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Authors:

Richard A. Dennis (METC)
Heather M. McDaniel (METC)
Thomas Buchanan (Gilbert/Commonwealth)
Herbert Chen (Gilbert/Commonwealth)
Lora Beth Harbaugh (Gilbert/Commonwealth)
Michael Klett (Gilbert/Commonwealth)
Roman Zaharchuk (Gilbert/Commonwealth)

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Richard A. Dennis
Heather M. McDaniel

Power Systems Technology Division
Morgantown Energy Technology Center
United States Department of Energy
Morgantown, WV

Thomas Buchanan
Herbert Chen
Lora Beth Harbaugh
Michael Klett
Roman Zaharchuk

Gilbert/Commonwealth
Engineers and Consultants
Reading, Pennsylvania

ABSTRACT

A cost comparison was conducted between the filter systems for two advanced coal-based power plants. The results from this study are presented. The filter system is based on a Westinghouse advanced particulate filter concept, which is designed to operate with ceramic candle filters. The Foster Wheeler second-generation 453 MWe (net) pressurized fluidized-bed combustor (PFBC) and the KRW 458 MWe (net) integrated gasification combined cycle (IGCC) power plants are used for the comparison. The comparison presents the general differences of the two power plants and the process-related filtration conditions for PFBC and IGCC systems. The results present the conceptual designs for the PFBC and IGCC filter systems as well as a cost summary comparison. The cost summary comparison includes the total plant cost, the fixed operating and maintenance cost, the variable operating and maintenance cost, and the effect on the cost of electricity (COE) for the two filter systems.

INTRODUCTION

Integrated gasification combined cycle (IGCC) and pressurized fluidized-bed combustion (PFBC) power systems have made it possible to use coal while still protecting the environment. Such power systems significantly reduce the pollutants associated with coal-fired plants built before the 1970s. This superior environmental performance is possible, in part, because chemical and particulate gas stream cleanup is conducted at high-temperature and high-pressure process conditions.

Both the IGCC and PFBC power systems require particulate cleanup systems. Although they are sized differently because of the inherent differences in the coal conversion process and the volume of process gas that must be filtered. To assess the cost of PFBC and IGCC systems the cost of the respective filter systems must be assessed. This paper presents filter system costs for both applications and compares these costs to the total power plant cost. The general differences of the two power plants are compared as well as the process-related filtration conditions for PFBC and IGCC systems. Conceptual designs for the PFBC and IGCC filter systems are presented as well as a cost summary comparison. This comparison includes the total plant cost, the fixed operating and maintenance cost, the variable operating and maintenance cost, and the effect on the cost of electricity for the two filter systems.

As a basis for the cost comparison a Westinghouse Science & Technology Center advanced particulate filter (APF) design is used. We present a discussion of the conceptual design and design differences for two different applications.

ADVANCED POWER SYSTEMS

To provide a basis for an economic comparison of IGCC and PFBC filter systems, a nominal 450 MWe power plant size was selected. The KRW air-blown gasifier represents the IGCC system and the Foster Wheeler (FW) Second-Generation PFBC represents the combustion system. A brief description of these power plants is presented below. Included in this description are the process outputs relevant to the conceptual design of the filter system.

KRW Integrated Gasification Combined Cycle Power System

A nominal 458 MWe net power output KRW air-blown gasifier was selected for the IGCC base case.[1] Air, steam, sorbent and coal are processed through a fluidized bed reactor to produce a low-Btu fuel gas. The fuel gas is partially desulfurized from the in-bed sorbent. This fuel gas is cooled and pre-cleaned with cyclones prior to entering the filter system. Downstream of the filter, additional desulfurization is performed after which the gas enters a combustor and turbine system for power generation. Table 1 presents the process conditions as the KRW fuel gas enters the filter.

