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COAL FIRED COMBUSTION SYSTEM,PHASE 3"

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## ABSTRACT

In the second quarter of calendar year 1997, 9 days of combustor-boiler tests were performed, including 3 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 1997 in the task 5 effort to 83 days. This compares with a total of 63 test days needed to complete the task 5 test effort, and the number of tests days required to meet the task 5 project plan have been completed. The key project objectives in the areas of combustor performance and environmental performance have been exceeded. With sorbent injection in the combustion gas train, $NO_x$ emissions as low as 0.07 lb/MMBtu and $SO_2$ emissions as low as 0.2 lb/MMBtu have been measured in tests in the previous quarter. The emphasis of tests in the present quarter have been on further optimizing post-combustion sorbent injection for SO2 and NOx control processes, with most of the test effort focused on the NOx control process. Many factors which control the NOx reduction were identified in tests on the 20 MMBtu/hr combustor-boiler. Another very important milestone in this quarter was the successful test of this Coal Tech post combustion NOx control process on a 100 MW utility boiler, where in a preliminary test 25% NOx reduction was measured.

TABLE OF CONTENTS



LIST OF FIGURES

## 1. EXECUTIVE SUMMARY

The focus of the effort of present quarterly reporting period was on optimization of Coal Tech's new post-combustion NOx emission control process, further tests on post combustion sorbent injection for SO2 control, and further tests with the high ash Indian coal. The last item was implemented as part of a parallel project on sulfur retention in slag. All the tests were performed on the 20 MMBtu/hr combustor-boiler at Coal Tech's Philadelphia site. In addition, initial tests were performed with Coal Tech's post-combustion NOx on a 100 MW utility boiler, where 25% reduction in NOx emissions were measured. Since this work is potentially patentable, only general results will be presented at this time.

<u>20 MMBtu/hr Combustor-Boiler Test Operations:</u> In the second quarter of calendar year 1997, 9 days of combustor-boiler tests were performed, including 3 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 1997 in the task 5 effort to 83 days. This compares with a total of 63 test days needed to complete the task 5 test effort. The key project objectives in the areas of combustor performance and environmental performance have been exceeded. With sorbent injection in the combustion gas train, $NO_x$ emissions as low as 0.07 lb/MMBtu and $SO_2$ emissions as low as 0.2 lb/MMBtu have been measured in tests in the previous quarter. Tests in the present quarter have resulted in further optimizing of the post combustion SO2 and $NO_x$ control processes. A very important milestone in this quarter was initial successful in scaling up Coal Tech's post combustion NOx control process by a factor of 100 from the 20 MMBtu/hr combustor-boiler to a 100 MW utility boiler. The following is a brief summary of the key results:

<u>Post Combustion NOx Emission Control with Sorbent Injection:</u> In the two previous Quarterly Report, the results of a new method for reducing NOx emissions from the air cooled, 20 MMBtu/hr slagging coal combustor using post combustion control, was reported. In the present quarterly reporting period a major focus of the tests was directed at further understanding and this process and on optimizing the NOx reduction.

The first of two tests performed in April was with post combustion sorbent injection downstream of the combustor for NOx control firing only with oil. Only 25% NOx reduction was achieved. In the next test, the oil flow rate was almost doubled from the previous test in order to increase the downstream combustion gas temperatures. However, there the NOx reduction remained at 25%. On shifting to coal firing, the reduction was about two-thirds, in the same range as the previous coal fired tests. However, the absolute level of NOx was much higher with coal than with oil. Note that the relative concentrations of sorbent to NOx concentration was maintained the same in both oil and coal firing conditions. Based on subsequent computer modeling of the combustion gas flow in the post combustion zone, it appears that the temperature distribution with oil is substantially different than with coal, which would explain the different NOx results with the two fuels.

An additional pair of day long NOx control tests was performed in June. The objective was to determine the impact of different injection locations on the magnitude of NOx reduction by post combustion sorbent injection. The results showed that injection location is critical to NOx reduction. This was verified by three dimensional modeling of the combustion gas flow from the combustor through the boiler. Further tests are planned to improve the utilization of the sorbent and the effectiveness of the NOx reduction.

