Preliminary results of an economic and engineering evaluation of two coal-based combined cycle power plant technologies

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Introduction

The capital cost of a coal-based power plant contributes over 50% to the busbar cost of electricity. For new coal-based power plants to be competitive, it is imperative that the capital cost be reduced. One of the most cost-competitive, coal-based power plant technologies is believed to be an air-blown, combined cycle incorporating a partial gasifier and pressurized char combustor. These two coal-conversion stages provide a fuel gas and a flue gas used to fire a combustion turbine. To protect the turbine from particle erosion damage, all the dust must be removed from the two hot gas streams. This operation involves high temperature, high pressure (HTHP) filtration, a technology currently under development at several locations funded by the Department of Energy. One of these locations is the Power Systems Development Facility at Wilsonville, Alabama. At this same site two potential air-blown, combined cycle power plant technologies are under development. These are; The M. W. Kellogg Company's (Kellogg) integrated gasification combined cycle (IGCC), incorporating their transport reactor design as both the gasifier and the combustor; and Foster Wheeler's (FW) topped pressurized fluidized bed combustor (PFBC), incorporating a bubbling-bed carbonizer and a circulating PFBC.

It was decided to complete an engineering and economic evaluation of the technologies under development at the PSDF. The results were expected to quantify the economic advantages offered compared to other coal-based options, and to focus the supporting Research and Development activities on those areas offering the greatest economic advantage.

Southern Company, which manages the PSDF program, is the prime contractor for the studies. Foster Wheeler is subcontracted to determine the plant cost and performance data for the two technologies in several different operating configurations. They receive support from M. W. Kellogg and Westinghouse, the supplier of the HTHP filters and the gas turbine used in the study. From the plant cost and performance data Southern Company will determine the cost of electricity generated utilizing economic data and assumptions (e.g. fuel costs and labor rates) specific to their electric system.

Cases

Nine cases have been identified, four greenfield and five repowering:-

Greenfield cases
1. Kellogg air-blown IGCC
2. As Case 1 but replacing feed lock hoppers with a Stamet dry feed pump
3. FW topped PFBC
4. FW circulating PFBC

Repowering cases
5. FW topped PFBC
6. FW circulating PFBC
7. FW natural gas topped PFBC
8. Kellogg air-blown IGCC
9. FW topped PFBC with reduced filter inlet temperatures

This paper reports the total plant costs for Cases 1 and 3.

Design criteria

General design criteria for the nine cases include:-

1. The greenfield site is on the Gulf coast with the following temperatures,

Average annual dry bulb	67°F
Peak (1%) dry bulb	93°F
Average annual wet bulb	62°F
Peak (1%) wet bulb	82°F

2. An advanced turbine system is used in the Greenfield cases
3. The condenser for the Greenfield cases operates at 2.4 inches of mercury
4. The repowering sites are within the Southern system
5. The temperatures, turbines, and condenser pressure used in the repowering cases all will be determined by the conditions at sites selected
6. Alabama dolomite (54% $CaCO_3$, 43% $MgCO_3$) is the sorbent used, being readily availability in the area and offering certain process advantages
7. The coal is a medium sulfur, Illinois Basin, bituminous coal

Moisture	6.7 %	Sulfur	2.8 %
Carbon	70.5 %	Ash	9.4 %
Hydrogen	4.7 %	Oxygen	4.4 %
Nitrogen	1.5 %		

Higher heating value, MBtu/lb. 12,700

8. All designs are for 95% sulfur retention
9. The HTHP filters used are Westinghouse's candle design

10. Equipment is sized to achieve 80% equivalent availability
11. All equipment is designed for a 30-year plant life
12. Plant designs are based on a mature technology ready for startup in 2010
13. Design emphasis is on minimizing plant costs, not maximizing efficiency

Evaluation approach

All three sub-contractors have access to design and cost data from the Piñon Pine 100-MWe IGCC Clean Coal Demonstration Project, which is now built and undergoing shakedown. In addition Foster Wheeler and Westinghouse have been involved in preparing design proposals for the Lakeland 180-MWe topped PFBC Clean Coal Demonstration Project. Consequently, there is a substantial amount of recently prepared equipment cost data available. These Base Cost Data have been scaled up, using industrially recognized procedures, to the equipment sizes required for the PSDF study.

