INTEGRATION OF COMBUSTION TURBINE SYSTEMS INTO PRESSURIZED FLUIDIZED BED COMBUSTION COMBINED CYCLES

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ABSTRACT
Currently, pressurized fluidized bed combustion (PFBC) combined cycle power plants apply multiple stages of cyclones to clean the combustion products prior to turbine expansion, and rugged, inefficient expanders are required for this dirty-gas duty. The turbine inlet temperature is limited to the fluid bed combustor temperature, about 843°C (1550°F), so the plant thermal efficiency is relatively low. The development of hot gas filtration and coal-gas topping for PFBC combined cycles is the next step in the evolution of PFBC, and will result in the use of modern, high-efficiency combustion turbines in PFBC applications as well as plant thermal efficiencies up to 47% (HHV).

Westinghouse is developing integrated combustion turbine systems that interface with PFBC plants and incorporate the functions of hot gas filtration, alkali vapor removal, topping combustion, hot gas piping and control, and turbine compression and expansion. This paper reports on the engineering considerations made by Westinghouse for these integrated combustion turbine systems and summarizes the current development activities and status.

INTRODUCTION
Pressurized fluidized bed combustion (PFBC) of coal for combined cycle power generation is a near-commercial technology that has been under development throughout the world for some 30 years. The Westinghouse Electric Corporation was the first U.S. company to evaluate this technology, working with the Foster Wheeler Corporation under the U.S. Environmental Protection Agency (EPA) sponsorship in the early 1970s. Results of that evaluation indicated that there are some potential economic and environmental benefits of PFBC technology over the conventional pulverized-coal power plant (Archer et al., 1971).

The turbine inlet temperature is constrained by the operating temperature of the Base-PFBC. This constraint limits the plant thermal efficiency to only moderate levels. Base-PFBC technology has followed a development path leading to first commercial operation using conventional cyclones for cleaning the combustion gas before it is expanded through the turbine. Because of the large penetration of particles through even several stages of cyclones, rugged, inefficient turbine expanders must be used for this duty.

Currently there are four operating Base-PFBC plants located in the United States, Sweden, Spain, and Japan. All are based on the nominal 70-80 MWe, ABB Carbon, P200, bubbling fluid bed combustor technology (Hafer et al., 1993). Several, nominal 320 MWe, Base-PFBC plants based on the ABB Carbon, P800, bubbling fluid bed combustor are in early design phases (Anderson and Nilsson, 1993).

Parallel development of two technologies in recent years, hot gas filtration and coal-based topping cycles for PFBC, now promise to raise the efficiency of the PFBC power cycle. The latest of the ABB Carbon Base-PFBC plants, the Wakamatsu plant in Japan, incorporates a demonstration of hot gas filtration, the Asahi Glass Co., Ltd. filter technology, into the Base-PFBC cycle (Fujita et al., 1993). Ahlstrom Pyropower has developed a circulating fluid bed combustor technology that is planned for use on the Clean Coal III program at Midwest Power. This Base-PFBC power plant project will utilize a modern, high efficiency turbine expander with the Westinghouse hot gas filter, a major candidate to protect the expander.

The U. S. Department of Energy is supporting the development of an advanced PFBC cycle, Topping-PFBC, through the Foster Wheeler Development Corporation. This raises the turbine inlet temperature to modern, clean-fuel program combustion turbine levels, using a coal-derived fuel gas (Robertson et al., 1993). The Topping-PFBC technology will also apply hot gas filtration and alkali removal.

Westinghouse is currently involved in the development of inte...
grated combustion turbine systems for both Base-PFBC and Topping-PFBC applications. The integrated combustion turbine system for PFBC applications differs substantially from the conventional combustion turbine system. It must incorporate several components and functions that deal with the dirty PFBC gas environment, with respect to turbine protection, environmental protection, plant reliable operation and control. This paper summarizes the engineering considerations made for this integration and reports on the current status of Westinghouse development activities.

**PFBC POWER PLANTS**

Current coal-fired PFBC process configurations being demonstrated, or nearing demonstration phases of development are placed into the following three categories:

- **Base-PFBC** using cyclone-based gas cleaning,
- **Base-PFBC** using hot gas filtration,
- **Topping-PFBC**.

