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TASK 2.1: PRELIMINARY SYSTEMS TEST PLAN

FOR PROJECT

"DEVELOPMENT & TESTING OF AN INDUSTRIAL SCALE COAL FIRED SLAGGING COMBUSTION SYSTEM, Phase 3"

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1. INTRODUCTION

The planned effort for the task 2 tests has four major objectives. They are computer controlled combustor operation, optimization of SO₂ reduction, combustor materials durability, and testing focused on application to industrial coal fired boilers. Several major advances in the combustor development have occurred since this original plan was proposed in 1991. Some of these advances occurred in tests performed in a project that was completed in June 1992, while others occurred during the design and shakedown tests of equipment that was installed in task 1 of this project. Therefore, the present test plan is based on the current status of the combustor technology, and it differs somewhat from the preliminary test plan that was prepared in April 1992. Depending on the results in the early tests in this task, further test plan modifications may be required. However, the general objectives will most probably remain unchanged.

1.1. Computer Automation: The original 1991 plan for the task 2 tests was to complete the installation of the computer controlled equipment on the combustor and to test this equipment during combustor operation. In the interim, and prior to the start of the task 1 effort on this project, many of the critical control components were installed and tested. In addition, almost all the components that were procured and installed, as well as much of the the upgrading of the control software, were tested in task 1 during two shakedown tests. These test revealed the need for further refinements, and it is planned to incorporate them as the task 2 testing proceed. Some of these refinements are not critical to meeting the task 2 tests goals. For example, the task 1 test activities showed the need for a backup computer control board in the event of failure of internal circuits. This failure can shut down the combustor. While it is planned to further upgrade the control and data acquisition capability of the computer as the test proceed, the extensive computer control development contained in the 1991 test plan has been already accomplished. The emphasis in this task will be on refining and expanding the computer control capability.

1.2. SO₂ Control: A major objective of this project is to achieve a maximum reduction of SO₂ emissions to below 0.4 lb/MMBtu. This equals about 90% and 95% reduction in 2% and 4% sulfur coals, respectively. When the original test effort was planned in 1991, it was anticipated that this could only be achieved by sorbent injection both in the combustor and in the boiler at the combustor exit. This was based on sulfur capture test results achieved up to that time. However, tests in 1992 at the end of a previous project, as well as test results during shakedown activities in task 1, have yielded SO₂ reductions with calcium hydrate injection in the combustor in the 85% to over 90% range in a 1.54% sulfur coal. However, the controlling parameters have not been clearly identified. Specifically, it is not yet known whether the high

reduction is caused by a thermal effect and/or a chemical effect during the sulfur-sorbent reaction. As a result, a major objective of the task 2 tests will be to clarify and optimize the SO₂ reduction with sorbent injection in the combustor.

1.3. Combustor Materials Durability: Another important objective is to demonstrate combustor materials durability. With the introduction of computer control it has been found that the combustor liner can be replenished by slag deposition, using either the ash in the coal or by injecting additional fly ash. This procedure worked very effectively in testing during the past two years of a fly ash vitrification project. For this task, it is proposed to use a basic metal oxide, namely alumina to replenish the combustor's ceramic liner. The advantage of using this material is that it can be purchased at a specified narrow particle size distribution. This assures maximum solids retention in the combustor. On the other hand, use of coal fly ash results in relatively high carryover of the fine ash particles out of the combustor. To demonstrate the difference between ash or alumina addition, consider one of the typical coals tested previously in this combustor. This coal had the following composition (dry), S=1.78%, ash=12.8%. The four main ash components, normalized to 100%, were: SiO₂=53%, Al₂O₃=24%, Fe₂O₃=20%, CaO=3%. When adding CaO to reach a Ca/S ratio of 3, the new normalized (to 100%) composition is: SiO₂=32%, Al₂O₃=14%, Fe₂O₃=12%, CaO=42%. Using this composition in figure 1 (from reference 1), which shows the slag fluidization temperature, (defined as T₂₅₀, the temperature at which the slag viscosity is 250 poise), one notes that the fluid temperature is about 1640K (2492F). This is at the upper range where this combustor operates. Therefore addition of a basic material, i.e. basic coal ash or alumina powder, will move the fluid temperature toward the left to a lower temperature.

1.4. Industrial Coal Fired Boiler Systems: The overall objective of the present project is to commercialize the coal fired combustor for industrial applications. The original plan focused on the use of the combustor with coal fired boilers for industrial steam heat or power generation. Coal Tech's economic studies showed that with current fuel prices, a steam power plant using the air cooled combustor would be economical in the 7 to 10 MWe range *only* in regions of high power costs.

On the other hand, the use of air cooling in the combustor allows its integration in combined gas turbine-steam turbine cycles. This can be done by either passing the compressor exhaust air through the air cooling passages or by passing the fuel lean gas turbine exhaust through the air cooling passages. Integrating the air cooled combustor into the combined cycle also increases the cycle efficiency. One cycle configuration of interest is to use steam injection in the topping gas turbine. This cycle is being investigated in task 4 of this project. Therefore, an important element in the task 2 tests will be to operate the combustor under conditions that partially simulate the conditions the combustor would encounter in the gas-steam turbine combined cycle. This simulation includes steam injection into the combustor. This injection will be both into the combustor and into the inlet plenum of the combustor cooling air. These conditions were already tested successfully in the task 1 shakedown tests.

2. TASK 2-GROUP 1 COMBUSTOR TESTS

The first group of tests will consist of three one-day parametric tests, each of about 8 hours duration on coal. Originally the first two tests were to focus on uniform coal feeding and efficient fuel rich combustion by using high air pre-heat. Both tests were to be performed at 10 MMBtu/hr and 15 MMBtu/hr. Subsequent test work solved the uniform feed problem, and evaluation of the fuel rich test results showed that at heat inputs above about 16 MMBtu/hr, efficient combustion can be achieved at fuel rich conditions in the combustor. Therefore these tests will be replaced with the following tests.

