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1. SUMMARY

In the second quarter of calendar year 1996, 16 days of combust-boiler tests were performed, including 2 days of tests on a parallel DOE sponsored project on sulfur retention in a slagging combustor. Between tests, modifications and improvements that were indicated by these tests were implemented. This brings the total number of test days to the end of June in the task 5 effort to 28, increased to 36 as of the date of this Report, 8/18/96. This compares with a total of 63 test days needed to complete the task 5 test effort.

It is important to note that the only major modification to the Williamsport combustor has been the addition of a new downstream section, which lengthens the combustor and improves the combustor-boiler interface. The original combustor section, which includes the fuel, air, and cooling water delivery systems remained basically unchanged. Only the refractory liner was completely replaced, a task which occurs on an annual basis in all commercial slagging utility combustors. Therefore, this combustor has been operated since 1988 without replacement.

The tests in the present reporting period are of major significance in that beginning with the first test on March 31st, for the first time slagging opening conditions were achieved in the upgraded combustor. The first results showed that the present 20 MMBtu/hr combustor design is far superior to the previous one tested since 1988 in Williamsport, PA. The most important change is that over 95% of the slag was drained from the slag tap in the combustor. This compares with an range of one-third to one-half in Williamsport. In the latter, the balance of the slag flowed out of the exit nozzle into the boiler floor. In addition, the overall system performance, including the combustor, boiler, and stack equipment, ranged from good to excellent. Those areas requiring improvement were of a nature that could be corrected with some work. but in no case were the problems encountered of a barrier type.

Of even greater significance is that the current tests are on the entire "combustion island", which includes the pulverized coal delivery, storage, and feed sub-system; the sorbent storage and feed sub-system; the combustor and its auxiliary sub-systems, namely gas and oil fuel feed and control, water cooling feed and control, compressed air delivery and control; boiler; stack gas cleanup ducting and components; and overall control system.

Also of importance is that these tests were implemented with two to four operating personnel, which is one-half the number of operators used in Williamsport.

The strategy followed in these tests was to focus on combustor liner durability, slag tap operation, combustion efficiency, and operational reliability of auxiliary sub-systems. Since the upgraded computer process controlled software was not available during this period, all combustor operation was with operator control. However, even here a major improvement has been made in that programmable logic control (PLC) was used to replace the original relay controlled operation. As a result, multiple unscheduled flameouts and shutdowns, which was a regular occurrence in Williamsport, was the exception in the current test series. In fact the bulk of flameouts were caused either by operator error, such as allowing the boiler water level to drop below shutoff

during boiler blowdown, or forgetting to start the coal replenishment control circuit, or failure of an auxiliary component, such as the mechanical slag tap breaker, or improper installation.

The following are highlights of the work and accomplishments in the present quarterly reporting period. Details are given in Section 3.

a) As reported in the previous quarterly, off site pulverized coal was used for these initial tests. Initially 50 pound bags were manually loaded through the top of the 22 ft high 4 ton pulverized coal storage bin. This was followed by development of a pneumatic feed system to load the coal from ground level. By the end of this quarter, coal was loaded from 1 ton supersacks through this ground level pneumatic system. It uses the same blower that feeds the coal into the combustor. The 4 ton bin can be refilled in 4 hours with minimum operator attention. This method will be used for most of the task 5 effort.

b) A major effort was expended on improving the slag tap operation under upset or scheduled shutdown conditions. Both the mechanical slag tap breaker and the slag tap heater system were improved to the point where by the time of the July 1996 tests, the slag tap remained open under all conditions.

c) A chemical feed system for treating the boiler feedwater with the once through steam blowoff operation was used in these tests. While it functioned reasonably well in these tests, the metering pump broke down as more and more sludge accumulated in the chemical feed tank. The use of alternate pumps are being investigated.

d) Low cost baghouse bags suitable only for low temperature are being used to control particulates. This requires cooling the stack gases by several 100°F in the duct between the boiler and baghouse. Various methods of cooling with water sprays were evaluated with the objective of preventing rapid accumulation of ash on the ducts. In some cases, ash deposits reduced the duct area by 2/3 in a matter of hours. As of the date of this report major progress has been made in eliminating this problem.

e) In all, 16 days of testing implemented in this quarter. Excellent slagging conditions were achieved almost immediately. Also, an improved method of coal startup with gas and oil was developed. As a result, the gas/oil heatup time and gas/oil consumption were greatly reduced from the levels used in Williamsport. In addition, while in the first few tests in this period, auxiliary oil firing was maintained while on coal, it was eliminated for the bulk of the remaining tests. As a result, it was possible to maintain facility operation with only 550 gallon on site oil storage capacity, and average oil consumption on test days is under 100 gallons. By comparison in Williamsport, oil consumption was generally well in excess of 100 gallons. Also, gas consumption was cut by 2/3 to less than 1 MMBtu/hr from the 3 MMBtu/hr level maintained in almost all the test operations in Williamsport.

f) Slag retention and removal through the combustor slag tap was excellent with an average of 2/3 to 3/4 mineral matter retention. Less than 5% of the slag flowed out of the exit nozzle.

Also ash deposits in the boiler were very low in the tests. This eliminated the need for regular ash removal from the boiler floor.

g) The baghouse removed the fly ash and no visible plume was noted in any of the tests. This compares with visible plume during upset conditions in Williamsport.

h) Liner durability was good with generally modest loss of wall refractory. This was accomplished with a material that is generally not very resistant to slag attack. The previous liner material used in Williamsport was eliminated due to some concerns on its disposal.

i) Initial test results on NO_x and SO₂ reduction were obtained. Due to an error by our coal supplier, the bulk of the tests were performed with 2.75% sulfur coal, instead of the 1.2% sulfur coal used in the very first tests at the beginning of the year. Therefore to determine if the stringent SO₂ standards for Philadelphia, namely 0.5 lb/MMBtu, could be met, hydrate was injected into the boiler. About 70% SO₂ reduction in the 2.75% sulfur coal to about 0.6 lb/MMBtu was measured. It is to be noted that the main objective of these tests was reliable combustor operation. Therefore, no attempt at optimizing emission performance was made. Also, there is some unresolved issue relating to the correction factors to be used on this SO₂ instrument. Therefore, the results are at present only qualitative.

The corresponding NO_x emission levels were 0.46 lb/MMBtu. This compares with the very stringent Philadelphia standard of 0.3 lb/MMBtu. Again note that these tests at not optimized with respect to stack emissions.

j) A great deal of effort was expended on testing and improving auxiliary components for the entire system. The objective is to develop a very low total capital cost coal fired steam generating system for world wide export of power plants in the 1 to 20 MW range. The results of this quarter's slagging combustor operation strongly indicate that this goal is being met, and we are very optimistic that this technology will be most probably the lowest cost coal fired, steam power system on the market.

The effort of the next quarter should confirm this conclusion, and the in-depth marketing of this technology will begin.

2. PROJECT DESCRIPTION

2.1. Objectives

The primary objective of the present Phase 3 effort is to perform the final testing, at a 20 MMBtu/hr commercial scale, of an air cooled, slagging coal combustor for application to industrial steam boilers and power plants. The focus of the test effort is on combustor durability, automatic control of the combustor's operation, and optimum environmental control of emissions inside the combustor. In connection with the latter, the goal is to achieve 0.4 lb/ MMBtu of SO₂ emissions, 0.2 lb./MMBtu of NO_x emissions, and 0.02 lb. particulates/MMBtu. To meet the particulate goal a baghouse will be used to augment the slag retention in the combustor. The NO_x emission goal will require a modest improvement over maximum reduction achieved to date in the combustor to a level of 0.26 lb./MMBtu. To reach the SO₂ emissions goal may require a combination of sorbent injection inside the combustor and sorbent injection inside the boiler, or stack.

