Evaluation of Combustion Turbine Systems for the Direct Combustion of Coal

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ABSTRACT

A combustion turbine combined cycle that uses coal-derived dirty fuels can be economical if the fuel is processed at the plant site and cost of electricity (COE) is used as the criterion for configuring the power system and selecting its components. In a DOE/METC-sponsored study, 12 combinations of power components and conditioning components were evaluated for each of two fuels: a gas made from coal and a coal/water slurry. One baseline system was selected from each group of 12 systems, based on its potential to achieve a low COE. Each baseline system was then parametrically evaluated to show the effects of specific components on the COE of the power plant. In one of these studies, on-site coal conversion was shown as the key to reducing the COE and the operating cost of the plant, thus improving the chances of the plant being used for baseload operation.

INTRODUCTION

The program described in this paper was initiated by the U.S. Department of Energy Morgantown Energy Technology Center to investigate the economic feasibility of using dirty fuels made from coal in a combustion turbine cycle, and to identify the research and development required. The fuels selected for this study were a coal gas and a coal/water slurry.

This study had three objectives: to define the best feasible power cycles using dirty fuels from coal; to define the technical problems and uncertainties that impede commercialization of these technologies; and to define the needed research and development programs. The power cycles presented in this paper result from work on the first objective.

The scope of the study was limited to utility-sized gas turbine power plants. In addition, the turbine inlet temperatures were limited to a maximum of 2000°F (1093°C) to reflect current technology for gas turbines burning natural gas or oil.

The original comparison of COEs was based on the assumption that the fuel would be produced off-site and then delivered to the power plant. In the course of the study, the COE evaluations were expanded to include coal gas and coal/water slurry prepared at the power plant.

CANDIDATE CONFIGURATIONS

The technical approach was to define combinations of power trains and conditioning systems that could use a fuel made from coal, to select the combination with the lowest COE, and to study the effects of selected parameters on the COE. The cycles were selected on the bases of minimum COE (cost of electricity), simplicity, and ease of commercialization. The outline of these steps is shown in a block diagram, Figure 1.

Four power trains were initially defined along with three cleanup systems for each of the two fuels. The four potential power trains are the blocks shown at the top in Figure 1. The three smaller rectangles (A, B, and C) immediately below each power train represent three arrangements of expander gas cleaning components. From this group of 12 systems, two baseline systems were selected -- one for each fuel -- based on their potentially low COEs.
This chosen combination of power train and gas cleaning arrangement gave the lowest COE (with reasonable complexity), and was used as the basis for more detailed analyses. This recommended configuration is represented (Figure 1) by the shaded rectangle in the next level down.

Parametric studies were performed on each of the two baselines (one slurry-fired, the other gas-fired) to show the influence of certain components, the most fruitful areas for additional work, and the crucial unknowns that must be resolved before significant progress can be made. Parametric studies are represented by the row of squares across the lowest portion of the diagram.

POWER TRAINS

The first candidate power train is a conventional combustion turbine with a heat recovery steam generator and a steam turbine bottoming cycle. The second system uses an indirectly fired air heater to add reheat to the combustion turbine cycle. The third power train features a regenerative combustion turbine with reheat and wet compression. This third cycle represents the highest efficiency that a gas turbine system can achieve without a bottoming cycle. The fourth power train also has a reheat combustion turbine with wet compression, but a steam turbine bottoming cycle is substituted for the regenerator. Each of the four candidate power trains (Figures 2 and 3) was evaluated with both fuels.

CONDITIONING SYSTEMS

Six arrangements of cleanup systems were identified: three for the gas-fired power trains and three for the slurry-fired power trains. The gas cleanup trains are shown in Figure 4, and the slurry cleanup trains are shown in Figure 5.

In the first gas cleaning arrangement (Figure 4), sulfur, alkali, and particulate material are removed from the hot dirty gas, so the combustor and expander can be similar to those that use clean conventional fuels. In the second gas cleaning system, the fuel gas is cooled so it can be washed by wet cleaning devices. Sulfur is removed by a sulfur washer, while alkali and other particulate matter are removed by a venturi scrubber. In the third cleanup system, minimally cleaned coal gas is burned in the combustor and the dirty products of combustion are handled by a strengthened expander. Sulfur and particulate removal devices in this system are in the exhaust stack.

In the first cleanup system for slurry-fired turbines (Figure 5), the sulfur, alkali, and particulate matter are removed after combustion but before they can enter the expander. The second system has no alkali getter. Its dust and sulfur removal devices are located in the exhaust stack, so the combustor can be close-coupled to the turbine. A strengthened expander is needed in this arrangement due to the high dust loading. The third arrangement also dispenses with the alkali getter and uses dust and sulfur removal devices in the exhaust stack. However, a cyclone separator is added between the combustor and the expander to remove the large particles (the combustor and turbine cannot be close-coupled). This cleaning arrangement also requires a strengthened expander.
Two turbine configurations were studied to assess their susceptibility to corrosion, erosion, and deposition.

