commercial success of the combustor, as it will allow automatic combustor operation with minimum supervision. This is critical in small boiler applications. Since May 1990, the computer system has been used to control the combustor operation with manual control inputs. In addition, more and more combustor control functions are being automated in each succeeding test. The objective is to achieve completely automated combustor operation.

Figure 9 shows the location of the computer relative to the computer and manual control panel. Figure 10 shows the computer screen with the Coal Tech operating logo. Figure 11 shows a sample control strategy for the combustor. Figure 12 shows the computer screen of the combustor control sequence.

3.3.3.6. Miscellaneous

During shakedown testing of the system, excessive noise and vibration from the high pressure cooling/combustion air fan was noted. Although not strictly a compliance problem, the noise level was a considerable nuisance. After extensive consultations with the manufacturer, the problem was discovered to be mainly caused by a design defect in which the fan operated in the surge mode to the point where damage to the fan housing supports occurred. Coal Tech devised a temporary method of operating the fan which eliminated the surge, but the problem was not fully solved until the fan was returned to the manufacturer for rebuilding. The rebuilt fan was installed during the combustor refurbishment, and it now operates satisfactorily at a noise level far below that of other equipment at the test site.

Although the scrubber has probably been the most reliable commercially installed hardware component of the entire system, there were three occasions when it needed repair, all in the second half of Phase 3. The first occasion involved replacing a section of the cyclone wall where it had been worn by solids abrasion. In order to minimize the scrubber cost and in view of the limited lifetime required for this equipment, a low cost and thin wall section had been originally installed. A heavier gage, abrasion resistant steel patch was installed to repair this section. The second repair involved replacing the scrubber fan owing to imbalance which was most probably caused by scrap material released during the scrubber wall failure. The imbalance loosened the fan bearings. The scrap metal also damaged the stack damper outlet used to modulate the fan. The third incident was related to the first, in that a side panel of the scrubber inlet developed a shear tear, which was probably caused by the stress induced by the first repair. This section was provided with added supports to reduce the shear load. To prevent future fan and scrubber vessel problems, a procedure was implemented to clean the scrubber fan and scrubber inlet after each test.

Two pin-hole leaks in the water cooled burner developed during Phase III. These leaks had no adverse effect on operation and were fixed between test runs.

3.3.4. Test Results

In this section the technical results are presented by specific topic, and categorized as either a combustor or an environmental performance observable. Combustor performance refers to operation of the unit as a burner and thermal process device. Here, specific observables include combustion efficiency or fuel utilization, thermal characteristics such as heat release and operating temperature, slag retention/rejection, and refractory wear. Environmental performance deals with project goals in the environmental control area, addressing NOx and SOx reduction as well as slag reactivity. In addition, results of regulatory compliance testing for particulates and wastewater are included.

In an attempt to unravel the complex interactions of combustor operating conditions on test observables, the Coal Tech Clean Coal data base, supplemented by the DOE and EPA ash conversion data, was subjected to statistical analysis. The extensive data base consisted of a matrix sized 207 X 45, i.e. there were 207 separate test conditions, each having up to 45 different observations or measurements. Thus the matrix potentially consisted of over 9000 entries. However, in many cases certain measurements were not always taken so that the actual data base consisted of about 6500 entries. It should be noted that the Clean Coal data base did not include tests with the initial liner since most of that data was obtained in preliminary testing, where combustion efficiency and slagging were very poor and, in any case, the recorded data were not as comprehensive as with the new liner. Thus, all statistical results are for the new liner only.

After evaluating hundreds of models, it was determined that all key process observables could be adequately accounted for by models having four independent variables, namely, first stage inverse equivalence ratio (SR1), combustion swirl air pressure (SWIRLPR in inches of water column or "WC), total fuel heat input (HEATIN in MMBtu/hr), and percent contribution of coal to the total heat input (PCTPC). In addition, models of the sulfur related independent variables included the Ca/S mole ratio (CASRAT). It is important to note that all experimental observables or dependent variables, including measured SO2 reduction in the boiler outlet (SREDBO), provided independent variable or operating parameter models having a low (< .05) probability (two-tailed significance) of zero coefficient. This suggests that the measured changes in test observables, as a function of parametric operation, were in fact due to changes in operating conditions and not simply random events.

It should be emphasized that the statistical method, while useful in gauging relative effects at average conditions, is less useful, and may even be misleading, in predicting the true or actually measured range of values for the various dependent variables. This resides in the fact that model predicted values used in this analysis are based on the full range of one independent variable plus the average values for the other independent variables in the model. In actual operation, the negative effects of one of the process variables on good operation were ordinarily compensated for by varying other parameters, usually away from their average values.

In the following subsections a brief technical description of the relevant physical and chemical processes is first presented as background. Following this, the test results are presented and discussed. Key results from the statistical analysis are also included; however, a detailed presentation of the statistical analysis is found in Appendix II.

3.3.4.1. Combustor Performance

3.3.4.1.1. Combustion Efficiency

Coal combustion may be thought of as occurring in two steps: combustion of volatiles followed by char burnout. Under oxidizing (fuel-lean) conditions the major products of combustion (POC's) are CO_2, H_2O, N_2, and O_2 with small amounts of CO, NO_x, and SO_2 depending on exact fuel composition and details of the combustion process. With reducing conditions, as would be encountered in fuel-rich staging, the char residue is gasified by endothermic reactions with the CO_2 and H_2O produced from "normal" combustion. Here the major POC's are CO_2, CO, H_2O, H_2, and N_2 along with some unburned hydrocarbons (UHC) and other reduced species.

The efficiency of this carbon conversion or utilization process depends on temperature, residence time, and stoichiometry as well as char particle size. In addition, char not converted in the fuel-rich first stage may be consumed if it is carried over to the second, excess air stage, resulting in good overall combustion efficiency. Even with less than 100 % carbon conversion or char burnout in the fuel rich first stage, both the coal sulfur and nitrogen are essentially completely evolved if they are organically bound (5). However, this conclusion does not apply to coals with high inorganic sulfur or nitrogen.

Shakedown testing of the system was conducted with coal-water slurry (CWS) and resulted in near 100% fuel utilization based on measured CWS and air flows plus stack gas combustion product analysis. Initial dry coal testing, however, resulted in estimated combustion efficiencies < 80 %, as already noted. To see if coal/air mixing was playing a role, coal injection geometry was modified with inconclusive results. Efforts were then directed to providing sufficient combustor preheat prior to coal injection. This required installation of a high thermal input light oil gun. The initial results of this effort were still poor.

Evaluation of the coal chemical composition showed low volatile matter (VM) and an extremely refractory ash, having a T-250 of about 2800 F. It should be noted that the poor combustion characteristics of the coal were simultaneously related to poor slagging and high solids carryover into the boiler. With these apparently related results in mind, limestone injection was tried to flux the ash. The results were greatly improved slagging, which will be discussed in more detail later, and an improved combustion efficiency estimate of = or > 95 %. This encouraging result was obtained by the fourth Phase III test and was subsequently improved with higher VM and less refractory ash coals to yield overall coal combustion efficiencies, during steady state operation, of 95 to 99 %, based on stack gas, slag carbon, and scrubber particulate analysis.

Testing aimed at fuel-rich combustor operation to optimize NOx and SO2 control was initially plagued by poor overall carbon burnout. However, reconfiguration of the Tertiary Air piping, leading to improved fuel/air mixing in the combustion second stage within the boiler, allowed fuel-rich combustor operation (0.7 inverse equivalence ratio) with good overall combustion efficiency.

However, recent (post Clean Coal Technology project) tests have shown that previously undetected coal feed induced non-uniformities produce multi-second flame pulsations even at fuel lean conditions in the combustor. These pulsations would have had an even greater adverse impact on the local fuel burnout in the combustor under fuel rich conditions. This in turn would adversely affect processes such as sulfur capture in the combustor. The feed fluctuations have been very recently greatly reduced by reconfiguring the coal feed. It is, therefore, essential that fuel rich combustor tests, including sulfur capture tests, be repeated under the new fuel feed conditions.

In the statistical analysis there were three independent methods to assess the degree of fuel utilization or combustion efficiency as a percent of total combustibles: slag carbon content (SLAGCEFF), measured air and fuel flows vs. stack oxygen (GASCEFF), and carbon content of the solids discharged by the scrubber (TSSCEFF). These values are expressed as percent conversion of fuel combustibles to final products. SLAGCEFF (slag carbon combustion efficiency) relates directly to the combustor's operation, which includes fuel rich conditions, while the other two relate to overall efficiency, including second stage combustion with excess air. In percent units, the average measured value, standard deviation, plus high and low values for each of these variables is: SLAGCEFF (slag carbon combustion efficiency): 99.8, 0.7, 100.0, 95.0; GASCEFF (flow and oxygen combustion efficiency): 107.0, 9.0, 135.0, 81.0; TSSCEFF (scrubber carbon combustion efficiency): 94.4, 3.8, 99.8, 80.8.

Based on statistical modeling, the dependence of each combustion efficiency variable on key operating parameters was determined. Although each of the combustion efficiency variables depends on several operating parameters, the relative effects vary.

All three combustion efficiencies increased as SR1 (first stage inverse equivalence ratio) increased, which is expected on the basis of improved combustion at stoichiometric and low excess air conditions. The effect of SR1 (first stage inverse equivalence ratio) is nearly equal for all three combustion efficiency variables. Combustion air swirl pressure (SWIRLPR) had a small effect on combustion efficiency with all three combustion efficiencies decreasing as air swirl pressure was increased. This effect is likely due to increased liner surface cooling at higher swirl pressure. This phenomenon had been observed on several occasions. This cooling probably results in partial quenching of the wall coal burning reactions, especially at low SR1 (first stage inverse equivalence ratio) where endothermic char gasification reactions must proceed to completion to obtain good fuel utilization and/or combustion efficiencies. All combustion efficiencies increased as fuel heat input increased. This effect is probably attributable to increased combustion intensity at higher firing rates, resulting in improved fuel utilization.

The percent of fuel heat input due to coal (PCTPC) effects indicated that all combustion efficiencies increased as the percent of coal firing increased. At first glance, this appears to be unexpected since coal is more difficult to burn than natural gas or light oil, the auxiliary fuels used in the tests. However, as PCTPC (percent coal firing) increases, the percent of auxiliary fuel decreases and there is therefore less competition for oxygen from the premium fuels, and coal combustion can proceed to a greater extent. In addition, and probably more importantly, coal char combustion/gasification takes place to some extent in the combustor wall slag layer. As PCTPC (percent coal firing) goes up, there is relatively more coal ash/slag in which the char particles can be embedded for subsequent reaction via gas scrubbing. This interpretation is supported by testing in early Phase III, which showed that the presence of a liquid combustor wall slag layer was necessary to ensure good coal combustion.

Unlike SR1 (first stage inverse equivalence ratio), SWIRLPR (swirl air pressure), and HEATIN (total fuel heat input), the effect of PCTPC (percent coal firing) on the three combustion efficiency variables is not of comparable magnitude. This is illustrated in figure 15. PCTPC (percent coal firing) appears to affect SLAGCEFF (slag carbon combustion efficiency) about twice as much as GASCEFF (flow and oxygen combustion efficiency) or TSSCEFF (scrubber carbon combustion efficiency). This is not unexpected inasmuch as the latter two variables are measures of overall combustion efficiency and thus include the effects of second stage burnout, which always takes place under excess air conditions. SLAGCEFF (slag carbon combustion efficiency), however, includes fuel rich combustion and would therefore be more susceptible to the oxygen competition and wall burning effects of PCTPC (percent coal firing) than the other variables.

In conclusion, the present project achieved many of the technical goals required to demonstrate commercial readiness of this technology for boiler retrofit applications. Optimization of combustor operation in a safe and efficient mode, which was a major goal of the test program, was generally achieved. A key element in reaching this goal was achieving near 100% overall combustion efficiency. It should be emphasized that the ultimate success in this area required simultaneous improvement in combustor slagging, as well as proper process temperature control. The latter optimization was achieved by flexibility provided by combustor air cooling, and its effects on wall temperature control. Air cooling was decisive in achieving not only good combustion efficiency but also enhanced operation and control in other areas as will be discussed later. Attaining high levels of combustion efficiency with a wide variety of coals, under both oxidizing and reducing conditions, was therefore a major accomplishment of this project.

3.3.4.1.2. Thermal Performance

Actual combustor operating temperature was determined by three experimental observables. The calculated liner surface temperature (LINERTEM), degrees F, is an indicator of the combustor wall temperature. The combustor cooling air tube-hot-side temperature (THSTEMP), degrees F, is a directly measured variable which relates to the amount of heat being generated in and extracted from the combustor. Finally, the wall heat flux in Btu/hr/ft2, as calculated from the cooling air flow and delta-T (AIRFLUX), is an overall measure of the thermal interaction between the hot combustion gases and the combustor wall *.

Basically, process temperature variables are affected by the same independent variables, and to the same degree, as the combustion efficiency variables. This is to be expected, since good combustion is associated with high heat release.

Statistical analysis of the effects of SR1 (first stage inverse equivalence ratio) on the three process temperature variables showed that all temperature indicators increased as SR1 (first stage inverse equivalence ratio) increased, which is expected on the basis of improved combustion efficiency and/or heat release at stoichiometric and low excess air conditions. This effect is natu-

(*)-"Added thermal performance data is contained in the Proprietary Document".

rally coupled to the effect of SR1 (first stage inverse equivalence ratio) on combustion efficiency discussed above. The effect of SR1 (first stage inverse equivalence ratio) is nearly equal for LINERTEM (combustor wall temperature) and THSTEMP (air cooling tube temperature) but considerably less for AIRFLUX (wall heat transfer). This difference is probably due to the fact that AIRFLUX (wall heat transfer) is a measurement integrated over the entire combustor wall surface, including both the relatively cool mixing zone as well as the main flame or combustion zone. The other two measurements are localized to the downstream side of the combustor where the main flame zone is located. Peak flame temperatures strongly depend on SR1 (first stage inverse equivalence ratio) so that flame zone wall temperature measurements are expected to be highly influenced. Alternatively, integrated or averaged wall thermal effects would tend to smooth out this SR1 (first stage inverse equivalence ratio) effect due to combustor geometry effects on radiative heat transfer.

Analysis of combustor circumferential and axial wall thermocouple (TC) temperature measurements, made in early Phase III testing (March, 1988), showed that combustor heat release was essentially radially uniform but axially non-uniform. Excluding the exit nozzle, approximately the first one-third of the combustor served as an air/fuel/sorbent mixing zone and had a relatively low temperature, accounting for less than 30% of the heat release, while the rest of the combustor had higher temperature and heat release. It should be emphasized that these measurements reflect the smoothing effect of radiative heat transfer, so that the actual differences in combustor zone gas temperatures are probably much greater than those suggested by the wall TC measurements.

Combustion swirl air pressure (SWIRLPR) effects on LINERTEM (combustor wall temperature), THSTEMP (air cooling tube temperature), and AIRFLUX (wall heat transfer) were small*. Analysis of fuel heat input (HEATIN) effects indicated that all process temperatures increased as fuel heat input increased. This effect is attributable to increased combustion intensity at higher firing rates, resulting in higher heat release. The effect of HEATIN (total fuel heat input) is about the same for all three process temperature variables. The percent of fuel heat input due to coal (PCTPC) caused all process temperature indicators to increase as the percent of coal firing increased. This effect is no doubt coupled to improved combustion efficiency at higher PCTPC (percent

(*)"Added thermal performance data is contained in the Proprietary Document".

coal firing) as already noted. However, the relative effect is larger for process temperature than for combustion efficiency. This is probably attributable to enhanced wall heat transfer as PCTPC (percent coal firing) increases, owing to its higher flame emissivity vs. oil & natural gas (NG), and the effects of wall burning. The effect of PCTPC (percent coal firing) on the process temperature variables is essentially the same for LINERTEM (combustor wall temperature) and THSTEMP (air cooling tube temperature), but is somewhat higher for AIRFLUX (wall heat transfer). Figure 16 illustrates the effect of HEATIN (total fuel heat input) on wall flux for coal and oil firing.

In addition to operating temperature, thermal performance includes the combustor's efficiency as a burner or combustion chamber. This aspect has already been discussed in the preceding section. It also refers to the combustor as part of an overall system, namely, as a heat source for a package boiler. In this regard, effects of the combustor on process efficiency are important. Unlike water cooled combustors, the present air cooled unit recovers combustor enthalpy as regenerative air preheat, resulting in combustion air temperatures of between 300 and 500 F. Minimal water cooling to combustor components resulted in permanent heat losses of only 2 to 3% of total heat input. Thus recovery and direct utilization of combustor thermal energy is one significant advantage of the Coal Tech air cooling concept as compared to water cooled units. In the latter, water cooling energy is low grade heat that cannot be efficiently utilized in a power cycle.

Another advantage is the high level of flexibility that air cooling provides with regard to tailoring wall temperatures for efficient combustion and slagging. This permits operation over a wide range of conditions [e.g. SR1 (first stage inverse equivalence ratio), HEATIN (total fuel heat input)] for a variety of fuels which would not have been attainable with water cooling. This flexibility is a major plus in spin-off applications such as incineration and vitrification of environmentally active solids. Furthermore, the integrity of air cooling proved to be far superior to water cooling. Namely, even with partial failure of the first liner and perforation of some of the cooling tubes, the unit was still operable such that it could be shut down in a safe and gradual manner. This is important since with water cooling, a water tube failure of similar magnitude would have resulted in immediate shutdown and additional refractory damage owing to thermal shock, as well as possible system overpressure due to steam generation. Thus the potential for catastrophic cooling failure is much less with air than with water; an important consideration in a commercial process application.

Another important aspect of thermal performance is boiler derating, which is almost always required with retrofit of conventional PC burners to oil fired boilers. In the Clean Coal test program, with the combustor itself acting as a combustion zone, there was no evidence of flame impingement or boiler tube erosion/corrosion in the firebox, even with staged combustion. However, dry ash deposits did form on the boiler tubes. They were easily brushed off, and soot blowing and/or mechanical tube cleaning must be an integral part of the maintenance schedule for a commercial boiler using this combustor. There was not sufficient operating time to establish a tube cleaning maintenance schedule.

3.3.4.1.3. Slag Retention

In general, efficient operation of the slagging process requires rapid removal of the slag from the combustor. To achieve rapid slag flow requires a relatively low slag viscosity, generally below 80 poise (6) and possibly considerably lower (7). The viscosity of coal slags depends on composition and temperature. Highly acidic (high silica or alumina content) or highly basic (high iron, calcium, or magnesium oxide content) slags have high melting points or equivalently high relative viscosities. Numerous studies to measure the viscosity of coal slags and to correlate the viscosity to the slag composition have generally indicated that most coal slags will have the required viscosity for rapid slag flow in the temperature range of 2200 to 2700 F.

Owing to materials durability and other process constraints such as minimization of trace metal vaporization, it is usually not advisable to operate a slagging unit above about 2400 to 2500 F wall temperature, i.e. a key requirement is to provide a slag with a low enough viscosity to flow at about 2500 F in the combustor. In cases of highly refractory, acidic coal ash it is known that additions of a fluxing agent such as calcium oxide (CaO), usually introduced as limestone ($CaCO_3$), which quickly calcines to CaO, will produce a slag having decreased fluid temperature and viscosity. As noted in a previous section, initial testing on dry PC resulted in poor combustion efficiency and slagging due to the high viscosity of the slag. It was not until limestone

(LS) injection was routinely implemented that both combustion efficiency and slag retention/rejection were greatly improved.

Of the total solids injected into the combustor, which include coal, sorbent, and, on occasion, fly ash, various percentages of the non-combustible and/or non-volatile solids report as slag rejected by the combustor (SLAGREJ), as boiler deposits (BOILREJ), as scrubber solids (SCRUBREJ), and as atmospheric emissions. In a separate DOE SBIR project, aimed at evaluating the feasibility of converting utility fly ash to an environmentally inert slag, using the Coal Tech combustor, non-isokinetic particulate sampling of the atmospheric discharge, downstream of the scrubber, was performed. Results of these preliminary measurements showed that with coal firing (HEATIN, total fuel heat input, = 10.6 MMBtu/hr; PCTPC, percent coal firing, = 75%), plus combustor sorbent and fly ash injection (0 to 150 PPH), the solids discharged to atmosphere accounted for about 0.5 to 3% of the total solids input. This relatively small amount was neglected in the present bulk solids distribution analysis.

SLAGREJ (combustor tap slag rejection) is actually a lower limit on combustor slag retention since the measurement only occasionally included slag inventoried in the combustor and exit nozzle and basically was only the slag rejected through the tap. In our assessment, the slag depositing in the exit nozzle, and flowing onto the boiler front wall and hearth, should be considered as part of the combustor slag. This is especially important at high coal fire, when there can be large slag deposits in the exit nozzle, since this material can rarely backflow into the combustor and be rejected through the tap. However, in practice, this material was seldom included in the SLAGREJ (combustor tap slag rejection) measurement since retrieval of this slag required considerable effort and downtime. Thus, in the statistical analysis, this slag was included as BOILREJ (boiler solids retention) by default. (In recent post Clean Coal project tests, very high ash injection levels have been utilized to the point where inventoried slag/ash in the boiler is being recovered after each one day test. These recent results show that slag rejection is better than the levels reported for the Clean Coal project.)

An examination of factors leading to exit nozzle slag buildup is relevant to this section. Exit nozzle slagging can occur either as an upset in operation or as a normal adjunct to operation at moderate to high fire. Upset exit nozzle slag buildup/blockage has two requirements: (1) poor slagging in the combustor; and (2) a hot exit nozzle. The former requirement is usually accompanied by poor combustion as evidenced by "char balls" in the rejected slag. Poor slagging/combustion occurs when the ash/slag is not tacky or sticky so that injected solids tend not to be trapped on the combustor wall but are carried out to the exit nozzle. Since the exit nozzle is almost always hotter than the combustor, due to heavier insulation and the lack of active cooling, slagging occurs here with buildup and potential blockage, or with slag flow into the boiler.

Conditions in the combustor itself, which are not conducive to good slagging/combustion can arise if (1) the combustor is too cold; (2) the flame temperature is too low; or (3) the slag T-250 is too high. The first case occurs when the combustor is cooled too much or if the switch-over from oil to coal is premature. The second condition occurs when SR1 (first stage inverse equivalence ratio) is too low (< 0.6) or too high (>1.5 as per test FA4 of the DOE SBIR project), in which cases there is poor heat release to the combustor due to incomplete combustion or excessive flame cooling, respectively. Thus the interplay of these three factors can account for poor slagging/combustion as well as exit nozzle slag buildup. As noted above, there is almost always some nozzle slagging at moderate to high fire owing to direct flame impingement.

One final point on this subject is that overnight heating of the combustor, even at low levels, revealed that the refractory insulated exit nozzle, unlike the air cooled combustor, runs near-adiabatic, retaining much of its thermal storage. This resulted in initiation of slag formation in the exit nozzle, probably in addition to combustor wall slagging. This was not evident during the one-day parametric tests. Depending on the combustor's operating conditions, and on the geometry and contour of the exit nozzle, it is possible to either close a major part of the exit nozzle with slag, or to alternatively produce significant slag flow onto the boiler furnace floor. This complex issue was investigated in detail during the test effort, and procedures to prevent exit nozzle closing or slag flow into the boiler were developed.

It should be noted that the lower SLAGREJ (combustor tap slag rejection) measurements were obtained for non-optimized parametric operation. This kind of operation was necessary for scoping the effects of operating conditions on

SLAGREJ (combustor tap slag rejection), but does not reflect optimum performance. SCRUBREJ (scrubber solids rejection) was determined from the scrubber water discharge solids content and flow. BOILREJ (boiler solids retention) was obtained by difference, namely, BOILREJ (boiler solids retention)= 100-SCRUBREJ (scrubber solids rejection)-SLAGREJ (combustor tap slag rejection), and is therefore an upper limit. As percents of total permanent solids, the average measured value, standard deviation, plus high and low values for each of these variables is: SLAGREJ (combustor tap slag rejection): 45, 13, 80, 18; BOILREJ (boiler solids retention): 19, 14, 50, 0; SCRUBREJ (scrubber solids rejection): 36, 16, 66, 1.

Statistical analysis of the three bulk solids distribution variables showed that SLAGREJ (combustor tap slag rejection) and BOILREJ (boiler solids retention) increased as SR1 (first stage inverse equivalence ratio) increased, while SCRUBREJ (scrubber solids rejection) decreased. The considerable positive effect of high SR1 (first stage inverse equivalence ratio) on SLAGREJ (combustor tap slag rejection) is probably related to the already discussed enhancement of combustion efficiency and process temperature, which is expected to result in better solids melting and slagging. In a similar way, high BOILREJ (boiler solids retention) is also associated with high SR1 (first stage inverse equivalence ratio). As noted above, a substantial fraction of BOILREJ (boiler solids retention) could be conceptually considered as part of SLAGREJ (combustor tap slag rejection). Thus, it is reasonable that SR1 (first stage inverse equivalence ratio) should produce the same qualitative effect on both variables. In addition, it is possible that with improved combustor melting, the material carried out of the combustor is partly melted and thus sticks easier to boiler surfaces than dry ash. The effect of increasing SR1 (first stage inverse equivalence ratio) on SCRUBREJ (scrubber solids rejection) is negative. This is expected due to mass balance considerations, i.e. if more solids are retained by the combustor/boiler at high SR1 (first stage inverse equivalence ratio) then less will be in the scrubber.