The original plan was to meet the project objectives by a series of increasingly longer duration tests totaling up to 800 hours, with over 500 hours in the task 5 "Site Demonstration" effort. In the implementation of the first three project tasks, it was determined that this objective could met by daily cycling of the combustor in these three tasks, and by focusing the test effort on fuel flexibility and optimized combustion and environmental performance. Cycling without combustor refurbishment between cycles provides a more stringent test of combustor durability. In task 5, the steam output will be blown off. However, the option has been added to use the steam for process heat or steam turbine power generation if a means for generating revenue from this energy is developed during task 5. This last option will only be implemented after the completion of the required testing under the present project.

The final objective is to define suitable commercial power or steam generating systems to which the use of the air cooled combustor offers significant technical and economic benefits. In implementing this objective both simple steam generation and combined gas turbine-steam generation systems will be considered.

2.2. Technical Approach

2.2.1. Overview

The work of this Phase 3 project is being implemented on Coal Tech's patented, 20 MMBtu/hr, air cooled cyclone coal combustor that is installed on an oil designed, package boiler. The task 2 and task 3 testing were performed at a manufacturing plant in Williamsport, PA, where this combustor was installed in 1987. The task 5 tests are being implemented at a new site in Philadelphia, PA which was selected after the completion of the task 3 tests. The combustor has undergone development and demonstration testing since 1987. The primary fuel has been coal. Other tests, including combustion of refuse derived fuels and vitrification of fly ash, have been successfully performed.

The combustor's novel features are air cooling and internal control of SO₂, NO_x, and particulates. Air cooling, which regenerates the heat losses in the combustor, results in a higher efficiency and more compact combustor than similar water cooled combustors. Internal control of pollutants is accomplished by creating a high swirl in the combustor which traps most of the mineral matter injected in the combustor and converts it to a liquid slag that is removed from the floor of the combustor. SO₂ is controlled by injecting calcium oxide based sorbents into the combustor to react with sulfur emitted during combustion. The spent sorbent is dissolved in the slag and removed with it, thereby encapsulating the sulfur in slag. Part of the sorbent exits the combustor with the combustion products into the boiler where it can react with the sulfur. The spent sorbent either deposits in the boiler or it is removed in the stack particle scrubber. NO_x is controlled by staged, fuel rich combustion inside the combustor. Additional reductions are achievable by reburning in the boiler or by ammonia injection in the stack gases. Neither of the latter two procedures has been attempted in this project to date, but they may be required to meet the task 5 operating conditions at the site selected for this effort. Final combustion takes place in the boiler.

Excellent progress had been made prior to the start of the present project in meeting several of these combustor performance objectives. One of the most important objectives of this technology development effort is to demonstrate very high SO₂ reduction in the combustor. Prior to the start of the present Phase 3 project, the peak SO₂ reduction achieved with sorbent injection in the combustor had been 56%, (+/-) 5%. Of this amount a maximum of 11% of the total coal sulfur was trapped in the slag. On the other hand, up to 81% SO₂ reduction has been measured with sorbent injection in the boiler immediately downstream of the combustor. Tests in the past several years have revealed the critical role played by optimum operating conditions in the SO₂ reduction process. Specifically, combustor operation must be automatically controlled, and solids feed and air-solids mixing in the combustor must be optimized. Progress in both areas has been accomplished in the past 5 years by using a microcomputer to control the combustion process and by testing various methods of feeding and mixing the coal and sorbents. In the summer of 1992, tests performed in a prior project indicated that in excess of 90% SO₂ reduction could be achieved by sorbent injection in the combustor. However, to date this result has not been duplicated, in part due to focus on other areas of combustor testing. In general, 70% SO₂ reduction has consistently obtained in tasks 2 and 3 at Ca/S ratios between 3 and 4.

Combustor durability is an essential requirement for commercial utility of the combustor. Due to the aggressive nature of the combustion process and the need to utilize refractory materials inside the combustor to withstand the 3000F gas temperatures, durability has been one of the key challenges in the development process. Here also the use of computer control has been the means whereby this problem is being solved. Since introduction of computer control four years ago, the need for frequent refractory liner patching inside the combustor has been sharply reduced. The durability issue can be addressed by accumulating running time in daily cyclic operation without combustor refurbishment between runs. This approach has been used in the latter task 2 and task 3 effort. All tests between May 1 and December 2, 1993, consisting of 26 hours of operation in task 2 and 185 hours in task 3, have been performed without significant internal combustor refurbishment.

The final project objective of placing the combustor in a viable industrial steam or power generating system was accomplished by detailed engineering analysis on the use of the combustor in one or more steam generating cycles. This effort included an assessment of the requirements for commercializing the combustor for several industrial application. To assure commercialization of this technology, the final project task is being implemented in a system that duplicates a commercial prototype power plant utilizing the air cooled coal combustor technology.

2.2.2. Task Description

Task 1: Design, Fabricate, and Integrate Components

This task consists of components design, component fabrications, and components integration, and shakedown tests. The 20 MMBtu/hr combustor will be modified to allow safe and environmentally compliant operation for periods of up to 100 hours. This task is complete.

Task 2: Preliminary Systems Tests

The modified combustor system will undergo a series of one day parametric tests of total duration of up to 100 hours to validate the design changes introduced in task 1, and to accomplish the project objectives and goals. This task is complete.

Task 3. Proof of Concept Tests

The durability of the combustor will be determined in a series of tests of between 50 and 100 hours of accumulated operation with no combustor refurbishment between tests. The total test period will be up to 200 hours. This task is complete.

Task 4. Economic Evaluation & Commercialization Plan

The economics of one or at most two different industrial scale steam based cycles using the combustor will be evaluated. A commercialization plan will be developed for marketing the combustor in an industrial environment both in the US and overseas. This task is complete.

Task 5. Conduct Site Demonstration

This task will be the final test activity in the project. Its objective will be to demonstrate the durability and hence the commercial readiness of the combustor for its intended industrial application(s). The effort will consist of two sub-tasks. In the first one any changes required as a result of prior tests will be made to the combustor. In the second one, a series of tests, each of up to 100 hours of continuous coal fired operation will be performed, with a total test time of 500 hours. This task is now in the initial test phase.

Task 6. Decommissioning Test Facility

The test facility will be removed from the boiler installation and disposed in accordance with required regulations.

3. PROJECT STATUS.

3.1. Task 5. Site Demonstration

The installation of the combustor-boiler facility at the Philadelphia site was completed at the end of 1995 and initial shakedown tests began. It had been planned to divide the task 5 tests into two phases. In the first phase, it was planned to operate the first 16 days (nominally 100 hours) of the 63 days (nominally 500 hours) of the task 5 combustor tests with off-site pulverized coal. The final 400 hours were to be performed using the on site raw coal storage and pulverization system. However, an economic tradeoff analysis performed late in 1995 showed that using off site pulverized coal for the bulk of the task 5 tests was more cost effective if a simple method of loading the off site pulverized coal into the existing 4 ton bin could be developed. An effective means for accomplishing this was tested in the previous quarter and perfected in the present quarter. This method will be used until late in the test effort, when the raw coal system will be briefly tested.

