SMALL, MODULAR, LOW-COST COAL-FIRED POWER PLANTS FOR THE INTERNATIONAL MARKET

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ABSTRACT

This paper presents recent operating results of Coal Tech's second generation, air cooled, slagging coal combustor, and its application to power plants in the 1 to 20 MW range. This 20 MMBtu/hour combustor was installed in a new demonstration plant in Philadelphia, PA in 1995. It contains the combustion components of a 1 MWe coal fired power plant, a 17,500 lb/hour steam boiler, coal storage and feed components, and stack gas cleanup components. The plant's design incorporates improvements resulting from 2000 hours of testing between 1987 and 1993 on a first generation, commercial scale, air cooled combustor of equal thermal rating. Since operations began in early 1996, a total of 51 days of testing have been successfully completed. Major results include durability of the combustor's refractory wall, excellent combustion with high ash concentration in the fuel, removal of 95% to 100% of the slag in the combustor, very little ash deposition in the boiler, major reduction of in-plant parasitic power, and simplified power system control through the use of modular designs of sub-systems and computer control. Rapid fuel switching between oil, gas, and coal and turndown of up to a factor of three was accomplished. All these features have been incorporated in advanced coal fired plant designs in the 1 to 20 MWe range. Incremental capital costs are only $100 to $200/kW higher than comparable rated gas or oil fired steam generating systems. Most of its components and subsystems can be factory assembled for very rapid field installation. The low capital, low operating costs, fuel flexibility, and compatibility with very high ash fuels, make this power system very attractive in regions of the world having domestic supplies of these fuels.

I. INTRODUCTION

This paper updates the results of work performed on Coal Tech's commercial scale 20 MMBtu/hour air cooled, slagging coal combustor since the last report at the 1995 Clean Coal Conference [1]. During the past year, a second generation, 20 MMBtu/hr combustor has been placed in operation in a coal combustion system. It incorporates all the features of Coal Tech's new low power cost, solid fuel plant. The central feature of this plant is an air cooling combustor whose wall heat transfer loss is recuperated to the combustion air, making this heat available to the thermodynamic cycle. A portion of the SO_2 and NO_x emissions are controlled inside the combustor, which is designed for new and retrofit boiler applications. Coal Tech’s development of the air cooled combustor began in the late 1970's in a 1 MMBtu/hr air cooled, cyclone combustor [2], continued in the mid 1980's in a 7 MMBtu/hr water cooled, cyclone combustor [3], and was followed by 2000 hours of operation of a first generation, 20 MMBtu/hr, air cooled combustor between 1987 and 1994 [4-7]. The latter facility was located in an industrial heating plant in Williamsport, PA. Fuels tested include coal, coal water slurry, refuse derived fuel, oil, and gas. Test operations to 1991 were sponsored in part by the United States Department of Energy Clean Coal Technology Program [4].

Subsequent testing under another DOE sponsored project began in 1992 [5-7]. The first phase focused on improving combustor durability and combustor operation under automatic computer control. Several hundred hours of operation over a 7 month period in 1993 were implemented without requiring any internal refurbishment of the combustor walls.

The second phase of this project began in 1994 and is currently in progress. The results of prior testing were incorporated in the design of a new coal fired power plant using a second generation combustor rated at 20 MMBtu/hr and capable of generating up to 1 MW of electric power. The combustion parts of the plant were fabricated and installed in 1995 at an industrial site in Philadelphia, PA. The subsystems of the plant were designed to take advantage of the unique features of the air cooled combustor. This includes an oil design flat bottom boiler that was modified for real time removal of any ash or slag carried over from the air cooled cyclone combustor. It also includes a coal processing system that produces coarsely pulverized coal (50% passing 100 mesh compared to previous operation at 70% passing 200 mesh). This greatly reduces the capital and operating cost of the coal handling system. All the auxiliary subsystems, such as combustor cooling and combustion air supply, fuel supply, and cooling circuits were modularized to reduce capital cost and operating and maintenance costs. As part of this latter effort, the power requirements for the 20 MMBtu/hr combustor were reduced by two-thirds compared to the prior unit. Some features of this new plant were described at the Clean Coal Conference in Denver, CO in 1995 [1].