Test No. 1 This test will be performed at a minimum of 15-16 MMBtu/hr, and at a stoichiometric ratio, SR, of 0.7 to 0.75.

Recent tests in the previous project as well as shakedown tests in task 1 showed that the effectiveness of fuel/sorbent/air mixing improved with 8 point coal and 8 point sorbent injection, with separate injection of each solid stream. At present the four inner coal and four inner sorbent injection points are separated from each other. On the other hand, the four outer injection points are coaxial, with the sorbent tubes located inside the coal ports. Due to a problem with wood chip contamination in the pulverized coal supply used in the task 1 shakedown tests, these outer coal ports tended to plug faster than the inner ports. In the last shakedown test, a screen was placed at the outlet of the coal feed auger. This screen removed almost all of the wood chips. However, near the end of a 6 hour test at a 1000 lb/hr of coal feed rate, the coal periodically backed up in the screen. Post test examination revealed that all the outer four coal feed lines were plugged, while only one of the four inner lines were plugged. As the coal in the bin was completely used, it is anticipated that the fresh coal that will be pulverized will be free of this tramp material. In 5 years of using this supplier, tramp material in the coal was found only two or three times previously. Therefore, the first test in task 2 will use the present 8 point injection system. However, if the outer ports continue to be prone to plugging, we will shift to a 6 point coal and 6 point sorbent injection system, with 2 of the outer ports on coal and two on sorbent.

In the preliminary test plan for task 2, prepared in March of this year, we had considered a parametric test, using both 4 and 8 coal injection ports. However, we are now reasonably certain that the 8 point injection system is more effective in air/fuel/sorbent mixing. Based on the wall heat transfer data, it appears that 8 point injection uses the combustor volume more effectively. We had anticipated that the FLUENT modeling results would provide some insight into the preferred mixing mode. However, as reported in the task 1 report and in the recent monthly reports, there are problems with the FLUENT results. Accordingly, we will defer the 4 point injection tests until the 8 point test results and/or the FLUENT code results indicate that this is warranted.

The preliminary test plan prepared in April 1992, proposed tests with and without steam injection directly into the combustor. Also, water droplet injection in the combustor wall cooling air was to be used to simulate wall cooling by the combustion-steam mixture exhaust of a gas turbine. In the interim, in performing the task 4 system work, it was learned that by Dalton's Law of Partial Pressures, steam injection in the combustor cooling air inlet plenum was feasible up to a steam mol fraction of 15%. This equals the steam mass fraction of the gas turbine exhausts. The steam will not condense. Therefore, a new steam line was installed to allow steam wall cooling.

It was successfully tested during a task 1 shakedown test. However, the maximum steam mass flow rate was limited to about 380 lb/hr due to line pressure losses. The planned steam rate was 1500 lb/hr. It is, therefore, planned in this task to increase the steam pressure to allow a higher steam injection rate. Similarly, the direct steam injection rate into the combustor was limited to 800 lb/hr in the task 1 test. It is also planned to increase this rate to as much as 1500 lb/hr.

Another means of wall cooling is to inject water droplets into the combustor cooling air inlet plenum. After a number of trial and error tests, an air atomizing droplets system was successfully test in a task 1 shakedown test. It was possible to change the combustor wall temperature by 200F when changing the droplet mass flow rate by 50%. Accordingly, it is planned to utilize all three cooling methods, i.e. the two steam injection locations, and the droplet injection, to control wall temperatures in all the tests. The task 1 tests showed that the response time of each method varies considerably, with direct combustor injection having the most rapid response. Therefore, a new addition to computer control will be to automate one steam injection location. The steam and water droplet injection rates will be varied during the test from a minimum to a maximum of 1500 lb/hr. At that rate the mass fraction of steam will be about 15%, which equals that in a steam injected gas turbine. The minimum will be determined by combustor wall temperature requirements.

Calcium hydrate will be used as the sorbent. In the last task 1 shakedown test, it was noted that without sorbent injection, wall slagging was reduced and the combustion efficiency was reduced. The only reason for operating a test condition without sorbent is to obtain a baseline condition for SO₂ control. However, if the baseline occurs under poor combustion conditions then it is a misleading baseline. The reason being that under poor combustion, not all the sulfur is released from the coal. This has been verified numerous times from slag samples obtained from the combustor. For this reason, we plan to eliminate the sorbent free baseline test condition and replace it with variable Ca/S mass ratios.

Alumina powder in a 50 to 75 micron particle size range will be injected to replenish the ceramic liner and to control slag flow in one of the tests under conditions where the CaO mass fraction in the CaO-coal slag mixture exceeds 40%. The purpose of this test will be to maximize slag flow and sulfur retention in the slag. The powder will be procured in 50 lb bags. To eliminate the need for repiping the feed stream, the alumina will be premixed with the calcium hydrate and injected through the sorbent ports,

In the preliminary test plan prepared in April, it had been planned to measure the impact of varying the ratio of exit nozzle diameter to combustor diameter. It was to be accomplished by deliberately blocking the exit nozzle with slag during the test. This is done by changing the tertiary air mass flow rate at the nozzle exit. The change in scrubber solids concentration would indicate the impact of exit nozzle opening on slag retention. Up to 3/4 exit nozzle blockage has been observed in prior tests. On further consideration, it has been decided not to implement this step. In the first place, it will be difficult to exactly control the degree of closure. Therefore, there may be too many variables to allow a meaningful interpretation of the results. Instead, we will rely on the results of modeling of the combustion process to indicate the impact of variable exit nozzle opening on slag retention.

