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Granular-Bed and Ceramic Candle Filters in Commercial Plants - A Comparison

Topical Report

K.B. Wilson
J.C. Haas
M.B. Eshelman

Work Performed Under Contract No.: DE-AC21-90MC27423

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Combustion Power Company
1020 Marsh Road, Suite 100
Menlo Park, California 94025

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DISCLAIMER

ABSTRACT

Advanced coal fired power cycles require the removal of coal ash at high temperature and pressure. Granular-bed and ceramic candle filters can be used for this service. Conceptual designs for commercial size applications are made for each type of filter. The filters are incorporated in the design of a Foster Wheeler 450 MWe second generation pressurized fluidized bed combustion plant which contains a pressurized fluidized combustor and carbonizer. In a second application, the filters are incorporated in the design of a 100 MWe KRW (air) gasifier based power plant. The candle filter design is state of the art as determined from the open literature with an effort to minimize the cost. The granular-bed filter design is based on test work performed at high temperature and low pressure, tests at New York University performed at high pressure and temperate, and new analysis used to simplify the scale up of the filter and reduce overall cost. The incorporation of chemically reactive granules in the granular-bed filter for the removal of additional coal derived contaminants such as alkali or sulfur is considered. The conceptual designs of the granular-bed filter and the ceramic candle filter are compared in terms of the cost of electricity, capital cost, and operating and maintenance costs for each application.

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EXECUTIVE SUMMARY

INTRODUCTION

The objective of this program task is to develop conceptual design(s) of moving granular-bed filter and ceramic candle filter technology for control of particles from integrated gasification combined cycle (IGCC) systems, pressurized fluidized-bed combustors (PFBC), and direct coal fueled turbine (DCFT) environments. The conceptual design(s) of these filter technologies are to be compared, primarily from an economic perspective.

The U.S. Department of Energy is currently sponsoring programs to develop advanced coal fired, pressurized fluidized-bed combustors (PFBC's) and gasifiers to be used in combined-cycle, power generating systems. In these systems, a portion of the electricity is generated using a gas turbine driven by the high-temperature, high-pressure process gases. A hot gas cleanup train must be used before the gas turbine to remove the major portion of the particulate. This is necessary to prevent erosion of turbine materials and deposition of particles within the turbine.

The Department of Energy (DOE) specified two existing system studies to be used as the basis for developing conceptual designs and economics for both filter systems. One is a study by Foster Wheeler on a 452 MWe, second-generation pressurized fluidized-bed combustion plant[1]. The other is a study by Westinghouse on a 100 MWe integrated gasification combined-cycle (IGCC) plant which uses a Kellogg-Rust-Westinghouse (KRW) air blown gasifier[2]. Ceramic cross-flow filters in both of these systems are replaced with moving granular-bed and ceramic candle filters designed based on current technology.

SUMMARY OF CONCLUSIONS

The economic study shows that the granular-bed filter compares favorably with the ceramic candle filter from an economic standpoint. For the granular-bed filters, the capital costs are less, the projected maintenance costs are less, the costs of electricity (COE) are less. The summary COE's are presented in Table 1.

The cost of electricity is stated in terms of 10^{th} year levelized dollars. Current-dollar analysis includes expected effects of inflation on capital carrying charges and operating costs. It is used by most utilities in evaluating their business investments. Constant-dollar analysis does not incorporate inflation effects in capital carrying charges and operating costs. It is generally preferred by economic analysts; it makes levelized values appear close to today's values.

Table 1 Summary Cost of Electricity Values

Cost of Electricity	Plant with Granular-Bed Filters	Plant with Candle Filters
452 MWe Second Generation PFB Plant		
Current $, mills/kWh	74.1	76.5
Constant $, mills/kWh	52.8	54.5
100 MWe KRW (Air) Gasifier Plant		
Current $, mills/kWh	133.2	134.0
Constant $, mills/kWh	91.8	92.4

PLANT DESCRIPTIONS

The plant site given for the second generation, pressurized fluidized bed (PFB) combustion plant in the Foster Wheeler study is in the Ohio River Valley of southwestern Pennsylvania/eastern Ohio[1]. This site is considered within 15 miles of a medium-sized metropolitan area and with a well established infrastructure capable of supporting the required construction work force. The site is served by a river with adequate flow to serve as a navigable waterway suitable for shipping shop-fabricated major components to the site. The site is also considered to be served by a well developed road network capable of carrying AASHTO H-20 S-16[a] loads, with overhead restrictions not lower than 16 ft (Interstate Standard). No such assumptions were made in the study for the KRW gasifier based power plant; so to simplify our task, we used the same assumptions for both plants.