In recent years, to meet the challenge of deregulation and its emphasis on reduced costs, the approach to building new power plants has changed. The new measures affect equipment selection, construction methods, engineering design, degree of sparing, and operating practices. Examples of some of these measures include:

Utility-based design	Market-based design
Design minimizes life cycle costs	Design minimizes initial capital cost
Conservative design margins	Reduced design margins
Good load following capability	Part load operation not a design priority
90 days of coal storage	30 days of coal storage
3 x 50% condensate pumps	2 x 50% condensate pumps
Equipment sized for 1 shift operation	Equipment sized for 2 shift operation

These, and similar measures, were incorporated into the economic evaluation.

Process descriptions

One of the approaches identified to lower cost is to incorporate an advanced gas turbine into the design. The design selected is a Westinghouse Advanced Turbine System (ATS), currently under development. The rotor inlet temperature (RIT) of these machines is planned to be 2750°F compared to an RIT of 2350°F for the F-frame machines in current use. The ATS is expected to generate around 300 MWe and operate with a pressure ratio of 28:1. Smaller ATS designs may also be developed. To maintain the pressure differential between the compressor discharge and the turbine inlet at an acceptable value, a booster compressor is required in the compressor discharge line. A temperature control unit installed in the compressor air inlet duct helps to maintain the delivered air mass flow rate during periods of high temperature, so preserving the power output of the plant.

The ATS is fired with coal-derived fuel gas burned using air from the compressor supplemented with vitiated air from a char combustor. These are delivered at elevated temperatures which prevents the use of normal combustion canisters provided internal to the turbine. The burner selected is a multi-annular swirl burner (MASB), and multiple MASBs are located in silos external to the ATS. The fuel gas contains ammonia compounds that when burned could produce large amounts of NO_x. The MASB limits such emissions by means of rich-quench-lean combustion. The initial stage of combustion is sub-stoichiometric and raises the temperature to above 2600°F to reduce the ammonia to nitrogen and hydrogen. The swirl promotes good mixing. The remaining vitiated air is introduced through annular openings and serves to cool the MASB shell as well as to complete combustion and raise the RIT to 2750°F. An industrial-scale MASB, equivalent to 4 MWe, is to be tested at the PSDF.

As the Kellogg IGCC design is air blown, only around 95% of the coal is gasified, the remaining char being burned in a pressurized combustor. Because of the low amount of high-grade heat produced, the Kellogg IGCC design only supports a low-pressure steam cycle. In the Foster Wheeler design, around 60% of the coal is gasified. Consequently, to provide the amount of fuel gas required to meet the required RIT, the coal feed rate is higher than for the Kellogg unit. The residual char is burned in a circulating PFBC and there is sufficient high-grade heat available to support a higher pressure, more efficient steam cycle. Moreover, as more steam is raised the steam turbine output is also higher than that of the Kellogg IGCC. Consequently, in satisfying the demands of the ATS the overall power output of the Foster Wheeler unit is greater.

The designs of the IGCC and PFBC plants used in this study are described briefly and relevant process data are presented below. Alternative design configurations are possible with different performance and economic results.

Operating parameters for the two designs investigated

	MWK IGCC	FW topped PFBC
Steam conditions, psia/°F/°F	1815/1000/1000	2415/1000/1000
HTHP filter temperatures, °F		
Gasifier/Carbonizer	750	1400
Combustor	750	1600
Feed top size, microns	500	3200
Ca/S molar ratio (*)	1.49	1.73
Percent of coal gasified	96	62

(*) for 95% retention

Air-blown IGCC utilizing Kellogg's transport reactor (See Figure 1)

Coal and sorbent are both dried and crushed to a top size of 500 microns and fed to the single-train gasifier, operating at 450 psia and 1670°F, through lock hoppers and pneumatic conveying systems. The gasifier consists of two sections; a lower, relatively short, large diameter section where the coal and sorbent feed are mixed with recycled char; and an upper, taller, small diameter section where most of the gasification occurs. The gaseous reactants, air and steam, are introduced at the bottom of the mixing zone. In addition to devolatilization, carbon-oxygen, and carbon-steam reactions, most of the sulfur released from the coal is captured by the sorbent as calcium sulfide, CaS. As the Kellogg system uses finer sorbent than the Foster Wheeler system, less sorbent is required for the same sulfur capture.

