APPLICATION OF RQL COAL COMBUSTOR TECHNOLOGY TO LARGE UTILITY GAS TURBINES

C. Wilkes, R.A. Wenglarz, P.J. Hart, and H.C. Mongia
Allison Gas Turbine Division
General Motors Corporation
Indianapolis, Indiana 46206

ABSTRACT

This paper describes the application of Allison’s rich-quench-lean (RQL) coal combustor technology to large utility gas turbines in the 100 MWe+ class. The RQL coal combustor technology was first applied to coal derived fuels in the 1970s and has been under development since 1986 as part of a Department of Energy (DOE)-sponsored heat engine program aimed at proof of concept testing of coal-fired gas turbine technology. The 5 MWe proof of concept engine/coal combustion system was first tested on coal water slurry (CWS); it is now being prepared for testing on dry pulverized coal. A design concept to adapt the RQL coal combustor technology developed under the DOE program to large utility-sized gas turbines has been proposed for a Clean Coal V program. The engine and combustion system modifications required for application to coal-fueled combined cycle power plants using 100 MWe+ gas turbines are described. Estimates for emissions and cycle performance are given. Included are comparisons with a conventional pulverized coal plant that illustrates the advantages of incorporating a gas turbine on cycle efficiency and emission rate.

INTRODUCTION

The use of coal as a fuel for combustion turbines has long been pursued. About 40 years ago, two extensive programs were initiated in the U.S. (Smith, et al, 1966) and Australia (Interdepartment Gas Turbine Steering Committee, 1973) to develop turbines directly fired with coal for locomotive applications. While these programs did not produce commercial coal-fired turbines, significant progress was made in overcoming the technology barriers of pressurized coal injection, combustion, and protection of the turbine flow path from the degrading effects of coal ash and contaminants.

An RQL combustor concept was first applied by Allison Gas Turbine Division of General Motors Corporation to a coal-derived fuel program sponsored by NASA in the 1970s (Novick and Troth, 1981) and later taken over by DOE. During this program, an air-quenched RQL combustor was successfully run on coal derived liquid fuels and simulated low Btu gas containing ammonia.

In the early 1980s, the U.S. Department of Energy initiated new projects concerning direct coal-fired turbines (Pitrolo, 1983). Following initial systems evaluations and coal combustor tests in these projects, several programs were awarded to gas turbine manufacturers to develop components and conduct proof of concept tests for coal-fueled turbines. One of the programs was awarded to Allison. In that program, the RQL combustion approach from the previous NASA/DOE program has been adapted for the combustion of coal slurry fuels and dry coal.

A bench-scale RQL combustor and a full-scale RQL combustor sized for the Allison Model 501-K industrial turbine have been tested (Wilkes and Santanam, 1991). The full-scale combustor has been integrated with an Allison 501-K turbine. The combustor/turbine system has been tested with distillate oil and with a coal-water fuel for four hours (Wenglarz, Wilkes, et al., 1992). The combustion system has met commercial goals for combustion efficiency and NOx emissions. The engine test produced no detectable erosion or corrosion of
the turbine, but deposition did occur. Water soluble vane deposits were readily removed by washing after the test.

Systems and economic evaluations have been conducted for coal-fueled turbine cogeneration systems and combined cycle plants using the RQL combustion approach. This paper describes a commercial coal-fueled combined cycle plant based on the RQL combustion/emissions control technology that is being developed.