Combustion swirl air pressure (SWIRLPR) effects on SLAGREJ (combustor tap slag rejection), BOILREJ (boiler solids retention), and SCRUBREJ (scrubber solids rejection) indicated that SLAGREJ (combustor tap slag rejection) increased, but BOILREJ (boiler solids retention) and SCRUBREJ (scrubber solids rejection) decreased, as SWIRLPR (swirl air pressure) increased. Improved slag rejection at higher SWIRLPR (swirl air pressure) is likely due to enhanced cyclonic action of the swirl air. Although the modeled strength of this effect on SLAGREJ (combustor tap slag rejection) is relatively small, the large negative influence it has on BOILREJ (boiler solids retention) and SCRUBREJ (scrubber solids rejection) can only be attributable to enhanced combustor slag retention at high swirl pressure. The relatively small strength of SWIRLPR (swirl air pressure) in the SLAGREJ (combustor tap slag rejection) model may reflect a non-linear threshold effect. In any case, the effect of SWIRLPR (swirl air pressure) on total combustor slag retention is believed to be of more significance than indicated by the SLAGREJ (combustor tap slag rejection) modeling results.

Fuel heat input (HEATIN) effects on SLAGREJ (combustor tap slag rejection), BOILREJ (boiler solids retention), and SCRUBREJ (scrubber solids rejection) indicated that all solid stream contents, as a percent of total solids, increased as fuel heat input increased. There appears to be a relatively small improvement in SLAGREJ (combustor tap slag rejection) as HEATIN (total fuel heat input) increases, conceptually in line with improved combustion intensity and melting as discussed previously. However, both BOILREJ (boiler solids retention) and SCRUBREJ (scrubber solids rejection) are also increased as the total fuel heat input goes up. Here we have a contradiction since mass balance considerations require that the sign dependencies of the dependent variables cannot all be the same.

Even though combustion efficiency/process temperature increase as HEATIN (total fuel heat input) increases, and you might therefore expect better ash melting and slag rejection, visual observations of the combustor exit nozzle have indicated that at higher HEATIN (total fuel heat input) a significant portion of the combustion takes place in the exit nozzle, particularly with staged combustion. In this situation the flame is not entirely confined within the combustor proper. Thus experimental observations suggest that the rate of combustor slag rejection increases at higher firing rates, but that slag retention, as percent of total solids input, probably has a negative dependence on HEATIN (total fuel heat input) when PCTPC (percent coal firing) is large, i.e. total solids loading to the combustor is high. This interpretation is at odds with the statistical result but is justified to some extent by the huge positive effects of HEATIN (total fuel heat input) on BOILREJ (boiler solids retention) and SCRUBREJ (scrubber solids rejection), and by the PCTPC (percent coal firing) effects discussed below.

The percent of fuel heat input due to coal (PCTPC) effects on SLAGREJ (combustor tap slag rejection), BOILREJ (boiler solids retention), and SCRUBREJ (scrubber solids rejection) indicated that both SLAGREJ (combustor tap slag rejection) and BOILREJ (boiler solids retention) are reduced, while SCRUBREJ (scrubber solids rejection) is increased, as the percent of coal firing increased. This result is in line with the above discussion where it was generally concluded that higher solids loading lead to decreased SLAGREJ (combustor tap slag rejection) in spite of better combustion efficiency and higher process temperatures. As PCTPC (percent coal firing) increases, we have higher solids input, with the associated negative effect on SLAGREJ (combustor tap slag rejection). It is important to emphasize that the positive effect of increased PCTPC (percent coal firing) on SCRUBREJ (scrubber solids rejection) is due to increased scrubber solids loading as ash, not as unburned coal. In section 3.3.4.1.1. it was determined that increased PCTPC (percent coal firing) lead to improved combustion efficiencies. Thus, the positive effect of increased PCTPC (percent coal firing) on scrubber solids cannot be due to poorer combustion efficiency and, hence, more unburned coal carryover to the scrubber. Instead, it must be due to more ash and other non-combustible carryover.

To summarize, SLAGREJ (combustor tap slag rejection) appears to be positively influenced by conditions which enhance ash melting via improvements in combustion efficiency/process temperature, and by reduced slag viscosity. But it is negatively influenced by conditions which increase total mass or solids input. As solids input increases, the rate of slag rejection also increases but SLAGREJ (combustor tap slag rejection), as a percent of total solids, goes down while the amount of solids in both the boiler and scrubber goes up. Part of this result is due to the narrow definition of SLAGREJ (combustor tap slag rejection) imposed by the experimental method. In addition, solids not captured in the combustor tend to end up in the scrubber rather than layout in the boiler as the total solids input increases. As SWIRLPR (swirl air pressure) increases there is better SLAGREJ (combustor tap slag rejection) and less boiler and scrubber solids.

In general, these results, plus test observations, support the view that the present combustor volume is underutilized, or that the combustor is too short to adequately retain and reject slag at high mass/thermal input. Reconfiguration of the solids injection geometry under the DOE ash vitrification project has recently resulted in a significant increase in combustor slag rejection owing to improved utilization of the combustor's air/fuel/solids mixing zone. In addition, the flame pulsations in the ash project also would be expected to have an adverse impact on slag retention. It is, therefore, believed that solids injection and combustor geometry design changes, as well as improved flame uniformity can result in combustor retention and rejection of slag currently depositing in the exit nozzle and on the boiler front wall.

3.3.4.1.4. Refractory Performance

In this section there are three areas of interest: (1) the combustor liner, (2) the exit nozzle, and (3) the combustor/boiler interface.

Owing to the highly refractory nature of the coals employed, plus the apparently cross-coupled interaction of combustion efficiency and slagging, all Phase III tests, from the fourth through the seventh, utilized limestone injection and/or very hot combustor liner wall temperatures to achieve the combustion efficiency and slagging test goals. This was not a desired mode of continuous operation since a previous literature survey indicated that the combustor refractory liner being used was not compatible with these operating conditions. Chemical analysis of slag samples obtained during this testing period bore out the literature-derived prediction by showing evidence of slag/liner chemical interaction. Eventually, visual combustor liner inspection, conducted after excessive combustor temperature readings were recorded during the seventh test, revealed partial liner failure due to thermal and chemical causes. It must be emphasized that the ultimate cause of liner failure was the refractory nature of the coal ash, requiring extreme conditions in the combustor to achieve proper combustion and slag flow.

Working within the operational constraints imposed by the available coals, a new liner material was selected and installed. In addition, a modified combustor diagnostic arrangement was devised and implemented to allow combustor control to be directly related to its thermal status. This control concept was implemented with the new liner to prevent thermal shock and/or overheating as well as to minimize slag corrosion. The new liner and control strategy were implemented during tests 8 and 9 in May of 1988, and have proved to be very satisfactory. Between 700 and 750 of the nearly 900 hours of combustor operation, since the start of the Clean Coal tests, have been performed with the new liner, without having to replace it.

This second combustor liner is contains chrome oxide refractory. Thus the presence of excess chrome as Cr2O3 (XSCHROM, as percent of slag sample weight) in the coal ash slag is an indication of liner loss. As percents, the average measured value, standard deviation, plus high and low values for XSCHROM (refractory chrome in slag) are: 0.83, 0.59, 2.23, 0.01.

The effect of SR1 (first stage inverse equivalence ratio) on XSCHROM (refractory chrome in slag) showed that as SR1 (first stage inverse equivalence ratio) increased there was less liner degradation. From the preceding discussions, we have determined that high SR1 (first stage inverse equivalence ratio) yields high heat release and process temperature, which are generally known to be unfavorable to refractory life (23). However, SR1 (first stage inverse equivalence ratio) also affects the nature of the gaseous environment in terms of oxidizing vs. reducing conditions. Articles in the literature (e.g. 24) indicate that reducing atmospheres usually promote refractory corrosion by slags. Thus, it appears in the present case that the negative effects of reducing atmosphere on refractory life outweigh the benefits of reduced gas temperature. Put another way, the positive effects of an oxidizing atmosphere on refractory life at high SR1 (first stage inverse equivalence ratio) outweigh the negative effects of higher temperature.

Combustion swirl air pressure (SWIRLPR) effects on XSCHROM (refractory chrome in slag) indicated that XSCHROM (refractory chrome in slag) decreased as SWIRLPR (swirl air pressure) increased. As in several of the above discussions, this effect may be attributed to increased liner/slag cooling at high SWIRLPR (swirl air pressure), which results in a kinetic rate reduction of slag /liner chemical interaction. The fuel heat input (HEATIN) effects on XSCHROM (refractory chrome in slag) indicated that liner degradation, as measured by XSCHROM (refractory chrome in slag), increased significantly as HEATIN (total fuel heat input) increased. This effect is likely due to increased process temperature at higher heat input, which accelerates the kinetics of slag corrosion of the liner. The percent of fuel heat input due to coal (PCTPC) effect on XSCHROM (refractory chrome in slag) indicated that XSCHROM (refractory chrome in slag) is greatly increased as the percent of coal firing is increased. As with HEATIN (total fuel heat input), increases in PCTPC (percent coal firing) lead to increased process temperature, with its associated negative effect on liner life. In addition, as PCTPC (percent coal firing) is raised, the amount of coal ash slag also increases, thereby providing greater potential for corrosive interaction between the slag and the liner.

To summarize, degradation of the second combustor refractory liner, as indicated by excess chrome in the rejected slag, is primarily caused by the presence of coal ash slag. This is undoubtedly a chemical corrosion effect which increases kinetically as process temperature increases, a HEATIN (total fuel heat input) effect. Although this coal ash effect is largely immune to effects of ash composition, analysis indicated that higher iron content slags somewhat accelerated the negative effect of coal ash on liner wear. Alternatively, the presence of basic sorbent material had no discernible impact on liner loss. Increased SWIRLPR (swirl air pressure) partially offsets slag corrosion by cooling the liner/slag surface. In addition, liner wear appears to be more severe under reducing vs. oxidizing conditions, a SR1 (first stage inverse equivalence ratio) effect, in line with the literature.

On the surface, the liner degradation results appear unfavorable to continuous operation at high coal firing rates, dictating frequent liner replacement, with resultant high cost due not only to labor and materials for repair but also due to down time. However, toward the end of the Phase III testing, an operating technique was developed to replenish the combustor walls with slag by precisely controlling the slag viscosity via coal ash/sorbent blending. This technique requires careful monitoring of process temperature as well as timely application in order to be effective. Thus, the adverse effects of high coal firing rate on liner life can be neutralized without derating the combustor. Development of this technique was a major accomplishment of the present project

Although the above technique was developed under manual combustor operation, it is believed that its full potential can only be achieved with computer process control. Economic factors related to the degree of operator supervision in a commercial use, also dictates an computer control procedure.

The second major operational difficulty encountered during the Phase III testing was refractory failure in the exit nozzle section, which connects the combustor to the boiler. In September of 1988, during test 14, hot combustion gases vented out of the boiler through small openings in the boiler access door. Post test inspection revealed extensive damage to the boiler front wall. However, the refractory in the exit nozzle was not damaged, and it indeed survived the entire 900 hours of operation. Detailed mechanical and heat transfer analysis led to the conclusion that the failure occurred mainly due to inadequate insulation at the nozzle/boiler interface. A different installation design, using different refractory materials, was implemented and has performed satisfactorily.

A third area of difficulty was overheating at the combustor/exit nozzle thermal interface. While temporary solutions controlled the problem initially, it was decided in the Summer of 1989 to design and install a modified interface refractory the next time the problem reappeared. This did not occur until February 1990, after about 250 to 300 hours of operation. Since the combustor was being used for testing under other projects, the modification was implemented in two steps in March and June 1990. In recent tests, the modification has performed as per design. Nevertheless, thermal data show that a modest degree of additional cooling is required at the boiler front wall in order to allow round-the-clock operation at full thermal combustor load.

3.3.4.2. Environmental Performance

The main impetus for the Clean Coal I project was the demonstration of the Coal Tech combustor for environmental control of NOx and SO2 as well as particulates during combustion of PC. Within the framework of operational and materials constraints discussed above, significant progress was made in the environmental control area. It should also be added that some portion of the effort made in this area was related to testing for compliance with the various air, water, and solid waste stream regulations.

The major objective of the Environmental Monitoring Plan (EMP) generated in Phase I was to provide a detailed description of Coal Tech's environmental compliance and supplemental monitoring tasks. These, in turn, served to provide operational and performance data aimed at ensuring that the demonstration project was not in violation of the applicable environmental standards and was otherwise not detrimental to human health or the environment. However, since one of the technical objectives of this project was to establish performance characteristics of the combustor, it was necessary to operate the combustor over a range of parametric test variables, some of which fell outside the range of acceptable environmental performance, if only for brief periods. With the exception of these short test periods, the combustor was operated within environmental standards. The compliance performance results fall into three categories: Air Emission Monitoring, Waste Water Effluent Monitoring, and Solid Waste Monitoring.

Air quality compliance monitoring requirements were specified by the Pennsylvania Department of Environmental Resources (PA DER), Bureau of Air Quality Control, viz. SO2 limit of 4 lb/MMBtu, particulate limit of 0.4 lb/MMBtu, and opacity limit of 20%. Water quality compliance requirements were specified by the Williamsport Sanitary Authority, in concurrence with the PA DER, Bureau of Water Quality Control. As per the Authority, the following parameters were monitored: total water discharged into the sanitary system; total suspended solids (TSS) in the discharged water; the heavy metals cadmium, copper, and selenium suspended in the water; the water discharge temperature and pH. The discharge limits are 0.5 lb of Cd/day, 1.0 lb of Cu/day, 0.1 lb of Se/day, maximum water temperature of 135 F, and $5 < pH < 9$.

The solid waste compliance monitoring requirements were specified by the Resource Conservation and Recovery Act (RCRA), and administered by the PA DER, Bureau of Solid Waste Management. The pertinent substances that fell under the RCRA are the slag nitrogen and sulfur reactivity to form gas phase cyanide and sulfide compounds, and the leaching potential of heavy metals and cyanide in the slag; the reactivity limits are 250 mg/kg for cyanide and 500 mg/kg for sulfide while the heavy metal limits are found in EPA-SW-846, 2nd ed., section 2.1.4. The evaluation of compliance was to be determined by preparation of a Module 1 document in which the characteristics of the solid waste product are documented, using laboratory test results as a basis, to obtain the necessary landfill permits.

In practice, once operating conditions were stabilized, time resolved boiler outlet and stack gas, scrubber discharge water, and rejected slag samples were obtained at varying intervals. The boiler outlet gas samples were analyzed on site via continuous sampling to a bank of instruments giving direct readings on oxygen, carbon dioxide, carbon monoxide, nitrogen oxides, unburned hydrocarbons, and sulfur dioxide. Periodically, this system was switched over to monitor the scrubber stack emissions to atmosphere. It should be noted, however, that since one of the main goals of the project was to evaluate combustor environmental performance, the bulk of the gas sampling focused on the boiler outlet upstream of the scrubber. In addition, combustion conditions were routinely checked by oxygen and combustible measurements in the boiler outlet provided by a Teledyne (and later an Enerac) portable analyzer.

Although the combustor is mostly air cooled, some internal members are water cooled. With coal firing, this cooling water was then used as the slag quench water and the scrubber water. The slag quench tank (SQT) and scrubber water streams were then discharged to the sanitary drains at the test site. The scrubber water discharge was routinely sampled and analyzed for compliance with the thermal, suspended solids, and heavy metal trace elements standards and regulations of the Williamsport Sanitary Authority. Scrubber water samples, taken in plastic bottles, and slag samples were collected at definite time intervals, nominally every half hour. Selected water and slag samples were subsequently sent to a commercial laboratory for chemical analysis.

In the following subsections, the environmental monitoring results for the various waste streams are presented. These results are reported in more detail in the Annual Environmental Reports.

3.3.4.2.1. NOx Control

There are two sources of NOx in coal combustion, namely fuel-bound-nitrogen (FBN) and molecular nitrogen (N2) in the combustion air. It is well known (e.g. 8) that staged combustion with a fuel rich first stage, followed by gas cooling for about 0.5 to 1 second duration, prior to introduction of the final combustion air, usually results in significant overall total NOx reduction.

In general, FBN conversion to NOx is relatively insensitive to temperature while N2 conversion is very temperature dependent, being the primary source of thermal NOx. Thermal NOx is controlled by the Zeldovich mechanism which at high temperature, and under excess air conditions, is dominated by the reaction (9)

$$N_2 + O = NO + N$$

Ordinarily, thermal NOx is supressed by reducing the combustion temperature to below about 3000 F by delaying second stage air mixing, allowing some combustion gas heat loss to surroundings, or by thermal quenching via recirculated flue gas.

With fuel-rich combustion the FBN is found in the gas as HCN, NH_3, and NO, (e.g. 10). The key to reducing NOx from FBN is to convert the above species to N_2 prior to the introduction of the final combustion air; otherwise they will oxidize to NOx. Calculations performed in (5) suggest that significant reduction of the fuel-NOx intermediate species can occur in around 10 to 100 msec at an inverse equivalence ratio of 0.7 in the temperature range of 2500 to 3200 F.

One of the main goals of the Clean Coal project was to reduce the atmospheric emissions of oxides of nitrogen (NOx) to 100 ppm or less. The technique used to achieve this was staged combustion, with a fuel rich first stage to convert fuel-bound-nitrogen (FBN) to molecular nitrogen, followed by a fuel lean second stage to complete fuel burnout, but without generating excessive thermal NOx. In the present project, the combustor itself was the first stage, while second stage or tertiary air was injected into the boiler firebox surrounding the combustor gas exit nozzle. The effects of this control strategy were determined by measuring NOx (ppmv, dry basis) at the boiler outlet. For comparison, the measured NOx levels were converted to equivalent values at 3% oxygen or 15% excess air (NORMNOX). In addition, a small further reduction in NOx was obtained due to the action of the wet particulate scrubber. This effect contributed an additional 5 to 10% reduction in NOx emitted to atmosphere. As ppmv, dry basis, and normalized to 3% O_2, the average measured value, standard deviation, plus high and low values for NORMNOX (normalized NOx in the boiler outlet) are: 355, 148, 769, 81. It should be noted that the lowest value corresponds to oil-only firing and that the minimum with coal firing was 184 ppm. The minimum coal fired NOx level in the scrubber stack was 160 ppm.

The results of the statistical analysis showed that as SR1 (first stage inverse equivalence ratio) increased the level of NOx in the boiler outlet increased. This relationship has been demonstrated many times by various groups, and is due to increased oxidation of FBN to NOx at higher SR1 (first stage inverse Equivalence ratio). For high coal firing as percent of total heat input, namely PCTPC > 70%, the degree of control of NOx at the boiler outlet, obtained by staged combustion, is shown in figure 17. As can be seen, a minimum in NOx occurs at SR1 (first stage inverse equivalence ratio) around 0.75. Globally, measured NOx levels have been reduced from an unstaged value of 769 ppm to below 200 ppm, a reduction of more than 75%.

Combustion swirl air pressure (SWIRLPR) effects on NORMNOX (normalized NOx in the boiler outlet) indicated that NORMNOX (normalized NOx in the boiler outlet) increased as SWIRLPR (swirl air pressure) increased. As SWIRLPR (swirl air pressure) increases, we have seen that slag combustion efficiency and process temperature decrease while combustor slag rejection increases. The former effect is due to higher liner/slag surface cooling, while the latter result is caused by higher cyclonic action. With regard to NOx control via staging, it is important to release the FBN in the fuel rich first stage. Otherwise, FBN carried over to the fuel lean second stage will be easily converted to NOx. In the present instance, the twin effects of increasing SWIRLPR (swirl air pressure) on FBN release are at cross-purposes. Decreased combustion efficiency and process temperature are expected to result in lower FBN release, while higher combustor solids retention is expected to improve FBN release. Since the overall effect of increased SWIRLPR (swirl air pressure) is to increase NOx emissions, the solids retention effect must be subordinate to the combustion efficiency and temperature effects, i.e. there is poorer release of FBN in the combustor, resulting in more NOx formation on the second stage.

The fuel heat input (HEATIN) effect on NORMNOX (normalized NOx in the boiler outlet) indicated that NORMNOX (normalized NOx in the boiler outlet) decreased as HEATIN (total fuel heat input) increased. This effect is likely due to increased slag combustion efficiency and process temperature at higher heat input, which accelerated the release of FBN in the combustor. The percent of fuel heat input due to coal (PCTPC) effect on NORMNOX (normalized NOx in the boiler outlet) indicated that NORMNOX (normalized NOx in the boiler outlet) increased as the percent of coal firing increased. As PCTPC (percent coal firing) increases the total amount of FBN increases. It is generally agreed that fuel-NOx is highly dependent on the amount of fuel nitrogen or FBN present in the system. For the eight coals tested, fuel nitrogen averaged 1.27% by weight, with a range of 1.12 to 1.83%. This narrow range of FBN content was tested in models of NORMNOX (normalized NOx in the boiler outlet) but had a relatively low tolerance of PCTPC (percent coal firing), which was a more important variable.

In review, the control of nitrogen oxide emissions during the Clean Coal I project was accomplished by rich/lean staged combustion. With SR1 (first stage inverse equivalence ratio) around 0.75, NOx levels at the boiler outlet were reduced by > 75% from the unstaged, excess air (XSA) values. This corresponds to about 184 ppm, normalized to 3% oxygen, or 69 ppm at gas turbine outlet conditions, namely 15% oxygen. Additional NOx reductions of 5 to 10 % were obtained in the scrubber outlet discharging to atmosphere. As SR1 (first stage inverse equivalence ratio) and PCTPC (percent coal firing) increased, NOx increased as expected. As HEATIN (total fuel heat input) increased, NOx decreased due to better FBN release on the first stage, owing to higher combustion efficiency and process temperature. This resulted in lower overall NOx with staged combustion. As SWIRLPR (swirl air pressure) increased, NOx increased due to the liner/slag cooling effect quenching FBN release.

Further reductions in NOx emissions are no doubt possible with improved combustor volume utilization. This would result in longer first stage residence times and thus enhance FBN release and conversion to molecular nitrogen. In addition, the orientation of tertiary air injection is known to be another critical factor in overall NOx control. This parameter was not evaluated in the Clean Coal I project due to limited resources and the demands of other project objectives.

3.3.4.2.2. SO2 Control

One of the most significant results to emerge from recent work on cyclone coal combustors is the discovery of reductions in sulfur oxide emissions with sorbent injection into the combustor. However, fire-side or "in situ" sulfur capture and retention by sorbent injection is complicated, involving several heterogeneous processes.

In general (11), the first step in the sulfur capture process with limestone (LS) is calcination, where $CaCO_3$ is converted to CaO. This reaction is very fast and is essentially complete at about 1300 F for atmospheric combustion of fossil fuels. A similar reaction also occurs with calcium hydrate where H_2O instead of CO_2 is driven off. A porous CaO structure is left after calcination and, with excess O_2, sulfur capture via gaseous diffusion through the pore structure leads to the formation of $CaSO_4$. Eventually, a layer of $CaSO_4$ encapsulates the particle and hinders the reaction. Kinetic modeling results (12) suggest that for 10 to 50 micron LS particles significant sulfur capture can occur if the particles are suspended in the gas stream for about 100 msec.

An alternate or complementary capture mechanism is the reaction of CaO with H_2S to produce CaS (13), which has about the same kinetics as the sulfate reaction. This pathway would be available only at very fuel-rich conditions, namely inverse equivalence ratio < 0.7. In either case, total sulfur capture times depend mainly on sorbent particle size and porosity as well as the temperature and the partial pressures of the gaseous species. Also, depending on collection efficiency, the bulk of the sulfur-bearing sorbent may be expected to report to the slag.

Under equilibrium conditions in oxidizing atmospheres, the $CaSO_4$ moves toward dissociation above about 2200 F (14). This results in the possibility of sorbent desulfurization if the sulfur-bearing sorbent is allowed to reside in the hot combustion environment for an extended time period. The objective then is to remove it with the slag in the combustor before it can re-evolve gaseous sulfur compounds.

For oxidizing conditions in the combustor, an experimental study (15) suggested that super-equilibrium levels of SO_2 can be retained in slag melts for periods up to 20 minutes. This result has been confirmed on an order-of magnitude basis by a more recent study and forms the basis of Coal Tech's unique sulfur removal concept.