All the feed stock is carried from the mixing zone into the riser and out of the reactor. The majority of the unreacted char and sorbent-derived material leaving the riser is captured by a cyclone assembly and recycled back to the mixing zone through a J-valve. This increases the effective solids residence time, increasing the carbon conversion and improving sorbent utilization. The fuel gas and residual char leaving the cyclone are cooled to 750°F in a fire-tube exchanger raising high-pressure steam. HTHP filters are used to remove the residual char from the fuel gas which then passes on to the MASB. A small portion of the flow is removed, cooled and pressurized, and used as blowback gas to remove the char cake from the filter elements

For this study, Kellogg elected to cool the fuel gas to 750°F to allow the use of metal filter elements. It is believed that this will improve filter reliability and, as it reduces the volumetric flow, will reduce the number of elements and the number of filter vessels required. Further, as the temperature is well below the 1440°F necessary to condense out any alkali vapor, alkali will be removed on the char filter cakes. This eliminates the need for some means of adsorbing the alkali from the fuel gas. Condensation of alkali in the turbine would promote corrosion and fouling, adversely affecting the life of rotor and stator components. The extent of the cost savings achieved by cooling the fuel gas, and the extent to which it is offset by the cost of the cooler and the increased heat rate, will be established later in the study.

The char collected by the HTHP filter and excess char from the recycle loop are cooled in screw coolers, the heat being transferring to the boiler feed water. The cooled char is then pneumatically conveyed into the pressurized combustor operating at 450 psia and 1650°F. This too is a transport reactor with a mixing zone and riser section, followed by a cyclone and HTHP filter. Unlike the gasifier, a heat exchanger is incorporated into the recycle loop to remove the heat released and raise steam. Also, the combustion air entry is staged to control NO_x emissions.

The combustor is required not only to burn the char but also to oxidize the CaS, formed in the gasifier, to $CaSO_4$. Calcium sulfide is regarded as a hazardous material as, under acidic conditions, it can release H_2S. In the combustor almost all the sulfide is converted to the non-hazardous sulfate.

Kellogg also elected to cool the flue gas ahead of the HTHP filter to 750°F for similar reasons, and with similar benefits, to those cited for the gasifier train. Again the cost effectiveness of this decision will be determined later in the study. The ash collected by the cyclone and the filter is cooled in screw coolers, depressurized through lock hoppers, and finally disposed of in a landfill. After filtration, the flue gas passes on to the MASB. A small portion of the flow is removed, cooled and pressurized, and used as blow-back gas to remove the ash filter cake from the elements and to convey the coal and sorbent into the gasifier.

The dust-free flue gas is used as the oxidant to burn the dust-free fuel gas in the externally mounted MASBs. For this design configuration the ATS generates 298 MWe and exhausts at 1200°F into the heat recovery steam generator (HRSG) which discharges flue gas to the stack at 265°F. The heat transferred raises additional steam, and provides all the superheat, reheat, and economizer duty. The steam turbine generates 176 MWe but due to the low amount of high-grade heat available, the steam conditions are relatively modest at 1815 psia/1000°F/1000°F.

Topped PFBC utilizing Foster Wheeler technology (See Figure 2)

Coal and sorbent are both dried and crushed to a top size of 1/8-inch and fed to the single-train carbonizer, operating at 480 psia and 1780°F, through lock hoppers and pneumatic conveying systems. The carbonizer is a jetted, bubbling fluidized-bed design. The coal, sorbent, air and steam are fed at the bottom creating the jet and promoting rapid mixing of the feed stock with the bed material. The vessel consists of two sections; a lower, tall, small diameter section containing the bubbling bed and where most of the carbonization occurs; and an upper, shorter, larger diameter section where the gas velocity is reduced and most elutriated solids disengage and settle back to the bed. The reactions occurring are similar to those occurring in the Kellogg gasifier except that, despite the higher operating temperature, the extent of the carbon conversion is lower. This lower conversion arises because there is no recycle loop and the solids residence time is correspondingly lower. It should be noted that the design basis for the Foster Wheeler topped PFBC system does not call for as high a carbon conversion as does that for the Kellogg IGCC system.