Test operations began in early 1996, and to date 51 days of testing have been completed. Results have substantially exceeded design performance. For example, the amount of bottom fly ash deposits in the boiler has been so low that its real time removal has not yet been necessary.

This paper summarizes the recent test results and discusses the use of this new design for low cost power plants in the 1 to 20 MWe range. This power system is especially attractive in regions with local deposits of high ash coals.

Coal Tech's Advanced Air Cooled, Cyclone Coal Combustor

The cyclone combustor is a high temperature (> 3000^oF) device in which a high velocity swirling gas is used to burn crushed or pulverized coal. Figure 1 shows a schematic of Coal Tech's patented, air cooled combustor. Gas and oil burners rapidly preheat the combustor and boiler during startup. Pulverized coal and powdered sorbent for SO_2 control are injected into the combustor in an annular region enclosing the gas/oil burners. Air cooling is accomplished by flowing combustion air through tubes on the outside of a ceramic liner in the combustor. This cooling air provides over 90% of the combustion air in the combustor, and it is introduced tangentially in a swirling manner into an annulus enclosing the fuel injection cylinder in the combustor, (see figure 1). The ash and reacted sorbent melt on the liner and the resultant slag is drained through a tap at the downstream end of the combustor.

Nitrogen oxide emissions are reduced by operating the combustor in a fuel rich mode, with final combustion taking place in the boiler. Operations in the first generation 20 MMBtu/hr combustor in Williamsport yielded, under optimum conditions, about two-thirds NO_x reductions to 0.26 lb of gas/MMBtu, or 200 ppm (at 3 % O_2) at about 70% of stoichiometric air/fuel ratio in the combustor and high combustion efficiencies. The stoichiometric ratio for the combustor/boiler was between 1.25 and 1.5. Sulfur emissions are controlled primarily by sorbent injection into the combustor. Measurement of SO_2 levels at the stack gas outlet from this previous boiler yielded average SO_2 reductions of 50% to 70%, and as high as 85%, with calcium hydrate injected into combustor at Ca/S mol ratios of 3 to 4. Particulate emissions were controlled in part by slag retention in the combustor. It was augmented with a wet particle scrubber which reduced the particle emissions to as low as 0.26 lb of solids /MMBtu.

II. THE SECOND GENERATION, 20 MMBTU/HR COMBUSTOR/BOILER PLANT IN PHILADELPHIA, PA

The design of this plant was based on the results of tests in the 20 MMBtu/hr air cooled combustor in Williamsport, PA, and on various site specific combustor applications studies for power plants in the 1 to 20 MW range that were performed in the past several years [6,7].

It was originally planned to install the 20 MMBtu/hr combustor/boiler at the new site with an atmospheric back pressure turbine to generate about 500 kW of power from the 17,500 lb/hr, 250 psig boiler. Sale of this power would partially defray the cost of more extensive durability tests on the combustor/boiler system. However, due to excellent progress this year in the combustor test effort, it was decided to eliminate the power generation step and proceed to commercial introduction of the technology.

To meet the particle emission standard for Philadelphia, a baghouse was required in place of the wet particle scrubber that was used in Williamsport. The latter's best performance resulted in a particle emission of 0.26 lb/MMBtu, which was below the Williamsport standard of 0.4 lb/MMBtu. The Philadelphia standard is 0.06 lb/MMBtu. The manufacturer of the baghouse has stated that particle emissions of less than 0.03 lb/MMBtu can be readily achieved under the operating conditions existing in the present facility.

