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# THE COAL TECH ADVANCED CYCLONE COMBUSTOR DEMONSTRATION PROJECT

## A DOE ASSESSMENT

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# EXECUTIVE SUMMARY

This document contains an assessment of the first project to be completed under the U.S. Department of Energy Clean Coal Technology Program. The project was selected under Round I and is known officially as "The Demonstration of an Advanced Cyclone Coal Combustor, with Internal Sulfur, Nitrogen, and Ash Control for the Conversion of a 23 MMBtu/hour Oil-Fired Boiler to Pulverized Coal." The project was carried out by the Coal Tech Corporation over the period March 1987 - February 1991 at the site of the Keeler/Dorr-Oliver Boiler Company in Williamsport, Pennsylvania. The project was a three-year demonstration scale test of a 30 MMBtu/hr air-cooled ceramic slagging cyclone combustor retrofitted to a horizontal 23-MMBtu/hr oil- or natural gas-fired Keeler/Dorr-Oliver DS-9 boiler that was previously used for space heating. During the project, the combustor was operated for a total of 900 hours on oil, gas, and dry pulverized coal. One-third of the operational time was on coal and 125 tons were consumed.

A slagging cyclone combustor is a high-temperature device in which a high-velocity swirling gas is used to burn crushed or pulverized coal. The key novel feature of this combustor is the use of air cooling. This is accomplished by using a ceramic liner which is cooled by secondary air and maintained at a temperature high enough to keep the slag in a liquid, free-flowing state. The arrangement also promotes slag retention in the combustor, an important feature for retrofitting in boilers designed for oil/gas.

The objective of this project was to demonstrate a technology for retrofitting oil/gas designed boilers, and conventional pulverized coal-fired boilers, by using the patented air-cooled slagging coal combustor in place of oil/gas/coal burners. The project aimed to utilize coals with a wide range of sulfur contents and to achieve efficient combustion under fuel-rich conditions. The three performance goals of the combustor were to limit emissions of $SO_2$ and $NO_X$, while maintaining maximum sulfur retention in the slag removed from the combustor. In addition, the development of an operational database relating various aspects of thermal performance was desired.

The project used eight different Pennsylvania coals to demonstrate the ability of the air-cooled cyclone combustor to meet most of the project objectives. $SO_2$ control was accomplished through the use of sorbent injection into the combustor. $NO_X$ control was achieved through the use of staged combustion. A 58% reduction in $SO_2$ emissions was achieved with sorbent injection of limestone into the combustor. Better performance resulted from supplementary injection of limestone directly into the boiler. An 81% reduction was achieved with sorbent injection in or near the combustor outlet. A high of 11% of coal sulfur was retained in the slag. However, the desired reduction of sulfur oxides in flue gas and maximum sulfur retention in the slag removed from the combustor were not achieved concurrently. During the test program, optimizing the operating conditions to simultaneously achieve the three performance goals was not possible. Reduction of $SO_2$ in the stack increased with fuel-richness, but sulfur retention in the slag removed from the combustor decreased with fuel-richness. Likewise, the reduction of $NO_x$ emissions was not optimized during the test effort.

Waste streams consisting of slag/sorbent mixture discharge, scrubber sludge, and wastewater were found to have minimal environmental impacts. The stack gas sulfur dioxide, nitrogen oxides, and particulate emissions were found to be at higher levels than anticipated.

A database for continuous and long duration operation of this combustor has been established.

The test effort experienced a number of complications typical of pioneer projects. Many were resolved during the test effort. Additionally, a significant number of problems have been remedied by R&D conducted outside the bounds of the Clean Coal project. Therefore, a discussion of the status of the technology is included in this document to present an accurate assessment of the Air Cooled Cyclone Combustor.

Three potential markets have been identified by Coal Tech for the commercialization of this technology: large scale industrial applications, solid waste control retrofit applications, and the retrofit of small oil- and gas-fired boilers. Based on the current status of the technology, the industrial market appears to be an appropriate target at the 100 MMBtu/hr size. Inasmuch as the Air Cooled Cyclone Combustor offers substantial operational and economic incentives, supplemental control technology (including a baghouse and sodium scrubber) could be added to make it an environmentally acceptable alternative to oil- and gas-fired industrial boilers.

An economic analysis of the advanced slagging combustor has been developed based on a comparison of two approaches to upgrading a 15-year-old, 100-MMBtu/hr oil-fired steam generating plant. One approach, which invites meaningful comparison to the new technology, includes an environmental upgrade, i.e., installation of a sodium scrubber that permits continued operation of oil firing with reduced $SO_2$ emissions. The other approach is to retrofit with the demonstrated cyclone combustor, switching to coal as fuel. For the latter approach, a sodium scrubber and fabric filter baghouse are included in the retrofit so that emissions of $SO_2$, $NO_X$, and particulates are comparable for the two approaches. The differential fuel price between coal and oil/gas determines the point at which the new technology will be cost competitive with the environmental upgrade and continued oil firing. For the retrofit with the demonstrated cyclone combustor, three cases are considered representing different capital outlays, treating the possibility that some equipment needed for conversion to coal is available without purchase. A fuel price differential large enough to make the demonstrated technology economically competitive is expected to be realized in the current decade. Commercialization of the demonstrated technology in this application will depend on fuel price differential.

The Air Cooled Cyclone Combustor offers a number of unique advantages. The economic and operational incentives are substantial and the environmental performance shows promise.

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# I. Introduction

The goal of the U.S. DOE Clean Coal Technology program is to furnish the energy marketplace with a number of advanced, more efficient, and environmentally responsive coal utilization technologies through demonstration projects. The projects seek to establish the commercial feasibility of the most promising advanced coal technologies that have already reached the proof-of-concept stage.

This document serves as a DOE post-project assessment of the first project to be completed in the U.S. DOE Clean Coal Technology program. In March 1987, DOE and the Coal Tech Corporation (Coal Tech) entered into an agreement to demonstrate an advanced air-cooled slagging cyclone combustor. The test effort ended in May 1990 and the project was completed in February 1991. The independent evaluation contained herein was principally derived from the Final Technical Report and its five appendices, prepared by Coal Tech, dated August 30, 1991 (Reference 1); other documentation supplied by Coal Tech to DOE (References 3–9); and other references as cited.

A slagging cyclone combustor is a high temperature (>3000° F) device in which a high velocity swirling gas is used to burn crushed or pulverized coal. Sorbent may be fed together with the coal. A sorbent slagging agent, limestone, is fed to the combustor to improve $SO_2$ capture and control slag viscosity. The key novel feature of this combustor is the use of air cooling. Air cooling is accomplished by using a ceramic liner, which is cooled by secondary air and maintained at a temperature high enough to keep the slag in a liquid, free flowing state. The secondary air tangential injection velocity and off-axis coal injection are designed to ensure quick and complete mixing of fuel and air, resulting in suspension burning of the coal particles near the cyclone wall with high combustion efficiency. The combustor was expected to be capable of removing between 90 and 95 weight percent of the coal ash and sorbent as slag tapped from the combustor.

The objective of this project was to demonstrate a technology for use in retrofitting oil/gas designed boilers, and conventional pulverized coal-fired boilers, by using the patented (References 8,9) air-cooled slagging coal combustor in place of oil/gas/coal burners. Coals with a wide range of sulfur contents were used. The project attempted to achieve efficient combustion under fuel-rich conditions to limit emissions of $SO_2$ and $NO_X$ with maximum sulfur retention in the slag removed from the combustor. In addition, the development of an operational database relating various aspects of thermal performance was desired.

The 30 MMBtu/hr Coal Tech air-cooled cyclone coal combustor was designed, fabricated, and retrofitted to a horizontal 23 MMBtu/hr oil designed packaged boiler in work pre-dating the Clean Coal Technology Project. It was originally fired with low ash, low sulfur, coal-water slurry fuels. An important result of this pre-project effort was that combustor preheat to operating temperature was accomplished with the slurry fuel. Once the Clean Coal Technology Project was initiated, equipment to allow dry pulverized coal firing was designed and installed. This included: an on-site pulverized coal (pc) storage system, a pneumatic coal delivery system to the combustor, a 1/2 ton dry pulverized limestone storage and pneumatic feed system, and a wet stack particulate scrubber. Initially, plans called for all the necessary equipment to be purchased commercially, but certain components were not available, or performed poorly and had to be modified considerably.

# II. Technical and Environmental Assessment

## A. *Promise of the Technology*

When this project was selected in the first round of the Clean Coal Technology program, the participants recognized that substantial environmental, operational, and economic benefits could be realized by successfully demonstrating the technology. The cost was relatively low for a demonstration project, being less than one million dollars. The potential rewards justified cost-sharing by DOE in demonstrating the technology.

The specific environmental objectives of the project were to demonstrate between 70 and 90 weight percent removal of sulfur dioxide for coals containing 2-4% sulfur, and removal of nitrogen oxides from the combustion gases, resulting in nitrogen oxides emissions of 100 parts per million by volume (ppmv) or less. Additionally, the project was expected to demonstrate the removal of between 90 and 95 weight percent of the ash/sorbent mixture as slag, thus reducing fly ash carryover. These objectives were well within the broad environmental objective of Round I of the Clean Coal Technology Program to "use coal in a more environmentally responsive and efficient manner."

Novel features of the technology offered the following potential benefits:

**Environmental:**

- Low $NO_X$ production
- Major $SO_2$ removal in ash
- Major ash removal in slag, allowing retrofit to oil and gas boilers

**Operational:**

- Improved thermal efficiency compared to water-cooled slagging combustors
- Better performance than a water-cooled combustor in the event of failure of the combustor cooling system
- Reduced downtime for boiler maintenance compared to a conventional power plant (due to low ash carryover which should reduce the fouling and ash deposits in the boiler)
- Less complicated maintenance as modular air cooling combustor design would allow removal of individual combustors and enable their replacement with spares in a period that is much shorter than in-boiler maintenance of water-cooled slagging combustors. (This is because the combustor is not connected to the boiler water steam loop.)

**Economic:**

- An air-cooled combustor would be expected to have capital costs approximately 20% lower than a water-cooled system.

- Compared to firing with oil or gas, firing of coal (which is the least expensive of the three fuels) would offer lower operating costs. Firing with coal would become increasingly more desirable if the price differential between these fuels increases as expected.
- Maintenance costs would be expected to be lower than for water-cooled systems due to reduced downtime and avoidance of interference with the boiler water steam loop

## *B. Equipment Description*

The attached schematic process flow diagram (Figure 1) shows the major equipment items and locations.