Base-PFBC using hot gas filtration, and Topping-PFBC process configurations are illustrated in Figure 1. The figure defines the boundaries of the integrated combustion turbine system and highlights the major components. Base-PFBC with hot gas filtration, Figure 1a, can apply modern, high-efficiency turbines that have been adapted to the externally-combusted, low-temperature inlet gas conditions of Base-PFBC.

The integrated combustion turbine system in the Base-PFBC process configuration, Figure 1a, contains several developmental or adapted components: the hot gas filter system, the adapted combustion turbine expander and compressor, the turbine control strategy applying high-temperature control valves, and the connecting hot-gas piping. The compressed-air discharge line carries the compressed air from the center section of the combustion turbine and routes it through various piping systems to the pressurized fluid bed combustor. An inlet valve in the compressed-air piping isolates the turbine from the fluid bed combustor unit. The combustion gas passes through stages of conventional cyclone cleanup before entering the integrated combustion turbine system. The hot gas filter removes most of the remaining particulate from the combustion gas before it is expanded in the turbine. It is generally assumed that alkali vapor levels (sodium and potassium chlorides and sulfates) are low in Base-PFBC, so no alkali control is incorporated into the process. This may not be the case with high-alkali coals and higher combustor operating temperatures. The filtered hot gas is piped back to the inlet pipe of the center section of the turbine casing. The hot gas enters the internal manifold and passes through the transitions to the turbine inlet.

An outlet, overspeed trip valve isolates the fluid bed combustion unit from the turbine and rapidly shuts off the hot combustion gas to the turbine. A vent valve is provided for the fluid bed combustor. A bypass line connects the compressed-air piping and the hot gas piping so that the turbine can be started with a startup combustor. Depending on the control strategy, this valve may also be used to provide a controlled bypass to moderate the inlet temperature, thereby controlling the power output of the turbine. During emergency shutdown this valve will also open to cool the turbine inlet, quickly reducing power and providing overspeed protection. The high-temperature overspeed trip valve shown in the figure is the major developmental valve in the system.

Topping-PFBC, Figure 1b, has the capability of raising the combustion turbine inlet temperature far above that of the fluid bed combustor temperature by first partially converting coal to produce a low-Btu fuel gas in a parallel fluidized bed reactor. Compressed air is supplied by the turbine compressor to both the fluid bed combustion unit and to the fuel gas generator. A booster compressor is placed in the compressed air line to the fuel gas generator. The plant coal and sulfur sorbent is fed to the fuel gas generator. The char/sorbent produced in this conversion stage is combusted in the parallel fluid bed combustor, and the vitiated air from the fluid bed combustor unit is used as the oxidant in the low-Btu fuel gas topping combustion. Cyclone separators provide precleaning of the fuel gas and the vitiated air streams before they enter the integrated gas turbine system. Both of the gas streams might also be precooled before entering the combustion turbine system, potentially reducing the severity of the environment for the integrated combustion turbine system components. Several
cycle variations are possible in Topping-PFBC, and the added complexity of the plant is offset by its greatly improved thermal efficiency.

In Topping-PFBC, the developmental and adapted components of the integrated combustion turbine system consist of the hot gas filtration systems for the fuel gas generator and for the fluid bed combustor unit, the topping combustor, the adapted gas turbine compressor and expander, the turbine control strategy applying high-temperature control valves, and connecting hot-gas piping. Alkali vapor removal may also be required with Topping-PFBC. Control and vent valves used in the Topping-PFBC plant are similar to those in the Base-PFBC plant, but the major developmental valve is now the high-temperature, fuel gas overspeed trip valve.

**Integrated Combustion Turbine System Conditions and Performance Requirements**

The gas conditions entering the integrated gas turbine system, representative of Base-PFBC and Topping-PFBC, are listed in Table 1. The hot gas cleaning conditions show a range for Base-PFBC that reflects current practice for bubbling and circulating fluid bed combustor systems, with the circulating fluid bed combustor units operating at a slightly higher temperature and with generally higher dust loadings. The hot gas cleaning temperatures for Topping-PFBC have an even larger range reflecting the possibility of cooling of the gas streams prior to cleaning. The volumetric gas flow rates shown in the table are relatively large, about 25% of an equivalent, conventional, coal-fired, power plant stack gas volumetric flow, and again a larger range exists for Topping-PFBC because of its flexibility in process configuration. In Topping-PFBC, the fuel gas volumetric flow is almost an order of magnitude lower than the vitiated air volumetric flow rate, and this is reflected in the size of the equipment components for the respective gas streams. The hot gas cleaning temperatures listed also represent the temperatures of the hot gas piping and hot gas control valves, as well as the inlet temperatures for the topping combustor in Topping-PFBC.