Foster Wheeler Second-Generation Pressurized Fluidized Bed Combustor Power System

A nominal 453-MWe net power output Foster Wheeler second-generation PFBC is selected for PFBC base case.[2] Coal mixed with sorbent is pyrolized in a pressurized air-blown fluidized bed carbonizer to produce a low-Btu fuel gas and char. The char and partially utilized sorbent are sent to a circulating fluidized-bed combustor. Combustion air, additional sorbent, and possibly more coal are added to the combustor to generate a high-temperature oxygen-rich flue gas. The second-generation PFBC system requires two filter systems. Flue gas from the combustor is precleaned in a cyclone and fed to the combustion filter system. Fuel gas from the carbonizer flows through a precleaning cyclone before entering a separate filter system. The particulate-free fuel gas from the carbonizer and the oxygen-rich combustion exhaust are then mixed and combusted to drive a gas turbine. Table 1 presents the process gas conditions entering the filter vessels.

FILTER SYSTEM DESCRIPTION

The Westinghouse advanced particulate filter (APF) was selected as the basis for the economic comparison.[3] The Westinghouse APF has cluster modules that support plenums or arrays of candle filters. For both power plants being considered, the conceptual design of the filter system will include four clusters, with each cluster supporting four plenums. Each plenum holds up to 74 candle filters. Each cluster is individually supported from an uncooled high alloy tubesheet. Thermal expansion of the tubesheet is accommodated through an expansion cone which connects it to the inner wall of the filter vessel. Each cluster is attached to the tube sheet with a split ring assembly, which facilitates dismantling and maintenance of the cluster assembly. During thermal expansion, the clusters are free to grow down. Figure 1 shows the basic filter-system concept for the two power systems.

This filter design is very similar to the design used for the Tidd 70-MWe PFBC one-seventh-flow slip-stream testing.[4] In the Tidd APF design, three clusters with three plenums each were housed in a single pressure vessel, with up to 56 filters per plenum.

In this design, dirty gas passes through the candle filters; dust is deposited on the candle filters, forming a cake-like structure. Cleaned gas is conveyed through the inside diameter of the candle filter and is commingled in a common plenum. The cleaned gas is then conveyed through a dedicated pipe to the clean side of the tubesheet. Once above the tubesheet, the cleaned process gas exits through a nozzle in the pressure vessel head.

The on-line filter cleaning system is similar to the one used in the Tidd filter facility, and consists of a compressor, air dryer, primary accumulator tank, air filter, and several secondary accumulator tanks with 2-inch fast-acting back-pulse valves. When the back-pulse valves are activated during candle filter blowback, a short duration pulse of cleaning fluid is blown through piping into the candle filter plenum and then into the candle filters.

In our evaluation, we have the pulse blown into a plenum that contains up to 74 candles. The blowback gas for PFBC is compressed air. The blowback gas for the gasifier and carbonizer is fuel gas taken from the clean gas stream and then cooled and compressed.

At the filter, a pressure differential of only a few psig is needed to blow off the filter cake. Because of the very high pressure drop from the tank to the individual candle filters, high tank pressures are required. At Tidd, the tank and compressor are rated for 1,500 psig. Normally, the back-pulse pressure has been 800 psig, but up to 1,200 psig has been needed at times. For this evaluation, a 400 °F maximum blowback gas will be used in the design.

Operational conditions for the filter systems were developed by Gilbert/Commonwealth using a first-principle based spread-sheet model.[5]

Filter System For the Foster Wheeler Second Generation PFBC

For the 453 MWe power plant, ten candle filter vessels were required using a 10 feet per minute (fpm) filter-face velocity. This is a reasonable face velocity assuming a cake-specific resistance of 15.6 (in.w)/(fpm)/(lb/ft^2). The dust loading to the filter is 1,000 ppmw, since cyclones precede the filter vessels.

The reservoir blowback pressure required to remove the dust cake from the filter every 60 minutes is 729 psi. The blowback pressure is sensitive to the hardware between the reservoir and the candle filter. Table 2 summarizes the candle filter vessel design. Table 3 summarizes the blowback system design and process conditions. Figure 2 shows the piping arrangement and Table 4 presents the piping specifications. Compressed air at 400 °F is supplied to the reservoir by a reciprocating compressor with intercoolers. The brake horsepower required for the compressor is 167 Hp. When the trigger pressure is reached in the plenum, the Atkomatic valve is opened and the candles are blown back with 10.2 lb of air in a timeframe of 700 milliseconds. In order to lessen the amount of particulate re-attachment, the candles are blown back one cluster at a time, starting with the top plenum and moving down in sequence until the 16 plenums in the vessel are cleaned. The total amount of blowback air is 1,631 lb/hr. This is an insignificant amount when compared to the total flue gas flow of 5,288,600 lb/hr; therefore, the dilution effect can be ignored.