Briefly, the operation of the combustor is as follows: a gas burner, located at the center of the closed end of the unit, is used as a pilot to preheat the combustor and boiler on initial operation. A light-oil gun, similarly located, is then used to preheat the ceramic lined combustor wall and to start coal combustion. Dry pulverized coal is transported by primary air and injected into the combustor through tubes in an annular region enclosing the gas and oil burners. In a similar way, limestone or calcium hydrate powder, used to control slag viscosity and/or $SO_2$ emissions, is conveyed and injected into the combustor. The ash is separated from the coal in liquid form on the cyclone combustor walls, from which it flows by gravity toward a port located at the downstream end of the device. The combustor can simultaneously or separately fire all three fuels noted above; in addition, coal-water slurries can be fired if a slurry gun is installed in place of the oil gun.

The major novel feature of this combustor is the use of air cooling. Air cooling is accomplished by using a ceramic liner cooled by secondary air and maintained at a temperature high enough to keep the slag in a liquid, free flowing state. Secondary air is used to adjust the overall combustor stoichiometry for $SO_2$ and $NO_X$ control. The secondary air tangential injection velocity and the off-axis coal injection are designed to insure quick and complete mixing of fuel and air, resulting in suspension burning of coal particles near the cyclone wall with high combustion efficiency. Final or tertiary combustion air is injected directly into the boiler to establish overall stoichiometry.

For the demonstration project, coal pulverization was off site with regular fuel delivery by pneumatic tanker truck. The basic coal storage system consisted of an upper (4-ton capacity) bin which discharged automatically into a small lower bin that was integrated with a screw feeder. The latter discharged the coal into a pneumatic air line that delivered coal to the combustor where it was injected either axially through a pintle, or off axis, downstream of a pneumatic coal flow splitter.

A limestone bin of 1/2 ton capacity, placed alongside the combustor, delivered the sorbent powder to the combustor in a manner similar to the coal feed.

The liquid slag was drained into a water quench tank where the solidified material was monitored for leach potential and reactivity and then removed by a belt conveyor to a drum for subsequent disposal. The balance of slag/spent sorbent particulates that was not retained in the combustor or deposited in the boiler was conveyed by the flue gases to a venturi type wet scrubber with a recirculating water loop. The scrubber was located on the boiler house roof. (Slag retention in the combustor is most favorable; however, retention in the boiler is preferable to carryover in the flue gas exiting the boiler.)

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

An existing stack gas sampling system in a Tampella/Keeler test facility adjacent to the combustor facility was made available for use in the combustor project. Sampling lines were installed to allow extractive combustion gas sampling from either the boiler outlet, upstream of the scrubber, or from the scrubber fan stack exhausting to the atmosphere. The gas was monitored for particulates, $SO_2$, $NO_X$, CO, and opacity.

## C. *Project Objectives/Results*

The first tests began in November of 1987 with the ten objectives specified below. The objectives and important test results are summarized below and a test history is provided in Table 1.

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

Eight different Pennsylvania coals with different sulfur contents were used. The coal feed rate ranged from zero to 1400 lb/hr (with co-firing of other fuels), and the sulfur content ranged from 1 to 3.3% with volatile matter contents ranging from 19 to 37%. Dry pulverized coal (70% minus 200 mesh or finer) was used.

### 2. Reduction of 70 to 90 weight percent in sulfur oxides in the stack (based upon 2 to 4% sulfur coals), with maximum sulfur retention in the slag.

A maximum $SO_2$ reduction of 58% was measured at the stack with limestone injection into the combustor at a Ca/S ratio of 2. To increase $SO_2$ removal, supplementary injection of limestone directly into the boiler was employed. A maximum of over 80% $SO_2$ reduction was measured at the boiler outlet stack, using sorbent injection in the boiler at various Ca/S ratios with no effort made at parametric optimization. A maximum of 1/3 of coal sulfur was retained in slag and dry ash, some of the latter carried into the boiler by combustion gas.

Close inspection of combustor performance regarding this objective reveals that the two parts of this objective were not simultaneously achieved. Sulfur capture in the combustor requires efficient, fuel-rich combustion as well as rapid slag removal to prevent desulfurization of the slag. Maximum slag sulfur content is achieved under fuel-rich conditions, but rapid slag rejection is achieved under fuel-lean conditions.

By the end of the test effort, significant progress had been made in $SO_2$ reduction, but high sulfur capture in the combustor with simultaneous retention in the slag removed from the combustor had not been achieved.

3. **Reduction of 70 to 80 weight percent of $NO_x$ from combustion gases, resulting in emissions of 100 ppmv or less.**

In general, $NO_X$ emission control in a combustor requires fuel-rich operation. In staged combustion, a fuel-rich mixture is maintained in the combustor, and tertiary air is injected into the boiler to complete combustion while reducing the formation of nitrogen oxides. With the two-stage combustion employed in this demonstration, $NO_X$ emissions were reduced by 75% to 184 ppmv (0.3 lb/MMBtu) from the unstaged excess air values.

4. **Combustor solid products, i.e., slag/sorbent/sulfur compounds, are environmentally inert or readily convertible to inert form.**

All slag trace metal leachates were well below EPA Drinking Water Standards when subjected to EPA TOX test, and yielded sulfide and cyanide reactivities within the regulatory limit. Slag and scrubber solids were subjected to Toxicity Characteristics Leaching Procedure (TCLP) tests (40 CFR Part 261.24 and 40 CFR 261 App II). The slag is environmentally inert and may be marketable.

5. **High combustor slag retention and removal, with the goal of 90-95 weight percent, as well as compliance with local particulate emission standards.**

Initial testing on dry pulverized coal resulted in poor combustion efficiency and slagging due to high viscosity of the slag. Efficient operation of the slagging process requires rapid removal of slag from the combustor. To achieve this, slag should have a relatively low viscosity (80 poise or lower). Viscosity is a function of composition and temperature. Most slags have acceptably low viscosity in the temperature range of 2200°–2700°F, but due to concerns for materials durability it is not typically advisable to operate at temperatures above 2500°F. Addition of a fluxing agent such as calcium oxide, usually introduced as limestone, will produce a slag having decreased fluid temperature and viscosity.

Sorbent injection, in the form of pulverized limestone, improved slag retention in this project. Slag retention was demonstrated to be sensitive to sorbent injection location. Total slag retention in the combustor, exit nozzle, and rejection to the slag quench tank averaged 72% with a range of 55-90%. Operation at near stoichiometric conditions favored retention of slag in the combustor and boiler, typical retention being 80% with a range of 65% to 90%. Simultaneously achieving sulfur retention in the slag and slag rejection in the combustor is a delicate process with narrow parametric windows. Slag rejection decreases with increasing fuel-rich operation, and the fuel-rich conditions required for sulfur capture and $NO_X$ emission control precluded attainment of the first part of this objective.

Compliance with the local particulate emission standard of 0.4 lb/MMBtu was met with a standard single stage, wet venturi, particulate scrubber.

### 6. Efficient combustion under (fuel-rich) reducing conditions.

Initial testing on dry pulverized coal resulted in low combustion efficiency (approximately 80% carbon conversion) in the first tests due to the high viscosity of the slag. Carbon combustion efficiency was improved by using an oil burner to preheat the combustor walls to operating temperature prior to the introduction of coal. Limestone injection improved slagging and further improved combustion efficiency to approximately 95%. Fuel-rich operation below 90% of theoretical combustion air, which is necessary for both $SO_2$ and $NO_X$ control, only became possible when coal feed fluctuations were reduced from a high of about 17% to approximately 1% of the coal feed rate. The maximum coal feed rate was 1400 pounds per hour. Variability or oscillations in the rate coal entered the combustor, which ranged from a high of about 17% to a low of slightly over 1% of the nominal coal feed rate, resulted from excessive interaction between the coal feed and pneumatic conveying system. The problem was ameliorated by testing various arrangements of the pneumatic lines, and the delivery system was also modified. Once a new arrangement was well established, combustion efficiencies exceeding 99% were routinely obtained under fuel-rich conditions.

### 7. Determination of combustor turndown, with a 3-to-1 objective.

A turndown from 19-MMBtu/hr to 6-MMBtu/hr (3.2 to 1 turndown) was achieved with coal. Coal Tech contends that a 4-to-1 turndown from 20 MMBtu/hr can be achieved with coal.

### 8. Evaluation of materials compatibility and durability.

Materials compatibility and durability were evaluated throughout the test effort. A mismatch between the thermal properties of the combustor refractory wall and the rate of combustion gas heat transfer resulted in operation of the combustor wall beyond the safe operating envelope. This caused refractory wall failure which necessitated complete disassembly of the combustor. A new ceramic liner with compatible thermal properties was subsequently installed and successfully employed.

The combustor exit nozzle operated under near adiabatic conditions and successfully withstood the corrosive slag environment. However, the nozzle-combustor interface and the nozzle-boiler wall interface suffered materials breakdowns due to differential expansion of the components at the interfaces and/or the use of ceramics with poor slag or thermal resistance. The boiler front wall was redesigned in the fall of 1988. The combustor exit nozzle was redesigned in 1991. These changes have resulted in a design that appears to be suitable for long term operation. However, the present design requires a small amount of additional wall cooling in the exit nozzle to allow round-the-clock coal-fired operation at fully rated coal- fired thermal input. Nonetheless, the combustor wall is currently capable of operating continuously at full rated thermal input.

The demonstration of the combustor in the Clean Coal project was a more rigorous testing of materials than would be encountered in a commercial situation due to daily thermal cycling and the wide range of operating conditions experienced during the parametric test effort. This has provided an excellent understanding of materials compatibility and durability. Suitable operating procedures and materials for each section have been identified.

**9. About 900 hours of steady-state combustor operation on coal with frequent start-ups and shutdowns.**

Coal could be used to preheat the combustor; however, if the walls were too cold to slag the coal ash, a large fraction of the coal particles would blow out of the combustor. The furnace section is not designed to burn coal. Therefore, significant unburnt coal would entrain in the stack exhaust and overload the scrubber. To prevent this, oil-firing was used to preheat the combustor.

Only about one-third of the planned 900 hours of operation on coal was accomplished, consuming 125 tons of coal. The change in preheat from coal to oil was the major reason for the decrease in operational time on coal. Night-time operation was on gas, daytime heat up and cool down on oil, other daytime operation on coal. All but the last 7 tests were nominally 24 hours in duration, including heat up and cool down on auxiliary fuels. The last series of tests was multiday with overnight firing on pilot natural gas. The final four tests involved 3 and 4 day consecutive operation.