RQL Combustion Approach

A key to the successful development of a commercial coal-fired gas turbine is the ability to control NOx, CO emissions while maintaining an acceptable carbon conversion efficiency above 99%. In addition, the removal of ash from the system must be performed in a manner that does not incur excessive heat loss or result in the formation of large deposits. The Allison RQL combustion system has been developed to meet these goals and has been demonstrated during the proof-of-concept engine run on 100% CWS (Wenglarz, Wilkes, et al., 1992). NOx emissions are controlled by a fuel-rich, fuel-lean staged combustion process that inhibits the conversion of fuel bound nitrogen to NOx and reduces the formation of thermal NOx by limiting the rich and lean zone flame temperatures. The rich zone operates at a temperature of 3000°F and an equivalence ratio of approximately 1.8, producing a low heating value gas containing H2 and CO. More than 99% of the carbon present is converted to CO and CO2. Water injection is introduced into the quench zone to lower the gas temperature to 2000°F and freeze the droplets of molten slag that form in the rich zone. A water gas shift reaction also takes place in the quench zone, oxidizing some CO to CO2 and forming H2 from H2O. The frozen ash is removed from the system as a dry nonagglomerated particulate. The quench zone gas temperature is further reduced by a heat exchanger for downstream sulfur clean-up. After sulfur is removed, the low heating value gas is fully oxidized in the lean zone with the introduction of additional combustion air. Auto-ignition of the gases eliminates potential difficulties with flame stability and reduces CO emissions to less than 25 ppmvd corrected to 15% O2. Figure 1 shows CO emissions as a function of NOx obtained from combustion rig and engine tests. Each data point represents a unique rich, quench, and lean zone operating condition. By adjusting airflow distribution and water injection rate, both NOx and CO2 are shown to be simultaneously controlled to less than 25 ppmvd at 15% O2.

The combustion system that produced the emissions performance shown in Figure 1 is sized for the Allison 501-K turbine which generates about 5 MWe for operation with coal-water fuels. The system is now being prepared for operation with dry coal. A design approach to adapt the RQL coal combustion technology to large utility sized turbines has been proposed for a Clean Coal V program. Scale-up from 5 to 50 MWe (nominal gas turbine output) will be accomplished by use of multiple fuel nozzles, each of which is the same size as the single nozzle used in the 5 MWe demonstration engine. Scale-up to 100 MWe+ turbines will be accomplished by use of two combustion trains.

COAL-FUELED TURBINE, COMBINED CYCLE SYSTEMS

System Description

The coal-fueled turbine combined cycle (CFTCC) approach is illustrated by the simplified block diagram in Figure 2. The system consists of two major blocks, the RQL coal combustion/emissions control block and the power generation block. The power generation block is a combined cycle (gas turbine and steam turbine cycle) system and uses equipment designed to operate with conventional turbine fuels (e.g., natural gas). The RQL coal combustion/emissions control block adapts the conventionally fueled combined cycle equipment to operation with coal. As to be later discussed, the coal combustion equipment uses gas turbine technology rather than process plant technology and provides compactness and cost advantages over other coal utilization systems.

Referring to Figure 2, a portion of the gas turbine compressor discharge air is directed to the combustion/emissions control block where it is reacted with coal to produce a combustion...
Combustion/emissions control block

Water quench

Coal

Rich zone

Cyclone

Heat exchanger

Sulfur removal

Particle removal

Lean zone

Lean zone

Compressor

Gas turbine

Expander

Steam turbine

Power generation block

Figure 2. Simplified coal-fueled turbine combined cycle schematic.

stream from which coal contaminants (e.g., sulfur and ash particulate) are removed before final combustion and expansion in the turbine. Quench water and heat extraction are used in the combustion/emissions control block to lower the temperature of the combustion products to a suitable value (1340°F) for removal of coal contaminants and control of emissions. The heat extracted in the combustion/emissions control block is used in the steam equipment of the combined cycle power generation block to produce power.

Combustion/Emissions Control Block

Nitrogen oxides (NO\textsubscript{x}) are controlled in the combustion/emissions block by rich-quench-lean (RQL) combustion of the coal. The rich zone of the combustor operates under fuel rich conditions, which inhibit NO\textsubscript{x} formation from fuel bound nitrogen in the coal. The quench and final lean zone combustion within the turbine involve relatively low reaction temperatures which inhibit thermal NO\textsubscript{x} formation. As previously discussed, tests with the RQL coal combustor sized to the Allison 501K turbine have controlled NO\textsubscript{x} and CO levels to under 25 ppmvd (at 15% O\textsubscript{2}) with prospects for lower levels after further combustion optimization tests.