The unreacted char is transferred from the carbonizer to the circulating PFBC. A portion of the char leaves the carbonizer with the fuel gas, the majority of which is captured by a cyclone assembly and discharged to a char transfer hopper (CTH). Excess char from the carbonizer flows into the CTH over a weir that maintains the bed height constant. Char collected by the HTHP filters also passes to the CTH. As the CTH operates at the same pressure as the HTHP filter, the flow streams from the carbonizer and cyclone require J-valves to form a pressure seal. None of these three solids flow streams contains a cooler.

The fuel gas and residual char leaving the cyclone are cooled to 1400°F by injecting water into the flow stream. High temperature, high pressure (HTHP) ceramic filters are used to remove the residual char from the fuel gas which then passes on to the MASB. A small portion of the flow is removed, cooled and pressurized, and used as blowback gas to remove the char filter cake from the elements. Foster Wheeler elected to cool the fuel gas to 1400°F to improve the reliability of the ceramic filters. This temperature is believed to be sufficiently below 1440°F to condense any alkali vapor so that it can be removed on the char filter cake.

The char is transferred from the CTH into the circulating PFBC through an N-valve pressure seal. A small amount of coal is also fed to the combustor to utilize excessive oxygen, maximizing heat release and steam turbine power output. As the coal bypasses the Brayton cycle, the heat rate is increased. The cost effectiveness of this approach will be assessed later in the study. The combustor operates at 430 psia and 1580°F and contains all the heat transfer surface raising steam and providing final superheat and reheat duty. As for the Kellogg combustor, air entry is staged to control NO_x emissions. It is expected that almost all the sulfide contained within the char will be oxidized to the sulfate. The flue gas leaving the combustor is not cooled so the HTHP ceramic filters operate at 1580°F. Foster Wheeler believes that the alkali content in this gas stream is insufficient to cause any problems in the ATS.

The ash withdrawn from the combustor and the HTHP filters is cooled and depressurized in a proprietary device that is a lower cost option than the lock hoppers used in the Kellogg design. The ash is disposed of in a landfill. After filtration, all the flue gas, unlike in the Kellogg IGCC process, passes on to the MASB.

The dust-free flue gas is used as the oxidant to burn the dust-free fuel gas in the externally mounted MASBs. For this design configuration, the ATS generates 313 MWe, 15 MWe more than for the Kellogg IGCC unit. This increase is due to the increased gas flow rate to the ATS arising from the evaporative cooling of the fuel gas. The expanded gases exhaust at 1200°F into the heat recovery unit (HRU) which discharges flue gas to the stack at 265°F. The heat transferred provides the primary superheat and economizer duty. The steam turbine generates 396 MWe, more than double that of the Kellogg IGCC unit, because of the larger amount of high-grade heat available. The steam conditions are also higher at 2415 psia/1000°F/1000°F.

Preliminary results

The total plant cost (TPC) for the two coal-based technologies were estimated to be below $900/kW, well below the price projections of a few years ago. The main cost and performance data are presented in the following Table.

	MWK IGCC	FW topped PFBC
Gas turbine, MWe	298.3	313.4
Steam turbine, MWe	176.4	396.2
Auxiliary power, MWe	14.5	21.9
Net power, MWe	460.2	687.7
Net heat rate, Btu/kWh (HHV)	7000	7240
Total plant cost, $/kW (1)	883	828

(1) Includes all materials, field labor, indirect and engineering costs, and contingencies. Does not include owner's costs, initial chemicals, or an allowance for funds used during construction.

TPC is lower for the FW unit by approximately $50/kW, but assessment shows that this difference is attributable primarily to the economy-of-scale effect. It is expected that for the same sized units the TPC for the two technologies would be virtually the same.

It is expected that the TPCs presented above can be reduced further. Once these potential cost reductions are incorporated, costs of electricity will be calculated and compared with other coal-based technologies. To achieve valid comparisons, part of the study will be to ensure that all the technologies are on similar engineering and economic bases.

Work proposed to improve cost parameters

To improve the cost competitiveness of the two technologies, the design basis selected has been scrutinized to see how TPC and operating costs can be reduced further. Two means of reducing costs have been identified that will be fully evaluated later in the study. One is a change of sorbent from dolomite to limestone, and the other involves changes to certain aspects of plant design.