Figure 2 is a side view of the new 20 MMBtu/hr combustor/boiler installation in Philadelphia. PA. Its total size is such that it can be shipped by tractor trailer to any site. Figure 3 shows a plan and side view of the Philadelphia facility. It includes provision for a 25 ton raw coal delivery and storage area,

Figure 1
Coal Tech's Air Cooled Combustor

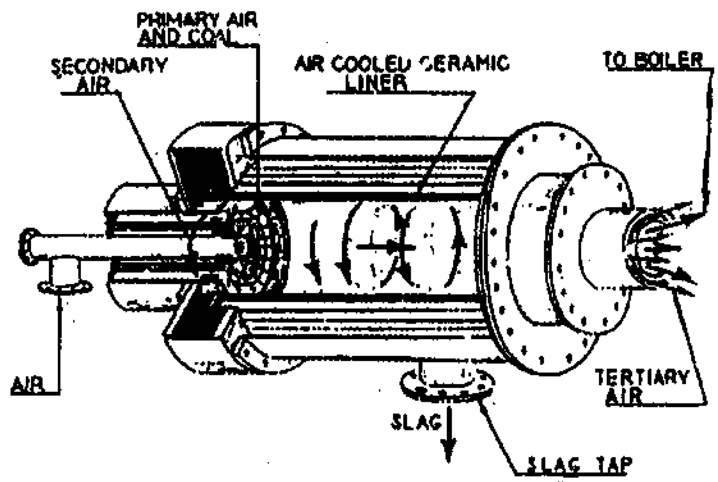
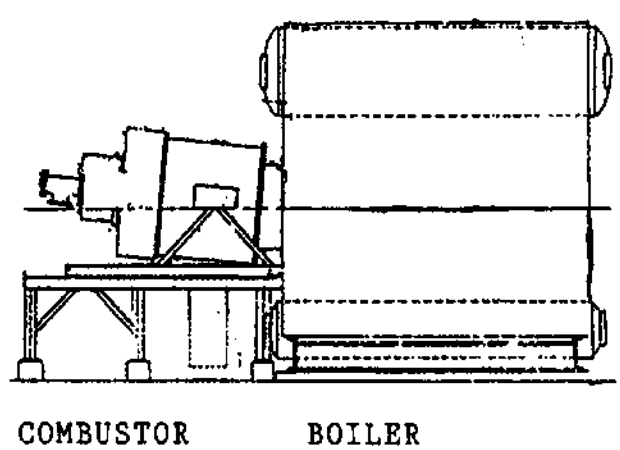