SO2 Control with Post Combustion Sorbent Injection: The objective of the next two tests was to extend the previous effort on the effectiveness of sorbent injection downstream of the combustor for SO2 control. Prior tests in low sulfur (<2%) coal had yielded SO2 reductions ranging from 50% upstream of the baghouse to 90% downstream of the baghouse. In the latter case, the SO2 measured was as low as 0.2 to 0.3 lb/MMBtu. For the present tests, a medium (2.5%S) sulfur coal was used. There was no substantial additional reduction of the SO2 with the furnace injection over the reduction from sorbent injection into the combustor. Also, the SO2 reduction measured at the boiler stack outlet was about 30% due to sorbent injection in the combustor only. It increased to 42% with the additional injection downstream of the combustor. Unlike earlier tests, the SO2 measurements downstream of the baghouse was slightly lower. However, the Ca/S mol ratio from the sorbent injected in the combustor was only 0.96, while the additional furnace sorbent injection added a Ca/S of 1.5 and 1.9. This was about one half the Ca/S mol ratios used in the low sulfur coal. Higher sorbent injection rates could not be achieved due to feeding equipment limitations. This suggests that a longer injection period may be required to properly coat the baghouse surfaces with higher sulfur coals.

Very High Ash Indian Coal: The next three tests were performed under the other project, and in two of these tests, the balance of the very high (37%) ash Indian coal that had been tested in January 1997, was used. The results are reported in that project's Technical Quarterly Report for the present reporting period. For the purposes of this project, the excellent slagging performance that was observed proves that the air cooled combustor is especially suited for very high ash coals.

Post Combustion NOx Control in a 100 MW Electric Utility Boiler: The Coal Tech post combustion process is readily adaptable to large boiler. A search was initiated late in the previous quarter for a suitable test boiler, and one was found in March. An inspection trip to this boiler was made in April, suitable locations for sorbent injection, based on the results on the 20 MMBtu/hr combustor-boiler, were identified. In June, a NOx control test on the 100 MW boiler was performed. The initial injection points, which were selected on the basis of results on the small boiler, produced no NOx reduction. A subsequent test at the second pre-selected injection area, using only one-half the injection points, yielded a 25% NOx reduction. This was a significant milestone in this project since a factor of 100 scaleup of the NOx control process was successfully implemented. Further tests are planned on this boiler and another smaller utility boiler in the next quarter. Due to limited project resources, subsequent tests must be carefully planned.

Marketing: Efforts began in this quarter to market small power plants based on the Coal Tech combustor. Due to the success with very high ash Indian coal, the initial effort focused on India and contacts with several manufacturing and user organizations in India were initiated. The initial focus is on construction of a 10 MW coal fired power plant.

Conclusions: The total of 83 test days completed in task 5 by the end of this quarter without any significant refurbishment of the combustor indicates that the combustor is nearing commercial readiness. The modifications and maintenance performed are relatively minor in nature. Most of these modifications are the result of the daily startup and shutdowns and the frequent changes in operating conditions.

The most significant new results in this quarter was the successful application of Coal Tech's post combustion NOx control process on a 100 MW utility boiler. Of equal significance was the validation of the superior performance attainable with the Coal Tech air cooled combustor when burning very high ash coals. These coals are widely used in Asia, Europe, and South America.

## 2. RESULTS AND DISCUSSION

### 2.1. PROJECT DESCRIPTION

#### 2.1.1. 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 $SO_2$ emissions, 0.2 lb./MMBtu of NOx 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 NOx emission goal will require a modest improvement over maximum reduction achieved to date in the first generation combustor to a level of 0.26 lb./MMBtu. In the present second generation combustor, the best NOx levels with fuel rich conditions in the combustor was in the range of 0.3 to 0.4 lb/MMBtu. To reach the $SO_2$ 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.

#### 2.1.2. Technical Approach

##### 2.1.2.1. 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 $SO_2$, NOx, 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. $SO_2$ 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. NOx is controlled by staged, fuel rich combustion inside the combustor. Additional reductions are achievable by reburning in the boiler or by ammonia injection if 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 $SO_2$ reduction in the combustor. Prior to the start of the present Phase 3 project, the peak $SO_2$ 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% $SO_2$ 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 $SO_2$ 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% $SO_2$ reduction could be achieved by sorbent injection in the combustor. Recently this result has been duplicated in gas samples taken in the boiler furnace. However, the SO2 reduction in the stack for the same conditions were less, and no conclusive explanation for this has been as yet been found.