All filter systems were designed to fit within the plant areas chosen by the original designers. For the second generation PFB combustion plant, layouts published in the report were used to define these areas. Elevations of the filters were set by the inlet ducting locations. For the KRW gasification plant, only process schematics were published. Layouts were prepared based on separately supported filters. Both sites are considered to be on relatively flat land.

In this second generation PFB combustion plant concept, coal is fed to a pressurized carbonizer which produces a low BTU fuel gas and a char. The char from the carbonizer is burned in a CPFBC with high excess air. Hot gas clean up (HGCU) devices

a. American Association of State Highway and Transportation Officials.

are used to remove the particulate from the carbonizer fuel gas and from the vitiated air from the combustor. The cleaned fuel gas is burned in a topping combustor with the cleaned vitiated air from the combustor. The high temperature, high pressure products of combustion from the topping combustor expand in a gas turbine which in turns drives an electric generator and a compressor which supplies air to the combustor and carbonizer. Steam generated in a heat recovery steam generator downstream of the gas turbine and in a fluidized bed heat exchanger, drives the steam turbine generator which supplies the balance of the plant electricity.

The proposed plant produces 452.8 MWe at a heat rate of 7822 Btu/kWh. The plant is divided into two modules with each module consisting of a carbonizer, a CPFBC, HGCU, and a gas turbine module. A 2400 psig/1000°F/1000°F/2-1/2 in. Hg steam turbine is supplied with steam from each module. The carbonizer operates at 1500°F, the PFBC at 1600°F, and the topping combustor at 2100°F.

Each HGCU module for the CPFBC is sized for 175,000 acfm at 1600°F and 188 psia (2,644,236 lb/hr) with an inlet ash concentration of 4000 ppmw. There are four granular-bed or ceramic candle filters per 226 MWe module. Each HGCU module for the carbonizer is sized for 15,800 acfm at 1500°F and 208 psia (244,650 lb/hr) with an inlet ash concentration of 10,000 ppmw. In the original study by Foster Wheeler, the PFB combustor had two ceramic cross-flow filters for each 226 MWe module and the carbonizer had one ceramic cross-flow filter. The ceramic cross-flow filters are replaced with moving granular-bed filters and for cost comparison purposes, with ceramic candle filters.

The KRW air blown gasifier[2] was designated as the second power cycle to be considered in the conceptual designs of the filters. In this process, coal is gasified in an entrained flow reactor using air as the oxidant. Fuel gas and recycle solids from the gasifier are quenched with cooled recycle gas. A primary cyclone returns recycle solids to the gasifier. A secondary cyclone removes additional solids from the fuel gas before the fuel gas enters the HGCU device. The gas is further cooled in a heat recovery boiler and then passes through a fixed bed of zinc ferrite for removal of H_2S. The fuel gas is burned in a gas turbine with air from the turbine driven compressor. Further heat is recovered in a heat recovery boiler which generates steam for the steam turbine. The plant power output is 100 MWe with a net heat rate of 9000 Btu HHV/kWh. The gas flow to the filter is 12,600 acfm at 1600°F and 385 psia (312,800 lb/hr). As in the Foster Wheeler study, the ceramic cross-flow filters are replaced with moving granular-bed filters and, for cost comparison purposes, with ceramic candle filters.

GRANULAR-BED FILTER DESCRIPTIONS

Although the filter tested at New York University (NYU) was able to achieve high particulate removal efficiency and meet New Source Performance Standards, the multiple element approach to a commercial design[3] was perceived to be undesirable due to weight, complexity and cost. It is the goal of this study to improve the commercial design of the moving granular-bed filter, and show that it can be simpler and less costly. Four conceptual designs of moving granular-bed filters were considered. The first design was a screenless granular-bed filter configuration like that tested at New York University[3]. To simplify this design, and increase the throughput, we abandoned the multi-element approach in favor of simply increasing the single element size. The second type of filter considered was a screenless filter with multiple gas inlets instead of a single centrally located gas inlet. Next considered was a screened filter in which louvered screens retain the downward moving media while the gas passes horizontally through the screens and the media. The fourth design considered was a high throughput filter which features a screenless inlet and a screened outlet. The lowest cost approach is a single-inlet filter, such as that tested at NYU. Most of the other approaches are within 20% in estimated cost.