The phase 1 effort was further divided into two stages. In the first stage, the combustor was to be operated by manual control in order to develop the input parameters to program the computer control of the combustor. In the second stage of phase 1, computer control of the combustor was to be used. This first stage was essentially completed with the combustor tests at the end of March. However, the upgraded computer process control system software was not received until the end of April, and Coal Tech's software developer has only completed adapting it to the combustor system recently. Accordingly, the original software used in Williamsport was upgraded for the present configuration in the present reporting quarter. It was, however, used only for recording the combustor's operation because the test effort showed that the control logic developed for Williamsport was no longer adequate. In some areas, such as controlling the air cooling, a much simpler procedure was found to be effective. In addition, the use of programable control logic (PLC) in place of the earlier relay control was much simpler and more reliable. It was therefore possible to operate the combustor manually with much less direct operator fine tuning.

In the following sub-sections, the progress made in the past quarter will be summarized.

3.1.1. Modifications and Installations

Boiler Feedwater Treatment: A batch of four chemicals mixtures was purchased to treat the boiler feedwater. The boiler is operated in a once-through mode with municipal fresh water at temperatures below 100F. All the steam produced is blown off. As a result, the boiler is subject to high concentrations of alkalis and oxygen. The former coats the inner boiler tubes and lowers the heat transfer, while the latter corrodes the inner water wall of the boiler. It is, therefore, necessary to inject high concentrations of chemicals to remove and dissolve these compounds. A chemical metering pump and storage system were procured and integrated with the feedwater supply train. As reported in the last quarter, problems were soon encountered because one of the chemicals turned into a sludge after several days of storage. The sludge could not be pumped. The sludge was dissolved by adding water and repiping the chemical feed to accommodate the added higher feedrate. Regular boiler blowdown and analysis of the boiler water chemistry showed that it was

difficult to maintain the water chemistry within desirable limits. As a result efforts were directed toward a more reliable means of pumping chemicals into the boiler. This work is continuing and one of two alternate pumping schemes are being currently explored.

The boiler blowdown has yielded metals discharges into the sanitary drains within City water standards.

Controls: The PLC controls have greatly simplified the operation of the combustor in that identifying the cause of startup or shutdown problems can be made in a matter of seconds. Also, the flame safety system has been redesigned to the point where it is very reliable. Previous problems regularly encountered in Williamsport which false shutdowns caused by the flame detectors have been eliminated. While the UV detectors still shutdown at high coal firing rates, the IR detector is now so sighted that it maintains firing.

Also, a substantial part of the prior automatic control of the combustor was used to maintain acceptable combustor wall temperatures. This was accomplished by computer control of the various air flow valves. In the present unit, new means were developed for accomplishing this task without the need for regular adjustments of these valves. Therefore, computer control is not as critical to the present operation as initially assumed. The entire issue of the best method of controlling the system will be evaluated in the third quarter of 1996. For example, the upgraded software that was purchased in April has been found to be much more complex to use, and we may return it. This is in keeping with the design philosophy for this system, namely simplicity and low cost.

Cooling Water System: A totally new insight has been obtained on the water cooling system in the present quarter.

One area concerns the relationship of operating conditions and water cooling rate. Here it was found that the cooling rate is not proportional to the total heat input. Instead it depends on the thermal distribution inside the combustor. This matter will be further explored and it should result in reduced water cooling load.

A second area relates to the water discharge to the sanitary system. The sewer charges in Philadelphia are extremely high, being double the cost of fresh water. Since almost all the water is used for non-contact cooling through heat exchangers, it is wasteful to discharge this into the sanitary system. All water to the boiler is blown off as steam for which there is no sanitary charge. To reduce sewer discharge, the fill cycle of boiler feedwater was gradually reduced. This has not only reduced the waste water discharge, it also reduced the fluctuations in steam pressure. With long feedwater fill periods, the coal water quenches the steam pressure in the boiler and results in wide fluctuations in steam pressure.

As noted previously, a water-water heat exchanger is used in the combustor cooling circuit. One problem area has been the gradual increase in City water temperature as Spring turned to Summer. In the Winter the inlet water was in the 40°F range, while by mid-Summer it reached the mid-70°F range. As a result, it has been necessary to operate at higher discharge temperatures on

the combustor side of the water loop. Nevertheless, safe cooling water conditions were maintained at discharge temperatures where problems had been encountered in the once through system used in Williamsport.

Finally, the slag quench tank has been successfully cooled with the water-water heat exchanger and with water temperatures considerably higher than used in the once through system in Williamsport.

Stack Damper: Considerable effort was spent in the previous quarter on proper operation on the control of the stack gas flow damper. The stack damper is critical in the present facility because it is necessary to maintain a negative draft in the boiler to prevent combustion gas leakage into the room. This means that at startup, in the absence of a stack damper, the furnace draft would be too negative. However, as more experience was gained in the operation of the system, a simple manual means was found to operate the stack fan with the stack damper wide open all the time. Consequently, the damper control components were removed.

Pulverized Coal Loading: In the early tests in this quarter, coal was purchased in 50 lb bags, and it was pneumatically blown from ground level into the bin. Midway during this period, a fork lift truck was purchased. The coal was then purchased in 1 ton supersacks which were discharged into the pneumatic filling circuit to the 4 ton bin. The rate was about 1 to 1.5 tons/hr. The theoretical fill rate was 1.5 tons per hour. The original plan to use a gantry crane for the supersacks was abandoned because the fork lift has multiple uses. To-date, 37 tons of pulverized coal have been purchased.

Slag Tap Heating System and Mechanical Slag Breaker: In the present quarter, the slag tap heating system was used extensively for the first time. Considerable problems were encountered in maintaining its flame safety system and in preventing slag blockage of the heaters. As a result a number of different heater configurations and heater types were investigated. In addition, various modifications were made to the mechanical slag tap breaker. Several tests had to be terminated when the mechanical breaker failed. Also, extensive tests were performed with various tap heaters and several heater configurations. This also included different heat sources. All these methods had been tested and used extensively in the prior combustor in Williamsport.

One problem area encountered was in the water cooled chamber that encloses the slag tap. This developed water leaks on three occasions which were due to poor original fabrication welds. One positive benefit of these water leaks is the opportunity it provided to determine the time required to disassemble the entire slag tap system and replace it. In Williamsport this was a major effort due to the inaccessibility of the components underneath the combustor, and it required several days of effort. With the present design, the entire system can be removed and replaced in hours. After the last water leak repair, a change in the operating procedure has been implemented to reduce the possibility of developing an unacceptable water leak. Note that the water cooled chamber used in Williamsport had no leaks in 6 years of operation.

Stack Baghouse Operation: A key element in the baghouse specification was the selection of low temperature bags whose cost is 3 to 6 times less than bags capable of operating at the boiler

outlet gas temperatures. To use the low cost bags, the stack gases must be cooled upstream of the baghouse. A water spray method used initially proved effective in cooling the gases but also resulted in excessive ash laden water flow out of the base of the baghouse, and it also caused extensive deposits on the duct walls. In some tests this blockage became so severe that the test had to be terminated. Part of this blockage was caused in some tests by high ash levels due to either boiler injection of sorbent or poor combustion resulting in high ash carryover to the stack.

Various cooling devices were tested until a device and procedure that functioned with minimal duct ash deposits was developed. To date the results for long term operation of this new procedure are not available, but it appears that this procedure warrants further effort due to the major cost saving. Of course the option remains of installing higher temperature, more costly bags remains.

3.1.2. Combustor-Boiler Tests:

Coal fired combustor tests were performed in all three months on the present quarter. 6 tests days were performed in April, 5 test days in May, including one for the parallel sulfur-slag project, and 5 days in June, including one day for the sulfur-slag project. All the tests were with coal firing under slagging operating conditions. This brings the total number of test days in task 5 to 28, compared to the maximum planned 63 test days.

April 1996 Tests:

The results of the first two tests in April were reported previously.