Turbine expander protection standards and environmental standards are also shown in Table 1, representing the performance requirements of the integrated combustion turbine system. In general, the turbine protection requirements are more stringent than the environmental requirements for particulate control. Alkali vapor content of the gas is also a concern, and alkali removal is expected to be required in these plants. The current NOx requirements for coal-based power plants are also listed. Carbon monoxide emissions are another consideration for the integrated combustion turbine system. Estimates of power plant thermal efficiency performance for Base-PFBC and Topping-PFBC plant alternatives are listed in the table, indicating the major incentive for the Topping-PFBC process. The Base-PFBC plant thermal efficiency is only slightly higher than the conventional coal-fired power plant thermal efficiency.

**ENGINEERING CONSIDERATIONS AND DEVELOPMENT ACTIVITIES FOR BASE-PFBC**

The integrated combustion turbine system for Base-PFBC applications must include hot gas cleaning components that can reliably meet the turbine protection and environmental standards for particulate content. Also, reliable high-temperature valves for flow control and for overspeed protection, reliable interconnecting hot gas piping, and appropriately adapted compressor and turbine expander to interface with the Base-PFBC plant conditions and requirements must be provided.

**Hot Gas Filtration Technology**

The Westinghouse hot gas filter technology has been developed around the following requirements for commercially viable application to Base-PFBC:

- **Operability** - meet particle control requirements for a range of plant feedstocks and operating conditions,
- **Performance** - meet turbine and environmental particle emission requirements with acceptable system pressure drop, heat losses, pulse cleaning gas rate and auxiliary power consumption,
- **Availability** - should be similar to other key plant components,
- **Maintainability** - provide with simple access to filter internals and with short turnaround for inspection and maintenance.

To meet these general requirements the Westinghouse ceramic barrier filter design applies the following principles:

- **Features simplicity of design,**
- **Uses uncooled metal structures,**
- **Applies modularity of filter internals,**
- **Shop fabrication and assembly of major components,**
- **Incorporates fail-safe features,**
- **Incorporates pulse-gas temperature regeneration to minimize thermal shocking of ceramic elements,**
- **Uses redundant critical components,**
- **Designed with capability to retrofit alternative filter element technologies.**

The Westinghouse filter design, utilizing currently commercial ceramic candle technology, is schematically shown in Figure 2. Figure 2a illustrates the hot gas filter system components. The filter system consists of a filter pressure vessel, pulse gas control system, and pulse gas compressor system. The filter pressure vessel houses the ceramic filter elements and their support structures. The pulse control system contains the pulse valves, accumulation tanks, piping and control logic that supplies appropriate pulses of cleaning gas to remove the filter cake from the ceramic filter elements. The pulse gas compressor system boosts the pulse gas from its supply pressure to the pressure required for pulsing.

Figure 2b shows the filter vessel conceptual layout. The filter vessel consists of a refractory-lined, coded pressure...
### Table 1. Integrated Combustion Turbine System Conditions and Performance Requirements

<table>
<thead>
<tr>
<th>GAS CLEANING CONDITIONS</th>
<th>Base-PFBC</th>
<th>Topping-PFBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature (°C)</td>
<td>843-885</td>
<td>700-930</td>
</tr>
<tr>
<td>Gas flow (m³/1000 kg coal):</td>
<td>3400-3500</td>
<td>3400-4100 (vitiated air) 570-680 (fuel gas stream)</td>
</tr>
<tr>
<td>Inlet dust loading (ppmw):</td>
<td>500-20,000</td>
<td>5,000-25,000</td>
</tr>
<tr>
<td>Inlet alkali vapor (ppbv):</td>
<td>20-200</td>
<td>10-500 (vitiated air) 20-2000 (fuel gas stream)</td>
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<table>
<thead>
<tr>
<th>TURBINE INLET CONDITIONS</th>
<th>Base-PFBC</th>
<th>Topping-PFBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C):</td>
<td>843-885</td>
<td>1260-1330</td>
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<tr>
<td>Pressure (bar):</td>
<td>12</td>
<td>12</td>
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<table>
<thead>
<tr>
<th>PERFORMANCE REQUIREMENTS</th>
<th>Base-PFBC</th>
<th>Topping-PFBC</th>
</tr>
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<tbody>
<tr>
<td>Turbine maximum particle loading (ppmw):</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Environmental particle emission (ppmw):</td>
<td>30</td>
<td>20-30</td>
</tr>
<tr>
<td>Turbine maximum alkali content (ppbv):</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Plant NOₓ emission (ppmv):</td>
<td>350d</td>
<td>200-300e</td>
</tr>
<tr>
<td>Plant CO emission (ppmv):</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PROJECTED PLANT PERFORMANCE</th>
<th>PLANT THERMAL EFFICIENCY (%)</th>
<th>HHV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base-PFBC</td>
<td>Topping-PFBC</td>
</tr>
<tr>
<td></td>
<td>37-40</td>
<td>45-47</td>
</tr>
</tbody>
</table>