A PA bituminous coal will be used for the tests. As the coal properties vary from truck load to truck load, it is not possible to exactly specify the coal prior to the test. We obtain our coal through the PP&L Coal Purchasing Department, who in turn purchase the coal from local mines. For these first tests, we have specified a coal with a HHV of 12,000 to 13,000 Btu/lb, 1.5 to 2% sulfur, 25-30% volatiles, and 13 to 15% ash. The reason for the high ash is to allow the use of high Ca/S ratios without the need for added acid ash for fluxing the slag-sorbent mixture. Also, higher ash reduces the need for ash injection to replenish the wall material. For the alumina injection tests, we can increase the Ca/S ratio to 4, or even 5, if necessary.

The test will be implemented with ash blowing in both the boiler's furnace floor and underneath the lower boiler drum.

This test will also be performed with the finer tramp material screen at the coal auger outlet. Also, the automatic slag breaker will be used, assuming it functions properly in shakedown testing without turning on the combustor.

The following is a tentative test matrix for the first test. (Assume 1.75%S):

TABLE 1: Test Matrix for Test No. 1, Group 1.

Activity	Heat in	Run time	Fuel	Fuel use	Ca/S	CaOH ₂	Al ₂ O ₃	Test Objective
	MMBtu/hr	Hours		(lbs)		(lbs)	(lbs)	
Heatup	9.5 ave.	3	#2 Oil	1520	0	0	0	
8 pt. injection, steam/droplets	16	2	Coal	2500	1	116	0	Vary H ₂ O & Ca/S=1
8 pt injection steam/droplets	16	2	Coal	2500	2	232	0	Vary H ₂ O & Ca/S=2
8 pt. injection steam, droplets	16	2	Coal	2500	3	348	0	Vary H ₂ O m & Ca/S=3
8 pt. injection, steam, droplets	16	1	Coal	1280	4	118	50	S in slag & replenish liner
Cooldown	9.5	1	#2 oil	300	0	0	0	

Test No. 2. This test will be also performed at a minimum of 15-16 MMBtu/hr, and at a stoichiometric ratio, SR, of 0.7 to 0.75. The preliminary plan in April for this test was to focus on sulfur retention in slag and spent sorbent re-use. To test slag desulfurization, we had planned to inject gypsum, i.e. calcium sulfate, in the combustor. To test the re-use of partially spent sorbent for furnace injection, we had planned to inject a mixture of gypsum and calcium hydrate into the boiler, near the outlet of the combustor's exit nozzle. However, with the new emphasis on combustor injection of sorbent, it is planned to eliminate this last step. It will be replaced with one of two test conditions. If post test inspection reveals continued plugging with the outer

coaxial coal/sorbent injection ports, then test No.2 will be performed with 6 point coal and sorbent injection. If no problems are encountered, the balance of the test will be performed at the test condition that yielded the lowest SO₂ output in test 1.

Another change from the original April 1992 test plan is the elimination of the oil fired gypsum-alumina injection test. The motivation for this test was the desire to obtain a baseline condition on slag desulfurization without any interference from the coal sulfur. However, examination of the CaO-Al₂O₃ phase diagram shows that the lowest melting point for this mixture is 1455C (2650F). This is too high a temperature for the present liner.

The coal fired gypsum injection test will be performed at a gypsum mass injection rate at which its sulfur concentration is equal to that of the coal sulfur. Thus any substantial desulfurization will be measurable on the boiler outlet SO₂ meter.

Another key element is the baseline SO₂ measurement. Under very fuel rich conditions, the combustion efficiency is reduced without the slag fluxing effect of CaO. As a result not all the coal sulfur is released from the coal. This will make comparison of slag desulfurization by gypsum more difficult to discern. There, the gypsum test will be implemented at only slightly fuel rich condition, e.g. $0.85 < SR < 0.95$. The exact point will be set at the condition where the SO₂ meter most closely approaches the coal sulfur concentration.

Another possible new feature will be ash suction from underneath the lower boiler drum. If the first test shows that ash blowing in this location has limited impact in eliminating ash accumulation underneath the lower drum, an eductor driven ash suction system will be installed prior to this test. This will consist of a suction tube extending the entire length of the boiler, a cooling coil for the combustion gases, a cyclone to retaining the larger ash particles, and a return pipe to a pipe fitting on the same wall near the top boiler drum. The gas temperature at the boiler exit is measured in every test. During the first test, it is planned to measure the gas temperature underneath the lower drum at the other end of the boiler where the ash suction device is inserted. This will provide the datum on the required cooling load in the cooling coil.

The following is a tentative test matrix for the second test using the same coal (1.75% S). Note: To consume 5.1 tons of coal will require refilling the bin during the test.

TABLE 2: Test Matrix for Test No. 2, Group 1.

Activity	Heat in	Run time	Fuel	Fuel use	Gypsum	CaOH2	Test Objective
	MMBtu/hr	(Hours)		(lbs)	(lbs)	(lbs)	
Heatup	9.5 ave.	3	#2 Oil	1520	0	0	
6 or 8 point injection/steam	16, (.85<SR<.95)	1	Coal	1280	0	0	Coal Sulfur Baseline
6 or 8 pt.inj, steam &gypsum	16, (.85<SR<.95)	2	Coal	2560	400	0	Slag deSulfur., CaSO4=35% of total slag
6 or 8 pt. inj, steam	16 (SR=.75)	5	Coal	6400	0	890	Optimum SO2 red.condition
Cooldown	9.5	1	#2 oil	300	0	0	

Test No.3. This test will be performed at maximum boiler rating of 20 MMBtu/hr. The best condition achieved in the prior tests will be used for this test. In the April test plan, it was planned to include ash re-injection into the combustor. However, the measured ash collected under the lower drum in the 6 hour coal run in task 1 was only 10 to 20 lb. This is too small a quantity to justify ash re injection. Therefore, either fly ash or alumina will be injected to further test liner replenishment. Again note that the baseline will be at Ca/S= 1, not zero, as explained for test 1.