Filter System For The Foster Wheeler Carbonizer

A filter face velocity of 5 fpm was selected for the FW carbonizer filter vessels. This is a reasonable face velocity for gasifier particulate matter. Two filter vessels are needed with four tiers of candles and four candle clusters per tier. The particulate matter leaving the carbonizer is different than that leaving a circulating PFBC and this has an effect on the candle filter design and blowback requirements. The mean particle size is smaller at 1.6 micrometers, and the cake-specific resistance is estimated to be 28.5 (in.w)/(fpm)/(lb/ft^2), which is twice that of PFBC cake. Dust loading entering the filter vessel is at 3,000 ppmw, which results in a blowback time between pulses of 60 minutes.

The FW carbonizer produces a low-Btu fuel gas that is highly reactive; therefore, compressed air cannot be used to clean the candle filters. Either nitrogen or recycled clean fuel gas are options, but we used fuel gas. A slip stream of clean gas is cooled and then compressed to the required blowback pressure. The blowback system hardware is identical to that of the combustor filter system. The blowback system shown in Figure 3 utilizes a 24 ft^3 reservoir and fuel gas that is compressed to 769 psi. Table 3 presents the process parameters for the blowback system, and Table 4 lists the piping specifications for the blowback system. Each plenum contains 71 candle filters. The fuel gas compressor requirement is 22 Hp. Each pulse requires 11.5 lb of fuel gas, but this gas is recycled and not consumed. The plenums are blown back in sequence from the top tier to the bottom tiers.

Filter System For The KRW IGCC

As shown in Table 2, the KRW IGCC filter system consists of four filter vessels operating at a face velocity of 5 fpm. As shown in Table 3 the inlet loading is 1,500 ppmw and the mean particle size is 1.2 micrometers.

When using the Gilbert/Commonwealth spreadsheet [5] to determine the operating conditions of the blowback system the cake-specific resistance is an important parameter. In the PFBC, this resistance is 15.6 (in.w)/(fpm)/(lb/ft^2) which is considered reasonable. The carbonizer cake is double this, at 28.5(in.w)/(fpm)/(lb/ft^2). For the gasifier, however, the specific resistance has been reported as high as ten times that of PFBC. A choice of 43.9 (in.w)/(fpm)/(lb/ft^2), three times that of CPFBC, was made for the gasifier. This has resulted in the highest blowback pressure at 1,094 psi, and the shortest time between pulses at 40 minutes. Fifteen pounds of fuel gas are used per pulse.

Clean fuel gas is cooled, then compressed and stored in the blowback reservoir until needed. The reservoir size is 55 ft^3, double that of the CPFBC reservoir to keep the reservoir pressure below 1,000 psig. Table 3 presents process parameters for the blowback system. Each plenum holds 62 candle filters. The fuel gas compressor requirement is 94 Hp, relatively high because of the pulse pressure and quantity needed for blowback. Figure 4 shows the piping arrangement and Table 4 lists piping specifications.

ECONOMIC ANALYSIS

The economics of ceramic barrier filter systems were developed by consistently defining the capital and operating costs, and then performing an economic analysis based on the incremental cost of electricity (COE) as the figure of merit. The conceptual cost estimate was determined on the basis of system scope, equipment quotes, the CPFBC and the IGCC reference plants, and Gilbert/Commonwealth in-house cost data.[5]

Table 5 shows the total plant cost (TPC) and the component COE costs for each case. The face velocities for these applications as well as particle loading determine the number of vessels required for each system. As shown in Table 5, the COE of the systems with similar applications are equivalent. The Foster Wheeler CPFBC and carbonizer have the same working pressure so the TPC is equivalent on a cost-per-vessel level. The IGCC filter system has a higher working pressure, and more expensive vessels and thus has a higher TPC on a per-vessel basis.

We emphasized obtaining good cost results at the TPC level for the two systems. To highlight the cost of the filter systems, the battery limits of the estimate are from the inlet piping of the filter vessels to the inlet of the ash coolers. Costs include equipment, materials, labor, indirect construction costs, engineering, and contingencies. Table 6 lists TPC components.