- Normal expander: A current design modified to accommodate increased cooling flow necessary to limit the maximum metal temperature to the levels needed to inhibit corrosion.
- Rugged expander: The normal expander with aerodynamic changes to the blades and vanes that reduce corrosion, erosion, and deposition.

Factors that affect turbine susceptibility to corrosion, erosion, and deposition include gas velocities relative to airfoils the peripheral speed of the airfoils, and the amount of turning and rate of turning in each row. The moderately rugged expander has identical blade velocities and produces the same power as the normal expander, but has significantly reduced turning and higher reaction.

Heavy-duty combustion turbines are manufactured with burners either integral with the turbomachinery or external to the the turbomachinery. Although the integral types have been favored by U.S. manufacturers, the external types have been thoroughly developed, and they are in widespread use internationally. Results from coal/water slurry combustion tests show that the external combustor should be selected for this fuel. With the present state of the technology, the large volume available in an external combustor is needed to burn coal/water slurry, to give adequate residence time to complete the combustion. An added advantage of the external combustor is its ability to fit with pre-expander cleanup devices.

Whether the fuel is coal gas or coal/water slurry, the probability is high that it will contain nitrogen bound in the fuel molecules. This fuel-bound nitrogen must be dealt with in the combustor to meet environmental limits for NOx, which leads to the conclusion that a rich/lean combustor must be employed, since it can be adapted to either the integral or the external configuration. Westinghouse has tested multi-annular swirl burners with both coal gas and coal/water slurry in small scale, and a full-scale design could be produced for slurry that would integrate rich/lean elements into the external unit for engine application.

Combining the four power train options with the three cleanup options resulted in 12 combinations for coal gas and 12 combinations for coal/water slurry. The relative COE for each combination was optimized by adjusting its design conditions.

Parametric studies were done after the baseline configurations for each of the two dirty, coal-derived fuels were determined. These studies define in more detail the lowest COE configuration for each fuel, and define the best development approaches to control expander corrosion, erosion, and deposition. The principal issues that were studied were: location of fuel processing, location of cleanup devices, method of corrosion protection, effect of turbine redundancy, effect of firing temperature, and effect of blade cooling.

The conclusions drawn from the COE review were that the more complex power cycles do not result in sufficient reduction of the COE index to justify development, and that the cleanup system affects generating costs more than the power cycle does.

The simple cycle gas turbine with steam bottoming cycle was the choice for both fuels. Figure 6 shows the two configurations. In the chosen slurry-fired baseline, the desulfurizer, dust filter, and alkali

![Diagram of slurry cleanup systems](https://example.com/diagram.png)
getter bed (if any) are located between an external combustor and the expander. The gas-fired baseline system employs a combustor integral with the turbomachinery; the dust removal, desulfurizer, and alkali getter (if any) are located in the fuel feed line upstream of the combustor and expander. Other cleanup arrangements were rejected because of their higher COEs.

Both use the same style of compressor, turbine, generator, and heat recovery steam cycle. The differences are in the combustion system. The specific COE indices for the 12 gas-fired systems are shown in Figure 7, and the specific COE indices for the 12 slurry-fired combinations appear in Figure 8.

A qualitative index was used to account for the relative effort that would be required to develop each component into a commercial offering. Fifteen technical experts were asked to rate the relative development effort for each component. These component development indexes were averaged and combined into system development indexes.

The development indexes and COE indexes for the 24 candidate systems are compared in Figure 9. System G1CC was selected as the gas-fired baseline because it shows the best potential for low-cost power, and because it is closer to commercialization than any other gas-fired candidate at the left of the figure. System S1CC was chosen as the slurry-fired baseline for the same reason. The added developmental complexity of the reheats cycles with wet compression at the top of the chart could not be justified because they gave too little COE improvement.

![Figure 7. COMPARISON OF CANDIDATE COAL GAS POWER SYSTEMS AND CLEANUP TRAINS ON THE BASIS OF COST OF ELECTRICITY INDEX](https://fluidsengineering.asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1985/79399/V002T05A001/2396041/v002t05a001-85-gt-8.pdf)

![Figure 8. COMPARISON OF CANDIDATE COAL/WATER SLURRY POWER SYSTEMS AND CLEANUP TRAINS ON THE BASIS OF COST OF ELECTRICITY INDEX](https://fluidsengineering.asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1985/79399/V002T05A001/2396041/v002t05a001-85-gt-8.pdf)

![Figure 9. COST/RISK COMPARISON](https://fluidsengineering.asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1985/79399/V002T05A001/2396041/v002t05a001-85-gt-8.pdf)
Therefore, on-site conversion of power plant coal to gas or coal/water slurry would improve if the fuel supply were normal power gas or slurry with the associated on-site coal cleaning. This effect led to the choice of configurations in which cleaning was done upstream of the expander, not downstream.