To better understand the fluid mechanics and flow patterns in a larger diameter single entry filter, a computational fluid dynamics (CFD) model was created. The model provides data on the streamline pattern, the flow distribution, and the pressure drop through the filter. The use of the model provides a means of evaluating the effects of changes in filter geometry and flow conditions.

For the CPFBC, the carbonizer, and the KRW gasifier, the granular-bed filter process is nearly identical. Figure 1 shows the general process flow diagram for a granular-bed filter. For each CPFBC there are four filter vessels that are serviced by a single media circulation system. Each carbonizer and gasifier is serviced by a single filter vessel. The following description applies to the granular-bed filters used with the CPFBC, carbonizer, and the gasifier.

Particle laden gas enters each filter vessel through a centrally located, vertical duct submerged in filter media. The media moves continuously downward toward the cone section of the filter. Particles are removed as the gas turns and flows upward through the filter media. The particle-laden media from each filter is withdrawn at the bottom of the filter element and transported pneumatically in a lift pipe to a de-entrainment vessel where the filter media and the ash particles are separated. The clean media flows by gravity back to each filter vessel. The media is distributed in the filter vessel through numerous pipes and through an annulus around the central inlet pipe. The lift gas and the particles leaving the de-entrainment vessel are cooled to 500°F in a regenerative heat exchanger. Ash is removed from the cooled lift gas in a pressurized baghouse. The lift pipe transport gas is further cooled to 250°F in a water-cooled heat exchanger, boosted in pressure with a blower, reheated in the regenerative heat exchanger and recycled to convey particle-laden media up the lift pipe. Figure 2 shows the basic configuration of the granular-bed filter.

The media used in the filter are 6 mm, manufactured spheres composed mainly of aluminum oxide and mullite. Bulk density is 110 lb/ft^3. Based on experience with 2 mm and 3 mm media at NYU and Combustion Power, it is expected to be very tough and wear resistant. Wear rates on similar 3 mm media used in the testing at NYU were too low to be measured.

The 452 MWe, second generation PFB combustion plant is arranged in two identical trains of equipment, each sized for 226 MWe. Each train includes a CPFBC and a carbonizer. There are four granular-bed filter vessels for each CPFBC and one granular-bed filter vessel for each carbonizer.

For the CPFBC, the granular-bed filter inside diameter is 20'-0"; see Figure 2. Gas flow to each of the four filter vessels in each 226 MWe train is 661,000 lb/hr at 1600°F and 188 psia, with an inlet particulate loading of 4000 ppmw.

The carbonizer will use one granular-bed filter with an inside diameter of 14'-0" for each 226 MWe module. The gas flow to each filter is 244,650 lb/hr at 1501°F and 208 psia. The ash concentration in the inlet gas stream is 10,000 ppmw.

For the 100 MWe, KRW, air blown gasifier, a single granular-bed filter vessel is proposed. The KRW gasifier will use a 14'-0" diameter filter similar to that used for the carbonizer. The gas flow to the filter is 312,800 lb/hr at 1600°F and 385 pisa. The ash concentration in the inlet gas stream is 8,500 ppmw.

CANDLE FILTER DESCRIPTIONS

Currently, the ceramic candle filter appears to have the most promise for successful development. Ceramic candle filter elements are commercially available from a few sources. These filter elements are rigid tubes, closed at the bottom and flanged at the top. They are formed by bonding ceramic fibers and/or grains with an aluminosilicate binder. Lengths are typically 1 to 1.5 m and outside diameters are 60 mm with a wall thickness of 10 to 15 mm. Candle filter elements are mounted in tubesheets, utilizing a variety of arrangements to clamp and seal the filter element flanges. Tubesheets not only support the candle filters, but seal the clean gas plenum from dirty gases. Candle filters are cleaned periodically by high pressure bursts of gas delivered near the filter element outlets. In combustion systems, high pressure air is used to clean the filter elements. In gasifiers, nitrogen or process gas is used.