Operation and maintenance (O&M) cost values were determined on a first-year basis and subsequently levelized over the 30-year plant life. Consumable were evaluated on the basis of the quantity required; operation cost was determined on the basis of the number of operators; and maintenance was evaluated on the basis of maintenance costs required for each major plant section. These operating costs were then converted to unit values of $/kW-yr or mills/kWh.

The capital and operating costs of the plant are combined with plant performance in the comprehensive evaluation of COE.

In summary, the following economic assumptions were made:

- Plant book life is 30 years
- Capacity factor is 65 percent
- Plant in-service date is January 1995
- COE determined on a levelized, current dollar basis
- COE methodology was based on EPRI TAG methodology

CONCLUSIONS

The cost driver of the total system cost are the vessel costs. The vessel costs represent approximately 75 percent of the total plant cost. The blowback systems, including gas compression, only represent a small percentage of the total system cost.

The cost of the ceramic barrier filter system for the advanced PFBC plant is about 2.5 times that for the IGCC plant. The PFBC plant requires two filter systems, one for the combustor and one for the carbonizer, and has a much higher gas volume. The cost of the cleanup system as compared to the total plant cost, however, is relatively small: 10 to 12 percent for the advanced PFBC and 4 to 5 percent for the IGCC.

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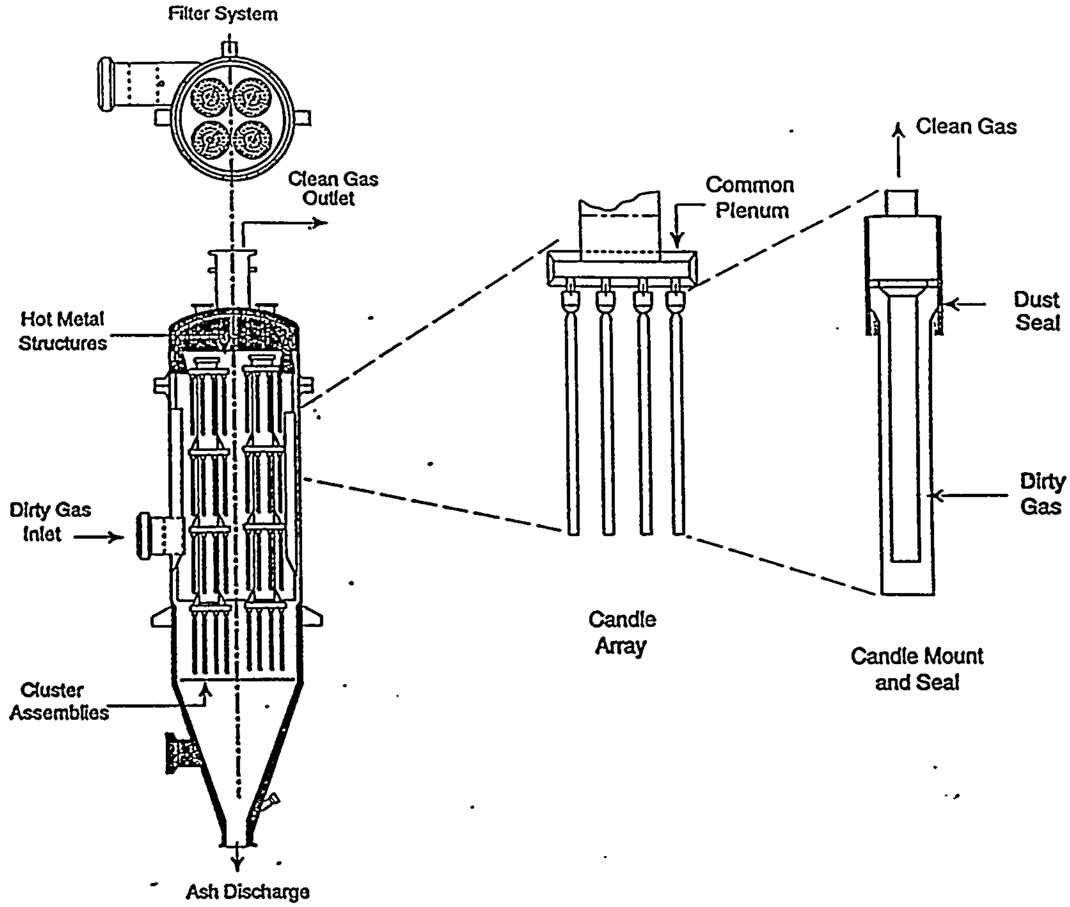