The next test on April 18 test consisted of coal fired operation for a total of 8 hours, including oil and gas heatup and cooldown. Heat input reached 13.5 MMBtu/hr, of which about 77% was coal, equal to 825lb/hr per hour input. [Note: Calibration of the coal feeder was originally performed for short periods of 1 to 2 minutes. In July, additional calibrations were performed which showed that variations in the feed rate result from changes in the amount of coal in the bin immediately above the coal feeder. As a result the average feed rate is reduced over longer time intervals by 10% to 15% depending on the absolute feed rate. The present data are corrected for this.]

Slagging operation was excellent with over 90% of the slag (equal to 225 lbs) collected through the slag tap, and only 17 lbs flowing out of the exit nozzle into the boiler inlet. Since part of the slag contained combustor liner material, the coal ash and injected limestone retained in the combustor is less than 90%. Nevertheless, this result is excellent when compared with almost a 50-50 distribution of slag flowing through the slag tap and into the boiler in the prior Williamsport tests. Also, note that 16 to 17 MMBtu/hr is at the upper end of the range where most of the Williamsport test were performed. The combustor briefly reached a thermal input of 16.8 MMBtu/hr on the 18th.

The combustor air cooling performance was good. This was accomplished with over 50% less cooling fan power than had been used in Williamsport. Stack gas temperature control was

within the range appropriate for the low temperature baghouse. For the first time, stack gas results for O₂, CO, and NO were obtained. However, calibration gases were not yet received and this data cannot be analyzed quantitatively.

Another important result was that coal fired operation with slagging conditions could be achieved at much lower initial oil fired heatup of the combustor. In Williamsport, this had occurred when the oil heat input reached over 60% of rated boiler heat input. In the present combustor, coal firing with slagging was achieved at less than 40% of rated heat input.

The test on the 24th was a repeat of conditions used on the 18th. This test provided proof of a long held assumption, namely that good slag tap operation, requires a certain minimum coal, i.e. coal ash throughput in the combustor.

During operation of the water cooled mechanical slag tap breaker, a power failure on the electric circuit used to operate the slag breaker occurred while the breaker was in the combustor. A small piece of steel on the breaker shell broke and the cooling water flooded the combustor, necessitating a shutdown. In three years of operation in Williamsport, the breaker had become stuck inside the combustor on many occasions. However, the outer shell had never before cracked. The steel was submitted to an outside laboratory for chemical and crystal structural analysis. The results showed that the small section that failed, about 1" x 2" in size, had recrystallized into fine elongated crystals. It has also absorbed sulfur and carbon from the coal. However, the latter were statistically no different in concentration from other sound sections of the steel. It is tentatively concluded that a defect developed in the steel from unknown causes, either during our operation or during manufacture.

The next day, the combustor was internally inspected and no water damage was observed. A gradual heatup on propane was conducted for part of the day, and the combustor was dried. This is probably the more important result in that it shows the combustor floor can survive major water flow during operation without damage to the refractory. In Williamsport, the combustor had been operated for extensive periods of time with a water leak in one of the cooling circuits. However, this water leak was never at the level where it could flood the combustor floor during high temperature operation. This result is also another example of the advantage of air cooling because in a water cooled unit, a cooling tube failure would require complete refurbishment of the combustor.

On the 29th, another coal fired test was performed, and coal fired operation was conducted at 14 MMBtu/hr, with 75% on coal. In this test the coal firing ramp up was introduced much more rapidly than in the previous test, and excellent slagging operation was immediately achieved. This procedure was adopted in order to reduce the frequency of slag breaker operation during conversion from oil to coal firing. Stack gas sampling was performed for O₂, CO, NO_x, and SO₂. As noted, the calibration gases were not yet received.

515 lb. of slag were removed through the slag tap, compared with only 35 lbs through the exit nozzle into the boiler. This continued the excellent slagging and slag retention observed in the

previous tests. Retention was at least 75%. Figure 1 is a summary of the slag retention results, and it will be discussed after all the test are discussed individually.

An extremely important result was that the only ash deposited on the floor of the boiler was very fine, with no evidence of unburned char, as was always present in Williamsport.

May 1996 Tests.

A total of four days of coal fired combustion tests were performed on May 1, 15, 17, and 30. In addition, on May 21, the first test in the concurrent project on sulfur retention in slag was performed. In all tests, excellent combustion and slagging conditions were achieved, and the performance continued to be far superior to that achieved in the prior operation in Williamsport. These tests were the first ones in which stack gas sampling compared to calibrated sample gases were obtained. It was also the first tests in which calcium hydrate, which has superior SO₂ capture capabilities, was injected into the combustor.

In the first coal fired test on May 1st, after a short period of coal fired operation, combustion gases began to escape from cracks in this old boiler. This does not usually occur because the boiler is operated under negative draft. Almost simultaneously, the belt on the slag conveyor broke and the slag tank overheated. The test was therefore terminated.

Post test observation revealed that fly ash had deposited in an elbow inlet to the baghouse which increased the pressure drop and resulted in positive draft in the boiler. This deposition was caused in part because no provision had been made to remove accumulated fly ash from the bottom of the baghouse. We had not anticipated such excellent combustor performance and had not yet addressed this matter. The baghouse supplier offered two solutions by providing drain valves that can remove ash. However, we designed a simple system that costs about 5% to 10% of the cost of the drain valves, and it was installed.

The problem with the slag tank developed as a result of the excellent slagging of the combustor. The quenched slag heated the slag tank water. Slag was sucked into the hoses leading to the water-water heat exchanger and resulted in their blockage. This result was unexpected because a commercial device for removing solids from water had been in use since the last year of testing in Williamsport. In Williamsport, only once-through cooling was used, and slag tank overheating was not a problem. Various alternate means of operating this slag tank recirculation system were explored. In the end, the slag grit removal circuit was separated from the slag tank cooling water circuit, and after several trials in subsequent tests, the cooling circuit has performed satisfactorily. A design and operating procedure was also developed for operating the water-grit separation system in order to remove slag grit that deposited outside the conveyor belt. However, due to the press of other activities, this redesigned system has not been used. Instead accumulated slag is periodically removed from the bottom of the slag tank after several test days. This is not viewed as a high priority item, as a number of solutions can be used to remove this grit. It generally represents only a small fraction of the total slag removed from the slag tank.

Analysis of the slag removed from the combustor and ash removed from the baghouse showed that the combustor refractory liner had been operated at very high temperature which resulted in some refractory loss, some of which was replaced by slag.

The baghouse ash in this test had less than 1% unburned carbon, which compares to about 50% carbon observed in Williamsport. This shows that the combustion efficiency was over 99%. In the earlier April tests, unburned carbon was up to 50% in the baghouse ash.

One problem with the baghouse use is that real time ash samples are very difficult to obtain. In several of the tests real time samples were collected. However, this collection interfered with stack gas operation. In Williamsport, a wet particle scrubber was used and real time sampling of the scrubber water was no problem.

Another extremely important result was the observation that by adjusting the stack induced draft essentially all the fine ash accumulated on the floor of the boiler could be removed and blown into the stack baghouse. Also, compressed air was used for soot blowing in the boiler. This is very important in that it may eliminate the need for ash removal in the boiler. Provision for such a step had been made. However, in all the tests in this reporting period boiler ash removal was not necessary.

All the May tests were implemented at an average of 825 lb/hr of coal, equal to 10.4 MMBtu/hr, plus additional oil and gas to reach an average of 14 to 15 MMBtu/hr. The combustor continued to perform well in all the tests. A number of problems were encountered in some of the auxiliary components, some of which required early termination of the all day tests. The following summarizes the major results:

While stack gas sampling had been taken in the April tests, extensive delays in delivery of calibration gases prevented achieving accurate stack gas samples until the May 15 test. This test revealed that the sulfur concentration in the coal was higher than the value supplied by the coal company and obtained in initial coal analysis. The SO₂ level was over 1.5 times the maximum expected on the basis of the coal sulfur. Consequently real time coal samples were taken to analyze its content, and they revealed that the coal sulfur was about 2.75%, not 1.2% as in the first coal delivered.