During combustion the coal sulfur was partitioned among four streams: sulfur retained and rejected with the slag (ACTSLGS), sulfur deposited in the boiler (BOILSULF), sulfur found in the scrubber discharge (PCTSSCRB), in solution and/or as part of the suspended solids, and sulfur emitted to atmosphere

(ATMSULF). In practice, BOILSULF (sulfur retained in the boiler) was not measured directly but was determined by subtracting ACTSLGS (slag sulfur content) from the measured reduction in SO2 (as percent of total sulfur) in the boiler outlet or SREDBO. In a similar way ATMSULF (sulfur emission to atmosphere) was taken to be 100 - SREDFS (sulfur reduction in the scrubber stack), where SREDFS (sulfur reduction in the scrubber stack) is the measured reduction in SO2 in the scrubber fan stack. Essentially all of the sulfur emitted to atmosphere will be SO2. Baseline measurements with no environmental control performed in the Clean Coal and previous projects have confirmed this. Although no direct measurements have been made by us, boiler studies by others suggest that up to several % of the SOx may be SO3 on the basis of equilibrium.

As percent of total sulfur, the average measured value for all the tests, the standard deviation for all the tests, plus high and low values for each of the directly measured variables in all the tests was:

-ACTSLGS (sulfur content in the slag): 1.90, 2.54, 11.15, 0.16;

-SREDBO (sulfur reduction in the boiler outlet): 15, 17, 82, 0;

-PCTSSCRB (sulfur content in the scrubber water & solids): 25, 18, 100, 1;

-SREDFS (sulfur reduction at the scrubber stack): 35, 12, 57, 9.

It should be noted that the maximum value of sulfur reduction in the boiler outlet (SREDBO) of 82% was obtained with boiler sorbent injection. The maximum value obtained with combustor sorbent injection was 58%. The above average values yield a normalized sulfur balance of 2% in the slag (ACTSLGS), 12% as boiler deposits (BOILSULF), 24% in the scrubber discharge (PCTSSCRB), and 62% emitted to atmosphere (ATMSULF), for a total of 100%, averaged over all the sorbent injection tests.

For the four sulfur variables ACTSLGS (slag sulfur content), BOILSULF (sulfur retained in the boiler), PCTSSCRB (scrubber sulfur content), and ATMSULF (sulfur emission to atmosphere), statistical analysis of the effects of SR1 (first stage inverse equivalence ratio) indicated that overall system sulfur retention decreased as SR1 (first stage inverse equivalence ratio) increased, while emission to atmosphere increased. It is likely that these effects, taken as a whole, are due to increased sorbent deadburning at high SR1 (first stage inverse equivalence ratio), which has been shown to raise combustor temperature. On an individual basis, however, the different degrees of dependency of the sulfur variables suggest that other changes in operating conditions, due to variation in SR1 (first stage inverse equivalence ratio), must be at work.

The slag sulfur content is the sulfur variable most susceptible to SR1 (first stage inverse equivalence ratio) variation, as shown in figure 18. This profound dependency suggests that at low SR1 (first stage inverse equivalence ratio), around 0.6 to 0.7, local conditions of temperature and gas composition are optimized for in-situ sulfur capture by sorbent with subsequent rejection in the slag. This aspect had been studied in detail by Coal Tech in previous work (25) where it was found that first stage stoichiometry was a critical parameter in the sulfur capture process. For comparison, data obtained from Reference 25 are presented in figure 19, showing a remarkable qualitative similarity to figure 18.

It should be noted that good slag sulfur retention/rejection is also associated with rapid slag removal from the combustor, in order to minimize slag desulfurization. As discussed in section 3.3.4.1.3 good slag rejection depends most significantly upon high SR1 (first stage inverse equivalence ratio). This result contrasts with the slag sulfur results, which show maximum slag sulfur at low SR1 (first stage inverse equivalence ratio). This implies that local combustor thermal/chemical environment is more important than bulk slag removal in achieving good slag sulfur retention. In any case, it is probably necessary to optimize both ACTSLGS (slag sulfur content) and SLAGREJ (combustor tap slag rejection) by manipulation of operating parameters other than SR1 (first stage inverse equivalence ratio) and/or by incorporating combustor design changes as discussed in section 3.3.4.3.

It should also be noted that the Coal Tech concept of rejecting the captured sulfur with the liquid slag has been conceptually verified by slag chemical analysis wherein the presence of significant amounts of sulfur occurs only if CaO from sorbent is also present. Analysis of combustor slag samples from test 22 yielded values of 20 to 32% of the total sulfur present in the ash along with high CaO levels. While the maximum value obtained from rejected slags was 11%. These higher amounts of sulfur retention are extremely encouraging and clearly give impetus to the Coal Tech concept of "in situ" sulfur capture by injected sorbent; the requisite corollary being rapid rejection and removal with the slag.

Figure 20 illustrates the relative effects of SR1 (first stage inverse equivalence ratio) on BOILSULF (sulfur retained in the boiler), PCTSSCRB (scrubber sulfur content), and ATMSULF (sulfur emission to atmosphere). Both boiler and scrubber sulfur contents decrease as SR1 (first stage inverse equivalence ratio) increases. This is partly due to sorbent deadburning, as noted above. In the case of PCTSSCRB (scrubber sulfur content), however, the reduction at higher SR1 (first stage inverse equivalence ratio) is undoubtedly coupled to the fact that total scrubber solids (SCRUBREJ) also decrease as SR1 (first stage inverse equivalence ratio) increases, as discussed in section 3.3.4.1.3. In addition, it was shown in section 3.3.4.1.1 that increasing SR1 (first stage inverse equivalence ratio) lead to improved combustion efficiency and, thus, less unburned fuel. Since PCTSSCRB (scrubber sulfur content) increased as SR1 (first stage inverse equivalence ratio) decreased, it is fair to attribute part of the increase in scrubber sulfur to the presence of some unburned coal. Finally, more sulfur is emitted to atmosphere as the sorbent becomes less effective in capturing sulfur due to the deadburning effect of high SR1 (first stage inverse equivalence ratio). However, the correspondence is not proportional since the scrubber can remove some sulfur with or without sorbent.

Combustion air swirl pressure (SWIRLPR) effects on ACTSLGS (slag sulfur content) indicated that slag sulfur content greatly increased as air swirl pressure increased. The high positive effect of increasing SWIRLPR (swirl air pressure) on slag sulfur content may be due to a number of factors. First, it has been shown that high SWIRLPR (swirl air pressure) leads to increased liner/slag surface cooling. This could be important for slag sulfur retention by (a) helping to reduce sorbent deadburning, and (b) minimizing temperature dependent slag desulfurization. Secondly, it has also been shown that high swirl air pressure improves slag rejection. This would result in more of the sulfated sorbent being thrown to the wall and embedded in the slag. The other sulfur variables show only a weak dependence on SWIRLPR (swirl air pressure). These effects are believed to be indirect and coupled to the SWIRLPR (swirl air pressure) effects on combustion efficiency and process temperature, with their attendant impact on fuel sulfur release, and on bulk solids distribution.

The fuel heat input (HEATIN) effects on ACTSLGS (slag sulfur content), BOILSULF (sulfur retained in the boiler), PCTSSCRB (scrubber sulfur content), and ATMSULF (sulfur emission to atmosphere) indicated that ACTSLGS (slag sulfur content) and PCTSSCRB (scrubber sulfur content) increased when HEATIN (total fuel heat input) increased, while BOILSULF (sulfur retained in the boiler) and ATMSULF (sulfur emission to atmosphere) decreased as HEATIN (total fuel heat input) increased. The positive effect of higher fuel heat input on slag sulfur retention/rejection may be due to enhanced combustion efficiency/process temperature resulting in better coal sulfur release. Alternatively, the higher combustion intensity may promote more vigorous mixing of the air/fuel/sorbent. In addition, the rate of slag rejection, but probably not SLAGREJ (combustor tap slag rejection) as percent of total solids, also increases as HEATIN (total fuel heat input) increases, thus minimizing slag residence time and desulfurization in the combustor.

As HEATIN (total fuel heat input) increases there is a slight decrease in boiler sulfur. This may be due to unfavorably high flame temperatures and/or more sorbent deadburning in the second stage, which generally burns more intensely at higher HEATIN (total fuel heat input). The significant increase in scrubber sulfur with increasing heat input is no doubt largely related to increased bulk solids in the scrubber as discussed previously. In addition, higher fuel rates may provide a higher and more favorable sulfur/sorbent reaction temperature in the boiler, downstream of the second stage flame zone, and in the boiler outlet. For example, the boiler outlet stack temperature was found to increase most at higher fuel heat inputs. Finally, as HEATIN (total fuel heat input) increases, there is a fair decrease in atmospheric SO2. This drop is mainly due to improved scrubber sulfur retention at high HEATIN (total fuel heat input).

The percent coal firing (PCTPC) effect on the sulfur variables was analyzed statistically. The extremely large positive effects of higher PCTPC (percent coal firing) on slag, boiler, and scrubber sulfur contents are shown in figure 21. This situation arises since higher coal contributions to total heat input are expected to kinetically increase the sulfur/sorbent reaction rate by increasing the partial pressure of SO2. It has been variously shown (e.g. 26) that the overall reaction rate of sorbent and SO2 is proportional to the concentration of SO2, usually expressed in atmospheres. In the present analysis, this effect is believed to be mainly important for improved slag and boiler sulfur retention, while the enhancement of scrubber sulfur is mainly attributable to increased scrubber solids at high PCTPC (percent coal firing). A possible corollary effect is that at higher PCTPC (percent coal firing) there may be more condensation of SO_2 vapors on particles going to the scrubber. As with fuel-nitrogen, efforts to explicitly include coal-sulfur content in the models were not successful owing to high correlation with PCTPC (percent coal firing). With increasing PCTPC (percent coal firing), there is a moderate decrease in atmospheric sulfur, as expected from an overall sulfur balance.

It is important to note that the positive effects of increased PCTPC (percent coal firing) on slag and boiler sulfur retention are not due to lack of complete release of sulfur from the coal. That is, the sulfur measured in the slag and boiler solids is chemically associated with the presence of sorbent, and is not associated with the presence of unburned coal. With no combustor sorbent injection, slag and boiler solids sulfur contents are always below the level of detectability.

Scrubber sulfur content may be slightly associated with the presence of unburned coal. With no sorbent injection and TSSCEFF (scrubber carbon combustion efficiency) > 95%, PCTSSCRB (scrubber sulfur content) averaged 14% of total sulfur. Of this, the vast majority is due to the washing out of SO_2 (i.e. $SO_2 + 0.5\ O_2 + H_2O = H_2SO_4$), as indicated by the high dissolved sulfur content, accounting for 94% of PCTSSCRB (scrubber sulfur content), and the low pH of 4. Thus, with about 6% of PCTSSCRB (scrubber sulfur content) in the scrubber solids, presumably as unburned coal, less than 1% of the total sulfur can be associated with unburned coal under these conditions. In the relatively few cases where TSSCEFF (scrubber carbon combustion efficiency) < 95%, again with no sorbent injection, PCTSSCRB (scrubber sulfur content) averaged 26%, of which 77% is dissolved and 23% is in the suspended solids. Thus for these cases of low TSSCEFF (scrubber carbon combustion efficiency), only about 6% of the total sulfur can be associated with unburned coal. This would be the worst case.

With combustor sorbent injection, PCTSSCRB (scrubber sulfur content) averaged 24% while TSSCEFF (scrubber carbon combustion efficiency) averaged 94%. Here, around 58% of PCTSSCRB (scrubber sulfur content) is dissolved while 42% is in the solids. Based on the above analysis with no sorbent injection, the bulk of the sulfur solids cannot be coal since TSSCEFF (scrubber carbon combustion efficiency) is relatively high. This is confirmed by chemical analysis of the scrubber solids, showing high sulfur content only in the presence of sorbent calcium. In addition, the associated pH averages 9.5, showing the neutralization effect of hydrolyzed sorbent on the originally acidic scrubber water. Virtually all of the dissolved sulfur is present as sulfate, with measured dissolved calcium and sulfate concentrations corresponding to the solubility limit of $CaSO_4$. In this situation, "excess" $CaSO_4$ would remain as a solid, since the ionic solubility product cannot be exceeded.

The effects of the calcium/sulfur mole ratio (CASRAT) on ACTSLGS (slag sulfur content), BOILSULF (sulfur retained in the boiler), PCTSSCRB (scrubber sulfur content), and ATMSULF (sulfur emission to atmosphere) were also evaluated statistically. As anticipated, both slag and boiler sulfur contents increased significantly as the Ca/S ratio increased due to enhancement of the sulfur/sorbent reaction rate via increased sorbent availability. Since more sulfur is retained in the slag and boiler at higher CASRAT (calcium/sulfur mole ratio), the amounts retained in the scrubber and emitted to atmosphere correspondingly decreased. These effects of CASRAT (calcium/sulfur mole ratio) are illustrated in figure 22 for the slag, boiler, and scrubber sulfur variables.

The data show little or no dependence of the sulfur variables on combustor sorbent type. This result is in agreement with previous Coal Tech work, reported in reference 25 where no effect of sorbent type on sulfur capture was observed for limestone vs. pressure hydrated lime. No reactivity or porosity measurements were made for the commercially available sorbents used in the tests, while their compositions are given in Appendix V. However, data presented in reference 29 suggest that calcium hydrate may have a higher transitory internal surface area during calcination than limestone, thus potentially leading to better calcium utilization with the hydrate during sulfur capture. It is possible that calcium hydrate performed slightly better than limestone but only marginally so. In addition, injection of calcium acetate could not be fully evaluated due to feeding problems associated with combustion of the organics at the injection point, resulting in heavy ash buildup. It should also be noted that no evidence of ash alkali effects on sulfur capture was observed.

Although there was limited data on boiler sorbent injection, it is clear that this technique was most efficacious in reducing SO2. At a Ca/S ratio > 3, an 82% reduction in measured stack SO2, using hydrate, was obtained. With limestone injection at Ca/S > 3, the reduction in SO2 was less than 20%. However, this result is based on limited data from work mainly conducted under the ash melting projects. It should be emphasized that these results were obtained during preliminary trial runs which made no effort at parametric optimization. Until further testing can be performed, a full analysis of the results is not possible. In any case, improved SO2 reduction in the boiler outlet with hydrate vs. limestone was probably related to the lower calcination temperature of hydrate, which, in the present application, gave rise to more internal surface exposure, i.e. a higher porosity, for reaction with the SO2 than did the limestone. Besides sorbent type and Ca/S ratio, analysis of the limited data indicates that the temperature in the boiler sorbent injection area is also critical.

In the Clean Coal I project, at LS injection rates corresponding to various Ca/S ratios, reductions in measured SO2 at the boiler outlet of from 0 to > 50% have been obtained, depending on thermal and stoichiometric conditions. In addition, test data showed that the scrubber itself can reduce measured SO2 by > 40%; however, the sorbent and scrubber reductions are not additive. Even though the global phenomena are complex and not yet fully understood, several conclusions are possible. Slag sulfur retention and rejection is clearly a delicate process, having very narrow parametric windows in which to be optimized. Every independent variable in the ACTSLGS (slag sulfur content) model exercised great influence. Aside from the obvious requirements of sufficient sorbent, a CASRAT (calcium/sulfur mole ratio) effect, and high sulfur concentration, a PCTPC (percent coal firing) effect, maximum slag sulfur strongly depends on the local thermal/chemical environment as indicated by its sharp dependence on SR1 (first stage inverse equivalence ratio), which is believed to have a major impact on sorbent deadburning as well as sorbent/sulfur reaction kinetics and the stability of the sulfated sorbent product. Other variable enhancement factors seem to include minimum sorbent deadburning, minimum slag desulfurization, and good slag rejection, a SWIRLPR (swirl air pressure) effect; good coal-sulfur release and good air/fuel/sorbent mixing, a HEATIN (total fuel heat input) effect.

Except for HEATIN (total fuel heat input), boiler sulfur retention

(BOILSULF) is qualitatively affected by the independent variables in much the same way as ACTSLGS (slag sulfur content). Since the boiler observables implicitly include the exit nozzle and the surrounding boiler refractory face, it is not unreasonable to consider at least some portion of this zone as an extension of the combustor. Thus it is expected that parameters affecting combustor slag sulfur rejection also affect BOILSULF (sulfur retained in the boiler). The negative dependence of BOILSULF (sulfur retained in the boiler) on increasing HEATIN (total fuel heat input) may be attributed to second stage sorbent deadburning.

PCTSSCRB (scrubber sulfur content) appears to totally depend on the amount of bulk solids reporting to the scrubber since its dependence on the four major independent variables practically mirrors the SCRUBREJ (scrubber solids rejection) dependence. The negative dependence of PCTSSCRB (scrubber sulfur content) on increasing CASRAT (calcium/sulfur mole ratio) simply states that sulfur not retained in the combustor/boiler, due to sorbent capture, will end up in the scrubber or go to atmosphere. ATMSULF (sulfur emission to atmosphere) essentially increases when operating conditions tend to deadburn the sorbent, namely at high SR1 (first stage inverse equivalence ratio), or tend to reduce PCTSSCRB (scrubber sulfur content), namely at low HEATIN (total fuel heat input) and/or PCTPC (percent coal firing), which are in turn coupled to reduced SCRUBREJ (scrubber solids rejection).

Experimental evidence indicates that almost all observed reductions in boiler outlet SO2 were due to carried over sorbent. What is unclear is whether the actual SO2 capture took place within the combustor, with the sulfated sorbent being carried out, or whether the sorbent was first carried out, then reacted with the sulfur in the second stage. The overall impression, however, is that significant sulfur capture is actually taking place in the combustor but that there is insufficient reactive residence time to accomplish fuel burnout/ash melting at the higher coal firing rates needed to maximize slag rejection. Consequently, a large portion of the reactive solids, at high fire, are not retained and rejected by the combustor.

From the above it can be seen that the entire concept of sulfur capture inside the combustor with sulfur retention/rejection with the slag has not been operationally confirmed in the present combustor under the Clean Coal I project. The main difficulty being insufficient slag rejection in the combustor proper. However, individual process capture steps and independent slag sulfur evolution studies performed by others have validated critical aspects of the concept. Thus, we believe that our process does work and that it is simply a matter of implementing relatively minor design and operational changes to arrive at conditions where sulfur capture is optimum. Part of our confidence, as noted, is due to post-test chemical analysis of boiler solids, obtained late in the Phase III testing, which yielded a maximum of 30% total sulfur in the presence of CaO.

In terms of air quality compliance monitoring, the experimental test program was designed so that stack SO_2 levels could never, with one exception, exceed the prescribed limit, i.e. the sulfur contents of most of the coals used were such so as to be always in compliance even with no environmental sulfur control, as would occur during baseline parametric operation. For high sulfur coals, co-firing with oil & NG yielded an effective fuel sulfur content that almost always met emission requirements with no environmental control.

Calculations show that for 100% coal firing and 100% conversion of coal sulfur to SO_2 the 4 lb/MMBtu limit on SO_2 emissions would be exceeded only if the coal sulfur content were higher than 2.5%. The combustor was operated in 1988 with coals having sulfur contents ranging from 1.1 to just under 2.5%. In 1989 the combustor was operated with coals having sulfur contents ranging from about 2.1 to 2.3%, while in 1990 the range was around 1.1 to 3.3%. In practice, however, co-firing with oil & NG yielded an effective fuel sulfur content that was lower, such that emission requirements were almost always met even with no environmental control. The only exception was baseline operation with the 3.3% sulfur coal. In any case, the bulk of operating time was with sorbent injection so that the above "worst case" SO_2 emission rate was only for a brief period. Thus, measured boiler outlet and stack SO_2 levels were virtually always below the regulatory limit.

In 1988, boiler outlet SO_2 levels averaged 2.03 lb/MMBtu. In 1989, boiler outlet SO_2 levels averaged 2.30 lb/MMBtu, while in 1990, the figure was 3.58 lb/MMBtu. It should be emphasized that the yearly increase in SO_2 emissions was generally due to the use of higher sulfur coals as well as an increase in the coal firing rate relative to the auxiliary fuels. Since these data were obtained with the combustor operating over a wide range of parametric conditions, some of which were outside the envelope of maximum sulfur capture, the reported SO2 emission levels are not entirely indicative of optimum performance. It should also be emphasized that these emission rates are upper limits on actual atmospheric emissions since the wet scrubber itself had some sulfur capture capacity, partly independent of the level of sorbent injection, resulting, on average, in a further 20 to 25% reduction in the SO2 actually emitted. Details of this monitoring are presented in the Annual Environmental Reports.

3.3.4.2.3. Slag Reactivity

The DOE Clean Coal I project aimed at demonstrating the capture of coal sulfur by fire-side sorbent injection and rejection with the slag to form an inert material. Similarly, the DOE-SBIR Phase I project aimed at evaluating the feasibility of using Coal Tech's slagging cyclone combustor technology to convert fly ash powder into an inert, glassy slag retaining all or most of the initial fly ash trace metals, and thereby significantly reducing the potential risk for environmental harm upon disposal or recycle. Thus the properties of the slag as an inert solid waste are of importance. As noted in Reference 16, the attractiveness of glass as a long term disposal medium is its low leaching rate as well as its chemical inertness and mechanical strength. It is generally recognized that glass is the preferred waste form for disposal of nuclear wastes for geologic periods in underground repositories.

During coal combustion the trace elements undergo a partitioning among the slag, the fly ash captured by the particulate collection device, and the fly ash and vapors escaping to atmosphere. Laboratory studies of power plant type coal ash (21, 22) found that the more volatile trace elements are discharged to atmosphere as gases (most mercury and some selenium) and/or concentrated in the fly ash (arsenic, cadmium, chromium, copper, lead, and selenium). Some cadmium, chromium, and copper, less volatile elements, were also in the bottom ash/slag at levels more or less uniform with the fly ash while barium and strontium showed little preferential partitioning.

Leachate from ash disposal sites is of concern due to the possibility that heavy metals present in the ash may enter the groundwater system and contaminate present or future drinking water (17). This is of importance since metals are not subject to biodegradation and have, for practical purposes, infinite lifetimes. They cannot undergo "decontaminaticn" by chemical means and can only be diluted to innocuous levels or permanently confined or impounded in "secure" landfills (18). Unlike the behavior of most other contaminants, that of trace metals is determined by the specific forms of the metals rather than their bulk concentration (18). Thus, the quality of leachate is governed by physical/chemical characteristics of the ash and the soil/water matrix through which the leachate flows; hence, it is not possible to predict ash leachate quality at this time (17).

As part of the RCRA characterization testing of a solid for hazardous or non-hazardous solid waste classification, the material must be subjected to a leach test known as the Extraction Procedure (UP) Toxicity test wherein the resulting extract is not to exceed 100 X the National Drinking Water Standard for arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver (19). These standards are shown in Table 1. A 1975 study of ponded fly ash and bottom ash leachate (17) repcrted that heavy metals arsenic, cadmium, chromium, copper, lead, and selenium exceeded the Drinking Water Standards by about 10 to 500 X for fly ash, and about 1 to 10 X for bottom ash. These results clearly indicate the need to evaluate alternative methods to landfilling for the treatment, and possible recycling, of coal fly ash.

Table 1 US EPA National Drinking Water Standards

Element	mg/liter (17)	mg/liter (20)
Arsenic	0.05	
Barium	1.00	
Cadmium	0.01	0.01
Chromium	0.05	
Lead	0.01	0.05
Mercury	0.002	0.005
Selenium	0.01	
Silver	0.05	
Boron	1.00	
Copper	1.00	0.5
Iron		1.0
Zinc		1.0

As noted in the 1988 Annual Environmental Report, the EMP was developed on the basis of compliance monitoring requirements specified by the Resource Conservation and Recovery Act (RCRA), and administered by the PA DER, Bureau of Solid Waste Management. The pertinent substances that fall under the RCRA are the slag nitrogen and sulfur reactivity that form gas phase cyanide and sulfide compounds, and the leaching potential of heavy metals and cyanide in the slag. The evaluation of compliance is determined by preparation of a Module 1 document in which the characteristics of the solid waste product are documented, using laboratory test results, to obtain the necessary landfill permits.

In 1988, the slag chemical analysis and other properties provided by the testing lab (see Appendix IV) indicated that the material had none of the characteristics of a hazardous waste and could, therefore, be disposed in a landfill for non-hazardous solid waste. However, it was determined that the slag generated by the combustor qualified under the Pennsylvania Coal Waste Product Recycling Act and, as such, did not require extensive testing/analysis to obtain disposal permits. In view of this, it was arranged to dispose of the slag, in total amount of about 2.5 tons, at the PP&L slag processing center at the Montour powerplant.

In 1989/90, virtually all of the solid waste, approximately 10 tons, was also shipped to the PP&L landfill. A small amount of slag, around 1000 lbs, generated in the final Clean Coal test, could not be sent to PP&L owing to procedural difficulties involved in processing such a small shipment. Instead, this material will be sent to an Alabama landfill owned by Chemical Waste Management Company.

As part of DOE's Waste Management Program, which aims at identifying emerging coal utilization technologies and performs comprehensive characterizations of the waste streams and products, Coal Tech consented toward the end of the Clean Coal Technology project, to on-site waste steam sampling by an independent environmental sampling firm sub-contracted by DOE. Slag, scrubber discharge, slag quench water, as well as raw coal and inlet water samples were therefore obtained by this group during one of the multi-day test runs in February, 1990. The sampling protocols, analytical test results and evaluations have been presented in reference 30.