**10. Develop safe and reliable combustor operating procedures.**

The test effort resulted in optimization of combustor and support equipment as well as development of the operational database. A database for continuous operation of this combustor has been established.

## *D. Environmental Performance*

Environmental monitoring and control technology was applied to any streams or unit operations capable of producing or discharging gaseous, liquid, or solid pollutants into the environment, namely:

1. Scrubber design and operation
2. Production of sulfur dioxide and nitrogen oxides in the combustor
3. Limestone analysis and fugitive dust
4. Wastewater treatment/disposition
5. Landfill leaching of slag.

Each of the five streams or unit operations listed above was considered in this analysis. Most waste streams, consisting of slag/sorbent mixture discharge; scrubber sludge; and wastewater were found to be essentially innocuous. The other waste streams — stack gas sulfur dioxide, nitrogen oxides, and particulate emissions — were found to be present at higher levels than anticipated.

Detailed environmental information is available in References 2,3,7, and 10. In summary:

The Coal Tech slag is nontoxic (nonhazardous) by TCLP and probably exhibits small enough emissions of hydrogen sulfide and hydrogen cyanide to satisfy EPA regulations for disposal as a nonhazardous waste. More testing of the slag "reactivity characteristic" is needed.

The wastewater appears to be nonhazardous and is expected to be safely dischargeable to a POTW (Publicly Owned Treatment Works).

The sulfur dioxide, nitrogen oxides, and particulate emissions cannot be estimated for a commercial installation unless site specific details are known or assumed, and environmental controls would likely be required to achieve compliance.

## E. *Post Clean Coal Demonstration Achievements*

To achieve steady operation of the air-cooled cyclone combustor on pulverized coal, a number of operational impediments had to be overcome. Pertinent operational issues included: developing air cooling procedures, determining component materials durability, achieving uniform coal feeding, attaining continuous slag flow and removal, and accomplishing efficient combustion under fuel-rich conditions. Details of the extensive efforts to solve these problems during the Clean Coal Demonstration are provided in Reference 1.

In addition to the advances made during the Clean Coal project, the problems encountered during the project which were successfully remedied outside of the project bounds are discussed below to assess both the additional work required to fully explore this technology and to describe the commercial readiness of the air-cooled cyclone combustor. As of March 1991, an additional 100 hours of daytime coal operation were completed, and significant advances to the status of the technology were realized.

### Materials Durability

A new refractory liner with thermal properties consistent with the wall heat transfer characteristics was installed in March 1988. Afterwards, only occasional minor patching was needed, and no combustor wall patching has been necessary since the introduction of computer control.

The procedure to replenish the refractory wall during combustor operation, which involved adjusting process temperature and slag layer thickness, was developed late in Phase III testing of the Clean Coal project and further refined in post Clean Coal project tests.

### Feed System

After the Clean Coal Demonstration a new and improved solids injection procedure was used for fly ash injection into the system during testing conducted in another Coal Tech project. This was done to explore the use of the combustor as a means for disposing of hazardous waste. Reconfiguration of the solids injection geometry under the DOE ash vitrification project has recently resulted in significant increase in combustor slag rejection owing to improved utilization of the combustor's air/fuel/solids mixing zone. In recent tests, high ash injection levels have been utilized to the point where inventoried slag/ash in the boiler is being recovered after each one-day test. Results show that slag retention is better than the levels reported for the Clean Coal project. In one test, better than 80% slag retention in the combustor was measured. Very recently, 20% of the coal sulfur was retained in the slag, which was a factor of 10 greater than that measured earlier in the Clean Coal project.

### Computer Controls

An extensive, proprietary database has been developed for proper operation of the air-cooled combustor. During the Spring of 1990, sufficient operational data had been accumulated to implement computer-controlled operation. Under another project, a commercial software package for process control was customized for control of the air-cooled combustor. This system was installed prior to the final four-day Clean Coal test in May 1990. The objective of the fifth group of demonstration tests was to integrate the entire operating database into a computer controlled operating system. However, only after the Clean Coal project ended was this computer system placed in operation. It is currently undergoing shakedown as part of other test efforts. A series of tests after the Clean Coal project has resulted in a major improvement in the controllability of the combustor. Coal Tech has added controls for slag tap operation and combustor start-up and shutdown and expects to operate the combustor completely automatically. Successful implementation of this system is important to the commercial success of the combustor, as it will allow automatic combustor operation with minimal operator supervision.

### No slag deposits on boiler tubes

Post Clean Coal tests revealed that in three years of operation, including hundreds of hours of coal-fired operation, no slag deposits were formed on boiler tubes, only dry ash deposits. These deposits were easily brushed off; it appears that conventional soot blowing and/or mechanical tube cleaning would easily prevent buildup of solids on boiler tubes. This is an encouraging and significant finding for future oil-fired boiler retrofits.

# III. Operating Capabilities Demonstrated and Additional Advances Required for Commercialization

## A. *Size of Unit Demonstrated*

The combustor was retrofitted to a horizontal 23 MMBtu/hr oil- or natural gas-fired Tampella/Keeler DS-9 boiler that was previously used for space heating. The combustor was designed for a thermal input of 30 MM Btu/hr. However, boiler water and combustor cooling water availability limited the maximum firing rate during the test program to about 20 MM Btu/hr. Most of the testing was conducted at lower rates. During the project, the combustor was operated for a total of 900 hours on oil, gas, and dry pulverized coal. One- third of the operational time was on coal and 125 tons wasconsumed. Steady operation on pulverized coal was achieved.

The combustor would have to be scaled up to at least 100 MM Btu/hr for commercial application to industrial-sized boilers.

## B. *Performance Level Demonstrated*

The primary focus of the test program was to meet the 900 hour operation objective while assessing the performance of the slagging air-cooled combustor. The three performance parameters of primary interest were sulfur removal with maximum retention in combustor slag, slag rejection from the combustor, and nitrogen oxides reduction. More of the test program was directed at maximizing sulfur removal (either by retention in and rejection with the combustor slag or by boiler injection of limestone), than was directed at minimizing nitrogen oxides emissions and maximizing slag rejection from the combustor. During the test program, the operating conditions could not be optimized to simultaneously achieve these performance goals.

### Sulfur Removal

A maximum of 11% of the sulfur was retained and removed in combustor slag that was tapped from the combustor. With limestone injection in the combustor, the highest reduction in emissions of sulfur dioxide was 58% as measured at the stack. With supplemental limestone injection in the boiler, a maximum reduction in $SO_2$ emissions of 81% was measured upstream of the scrubber. Therefore, additional testing is needed to demonstrate the performance goal of 80 to 90% reduction in sulfur dioxide emissions. Based on data presented in the Final Report, it is anticipated that 30 to 40% sulfur capture and rejection in the slag could be achieved in commercial operation, depending on coal sulfur content, using limestone to maintain proper slag viscosity within the combustor.

### Slag Rejection

In the test program, an average of 45% of total solids in the combined coal and limestone was rejected in the combustor slag, up to a maximum of 80%. It is believed that this performance could be improved with changes in the combustor physical dimensions (i.e., a greater length-to-diameter ratio). With optimization of combustor dimensions and operating conditions, a commercial application could be assumed to have a slag rejection of about 80%.

### Nitrogen Oxides Emissions

The lowest concentration of nitrogen oxides measured at the boiler outlet was about 184 ppmv. This corresponds to about 0.3 lb/MMBtu and represents a reduction of about 75% from a high concentration of 769 ppmv without staged combustion. Since $NO_X$ emissions reduction was not optimized during the test program, it is anticipated that this technology should be able to meet current New Source Performance Standards for industrial boilers (i.e., 0.7 lb/MMBtu). Long-term measurements under variable load conditions would be needed to determine the lowest $NO_X$ concentration that could be continually sustained.

## *C. Additional Advances Required to Commercialize the Unit*

The environmental, operational, and economic potential of this technology has been significantly advanced as a result of the demonstration and other concurrent and subsequent activities. However, further efforts in the areas of control of sulfur dioxide, nitrogen oxides, and particulate emissions are indicated to (1) realize a commercial quality combustor, and (2) optimize the unit. While suggestions for future work to optimize the combustor are beyond the scope of this assessment, a discussion of the efforts advisable to commercialize the unit are provided below.

The most important areas remaining for future efforts are (1) the achievement of round-the-clock coal-fired operation; (2) the optimization of sulfur capture in the combustor; and (3) sulfur retention and slag removal from the combustor. With the improved coal feed and solid injection systems and the new computer controlled operating system developed in post Clean Coal Demonstration activities, efforts concerning these items can now be undertaken.

### 1. Round-the-Clock Coal-fired Operation

With a number of additional controls related to slag tap operation and combustor start-up and shutdown, operating the combustor completely automatically using computer controls is anticipated. In many cases, capital and non-fuel operating costs have a greater impact on energy costs than fuel costs and/or system efficiency. As this would be a critical consideration in small boiler operations, an essential objective would be to achieve completely automated combustor operation.

The recommendation is to undertake a series of increasingly longer continuous coal-fired tests at partial and full-load for 24 to 48 hours duration using the automated control system. Following successful achievement of these tests, efforts could focus on the need to demonstrate a sustained long-term (~ 3 months) round-the-clock operation.

### 2. Sulfur Capture

A maximum of over 80% $SO_2$ reduction was measured at the boiler outlet stack using sorbent injection in the furnace at various Ca/S ratios with no effort made at parametric optimization. Until further testing is performed, a full analysis of results is not possible.

Post Clean Coal project tests have shown that previously undetected coal-feed-induced nonuniformities produced multisecond flame pulsations even at fuel lean conditions. These pulsations would have an even more profound effect under fuel-rich conditions and would adversely affect sulfur capture. The feed fluctuations have since been greatly reduced by reconfiguring the coal feed system. The high frequency coal feed fluctuation probably existed throughout the test effort. With the improved feed system, increased sulfur capture in the slag may be possible. It is essential that fuel-rich combustor tests, including sulfur capture tests, be repeated and optimization attempted with the improved sorbent injection method as well as with the smoother coal feed system.

### 3. Slag Removal

Further slag sulfur retention is possible by increasing the slag flow rate, further improving fuel-rich combustion, and further refining sorbent/gas mixing. As of the date of this report, the jamming problems with the conveyor that transports the slag after it is removed from the combustor have been essentially eliminated.