The following is a tentative test matrix for the third test using 1.75%S, 12,500 Btu/lb, 13% to 15% ash coal:

TABLE 3: Test Matrix for Test No. 3, Group 1.

Activity	Heat in	Run time	Fuel	Fuel use	Ca/S	CaOH2	Al2O3	Test Objective
	MMBtu/hr	(Hours)		(lbs)		(lbs)	(lbs)	
Heatup	9.5 ave.	3	#2 Oil	1520	0	0	0	
6/8 pt./steam Baseline	20	1	Coal	1600	1	65	0	
6/8pt/w.steam	20	4	Coal	6400	3	585	0	Full load, Opt. SO2 red.
6/8pt/w.steam	20	1	Coal	1600	2	150	200 (or ash)	Liner replenish.
Cooldown	9.5	1	#2 oil	300	0	0	0	

3. TASK 2-GROUP 2 COMBUSTOR TESTS

The group 2 tests consist of three one day, 24 hour duration tests on coal. These test will be performed with automatic control of combustor fully operational. The original 1991 plan was for operation on coal for 14 hours at 12 MMBtu/hr, 20 hrs at 12 MMBtu/hr , 20 hrs at 16

MMBtu/hr. on coal. The same general schedule will now be maintained. However, the thermal input on each test will be increased by about 4 MMBtu/hr to 16 MMBtu/hr in test 1 and 2 and to 20 MMBtu/hr in test 3. Prior to the implementation of these tests, the new exit nozzle cooling system will be fully in place. It is describe din the task 1 report.

The test will consist of a 3 hour heatup cycle beginning at 7 AM. At 10 AM the combustor will shift to coal operation, and remain on coal for the time periods indicated. Alternatively, heatup will begin the prior evening, and coal firing will begin between 8 and 9 AM. The test will be at steady state operation at the optimum condition obtained in the group 1 test. The bulk of the operating time will be at this condition. However, periodically, wall replenishment material, with fly ash or alumina will be used. The ash blowing and or ash suction system will be in place.

4. TEST PROCEDURE

4.1. Coal: Preparation, Physical and Chemical Properties

Coal Chemical Properties: -For all the test in task 2, a Pennsylvania bituminous coal, having about between 1% and 2% sulfur, a 12% to 15% ash, volatile matter (VM) in the 25-30% range, a HHV of 12,000 to 13,500 BTU/lb, and an ash fusion temperature (T250) under reducing conditions of 2200 to 2300F, will be used. Table 4 shows a typical ultimate, proximate, and ash analysis of the type of a coal that has been tested in this combustor. It is similar to the coal to be used in the task 2 tests. Note that this coal has an acid type ash, i.e. the CaO and MgO levels are very low.

The properties specified do not represent the entire range of coal properties that have and can be burned in this combustor. While VM levels as low as 19% have been burned, under the planned fuel rich conditions, a higher VM level assures better combustion and sulfur release. The above fuel rich (i.e. reducing) T250 temperatures are needed to maintain the slag fluidity at acceptable wall temperatures without the need for high levels of fluxing with CaO. The ash levels are selected to allow operation at a Ca/S between 2 and 3, without substantially increasing the T250 temperature. As can be seen from figure 1, this condition can be met by keeping the CaO concentration below about 40%, by weight. This in turn dictates the maximum sulfur level in the coal that can be retained as a calcium-sulfur compound in the slag. For about 2% sulfur in the coal, a 13 to 15% ash concentration in the coal is required to satisfy all these conditions.

Coal Preparation and Physical Properties: Since 1986, Coal Tech has had an agreement with the PA Power & Light Company for free use of up to 900 tons of PA coal for combustor test purposes. To-date, in all prior projects, about 300 tons have been consumed. For the presently proposed task 2, 3 and 5 tests of about 800 hours, the maximum fuel usage will be under 500 tons, which is well within the PP&L supply agreement. This coal will be delivered by truck to the pulverization company from local PA mines.

The coal is delivered in pulverized form in a tanker truck to the test site in Williamsport, PA. The pulverization is performed in a location that is 20 miles from Williamsport. The coal is

ground to 80% smaller than 200 mesh [74 micrometers]. The coal is pneumatically blown from the truck into a 4 ton storage bin. As the maximum combustion rate is 0.8 tons/hr of coal, the bin holds enough coal for 5 hours testing at full load, and longer at part load. To allow round-the-clock operation the tanker truck which has been dedicated to Coal Tech operation will remain at the site during the test. Bin refilling has been done during prior tests. The tanker's 25 ton capacity allows 31 hours of operation at full load which is sufficient for each of the task 2 tests. One area of concern is to maintain the coal free from tramp material. In the last two tests in task 1, wood chips were found in the coal. Their origin has not been determined. This has been the first time in over a year that contamination of the coal has occurred. Provision has been made to remove these chips during operation. However, it is unlikely that trouble-free coal feed can be maintained for round the clock operation if substantial contamination occurs.

4.2. Sorbent-Preparation, Physical & Chemical Properties:

The sorbent to be used in the task 2 tests is calcium hydrate, which is purchased in 50 pound bags from a local agricultural supply house. The material is pulverized to less than 80%-200 mesh. For the group 1 tests, the sorbent will be manually loaded in the small (500 lb) capacity sorbent bin. For the group 2 tests, the larger (2500 lb) capacity bin. The latter is being equipped with a dust baghouse to allow pneumatic loading of the sorbent from the 50 lb bags, using an eductor.

4.3. Test Procedure-Details

The following test procedure will be generally used:

The evening before the day of the test, the combustor will be fired at a rate of 1 to 3 MMBtu/hr of gas. Preheating of the boiler overnight allows rapid heat-up to operating conditions the next morning, usually by 10 AM. If a morning startup from cold operation is initiated between 7 and 8 AM, coal firing is delayed to between noon and 1 PM. Overnight operation is on an automatic control system that was used in the Clean Coal project tests in 1989 and 1990. It is not computer controlled, and it was tested to a maximum of 3.5 MMBtu/hr.