- **a:** Estimate based on erosion and deposition damage
- **b:** Based on current New Source Performance Standards for coal-fired plants
- **c:** Target based on liquid fuel corrosion experience
- **d:** In Base-PFBC the NOₓ is controlled by the fluid bed combustor performance
- **e:** In Topping-PFBC, the fluid bed combustor and topping combustor NOₓ are additive
- **f:** Target based on general combustion turbine experience

A vessel that contains arrays of ceramic filter element assemblies such as candle arrays. The arrays are formed by attaching individual candle elements (Item 1) to a common plenum (Item 2) and discharge pipe. The arrays are cleaned from a single pulse nozzle source. For efficient packaging, several of the individual plenum assemblies are arranged vertically from a support structure, forming a filter cluster (Item 3).

The filter cluster represents the basic module needed for constructing a large filter system. The clusters used are commercially qualified clusters and a larger-scale power plant would use an increased number of these same clusters. The individual clusters are supported from a common, high-alloy tubesheet and expansion assembly (Item 4) that spans the pressure vessel and divides it into the "clean" and "dirty" gas sides. These are hot metal structures. The cluster approach provides a modular approach to scaleup and permits maintenance and replacement of individual filter elements. A feature of the Westinghouse design is that it can directly substitute equivalent clusters of alternative filter elements (advanced candles, cross-flow elements, ceramic bags, or others).

**Hot Gas Filtration Activities**

The Westinghouse hot gas filtration system for Base-PFBC, using ceramic candles, is currently being tested in two major demonstration programs:

- The American Electric Power (AEP), Tidd PFBC, Advanced Particle Filter (APF) Program
- The Ahlstrom Pyropower, Karhula filter test project

The AEP, Tidd PFBC plant is a 70 MWe, Clean Coal Technology plant, based on bubbling fluid bed combustion, and is located in Brilliant, Ohio. The Westinghouse filter handles one-seventh of the plant flow, having a nominal gas flow rate of about 215 m³/min (about 7,500 acfm), an operating pressure up to about 10 bar, and a temperature up to 843°C (1550°F). The filter vessel internals support 384 Schumacher DiaSchumalith F40 candle elements, made from silicon carbide (SiC), arrayed on nine plenums in a three cluster tiered arrangement. The nominal face velocity is 2.5-3.5 cm/s (5-7 ft/min). Its design, general arrangement, and method of operation have been described (Dennis et al., 1993).
FIG. 2. WESTINGHOUSE HOT GAS FILTER  
A) SYSTEM, B) FILTER VESSEL.

Operation of the APF was initiated in late October 1992 and is planned to continue well into 1994. More than 2000 hours of test exposure has been completed in long-duration tests on the APF with temperatures ranging from 649 to 843°C (1200 to 1550°F). Dust loading in the APF was relatively low, 500-1000 ppmw, and the flyash particle size was very small, 1 to 3 μm mass mean diameter. The results of the initial 500 hours of testing have been recently reviewed (Lippert et al., 1993). The major issues for the APF are:

- Maintaining drainage of captured flyash out of the vessel drain nozzle,
- Avoiding filter cake bridging within the candle array, especially at temperatures exceeding 760°C (1400°F),
- Long-term degradation of ceramic candle strength.