Reconfiguration of the solids injection geometry under the DOE ash vitrification project has recently resulted in a significant increase in combustor slag rejection owing to improved utilization of the combustor's air/fuel/solids mixing zone. The extent of slag rejection with the new design and verification of operability should be established by performance verification tests.

# IV. Market Analysis

## A. *Potential Markets*

Three potential markets have been identified by Coal Tech for the commercialization of this technology: large scale industrial applications (i.e., boiler size greater than 250 MMBtu/hr) solid waste control applications, and the retrofit of small oil- and gas-fired boilers. Based on the current status of the technology, the industrial market appears to be an appropriate near-term target. In 1990, this market (excluding coke production) consumed about 76 million tons of coal to produce electricity and steam (Reference 11). The boiler size ranges are normally categorized by the following: small—less than 100 MMBtu/hr; medium—100 to 250 MMBtu/hr; and large—greater than 250 MMBtu/hr. Total uncontrolled emissions for $SO_2$ are about 0.75 million tons per year and for $NO_X$ are about 0.30 million tons per year. The growth rate is anticipated to be about 0.4% per year through the year 2010 (Reference 12). A similar assessment can be made for oil and gas boilers.

### 1. Large Commercial Applications

A compact design for the attachment of multiple 100 MMBtu/hr combustors to a 125 MWe power plant has been developed by Coal Tech. Another study considered the retrofit to power plants up to 800 MWe rating (Reference 11). This is a longer term goal than the following two applications and will not be considered in this document.

### 2. Solid Waste Control Applications

Another combustor application involves solid wastes, such as ash vitrification, organic waste incineration, or solid waste combustion as Refuse Derived Fuel (RDF). The key elements in the technical and economic feasibility of this application are the maximum attainable feed rate, and the degree of retention or destruction of organic and inorganic pollutants in the slag or in the combustor. The solids feed problem is challenging and is the focus of current tests on the 30 MMBtu/hr combustor. This application, although promising, will not be considered in this document because the work done under the Clean Coal project does not directly support this application.

### 3. Retrofit to Industrial Oil and Gas-Fired Boilers

Coal Tech anticipates commercialization of the Advanced Cyclone Air Cooled Combustor in the industrial sector, with initial penetration occurring in the retrofit/replacement of small oil/gas-fired boilers. The work done in the Clean Coal project directly supports this application. An economic analysis of the retrofit of a 100 MMBtu/hr residual oil-fired boiler is presented here to investigate the economic potential of this strategy.

Residual oil-fired boilers are frequently used in the industrial sector. Residual fuel oil is primarily obtained from the vacuum tower bottoms of an oil refinery. It is considered a by-product of oil refining and sells for less than refined products. During 1989, residual oil consumption in the industrial sector was 0.64 quads (a quad is $10^{15}$ Btu). This is equivalent to about 100 million barrels of oil per year. The quality of residual oil varies greatly, with critical specifications being a maximum viscosity of 110 Saybolt Seconds Furol (SSF) at 122° F, and generally a maximum sulfur content of 1 weight percent. The recent Clean Air Act (CAA) legislative requirements are expected to place a constraint on the quality of residual oil consumed by the industrial sector in the future. The maximum emission of sulfur dioxide (assuming an oil sulfur content of 1 wt%) from combustion of residual oil in the United States was 0.34 million tons for 1989.

Some baseline sample characterization of $NO_X$ emissions from combustion of residual oil in industrial boilers has been reported by EPRI (Reference 14). The mean baseline $NO_X$ emission was 251 ppm @ 3% $O_2$ (about 0.3 lb $NO_X$/MMBtu) with a range of about 200 to 450 ppm. These values are comparable to those obtained in the Clean Coal project.

The average cost of residual oil incurred by the industrial sector was $2.60/MMBtu during 1989 (Reference 15). This compares with an average steam coal price for the industrial sector of $1.64/MMBtu (Reference 16) (representing just under a $1/MMBtu differential price).

## *B. Supplemental Control Technology Options*

To utilize the Air Cooled Cyclone Combustor in an environmentally acceptable industrial application, supplemental control technology could be added to ensure $SO_2$ and particulate emissions compliance. Specifically, downstream control technology could be added to reduce emissions of sulfur dioxide to levels consistent with New Source Performance Standards (NSPS) for industrial boilers (>90% removal and <1.2 lb/MMBtu). In specific cases where NSPS would not apply and local regulations would allow emissions greater than NSPS, the capital and operating costs for the downstream control equipment could be avoided. This would also be true in the event that future development allows sulfur capture and rejection with the combustor slag to achieve greater than 90% reduction in emissions.

Similarly, it is assumed that a baghouse could be installed downstream of the boiler to control particulate emissions to levels consistent with NSPS (i.e., 0.05 lb/MMBtu). A baghouse is indicated since the demonstration did not achieve NSPS limits with a venturi scrubber for particulate control. In addition, limits on wastewater discharges could preclude the use of venturi scrubbers for control of particulate matter in a typical commercial application of this technology.

For the present analysis, the combustor is conceptually scaled up to a nominal 100 MMBtu/hr unit for commercial operation. The analysis is performed at this rating because the application requires a minimum thermal input of 100 MMBtu/hr to justify investment in coal handling equipment, and because it is also in the modular size range to be used in larger boilers. If scaling up is desired, the additional capacity could be achieved by increasing the combustor length.

## C. *Economic Assessment for Industrial Boiler Application*

The demonstrated technology is conceptually applied as a 100 MMBtu/hr retrofit to an existing residual oil-fired boiler. Besides the combustor, ancillary equipment is needed for the retrofit, including a coal feeding and handling subsystem, a limestone injection subsystem, a fabric filter baghouse, and a sodium scrubber. For comparison, a second kind of upgrade is considered. In this case, the boiler continues to be fired with residual oil, but a sodium scrubber is added so that the $SO_2$ emissions of the systems are comparable to permit a meaningful comparison of the two options (Reference 16). The two upgraded systems are shown schematically in Figure 2.

The cost of the Advanced Slagging Combustor system includes augmentation with additional commercial technology that allows for a direct comparison of costs associated with the upgraded oil-fired boiler. Both alternatives have essentially the same pollutant discharge to the atmosphere with an equivalent steam generating capacity. The baseline design parameters are provided in Table 2 and the design criteria for the coal combustor retrofit are in Table 3.

The economic analysis for the advanced slagging combustor is based on a comparison of an industrial retrofit of an oil-fired steam generating plant to that of continued operation of the plant with environmental upgrade. The evaluation allows for an economic comparison based on capital investment and operating and maintenance (O&M) costs for the two alternatives. The economic assumptions employed are given in Table 4. The plant is assumed to have a remaining useful life of 15 years. The term "retrofit factor" used in Table 4 is the ratio of the cost of a retrofit to the cost of a greenfield installation. In general, space may be a concern in the retrofit of residual oil-fired boilers. A physically tight arrangement is likely to result if a baghouse or other supplemental control equipment is added to a residual oil-fired boiler. This is an added constraint for this scenario, which is included in the retrofit factor. The term "installation factor" used in Table 4 is the ratio of installed costs to equipment costs. The costs associated with the analysis are expressed in constant 1990 dollars. A cost-estimating technique with an expected accuracy of +50/-30 percent has been used. This level of accuracy is considered to be reasonable in light of the large cost variance that can be experienced as a result of site-specific requirements.

The cost-estimation technique uses two primary cost categories, capital costs and O&M costs. Capital costs are developed from material requirements and standard algorithms that account for complete installation of the technology including project contingency and retrofit difficulty. O&M costs are further grouped into variable and fixed costs. Variable costs include consumption and disposal costs that are directly related to the time-on-stream and account for solid waste handling. It is assumed that slag is sold for $4.00/ton. In Tables 6–8, solid waste disposal is treated as an operating cost associated with the baghouse. Fixed costs are associated with labor and material requirements that are expected to occur repeatedly on an annual basis, independent of the time-on-stream.

Two independent parameters influence the life-cycle costs of the two upgrade options, one affecting capital costs and the second affecting O&M costs. The first, the cost of money (e.g., the interest rate), is determined by the financial community; the second, the differential price of fuel (e.g., the cost of oil/gas compared to coal on a per MMBtu basis), is determined by the energy market. The coal option is more capital intensive, but fuel costs are less.

For any particular cost of money, there is a corresponding differential price of fuel such that the life cycle cost of the two retrofit options are equivalent. Coal, on an energy equivalent basis, currently has a price of about $1/MMBtu less than that for residual oil. This differential fuel price is expected to increase in the future (Reference 10). Projected price differential for residual oil and coal through the year 2010 has been developed from EIA data and is shown in Figure 3 (Reference 11). This price differential is expressed in constant 1990 dollars. As the fuel price differential increases, the economic competitiveness of the Clean Coal technology increases.

Table 5 provides the information sources upon which the cost estimates are based. All costs have been consistently updated to 1990 dollars using the construction equipment (CE) index. Capital costs have been extrapolated by standard economic power law relationships when required.

The annual cash flow related to technology cost has been expressed in a simplified format.

$$\text{Annual Cost} = \text{TCI} * \text{CRF} + \text{OMC}$$

Where: TCI - total capital investment

CRF - capital recovery factor

OMC - annual operating and maintenance cost (excluding fuel)

The total capital investment includes any working capital or preproduction costs. The capital recovery factor represents the replacement of the original cost of an asset and associated cost of money. An annual worth analysis is used to derive the following expression for the capital recovery factor.

$$\text{CRF} = \frac{i\,(1+i)^n}{(1+i)^n - 1}$$

Where: i - cost of money

n - payout period

As the cost of money approaches zero, the capital recovery factor approaches (1/n), which is simply the annual capital recovery requirement neglecting the time value of money. The payout period used in the present analysis is chosen as the useful life of the investment.

Three cases, baseline coal-fired boiler retrofit, baseline coal-fired boiler retrofit without coal handling (in the event that coal handling equipment is existing prior to the retrofit), and baseline coal-fired boiler retrofit without coal handling equipment and baghouse unit (in the event that both coal handling equipment and baghouse unit are existing prior to the retrofit) are described in Tables 6,7, and 8, respectively. If coal handling equipment and a baghouse are available prior to the retrofit, the economic attractiveness of the coal-based retrofit increases accordingly.

Figure 4 shows results for the baseline design, which includes capital costs for coal handling and baghouse equipment as well as the cyclone combustor. As the differential fuel price increases, the cost of money for which the two retrofit options are economically equivalent also increases. The equivalence point for a cost of money of 10%, for instance, is for a fuel price differential of slightly more than $2.50/MMBtu. In the Figure, any combination of cost of money and fuel price differential that falls below the graph indicates the coal retrofit has the lower lifetime cost, while in the area above the graph the oil retrofit is more economical.