Figure 2:
20 MMBtu/hr Combustor-Boiler Installation at Philadelphia Plant



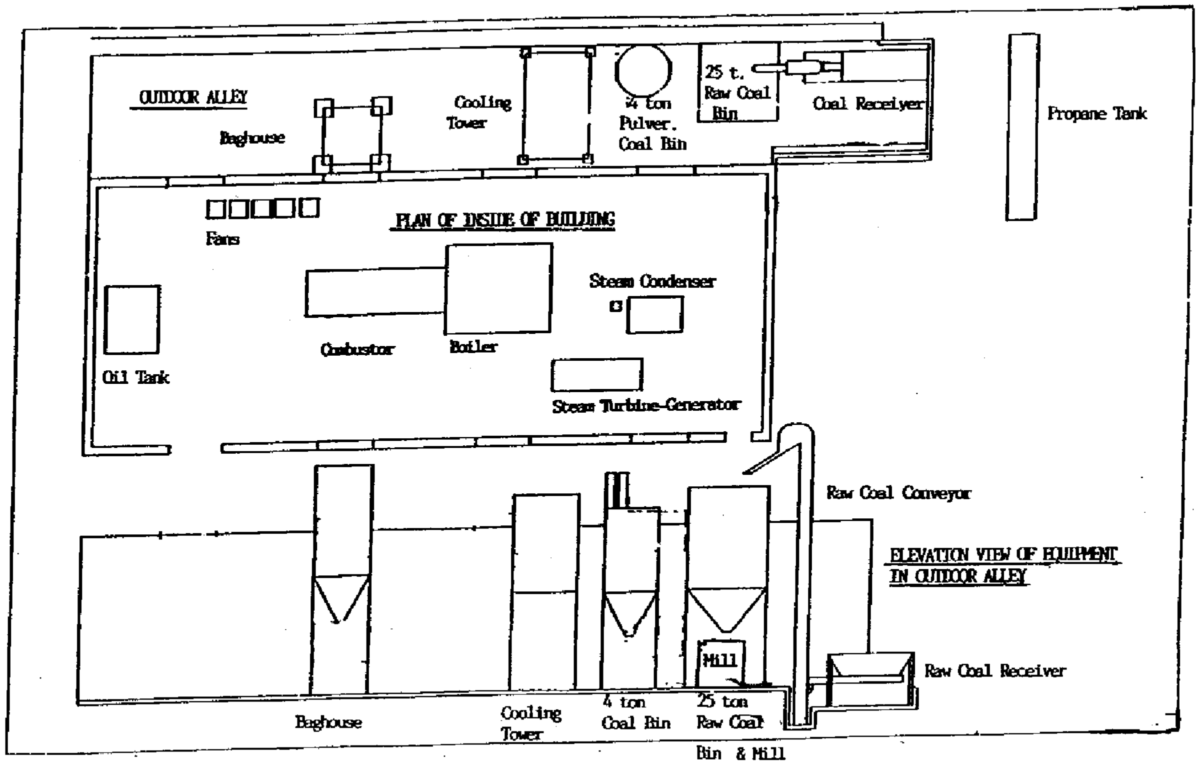


Figure 3: Plot Plan of the 20 MMBtu/hr Combustor-Boiler Test Site in Philadelphia.

a low cost coal mill, a 4 ton pulverized coal storage bin, sorbent storage bins, pneumatic coal and sorbent delivery, a boiler, the combustor and its auxiliary subsystems, specifically, water cooling, oil, gas, combustion air, cooling air, compressed air, slag removal, and the stack system, including the baghouse, and induced draft fan. The entire system is controlled by programmable logic controllers (PLC) and computer process control. Performance parameters are measured and recorded on a computer. Combustion gases, O_2, CO, NO_x, and SO_2, are measured in the boiler radiant furnace section, boiler stack outlet, and baghouse outlet. Novel Features and Operating Experience of the Second Generation Combustor/Boiler Facility.

The facility was designed to include the major features that will be incorporated in Coal Tech future commercial power plants in the 1 to 20 MWe range. Therefore, the primary design objective was to minimize capital, operating and maintenance costs.

Capital cost is minimized by factory assembly of major subsystems of the plant. Oil/gas designed boilers are compatible with the air cooled, coal combustor. These boilers are factory assembled for thermal ratings of up to 200 MMBtu/hr. Air cooled combustors can be fabricated up to 150 MMBtu/hr. The combustor's auxiliary subsystems are assembled in modules and attached to the combustor support structure. Therefore, the combustor and boiler can be shipped from the factory in two modules.

Another important capital cost saving results from the fuel flexibility and rapid shift among the various fuels. This sharply reduces the need for on site fuel storage.

Air cooling operation was much improved in the present combustor to the point where gas and oil fuel consumption for heatup and cooldown of the combustor was reduced by about a factor of two from the quantities used in the Williamsport combustor. Another major result of the improved air cooling was a factor of two reduction in the cooling fan power requirement. In addition, the quantity of compressed air flow required to operate the facility was sharply reduced. Finally, the use of a baghouse in place of the wet particle scrubber sharply reduced the induced stack fan power. As a result, the total power used in the Philadelphia plant was reduced to one-third of the level required in the first generation Williamsport facility.

The improved combustor operation reduced the combustion gas temperature at the boiler outlet an average of 100°F to 150°F for identical coal firing and sootblowing conditions in the previous combustor. Additional cooling of the stack gases was added to allow the use of substantially lower cost bags for the baghouse and to further reduce the stack fan power.

The combustor is a higher maintenance component than the boiler. It is, therefore, essential to minimize downtime when it requires refurbishment. Consequently, the current combustor design allows its removal from all its auxiliary sub-systems and from the boiler in less than 1 day.

A high maintenance item has been the combustor's slag tap assembly, primarily during the initial tests. Subsequent modifications were made which have sharply reduced maintenance to this item.
The relay controlled system used in the previous combustor system was replaced with programmable logic controllers (PLC). The PLC assure that the combustor's fuel supply and the boiler's steam

supply operate with all safety interlocks functioning. The previous computer process control software was upgraded to account for the changes in the design of the present combustor. As the test effort proceeded, it was found that the combustor could be controlled with a much simpler procedure than was used for the previous combustor, and the software was changed accordingly.