Filter element failures experienced in the APF testing have occurred through events related to the first two issues above -- partially loading the filter vessel with ash above the level of some of the candles, and heavy bridging during operation at high temperatures. Successful pulse cleaning of the large arrays of candles has been demonstrated in the testing, as well as the ability of the vessel to be effectively maintained and inspected in the utility environment. The uncooled, metal structures of the filter internals have performed without issue.

The high-temperature filter gaskets have performed very reliably in the testing. The SiC candle filter elements, based on surveillance candle testing, have shown a degradation in strength with increased exposure time, but appear to be leveling out to an acceptable steady-state, strength value.

The Ahlstrom Pyropower filter testing is on a 10 MWt circulating fluid bed combustor located in Karhula, Finland, and supports the Midwest Power, DMEC, Clean Coal Technology Program, as well as supporting the selection of other test activities to be conducted at the AEP, Tidd APF demonstration facility. Westinghouse provided a single cluster structure having a design similar to the clusters used in the APF filter unit, with the materials of construction modified for the higher temperature operation at this site. The cluster was placed in an existing pressure vessel, and specifications for baffles and pulse gas conditions were supplied by Westinghouse. The filter at Karhula handles a nominal gas flow rate of about 88 m³/min (3,100 acfm), an operating pressure up to 12 bar, and a temperature to 890°C (1650°F).

The cluster supports 128 candle elements made from an oxide-based ceramic (alumina/mullite) expected to have better long-term degradation properties than the SiC candles. The nominal face velocity of operation is about 3-4.5 cfm/s (6-9 ft/min). Operation of the Karhula filter was initiated in late October 1992 and is planned to continue into the first quarter of 1994. More than 1100 hours of hot test exposure have been completed on the filter with temperatures ranging up to 890°C (1650°F). Dust loading in the Karhula filter has been relatively high, 4,000-18,000 ppmw, and the flyash particle size has been relatively coarse, 12 to 22 μm mass mean diameter, resulting in a high-permeability filter cake that is easily removed by pulse cleaning. The results of the initial testing have been recently reviewed (Lippert et al., 1993).

The major issues for the Karhula ceramic candle filter testing differ from those of the APF primarily due to differences in the filter cake:

- Candle filter element damage from fluid bed combustor process upsets (mainly, temperature excursions),
- Long-term degradation of ceramic candle strength.

Successful filtration and pulse cleaning of the cluster of candles has been demonstrated in the testing, with a broad range of coal types and sorbent types tested. The hot metal structures of the filter internals have performed without issues, and the filter gaskets have performed reliably in the testing. Fail-safe and regenerator devices have been installed in the filter vessel for continued testing.

In addition to this demonstration testing, other Westinghouse in-house engineering and test programs are ongoing to advance the hot gas filtration technology:

- Filter element long-term degradation simulation,
- Characterization and testing of advanced filter elements,
- Testing of filter pulse cleaning design and operating features,
- Filter cold model and water model simulation of flow fields,
- Accelerated testing of individual components (valves, gaskets, fail safe devices, regenerators),
- Characterization of flyash and filter cake properties.
Compressor and Turbine Expander Adaptations

An evaluation of the design modifications required for a Westinghouse 251812 combustion turbine to be used in a Base-PFBC application was performed (Bannister et al., 1993). The Midwest Power, DMEC, PFBC demonstration was the basis of this evaluation. The introduction of the large volumetric flow of hot, corrosive, vitiated air into the turbine expander requires the following considerations:

- Compressor modifications for reduced air flow requirement,
- Inlet guide vane configuration,
- Thrust load capability,
- Blade cooling requirements,
- Casing inlet and outlet arrangement (stress analysis, flow/pressure drop analysis),
- Control system modifications, overspeed protection, and startup combustion system,
- Interconnecting hot gas piping layout design.

The production 251812 combustion turbine, as shown in Figure 3, has a center section in which air from the compressor is mixed with a fuel, such as natural gas, that is ignited in eight combustor baskets. The hot-gas is then ducted by transition liners into a uniform annular flow. The plant configuration for Midwest Power requires less compressed-air mass flow than the production 251812 can provide, so the compressor section was modified to reduce the flow. The center section of the combustion turbine was also modified. These modifications include adding an outlet to supply compressed air to the PFBC and an inlet to receive vitiated air from the PFBC. For higher flow requirements two inlets and two outlets would be necessary.