For the two cases shown in Figures 5 and 6 having smaller capital costs than the baseline design, the coal burning retrofit is more competitive. For a given cost of money, a smaller fuel price differential is needed for the coal and oil retrofit options to be economically equivalent. Figure 5 shows the case when purchase of coal handling equipment is not required. At a cost of money of 10%, the break-even fuel price differential is about $1.80/MMBtu. Figure 6 shows a case with still smaller capital requirements to retrofit with coal, as costs are not included for either coal handling equipment or a baghouse. Here economic equivalence for the oil and coal retrofits at a 10% cost of money occurs at a fuel price differential of less than $1.40/MMBtu.

Figure 3 shows that the fuel price differential is expected to be about $2.50/MMBtu by the end of the present decade. If this differential is realized, Figure 5 shows that the cost of money could be as high as 10% and the retrofit option using coal would still be economically favorable even when coal handling equipment and a baghouse are included. The prospects for the demonstrated technology to capture some share of the market for retrofitting gas and oil fired industrial boilers appear to be good.

# V. Conclusion

The Clean Coal project demonstrated the performance of a novel air-cooled slagging combustor. The best overall performance of the combustor was obtained for operation near its capacity. Air cooling was shown to provide more operational flexibility than water cooling. Unlike water cooled combustors, the present air-cooled unit recovers combustor enthalpy as regenerative air preheat, resulting in combustion air temperatures of between 300-500° F. Minimal water cooling to the combustor components resulted in unrecoverable heat losses of only 2-3% of total heat input. This is one of the advantages of air cooling in that combined fan power and water cooling represent only about 4% of the total thermal input as compared to 10% for water-cooled slagging combustors. Another advantage is the high level of flexibility that air cooling provides with regard to tailoring wall temperatures for efficient combustion and slagging - a major plus in incineration and vitrification of environmentally active solids. The air-cooled unit also performs well in case of failure of the thermal control system of the combustor. With the perforation of some cooling tubes during the demonstration project, the unit was still operable and shut down in a safe and gradual manner.

The economic analysis performed above determined the price differential between coal and residual oil needed for the demonstrated combustor to be economically competitive for retrofitting industrial boilers currently using oil or gas. A fuel price differential large enough to make the demonstrated technology economically competitive is expected to be realized within the current decade. The Air Cooled Cyclone Combustor offers a number of unique advantages. The economic and operational incentives are substantial and the environmental performance shows promise. Therefore, commercialization of the demonstrated technology in this application will depend on fuel price differential.

# REFERENCES

(1) Final Technical Report, including six appendices, "The Demonstration of an Advanced Coal Combustor with Internal Sulfur, Nitrogen, and Ash Control for the Conversion of a 23 MMBtu/hr Oil-Fired Boiler to Pulverized Coal," B. Zauderer and E.S. Fleming, Coal Tech Corp., Merion, PA, Aug. 31, 1991, DOE Cooperative Agreement DE-FC22-87PC79799.

(2) "Memo-to-File (MTF) and Final NEPA Determination for the Coal Tech Corporation Demonstration Project Under the Clean Coal Technology (CCT) Program," March 26, 1987.

(3) Environmental Monitoring Plan, "The Demonstration of an Advanced Coal Combustor, with Internal Sulfur, Nitrogen, and ash Control, for the Conversion of a 23 MMBtu/hr Boiler to Coal" "Coal Tech Corp., Merion, PA, DOE Grant No. DE-FC22-87PC79799, April 30, 1987.

(4) Project Evaluation Report, Phase I, p. 28.

(5) Final Technical Report, Proprietary Document Enclosed as an Appendix to the Final Report, "The Demonstration of an Advanced Coal Combustor with Internal Sulfur, Nitrogen, and Ash Control for the Conversion of a 23 MMBtu/hr Oil-Fired Boiler to Pulverized Coal," B. Zauderer and E.S. Fleming, Coal Tech Corp., Merion, PA, Aug. 31, 1991, DOE Cooperative Agreement DE-FC22-87PC79799.

(6) Technical Proposal Volume II, p. 130 Figure D.14, April 17, 1986.

(7) Annual Environmental Report for the period Jan. 1, 1988 to Dec. 31, 1988, "The Demonstration of an Advanced Coal Combustor with Internal Sulfur, Nitrogen, and Ash Control for the Conversion of a 23 MMBtu/hr Oil-Fired Boiler to Pulverized Coal," B. Zauderer and E.S. Fleming, Coal Tech Corp., Merion, PA, Aug. 31, 1991, DOE Cooperative Agreement DE-FC22-87PC79799.

(8) "Air Cooled Cyclone Coal Combustor for Optimum Operation and Capture of Pollutants During Combustion," Inventors: Bert Zauderer and Vincent Tilli, Assignee: Coal Tech Corp., Patent No. 4,624,191, Issued Nov. 25, 1986.

(9) "Method of Optimizing Combustion and the Capture of Pollutants During Coal Combustion in a Cyclone Combustor," Inventor: Bert Zauderer, Assignee: Coal Tech Corp., Patent No. 4,765,258, Issued Aug. 23, 1988.

(10) "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods," SW-846, 2nd Edition, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC, 1982.

(11) "Industrial Boiler $SO_2$ Cost Report," EPA-450/385-011, November 1984.

(12) "Annual Energy Outlook 1991 With Projections to 2010," Energy Information Administration, March 1991.

(13) B.Zauderer and E.Fleming, "The Air Cooled Cyclone Coal Combustor Project," Coal Tech Corp presented at the "Comparative Economics of Clean Coal Technologies" Conference, Vista International Hotel, Washington, D.C., March 25, 1990.

(14) EPRI Report, EA-2048, Volume 5, July 1983.

(15) "Annual Energy Outlook Long-term Projections," Energy Information Administration, January 1990.

(16) "Coal Data: A Reference," Energy Information Administration, November 1991.

# TABLES

## Table 1

## Objectives and Test History

| Objectives | Test History | |
|---|---|---|
| 1. Combustor operation with coals having a wide range of sulfur contents | 11/10/87— | pulverized coal (pc) #1; |
| | 1/19,20/88— | pc #2 (has lower fusion temperature ash); |
| | 5/24,25/88— | test pc #3; |
| | 8/16/88— | test pc #4; |
| | 2/11/90–2/15/90— | (4 day test) test the highest (>3%) sulfur coal |
| 2. Reduction of 70–90 weight% in sulfur dioxides in the stack, with maximum sulfur retention in the slag | 1/19,20/88— | first time limestone (LS) injection reduction of 7–36% $SO_2$; |
| | 2/16,17/88— | reduction 16–39%; |
| | 6/29/88— | 46% reduction measured between boiler outlet and scrubber stack; |
| | 11/8,9/88— | with and without LS injection scrubber removed 10–35% of the $SO_2$; |
| | 2/13/89— | with new sorbent, reduction of 22% and overall in stack ~49%; |
| | 3/9/89— | (day 4 of multiday test) ash samples obtained from in combustor ~25% of the total sulfur—may confirm concept of in situ capture of sulfur by injected sorbent |
| 3. Reduction of 70-80 weight% removal of $NO_x$ from combustion gases yielding emissions of 100 ppmv or less | 1/19,20/88— | reduced 60% (to 200 ppmv)<br>$SO_2$ reduction of 51–58% |
| 4. Solid products from combustor (slag/sorbent/sulfur compounds) are inert or able to be converted to inert | 1/19,20/88— | retained sulfur unreactive as per EPA Reactivity Test; |
| | 2/16,17/88— | slag contaminated with liner material yielded sulfide reactivities 30% above allowable limit; |
| | 2/24/88— | sulfide reactivity lower at 10% above limit |

## Table 1 (Continued)

## Objectives and Test History

| OBJECTIVES | TEST HISTORY | |
|---|---|---|
| 5. Achieve high combustor slag retention and removal (90-95 weight%) and comply with local particulate emission standards | 1/6,7/88— | qualitative improvement |
| | 2/16,17/88— | combustor slag rejection 70–80%; |
| | 3/9/89— | (day 4 of multiday run) cumulative combustor/boiler solids - 80% |
| 6. Achieve efficient combustion under reducing conditions | 11/10/87— | efficiency on coal-water slurry - 100%; |
| | 11/19/87— | efficiency on pc <80%; |
| | 1/19,20/88— | pc efficiency - 95%; |
| | 2/16,17/88— | pc efficiency>95%; |
| | 6/29/88— | pc efficiency -100% |
| 7. Determine combustor turndown, with a 3-to-1 objective | 11/8,9/87— | 3.2 to 1 turndown achieved; |
| 8. Evaluate materials compatibility and durability | 2/24/88— | liner failure; |
| | 1/6,7/88— | pc eductor showed excessivewear and was replaced with higher quality unit; |
| | 1/19,20/88— | evidence of slag-liner interaction; |
| | 2/16,17/88— | more evidence of continued slag-liner interaction; |
| | 2/24/88— | partial liner failure due to thermal and chemical causes,install new liner |
| | 5/10,11/88— | new liner and TC arrangement tested |
| | 9/22/88— | section of the front boiler plate surrounding the exit nozzle became red-hot due to poor insulating and thermal resistance properties of original boiler refractories, new materials and installation design were implemented; |
| | 1/3/88— | new refractories cured and thermal characteristics obtained; |
| | 11/8,9/88— | additional modifications to wall thermal profile indicated; |
| | 12/13,14/88— | the modified combustor-boiler interface maintained at desired temp accumulated frozen slag caused red glow at top of new slag chute; |
| | 9/24/89 to 9/28/89 — | post-test inspection revealed no ceramic material loss in the combustor or exit nozzle |