Figure 1. Westinghouse Advanced Particulate Filter

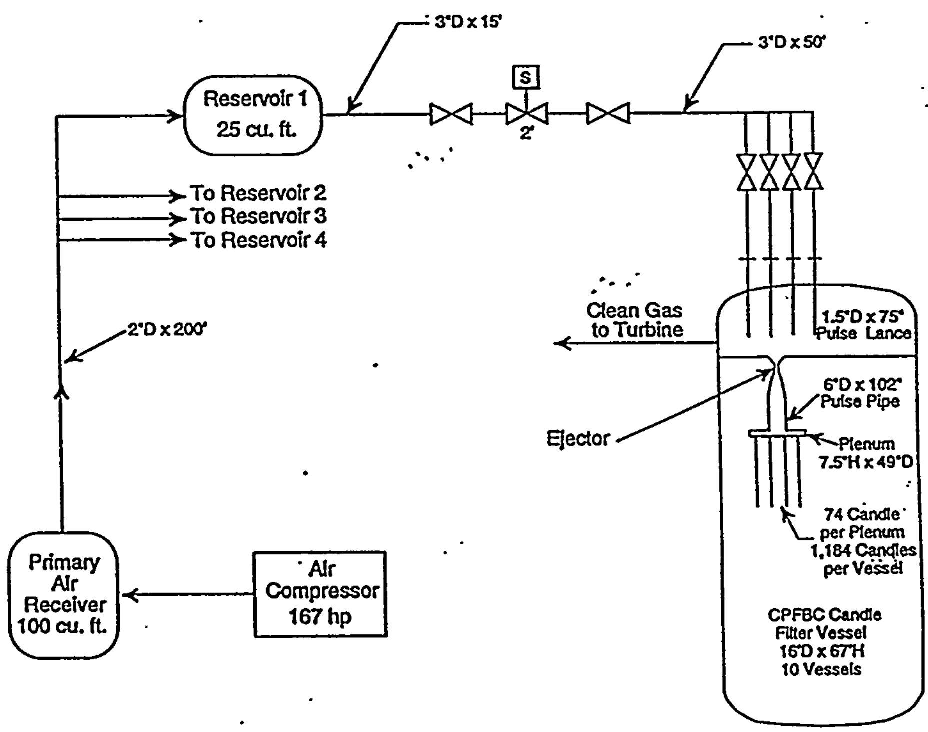

Figure 2. Blowback System For the Foster Wheeler Circulating PFBC

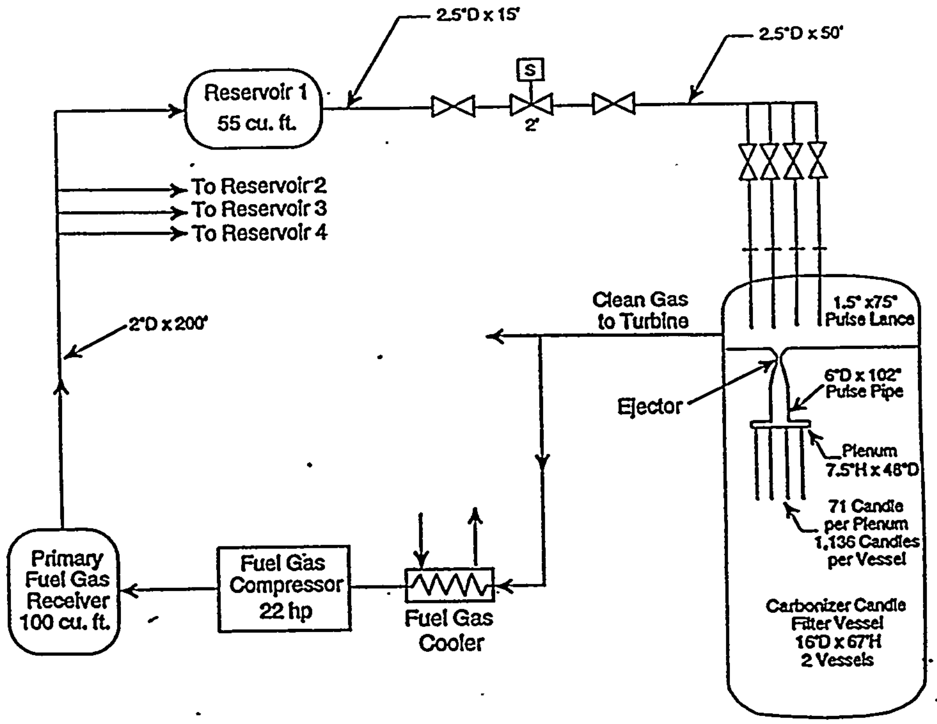

Figure 3. Blowback System For the Foster Wheeler Carbonizer

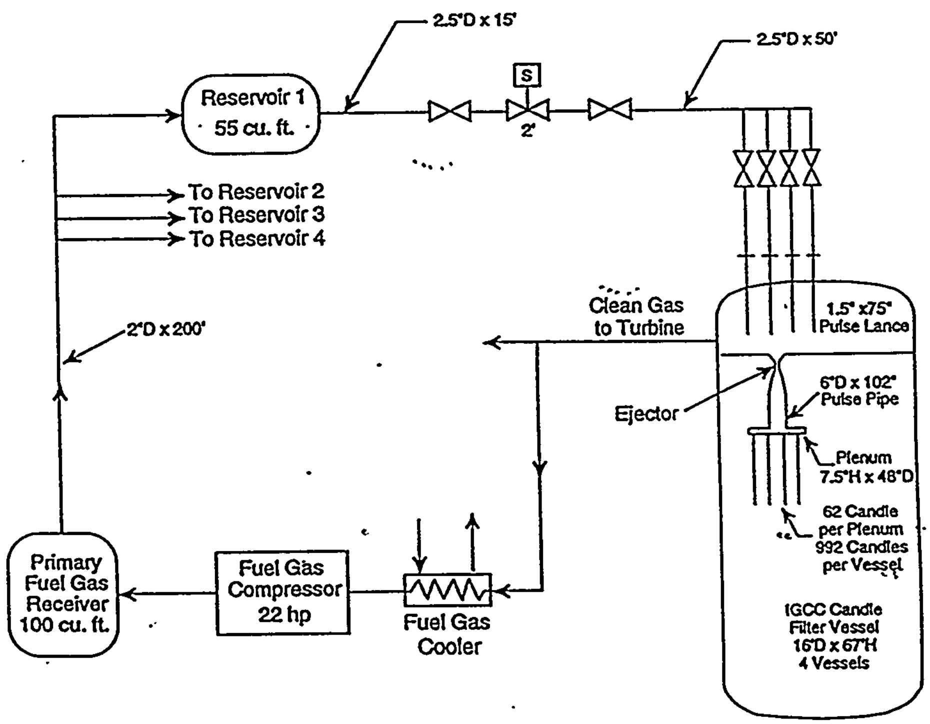

Figure 4. Blowback System For the KRW IGCC

Table 1. Candle Filter System -- Gas Inlet Parameters

Parameter	458 MWe KRW IGCC	453 MWe Foster Wheeler Second Generation PFBC	
		CPFBC	Carbonizer
MWe net	458	453	453
Pressure, inlet, PSIA	380	192	208
Temp., inlet, °F	1,015	1,600	1,500
Flow, inlet, lb/hr gas	1,904,867	5,288,600	492,562
Flow, inlet, ACFM	57,507	343,721	31,811
Inlet particulate loading, ppmw	1,500	1,000	3,000
D50 Particle size, micrometrs	1.2	2.1	1.6
Particle loading, lb/hr	2,857	5,289	1,478