With these improvements, the personnel needed to operate the facility was reduced from an average of six used in the Williamsport facility to two or three, depending on the specific test objectives.. Based on this experience, it is anticipated that a fully commercial plant can be operated with substantially fewer personnel than are used in a conventional coal fired plant.

20 MMBtu/hr Combustor Operation in the Philadelphia Facility

As soon as the present combustor was placed into operation, its exhibited performance was far superior to the earlier unit. Areas of improvement include combustion efficiency, slag retention, wall materials durability, and length of heatup and cooldown.

Slag retention, which is a key measure of slagging combustor performance, improved substantially. In the earlier 20 MMBtu/hr combustor, only one-half to two-thirds of the injected coal ash and sorbent minerals was converted to slag in the combustor. The balance of the ash and sorbent was blown out of the combustor as dry fly ash. Furthermore, over one-half of the slag formed in the combustor flowed out of the exit nozzle to the boiler floor, thus limiting the run time of the combustor. Although provision has been made to remove slag carryover from the combustor to the boiler by installing a combustor/boiler transition section, in the operations to date, the amount of slag carried over from the combustor to the boiler ranged from 0% to 5% of the total slag. Slag retention was also substantially better than before, averaging two-thirds of the injected mineral matter, which includes coal ash and sorbents.

Combustor refractory liner durability is another major performance parameter. Chemical reactions between the liquid slag and the combustor refractory wall can rapidly deplete the latter. However, by control of the combustor wall temperature, a layer of frozen slag can form on the combustor's refractory wall which maintains the integrity of the wall. Much progress had been made in perfecting this wall replenishment technique in the earlier 20 MMBtu/hr combustor. Replenishment of the refractory liner by injection of fly ash with the coal and sorbent proved to be very effective in the earlier combustor. In the present combustor, the combustor wall replenishment procedure has been further improved. Consequently, it has not been necessary to reline the combustor wall with refractory in the operations to date.

The cooling and combustion air distribution and control scheme was substantially modified for the present combustor in order to simplify the combustion and combustor wall cooling process. The new scheme has proven to be much simpler to control , and the need for the previous complicated computer control has been eliminated.

To minimize nitrogen oxide emissions it is necessary to operate the combustor under fuel rich conditions. Final combustion occurs in the furnace section of the boiler where the CO and H_2 rich combustor gas exhaust is mixed with additional air to complete combustion. Optimum No_x reduction occurs at about 70% stoichiometric air/fuel ratio in the combustor. [3,4]. However, operation of the earlier 20 MMBtu/hr combustor at this condition resulted substantially reduced combustion efficiency [3,4].

The three methods of measuring combustion efficiency in the slagging combustor are based on carbon in the slag, CO in the stack gases, and carbon in the stack fly ash. Under fuel rich conditions, significant amounts of carbon in the slag indicates poor combustion inside the combustor. In the present combustor, combustion efficiency, based on carbon in the slag, has been over 99% in almost all the tests including at fuel rich operation as low as 75% stoichiometric air/fuel ratio. Since carbon monoxide is an air pollutant, it is essential that it be minimized in the combustion process. The CO concentration in the stack was generally in the 200 ppm range which corresponds to better than 99% combustion efficiency.

Both these measurements of combustion efficiency do not account for unburned carbon that is carried over to the stack baghouse. Due to the difficulty in obtaining real time sampling of the baghouse fly ash, the carbon content in the fly ash was determined from random grab samples taken from all the ash collected on the day of testing. The carbon content of the ash ranged from 20% to 50% (dry basis). Since on average about one-third of mineral matter injected reported to the baghouse, one can compute the conversion of the solid carbon in the coal to CO2 and CO in the combustor from the amount of unburned carbon in the baghouse fly ash. This yielded a carbon conversion greater than 90% for most of the tests. In several tests small quantities of fly ash in the stack were collected in a filter. Analysis of the carbon content in one of these tests yielded a carbon conversion of 94%.