The 251812 combustion turbine is mounted on a bedplate for ease of handling and to prepackage much of the bleed air, control system, and auxiliary piping and wiring. For the reduced air flow requirements of the baseline application, a single inlet/outlet design with the piping on the lower right-hand side of the casing was developed to eliminate any need to modify the bedplate. An internal manifold was designed to route clean hot gas from the PFBC to the transitions and into the turbine. A computational fluid dynamic (CFD) analysis of the internal manifold was performed to ensure adequate distribution of the inlet hot gas.

The piping system and plant arrangement is shown in Figure 4. The arrangement satisfies baseline plant layout requirements and addresses the following design considerations:

- Isolating the turbine casing from pipe forces due to thermal expansion,
- Minimizing air volume in the startup combustor circuit,
- Minimizing cost consistent with reasonable pressure drop,
- Satisfying startup and shutdown airflow and turbine control requirements,
- Incorporating manufacturing requirements for insulated pipe.

![Figure 3. Typical 251812 Combustion Turbine](image)

**FIG. 3. TYPICAL 251812 COMBUSTION TURBINE**

![Figure 4. Plant Arrangement - Plan View](image)

**FIG. 4. PLANT ARRANGEMENT - PLAN VIEW**

Figure 5 details the compressed-air, startup combustor/bypass, and clean hot gas piping around the combustion turbine. In arranging the piping and components, the hot return pipe was considered first. The pressure-balanced expansion elbow was placed as close as possible to the casing flange and connected by a reducing section to mate the pipe insulation liner diameter with the casing liner diameter. The expansion joint provides an anchor point for the main run of hot pipe to isolate its motion from the casing.

On top of the expansion joint is a flanged tee that connects to the PFBC system outlet valve and the discharge of the startup...
combustor. Above the system outlet valve the PFBC outlet pipe expands to 152 cm (60 in.) in diameter. The turbine startup combustor line contains a throttle valve and an expansion joint. The combined lengths of the components in this crossover pipe determined the location of the compressor discharge pipe.

A reducer connects the 61 cm (24 in.) casing flange to the 76 cm (30 in.) compressor discharge pipe diameter. A 6.7m (22 ft) pipe section connects the reducer with a pressure-balanced expansion elbow. The outlet of the elbow connects to an 2.4m (8 ft) long vertical pipe section flanged to a tee leading to the startup combustor. Straight through the tee is the PFBC system inlet valve, which may be bypassed by the PFBC system purge valve.

The clean, hot gas piping is the most complex part of the combustion turbine/PFBC interface. The high-temperature gas supplied by the PFBC has passed through a ceramic candle filter that removes particulates harmful to the combustion turbine. The combination of high temperature, moderate pressures, and potential corrosiveness of the gases (if cooled) necessitates that the piping be specially designed.

Figure 6 shows the hot gas pipe design selected for the 122 cm (48 in.) and 152 cm (60 in.) hot gas pipes. The piping system includes a stainless steel liner (310), castable refractory thermal insulation, and a carbon steel pipe as the outside pressure boundary. The thermal insulation selected was Harbison-Walker Lightweight Castable 20. This insulation is designed to be cast in place and anchored at the pipe. The inner surface of the insulation is separated from the hot gas by a 1.6 mm (1/16 in.)-thick stainless steel liner to protect the insulation from erosion.

The final piping design must meet several additional mechanical design requirements because of the cast-in-place refractory insulation. These include:

- Maximum pipe section lengths for cast insulation.
- Insulated pipe that can be welded together with proper joint design.
- Flanged joints every 6 to 9m (20 to 30 ft) to provide access for inspection and repair.
- No insulation of the pipe liner except at one support location to permit axial thermal expansion. Slip joints must also be provided between liner sections.
- Gap between the liner and the insulation to permit radial thermal expansion. Flexible standoffs support the liner from the insulation.

ENGINEERING CONSIDERATIONS AND DEVELOPMENT ACTIVITIES FOR TOPPING-PFBC

The integrated combustion turbine system for Topping-PFBC applications differs considerably from the Base-PFBC integrated combustion turbine system, although many of the same design considerations are applied. It must include hot gas cleaning systems that can meet the turbine standards for inlet particulate content and alkali content, valves for flow control and for overspeed control, topping combustor for efficient and reliable combustion of the hot fuel gas using the hot, vitiated air stream from the fluid bed combustor, with sufficient environmental control (NOx and CO), and adaptation of the compressor and turbine expander to interface with the Topping-PFBC power plant conditions.