To condition the slag, all operating conditions are being implemented with limestone injection in the combustor. Prior test results in Williamsport showed that there appears to be little reduction in SO₂ with limestone injection.

Calcium hydrate is a much better sulfur sorbent. The May 30 test was the first one with hydrate injection into the combustor. The results were inconclusive. Only very short duration operating periods were possible with hydrate because it appeared to adversely affect the slagging properties of the coal. However, very careful observation of the combustor's internal slag coating has revealed that the slagging problem may have been due to poor coal-sorbent mixing. With the hydrate injection into the combustor, about 20% reduction in SO₂ was measured at the stack

outlet from the boiler, and over 40% reduction as measured at the baghouse outlet. However, these results were obtained under poor slagging conditions.

In the May tests, continued removal of over 95% of the slag though the slag tap inside the combustor was measured, and the slag carryover into the boiler remained negligible. Also, the ash deposits in the boiler were very small and easily removed by the induced draft stack fan. This is a very important result. It was not achieved in the Williamsport installation, and its present achievement augers well for future commercial use of this technology.

Even without computer control, it was possible to stabilize the combustor wall heat transfer, and the wall heat transfer rates were substantially lower than in the earlier unit.

The PLC control of the combustor proved to be far superior to the previous relay control system. Its major benefit has been the ability to rapidly troubleshoot the system. For example, the coal feed system shutdown in one test. Diagnosis of the PLC system showed within seconds that we had inadvertently turned off an air flow in the oil flow circuit which was tied into the coal control circuit. With the relay system, it would have taken much longer to find this cause.

Finally, on May 25th, the first test in the project on sulfur retention in slag was implemented. The results are reported in that project's reports.

June 1996 Tests.

A total of five days of coal fired combustion tests were performed in June, namely June 6, 11, 24, 25, and 28. The last test was the second test in the concurrent project on sulfur retention in slag. The focus of these tests was on improving the performance of the combustor, especially in the area of slagging operation and slag removal from the combustor. Continued good combustion and slagging conditions were achieved, and considerable test data on slag properties and stack gas sampling was obtained.

A major thrust of the month's work was to improve the reliability and ease of operation of the slag tap in the combustor. As reported previously, the slag is removed from the downstream end of the combustor through a tap on the combustor floor. This tap is maintained open by a combination of localized heating and mechanical action on the opening. A major change was accomplished in the past month by the introduction of a much simpler device for mechanically clearing the slag tap of frozen slag. In addition, work continued on improving the local slag tap heaters. The test results in this months showed that operating conditions were more important in achieving good slag removal than the thermal/mechanical operation of the slag tap. Slag tap blockage by frozen slag occurred almost exclusively during shutdown operation. Consequently, the shut down procedure was modified to essentially eliminate this problem. Further work is planned in July on improving the local thermal input to the slag tap, and to reduce the need for frequent operation of the mechanical slag tap clearing devices.

A second major result was achieved in the last test on the 28th. All tests to date were performed with manual operation of the combustor. As a result, variations in wall temperatures

occurred during the tests. This in turn resulted in a cumulative loss of some wall liner refractory. This loss was evidenced by measurement of the inner wall diameter after each test, and by chemical analysis of the slag which showed elevated concentrations of liner materials. In Williamsport, a procedure was developed for injecting fly ash to reline the combustor walls. In the June 28th test, it was possible to accomplish this same result by controlling the rate of sorbent injection and wall cooling. Post test internal measurements showed that a substantial fraction of the wall refractory liner was redeposited in a matter of hours on the combustor wall. Furthermore, it was possible to maintain fairly constant wall temperatures with a minimum of changes in the air cooling rate. In connection with this it should be noted, that the present combustor, which is larger than the Williamsport unit, is being cooled with one half the fan horsepower used in Williamsport.

Another very important result in these more recent tests was that a substantial fraction of the coal sulfur was captured in the slag. In Williamsport, the highest sulfur concentration in the slag from the coal ash was about 10%. In recent tests, concentrations in the high teens to 20% of the coal sulfur has been measured in the slag.

Summary of Slag Retention, SO₂, NO_x Reduction, and Sulfur in Slag.

The tests in this quarter were the first ones in which slagging operation was implemented in all the tests. Some variation in combustor performance occurred, and as a result only quasi-quantitative overall performance can be given. The following charts show these results in graphical form.

Figure 1 shows the slag removed through the slag tap as a percentage of the coal ash and calcium oxide sorbent injected into the combustor. This data applies to 9 of the 16 tests conducted in this period. These slag data also include liner material that was removed from the combustor wall. The liner material in the slag is determined from slag sampling chemical analysis. Note that in some tests the slag removed through the tap is low. However, in these tests much of the missing slag is replenished on the combustor wall, as was determined by post test measurements of the inner combustor dimensions. In figure 1, test number "g", the amount of fly ash collected in the baghouse is added to the slag removed. The number less than 100%. Some of the missing mineral matter is deposited on the liner of the combustor, as fly ash on the boiler floor, and in calibration errors in the amounts injected. For example, it was noted recently that an 8% to 15% overestimate of the coal feed rate was detected in the coal feeder calibration. The data in figure 1 are based on the original coal feed rate calibration. Therefore, the slag retention is actually about 10% higher. [It is not 15% because the coal ash is only a majority, not 100% of the injected minerals.] Therefore, the estimated average mineral matter retention in the combustor is between 65% and 75%. Once the combustor operation is fully optimized this number will increase.

The really important result from figure 1 is obtained by comparing it with figure 2. This figure 2 shows the slag retention in this combustor's previous design as used in Williamsport. The data was obtained in 1993 when the original combustor had been optimized. Note that while slag retention also averaged 65% to 70%, over 50% of this slag flowed into the boiler out of the combustor exit nozzle. Only an average of 20% was removed through the slag tap. This compares with the results in figure 1, and it is the key result and advantage of the present combustor.

As noted in all tests, limestone was injected with the coal for slag conditioning. For a number of operational reasons, only limited tests on calcium hydrate injection in the combustor were performed in this quarter. SO₂ reductions with limestone injection is not as effective, as has been reported on many occasions during the Williamsport tests. Due to an error by our coal supplier, the bulk of our tests have been performed with 2.75% sulfur coal, instead of the 1.2% sulfur coal used in the very first tests at the beginning of the year.

Figure 3 shows the percentage of the sulfur in the slag as a percentage of the total sulfur in the coal. Again these figures should be increased by 8% to 15% due to the correction in the coal feeder rate measured in July 1996. Note that this graph does not show the absolute amount of the total sulfur in the coal that reports to the slag, it only shows the ratio of sulfur in the slag to the ratio of sulfur in the coal. To estimate the ratio of the total sulfur that reports to the slag, these data need to be reduced by at least 25% because only 3/4 on average of the coal ash is retained in the combustor slag. In any case, the data show that as much as 20% of the total coal sulfur is retained in the slag in one of the tests. This is twice as high as the maximum of 10% ever measured in the Williamsport tests, which was also the maximum reported elsewhere to the best of the author's knowledge.

Similarly, figure 4 shows the percentage of sulfur in the baghouse fly ash as a percentage of the total ash in the coal. Here it is assumed that all the ash reports to the stack. In fact only about 1/4 to 1/3 of the coal ash reports to the stack. This indicates that a maximum of 10% of the total coal sulfur reported to the baghouse ash.