Alternative sorbent usage

Although dolomite was selected for the design study, limestone is now realized to offer certain economic advantages. As limestone contains more calcium than dolomite, a lower mass flow rate is required for the same Ca/S molar ratio. This lowers the cost for sorbent feed. Further, limestone is more widely available than dolomite. As there is less material fed so there is less material for disposal. This lowers the equipment costs to handle and prepare the feed and to remove and dispose of the ash. Also as the ash contains less magnesium compounds it is a more valuable byproduct suitable for a variety of high-volume applications including structural fill, fired blocks, road base construction, and synthetic aggregate. This combination of benefits is expected to reduce the COE from both the Kellogg IGCC and the Foster Wheeler topped PFBC by approximately 1 mill/kWh.

Nevertheless, dolomite was selected in preference to limestone for two reasons, one concerned with HTHP filter operation and the other with the conversion of CaS to $CaSO_4$. These two issues are discussed further.

HTHP filtration. It is believed that filter cakes formed from dolomite ash are more easily removed than those formed from limestone ash. However, there is evidence that this problem can be overcome by presenting coarser material to the filter and by operating at 1400°F or below. A sensitivity study was carried out to determine how the economics of the Foster Wheeler topped PFBC plant were affected by lowering the filter inlet temperature from 1580°F to 1400°F. Similarly to the fuel gas flow stream, the flue gas was cooled by water injection.

Filter inlet temperature	1580°F	1400°F
Net power, MWe	687.7	678.5
Net heat rate, Btu/kWh (HHV)	7240	7330
Total plant cost, $/kW	828	827

Lowering the temperature lowers the net power output but does not have any significant effect upon either the heat rate or the TPC. The lower temperature may extend the life of ceramic filter candles thus lowering fixed O&M charges. Further, at the lower temperature any alkali present will condense offering additional protection to the ATS. Consequently, adjusting process conditions to allow for the use of limestone does not appear to have any adverse cost or performance effects.

CaS conversion. Tests carried out by Kellogg indicated that the degree of CaS conversion achieved was greater for dolomite than for limestone. Although lower, the degree of conversion achieved may be adequate to qualify the ash produced as a non-hazardous material. CaS is a concern and warrants further investigation to allow the use of limestone and the economic benefit it offers.

Plant design changes

Possible changes include:-

- Replacing the coal and limestone feed lock hoppers by a dry feed pump currently under development. This is expected to lower both TPC and O&M costs.

- The HTHP filters used in the study are candle filter designs by Westinghouse. A more compact design, like the cross flow or Ceramen filters, may lower TPC.

- The FW topped PFBC design can be simplified and TPC reduced by eliminating the carbonizer cyclone and passing all the elutriated char to the HTHP filter. The coarser particles may ease cake removal.

- The Kellogg IGCC design could replace the ash lock hopper pressure let down system with the proprietary device used in the Foster Wheeler design. This may lower TPC and O&M costs.

- Establishing whether or not an evaporative cooler is a more economical option than a fire-tube design

- Investigating cost-cutting measures currently employed by independent power producers to lower the capital cost of pulverized coal plants. One measure not investigated is the partnership arrangement with equipment vendors.

- Extracting more energy from the steam cycle by going to higher steam conditions and/or lower condenser pressures. This is of most benefit to cycles with good high-grade heat availability

- Investigating whether or not there is an optimum ratio of gasification to combustion. For example, would the Kellogg IGCC process benefit from less gasification to make available more char for combustion and the release of more high grade heat? Conversely, would the Foster Wheeler topped PFBC process benefit from more gasification to place more energy in the Brayton cycle?

- Investigating the economic benefits of operating the Kellogg HTHP filters at temperatures above the 750°F initially selected. Also, investigating the cost effectiveness of using compressed air rather than recycled flue gas as the blow back gas to the combustor filter, and for conveying the feedstock into the gasifier.

- Investigating the effects of alternative coals such as sub-bituminous coal, which has a lower sulfur content and possibly a lower delivered cost.

Development issues

The capital costs presented from the study are projections assuming that certain technological items are developed. These include:-

Advanced turbine system. The Department of Energy, in conjunction with industrial partners, is funding the development of high-efficiency gas turbines. Machines with RITs approaching 2600°F will become available by the year 2000 with machines with yet higher RITs becoming available by 2010.