Westinghouse is supplying integrated gas turbine systems for two Topping-PFBC plants: the Southern Company Services (SCS), Power Systems Development Facility, located at Wilsonville, Alabama (Sears et al., 1993), and the Air Products, Clean Coal V, Four Rivers Energy Modernization Project (FREMP), located in Calvert City, Kentucky (Dellefield, 1993). The major developmental components being supplied to these plants are the hot gas filtration systems, the alkali removal equipment, and the topping combustors.
**Hot Gas Filtration**

Westinghouse is applying similar hot gas filtration equipment designs to Topping-PFBC combustion and fuel gas streams. The Topping-PFBC combustion gas filter design is identical to the Base-PFBC filter design. The fuel gas generator hot gas filter design utilizes similar candle cluster features, or alternative filter elements such as cross-flow filters, but the reducing gas environment and the nature of the flyash char/sorbent differs significantly from those of the combustion gas filter.

Westinghouse has been working with the Foster Wheeler Corporation on Topping-PFBC development under DOE funding since 1987, and filter testing has been conducted at the Foster Wheeler Development Corporation (FWDC), Livingston, New Jersey, pilot facility on both the fuel gas generator, a carbonizer, and the circulating fluid bed combustor. The Phase 2 test activities, with independent testing of each of these fluid bed reactors, is nearing completion, and the Phase 3 program, with integrated plant operation, is in the design phase. The Phase 2 testing has been previously reviewed (Newby et al., 1993; Lippert et al., 1994). The performance of the carbonizer filter testing was very good, with the carbonizer filter cake having relatively high permeability, being easily pulse cleaned, and having no bridging or bulk flow issues. The circulating fluid bed combustor testing at FWDC raises issues related to both the bridging of the candle filter array, difficulty in bulk ash drainage from the filter vessel, and the formation of hard filter cake deposits on the filter elements. These difficulties are strongly related to test operation at very high temperatures exceeding 871°C (1600°F).

Table 2 compares the design capacities of the hot gas filters in the FWDC, Livingston test facility, the SCS, Wilsonville facility, and the Air Products, Calvert City site. Both the FWDC facility and SCS facility will provide performance data to support the Air Products Four Rivers Project design. The scales of the facilities relate directly to their volumetric flow rates, with a scaling factor of about 10 from the FWDC facility to the SCS Wilsonville facility, and a scaling factor of about 5 from the SCS facility to the Air Products Project.

**Alkaline Removal**

Westinghouse has been developing two, alternative approaches to alkaline removal from both hot combustion gases and fuel gases:

- Packed bed sorption
- Sorbent injection into the hot gas filter vessel.

The packed bed approach places a pressure vessel loaded with pelletized alkaline sorbent, such as emathlite, kaolinite, and bauxite, after the hot gas filter vessel. The pelletized sorbent removes alkaline vapors continuously for 6 to 12 months of operation, and is recharged with fresh sorbent pellets during a planned plant maintenance period. The kinetics of the pellet alkaline reactions have been measured in laboratory equipment and a long-term demonstration was performed in a bench-scale rig (Bachowchin et al., 1986).

In the entrained alkaline sorbent approach, a pulverized alkaline sorbent is injected along with the dirty process gas into the hot gas piping upstream of the hot gas filter vessel. The small alkaline sorbent particles remove alkaline vapors while they reside in the gas phase and during their longer residence time within the filter cake. Reaction kinetics have been measured in laboratory rigs, and larger scale testing has been initiated in a nominal 2.8 m³/min filter test facility (Newby et al., 1992).

Conceptual commercial designs have been developed, and plans are to provide alkaline removal equipment for the FWDC Phase 3 test facility, for the SCS, Wilsonville test facility and for the Air Products, Calvert City Plant. Combustion gas and fuel gas cooling can permit the use of conventional valves. In addition, on the Calvert City Topping - PFBC plant with cooling to 703-760°C (1300-1400°F), alkaline removal may not be required due to condensing out alkaline vapors to an acceptable level.