TURBINE REDUNDANCY

Redundant gas turbines improve the availability of the power system but increase its capital cost, the net effect of which is reflected by the COE. For both the gas-fired and slurry-fired systems, the addition of a single redundant turbine reduces the COE, but the addition of a second redundant turbine is not cost-effective, as indicated in Table 1.

<table>
<thead>
<tr>
<th>Gas-Fired Systems</th>
<th>Slurry-Fired Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Redundant Turbines</td>
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</tr>
<tr>
<td>System Availability</td>
<td>0.865</td>
</tr>
<tr>
<td>Relative Capital Cost</td>
<td>1.000</td>
</tr>
<tr>
<td>Relative COE</td>
<td>1.000</td>
</tr>
</tbody>
</table>

The initial studies assumed an off-site fuel supply, but it became apparent that the economics would improve if the fuel supply were normal power plant coal, processed on-site into slurry or gas. This came about as studies showed that the costs for slurry were greatly increased by chemical additives needed for long storage and transit times. The high fuel costs of the gas or slurry delivered to the plant also increase the operating cost of the plant, which lessens the chances of economic dispatch and base load application. Therefore, on-site conversion of power plant coal to gas or slurry with the associated on-site coal cleaning is recommended.

Corrosion Protection Methods

The slurry-fired system with the lowest COE uses enhanced blade cooling to inhibit corrosion, but no alkali getter. On the other hand, the gas-fired system with the lowest COE uses an alkali getter to remove the corrosion-causing elements from the working fluid stream, removing the need for additional blade cooling. The alkali getter was cost effective for the gas-fired case (but not for the slurry-fired case) because the volumetric flow rate of the fuel gas is much less than the volumetric flow of the products of combustion. The getter in the gas-fired case, therefore, is much smaller and much less expensive than the getter for the slurry-fired case would be.

ON-SITE FUEL PROCESSING

One of the main results (Figures 8 and 9) is that pre-expander cleanup devices are more cost-effective than those downstream. This result is common to both coal gas and coal/water slurry. The reason for this phenomenon is shown in Figure 10.

The capital costs for the various gas cleanup devices are strong functions of their actual volume flow (not mass flow). The effect of volume flow on cost is so strong that it overshadows the device-to-device variations. This effect led to the choice of configurations in which cleaning was done upstream of the expander, not downstream.

Firing Temperature

The operating temperature of the fluid bed desulfurizer (FBD) was limited to 1850°F in this study because of concern over sintering of the dolomite. The slurry firing temperature is therefore limited to 1850°F to accommodate the bed. This temperature limitation has no performance effect in the gas-fired cases, because the desulfurizer was located in the fuel line, which has a temperature of 1200°F. The design of the slurry-fired expander is particularly sensitive to inlet temperature because of the amount of cooling flow required to cool the blades. A result of this study is that the COE of the slurry-fired system would not change much if the fluid bed desulfurizer could operate at 2000°F because any gain in performance is offset by the increased cost of the higher temperature expander.

Blade Cooling

Decreasing the blade metal temperature increases the required blade cooling flow, reduces the efficiency of the turbine, and increases its capital cost. However, there may be a blade metal temperature that is cool enough to solidify the molten compounds that cause some types of corrosion and warm enough to avoid other types of corrosion. An expander with appropriately cooled blades would not corrode, eliminating the need for an expensive alkali getter.

A sensitivity study evaluated the consequences of uncertainty about such a corrosion threshold temperature. The study showed that the COE increases about three percent with each 100°F reduction in allowable blade metal temperature, which is a substantial penalty.
CONCLUSIONS

Throughout this study the power plant was viewed, not as a collection of optimized components, but as a system with a single criterion: COE. Power systems and components were chosen based on their abilities to reduce the COE, a process involving tradeoffs among components with conflicting design characteristics. The conclusions summarized below reflect the results of those tradeoffs.

- A slurry-fired system with an 1850°F firing temperature has a lower COE than a hot gas-fired power system fired at 2000°F. The COE for a slurry-fired power system would not be improved by increases in the firing temperature, where improvements in heat rate are counteracted by increases in expander cost and cooling requirements.
- The power train with the lowest COE is a non-reheat gas turbine combined cycle with a steam bottoming cycle, whether the fuel is slurry or coal gas. Both power systems use the same style of compressor, turbine, generator, and heat recovery steam cycle. The gas-fired system can use a compact, integral combustor, but the burning of coal/water slurry needs the larger combustion volume of an external combustor.
- Cleanup systems should be located before the expander rather than in the exhaust stack, because their cost depends largely on the volumetric flow rate of the streams they clean. Changes in the cleanup system affect generating costs more than changes in the power cycle.
- On-site fuel preparation is more cost-effective than off-site preparation.
- The addition of a redundant turbine reduced the COEs of both the gas-fired and slurry-fired systems, but the addition of a second redundant turbine is not cost-effective.

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