## Table 1 (Continued)

## Objectives and Test History

| OBJECTIVES | TEST HISTORY | |
|---|---|---|
| 9. Operate combustor for 900 hours of steady state operation on coal with frequent start ups and shutdowns | The total combustor operating period was - 900 hours, about 1/3 of which was on coal | |
| 10. Develop safe and reliable combustor operating procedures | 11/19/87— | modified pc injection, rearranged pc pneumatic line piping; |
| | 12/16//87— | second pneumatic line rearrangement; |
| | 1/6,7/88— | modified (modification #2) pc injection, upgrade LS injection system; |
| | 2/24/88— | pc pneumatic line further modified, implement new thermocouple (TC) arrangement; |
| | 5/24,25/88— | a refractory extension to the slag tap chamber installed; |
| | 6/7,7/88— | extension caused slag tap blockage and was removed, vibrator installed on pc hopper and pneumatic line reconfigured; |
| | 8/16/88— | second feed hopper added; |
| | 11/8,9/88— | new hot gas bypass line installed to establish fuel-rich conditions in combustor - larger line needed and installed prior to next test, novel mechanical slag breaker equipment installed in slag chute; |
| | 12/13,14/88— | booster water pump installed to supply sufficient water pressure at slag chute; |
| | 1/23,24/89— | water flow rate further increased which solved the overheating problem noticed previously, steady state fuel rates and air flows plus combustor thermal conditions were determined to allow overnight combustor firing on NG; |
| | 2/13/89— | new slag conveying system installed and worked well; |
| (Continued) | | (Continued) |

## Table 1 (Continued)

## Objectives and Test History

| OBJECTIVES | TEST HISTORY | |
|---|---|---|
| 10. (Continued)—Develop safe and reliable combustor operating procedures | | (Continued) |
| | 3/6/89— | during first day of 4-day test the unit shutdown for an undetermined reason and the unattended automatic shutdown equipment performed reliably, design and fabrication of a slag breaker capable of operating in a hot gas environment began; |
| | 7/30/90 to 8/3/90— | (second continuous 4-day test) a 92-hour test: combustion for 87 hours, 50 hours unattended overnight operation on natural gas, 21 hours on heat up and cool down with oil, 16 hours coal-fired with 8 tons coal consumed, coal firing occurred at a steady 14 MMBtu/hr during the entire test period, first 3 days under fuel lean conditions, day 4 fuel-rich; |
| | 8/2/90— | (day 3 of 4-day test) coal was delivered and loaded into on-site coal bin while combustor was operating on coal validating the plan for continuous coal firing, new mechanical slag tap breaker performed excellently (which permits extended continuous combustor operation); |
| | 9/24/89— | (day 1 of 4-day test) fuel-rich conditions and no ash or slag deposits were formed in the exit nozzle and there was no slag flow into the boiler; |
| | 2/11/90 to 2/15/90— | No flameouts during the test despite extremely fuel-rich operation—attributed to high combustion efficiency and new multipoint flame detection system |

## Table 2

## Baseline Design Parameters

| | |
|---|---|
| Plant Size | 100 MMBtu/hr |
| Capacity Factor | 65% |
| Oil-Fired $NO_x$ Emission | 0.3 lb/MMBtu |
| Retrofit Combustor $NO_x$ Emission | 0.3 lb/MMBtu |
| Oil-Fired $SO_2$ Emission w/ FGD | 0.11 lb/MMBtu |
| Retrofit Combustor $SO_2$ Emission w/ FGD | 0.17 lb/MMBtu |
| Oil-Fired Particulate Emission | 0.05 lb/MMBtu |
| Retrofit Combustor Particulates | 0.01 lb/MMBtu |

## Table 3

### Key Design Criteria for Baseline Comparison
(Coal Combustor Retrofit)

| | |
|---|---|
| Subsystems | Limestone Feed/Handling; Coal Feed/Handling; Slagging Combustor; FF Baghouse; Sodium Scrubber |
| Coal Characteristics | sulfur content - 1.5 wt%<br>higher heating value - 11,700 Btu/lb<br>ash content - 10 wt% |
| Limestone Feed/Handling | 15 day supply; Ca/S molar feed ratio of 1.0 |
| Coal Feed/Handling | 30 day supply; conveyor/sizing equipment rated at 5 times the design feed rate |
| Slagging Combustor | single 100MMBtu/hr combustor with slag removal and recovery system rated for 80% ash+sorbent capture; 35% sulfur emission reduction |
| FF Baghouse | reverse air fabric filter baghouse; 99% particulate emission reduction |
| Sodium Scrubber | spray dryer operating with aqueous sodium carbonate solution; 90% $SO_2$ removal |

## Table 4

## Economic Assumptions for Tables 6, 7, and 8

| | |
|---|---|
| Cost of Money, % | 10 |
| Useful Life—Years | 15 |
| Pre-Combustion Installation Factor | 2 |
| Pre-Combustion Retrofit Factor | 1.5 |
| Combustion Installation Factor | 2 |
| Combustion Retrofit Factor | 2.12 |
| Post-Combustion Retrofit Factor | 1.5 |
| Year of Constant Dollar Analysis | 1990 |

## Table 5

## Subsystems and References

| Subsystem | Information Source | Year |
|---|---|---|
| Coal Handling | EPRI CS-4373 " Economic Evaluation of Dry-Injection Flue Gas Desulfurization Technology" | 1986 |
| | DOE DE-AC22-84PC72571 Subtask 8.2 "Market and Equipment Performance Analysis for the Application of Coal Based Fuels/Advanced Combustion Systems" | 1986 |
| Limestone Injection | EPRI CS-4373 " Economic Evaluation of Dry-Injection Flue Gas Desulfurization Technology | 1986 |
| Slagging Combustor | Clean Coal Project Reports | 1989 |
| | DOE DE-AC22-84PC72571 Subtask 8.2 " Market and Equipment Performance Analysis for the Application of Coal Based Fuel/Advanced Combustion Systems" | 1986 |
| Baghouse | EPA-450/3-85-011 "Industrial Boiler $SO_2$ Cost Report" | 1984 |
| Sodium Scrubber | EPA-450/3-85-011 "Industrial Boiler $SO_2$ Cost Report" | 1984 |

## Table 6

### Net* Coal-Fired Boiler Retrofit Cost
### (Baseline)

| Subsystem | Percentage of Total Capital Cost | Percentage of Total Operating and Maintenance (excluding fuel) |
|---|---|---|
| Coal Feed | 38.5 | 34.2 |
| Limestone Feed | 7.5 | 9.6 |
| Combustor | 29.7 | 9.1 |
| FF Baghouse | 22.8 | 33.5 |
| Net FGD | 1.5 | 13.6 |
| Total | 100.0 | 100.0 |

* Net refers to the difference in cost associated with common subsystems of the oil-fired and coal-fired plants.

## Table 7

### Net* Coal-Fired Boiler Retrofit Cost

(Baseline without Coal Handling)

| Subsystem | Percentage of Total Capital Cost | Percentage of Total Operating and Maintenance (excluding fuel) |
|---|---|---|
| Coal Feed | — | 34.2 |
| Limestone Feed | 12.2 | 9.6 |
| Combustor | 48.4 | 9.1 |
| FF Baghouse | 37.0 | 33.5 |
| Net FGD | 2.4 | 13.6 |
| Total | 100.0 | 100.0 |

* Net refers to the difference in cost associated with common subsystems of the oil-fired and coal-fired plants.

## Table 8

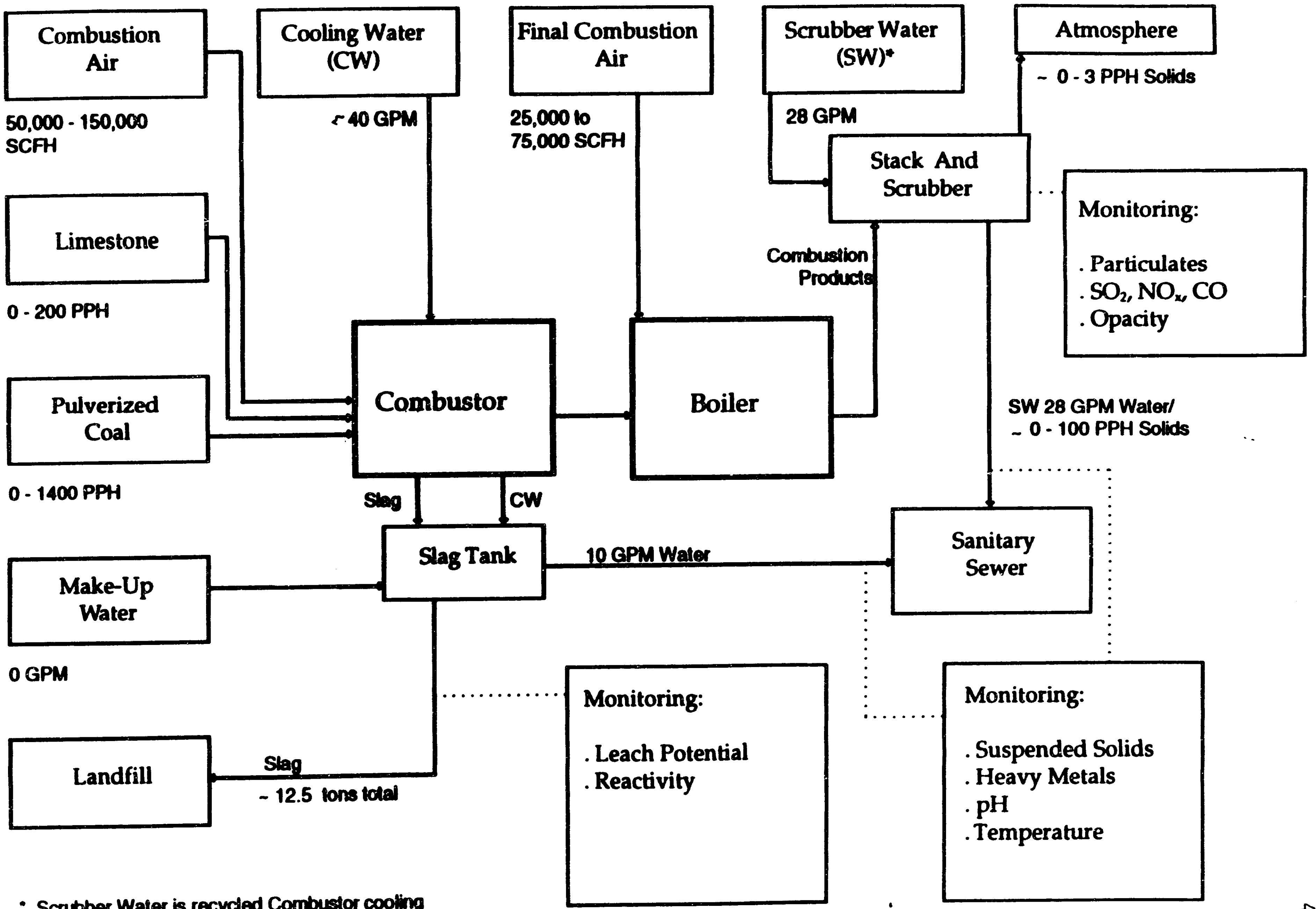
### Net* Coal-Fired Boiler Retrofit Cost