Under the Waste Management Program, slag and scrubber solids were subjected to the new, and more rigorous, TCLP (Toxic Characteristic Leaching Procedure) and the SGLP (Synthetic Groundwater Leaching Procedure) leach tests. In addition, cyanide and sulfide evolution rates were obtained. In all cases, none of the wastes contained concentrations of regulated elements high enough to be considered hazardous.

Supplemental monitoring in the EMP involved slag sample analysis for carbon, nitrogen, and sulfur. The yearly results were essentially identical, namely slag carbon < 0.01%, sulfur between < 0.01 to 0.05% with occasional values in excess of 1.0%. Slag nitrogen content remained uniformly low.

Also under the Waste Management Program, slag and scrubber solids were analyzed for 24 target-list organics. Both samples showed no significant concentrations of the target analytes.

Additional slag leachability data were obtained from the EPA SBIR Phase I project, which aimed at converting municipal solid waste (MSW) fly ash to an environmentally safe slag retaining a significant amount of the initial trace metals. This data is of interest here since it illustrates the global application of ash-to-slag conversion as a technique for producing environmentally inert material from potentially hazardous ash, regardless of the ash source. The main criterion for evaluation of slag environmental safety at that time was the EP Toxicity (1310 SW-846) or leach test, the results of which are shown in Table 2 for the parent fly ash (MSW 1) and two slags collected during test EPA1: EPA1-3 with oil plus NG firing, EPA1-4 with some PC firing. Key operating test conditions are given in the table at the beginning of Appendix I. Table 3 presents the corresponding metals contents.

Table 2. <u>Leach Test Results for Parent Fly Ash & Resultant Slags From Test EPA1</u>

	Metals in Leachate, mg/L			
	MSW 1	EPA1-3	EPA1-4	100X EPA Water Standard
Cadmium	2.14	< 0.03	< 0.03	1.0
Copper	1.05	< 0.09	< 0.09	100.0
Lead	22.3	< 0.2	< 0.2	1.0

Table 3. Metal Content of Parent Fly Ash and Resultant Slags From Test EPA1

	Metal Content, mg/kg		
	MSW 1	EPA1-3	EPA1-4 (a)
Cadmium	325	< 15.7	< 16.2
Copper	827	430	193
Lead	19117	191	< 108

(a) Use of PC in this test resulted in a slag which was 69 % MSW 1 ash and 31 % PC ash. The original PC ash contents are: cadmium < 17.4 mg/kg, copper not measured, and lead < 116 mg/kg.

The data in Table 2 show that leaching of parent fly ash cadmium and lead exceeds 100X the EPA Drinking Water limit used as a standard for hazardous classification in the EP Toxicity Test while copper is below the limit. The slag metals leaching data, even taking into account the reduced metals content of the slag vs. fly ash shown in Table 3, is at least an order of magnitude below the EPA limit, thereby confirming the environmental safety of the slag produced from the fly ash with and without coal firing.

3.3.4.2.4. Particulates

As noted, initial tests on dry PC gave rise to high solids carry-over to the boiler and the stack. However, even with these early adversities, the stack venturi wet scrubber performed well, giving a clean white, steam plume at the designed pressure drop. Upset operation, associated with extremely variable PC flow in the earlier tests, diminished the scrubber performance to the point where frequent cleaning of the scrubber duct inlets was necessary when the combustor operated in this mode. However, in general the scrubber has performed very well with far less problems than any of the other new equipment at the site.

In late Phase II and early Phase III testing, opacity meter readings taken at the 12 ft. location at the base of the stack (boiler outlet) were usually in the 40 to 60% range upon initial LS and PC injection and gradually climbed to 100% as fly ash deposited on the optical windows. It should be noted that either direct or indirect particulate level measurements made here are of little environmental concern since this location is upstream of the stack gas scrubber. However, it was possible to correlate these opacity readings with Bacharach smoke numbers obtained from a portable device which could be used in the stack, either upstream or downstream of the scrubber. This correlation was made by obtaining several simultaneous opacity and smoke number readings at the boiler outlet. The opacity data were then formulated as a linear function of the smoke numbers (namely opacity = 13.5 X smoke number) yielding the opacity value to within 20% on average. This expression was then used to convert scrubber stack smoke numbers to an effective opacity. This allowed us to indirectly determine the opacity of the stack gases discharging to atmosphere. The relevant data were presented in the 1988 Annual Environmental Report.

Based on measured stack gas smoke numbers, and the above correlation, the opacity of the gas being discharged to atmosphere was < 20% (even including the 20% uncertainty) when the scrubber pressure drop was = or > 15 "WC, the manufacturer's designed operating value. At a lower pressure drop, briefly tested as part of the parametrics, the opacity was higher. After these initial tests, scrubber pressure drop has been held at 15 "WC or more with visual observation of the scrubber stack discharge indicating good scrubber operation. For this reason, opacity measurements have not been continued beyond the initial tests noted above.

Representatives of the PA DER, Bureau of Air Quality, have been on-site during testing and are satisfied by the scrubber's operation. Successful performance of this relatively inexpensive technology in an urban environment is an encouraging development for other retrofit applications.

No stack particulate mass loading rate (EPA Method 5) or size distribution (cup filter, 10 micron cutoff) measurements were performed under the Clean Coal I project owing to limited resource allocation to other project goals. However, a measurement of particle mass (PMR) rate with coal firing via EPA Method 5 was made by a commercial testing firm under another project in July, 1990. In addition, non-isokinetic stack sampling was performed by Coal Tech, also under another project, in January of 1990.

The EPA Method 5 measurement of the particulate emission rate was conducted in July 1990 at a total fuel heat input of 9.0 MMBtu/hr with coal and oil co-firing, along with sorbent injection. The measurement was made in the boiler outlet stack, upstream of the scrubber. The resulting PMR is therefore an upper limit on the solids loading to the scrubber since it does not reflect solids layout in the ducting between the measuring point and the scrubber inlet. At 107% isokinetic, the boiler outlet solids emission was reported as 17 PPH or 1.89 lb/MMBtu. Analysis of scrubber discharge samples obtained in the same time interval yielded a scrubber solids rejection of 15 PPH or 1.67 lb/MMBtu. Discounting solids deposition losses, this places an upper limit of 0.22 lb/MMBtu on the particulate emissions to atmosphere.

In a separate DOE SBIR project, aimed at evaluating the feasibility of converting utility fly ash to an environmentally inert slag, using the Coal Tech combustor, non-isokinetic particulate sampling of the atmospheric discharge, downstream of the scrubber, was performed. These tests were conducted with coal and oil co-firing at a total fuel heat input of 10.6 MMBtu/hr, plus combustor sorbent and fly ash injection at various levels. With coal and oil co-firing, the atmospheric PMR was 0.20 lb/MMBtu. The addition of flyash yielded 0.09 lb/MMBtu, and for coal plus flyash plus sorbent the value was 0.30 lb/MMBtu. It should be emphasized that these figures are probably lower limits on the actual atmospheric emission rates due to sampling line losses. However, the values are in line with the one derived from the rigorous Method 5 measurement.

The scrubber flyash size or resistivity were not measured. However, the size distribution is expected to be similar to that reported for the 40 MMBtu/hr TRW slagging cyclone combustor in Cleveland, OH, namely, 11.1% < 0.5 microns, 19.5% < 1 micron, and 54.5% < 5 microns on a weight basis.

3.3.4.2.5. Wastewater

Water used for combustor cooling only, i.e. not in contact with any waste stream, was discharged to the storm sewer. With PC firing, the cooling water was recycled for slag quenching and scrubber operation. This resulted in two waste water streams, one generated in the scrubber and the other by contact with slag in the slag quench tank (SQT). These were eventually combined and discharged into a sanitary drain going to the Williamsport Sanitary Authority Central Treatment Plant. This facility is rated for a maximum flow of 10.5 million gallons per day (MGD). The daily average flow is typically 6 to 8 MGD or about 250,000 to 333,000 gallons per hour (GPH).

Compliance requirements are specified by the Williamsport Sanitary Authority, in concurrence with the PA DER, Bureau of Water Quality Control. As per the Authority, the following parameters were monitored: total water discharged into the sanitary system; total suspended solids (TSS) in the discharged water; the heavy metals cadmium, copper, and selenium suspended in the water; the water discharge temperature and pH. The discharge limits are 0.5 lb of Cd/day, 1.0 lb of Cu/day, 0.1 lb of Se/day, maximum water temperature of 135 F, and $5 < pH < 9$.

Testing in 1988 consumed around 750,000 gallons of water for cooling the combustor, for quenching and solidifying the molten slag, and for operating the venturi scrubber. In 1989 and 1990 the water consumption was around 1,250,000 and 560,000 gallons respectively. In 1988 about 37% of the water was discharged to the sanitary sewer, the remaining 63% being discharged into the storm sewer system. Of the amount discharged into the sanitary drain, about 67% was scrubber discharge while the balance came from the SQT. It should be noted that roughly one-third of the 1989/90 water usage occurred under projects other than the Clean Coal. Of these yearly totals about 25% was discharged to the sanitary sewer, the remaining 75% being discharged into the storm sewer system. Of the volume discharged into the sanitary drain, about 74% was scrubber discharge while the balance came from the slag quench tank (SQT).

Sanitary sewer discharge occurred only during PC operation. Thus, much operating time was not on PC but on natural gas or light oil firing for combustor heat-up and cool-down procedures, for refractory curing, and for overnight idling of the system during the multi-day tests. In these latter instances the discharged water was used only for combustor cooling via indirect heat exchange and therefore contained no waste materials.

Water discharged from the SQT was filtered and therefore had a low total suspended solids (TSS), spot checked in 1988 to be 19 mg/l, the solids being unburned coal. Owing to this low solids loading of the SQT water, as well as the relatively low flow of around 10 gallons per minute (GPM), water quality testing focussed on the scrubber where water samples were usually obtained several times during each test run for subsequent commercial laboratory analysis.

Discharged scrubber water Total Suspended Solids (TSS) averaged 5423 mg/l in 1989. This TSS level is higher than the average value of 3344 mg/l reported in 1988. The primary reason for the increase is the use of relatively higher coal firing rates in 1989. At the scrubber water use rate of 28 GPM the 1989 TSS discharge rate averaged 76 PPH. Variability in the TSS measurements is largely due to parametric operation which often resulted in less than maximum combustor solids retention. Complete data and operating conditions are given in the Annual Environmental Reports.

In 1988, several scrubber water samples were tested for the presence of the trace metals cadmium, copper, and selenium. The average levels, in mg/l, were < 0.03, 0.291, and 0.014, respectively. Independent determinations for cadmium and copper, made by the Williamsport Sanitary Authority, yielded < 0.001 and 0.046 mg/l respectively. For an eight hour test day our measured 1988 levels translate into < 0.0036, 0.035, and 0.0017 lb/day of Cd, Cu, and Se. Thus, our measured 1988 discharge rates for these metals are well below the Authority's limits noted above. In 1989/90, scrubber water samples were tested for the presence of the trace metals cadmium and copper. Selenium was not included in the analysis since its 1988 level was extremely low. The average levels of cadmium and copper, in mg/l, were 0.042 and 0.513.

Independent determinations of cadmium and selenium in filtered scrubber water, made under the Waste Management Program, yielded < 0.02 and 0.138 mg/l respectively. For an eight hour test day the highest measured 1989/90 levels translate into 0.0047, 0.0575, and 0.0155 lb/day of Cd, Cu, and Se. Thus, the measured discharge rates for these metals were well below the Authority's limits in 1989/90 as well.

In 1988, a scrubber discharge water sample was analyzed by the Authority for other metals in addition to the compliance monitored cadmium and copper noted above. The following species were measured (mg/l): lead (0.015), nickel (0.011), zinc (0.588), iron (93.0), and silver (< 0.001). Based on the dilution of the scrubber discharge at the treatment facility, these metal concentrations would have no, or only incremental, effects on the metal levels already handled by the plant, e.g. 0.011 mg/l of nickel, 0.138 mg/l of zinc.

Scrubber discharge water temperature has been uniformly between 100 and 120 F. In 1988, water pH was found to vary between a low of 3.2 and a high of 12.6. The average value is 9.2, which is nearly within the Authority's maximum value of 9. However, this figure would be misleading since the measured pH's exhibit a bimodal distribution depending on whether sorbent injection was on or off during PC operation. With no sorbent injection the SO2 produced from the coal sulfur acidifies the scrubber water resulting in an average pH of 4.9, while with sorbent injection the average is 11.35 owing to the basic chemical nature of the sorbent. The 4.9 pH is close to the acidic limit of 5, while the 11.35 value exceeds the basic limit of 9.

Water pH in 1989 was found to vary between a low of 4.5 and a high of 12.4. Because of the routine use of sorbent injection, the average value is 10.5, which somewhat above the Authority's limit. However, this waste water stream is diluted by the SQT water (pH normally 6 to 7, temperature < 100 F) in about a 3 to 1 ratio upon entering the sanitary drain. In addition, based on the Central Treatment Plant's average daily influent rate noted above, the relatively low flow of 1800 to 2280 GPH would be diluted at the plant by a factor of around 150 to 125, which is expected to result in little variation in total treated water pH.

Analysis of the SQT and filtered scrubber water was performed under DOE's Waste Management Program. The samples were checked for 10 regulated trace metals and 24 target-list organics. As noted in reference 30, none of the samples had concentrations of analytes high enough to be considered hazardous.

In addition to the trace heavy metals, supplemental monitoring was to address the carbon, nitrogen, and sulfur content of the water discharged to the sanitary system. As noted above, the SQT water, which had low solids content and flow, had low levels of partially burned PC. As per the Waste Management Program testing, scrubber water TSS were comprised of around 41% unburned carbon, 43% ash, 3% sulfur, and 13% calcium oxide from the injected sorbent. It should be noted that this carbon content corresponds to >95% overall coal combustion efficiency.

3.3.4.3. Impact on Combustor Design and Operation

Results of the Clean Coal I project, in terms of design and operation of a commercial air cooled cyclone coal combustor, are of great importance. Even though most of the technical goals were achieved with the present prototype combustor, evaluation of test observables as well as the statistical analysis of accumulated data has provided additional insight and guidance regarding future development and application. It is important to note that testing of the present demonstration unit was a necessary step between the initial bench or pilot scale studies and the development of a fully commercialized unit since the present combustor is at a scale appropriate to commercial units and was tested in a real process application. In this section the global effects of operating parameters on key process variables are discussed in terms of optimized operation. In addition, the test results are evaluated with regard to new design or operating changes needed to upgrade performance in key areas.

Overall, four major independent operating parameters were discovered to produce one or more general effects on the overall process. These effects, for increasing values of the variables, are as follows:

SR1:
- better fuel combustion, burnout, heat release.
- better ash melting.
- a more oxidizing atmosphere.
- higher flame temperature.

SWIRLPR:
- cooler liner/slag surface.
- more cyclonic action, better combustor solids retention.

HEATIN:
- higher air/fuel/sorbent mixing, combustion intensity, and heat release.
- better ash melting.
- higher mass throughput, less combustor gas and/or solids residence time.

PCTPC:
- more ash/slag system loading.
- more coal wall burning, different combustor heat release pattern.
- increased sulfur and fuel-nitrogen to the system.

Based on maximum effect in the statistical models, PCTPC (percent coal firing) was found to have the greatest impact on operation, followed closely by SR1 (first stage inverse equivalence ratio) and HEATIN (total fuel heat input). SWIRLPR (swirl air pressure) proved to have the least global influence although its contribution to slag sulfur retention was very high. For models containing CASRAT (calcium/sulfur mole ratio), its influence was about midway between SR1 (first stage inverse equivalence ratio) or HEATIN (total fuel heat input), and SWIRLPR (swirl air pressure). This relatively modest effect of Ca/S mole ratio may be due to some type of threshold effect and/or the fact that the scrubber can remove some sulfur even with no sorbent.

Consideration of the modeling results, as well as other experimental observations, yielded several conclusions and/or hypotheses applicable to operation and design of a commercial coal fired, air cooled combustor. One clear result was that best overall combustor performance was obtained at high fuel heat input. This is important from an operational and economic point of view. The maximum heat input during the tests was around 20 MMBtu/hr, even though the combustor was designed for 30 MMBtu/hr and the boiler was thermally rated at around 25 MMBtu/hr. This situation was due to facility limits on water availability for the boiler and for cooling the combustor. In fact, even 20 MMBtu/hr was borderline, so that most of the testing was conducted at lower rates.

Attempts to optimize process performance observables via independent parameter changes showed that there were two difficulties in this approach. The first was that changes in operating parameters to enhance one dependent variable often resulted in degradation of other process variables. For example, both NOx reduction (NORMNOX) and slag sulfur content (ACTSLGS) were optimized at low SR1 (first stage inverse equivalence ratio) while slag rejection (SLAGREJ) was decreased from the excess air value. In addition, NOx levels were significantly decreased at low air swirl pressure, but slag sulfur content was reduced. These results indicate that these performance variables cannot be simultaneously optimized in the present system by manipulation of operating parameters alone. This situation is largely inherent to the process physics and chemistry and cannot be disregarded. Here, one must either compromise and choose operating conditions which involve a trade-off in performance among the affected variables, or introduce changes in operating technique and/or combustor design which will offset the negative effects of certain operating conditions for one or more process variables.

This latter approach had been successfully implemented for XSCHROM (refractory chrome in slag) where liner life, at operating conditions associated with good overall performance but higher liner wear, was extended by wall slag replenishment. In a similar way, the addition of external air preheat is considered a possibility to upgrade combustion efficiency, if necessary, at low SR1 (first stage inverse equivalence ratio). It is possible that high air preheat at low SR1 (first stage inverse equivalence ratio) may also be helpful in improving the combustion efficiency/process temperature needs associated with good slag rejection, while at the same time retaining the stoichiometry/chemistry needed for good NOx and SO2 control. Here, the key parameter for slag sulfur retention and NOx control, SR1 (first stage inverse equivalence ratio), could be maintained while the combustion intensity necessary for good fuel utilization, heat release, and ash melting would be improved. Implementation of this external air preheat modification would require an auxiliary air preheater, electrical or gas fired, plus new piping including insulation.

Of perhaps more importance is the second difficulty, namely that the performance level of certain process variables could not be brought to acceptable levels for any practical combination of operating parameters. Even under optimum conditions, the best values for ACTSLGS (slag sulfur content), ATMSULF (sulfur emission to atmosphere), and SLAGREJ (combustor tap slag rejection) are considerably less than desired. It is observed in Table 4 that predicted SLAGREJ (combustor tap slag rejection) does not exceed 50% even under optimized conditions. Part of this result is due to the narrow operational definition of SLAGREJ (combustor tap slag rejection) as discussed previously. It should be noted that the values in Table 4 are from the statistical model and that during actual combustor operation the measured values sometimes surpassed these in performance. However, these "high water" marks were not typical and were probably due to a combination of operating conditions, likely including unobserved transitory or non-steady-state phenomena, which were not routinely accessible, and therefore were not easily repeatable.

Table 4. Statistical Model Simulation for Individually Optimized Process Observables

	Optimized Variables (a)							
	ACTSLGS	BOILSULF	PCTSSCRB	ATMSULF	SLAGREJ	NORMNOX	XSCHROM	TSSCEFF
ACTSLGS	6.5	5.6	4.2	4.2	4.0	4.2	3.1	1.7
BOILSULF	22	24	21	21	21	21	23	20
PCTSSCRB	47	19	48	48	40	48	12	41
ATMSULF	48	74	43	43	49	43	75	44
SLAGREJ	27	21	24	24	50	24	44	47
NORMNOX	258	409	168	168	467	168	620	379
XSCHROM	1.5	0.8	1.7	1.7	1.2	1.7	0.6	1.5
TSSCEFF	107	49	116	116	133	116	75	142
	Optimum Conditions							
-SR1	0.6	0.6	0.6	0.6	1.3	0.6	1.3	1.3
SWIRLPR	40	40	10	10	40	10	40	10
HEATIN	20	6	20	20	20	20	6	20

-(a) Optimized variables are in the horizontal row. Optimized values for each variable are found along the diagonal. The columns contain the values of the other variables when the row variable is optimized. The optimum conditions for the row variables are at the bottom. PCTPC (percent coal firing) = 100 and CASRAT (calcium/sulfur mole ratio) = 3 in all cases.

Regarding overall system sulfur retention, the upshot seems to be that sulfur capture and rejection in the combustor have not been optimized due to underutilization of the combustor volume, i.e. the air/fuel/sorbent mixing zone is too extensive, or the combustor is in fact too short to allow complete reaction to occur, including fuel burnout, sorbent sulfur capture, and ash melting, within the combustor proper. With the first stage reactions continuing in the exit nozzle and/or near the boiler front wall, especially with staged operation, it is not surprising that relatively little sulfur is captured and rejected with the slag, and that the amount of rejected slag is reduced. It is also not surprising that carried over sorbent/sulfur reactions in the boiler do not approach the efficiency of direct boiler sorbent injection since the sulfur capture reactions are either thermodynamically reversed, or the sorbent deadburned, as the first stage gases encounter the hot second stage flame front.

This second difficulty then suggests that optimization of the affected process variables is limited by some sort of barrier inherent to the present combustor operating technique and/or design. This in turn suggests that improvement can only be obtained by radically altering operating conditions. As already mentioned, experimental evidence strongly suggests that the combustor volume is underutilized, i.e. the air/fuel/sorbent mixing zone is too extensive, or the combustor is in fact too short, to allow complete reaction to occur, including fuel burnout, sorbent sulfur capture, and ash melting. Thus corrective operation or design modifications would include changes in the air/fuel/sorbent mixing via injection modification, or by making the combustor longer, i.e. increasing the length to diameter (L/D) ratio. With the present injection geometry, an estimated length increase of one to two feet would probably result in substantial improvement. Alternatively, modified air/fuel/sorbent injection geometry could have a positive effect if it reduces the size of the mixing zone. In fact, injection modifications have recently been implemented under the DOE ash project and have yielded significant improvement in SLAGREJ (combustor tap slag rejection). Additional testing of this new injection geometry for improving slag rejection and slag sulfur retention with coal firing would be extremely useful since up till now both parameters could not be simultaneously optimized.

One of the chief goals of the Clean Coal project was to capture the coal sulfur in the combustor and reject it with the slag. Although this concept was clearly validated, the quantitative levels of slag sulfur content were generally too low. Part of the problem was that two key process requirements, low SR1 (first stage inverse equivalence ratio) operation for maximum combustor sulfur capture, and high slag rejection, could not be simultaneously optimized in the present unit. The latter result is important since it basically says that atmospheric SO2 emissions cannot be reduced below about 43% of total sulfur with combustor sorbent injection, using the present combustor operational and design configuration. The fact that boiler sorbent injection resulted in atmospheric SO2 of less than 18% of total sulfur clearly shows that thermal/chemical regimes of high sulfur capture potential do exist in the current system configuration, but were not achieved by combustor sorbent injection. This is seen on Table 4 where even the optimized value of ACTSLGS (slag sulfur content) is disappointingly low.

Regarding atmospheric SO2 emissions, if combustor sulfur capture and rejection with the slag cannot be raised to acceptable levels by combustor operation or design changes, then direct boiler sorbent injection would be the preferred sulfur control technique. In this situation, combustor sorbent injection would mainly be for slag viscosity control, and only secondarily for sulfur capture. Another possibility is multi-point sorbent injection. However, these measures should be regarded as fall-back positions only, and not as recommendations since we believe that the fire-side capture process can be made to work.

3.3.5. Summary of Accomplishments

The Cooperative Agreement between DOE and Coal Tech work statement for this Clean Coal project listed a group of five objectives. They were:

A. Demonstrate that 70-90% of the potential sulfur oxide emissions from the combustion of a 2-4% sulfur coal can be picked-up in the combustor by a sorbent

B. Demonstrate that 90-95% of the ash contained in the feed coal plus the sorbent used for the SO2 pick-up can be discharged from the combustor as a low viscosity slag before it enters the boiler.

C. Demonstrate, on a commercial scale, that nitrogen oxide emissions can be reduced to 100 ppm, or less through fuel and air staging.

D. Prove that this combustor has a durability of approximately 900 hours of steady state operations, with frequent start-ups and shutdowns.

E. Developed the knowledge that this combustor is compatible with existing boilers, has a 3 to 1 turndown ratio, and will have the potential of bringing existing boilers to meeting New Source Performance Standards.

To implement the above five objectives, a set of 10 sub-objectives were formulated by Coal Tech. The following describes the progress that was made in meeting these 10 sub-objectives: (Each of these will be referenced to the letter corresponding to the 5 overall objectives, i.e. "Objective A-1" refers to overall objective A, sub-objective 1.)

Objective #A-1. Combustor operation with coals having a wide range of sulfur contents.

Tests were performed with about eight different Pennsylvania bituminous coals with sulfur contents ranging from 1% to 3.3%, and volatile matter (VM) content ranging from 19% to 37%. Early in the program, before proper procedures for air cooled operation had been developed, it was not possible to efficiently burn and slag very low VM coals. However, this problem was solved and all the coals were efficiently burned and slagged.

The use of an off-site source to provide the pulverized coal (PC) in a tanker truck, as opposed to on-site pulverization, was a high risk decision that was dictated by resource limitations. This procedure proved to be generally satisfactory. In the course of three years of testing, only two loads of coal were contaminated with foreign or tramp material, and the cause in each case was rapidly identified.