**Topping Combustor**

The major consideration in the design of the topping combustor is to provide a reliable combustor that will achieve acceptable NOₓ emissions when burning hot, low-Btu fuel gas with hot, vitiated air. The Multi-Annular Swirl Burner (MASB) has been selected for this application (Beer, 1989), and has been under development by Westinghouse for several years. The MASB is constructed from high-alloy metals, avoiding refractory construction so that refractory spalling or other failures will not result in turbine damage. The high-alloy metals, in close proximity to the staged combustion zones within the MASB, are cooled to acceptable temperatures by boundary layer cooling resulting from constraining the combustor with concentric annular passages carrying the vitiated air.

Westinghouse combustion turbines have internal, fuel combustors that are not suitable for combustion of the hot, low-Btu fuel gas produced in Topping-PFBC. The turbine pressure casing has been modified to accommodate the topping combustors. A commercial configuration of this modification is

**TABLE 2. TOPPING-PFBC HOT GAS FILTER FACILITY SCALES**

<table>
<thead>
<tr>
<th></th>
<th>FWDC Livingston, N J</th>
<th>SCS Wilsonville, AL</th>
<th>Air Products Calvert City, KY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonizer flow (m³/min):</td>
<td>3.4</td>
<td>48.1</td>
<td>226.5</td>
</tr>
<tr>
<td>Combinator flow (m³/min):</td>
<td>11.3 (Phase 2)</td>
<td>175.6</td>
<td>1387.5</td>
</tr>
<tr>
<td></td>
<td>21.2 (Phase 3)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
shown in Figure 7. Considerations of the integrity and rigidity of the main shell must be made, along with rotor dynamics and shipping of the assembled unit.

An MASB test rig, illustrated in Figure 8, has been used at the University of Tennessee Space Institute (UTSI), Tullahoma, Tennessee in the DOE Coal, Oil, or Gas-Fired Flow Facility (CFFF). The MASB has been tested using simulated fuel gases, with injected ammonia to represent fuel-bound nitrogen, at scales of 30.5 cm (12.7 in.) and 35.6 cm (14 in.) diameter, relative to the commercial, full-scale 45.7 cm (18 in.) diameter which is scheduled for testing in mid 1994. These tests have been previously described (Domeracki et al., 1994). In general, the testing has demonstrated:

- Acceptable outlet temperature uniformity,
- Acceptable metal surface cooling,
- Very low CO emissions (< 5 ppmv) with no soot or unburned hydrocarbons detected, and
- Conversion of less than 20% of the fuel gas ammonia to NOX, for NOX emissions of about 30 ppmv (corrected to 15% oxygen).

Further design improvements being evaluated are expected to provide even lower NOX emissions. Numerical, computational analyses and cold flow modeling are underway to provide design improvements. Remaining tasks include conducting full-scale testing with acceptable temperature patterns, metal surface temperature distribution, and NOX emission performance. Turndown operation with acceptable, staged temperature distribution control, and effective combustion of clean, high-Btu fuels for startup and for alternative plant operation capabilities must also be demonstrated. First operation of the MASB topping combustor using actual Topping-PFBC fuel gas and vitiated air is planned for the SCS, Wilsonville test program, in 1995.

CONCLUSIONS

The general conclusions drawn from the Westinghouse integrated combustion turbine system development activities are:

- The current PFBC technology, using cyclone-based hot gas cleaning of the combustion products, will be transformed into an economical and highly, thermally efficient, combined cycle technology by developments in hot gas filtration and coal-gas topping cycles.
- Westinghouse is developing integrated combustion turbine systems for the future FFBC power plant that interface with PFBC and incorporate the multiple functions of hot gas filtration,
alkali vapor removal, topping combustion, hot gas piping and control, and turbine compression and expansion.

U.S. Department of Energy, development programs are in place that will bring the integrated combustion turbine system to commercial realization:

- Westinghouse in-house testing,
- Foster Wheeler Development Corporation's Livingston, New Jersey, PFBC pilot plant,
- Southern Company Services, Wilsonville, Alabama, PFBC development plant,
- American Electric Power, Tidd, bubbling-PFBC, Advanced Particle Filter Demonstration Program,
- Pyropower/Ahlstrom, Karhula, Finland, circulating-PFBC filter test),

and demonstration programs:

- Midwest Power, DMEC, Clean Coal Technology III Program,
- Air Products, Calvert City, Clean Coal Technology V Program,

REFERENCES


Hafer, D. R., et al., 1993, "Test Results for the 70 MWe Tidd PFBC Demonstration Plant," Proceedings of the 1993 Int. Conf. on Fluidized Bed Combustion, ASME.