(Baseline without Coal Handling and Baghouse)

| Subsystem | Percentage of Total Capital Cost | Percentage of Total Operating and Maintenance (excluding fuel) |
|---|---|---|
| Coal Feed | — | 34.2 |
| Limestone Feed | 19.4 | 9.6 |
| Combustor | 76.8 | 9.1 |
| FF Baghouse | — | 33.5 |
| Net FGD | 3.8 | 13.6 |
| Total | 100.0 | 100.0 |

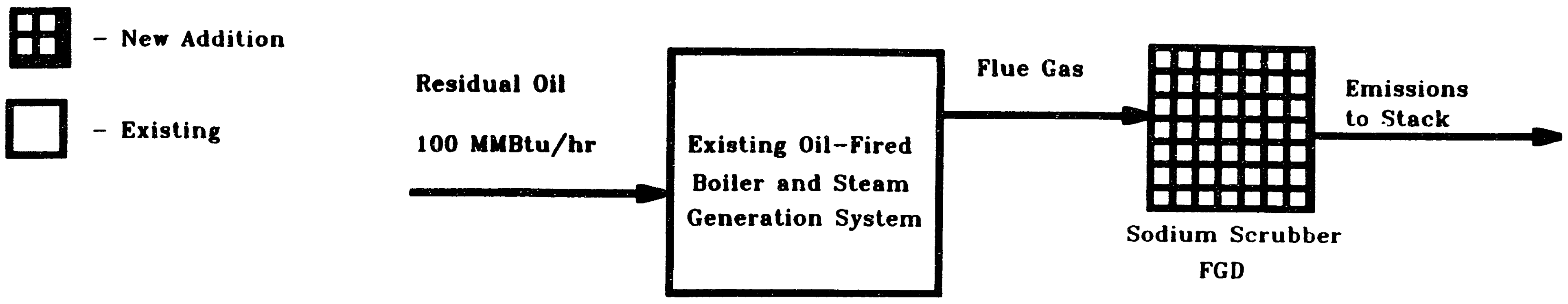
* Net refers to the difference in cost associated with common subsystems of the oil-fired and coal-fired plants.

# FIGURES

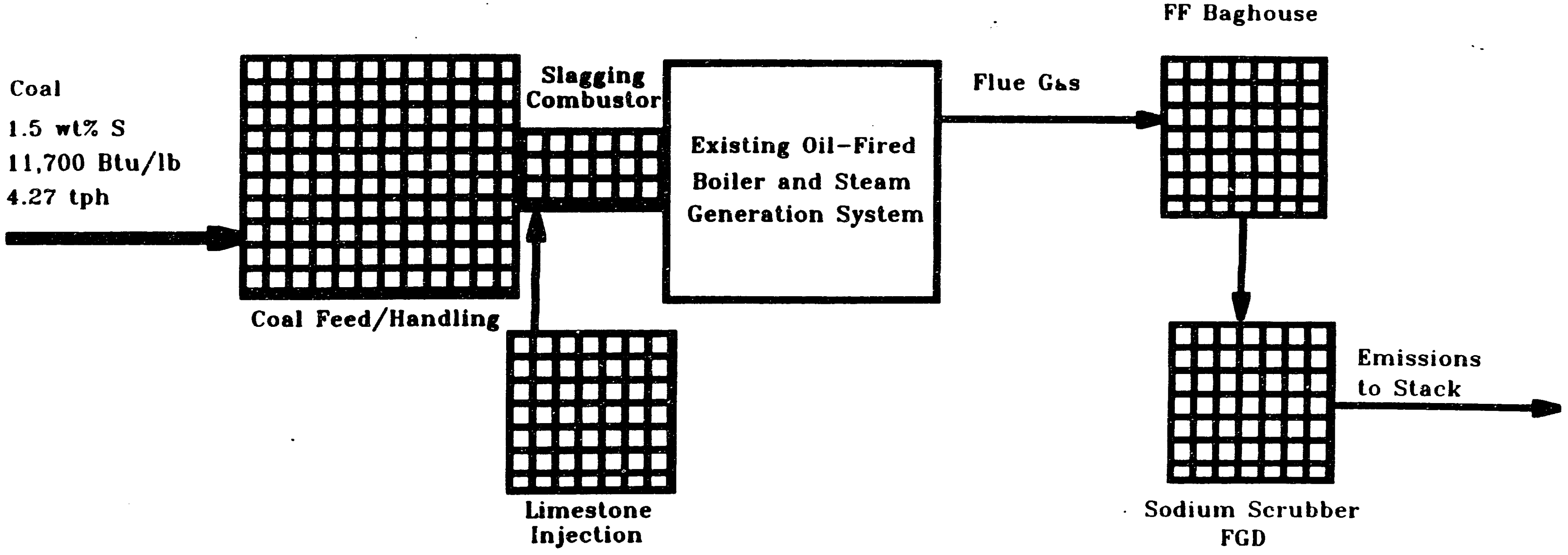


* Scrubber Water is recycled Combustor cooling water from the Slag Tank

FIGURE 1: PROCESS BLOCK FLOW DIAGRAM



Existing Oil-Fired Plant with FGD Upgrade



Coal Retrofit

**Figure 2: Schematic of Baseline Design Comparison**

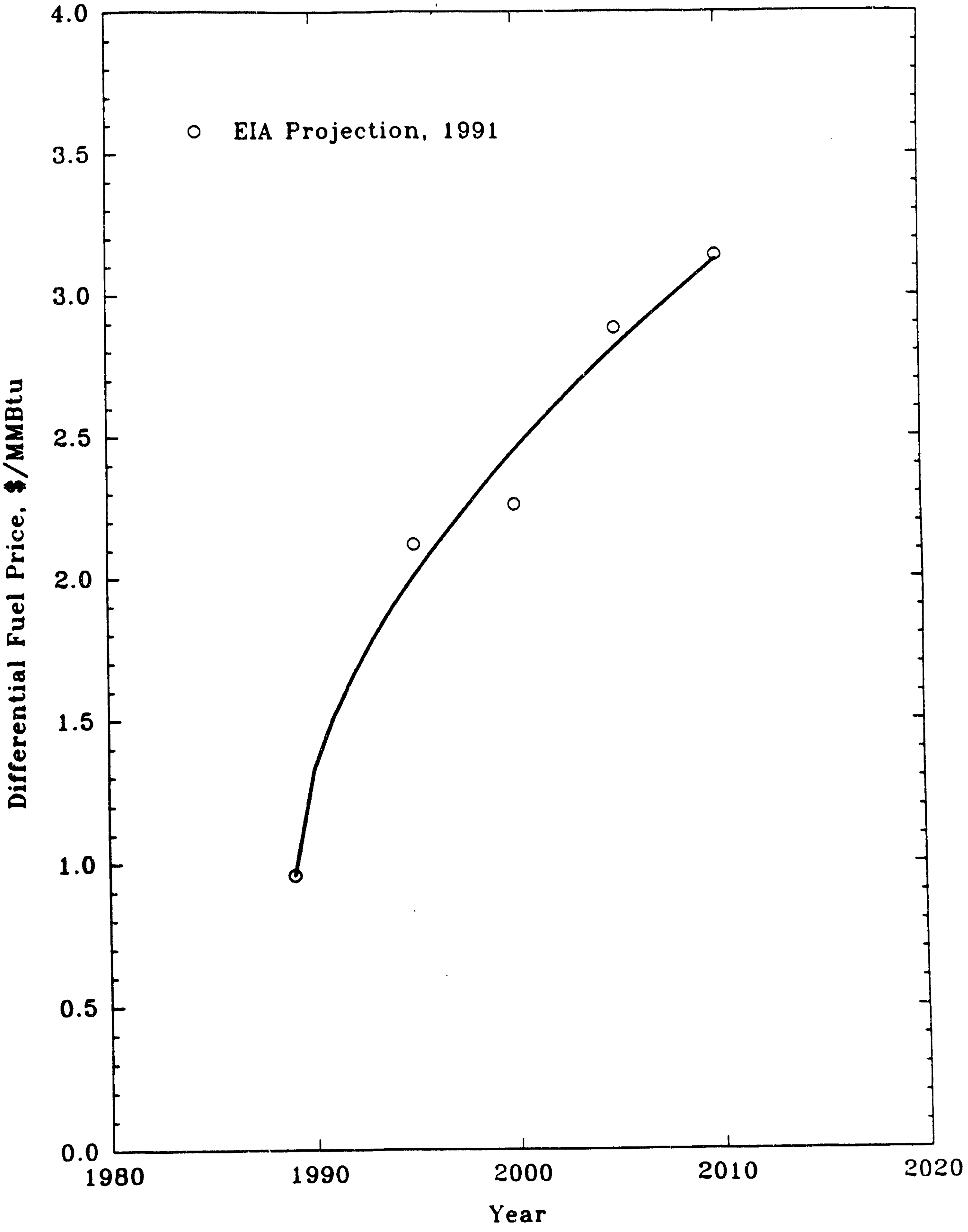


Figure 3: Projection of Differential Fuel Price.