Sulfur oxides (SO\textsubscript{x}) are controlled in the combustion/emission block by a Zn titanate sulfur sorber. Tests indicate that this control method should ultimately be capable of reducing SO\textsubscript{x} emissions by over 99%.

Particulates are controlled in the combustion/emissions block by cyclone separators and hot gas ceramic filters. A number of high temperature filter tests have reduced gas stream particle carryover to under 10 ppmw with some tests producing levels that were hardly detectable (probably 1 ppmw and lower). At this loading, particles should result in negligible erosion rates in the turbine section.

Applications

The CFTCC technology can be utilized for new power plants or for repowering of existing natural gas-fired, combined cycle power plants. Depending on the gas turbine used, this technology can provide coal-fueled power blocks with electrical outputs from about 85 MW (e.g., for the GE MS6000 turbine) to over 350 MW (e.g., for the Westinghouse 501F turbine) and even higher outputs for future advanced turbines. One RQL combustor/emissions control train would be used for plants based on 50 MWe class gas turbines. Two RQL combustor/emissions control trains would be used for plants based on 100 MWe+ gas turbines. Each would be similar to
the 50 MWe train and would be controlled to assure uniform gas production.

**Coal Specifications**

The current proof-of-concept (POC) engine program is aimed at burning the most commonly available coals including those from the Illinois No. 6 and Pittsburgh No. 8 seams. Typical specifications, based on a Pittsburgh No. 8 coal, are shown in Table 1.

<table>
<thead>
<tr>
<th>Spec</th>
<th>Wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>&lt; 2.00</td>
</tr>
<tr>
<td>Volatile matter (dry)</td>
<td>&gt; 35.00</td>
</tr>
<tr>
<td>Fixed carbon (dry)</td>
<td>&gt; 55.00</td>
</tr>
<tr>
<td>Ash (dry)</td>
<td>&lt; 10.00</td>
</tr>
<tr>
<td>Sulfur (dry)</td>
<td>&lt; 1.95</td>
</tr>
<tr>
<td>Alkali (% of ash)</td>
<td>&lt; 2.00</td>
</tr>
<tr>
<td>HHV (dry), But/lb</td>
<td>&gt; 13,500</td>
</tr>
<tr>
<td>Fusion temperature, °F</td>
<td>&gt; 2,000</td>
</tr>
</tbody>
</table>

**CFTCC PLANT BASED ON F CLASS GAS TURBINE**

The following describes a CFTCC plant which utilizes the Westinghouse 501F turbine. Two identical trains of coal feed, combustion, sulfur removal and particulate removal equipment provide a cleaned combustion stream to the gas turbine. The coal input rate is 112.9 tons/hr. The nominal gas turbine output is 192 MWe using an Eastern bituminous coal containing 2.5% sulfur and 16.4% ash. Heat is extracted from the gas turbine exhaust by a heat recovery stream generator (HRSG) and from the coal combustor quench zone by a heat exchanger in each combustor train. This heat is utilized in a dual pressure steam cycle to produce a nominal 170 MWe from a steam turbine. Plant parasitic power losses are 10.9 MW to result in a net plant output of 351.1 MW. A byproduct of the commercial plant is elemental sulfur. About 2.7 tons/hr of sulfur is extracted from the coal combustion stream using a zinc titanate sulfur capture system.

Figure 3 gives a block flow diagram showing the major plant sections of the CFTCC commercial plant. The following describes these plant sections.