Figure 5 shows the percent SO₂ reduction in the combustor for the May/June tests with limestone injection. Also shown are two tests with hydrate injection into the boiler. Note that these data were taken with a pulsed fluorescence instrument, which according to the manufacturer requires a correction factor which depends on the concentration of O₂, CO₂, CO, and the nature of the calibration gas. In the results reported for the Williamsport combustor tests such a correction factor which generally amounts to 1.35 to 1.38 was used to increase the measured SO₂ data when the calibration gas was 500 ppm SO₂ in nitrogen, as opposed to air. If the calibration gas is air, the correction factor for combustion gases is only 15% to under 20%. Since these issues are not clear at this time, the data obtained in the present combustor is being reported as measured by the instrument. Recalibration of the instrument with SO₂ in air will be performed to clarify this matter.

In any case, the data in figure 5 shows that substantial SO₂ reductions were obtained with limestone, which based on prior tests in Williamsport is about 1/3 as effective as hydrate. On the other hand, the calcium hydrate injection in the boiler is very effective. This test was performed to determine if the stringent SO₂ standards for Philadelphia, namely 0.5 lb/MMBtu could be met with sorbent was injected into the boiler when using a high sulfur coal. The uncorrected 70% SO₂ reduction in the 2.75% sulfur coal to about 0.6 lb/MMBtu appears to be within the range necessary. However, note that the main objective of these tests is at present reliable combustor operation. Therefore, no attempt at optimizing emission performance was made, especially since these tests are still classified as shakedown. If the standard cannot be met with this coal, then the

option remains to return to the 1.2% sulfur coal, where only 72% SO₂ reduction is needed to meet the standard.

The corresponding NO_x emission levels were 0.46 lb/MMBtu. This compares with the very stringent Philadelphia standard of 0.3 lb/MMBtu. Again note that these tests are not optimized with respect to stack emissions.

The 500 hours of planned tests require 63 days of single shift combustor operation. The 28 days of combustor testing conducted to the end of June thus represent a substantial fraction of the total number of planned test days. The tests were conducted in a 7 month period. This compares with a total of 24 test days throughout 1993, the last full year in which the facility was operational in Williamsport. As of the date of this report, 8/18/96, the total has reached 36 test days, all conducted without any significant combustor refurbishment or boiler cleanup. The only important activity between tests has been reopening the slag tap, and cleaning the ash from baghouse inlet stack. By the July tests both these problems appear to have been eliminated.

In closing, it is important to repeat that the original section of the combustor has undergone over 2000 hours of operation since 1988 without any major refurbishment.

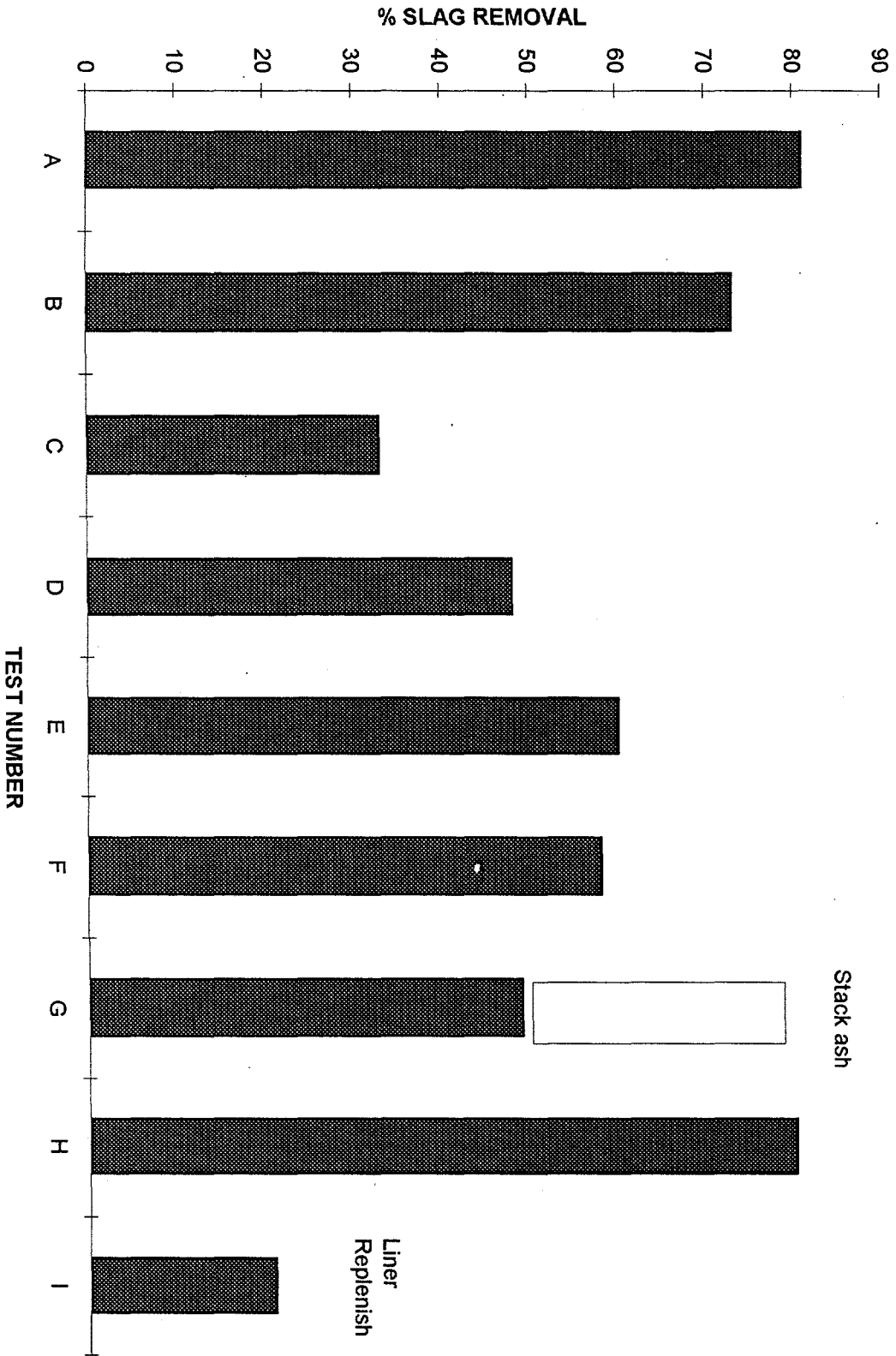
4. Effort of the Next Quarter

The task 5 demonstration test effort will continue in the next quarter. Off site pulverized coal will continue to be used. The focus of the tests will be on optimizing the combustor's combustion efficiency and environmental performance. Also the matter of combustor automation will be resolved using the results obtained in the past several months as a guide.