Table 2. Candle Filter Vessel Design

Process Parameter	FW Second Generation PFBC		KRW IGCC
	CPFBC	Carbonizer	Gasifier
Plant Size, MWe	453	453	458
Flow Total, ACFM	343,721	31,811	57,507
Filter Velocity, fpm	10	5	5
Filter Vessel Diam., ft.	16	16	16
Filter Vessel Height, Ft.	67	67	67
Number of Filter Vessels	10	2	4
Flow per Vessel, ACFM	34,372	15,906	14,377
Candles per Vessel	1,184	1,136	992
Candles per System	11,840	2,272	3,968
Number of Tiers in Vessel	4	4	4
Plenums per Tier	4	4	4
Candles per Plenum	74	71	62
Candle Filter Dimensions/Data			
OD, mm	60	60	60
ID, mm	30	30	30
Length, mm	1500	1500	1500
Material	SiC	SiC	SiC
Plenum Diam., in.	49	48	46
Pulse Reservoirs Required per Vessel	4	4	4

Table 3. Filter Blowback System Design and Process Parameters

Process Parameter	FW Second Generation PFBC		KRW IGCC
	CPFBC	Carbonizer	Gasifier
Dust Part Size, micrometers	2.1	1.6	1.2
Dust Loading, ppmw	1,000	3,000	1,500
Reservoir Volume, ft^3	25	24	55
Blowback Pressure, psi	729	769	1,094
Initial Res. Temp, °F	389	393	400
Blowback Gas	Air	Fuel Gas	Fuel Gas
Candles per Pulse	74	71	62
Time Between Pulses, min.	60	60	40
Nozzle Gas per Pulse, lb.	10.2	11.5	15.0
Pulse Temp. at Candle Filter, °F	510	350	390
Blowback Duration, sec.	0.7	1.2	1.0
Cleaning Efficiency, %	66.7	66.7	66.7
Specific Cake Resistance, K2	15.6	28.5	43.9
Compressor Requirements, Total, Hp	167	22	94

Table 4. Piping Specification for Each Filter Blowback System

Hardware Description	FW Second Generation CPFBC		KRW IGCC
	CPFBC	Carbonizer	
Connecting Pipe 2	3 in. Sch 80 15 ft.	2.5 in. sch 80 15 ft.	2.5 in. Sch 80 15 ft.
Connecting Pipe 1	3 in. sch 80 50 ft	2.5 in Sch 80 50 ft.	2.5 in. sch 80 50 ft
Pulse Lance	1.5 in. Sch 40 75 in.	1.5 in. Sch 40 75 in.	1.5 in. Sch 40 75 in.
Ejector	venturi throat 3.73 in. ID, 8 in. lg.	venturi throat 3.73 in. ID, 8 in. lg.	venturi throat 3.73 in. ID, 8 in. lg.
Pulse Pipe	6 in. Sch 40 102 in.	6 in. Sch 40 102 in.	6 in. Sch 40 102 in.
Plenum	7.5 in. , 49 in. dia.	7.5 in. , 48 in. dia.	7.5 in. , 46 in. dia.
Pulse Compressor	2 stage w/ inter-cooler, 90 % adiabatic eff.	2 stage w/ inter-cooler, 90 % adiabatic eff.	2 stage w/ inter-cooler, 90 % adiabatic eff.

Table 5. Filter System Cost Summary

	FW Second Generation PFBC		KRW IGCC
	CPFBC	Carbonizer	
MWe	453	453	458
TPC - $/kW	132.7	26.5	62.1
No. of Vessels	10	2	4
TPC/Vessel	13.3	13.3	15.5
Fixed O&M - mills/kWh	1.6	0.5	0.8
Variable O&M mills/kWh	0.9	0.2	0.4
Carrying Charge, mills/kWh	4.1	0.8	1.9
COE(*), mills/kWh	6.5	1.5	3.2

(*) No consumable were large enough to be recognized on a unit cost basis, although the costs are included in the annual costs. No fuel cost difference was recognized.

Table 6. Total Plant Cost Comparison
($ Millions)

	FW Second Generation PFBC		KRW IGCC
	PFBC	Carbonizer	
Filter Vessel	45.1	8.5	20.4
Hot Gas Piping	0.9	0.1	0.3
Blowback System	3.2	1.2	3.3
Ash Handling	6.0	1.2	2.4
Electrical	4.9	1.0	2.0
TPC	60.1	12.0	28.4