**Section 100 - Coal Receiving, Preparation, and Delivery**

Section 100 consists of coal receiving from trucks or trains (depending on the specific site), a coal storage pile, and two complete coal pulverization/drying and coal feeder trains. Each train consists of a coal silo used to feed the pulverizers; a pulverizer/dryer (about 60 tph capacity); a cyclone separator; a bag filter; and a complete coal pressurization, metering, and pneumatic feeder system, including a boost compressor for pressurized injection above the combustor operating pressure. Hot gases for drying the coal are supplied by two natural gas fired air heaters of about 10 MMBtu/hr capacity, each. Provisions are made to recycle a portion of the combustion gases from the natural gas heaters to reduce the oxygen content of the drying gases, so an inert gas system is not needed. The pneumatically transported coal/air mixture feeds the fuel nozzles in the rich zone of each combustion train (stream 1, Figure 3).

**Section 200 - Coal Combustor**

This section consists of two combustor trains, each of which includes a rich zone combustor, a water quench zone, and a heat exchanger. Also included are the inlet ducting to the turbine and the internal cans that complete lean zone combustion and produce the turbine expansion gases (stream 10). The coal feed and the portion of the compressor discharge air from the gas turbine entering both combustors are given by streams 1 and 3, respectively, on Figure 3. After combustion, the products (stream 4) are quenched with water (stream 5) to reduce the temperature of the gas (stream 6) entering the cyclone to 2000°F. Heat is extracted from the products leaving the cyclone to reduce the temperature of the gas (stream 7) to 1340°F which is appropriate for downstream sulfur removal and particulate cleanup with ceramic filters.

**Section 300 - Sulfur Control**

The sulfur control system is fed by stream 7 and terminates at the barrier filter, stream 8, in each train. Sulfur containing gases exiting the heat exchanger enter the Zn titanate circulating fluid bed (CFB) sorber, where H₂S and COS are captured as ZnS with an efficiency of >95%. The "sulfur-free" gases exit the sulfur capture system and enter the barrier filter. Sulfur containing sorbent is transferred to the regenerator where oxygen reacts with the sulfur in the sorbent to produce a gas stream containing SO₂. Oxygen also reacts with the Zn, from ZnS, to regenerate Zn titanate. The regenerated sorbent is transferred back to the sorber to capture more sulfur.

The SO₂ stream enters the catalytic direct sulfur recovery process (DSRP) (Gangwal, et al, 1991) section where the SO₂ is reduced to elemental sulfur, which is removed from the system (stream 18) and sold as a byproduct. There are no...
gaseous sulfur emissions from this system. Any sulfur that is not removed as elemental sulfur is sent back to the sorber for a second pass.

**Section 400 Particulate Control**

This section includes a large cyclone and three parallel ceramic tube hot gas filter units for each of the two trains. Also included is equipment to pulse clean the filters and water cooled screws to extract captured fines from the cyclones and filters for transport to the solid waste handling system (Section 700). The cyclone captures particulate from stream 6 exiting the quench zone to alleviate the particle loading entering the downstream heat exchanger, sulfur control system, and hot gas filters. The hot gas filters receive the gas flow (stream 8) from the sulfur control system and captures nearly all the entrained particulate to reduce loading in that flow (stream 9) to extremely low levels (under 10 ppm). This provides erosion and deposition protection for downstream components, including the lean combustors, turbine expander, and heat recovery steam generator. Very low environmental particle emissions (stream 12) from the plant are also provided by the hot gas ceramic filters.

**Section 500 - Gas Turbine/Generator**

A Westinghouse 501F gas turbine/generator and all the balance of plant equipment associated with the gas turbine installed in a combined cycle plant are included in Section 500. The balance of plant equipment associated with a combined cycle gas turbine is incorporated into Section 500 rather than balance of plant Section 800 for the purpose of later cost comparisons. Air (stream 2) enters the gas turbine compressor. A portion (stream 3) of the compressor outlet flow is directed to the rich zone to partially burn the coal. The remainder of the compressor outlet flow is split between the coal injector system, the lean zone combustors, and turbine cooling. The hot gas (stream 9) leaving the high temperature filter is completely burned out in the lean combustors within the turbine casing to produce the turbine expansion gases
The energy extracted by the turbine expander drives its compressor and generator to produce about 192 MW electricity (nominal). The turbine exhaust (stream 11) enters the heat recovery steam generator (HRSG) which extracts additional heat for the steam cycle. The gas (stream 12) leaving the HRSG is exhausted to the atmosphere through a stack.