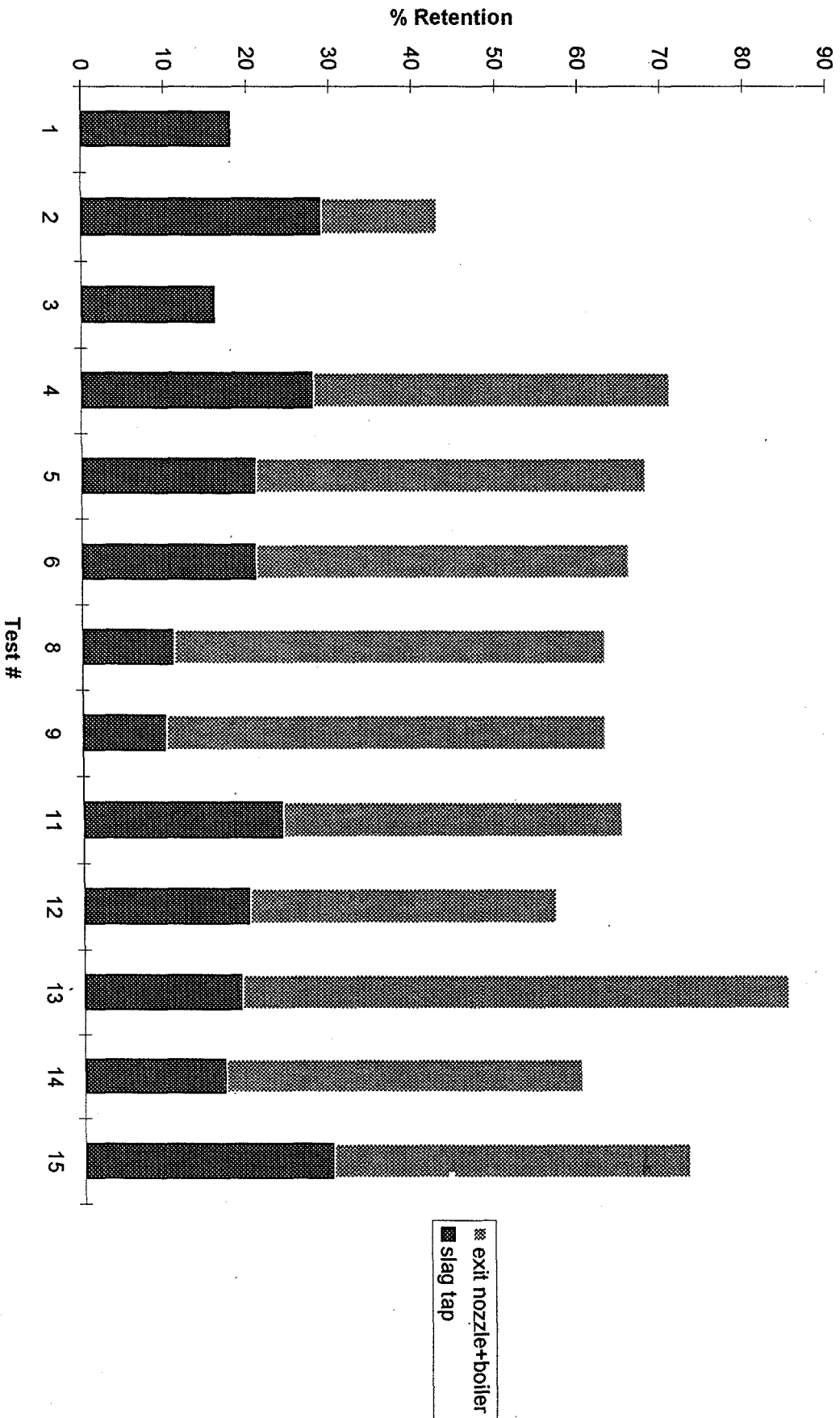
In addition, a major effort will be mounted to find joint venture partners, and/or licensees to market this coal fired combustion-steam generation technology worldwide in the 1 to 20 MWe output range. The results to date confirm that this technology is most probably the lowest cost coal fired system on the market.

Slag Ret.

1) % OF COAL ASH + CaO REMOVED AS SLAG FROM COMBUSTOR TAP
Est. Ave. Retention - 65 to 75%