Objective #A-2. 70 to 90% reduction in sulfur oxides in the stack, with maximum sulfur retention in the slag.

A maximum of over 80% SO_2 reduction was measured at the boiler outlet stack, using sorbent injection in the furnace at Ca/S ratios > 3. However, this result is based on limited data from work mainly conducted under the ash melting projects. It should also be emphasized that these results were obtained during preliminary trial runs which made no effort at parametric optimization. Until further testing can be performed a full analysis of the furnace injection results is not possible.

Good progress was being made toward the end of the test effort in meeting the second part of this objective. This involves a two-step process of sulfur capture, namely, sorbent injection in the combustor and retention of the sulfur bearing sorbent in the slag that is removed from the combustor. This process requires efficient combustion under very fuel rich conditions for the sulfur capture to occur, and rapid slag removal from the combustor of the sulfur laden slag. Efficient fuel rich combustion and rapid slag removal were only simultaneously achieved in the later stages of the three year test effort, following many incremental improvements in the combustor's operation. By the end of the project, a maximum 58% SO2 reduction had been measured at the boiler outlet stack with sorbent injection at Ca/S = 2 in the combustor. About one-third of the coal sulfur was retained in the dry fly ash removed from the floor of the combustor at the end of one of the tests. Very recently, with much improved slag removal from the combustor, 11% of the coal sulfur was retained in the slag, which was about a factor of 10 greater than that measured earlier in the project.

In tests subsequent to the completion of the Clean Coal project, high frequency (about 1 second frequency and several feet in amplitude) coal flame fluctuations were detected in the combustor at part load conditions and at near stoichiometric air/fuel ratio in the combustor. These fluctuations have been traced to the feed system. It is, therefore, quite probable that similar fluctuations exist in the sorbent injection system. This means that the temporal air/fuel ratio changes significantly in time periods of the order of the gas transit time in the combustor. At the higher firing rates used in most of the Clean Coal tests these fluctuations were not as pronounced, most probably they were masked by the intense luminosity of the combustor flame. Such a situation will have an even greater impact at very fuel rich combustor conditions. It is, therefore, possible that these fluctuations were in part the cause for the poorer and varying sulfur capture experienced in the present combustor compared to the results obtained in the smaller (5-7 MMBtu/hr) cyclone combustor used by Coal Tech at the Argonne National Laboratory (Ref.5).

A second factor that is of major importance in combustor sulfur capture is efficient sorbent, coal, and air mixing. This point has been noted previously in this report. Post Clean Coal project tests have been performed with an improved solids injection system and significant improvements in slag retention have been observed. This new injection system could be used to achieve better mixing during sorbent injection. It would be of great interest to repeat the sulfur capture tests in the combustor with the improved sorbent injection method as well as with the smoother coal feed system. In addition, other experiments have been defined which should conclusively validate the process of high sulfur capture and retention in the slag. We are very confident that this non-equilibrium process of sulfur capture and retention of the sulfur in the slag, for which Coal Tech has a patent, can produce the levels of sulfur reduction stated in this objective.

Recently, workers at AVCO Research Laboratory (R.Diehl, et.al.,"Emissions Control in a Coal Fueled Gas Turbine Slagging Combustor for Utility Applications" in 7th Heat Engines Contractors Meeting, NTIS #-DE90000480, p.113-122) reported measuring about 90% sulfur capture by this process in a slagging coal combustor in a 6 atm. pressure combustor using a similar non-equilibrium sorbent injection process.

Objective #C-3. <u>NOx reductions to 100 ppm or less.</u>

With fuel rich operation of the combustor, a three-fourths reduction in measured boiler outlet stack NOx was obtained, corresponding to 184 ppmv. An additional 5 to 10% reduction was obtained by the action of the wet particulate scrubber, resulting in atmospheric NOx emissions as low as 160 ppmv. This range of reduction is readily achieved in numerous staged combustion furnaces. The novel aspect of the present results is that they were achieved with final combustion air injection near the fuel rich exhaust from the combustor. In this kind of arrangement, it is known that reductions in overall NOx have not been optimized owing to the effects of second stage flame temperatures, which were probably higher than necessary to achieve good fuel utilization. Modification of tertiary air injection geometry to evaluate the effects on NOx control vs. combustion efficiency were not undertaken since project goals, as well as limited resources, dictated that most of the effort be directed toward improving sulfur capture.

Objective #B-4. The solid products from the combustor, i.e. slag/sorbent/sulfur compounds, are environmentally inert or can be readily converted to an inert form.

All slag removed from the combustor has yielded trace metal leachates well below the EPA Drinking Water Standard, when subjected to the Extraction Procedure (EP) Toxicity test. In the future, it is planned to test slag leachability with the newer TCPL test. In addition, combustor slags were tested nonhazardous with regard to cyanide and sulfide reactivity. Also, it remains to be determined whether high sulfur retention in the slag will maintain the slag leachability and/or reactivity of sulfides within acceptable limits.

The scrubber solids were disposed of in the Williamsport sanitary sewer system. This solution is unacceptable for long duration operation in large industrial and utility boilers. Coal Tech has a project currently in progress to determine the feasibility of converting fly ash collected in stack particulate equipment to inert slag by reinjecting the ash into the combustor. In any case, our scrubber fly ash represents only about one-quarter of the total ash, compared to 85 to 90% in a PC fired boiler. Fly ash is mostly landfilled while bottom ash and slag can be used beneficially.

Objective #B-5. Achieve high combustor slag retention and removal as well as compliance with local particulate emission standards.

The local particulate emission standard of 0.4 lb/MMBtu has been met with the use of a single stage, wet venturi, particulate scrubber. The resultant sludge is disposed of in the sanitary sewer system.

Slag retention is critically dependent on proper solids injection, efficient combustion, good slag flow and drainage from the combustor, and the duration of the run. The last item is of importance in that in single day runs, as in the bulk of the present project, a significant quantity of slag is inventoried in the combustor and/or collects in the exit nozzle. The degree of collection in the exit nozzle also depends on the operating conditions in the combustor. In any case, total slag retention under efficient combustion operating conditions has averaged about 72%, with a range of 55% to 90%. These figures include the slag inventoried in the combustor exit nozzle and on the boiler front wall. Under more fuel lean conditions, the slag retention averaged 80%.

In post Clean Coal project tests on fly ash vitrification in the combustor, modifications to the solids injection method and increases in the slag flow rate produced substantial increases in the slag retention rate.

An equally important aspect of slag retention is slagging of the boiler tubes in the boiler furnace and convective sections. In three years of operation with 100's of hours of coal fired operation, no slag deposits were formed on the boiler tubes, only dry ash deposits were formed. The latter were easily brushed off. This is a very significant result for future oil fired boiler retrofits.

Objective #A-6. Achieve efficient combustion under fuel rich conditions. Efficient coal combustion requires good slag coverage and, as noted above, this required development of proper air cooled combustor operation. After proper operating procedures were achieved in 1988, 99+% combustion efficiencies were measured in the boiler outlet stack with first stage inverse equivalence ratios (SR's) in the range of 0.85 to > 1. Achieving the same combustion efficiency at SR in the range of 0.65 to 0.85 required considerable development in the areas of air cooling, coal type and firing rate, slag flow, sorbent type and throughput, and process temperature. It was only in the latter part of the test effort that efficient combustion was achieved at SR = 0.7 or less. One should note that inefficient fuel rich combustion is characterized by extensive unburned char rejection in the slag tap.

Objective #E-7. Determine combustor turndown, with a 3 to 1 objective. This is one area where the air cooled combustor has a clear advantage over water cooled units since with air cooling wall temperatures can be adjusted over a wide range. Nevertheless, it required considerable effort to achieve this goal. Efficient turndown requires a proper integration of thermal input with wall cooling procedures. The initial approach selected to attain this was found to be incorrect and a number of alternate procedures were tried before the correct one was identified. One component of the correct procedure was to preheat and cooldown the combustor on oil since coal combustion was poorer at very low fire. This resulted in less coal consumption than had been originally planned. The resulting turndown was from 19 to 6 MMBtu/hr with coal, a 3.2 turndown. At this time we believe that a 4 to 1 turndown from 20 MMBtu/hr can be achieved with coal.

One other plus with air cooling is that the bulk of the combustor wall enthalpy was recovered as regenerative combustion air preheat while the small amount of cooling water to some of the combustor components accounted for only 2 to 3% of total heat input as permanent heat loss.

Another related result is that even with staging, coal fired flame lengths fit into the boiler firebox. Thus no boiler derating was required for this reason. This is in contrast to conventional PC burners wherein the entire combustion process must take place within the boiler. Several visual inspections of the boiler tubes in the radiant section showed no evidence of corrosion/erosion due to coal firing. In addition, the small dry ash buildup in the firebox was quickly removed between test runs by vacuuming. Periodic soot blowing at the end of a test series kept the convective section clean.

It is appropriate to note some of the constraints which prevented the combustor from being operated at its design maximum of 30 MMBtu/hr. In the first place, the 30 MMBtu/hr rating is based on fuel-rich, staged operation at 70 % or less of theoretical combustion air. In practice, it was discovered that the combustor could not be brought up to operating temperature under fuel-rich conditions. Thus, a stoichiometric or excess air heatup was required. At the 30 MMBtu/hr level there was insufficient combustion air to achieve a near-stoichiometric heatup. Secondly, the test boiler had a thermal limit of 23 MMBtu/hr. This fact put a ceiling on the thermal heat input regardless of combustor operation. Finally, the availability of water to the boiler was largely limited by supply pressure, which tended to fluctuate and drop, especially in summer afternoons, and/or by the flow capacity of the boiler water de-aerator. This set the practical operating limit at 19 to 20 MMBtu/hr.

Objective #D-8. Evaluate materials compatibility and durability.

Different sections of the combustor, i.e. the consumables injection section, air cooled liner, slag tap, and exit nozzle, have different materials requirements. Suitable materials for each section have been identified from test results. Also, the test effort has shown that operational procedures are closely coupled with materials durability. This applies especially to the refractory components including the air cooled combustor liner, slag tap, and exit nozzle. The procedure used in the tests of daily cycling the combustor between pilot heating and full thermal load imposed much more severe thermomechanical stressing on the system than steady state operation over extended periods. In any case, a combination of materials and operating procedures has been identified which will result in acceptable materials durability. For example, by wall temperature control it is possible to replenish the combustor wall thickness with slag, and this procedure has been recently successfully tested. Due to continuing changes in environmental laws concerning solid waste disposal, this area requires further work. For example, changes in leaching standards for solid waste produced in coal combustion may require changes in refractory selection or in operating procedures to maintain environmentally inert solid wastes.

Objective #D-9. Operate the combustor on coal for approximately 900 hours of steady state operations with frequent startup and shutdowns.

The combustor's total operating time during the life of the Clean Coal project was about 900 hours. This included about 100 hours operation in the ash-to-slag conversion tests. Of the total time about one-third was with coal. As noted above, the major cause for this lower coal firing period was the inability to use coal for preheat and cooldown, as had been originally planned. About 180 tons of coal were used in the course of the project, of which about 125 tons were consumed. Another factor in limiting the total operating time on coal was the considerable work that was expended, especially in the first half of Phase 3, in correcting operational problems in commercial auxiliary components, (e.g. fans, coal feed,etc.) (See comments in Objective D-10). It should be noted that in the latter part of the project, and after the completion of the Clean Coal project when the combustor computer control system was implemented, the actual coal firing tests times were very close to the scheduled coal fired tests times.

Objective #D-10. Develop safe and reliable combustor operating procedures.

In our opinion this was one of the major objectives of this project, and it was fully met. Operating procedures are necessary to achieve coal type flexibility, efficient air cooled liner operation, uniform coal and sorbent feed, continuous slag removal, acceptable combustor/boiler interface thermal performance, and acceptable particulate emission control. In planning the project, it was assumed that the auxiliary systems, e.g. solids feed, air fans, etc., were commercial "off-the-shelf" items. As such they would require essentially no additional development, and the bulk of the project effort would focus on the combustor. In practice, it was found that problems were encountered with all auxiliary systems. Fans had to be replaced, the coal and sorbent feed systems required extensive development, the scrubber walls eroded and had to be replaced. To each of these problems, unique solutions were developed. They now form a valuable and proprietary data base for operating this combustor.

The entire test effort was performed with manual control of the combustor during preheat, cooldown, and coal fired operation. This was done for two reasons: budget limitations, and lack of an operational data base for commercial scale air cooled combustors. A commercial conventional computer control system suitable for an R&D facility would have cost a significant fraction of the entire project budget. In the course of the final year of Clean Coal testing, sufficient data had been accumulated to allow conversion of the combustor to computer control. Coincidentally, Coal Tech had developed a computer control system for one of its other projects that was based on a personal computer. This system was combined with a commercially available generic process control software package, which was customized by Coal Tech for the air cooled combustor's operation. This system was installed for use in the final Clean Coal test in May, 1990. Due to "bugs" in the software, as well as some defects in purchased hardware, only limited computer control was implemented in this test. However, the computer was able to operate all the control components with manual input to the computer. It is anticipated that complete computer control will be implemented shortly under the ash project.

In conclusion, the procedures needed for long duration air cooled combustor operation have been developed during the Clean Coal Technology Phase III test effort. Additional round-the-clock continuous operation verification tests should validate this conclusion. Since there was some doubt among combustor experts whether air cooling would work, this is a major accomplishment. Air cooling was shown to provide more operational flexibility than water cooling. As an example, a three to one combustor turndown, which was a project objective, was achieved with a thermal input range of 6 to 19 MMBtu/hr.

3.4. Recommendations for Future Work

3.4.1. Near-Term Testing

The two most important tests that remain are optimization of sulfur capture in the combustor and sulfur retention slag removed from the combustor, and round-the-clock coal fired operation. With the new computer controlled combustor operating system and the improved feed and solid injection systems both steps can now be taken and Coal Tech has submitted a proposal to DOE for this purpose. The following briefly describes the nature of these tests:

3.4.1.1. Sulfur Capture Tests in Combustor

As has been noted in several places in this report, sulfur capture inside the combustor requires efficient very fuel rich combustion as well as rapid slag removal to prevent desulfurization of the slag. In addition, the data to-date suggests that the maximum sulfur concentration in the slag formed from the reacted sorbent and coal ash may be limited to a small fraction of the total coal sulfur. This problem can be solved by increasing the total slag mass flow rate by injecting additional ash into the combustor. Coal Tech is developing procedures for injecting fly ash into the present air cooled combustor as part of another DOE sponsored project on fly ash vitrification. To-date, the ash level injected has reached the equivalent of a 45% ash coal under conditions where good slag flow and slag removal from the combustor was sustained. This is considerably greater than the slag mass flow rates needed to capture sulfur in the combustor in very high sulfur coals and still maintain good slag flow. At these high ash level the degree of sulfur retention in the slag can be very low. For example, in a 4% sulfur, 10% ash, bituminous coal, with sorbent injection at a Ca/S ratio of 3, ash injection at the rate of 22% of the coal flow rate (total equivalent ash level is 32%), will produce acceptable slag flow properties in the combustor and result in less than an 8% sulfur concentration in the slag. The latter is within the sulfur concentrations measured in Clean Coal project tests.

The second part of the sulfur optimizations tests is to optimize the combustion efficiency. As noted, recent tests have uncovered strong multi-second flame fluctuations under part load, fuel lean conditions. These were most probably present in the higher thermal input fuel rich tests performed during the Clean Coal project. Very recently, a procedure has been found that has considerably smoothed out these fluctuations, and this points the direction for further improvements. This result is of some significance to the sulfur capture tests as temporally uniform coal and sorbent injection are essential to achieve rapid sulfur-sorbent reaction in the combustor.

Another part of the sulfur capture optimization process is to be able to inject sufficient sorbent to achieve a high Ca/S ratio and to assure rapid and uniform mixing of the sulfur and sorbent. The sorbent injection capability of the combustor during the Clean Coal tests was limited to a very low Ca/S ratio even in medium sulfur coals. Very recently a new injection system has been installed which allows a fivefold increase in the injection rate, as well as better mixing with the fuel.

Even with the above improvements it is still essential to separate the sulfur capture process from the sulfur retention process in the slag. To accomplish this a test was planned at the end of the Clean Coal project to inject calcium sulfate, instead of limestone, into the combustor, and to measure the fate on the sulfur in the combustion gas phase and in the slag. Unfortunately, this test was the one test when the mechanical slag breaker was damaged due to an oversight and the gypsum injection did not continue for a sufficiently long time to evaluate the fate of the sulfur. This test, as well as a test in which a surrogate material having an extremely rapid sulfur gas release, e.g. high sulfur oil or H_2S gas, should be implemented. These tests and the new procedures should finally resolve the sulfur capture potential of the combustor.

3.4.1.2. Round-the-Clock Coal Fired Operation

Due to manpower and budgetary constraints, there were no plans to perform round-the-clock coal fired tests in the Clean Coal project. In addition, only several tests were performed with round the clock manned operations in which substantial oil and gas heat inputs were used. This experience showed that overnight manned coal fired operations would be very costly since a full test crew including senior test engineers would have to be in attendance.

The automation of the combustor for overnight unattended operation with a gas fired pilot heat input in early 1989 was an important first step in the direction of continuous coal fired operation. However, it was only with the addition of the current computer control of the combustor that round-the-clock coal fired operation is feasible at a reasonable cost. The current computer control system has most of the components needed for automatic unattended coal firing. The only additions necessary would be automation of the slag removal and slag tap clearing, which can be easily implemented. In addition, the present coal and limestone storage systems are capable of one 8 hour shift operation at half load without refilling, and this step could also be partially automated by controlling the coal bin refilling from a tanker truck placed alongside the boilerhouse. In addition, the use of computer control and data acquisition has considerably reduced the manpower required to monitor and record the combustor performance.

Therefore, it has been proposed that a series of increasingly longer continuous coal fired tests at part and full (20 MMBtu/hr) boiler load be implemented with continuous coal firing for periods of 24 to 48 hours duration. The only modifications to the combustor needed to implement these tests would be to refurbish the boiler front wall to add a modest amount of additional cooling of the front wall of the boiler, and to refurbish one water cooled circuit at the upstream end of the combustor.

Some of the test data suggest that either additional air pre-heat or a somewhat longer combustor might result in improved combustion and sulfur capture inside the combustor. Several design approaches have been considered to implement these changes. One would involve a very modest change to the combustor, while the other would require the addition of another section. Whether this is in fact necessary, and which of these two approaches should be selected should become clearer as the above tests are implemented.

The total test time required to implement the above tests is estimated at an additional 500 hours. At their completion the sulfur capture capability, durability, and degree of automatic operation of the combustor would be established.

3.4.2. Long-Term Air Cooled Combustor RD&D

Coal Tech is currently testing the use of this combustor for the vitrification of coal fly ash and two one day tests on the vitrification of municipal incinerator ash were performed. The objective of these tests is to determine the degree of trace heavy metal retention in the chemically inert slag and the maximum throughput of fly ash through the combustor. Experiments to date are approaching 1/2 ton/hour ash throughput rates, and theoretical analysis suggests that this rate could be doubled in the present 30 MMBtu/hr combustor. The second application is the combustion of municipal refuse derived fuels (RDF) under conditions where no undesirable micropollutants are emitted with the stack gases, and where the resultant slag is also chemically inert. Four one day tests on co-firing of refuse derived municipal waste with coal were very successful. The ratio of RDF/coal was varied from 15%/85% to 55%/45% by weight. The slag properties of the solid waste were similar to those with coal only firing.

The next logical step in the commercial development of the combustor is a scale-up to the 100 MMBtu/hr size. Coal Tech has performed preliminary engineering design studies of a 10 MWe electric power plant using the Coal Tech air cooled combustor on an oil design boiler for this purpose. Several sites in the Southeast Pennsylvania area have been identified. The objective of this commercial scale project is to produce electric power for sale to a local utility over a 10 to 20 year period. The plant would also serve as a commercial demonstration site of this technology for future use in industrial and utility boiler applications because the 100 MMBtu/hr size range is the modular size that would be retrofitted on larger boilers in multiple units.

Another application is to use the combustor in a combined gas turbine-steam turbine cycle. Coal Tech has performed preliminary several analyses of two novel combined cycle configurations in which the air cooled combustor is fully integrated with the gas turbine gas stream. Both cycles result in substantial increases in overall cycle efficiency. In addition, in one of the cycles, the combustor's integration in the combined cycle could result, not only in higher cycle efficiency, but also much higher SO2 and NOx reductions, specifically above 95% and 90% respectively. The combined cycles would apply to power plants in the 5 MWe range and higher. The fuel could be coal, or coal co-fired with refuse derived fuel. The minimum economical thermal rating for the combustor would be about 50 MMBtu/hr, which is only about a factor of two scale up from the present combustor rating. By using combustors rated at 100 MMBtu/hr, these cycles could be scaled up to small utility sizes in the 100 MWe range. The 5 MWe commercial project could be implemented at the conclusion of the durability tests outlines in the previous sub-section.

3.5. Combustor Applications

3.5.1. Boiler Retrofit Applications

During the past decade, Coal Tech has explored several applications of the combustor. The primary focus in the first half of the 1980's were detailed studies on the retrofit of the combustor to various utility size boilers. The most extensive of these was to a 125 MWe oil fired power plant located in the Southern California Edison Company system (Ref.28). This study resulted in a detailed design of a 100 MMBtu/hr air cooled cyclone combustor that served as the prototype design for the present 30 MMBtu/hr unit. In addition, a considerable effort was expended on obtaining a compact design for the attachment of multiple 100 MMBtu/hr combustors to the 125 MWe power plant. Other unpublished studies considered the retrofit of this combustor to power plants up to 800 MWe rating, and as small as 100 MMBtu/hr industrial boilers.

One major combustor application is for sulfur control in utility boilers. The following sub-section will provide a summary of recent analysis of the economics of the retrofit of this combustor to a nominal 250 MWe power plant.

The second important application for this combustor is the retrofit of industrial boilers in the 100 MMBtu/hr size range and up, from oil/gas to coal. The 10 MWe power plant project mentioned in the previous section is an example of such an application. The design selected is economical for in-plant steam generation for a wide range of coals. It is also economical for over the fence power generation sales, if the coal fuel is mixed with a waste type fuel, such as RDF. As the economics of these smaller plants is very site specific no discussion will be presented at this time. However, note that the delivered fuel cost is a major factor in the plants economics. For economic application the plant must be generally within about 200 miles of the fuel source.

The third application is to boilers in the size range of the present combustor project, i.e. boilers less than 100 MMBtu/hr rating. Here the preferred fuel would be a slurry or an off-site central coal pulverization plant, or a waste fuel, such as RDF. In the first two cases fuel delivery would be by tanker truck, i.e. the method used in the prior coal-water slurry project and the present Clean Coal project. With oil/gas in the $20-30/barrel price range this application could become very important, provided the boiler operator costs are drastically reduced. This goal can be achieved if the present computer control system is fully demonstrated. Its use would allow the combustor to operate with little or no supervision. This application is the nearest to commercial readiness.

3.5.2. Solid Waste Control Applications

Another combustor application is to the economic use of solid wastes, such as ash vitrification, organic waste incineration, or solid waste combustion, such as RDF. The key elements in the technical and economic feasibility of this application are the maximum attainable feed rate, and the degree of retention or destruction of organic and inorganic micropollutants in the slag or in the combustor. The solution to these problems is the focus of current tests on the 30 MMBtu/hr combustor. The solids feed problem is very challenging, especially in materials such as RDF and fly ash. The novel feature of Coal Tech's approach to trace metal retention in the slag is to assure rapid ash melting and slag removal in a time that is less than the diffusion and vaporization time of the volatile trace metals, such as Pb, As, etc. To be economical these materials must represent a significant fraction of the total solids mass flow rate in the combustor.

3.5.3. Economics of Retrofit of a 250 MWe Coal Fired Utility Power Plant.

Plant Performance: The following discussion summarizes the results of an analysis performed during the past year that is based on the sulfur control results obtained in the Clean Coal project. Only experimentally demonstrated results were used. Therefore, better economics are attainable as the combustor sulfur capture improves. Full details and references are given in reference 27. The analysis was based on the conversion cost of the 250 MWe coal plant specified in the DOE Innovative Clean Coal Technology III Solicitation, and it considers only the cost of a retrofit with 16 Coal Tech's combustors, each rated at 150 MMBtu/hr. The economic assumptions used in the following cost data were obtained either from the guidelines that were specified by DOE Clean Coal III Solicitation (Ref.32) or by the groundrules specified for the "Comparative Economics of Clean Coal Technologie " Conference (Ref.27). Coal Tech makes no claims as to the validity of the economic assumptions in the three referenced documents. The following results are meant to be used for comparitive purposes. Also, Coal Tech's cost estimates on the combustor and immediate auxiliary equipment are based on proprietary data of the Company.