Very recently the Tampella Company, the owner of the test site, requested the use the test boiler for plant heating to allow the other steam heat boiler to undergo a one month refurbishment for a special test. Therefore, it is planned in one of the overnight pre-heat test, to determine if the present automatic overnight control system can operate the combustor-boiler at up to 6 MMBtu/hr, with the additional heat provided by No.2 oil. As with the pilot gas heat, only the primary air fan would be used for both combustor wall cooling and for all the combustion air. One consideration in overnight operation at higher heat input is to assure that the presently configured neat adiabatic exit nozzle does not overheat. This will not be a problem in the future, as it is planned to install exit nozzle cooling prior to the group 2 tests in task 2.

Once rapid heatup to the specified coal fired operating condition commences, the entire operation will be computer controlled. Oil firing occurs with a ramped fuel input designed to keep the rate of increase of the combustor wall temperature to a range of several 100F/hour. Once the desired wall temperature is reached, conversion to coal firing is implemented. Note that

for oil or coal firing, the combustor will be fully manned even with automatic computer control and even with round-the-clock coal fired operation.

Critical activities during coal fired operation are to frequently monitor the coal feed system, continuously monitor the combustor inner liner temperatures, the temperatures at the outlet of the various water cooled stream, the condition of the slag removed from the slag tank, and the state of the exit nozzle as viewed from the backside boiler viewport.

The automatic slag breaker will be used in all the tests to maintain the slag tap open and functioning. Slag is removed from the slag quench tank located beneath the combustor by means of a conveyor. The conveyor will dump the slag into a metal drum. As it is filled it will be removed and replaced by an empty drum. It had been planned to automate this removal step, but it was decided that it is not cost effective as the facility is fully manned during the test.

4.4. Test Personnel

The combustor test personnel will consist of the following: The project principal investigator will be present at all the tests. A Coal Tech chief test engineer will plan and supervise the test procedure and the data collection. A third test engineer will be responsible for the computer control system. The chief technician from Lyco Services, who is an expert in boiler systems, and who installed most of the electrical equipment and controls for the combustor, will be present to monitor the combustor and boiler performance and to respond to any need for rapid maintenance and repairs during the test. A Tampella boiler operator will be in attendance at least part time to monitor the boiler operation. Another mechanical technician and one or two laborers will be used to handle the consumables and waste products, such as limestone, slag, and coal reloading.

For the task 2, group 2, round the clock tests, the computer controlled system should be fully operational. The test sequence will be pre-programmed. It is, therefore, planned to perform the round-the-clock tests by rotating the above personnel

4.5. Pre-Test & Pro-Test Procedures

About 5 days after each test, the internals of the combustor and boiler are inspected for ash or slag deposits and for areas needing refurbishment. It is planned to clean the boiler after each test and remove all ash to allow a mass balance of all solid stream to be made. For the one day tests, this mass balance will be incomplete as it is not feasible to remove accumulated slag and ash from inside the combustor. However, this accumulation can be estimated from visual observations.

Any required maintenance and modifications prior to the next test are made at this time. Also during this period, the slag and scrubber water samples are analyzed by a contract laboratory. The test data are also analyzed. The results are used to adjust or modify the plan for the next test, if necessary.

When about 5 to 10 tons of ash/slag have been accumulated they will be taken to an approved landfill for disposal. Coal Tech has obtained a permit from the PA Department of Environmental Resources for this disposal.

5 INSTRUMENTATION, CONTROLS & DIAGNOSTICS

Controls: The fuel and air streams to the combustor were originally (from 1987-1990) manually controlled using the combustor's thermal performance as input variables. Figure 2 shows a photograph of the 20 MMBtu/hr combustor installed on the 17,500 lb/hr package boiler. The manual control panel is shown on the left background. This system was selected for two reasons:

- It was believed, correctly as it turned out, that automatic control features would have to be significantly modified as experience with the combustor was acquired.
- A commercial automatic control system would have been as much as 5 to 10 times more expensive, and beyond project resources.

During the first 3-1/2 years of testing, a very large operating data base was. Beginning in early 1989, an automatic control system was added. It allows the combustor to operate unattended for overnight operation on pilot gas fuel input. This allows rapid startup and shutdown of the combustor for daytime oil and coal fired operation. This procedure has worked well, and five tests with four days of round-the-clock operation were implemented in 1989 and 1990. Basically, this system uses only the 3.5 MMBtu/hr gas pilot and the primary air fan. The latter provides both combustion air and combustor wall cooling, a function that is normally done by the high power secondary air fan. The controls monitor the combustor wall temperature. If the pre-set peak temperature is exceeded the system shuts down. In addition, the flame system is coupled to the boiler controls to shutdown the flame if a boiler problem, such as low water level, occurs. As noted, during the present task 2, group 1 test, it is planned to test this automatic system to 6 MMBtu/hr by adding No 2 oil firing to the gas heat.

During the Spring of 1990, sufficient operational data had been accumulated to proceed with microcomputer controlled operation. A commercial process control software package was modified to control the combustor- using the operating strategy developed during the Clean Coal project. During the past 2 years, this system has undergone considerable development and testing, which included gradually adding to the number of function that are controlled.

The control system is currently configured to operate as follows: At the beginning of a test, the combustor is manually shifted from automatic overnight pre-heat (if used) to daytime operation. The computer then initiates and controls oil fired combustor heatup until operating combustor temperatures are reestablished. The heatup ramp is either installed in the software from heatup curves established in prior manual operations, or the necessary values are manually entered. When heatup is completed, a manually controlled shift from oil fired to coal fired operation takes place. The original plan to perform this step automatically was abandoned as it was found to be too cumbersome to implement. This changeover is a gradual process that occurs over a relatively short period of 15 to 30 minutes. The computer will then maintain the desired operating thermal input and wall temperatures by adjusting the cooling and combustion air flows.

the coal flow, and the level of sorbent injection. Any desired changes in operating conditions can either be preprogrammed or entered manually by the operator.