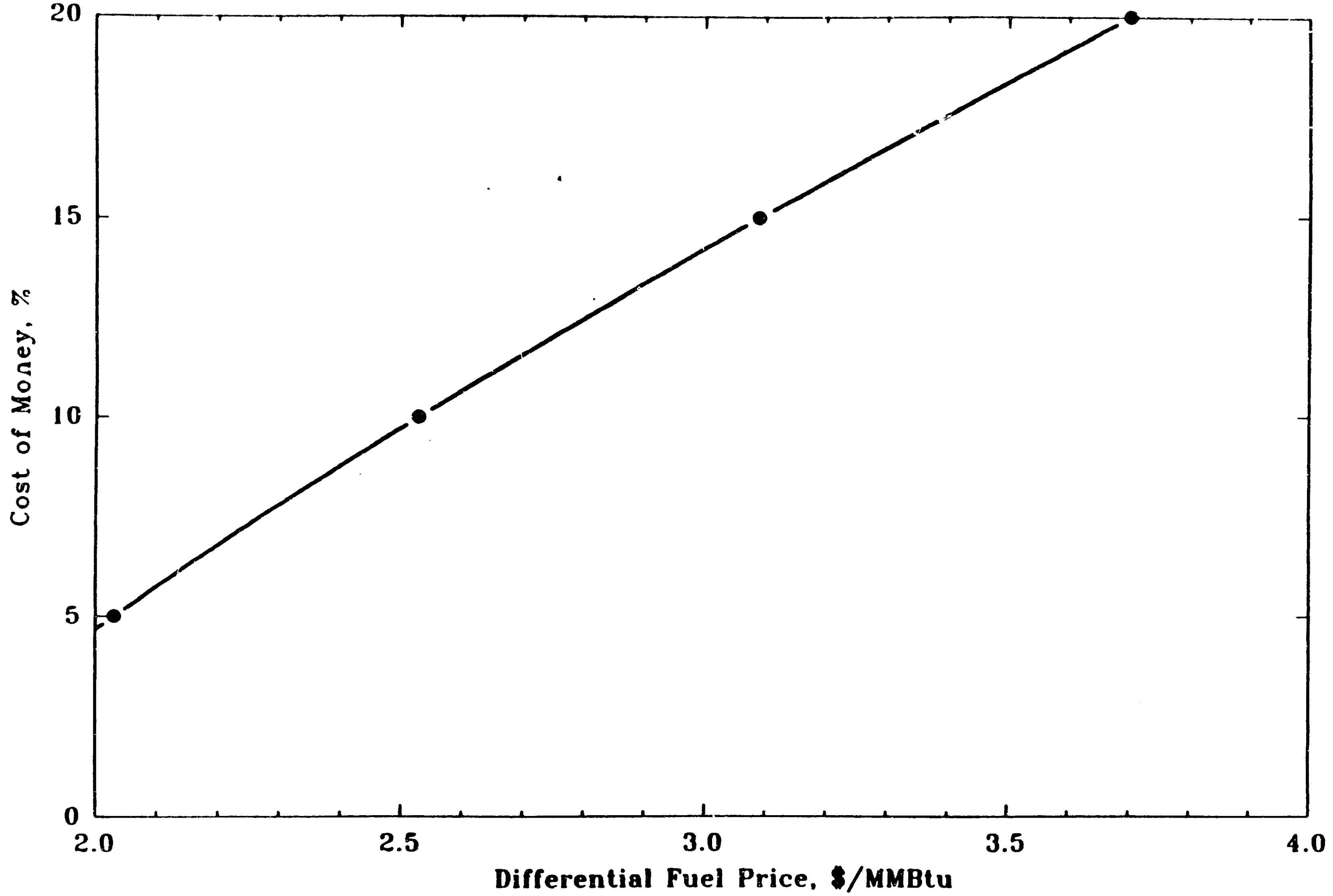


Figure 4: Sensitivity of Cost of Money to Fuel Price Differential.
I. Baseline Design

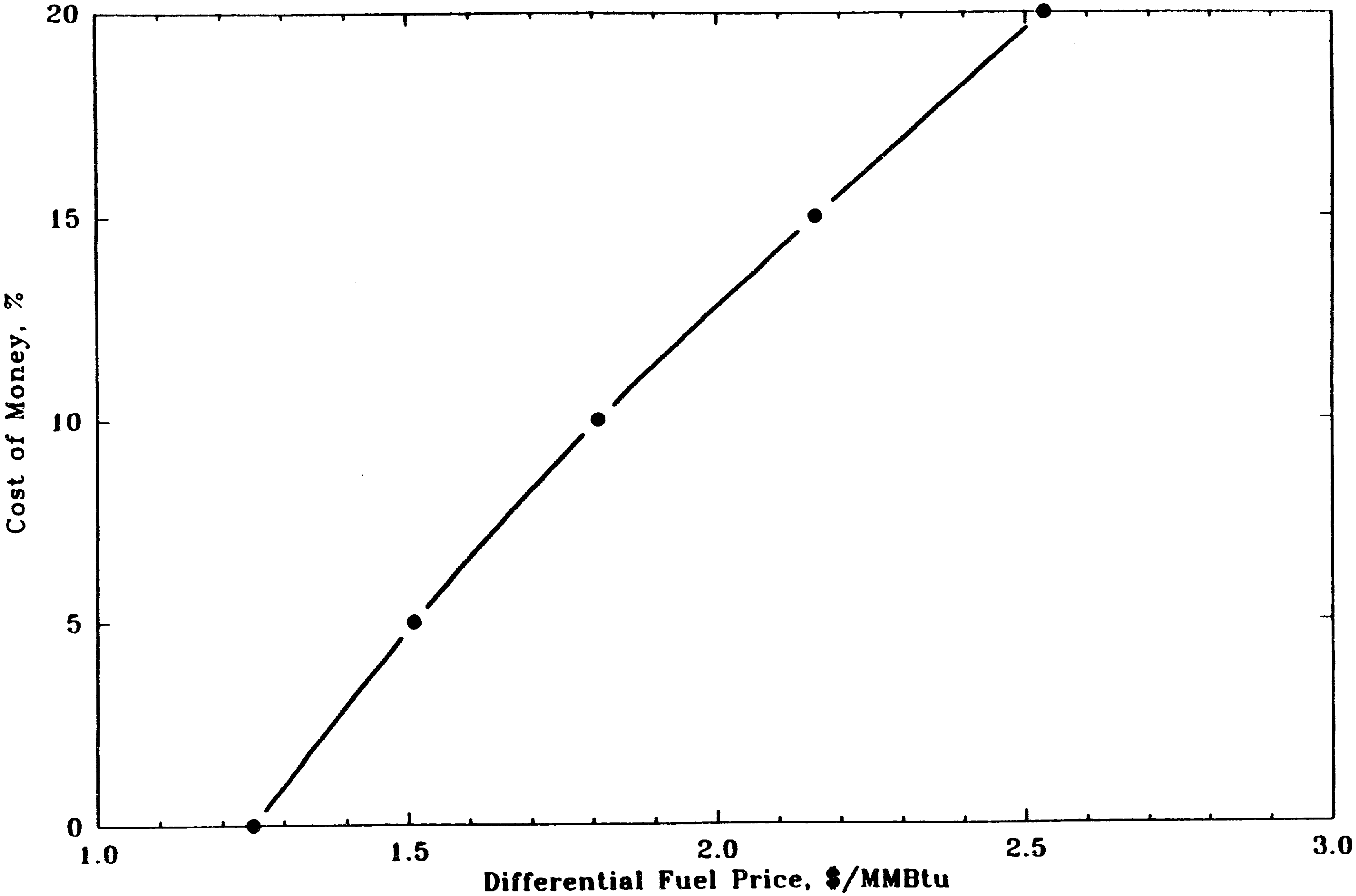


Figure 5: Sensitivity of Cost of Money to Fuel Price Differential.
II. Baseline Design without Coal Handling

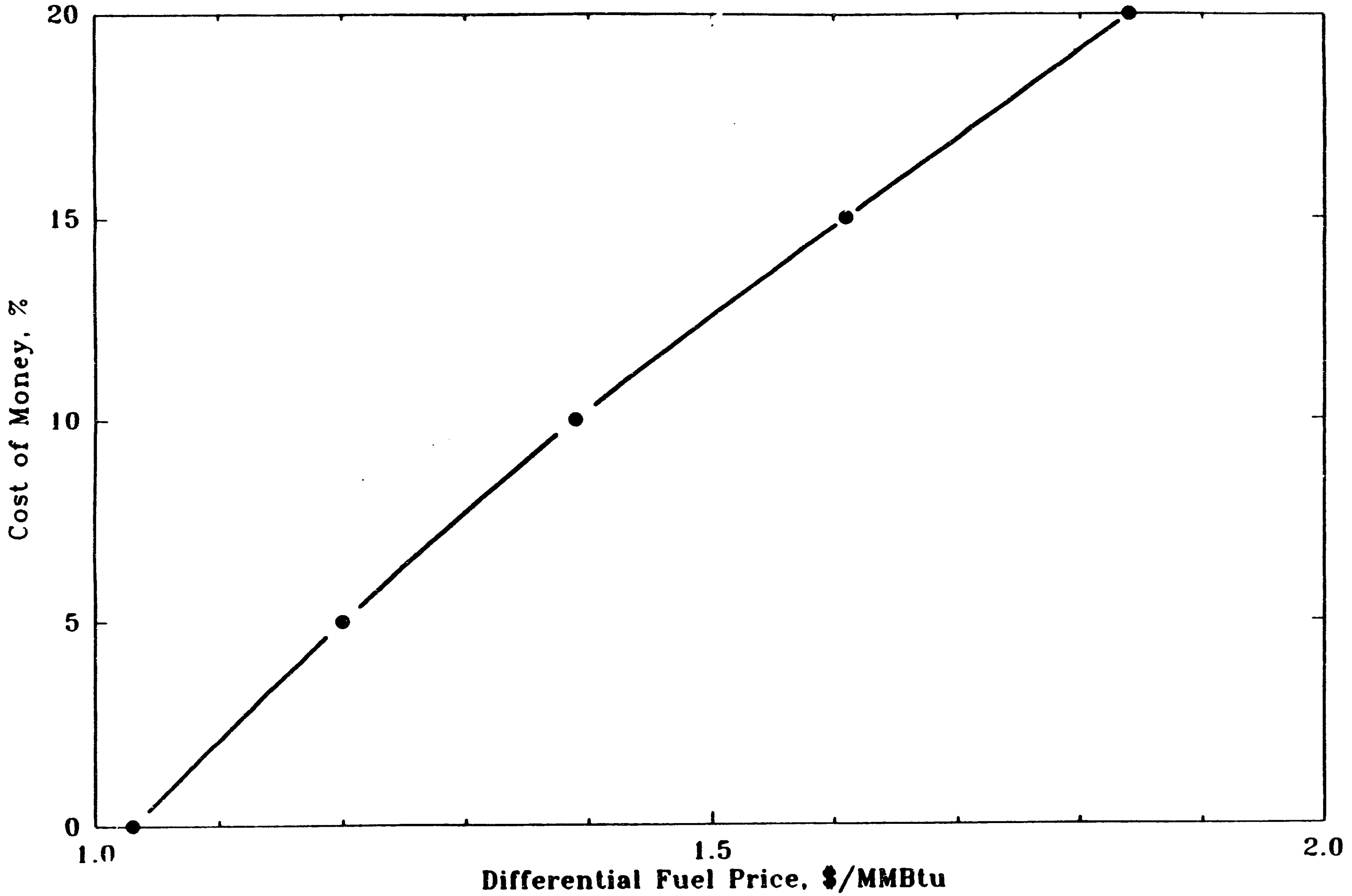


Figure 6: Sensitivity of Cost of Money to Fuel Price Differential. III. Baseline Design without Coal Handling and Baghouse

# END

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8/16/93