In our literature search, design variables and potential configurations for candle filters were identified. The most critical design variable is filter face velocity, expressed in ft/min (or cm/sec). This is the average velocity at which the process gas approaches the candle filter elements. Although a data base is forming, there are considerable, and varying, opinions on this variable.

Ash from the process collects on one side of the filter element. Periodically, the ash is removed by back flushing with a high pressure pulse of air or gas. The amount of pulse air, or gas, needed to clean each filter element is another important design parameter. There in quite a divergence between early design values, lab measured quantities, and field measured quantities. This flow is significant because it lowers the process gas temperature, can be a source of heat loss, and requires equipment of considerable capital cost.

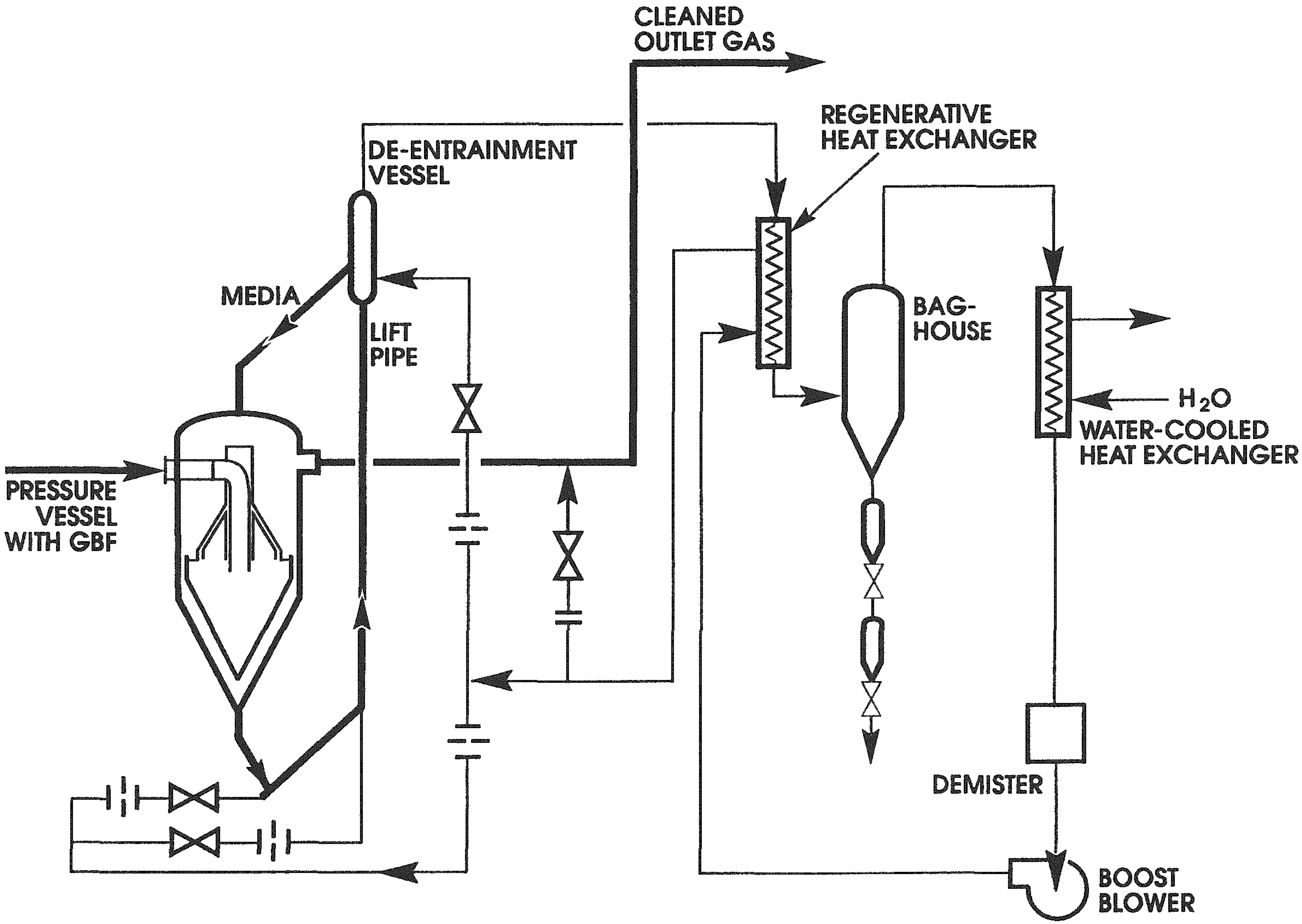

Figure 1 Process Flow Diagram for Granular-Bed Filter

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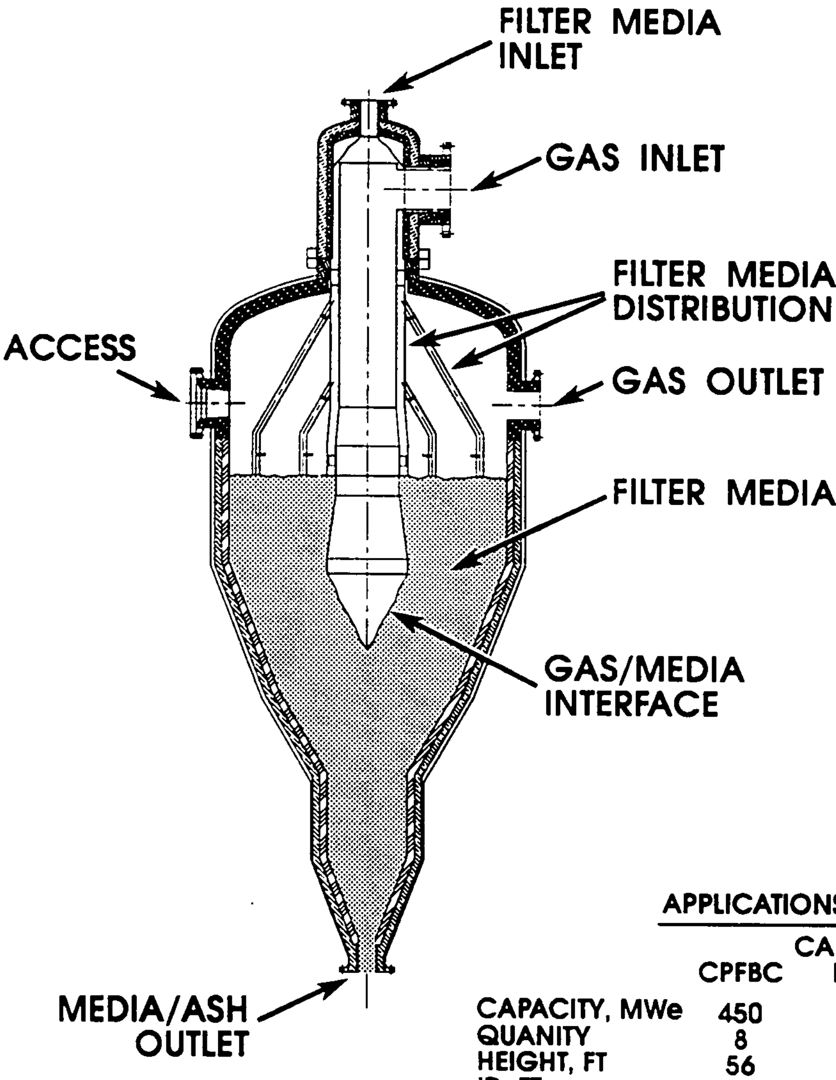