As the system has undergone testing, it has been found that further refinements were necessary. For example, it has been noted that the control of air cooling by adjusting as many as four different air flow control valves is too slow to respond to combustor wall temperatures. In other words, the temperature either overshoots or undershoots. The recent addition of the various water and steam cooling features have been found to provide a much faster response to wall temperature changes. As a result, it is planned to add at least one of these streams to computer control.

A key advantage of this computer control is that it is possible to adjust the solids and air inlet conditions to replenish the combustor wall thickness with slag.

Figure 3 is a photograph of the control panel screen from which the status of the combustor and boiler are determined and which records any manually entered changes to the operating conditions. Figure 4 shows a schematic of the control strategy. Basically, a diagnostic measurement, such as temperature is received and evaluated. Any necessary changes as a result of this evaluation are transmitted to a control switch which adjusts a cooling flow as needed to maintain the desired temperature. The computer also collects all the operational data in a format that allows its immediate analysis in Lotus type spread-sheet format.

Further details of the computer control and data acquisition system are described in the Task 1 Report. Briefly, the computer monitors the combustor wall temperatures, the combustor cooling water temperatures and flow rates, the steam flow, the various air flow streams, the coal flow, and the sorbent flow. It controls the cooling and combustion air flow streams, the coal flow and sorbent flow. It had been planned to add computer control of the automatic slag tap clearing device, refilling of the coal bin, and control of the slag conveying systems. However, the first item will be set on a repetitive times, the second and third item occur so infrequently that manual control will be retained.

Instrumentation & Diagnostics: The following diagnostics will be used, all of which are currently installed: Fuel, air (one primary, four secondary, one tertiary, and one coal and one sorbent transport), six cooling water flows, between 12 and 18 combustor wall and exit nozzle temperatures, two boiler ash blowing air flow rates, two stack gas temperatures, one steam mass flow rate, which is injected into the combustor. The four secondary air flows allow independent monitoring and control of the combustor cooling and combustion air. The various water flow measurements allow monitoring and control of the cooling of various sections of the combustor as well as the water droplet injection rates. The actual instrumentation consist of water flow meters, pitot tube type air flow meters, thermocouples, and pressure gauges.

The stack gases, CO₂, CO, SO₂, NO_x, and HC, are routinely sampled in the stack above the boiler outlet, and infrequently in the exhaust from the wet scrubber. These samples are analyzed in a portable Enerac diagnostic system. The SO₂ is also analyzed in a pulsed fluorescence detector, which is located at the outlet of a gas conditioning system to assure sample integrity. This instrument is calibrated against a known SO₂ gas source. It had been planned to

use the O₂ measurements from the Enerac as an input signal to control the combustion stoichiometry. However, this instrument is not suited for continuous monitoring and control. Also, other parameters, such as air and coal flows and wall temperatures, provide better control

It is planned to perform at least one stack gas particulate test using EPA method 5 upstream of the scrubber and downstream of the scrubber. This test will be performed by a testing organization that Coal Tech has used in prior tests on this combustor. This analysis will also include measurements of the particulate size distribution in the stack to test the impact of ash blowing in the boiler.

6. DATA ACQUISITION & ITS RELATION TO TEST OBJECTIVES

6.1. Test Data to be Taken: The test data to be taken were briefly noted in the previous sub-section. These data will be primarily collected by the controlling computer, and with some manual data collection for additional real time monitoring of combustor performance. The following test data will be taken:

- All gas and solid streams, i.e. gas flow, oil flow, all air streams, and all water streams used for cooling in the combustor and boiler.
- All the temperatures in the combustor and boiler, as well as pre-heat and stack temperatures, from which combustion efficiency is computed.
- Gas samples consisting of CO₂, CO, SO₂, NO_x are collected in the stack upstream of the scrubber.
- Periodically, at least once every 1/2 hours, [or 1 hour for the round the clock tests] slag samples will be collected at the base of the slag tap, and water samples will be collected in the scrubber for post test analyses of the solids and water. This information is used to extract data on the state of the combustor materials, as well as on other items, such as sulfur mass balance, slag retention in the combustor, combustion efficiency, and the presence of trace metals in the slag and scrubber solids. The analysis of all the water samples and solid slag and ash samples will be performed by the chemical analysis firm that has analyzed all the Coal Tech slag and water samples in the past 6 years.

All of the above procedures and data acquisition methods contain over 100 individual data points collected at one time. These data are converted to a spreadsheet format for subsequent analysis. During the test, critical data such as consumable streams, wall temperatures and stream flow rates are recorded on the computer control screen, figure 3, for use in controlling the tests.

6.2. Relation of Data Acquisition to Test Objectives.

The four major test objectives are computer automation of the combustor, combustor and boiler durability, SO₂ control, and relation of the test effort to commercial industrial systems that utilize the combustor. The relation of these objectives to the data acquisition is as follows:

Computer Automation: If the combustor were 100% automated, the success of this test objective could be measured in real time. If the computer maintains the combustor within the specified operating range, and shuts it down in the event of a components failure or consumable

flow interruption, it is performing as designed. Without full auto-mation, as is now planned, the effectiveness of the computer is measured by assessing the performance of its various functions. They are:

1) *Operation of the computer without computer components failure or software errors.* Several such problems have occurred in the recent past. For that reason, a computer engineer is present at all tests. For example, in one recent test a connection in one of the computer control boards failed, and the engineer repaired it. For this reason, it has been decided to purchase a backup board in case of failure during a test. In a commercial system, a second computer would shadow the primary computer and take over in case of its failure. In addition, a standby power supply has been acquired which provides power in case of a failure of the power source. In summary, the reliability of the computer equipment over the course of the test effort is one of the measurable of the success of computer automation.