The stoichiometric ratio in the combustor (SR1) ranged from fuel rich to fuel lean (0.75<SR1< 1.1). Final combustion air was added at the combustor outlet into the boiler which yielded a stoichiometric ratio in the boiler furnace (SR2) in the range from 1.3 to 1.8.

Several bituminous coals were tested having higher heating values (HHV) in the range of 12,000 to 13,700 Btu/lb, ash contents in the 11% to 15% range, and sulfur contents in the range from 1.18% to 3.7%. The bulk of the tests were performed with 3+% sulfur coal.

The initial test effort this year has been focused on overall combustor performance, with lesser emphasis on SO_2 and NO_x control. The most recent tests have focused on SO2 control and excellent results have been achieved, especially in low sulfur coal. The analysis of these data is incomplete, and the results will be presented at the Conference. Both limestone and hydrated lime were injected into the combustor for slag conditioning and sulfur removal. Previous results in the 20 MMBtu/hr combustor in Williamsport showed that limestone was much less effective than calcium hydrate for sulfur capture. With calcium hydrate injection into the previous combustor, excellent sulfur capture results were achieved, where a maximum reduction in the 85% range was measured [5,7].

The degree of sulfur capture in the present combustor was found to be very sensitive to combustion conditions, the method and quantity of sorbent injection, and the mineral matter injection rate. In recent tests at high slag mass flow rates firing 3+% sulfur coal, SO_2 reductions measured in the end wall of the boiler furnace and in the boiler gas outlet at the stack were in the range of 60% to 75% at Ca/S mol ratios of under 3. Similar reductions were measured with injection of calcium hydrate into the boiler furnace near the combustor gas inlet to the boiler. In this case, the Ca/S mol ratios were in the range of 3.5 to 4.9. However, in the latter case, a substantial amount of the hydrate fell to the floor of the boiler furnace. Therefore, the Ca/S mol ratio is not an accurate measure of calcium utilization in this case.

In very recent tests with 1.5% sulfur coal, the SO_2 reductions were substantially higher. Reductions in the range of 75% to as high as 95% were measured. When expressed in lb/MMBtu, SO_2 emissions as low as 0.22 lb/MMBtu were measured. This is well below the 0.5 lb/MMBtu SO_2 emission standard for Philadelphia, and it near the 0.2 lb/MMBtu that is one of the current test objectives. The reductions were higher at the end wall of the boiler furnace than in the stack at the outlet of the boiler. No conclusive explanation for this behavior has been found. It is suspected the higher SO_2 at the boiler outlet may due to blowby of combustion gases through gaps in between the boiler tubes on the convective tube side of the boiler. This reduces the reaction time of sorbent with combustion gas in the boiler furnace. This matter should be clarified when all the data are analyzed.
One interesting result has been finding relatively high sulfur concentrations (10% to 20%) in the slag in several of the tests. With high slag mass flow rates, as obtained with high ash coals or by injecting additional ash, it may be possible to encapsulate all the coal sulfur in the slag. Tests in which additional metal oxide powder was injected into the combustor at up to 40% injected mineral mass flow rates have been very recently completed. The analysis of the resultant slags is not yet complete.

NO_x emissions are controlled by operating the combustor fuel rich. Maximum reductions to as low as 0.26 lb/MMBtu were measured in the previous combustor at stoichiometric ratio (SR1) in the range of 0.7. In the present combustor, the tests were performed at less fuel rich conditions. At slightly fuel rich conditions, the NO_x, (reported as NO_2) has been in the range of 0.36 to 0.7 lb/MMBtu. The 0.36 lb/MMBtu value was measured at SR1 equal to 0.9.

The above discussion presents a general overview of the performance of the present second generation 20 MMBtu/hr combustor. Its performance has been found to be superior to the previous combustor, especially in the areas of combustion efficiency, slag retention and removal from inside the combustor, durability of the internal combustor wall, and simplicity of control and operation. Considerable data on SO_2 on NO_x control have been measured, but the analysis is not complete. Based on the results obtained to date, the best results achieved in the current combustor (namely SO_2 reductions to 0.22 lb/MMBtu and NO_x reduction to 0.36 lb/MMBtu) match those measured in the prior unit (SO_2 reductions to 0.34 lb/MMBtu and NO_x reduction to 0.26 lb/MMBtu).