**Section 600 - HRSG/Steam Turbine/Generator**

This section consists of all the equipment for the 2400 psig/1000°F/1000°F/2.5 in. Hg steam cycle. Included are the heat recovery steam generator (HRSG), steam turbine, steam turbine generator, water treatment plant for the steam systems, and all balance of plant equipment associated with the steam cycle installed in a combined cycle plant. This balance of plant equipment associated with a combined cycle plant is incorporated into Section 600 rather than Section 800 for the purpose of later cost comparisons.

Energy from the gas turbine exhaust (steam 11) is used to produce steam (stream 13) using the HRSG. Stream 13 from the HRSG and reheat stream 15 returning from the outlet of the HP steam turbine section enter the heat exchanger located at the outlet of the cyclone. Heat is extracted in that heat exchanger from the combustion gases leaving the cyclone to produce two streams (14 and 16) to the steam turbine. Stream 14 enters the high pressure section of the steam turbine and stream 16 enters the low pressure section of the steam turbine. The energy extracted by the steam turbine produces 170 MW electricity (nominal). The steam turbine exhausts to the condenser to recover the water to be recirculated in the steam cycle.

**Section 700 - Solids Waste Handling**

This section oxidizes the ash captured in the combustion system cyclone and barrier filters of both trains. Only one train of ash handling is used.

A schematic for the solids waste handling system is shown in Figure 4. The system includes a fluid bed ash oxidizer, a cyclone, a heat exchange to cool the entrained ash and gases exiting the cyclone and to raise the temperature of the air entering the fluid bed, and a bag filter to remove particulate from the effluent of the fluid bed. Ash is transferred pneumatically from the power plant particle removal equipment to the ash oxidation reactor. The ash is
removal equipment to the ash oxidation reactor. The ash is oxidized using the heated air stream to convert any CaS, and any other partially reduced or sulfided metals, to environmentally stable compounds (sulfates and oxides) in a fluidized-bed combustor. Most of the sulfated ash is captured by the cyclone on the outlet of the fluid bed reactor and is sent to a water cooled screw cooler. The ash that escapes the cyclone is sent with the hot gases through a heat exchanger that cools it to about 400°F. The gases and ash are separated by a bag filter. The ash from the bag filter is added to the ash from the screw cooler and all ash is removed from the pressurized system through lockhoppers (stream 17). The ash is then collected and landfilled.

Effluent from this system is ash for disposal.

**Section 800 - Balance of Plant**

This section consists of balance of plant associated with the coal combustion/emissions control island (Sections 100, 200, 300, 400, and 700). The balance of plant associated with the combined cycle power generation blocks has been included in Sections 500 and 600. This plant breakdown will allow the identification of the incremental cost/kW for the coal-fueled turbine, combined cycle (CFTCC) plant over that for a conventionally-fueled, combined cycle plant utilizing the Westinghouse 501F turbine.

**CFTCC PLANT PERFORMANCE**

**Emissions**

Emissions from the 351 MW CFTCC plant are given in Table 2 and are addressed in the following subsections. Emission rates are quoted on a higher heating value (HHV) basis when expressed as a function of heat input.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emission rate lb/MMBtu coal</th>
<th>Emission rate lb/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO&lt;sub&gt;x&lt;/sub&gt;</td>
<td>0.113</td>
<td>9.53E-4</td>
</tr>
<tr>
<td>SO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.101</td>
<td>8.53E-4</td>
</tr>
<tr>
<td>CO</td>
<td>0.029</td>
<td>2.49E-4</td>
</tr>
<tr>
<td>Particulate-PM</td>
<td>0.013*</td>
<td>7.74E-5</td>
</tr>
<tr>
<td>Solid waste/byproducts</td>
<td>Ash-13.3</td>
<td>0.112</td>
</tr>
<tr>
<td></td>
<td>Sulfur-1.92</td>
<td>0.016</td>
</tr>
</tbody>
</table>