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.

2.1.2.2. 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. For a number of reasons, this effort is being implemented in single daily shift operation with minimal combustor refurbishment between tests. The 500 hours are thus equal to 63 days of single shift operation. As of the end of the present reporting period, 57 test days have been completed.

Task 6. Decommissioning Test Facility

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

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*Post Combustion NOx Control:* Four tests were performed in the present quarter to further study and optimize Coal Tech's post combustion NOx control process.

The objective of the first two tests, performed in April, was to determine if the Coal Tech post combustion sorbent injection process for NOx control would be applicable on oil fuels. In the first test, the oil firing rate was 5.6 MMBtu/hr, which is at the low end of the 20 MMBtu/hr combustor turndown ratio. Only 25% NOx reduction was achieved. In the next test, the oil flow rate was almost doubled to 9.8 MMBtu/hr in order to increase the downstream combustion gas temperatures. However, there the NOx reduction remained at 25%. On shifting to coal firing, the

NOx reduction was about two-thirds, in the same range as the previous coal fired tests. However, the absolute level of NOx was much higher with coal than with oil. The relative concentrations of sorbent to NOx concentration was maintained the same in both oil and coal firing conditions. Three dimensional computer modeling of the combustion gas flow in the post combustion zone was performed for coal firing conditions in the this boiler. The results showed a wide variation in the temperature distribution in the post combustion zone. Limited temperature measurements with a thermocouple with coal firing appeared to confirm this modeling result. A complete temperature profile could not be obtained due to the limited access ports in the boiler. With oil firing, especially at the lower total heat input, this temperature non-uniformity will be much more pronounced. Although originally designed for oil firing, this boiler has been modified for coal firing. Therefore, the temperature distribution in the post combustion zone is substantially different that in a conventional oil fired boiler. Consequently, the present test results are a good measure of the suitability of the Coal Tech NOx control process for oil fired boilers. No further NOx control fired tests were implemented.

An additional pair of day long NOx control tests was performed in June. The objective was to determine the impact of different injection locations on the magnitude of NOx reduction by post combustion sorbent injection. The results showed that injection location is critical to NOx reduction. In the tests, the NOx reduction remained constant as long as the injection was at the appropriate temperature. However, at one injection point the NOx reduction decreased by about one half. Post test internal boiler inspection revealed that the injector had not been placed at the appropriate temperature location. Thermocouple temperature measured showed wide variations in the post combustion gas zone in the boiler. This was also confirmed by three dimensional modeling of the combustion gas flow from the combustor through the boiler.

Further tests are planned to improve the utilization of the sorbent and the effectiveness of the NOx reduction.

*The Indian Coal Tests*. As early as 1989, Coal Tech performed tests in the Williamsport 20 MMBtu/hr combustor in which coal fly ash was injected into the combustor with coal to achieve over 50% ash content in the mixture. However, due to the small ash particle size, (<10 microns), much of the ash was blown out of the combustor. The highest ash content in coal tested was about 15%. Last fall, a substantial number of tests were performed in which the artificial ash was injected into the combustor. These tests were performed for the parallel sulfur in slag project, and in the present project, as reported above. But these tests had specific objectives and they may not represent actual conditions of combustion of high ash coal. The latter coals are widely available in certain European and Asian countries.

As reported in the last quarterly report, in January 1997 Coal Tech obtained from DOE-Pittsburgh several tons on 37% ash, 0.4% sulfur, 8100 Btu/lb Indian pulverized coal. Two tests with coal were performed in January. Excellent slagging was achieved and the ash deposits on the combustor wall substantially reduced the wall heat transfer. However, the slag accumulated in large blocks in the slag tap. To determine if this was due to the short test time or if it was an inherent feature of burning high ash coal, two additional tests were performed with this coal in May 1997. The primary purpose of these tests was to validate the earlier results which showed that high slag mass flow rates are effective in retaining sulfur in the slag. The results of these tests are reported in the technical reports on the sulfur in slag project. For present purposes, the new aspect of the May tests are the substantial improvement in slag flow with the Indian coal. In place of very large, almost cubic foot volume slag blocks that dropped out of the combustor's slag chute at irregular intervals in the January test; in the May test, continuous slag flow was in golf ball size globules was observed throughout the test. These slag globules were much greater than the fine nominal ¼ inch slag grit that was obtained in typical US bituminous coal having maximum ash concentrations in the 10% range.