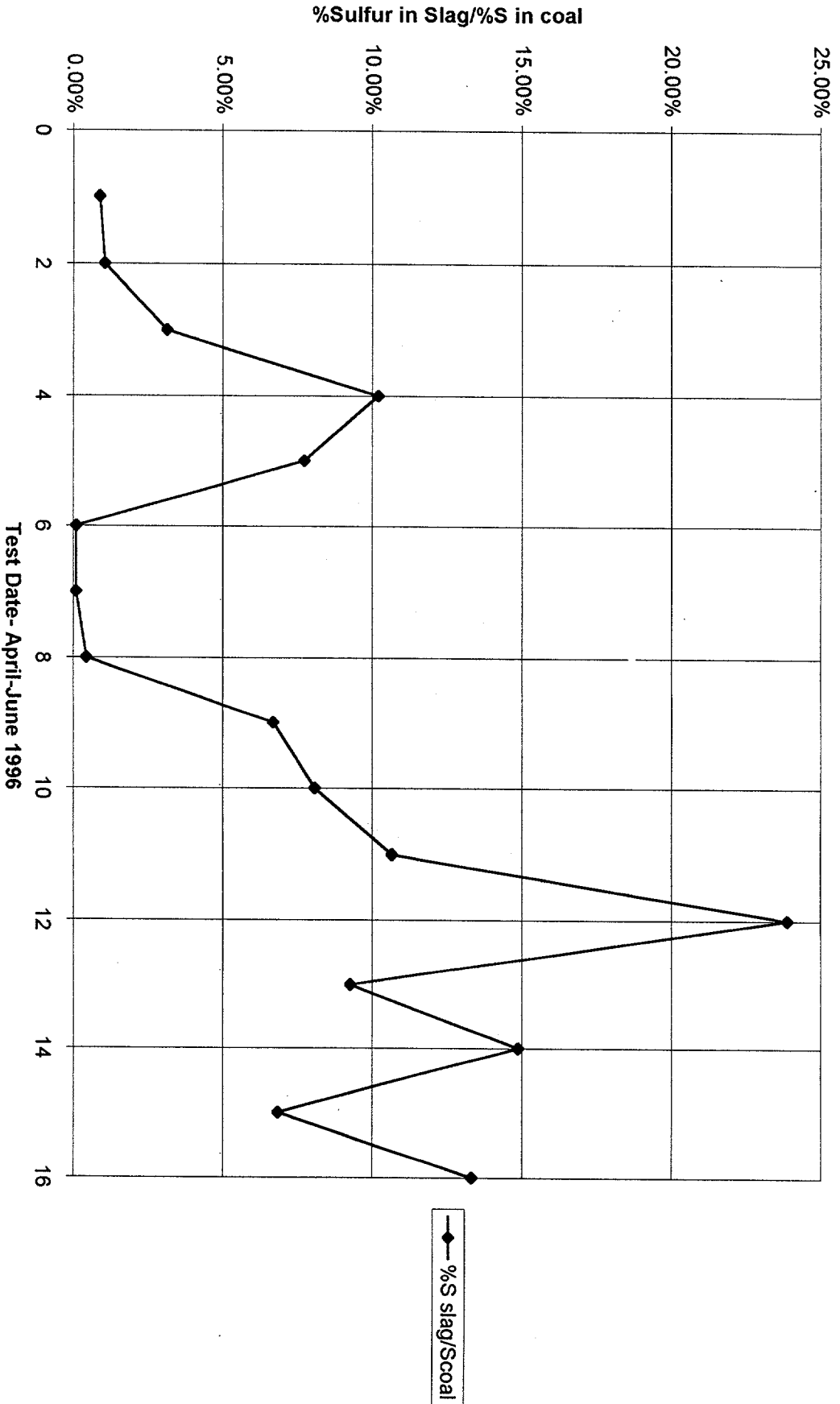


2) Slag Retention in Combustor-1993 Tests



\$S in Slag

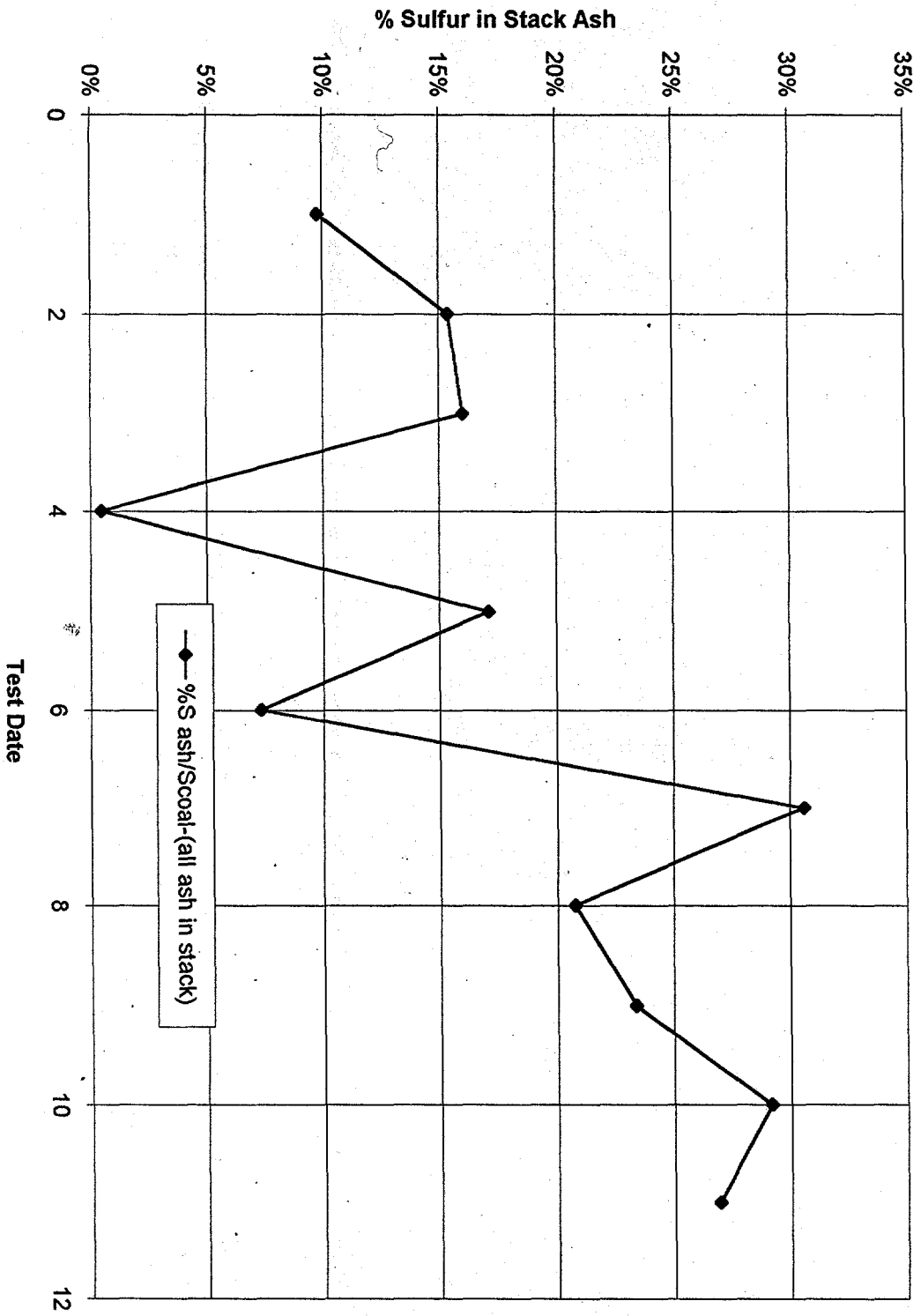
3) S in Slag/S in Coal vs Test Date (w/o Liner Loss)



2

%S in Ash

4) % Sulfur in Stack Ash/% S in Coal vs Test Date



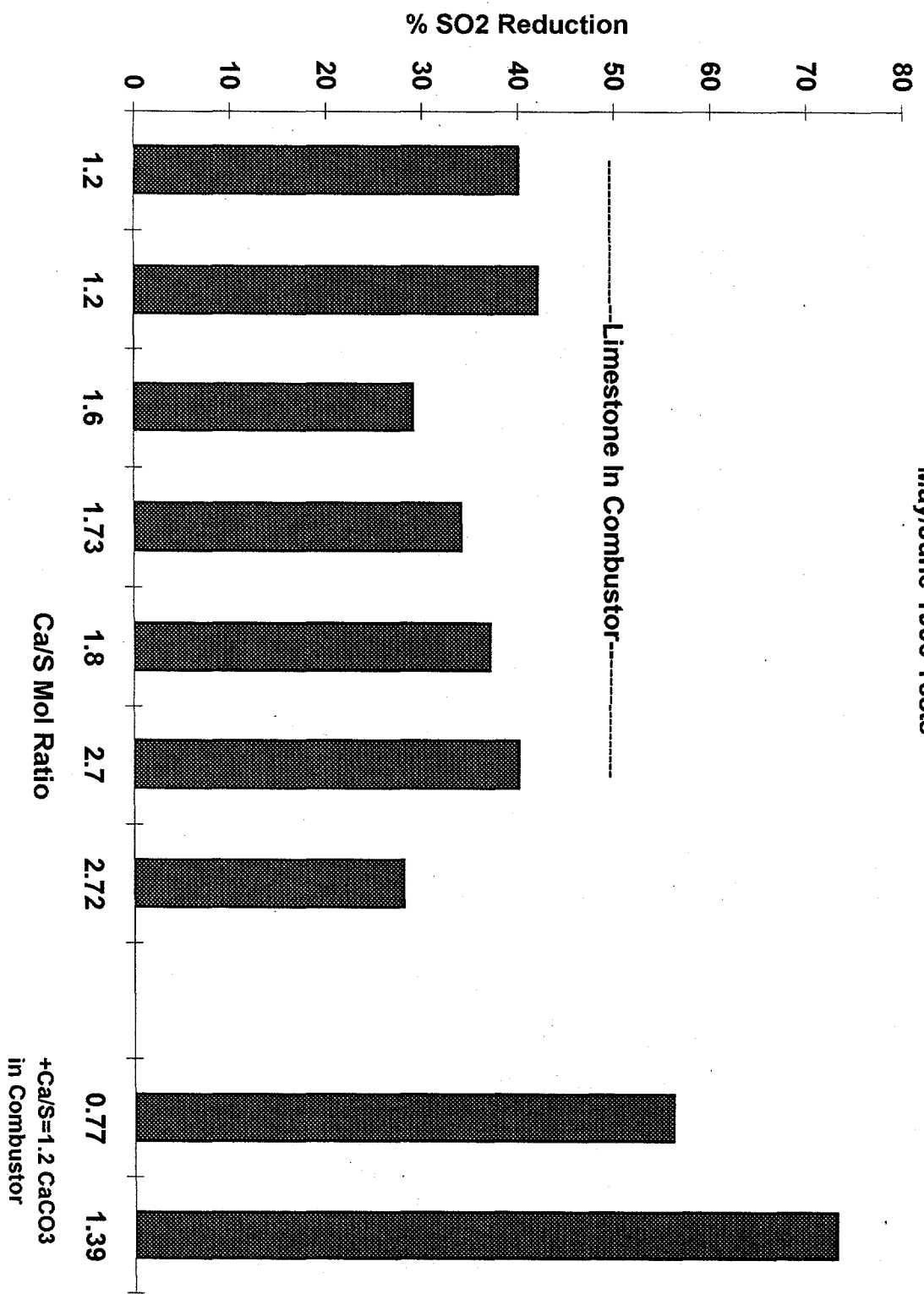
4

5)

SO2 Reduction vs Ca/S Mol Ratio of Sorbent

Injection
May/June 1996 Tests

Hydrate in Boiler



5