III. APPLICATION OF THE AIR COOLED SLAGGING COMBUSTOR TO 1 TO 20 MWe POWER PLANTS

The present second generation combustor facility was designed as a prototype for a low cost, modular, coal fired commercial power plant. As such, considerable attention was given to incorporate novel designs for all the components of the present facility in order to minimize cost. Key elements in the plant that result in cost saving are:

- The air cooled, coal combustor is compatible with compact boilers designed for oil firing, which have about one-half the volume of conventional coal fired boilers.
- Modular design of the combustor and its auxiliary subsystems.
- Fuel flexibility and rapid switching between fuels, which minimizes the need for on-site fuel storage, especially bulky coal storage.
- Optimization of stack gas particulate control system to minimize baghouse cost, and stack fan power.
- Combustion of coarsely pulverized coal to allow use of low cost coal mills.
- Automated microprocessor control of the plant.

All these factors were incorporated in the design of the present facility in Philadelphia. The best way of demonstrating the cost impact of a power plant based on Coal Tech's combustion system technology is to compute the incremental cost of this plant versus a comparable size gas or oil fired plant. The additional components/subsystems required by the Coal Tech plant are coal storage, processing, and feed systems, the air cooled combustor, the stack gas cleanup system, additional fans and blowers, and additional controls. All these items use Coal Tech designs that optimize performance and cost. The gas and oil fuel components and storage are used only for startup, cooldown and emergencies. Therefore, their thermal rating and fuel consumption is a only a few percent of the total energy used by the coal fired plant. In computing the added cost of this coal plant versus a conventional oil or gas plant, the incremental cost of the oil/gas burners and oil/gas storage and delivery components in the latter plant must be subtracted from the cost of the coal system. All power generation components, including the steam loop, generators, electric power distribution, such as turbine-generator, electric power distribution, are common to both plants.

A series of cost estimates were developed for several thermal ratings ranging from 20 MMBtu/hr to 125 MMBtu/hr. One combustor at 125 MMBtu/hr can produce about 10 MWe. Two combustors at this rating are attached to one boiler yield 20 MWe. For a steam generating plant only, the incremental cost of this coal plant over a conventional oil/gas plant is in the range of $10 to $25/lb/hr of steam, with the cost decreasing as the thermal rating increases. For a power plant, this incremental cost is in the $100 to $200/kW range.

The following example shows the economic benefit of this system. For a 125 MMBtu/hr coal fired steam plant with this combustor an incremental cost of $14/lb/hr of steam is obtained. Applying this to 7000 hour/year operation, a coal-oil or gas cost differential of $0.85/MMBtu, a 10%-90% equity-debt ratio, and a 4 year amortization, one obtains an internal rate of return (IRR) of **43%.** For the smallest plants, a higher coal-oil/gas differential is required to yield a similarly high IRR. The low cost of this coal fired power technology allows great flexibility in achieving excellent rates of return.

This technology is especially attractive for the international market in regions with domestic coal reserves but no domestic oil or gas reserves. In this case additional factors enter in the power plant analysis, such as import restrictions on clean fuels. The compatibility of this combustor with high ash fuels which are readily found in many international markets, further adds to the attractiveness of this technology. In the first generation combustor, operations with additional ash injection to 50% mineral matter was successfully implemented [5,7]. In the current combustor the total mineral matter injection rate has to date been as much as 40% of the total solid fuel injected.

IV. CONCLUSIONS

The results of the effort to date on the second generation 20 MMBtu/hr air cooled, slagging coal combustor facility have confirmed the performance and economic benefits of this technology. Very rapid progress in the test effort since the facility became operational at he beginning of 1996 have accelerated its commercial development schedule.

The compact and modular design of the plant in the 1 to 20 Mwe range allows factory fabrication and assembly of its subsystems and shipment of the modules to the site for rapid assembly. These features makes it attractive for steam and power generation at industrial sites in the US and overseas.

V. ACKNOWLEDGMENTS

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