2) *Ability of the computer to maintain the combustor wall temperature within the specified, safe operating range.* This is a key element of combustor durability. It is measured two ways. One is in real time, namely, observing that the wall temperature remains within the specified range. In the last two task 1 shakedown tests, manual override was necessary to maintain the temperature by adding to, or subtracting from, the air or water/steam cooling. This manual intervention is primarily required during major changes in operating conditions, such as heat input. Once a steady condition is achieved, the computer control is fairly effective. It is anticipated that as the task 2 effort proceeds, the computer will maintain this function for increasingly longer periods of time. In fact, a complete 24 hour round-the-clock test will absolutely require computer control of wall temperature. The second method of measuring the success of this objective is internal inspection of the combustor walls after a test by use of a borescope and if necessary by internal visual inspection.

3) *Data acquisition and real time monitoring.* This is a reliability measurement, and it relates to item 1 above. The computer must collect all the combustor performance data points for use in controlling the test and for post test analysis. In general the reliability of the computer is very high, and failure in this area is anticipated to be very infrequent.

In conclusion, computer automation is a real time activity. If the combustor stays on line throughout the planned test duration, it is most probable due to the effectiveness of the computer.

Combustor Durability: The two major elements in combustor durability are air cooled liner integrity and exit nozzle refractory durability. Measurement of liner durability has been discussed as part of computer automation. There is one other measurement of liner durability, and that is the frequency of liner replenishment with either fly ash or alumina. The need for replenishment will be determined from computer read wall temperatures. It is anticipated that by proper wall temperature control, replenishment will be infrequent, i.e. several times per day. In fact in a commercial system, replenishment should be dictated by the magnitude of fly ash re injection as collected by the baghouse and boiler deposits.

The exit nozzle's internal refractory has had an excellent record of resistance to slag attack in testing during the past 5 years. The only concern with long duration round the clock operation

is to maintain the refractory and steel sections, that support the internal exit nozzle refractory liner, within a safe temperature range. This will be monitored by thermocouples installed in these sections. As noted, this part of the exit nozzle will be cooled with air cooled tubes inserted in the support refractory. The effectiveness of this cooling will be measured by the success in keeping the various sections of the nozzle in the specified temperature range.

Boiler Durability: There are three measurables of durability. One is to minimize the ash deposition on boiler tubes and boiler floor. The second is to minimize slag flow from the exit nozzle into the boiler floor. The third one is to maintain boiler tube integrity in the face of slag and ash erosion. All these items are measurable only after a test. The first two are measured by removing and weighing the ash and slag from each section of the boiler. The third one is measured by measuring boiler tube wall thickness which occurs during the annual boiler inspection for insurance purposes.

SO₂ Control : Measurement of SO₂ reduction with sorbent injection is obtained by correcting the measurement of the SO₂ meter for quenching of SO₂ by the other combustion gases. In addition, it is important to obtain a baseline SO₂ measurement in the absence of sorbent injection. As was described earlier in this report, the absence of sorbent increases the slag viscosity, which yields poor slagging with the present PA coals. This reduces combustion efficiency which reduces the sulfur release from the coal into the combustion gases. Therefore, the effectiveness of SO₂ reduction will be measured by plotting SO₂ reduction versus sorbent injection rate, with a minimum Ca/S of 1 and a maximum of 4. A separate check of the sulfur capture is to perform a sulfur balance. This is obtained by collecting slag samples from the combustor slag tap and the scrubber water regularly during the test. Post test analysis provides the sulfur content. Also, after the test, the slag and ash from the boiler and base of the stack is collected and samples are analyzed for sulfur content. This latter method provides a complete sulfur balance independently of the boiler outlet SO₂ measurement. However, for accuracy the entire test must be performed at one condition. If the Ca/S ratio varies, then this second method provides an average sulfur content.

Relation of the test effort to commercial industrial systems: At present this objective is being applied to a steam injected combined gas turbine-steam turbine cycle. This objective can be evaluated by operating the combustor under conditions simulating those in the power plant, and measuring the combustor performance. In the present case, this means operating with steam injection. However, it will not be possible to simulate the 900-1000F gas outlet temperature from the gas turbine nor the combustion gas concentration in the gas turbine outlet. However, the latter two effects are secondary to that of steam injection.

7. DATA ANALYSIS

Each test provides several 100 data points per unit time interval. With the prior manual operation in the combustor only a fraction of this data could be collected and analyzed. The combustion efficiency is computed from the stack gas analysis, the steam flow measurement, the air, coal and sorbent feed rates. These data also provide corrected concentrations of SO₂ and NO_x. In prior tests, these data were analyzed by statistical methods to isolate parameters that control the combustor thermal and environmental performance. The results of this analytical approach were reported in the Clean Coal Project Final Report (Reference 2) and the Ash Vitrification Final Report (Reference 3). Key parameters that control combustion and environmental performance were found to be stoichiometric ratio in the combustor, combustor wall temperature, total thermal input, T₂₅₀, coal ash concentration, number of injection points, peak gas temperature, Ca/S mass ratio, and sorbent type. Details are given in these two reports.

With the new computer data collection in a spreadsheet compatible format, analysis of the data will be much easier and more rapid. It is planned to increase the number of real time measurements by adding items such as wall heat flux, slag composition, slag flow rate. This will allow fine tuning of the combustor during operation. In addition, it will now be possible to detect changes in combustor performance and combustor condition that would have been missed with manual data collection. Finally, the data can be directly converted to graphical form from the raw data. This will improve the efficiency of data analysis.

8. SCHEDULE

Task 2 consists of six one day tests, with the last three requiring two days of operation to complete. Historically, for one day duration tests, the combustor has been operated at the rate of one test per month, and this is reflected in the Project Milestone Schedule submitted to DOE, and shown in Table 5.