MASB. A test burner has operate at discharge temperatures of 2350°F with low NO_x emissions while burning simulated fuel gases. An industrial-scale burner will be tested at the PSDF burning coal-derived fuel gas using coal-derived vitiated air as the oxidant. Later in the program the operating temperature will be raised towards 2750°F.

HTHP filters. These still have to demonstrate the commercially acceptable operating life of around 3 years. The prospects for achieving such life times is good based on previous test results and the conclusion of the present study that allows for lower operating temperatures than previously thought possible. Filter development is the primary purpose of the PSDF.

Integrated plant operation. Sustained and controlled operation of an advanced power plant system transferring char from a carbonizer to a combustor, with HTHP filters in the fuel and fuel gas streams, and burning the fuel gas to drive a gas turbine/compressor still has to be demonstrated. The PSDF includes such a system with a 4 MW gas turbine and will determine the operability of such an advanced power system.

Conclusion

A study to investigate the economics of two air-blown, coal-based combined cycle power plant technologies is in progress. Nine design cases have been specified for investigation and preliminary results from the first two cases are available. The results show that both technologies have a total plant cost of below $900/kW, confirming their low-cost potential. Additional work is required to determine if it is possible to cut costs further. Once the total capital costs are finalized and the cost of electricity calculated for the two technologies, the results will be compared with other power generating options using criteria from the Southern Company electric system. The study will be completed in 1998, although results will become available progressively.

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Figure 1. Kellogg Air-Blown IGCC

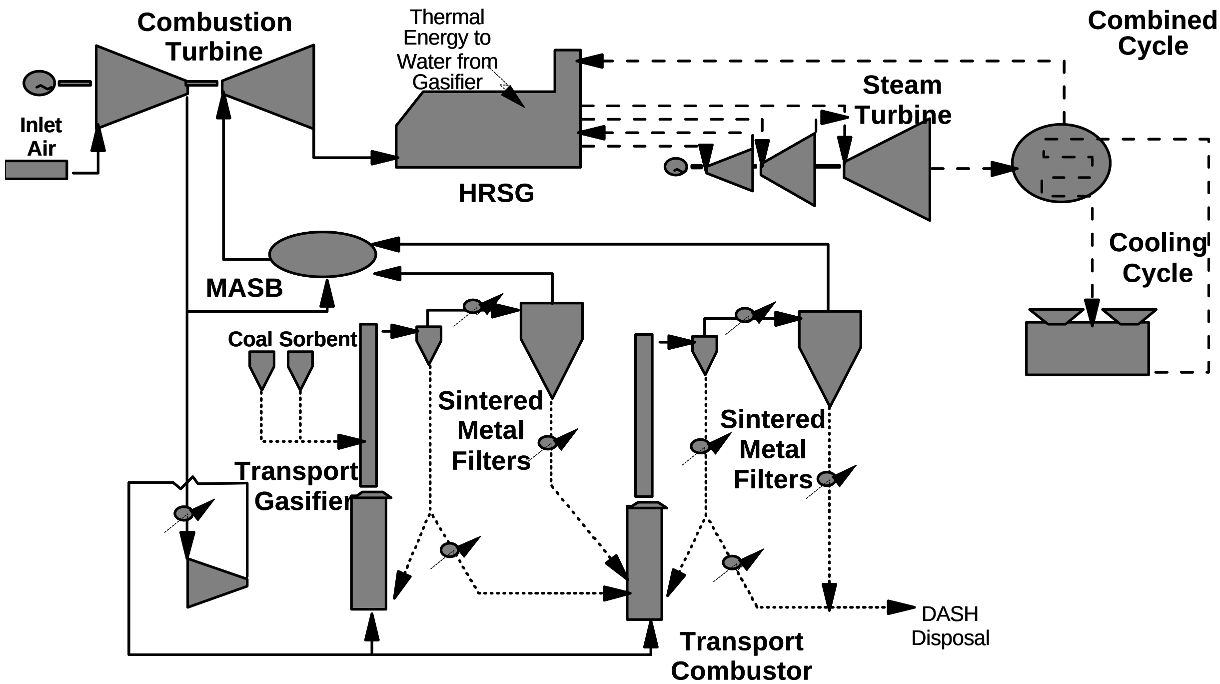

Figure 2. Foster Wheeler Topped PFBC