Table 5 shows the performance for the 250 MWe plant. The first column shows the original coal fired plant specified by DOE Clean Coal III. It does not control either SO_2 or NO_x. The 2nd and 3rd columns show respectively, the performance with a 2.4% and a 4.3% sulfur coal. The SO_2 reductions shown in Table 5 are achieved in two steps. With limestone injection into the combustor, 40% and 30% SO_2 reductions are achieved in the 2.4% and 4.3% coal respectively. The different reductions in the two coals are dictated by the need to maintain proper slag flow conditions in the combustor. The second step of 80% SO_2 reduction is achieved by lime injection downstream of the combustor into the boiler. With this 2 step process, overall SO_2 reductions of 88% and 86% are achieved for the two coals, with Ca/S ratios of 2.5 & 2.35, respectively.

The next item of interest in Table 5 is the parasitic power. This consists primarily of the added fan power dissipation required for the air cooling of the combustors and the limestone pulverization power. The second major source of parasitic losses are heat losses from calcination, water cooling of several parts of the combustor which cannot be air cooled, and heat losses due to quenching of the slag removed from the combustor. These losses are estimated at 112 MMBtu/hr [equal to 4.7% of the thermal input of 2370 MMBtu/hr], and 140 MMBtu/hr [5.9% of the thermal input for the 2.4%S and 4.3%S coals, respectively.

A 75% NOx reduction is assumed using staged combustion. It is assumed that the combustor will retain at least 80% of the mineral matter as slag, and that the injected sorbent in the boiler will partition in a manner similar to bottom ash and fly ash. Therefore, the existing stack particulate cleanup equipment will satisfy the 0.1 lb/MMBtu emission standard.

The net result of the above calculations reduce the net power output of the plant from 250 MWe to 232.5 & 229.1 MWe for the 2.4%S and 4.3%S coals, and the heat rates from 9480 Btu/kW-hr to 10,144 & 10,345, respectively.

Capital and O&M Cost: The capital cost of the retrofit is shown in Table 6. It consists of the following sub-systems: Limestone storage, pulverization, and feed system; coal feed to the combustors; 16 combustors, including fans and ducting; boiler sorbent injection; slag removal.

The total cost for the process equipment cost for the retrofit was derived from the DOE Clean Coal III guidelines (Ref.32). It is estimated at $39 million. This cost includes a Retrofit Difficulty Factor of 1.55 for the combustor sub-system, and 1.1 for the other retrofit sub-systems. Of the basic cost of $25.6 million, about 50% represents the combustor sub-system. To this cost are added Process Contingency Factors, as specified in ref.32. The total plant cost factor of 142% of the process cost, which accounts for general facilities, engineering, and other contingencies, results in a plant cost for the retrofit of $55 million.

The next item is the allowance for interest and price escalation during construction which is estimated to require 2 years, and equal to 3% of the total plant cost, or $ 1.66 MM. The 2 year period for actual construction is based on the fact that the air cooled combustors are attached to the boiler without any modifications to the heat distribution in the boiler. Therefore, the only changes to the boiler are breaching of the water wall, if a corner fired boiler is used. No added wall breaching is needed if a face fired boiler is used. The combustors are supported separately from the boiler.

The next item is pre-production costs which relate to startup costs, and consist mainly of one month's total operating costs. It is estimated at $1.81 MM & $2.04 MM. for the 2.4%S and 4.3%S coals, respectively. The next item is inventory capital, which equals a 60 day supply of incremental coal and limestone supplies for the retrofit. It is $0.86 MM & $ 1.21 MM for the two coals.

The total capital cost for the retrofit is $59.75 MM. ($257/kw) and $60.35

MM. ($263/kw) for the medium and high sulfur coal cases.

The next group of items in Table 6 are the operation & maintenance costs. (Again note that these costs were derived with the DOE-CC III guidelines, ref. 32). The first item, the variable operating cost/hour, consists of the following items: The cost of the parasitic power, which is charged at a rate of 5 cents/ kw-hr; the parasitic heat, which is charged at the coal te of $20/ton; the limestone, charged at a rate of $20/t; water loss, which is negligible: the slag [consisting of a melt of coal ash and Ca compounds] and calcium sulfates/ CaO, for which a credit of $ 4/ton is taken; and the maximum 20% of these materials that are captured as fly ash for which a $6/t charge is made. The justification for the slag sale is that it is chemically inert and could justify a price of at least $10/t as a construction material. Similarly, the partially reacted sorbent injected in the boiler is relatively ash free, and it could be used in gypsum manufacture.

The annual maintenance cost is taken as 5% of the process area capital. The annual incremental operating labor is based on 4 operators/shift. The annual fixed O&M costs are taken as 112% of the annual maintenance cost plus 130% of the annual labor costs. This results in a total annual O&M cost of $8.06 MM. & $10.85MM. for the 2.4%S and 4.3%S coals, assuming 7000 hour operation. This converts to 4.95 mills/kw-hr & 6.77 mills/kw-hr. It is to be emphasized that these are incremental costs only associated with the conversion of the 250 MWe plant with the Coal Tech combustors.

Economics of SO_2 & NO_x Reduction: Since the analysis of the 250 MWe power plant is for a retrofit whose primary purpose is to reduce SO2 and NOx emissions to NSPS requirements, the conversion cost analysis has been structured to allow a determination of the incremental cost of meeting NSPS requirements. The results are shown in Table 6, and they were arrived at in the following manner:

The economic assumptions were (Ref.27 guidelines): 10% cost of funds, 25% equity-75% debt financing, a 50% tax rate, and straight line depreciation. A 15 year life, including depreciation and amortization over 15 years was used. The reason for this was to allow comparison with an EPA/EPRI economic study of the LIMB process (Ref.31), which is similar to the present technical approach in that sorbent injection occurs in the boiler.

The O&M costs shown in Table 6 were escalated over a 15 year period using the GNP deflator, and added to the 15 year amortized debt service. After deducting taxes, an arithmetic average of the total 15 year cost was computed. To this was added, using an arithmetic average over the 15 year period, of the 25% equity investment. For the latter a 10% opportunity cost was assigned. The resultant levelized average annual cost over the 15 year period is shown in table 6. This capital and O&M cost of about 10 mills/kw-hr is essentially identical to the values quoted in the EPA/EPRI study for 10 different LIMB cases applied to a 300 MWe wall fired unit at 62.8% capacity factor and using 1985 dollars and 1.92%S & 3.36%S coals. These costs are about 1/2 of the equivalent wet flue gas scrubber costs cited in reference 31. However, the economic assumption used in the EPA/EPRI study were not fully specified and they may not be identical to the present ones.

The incremental capital costs for the present case of about $250/kw are in the range of the FGD costs, and about double those for the LIMB costs as given in the EPA/EPRI study. Again, the economic assumptions may not be identical.

The best means of comparison is the cost per ton of SO_2/NO_x removed. Here, the present analysis shows levelized values of $304/ton for the 4.3%S and $476/ton for the 2.4%S coal for removal of both pollutants. This compares with $752/ton for the 3.36%S coal, and $924/ton for the 1.92%S coal for SO_2 removal only in the EPA/EPRI study. The comparable FGD costs are $1359/ton and $829/ton for the two coals respectively. This much lower cost of the present approach is much too great to be due to different economic assumptions.

It should be noted that it has been assumed that the retrofitted plant has a higher availability than the conventional coal plant, 80% versus 75%. This assumption applies to a mature plant. It is also based on the use of modular air cooling combustor designs that would allow removal of individual combustor and their replacement with spares in a period that is much shorter than in-boiler maintenance of water cooled slagging combustors. The reason is that there is no connection of the combustor to the boiler water-steam loop. Also, the low ash carryover reduces the fouling and ash deposits in the boiler, thereby reducing downtime for boiler maintenance from a conventional coal plant.

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TABLE 5 250 MWe POWER PLANT PERFORMANCE

	Reference Plant 2.4%S / 4.3%S	CombustorReftrofit 2.5% S coal	CombustorReftrofit 4.3% S coal
1. Coal Feed Rate, t/hr	105 / 105	105	105
2. Limestone, t/hr	--	19.6	33.2
3. Slag-(Coal & Sorbent), t/h	--	13	13.9
4. Spent Sorbent & Fly Ash, t/hr	--	12.8	22.4
5. Emissions @ Stack, lb/MMBtu			
$-SO_2$:	3.8 / 7.6	0.46	1.07
$-NO_x$:	1.2 / 1.2	0.3	0.3
-Particulate	0.1 / 0.1	0.1	0.1
6. % Emissions Reduction			
$-SO_2$ in Combustor	-	40	30
$-SO_2$ in Boiler	-	80	80
$-SO_2$ Total	-	88	86
$-NO_x$ Total	-	75	75
7. Total Thermal Input, MMBtu/hr	2370	2370	2370
8. Parasitic Thermal Losses, MMBtu/hr	-	112	140
9. Parasitic Power, MWe	-	5.05	5.3
10. Power Production, MWe			
-Gross	264	251.6	248.4
-Net	250	232.5	229.1
11. Net Heat Rate, Btu/kW-hr	9,493	10,144	10,345
12. Plant Efficiency, %	36	33.5	33
13. Plant Availability, %	75	80	80

Note: The performance data for the reference plant are given in reference 8.

TABLE 6 CAPITAL COST & OPERATING COSTS OF THE 250 MWe RETROFIT

CAPITAL ITEM-(MM$)	2.4% S. Coal	4.3% S.Coal
A-Process Capital	39.05	39.05
B-Total Plant Cost	55.42	55.42
C-2 yr. Construction Financing & Escalation	1.66	1.66
D-Total Plant Investment	57.08	57.08
E-Preproduction Costs	1.81	2.04
F-Inventory Capital	0.86	1.21
G-Total Capital Cost	59.75	60.33
H-Unit Cost- $/kw	257	263
OPERATION & MAINTENANCE ITEMS		
I-Variable Operating Cost-$/hr	694	1,093
K-Annual Maintenance Cost-MM$	1.95	1.95
L-Annual Operating Labor-MM$ (4 Operators/shift)	0.78	0.78
M-Annual Fixed O&M Cost-MM$	3.2	3.2
N-Annual Variable O&M Cost-(7000 hrs/yr)-MM$	4.86	7.65
O-Total Annual O&M Cost-MM$	8.06	10.85
P-Unit O&M Cost-mills/kw-hr	4.95	6.77
15 YEAR LEVELIZED RETROFIT COST, mills/kw-hr [Includes capital and O&M costs; See text]	10.28	11.58
15 YEAR LEVELIZED SO_2 REMOVAL COST, $/TON	$603	$346
15 YEAR LEVELIZED SO_2 & NO_x REMOVAL COST, $/TON	$476	$304

NOTE: Above levelized costs are based on using GNP deflator & 1992 start of operations.[See text]

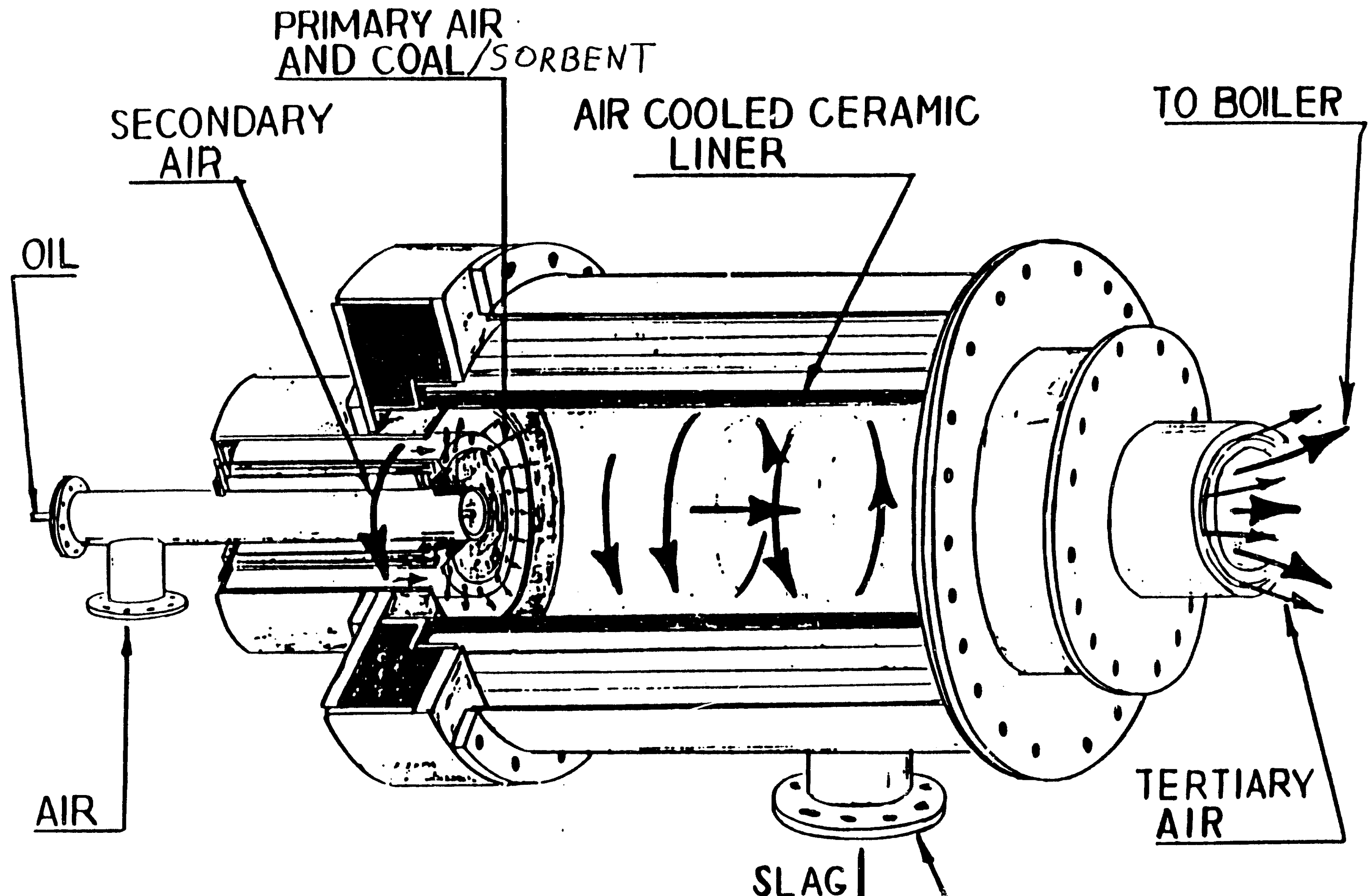


Figure 1.

COAL TECH CORP'S
AIR COOLED CYCLONE COAL COMBUSTOR

Figure 2. Tampella/Keeler Boilerhouse. The combustor is attached to the right side boiler, beneath the original stack and scrubber on the roof. The 4 ton coal bin is on the right of the boilerhouse.

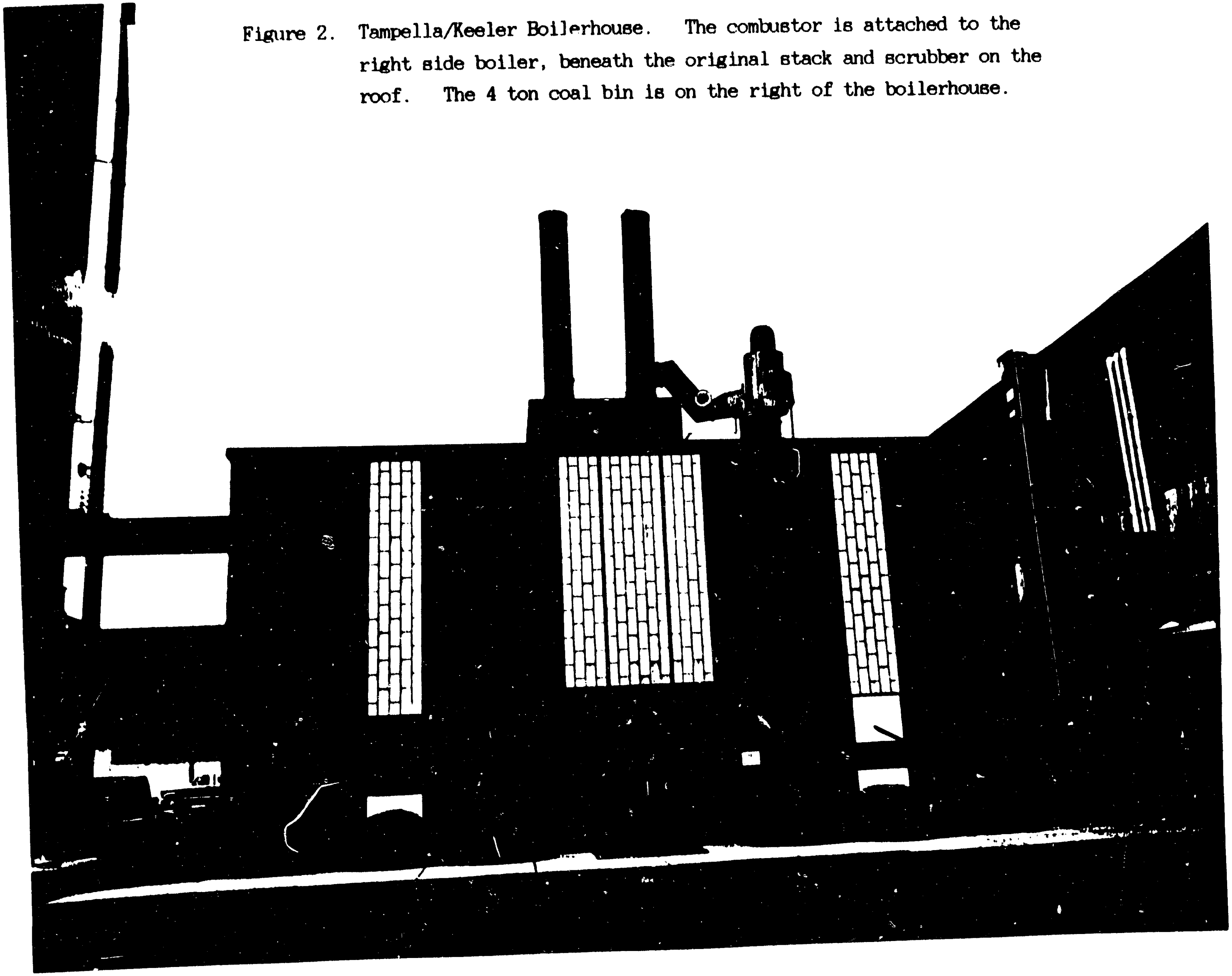


Figure 3: Photograph of the 30 MMBtu/hr Combustor in Keeler Boilerhouse

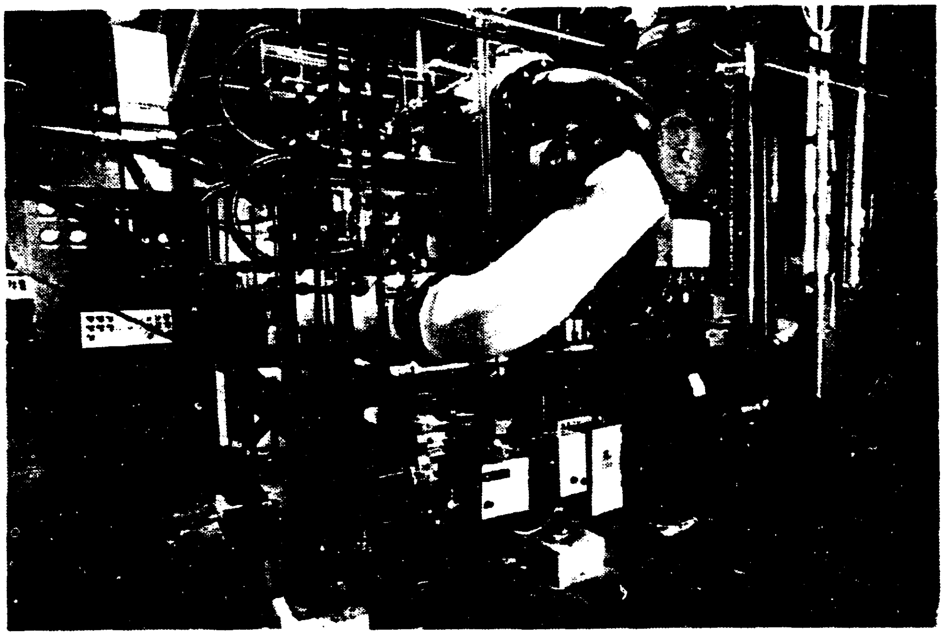


Figure 3. Drawing of the 30 MMBtu/hr Combustor & the 17,500 lb/hr Boiler

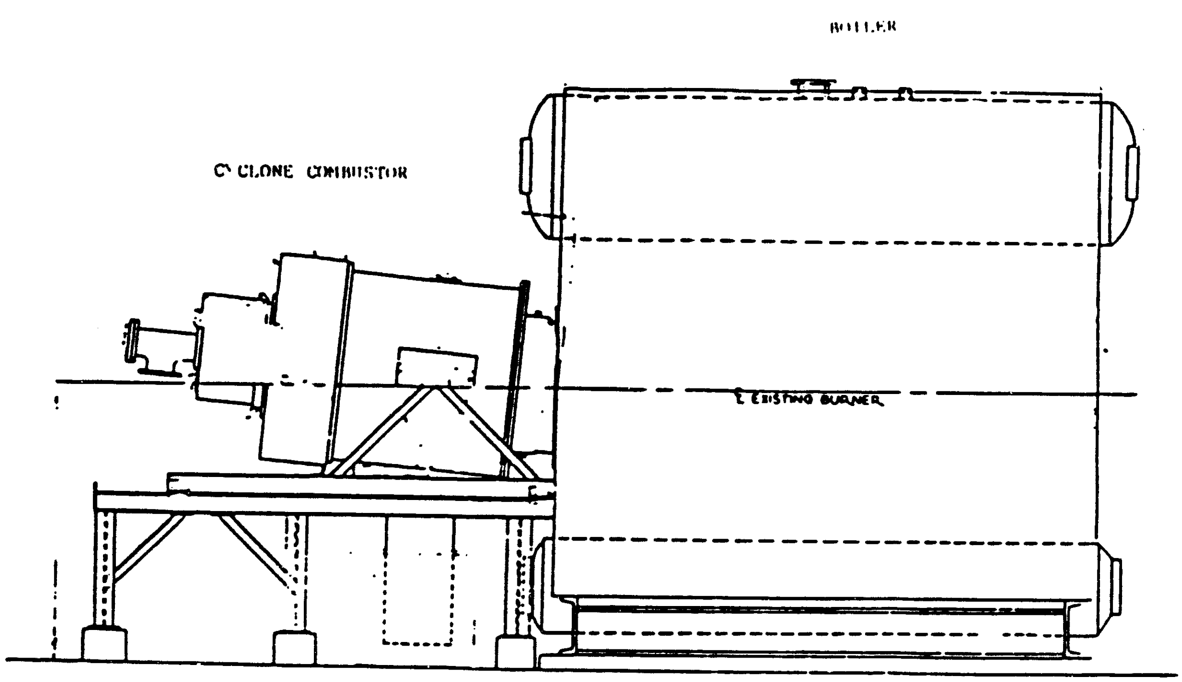
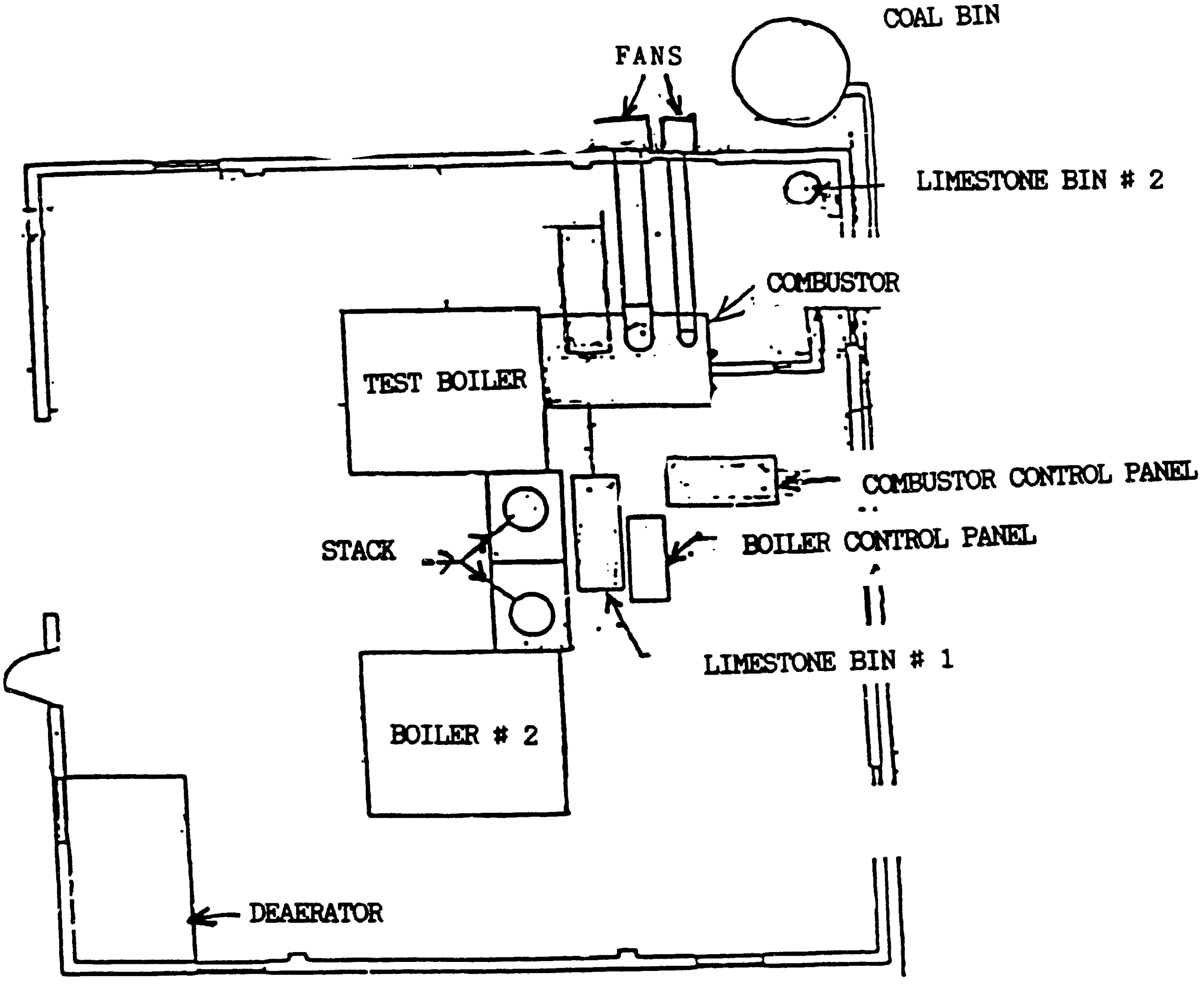


Figure 4. Plot Plan of the Installation inside the Boilerhouse.