Reference coal used: Eastern Bituminous Coal

* Includes coal particulates from pulverizer/dryer, ash from ash sulfator, and ash in turbine exhaust

**Gaseous Emissions**

Using the proper operating conditions in the rich-quench-lean (RQL) combustors, NO<sub>x</sub> and CO emissions will be controlled below 25 ppmv (15% O<sub>2</sub>, dry) in the turbine exhaust. This corresponds to about 0.113 lb NO/MMBtu or 9.53x10^-4 lb NO/kWh and 0.029 lb CO/MMBtu or 2.49x10^-4 lb CO/kWh.

There are no SO<sub>2</sub> emissions from the sulfur control section (Section 300), since there are no outlets to the atmosphere. Any sulfur not captured will exit the system in the turbine exhaust, as SO<sub>2</sub>. Using a conservative estimate of 95% overall sulfur capture by the Zn titanate sorbent, SO<sub>2</sub> emissions will be 0.101 lb/MMBtu or 8.53x10^-4 lb/kWh.

**Particulate Emissions**

Particulate emissions arise from three sources: fine coal particles that escape the cyclone and bag filter (Section 100), ash fines escaping the cyclone and bag filter of the solids waste handling system (Section 700) and those that escape the barrier filter (Section 400) and pass through the turbine into the exhaust. Coal particulate emissions from the coal feed system would be about 0.0078 lb/MMBtu or 6.62x10^-4 lb/kWh. Ash particulate emissions from the waste handling system would be 0.0013 lb/MMBtu or 1.12x10^-3 lb/kWh.

Particulate emissions from the turbine exhaust arise from ash that passes the cyclone and high temperature filter. It is assumed that these particles are all <10 μm in diameter and so are all PM<sub>10</sub> emissions. The expected overall efficiency of the combustor cyclone and high temperature filter is about 99.97%, 70% for the cyclone and 99.9% for the barrier filter. Expected emissions in the turbine exhaust will be 0.0041 lb/MMBtu or 3.5x10^-3 lb/kWh.

Total particulate emissions from all sources are therefore 0.0132 lb/MMBtu or 11.24x10^-3 lb/kWh.

**Solid Wastes and Byproducts**

The only solid waste stream in this plant is the ash which has been oxidized in the sulfator (Section 700). The ash rate for this plant is 13.26 lb/ash/MMBtu or 0.112 lb/kWh. Ash contains small amounts of Zn titanate sorbent that is lost from the sulfur capture system as fine particles that have formed by attrition. This solid is included in the preceding ash rates.

Sulfur is the only byproduct in this plant. Elemental sulfur rates are about 1.92 lb/MMBtu or 0.016 lb/kWh with this system and coal. About 2.7 ton pure sulfur/hr will be obtained as a salable byproduct.
### Comparison with Pulverized Coal Boiler Plant

A comparison of $NO_x$, $SO_2$, and particulate emissions from an existing 300 MW\textsubscript{e} coal boiler plant without provision for $SO_2$ and $NO_x$ control and the CFTCC plant shows the lower emissions from the CFTCC system (see Table 2). The CFTCC emissions are also substantially lower than the Federal New Source Performance Standards (NSPS) shown in Table 3.