In view of the excellent results with this coal, efforts are underway to obtain additional supplies of these coals. Mine wastes and conventional high ash coal sources are being explored.

Post Combustion SO2 Reduction: Various methods of injecting sorbents into the hot gas stream, downstream of the combustor have been tested on the 20 MMBtu/hr combustor previously. Furnace injection had been attempted earlier in this project. However, the Ca/S mol ratio in those tests was relatively high. In the previous quarter test results were reported whose objective was to minimize the Ca/S mol ratio to below 3. SO2 reductions ranging from 50% upstream of the baghouse to 90% downstream of the baghouse were measured. In the latter case, it is hypothesized that calcined CaO deposited on the bags, thereby aiding in SO2 reduction. The SO2 measured was as low as 0.2 to 0.3 lb/MMBtu. These tests were performed with low sulfur coal, S< 2%. Later in the month, higher sulfur (S>2%) coal was received. However, due to a number of operational problems, the number of tests with hot gas stream sorbent injection was limited.

In May, 1997, two tests were performed whose objective was to extend the previous effort on the effectiveness of sorbent injection downstream of the combustor for SO2 control. A medium (2.5%S) sulfur coal was used. However, unlike the low sulfur coal test results, there was no substantial additional reduction of the SO2 with the furnace injection over the reduction from sorbent injection into the combustor. Also, the SO2 reduction measured at the boiler stack outlet was about 30% due to sorbent injection in the combustor only. It increased to 42% with the additional injection downstream of the combustor. Unlike earlier tests, the SO2 measurements downstream of the baghouse was now only slightly lower. However, the Ca/S mol ratio from the sorbent injected in the combustor was only 0.96, while the additional furnace sorbent injection added a Ca/S of 1.5 and 1.9. This was about one half the Ca/S mol ratios used in the low sulfur coal. Higher sorbent injection rates could not be achieved due to feeding equipment limitations. This suggests that a longer injection period may be required to properly coat the baghouse surfaces with higher sulfur coals. On the other hand, to determine the limitations of sorbent injection into the boiler for medium content (>2%S) sulfur coal, means for increased the sorbent injection rate must be developed. Efforts in that direction are underway.

Post Combustion NOx Control in a 100 MW Electric Utility Boiler: The Coal Tech post combustion process is readily adaptable to large boiler. A search was initiated late in the previous quarter for a suitable test boiler, and one was found in March. An inspection trip to this boiler was made in April, suitable locations for sorbent injection, based on the results on the 20 MMBtu/hr combustor-boiler, were identified. In June, a NOx control test on the 100 MW boiler was performed. The initial injection points, which were selected on the basis of results on the small boiler, produced no NOx reduction. A subsequent test at the second pre-selected injection area, using only one-half the injection points, yielded a 25% NOx reduction. This was a significant milestone in this project since a factor of 100 scaleup of the NOx control process was successfully implemented. Further tests are planned on this boiler and another smaller utility boiler in the next quarter. As of the date of this report, the additional tests have been completed and the results will be reported in the next quarterly report.

## 3. CONCLUSIONS

The total of 83 test days completed in task 5 by the end of this quarter without any significant refurbishment of the combustor indicates that the combustor is at commercial readiness. The modifications and maintenance performed are relatively minor in nature. Most of these modifications are the result of the daily startup and shutdowns and the frequent changes in operating conditions.

The most significant new result obtained in this quarter was the initial successful , application of the sorbent injection process for NOx control to a 100 MW utility boiler. As of the date of this report additional tests have been performed on two coal fired utility boiler with even better results than in the June 1997 tests. This effort is continuing.

The second key result of this quarter is the verification tests with the 37% ash Indian coal on the 20 MMBtu/hr air cooled, cyclone combustor. This result was used in the present reporting period to initiate marketing effort of this technology in Asia.