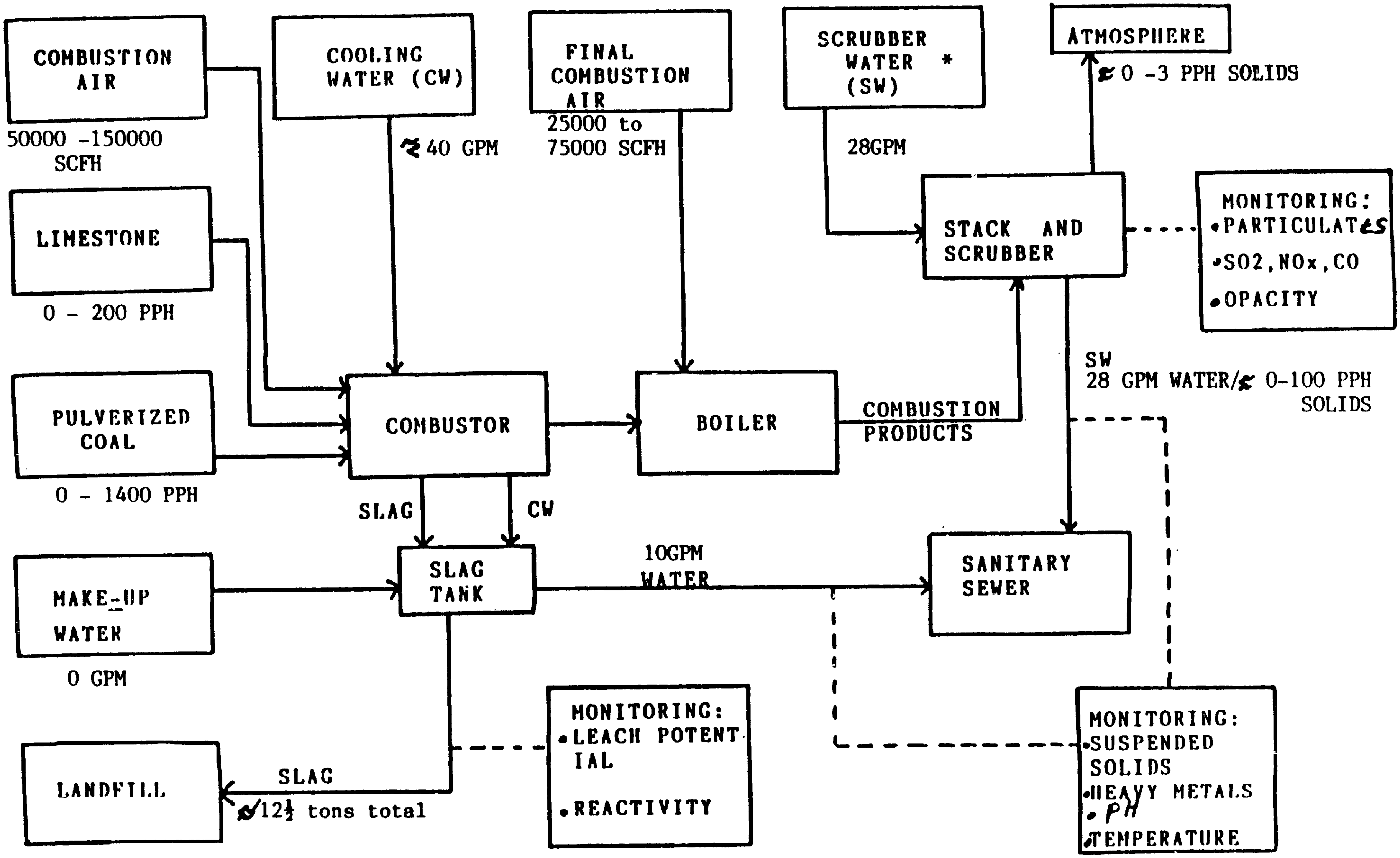


FIGURE 5: PROCESS BLOCK FLOW DIAGRAM

* Scrubber Water is recycled Combustor cooling water from the Slag Tank

Figure 6 View of the Wet Particle Scrubber on the Roof of the Boiler Building at the Williamsport, PA Test Site.
The ID fan is in the foreground, and the scrubber vessel is in the rear center. The original stack is on the right side.

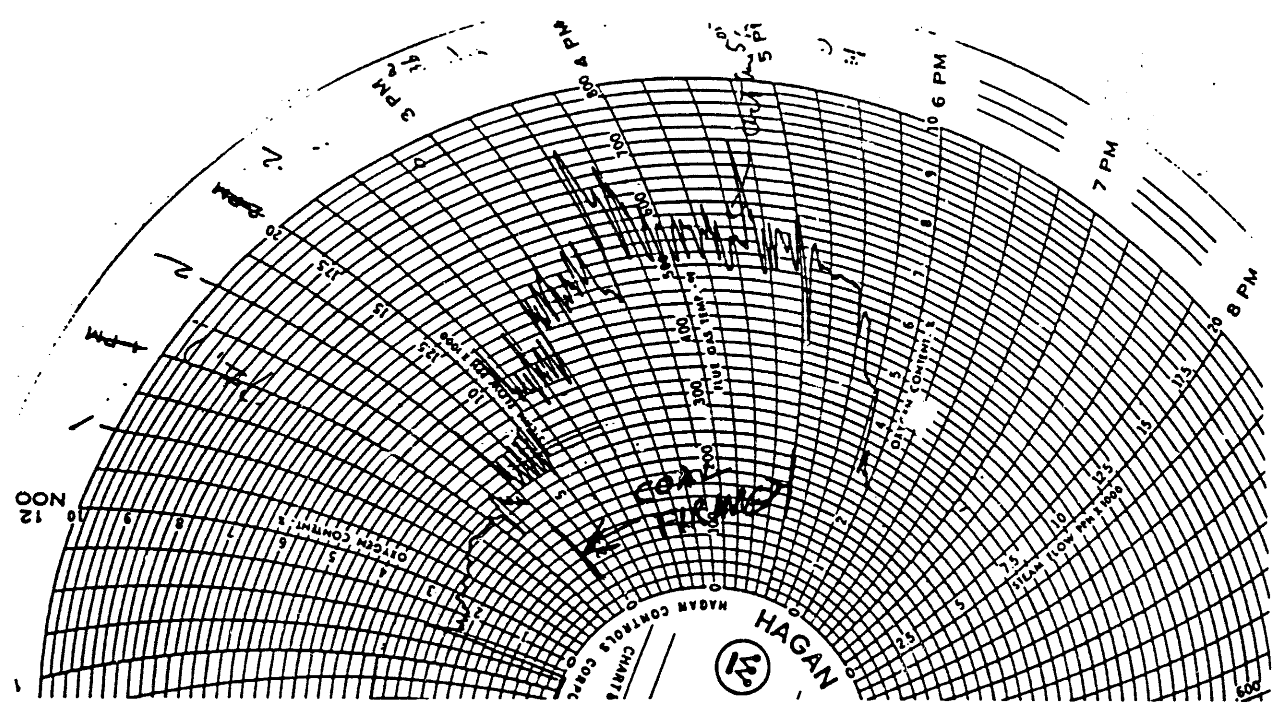


Figure 7A: Steam Mass Flow Rate in Test with High (>10%) Coal Feed Fluctuations

Test No.PC 11 on 6/29/88, early in Phase 3. Oscillations in steam flow of the order of 5 minute frequency are due to coal feed fluctuations. 4 hour period on coal is shown near center of chart.

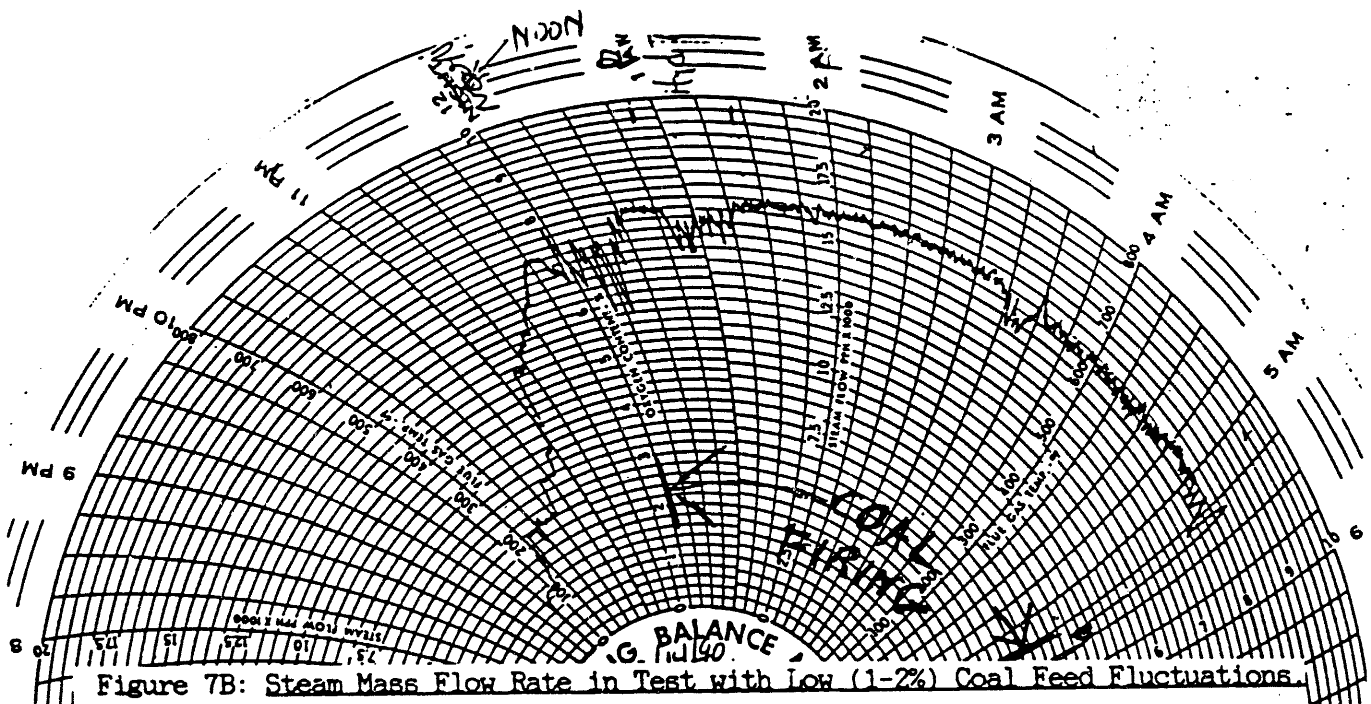


Figure 7B: Steam Mass Flow Rate in Test with Low (1-2%) Coal Feed Fluctuations

Test No.PC 25 on 2/14/90, late in Phase 3. Oscillations in steam flow early in coal fired period & @ 3:30 PM are due to change in operating conditions. High frequency multi-second feed pulsations are not detectable from chart.

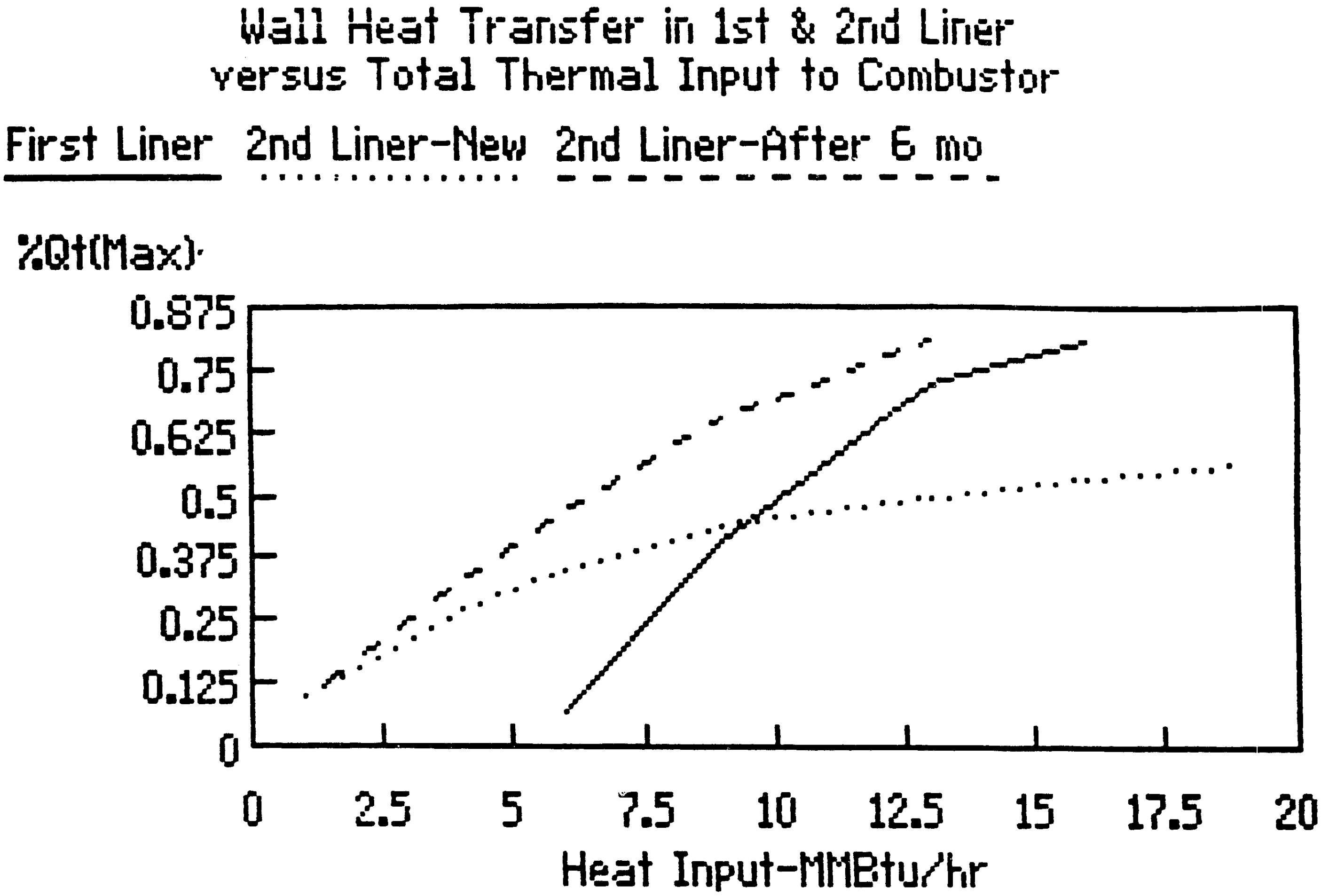


Figure 8: <u>Comparison of Wall Heat Transfer in the Old and New Liner.</u>
The average air cooled wall heat transfer, shown as a % of the peak wall heat transfer measured in the combustor, versus the thermal input to the combustor.
Note that the first liner had a high thermal conductivity which resulted in a weak dependence of wall heat transfer on thermal input. This feature was a factor in the liner failure. The second liner's thermal conductivity was well matched to the thermal input. Its higher rate of change of heat transfer after 6 months operation was due to liner material loss from slag attack. This was subsequently corrected by modifying the operation procedure.

"Additional data is contained in the Proprietary Document".

Figure 9 Photograph of the Control Computer for the Combustor showing its position in relation to the manual combustor control panel and the combustor.

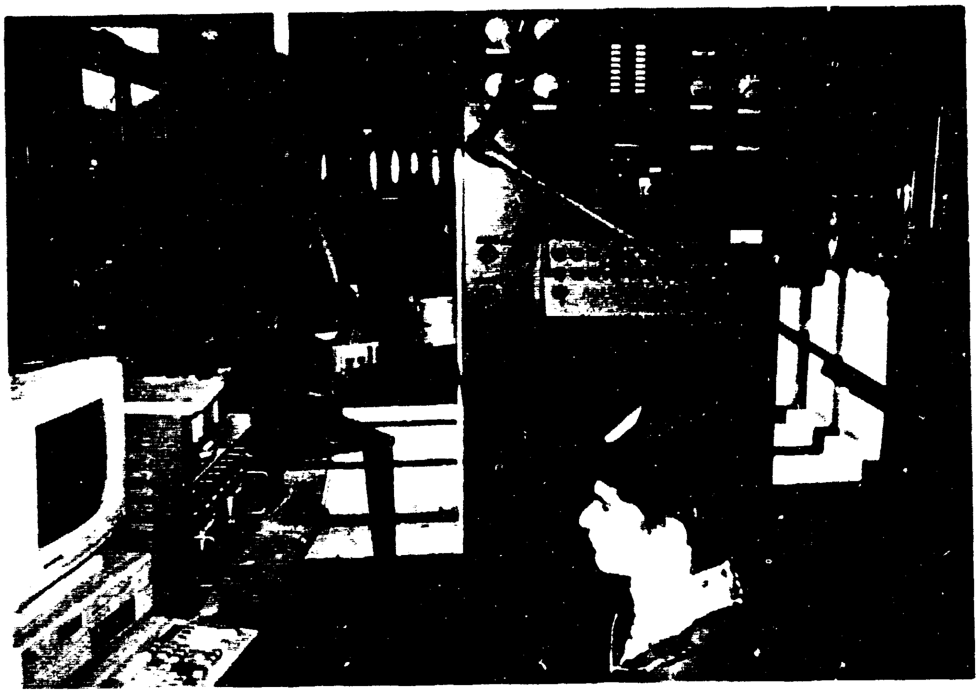


Figure 10 Photograph of the Computer Screen with the Operating Logo.

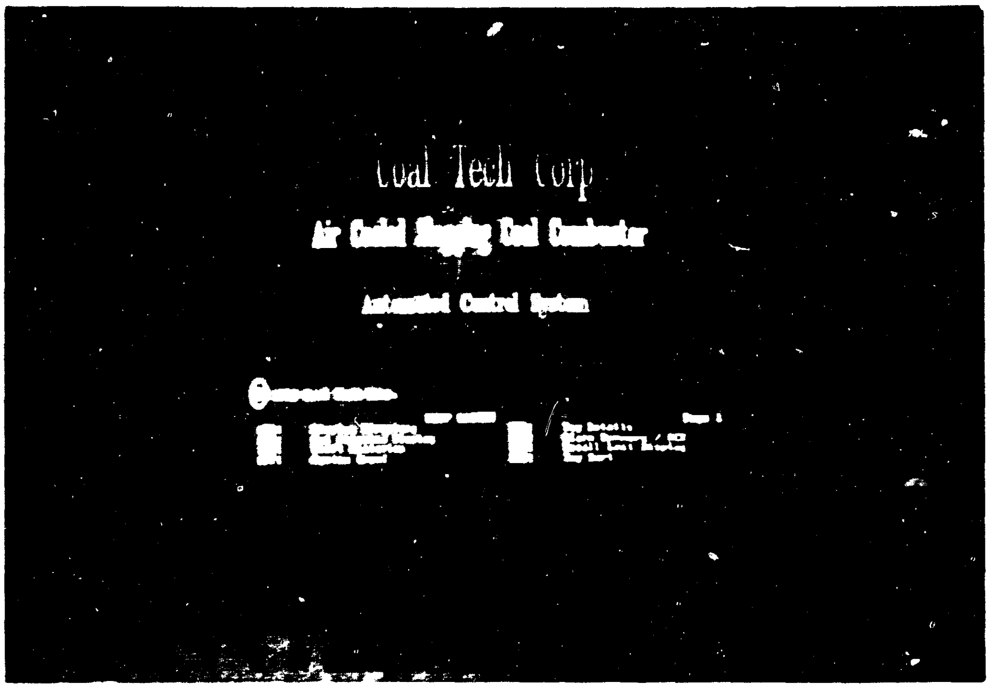


Figure 11. Ph... of the Process Control ... the Combustor

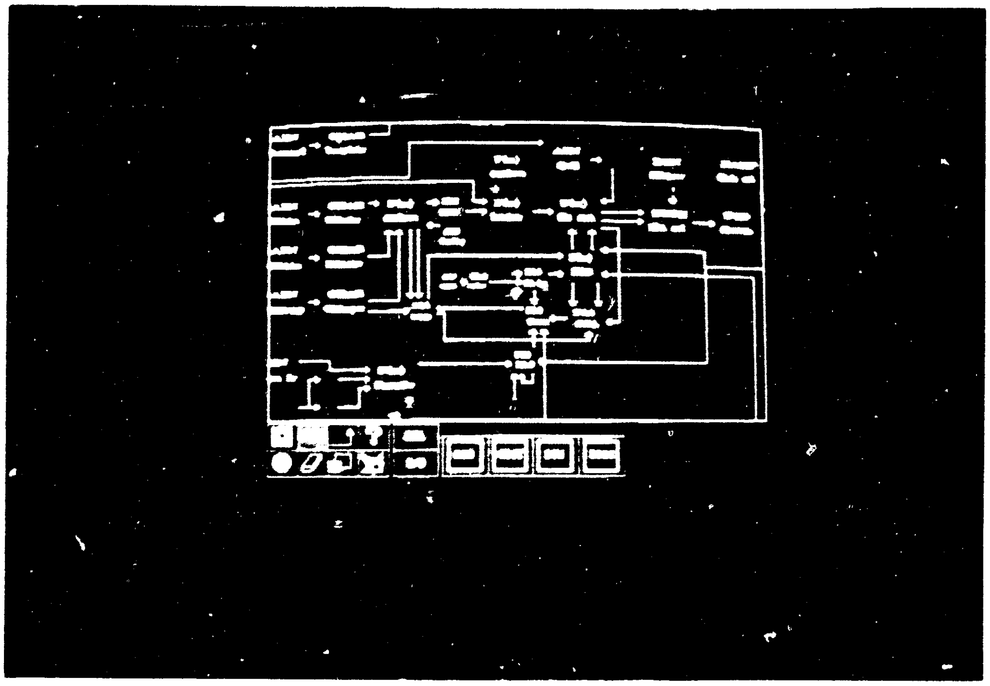


Figure 12. Photograph of the Computer Screen from which the Combustor is Controlled.

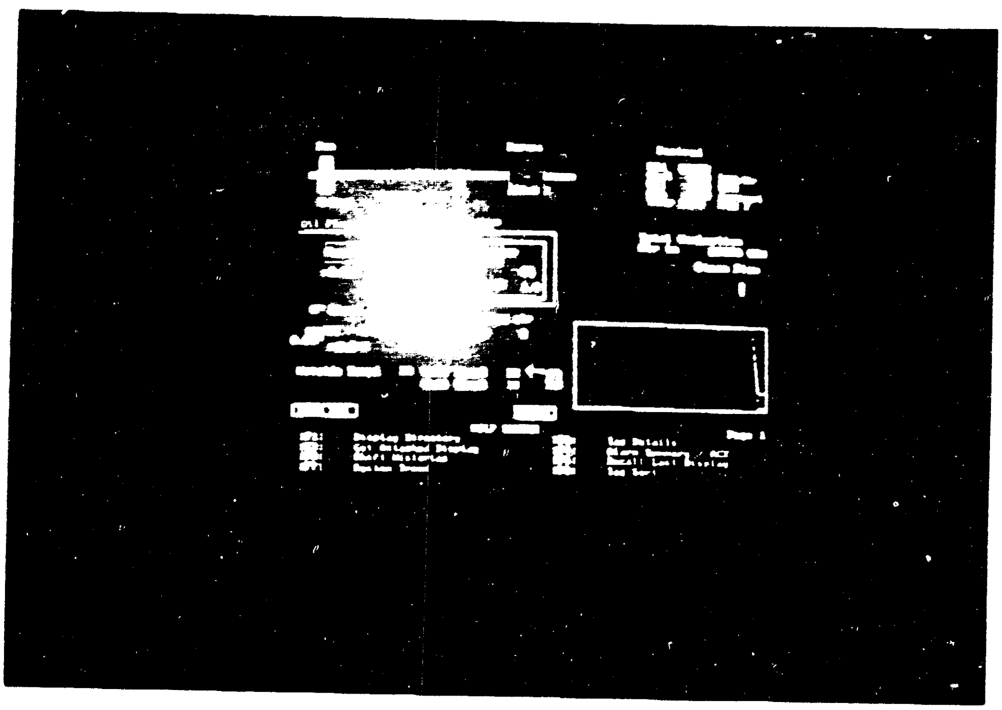


Figure 13. Photograph of the Slag Conveyor Installed and in Operation in the Slag Tank. Granular slag can be seen on the conveyor belt.