#### Table 3.
Comparison of air emissions of 300 MW\textsubscript{e} coal boiler plant with the CFTCC plant.

<table>
<thead>
<tr>
<th>Emission species</th>
<th>PC boiler (HHV basis)</th>
<th>CFTCC plant</th>
<th>NSPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$NO_x$, lb/MMBtu</td>
<td>1.24</td>
<td>0.113</td>
<td>0.50</td>
</tr>
<tr>
<td>$SO_2$, lb/MMBtu</td>
<td>3.96</td>
<td>0.101</td>
<td>1.20</td>
</tr>
<tr>
<td>Particulates, lb/MMBtu</td>
<td>0.10</td>
<td>0.013</td>
<td>0.03</td>
</tr>
</tbody>
</table>

#### Efficiency

Table 4 shows the efficiency of the 351 MW\textsubscript{e} CFTCC plant and the efficiency of the 300 MW\textsubscript{e} pulverized coal (PC) boiler plant. The CFTCC plant efficiency is over 7 percentage points higher than that for the existing conventional power plant.

#### Table 4.
Power plant efficiencies.

<table>
<thead>
<tr>
<th>System</th>
<th>Heat rate Btu/kW-hr</th>
<th>HHV basis</th>
<th>Efficiency - %</th>
</tr>
</thead>
<tbody>
<tr>
<td>351 MW\textsubscript{e} CFTCC plant</td>
<td>7785</td>
<td>43.8</td>
<td></td>
</tr>
<tr>
<td>300 MW\textsubscript{e} PC boiler plant</td>
<td>9493</td>
<td>36.0</td>
<td></td>
</tr>
</tbody>
</table>

#### Costs

As discussed earlier, the CFTCC system design approach adapts a conventional combined cycle plant design to operation with coal by using the RQL combustor/emissions control island. The distinction of equipment on Figure 3 between combined cycle equipment (plant sections 500 and 600) and coal combustion/emissions control equipment (remaining plant sections) allows identification of the incremental capital costs per kilowatt for the coal-fueled turbine, combined cycle plant compared to a combined cycle plant that uses conventional fuels. Cost evaluations have indicated a total plant incremental cost of $476/kW for the coal combustion/emissions control equipment.

### SUMMARY AND CONCLUSIONS

The direct coal-fueled turbine combined cycle (CFTCC) power plant has been described in this paper. This plant is essentially a conventionally-fueled combined cycle system adapted to coal by a RQL combustor/emissions control island. The combustion/emission control island produces cleaned coal combustion gases for expansion in the gas turbine. The gases are cleaned to protect the turbine from flow-path degradation due to coal contaminants and to reduce environmental emissions to comparable or lower levels than alternate clean coal power plant technologies.

Most of these alternate clean coal technologies have been developed by organizations that design process plants. As a result, incorporation of these coal technologies with a combined cycle power generation system requires integration of turbine equipment with a process plant. An advantage of the CFTCC system over other clean coal technologies using gas turbines results from the CFTCC system having been designed as an adaptation to coal of a natural gas-fired combined cycle plant. Gas turbines are built for compactness and simplicity. The RQL combustor is designed using gas turbine combustion technology rather than process plant reactor technology used in IGCC and other coal systems. The result is simpler and more compact combustion equipment than for alternate technologies. The natural effect is lower cost and improved reliability.

By way of example, the residence time in the rich zone of the RQL system is typically only about 20 to 30\% of that for many entrained coal gasifiers, which have the shortest residence times of the alternate coal technologies. This results in a more compact system. Combustion in the RQL system is achieved with air, thereby not requiring the complexity and high cost of the oxygen plant needed for many coal gasification systems. No equipment is necessary in the RQL combustion system to capture and recycle combustion product fines while such equipment is usually needed for efficient coal consumption in advanced pressurized fluidized bed combustion and gasification systems.

In addition to new power generation plants, a future application for CFTCC technology will be relatively compact and gas turbine compatible coal combustion/emissions control islands that can adapt existing natural gas-fired combined cycle plants to coal when gas prices rise to the point where conversion is economically attractive. Because of simplicity, compactness, and compatibility of the RQL combustion/emissions control island compared to other coal technologies (e.g., coal gasification), it is expected to be a primary candidate for such conversions.
REFERENCES