This test frequency is based on the following considerations: It takes about 5 days, for the boiler to cool sufficiently to allow personnel entrance for inspection and ash/slag removal. It takes several days after the test to perform a preliminary test analysis from which the slag and scrubber water samples are selected for analysis. The chemical analysis takes about 2 weeks. In addition, repairs or modifications to the combustor, in preparation for the next test, can take from a few days to several weeks, depending on personnel availability and the nature of the repairs. Finally, as Coal Tech is a lessee of the facility, we must adjust our test schedule to that of the Tampella fluid bed pilot plant and more recently to tests on the other package boiler in the boiler house. The latter will result in a scheduled shutdown of the other boiler for at least one month during the Fall or Winter of 1992. During this time, either the air cooled combustor or a rented boiler will provide steam heat to the Tampella plant. In the latter case, there will be no impact on our schedule. In the former case, this one month period will not be available for testing. These scheduling conflicts can sometimes delay the test frequency to less than one per month. For example, this past summer, the boiler feed water pump and boiler steam blowoff valve failed during a pilot plant test, and the boiler was not available for nearly two months. Finally, the delay in NEPA approval caused a general slippage of almost one quarter in the schedule.

In view of all these factors, it is planned to proceed before the end of September 1992 with the first of the task 2 tests. The second test will be October, and the third one in November. Depending on the results of these tests, and assuming no slippage due to Tappella scheduling conflicts, the group 2 tests will be compressed into a shorter period. Specifically, if after the first group 2 test no modifications are indicated, the second group 2 test will be implemented in the third week after the second test. The final test will be implemented within 4 weeks after the second one. Therefore, all task 2 tests will be completed by mid to late February or early March. This will reduce the project schedule slippage from present 3-1/2 months to 2-1/2 to 3 months.

REFERENCES

1. M. Petrick & B. Ya. Shumyatski, Ed. Open Cycle MHD Electric Power Generation, (Argonne National Laboratory, Argonne, IL, 1978)
2. B. Zauderer & E. S. Fleming, "The Demonstration of an Advanced Coal Combustor with Internal NO_x, SO₂, and Ash Control for the Conversion of a 23 MMBtu/hr Oil Fired Boiler to Coal", US DOE Clean Coal Project Final Report, August 30, 1991
3. B. Zauderer & E. Fleming, "Conversion of Fly Ash to Inert Slag in a Cyclone Coal Combustor, DOE SBIR Project Final Report, June 1992

TABLE 4

CERTIFICATE OF ANALYSIS

CLIENT: COAL TECH CORP.
P. O. BOX 154
MERION, PA. 19066-0154

DATE REPORTED: 2/5/88
REPORT NO: 8813725-001

SAMPLE TYPE: Coal #2

DATE SAMPLED: Unknown

SAMPLED BY: Client

DATE RECEIVED: 1/22/88

SAMPLE IDENTIFICATION: Pulverized Coal -
Sample A

PURCHASE NO.: DOE-CC-41

ORDER NO.:

		AS RECEIVED	DRY BASIS
Total Moisture	%	0.66	
Volatile Matter	%	22.8	22.9
Fixed Carbon	%	63.6	64.0
Ash	%	12.9	13.0
Heating Value	Btu/lb	13,420	13,510
Sulfur	%	1.25	1.26
Carbon	%	76.8	77.3
Hydrogen (Excluding H in moisture)	%	4.23	4.18
Hydrogen (Including H in moisture)	%	4.16	
Nitrogen	%	1.30	1.30
Oxygen (Excluding O in moisture)	%	3.54	2.97
Oxygen (Including O in moisture)	%	2.95	

Respectfully submitted,

CARL J. WUMMER - GROUP LEADER
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(301) 494-0500

TABLE 4

CERTIFICATE OF ANALYSIS

CLIENT: COAL TECH. CORP.
P. O. BOX 154
MERION, PA. 19066-0154

DATE REPORTED: 2/5/88
REPORT NO: 8813726N
DATE SAMPLED: Unknown
DATE RECEIVED: 1/22/88
PURCHASE NO.: DOE-CC-41
ORDER NO.:

SAMPLE TYPE: Coal Ash #2

SAMPLED BY: Client

SAMPLE IDENTIFICATION: 001: Sample A Ash FROM
COAL SAMPLE

ANALYSIS

001

Aluminum Oxide as Al_2O_3	%	23.8
Calcium Oxide as CaO	%	1.25
Iron Oxide as Fe_2O_3	%	10.7
Potassium Oxide as K_2O	%	2.72
Sodium Oxide as Na_2O	%	0.37
Silica as SiO_2	%	53.2

Respectfully submitted,

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TABLE 5

Milestone Schedule for "INDUSTRIAL COAL FIRED COMBUSTION" Project

		J	F	M	A	M	J	J	A	S	O	N	D	2Q	3Q	4Q	1Q	2Q	3Q	4Q
Task 1.1	Design																			
Task 1.2	Fabricating																			
Task 1.3	Integrate																			
Task 2.1	Test Plan																			
Task 2.2	System Test																			
Task 3.1	Refurbish																			
Task 3.2	Proof Test																			
Task 4.1	Economics																			
Task 4.2	Commercial																			
Task 5.1	Demo Plan																			
Task 5.2.1	Procure																			
Task 5.2.2	Install																			
Task 5.2.3	500 hr. Test																			
Task 6	Decommission																			
Final Report																				

FIGURE 1
 —Dependence of slag flow
 temperature on CaO and Fe_2O_3 content.
 Slag types: A) highly acidic, B) acidic, C)
 basic, D) high basic

Figure 2 Photograph of the 20 MMBtu/hr Combustor at the Test Site

Figure 4 Photograph of the Process Control Strategy for the Combustion.

Figure 3 Photograph of the Computer Screen from which the Combustor is Controlled.

END

**DATE
FILMED**

8/27/93