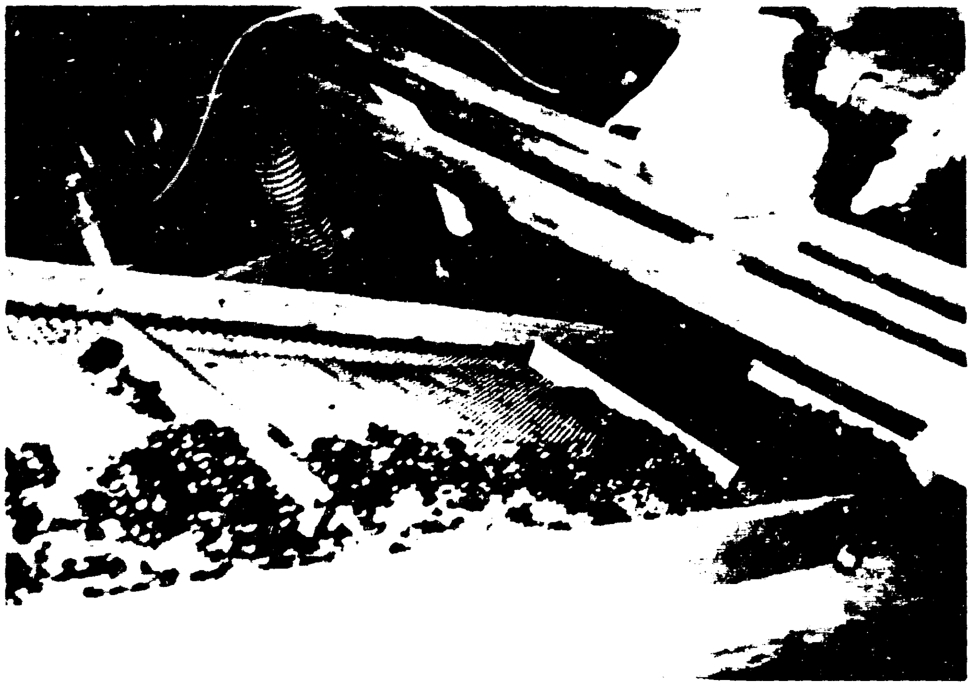
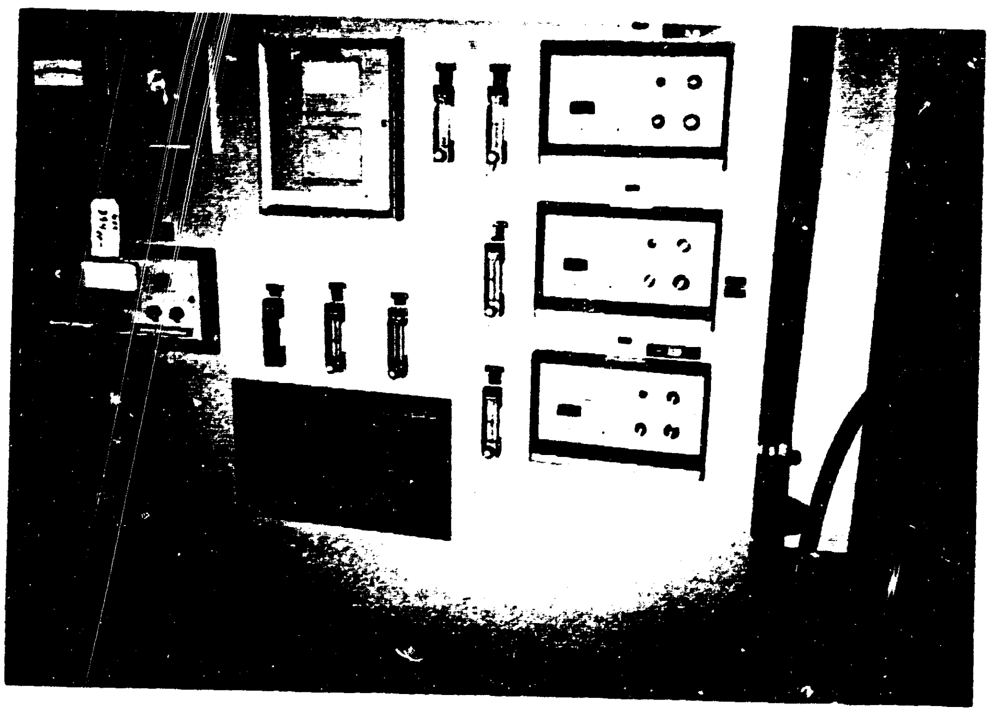


Figure 14. Photograph of the Beckman Gas Analyzer Bank located in the Pilot Plant Adjacent to the Boilerhouse



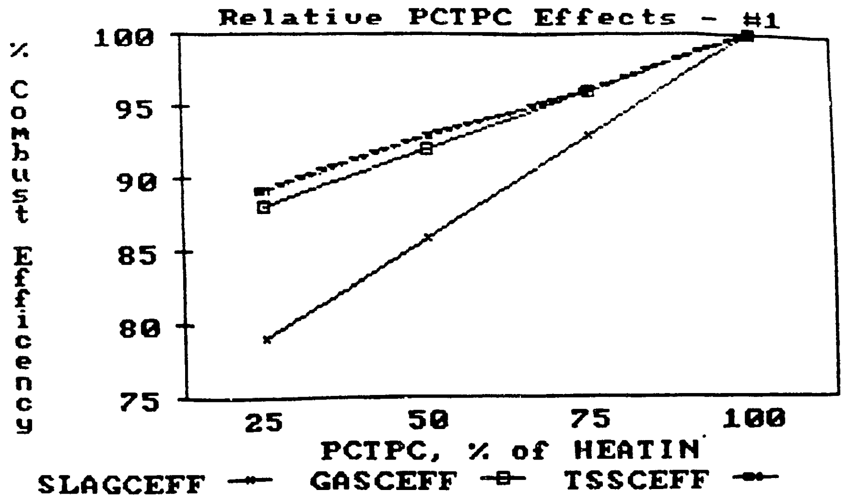


Figure 15: Combustion Efficiency versus the Ratio of (Coal Input)/(Total Heat Input), as Predicted by Statistical Modeling of the Test Data

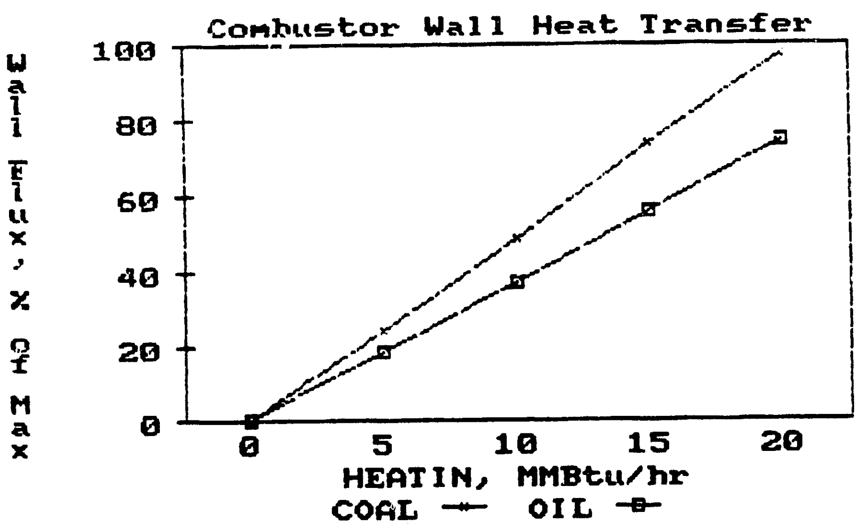


Figure 16: Average Wall Heat Flux versus as a Function of Total Heat Input, for Oil or Coal, as Predicted by Statistical Modeling of the Test Data.

SLAGEFF= Combustion Efficiency Computed from Carbon Content in Slag
GASEFF = Combustion Efficiency Computed from Measured Fuel & Air Input & Measured Stack Oxygen
TSSEFF = Combustion Efficiency Computed from Carbon in Scrubber Solids
PCTPC = Percent Contribution of Coal To Total Heat Input
HEATIN = Total Heat Input to Combustor

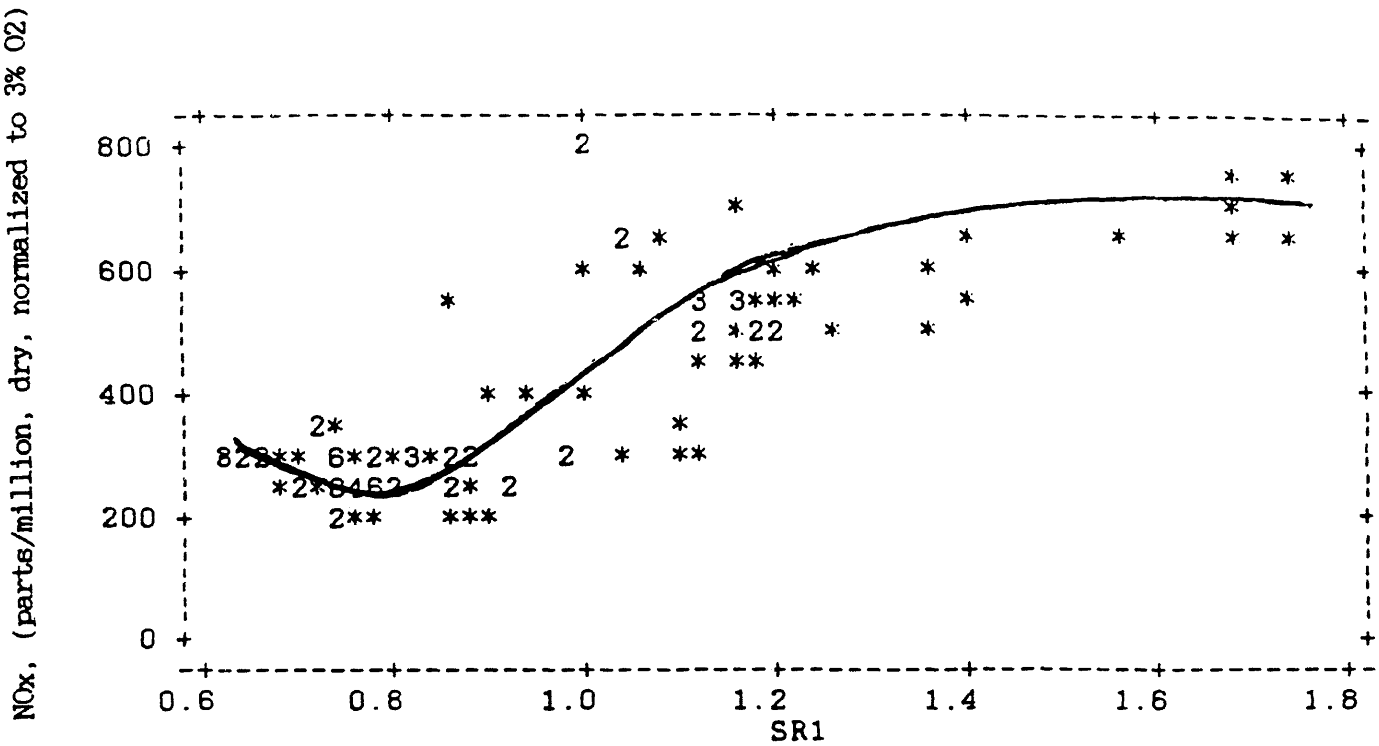


Figure 17: Measured Boiler Outlet NOx versus First Stage Stoichiometry

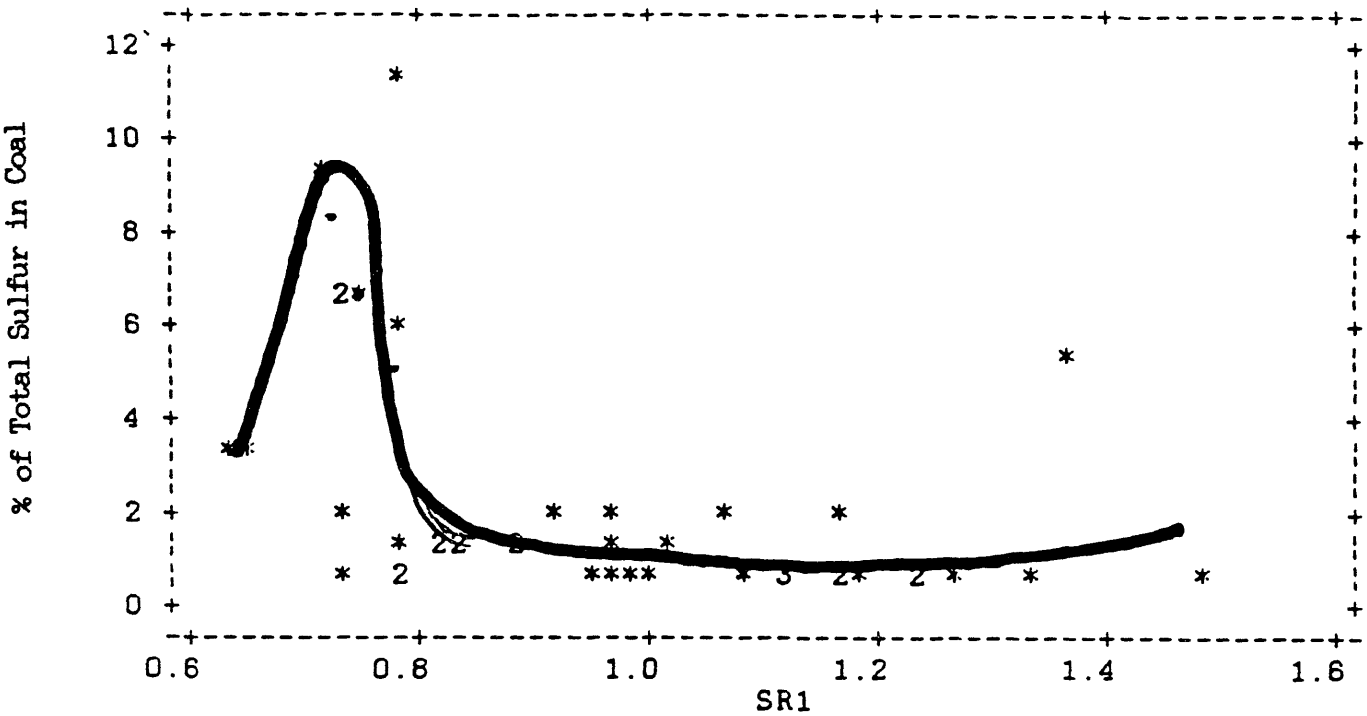


Figure 18: Measured Sulfur Content in the Slag with Sorbent Injection into the Combustor versus First Stage Stoichiometry

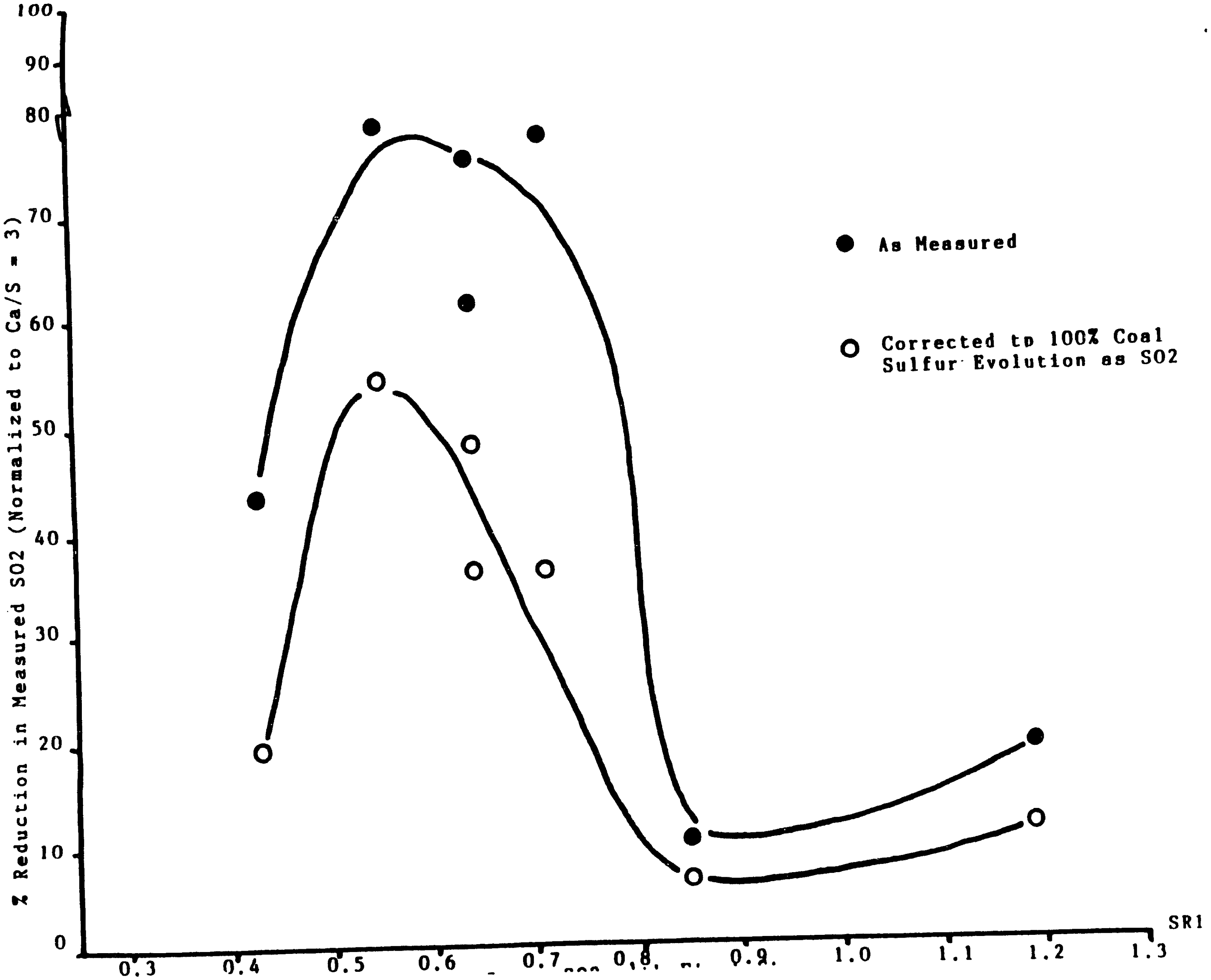


FIG 19: Reduction in First Stage SO2 with Sorbent Injection vs First Stage Stoichiometry (from Ref. 25)

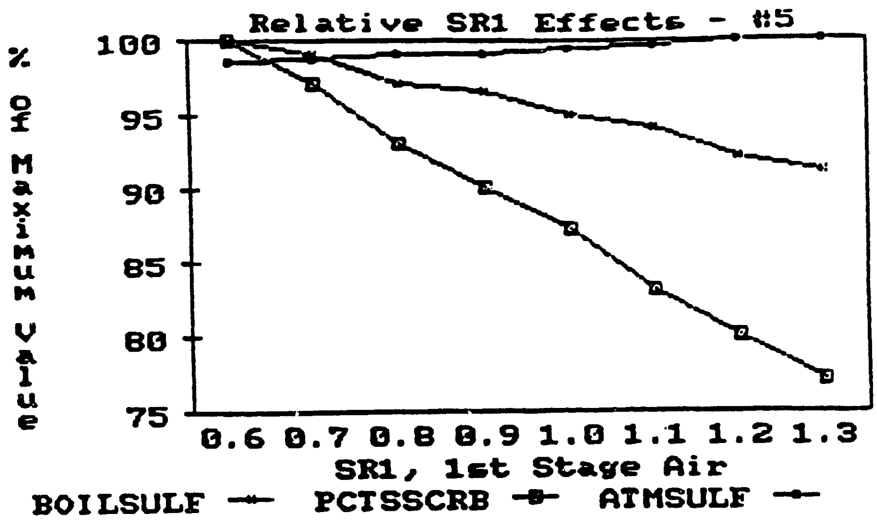


Figure 20: Relative Sulfur Partitioning in the Combustor-Boiler System versus First Stage Stoichiometry, as Predicted by Statistical Modeling of the Test Data.

BOILSULF- Sulfur retained in the boiler as percent of total sulfur.
PCTSSCRB- Sulfur retained in the scrubber as percent of total sulfur.
ATMSULF - Sulfur emitted to atmosphere as SO_2, percent of total sulfur.
SR1 - First Stage (i.e. Combustor) Stoichiometric Ratio

"Additional data is contained in the Proprietary Document".

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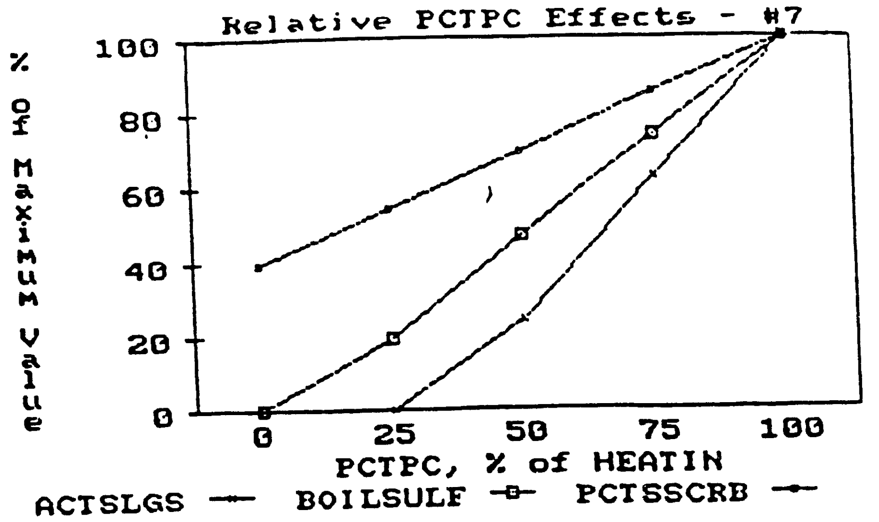

Figure 21: Sulfur Partitioning versus the Ratio of (Coal Input)/(Total Heat Input), as Predicted by Statistical Modeling of the Test Data

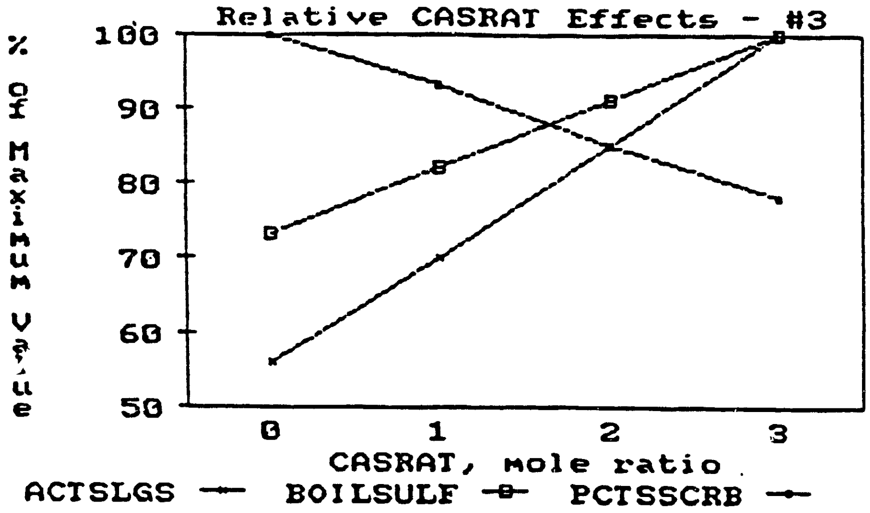

Figure 22 Sulfur Partitioning versus the Calcium/Sulfur Mole Ratio, as Predicted by Statistical Modeling of the Test Data

ACTSLGS - Slag sulfur content as percent of total sulfur.
BOILSULF- Sulfur retained in the boiler as percent of total sulfur.
PCTSSCRB- Sulfur retained in the scrubber as percent of total sulfur.
PCTPC - Percent Contribution of Coal To Total Heat Input
HEATIN - Total Heat Input to Combustor
CASRAT - Calcium/Sulfur Mole Ratio

END

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