APPLICATIONS

	CPFBC	CARBON-IZER	KRW GASIFIER
CAPACITY, MWe	450	450	100
QUANITY	8	2	1
HEIGHT, FT	56	45	45
ID, FT	20	14	14

Figure 2 Configuration of Granular-Bed Filter

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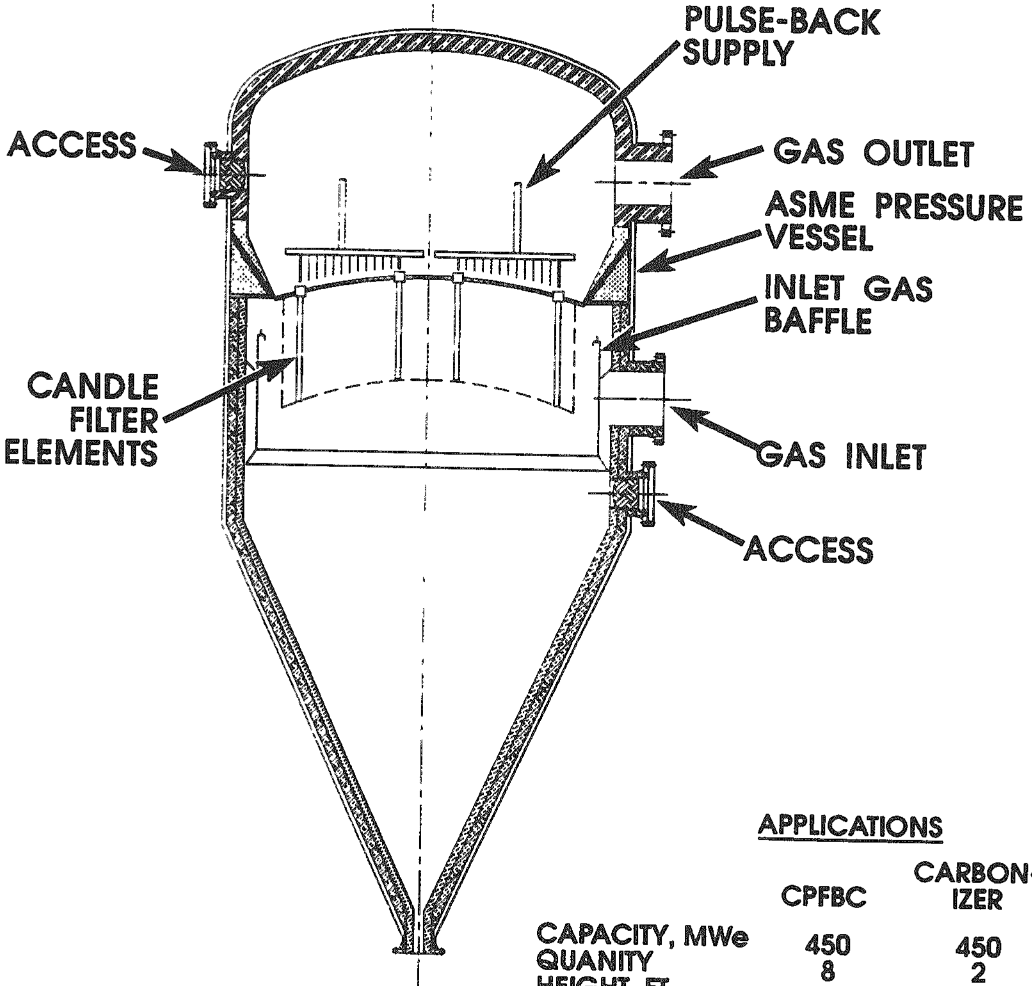
The number of filter elements that can be pulsed by single manifold is another difficult tradeoff. A large quantity of filter elements serviced by a single manifold results in fewer manifolds and a less bulky supply system. The drawback is in attenuation of the air or gas pulse as it is spread through a higher volume manifold. Other design parameters can also have a profound effect on the filter design. These are: filter element size, filter element spacing, and pulse gas pressure.

The candle filter configuration shown on Figure 3 is based on utilizing the largest tubesheet possible. This was shown feasible by stress analysis on a unique tubesheet and tubesheet support design. All filter elements are attached to the tubesheet to simplify the filter element layout and the pulse gas piping. In this configuration, filter elements can be inspected and maintained from inside the filter vessel.

Hot process gases and particulate enter at a single port on the side of the vessel below the tubesheet, and are distributed by a cylindrical baffle around the outer edge of the candle filter array near the upper end of the candle filters. The ash cake collected on the outside surface of the elements is dislodged by periodic high pressure bursts of pulse gas. For filters in oxidizing atmospheres, air is used for pulse cleaning of the filter elements. For filters in gasification environments, either process gas or nitrogen may be used for pulse gas. The ash cake dislodged from the filter elements is collected in the conical hopper below the tubesheet and is discharged into a suitable ash handling system. In the gasifier filter, the ash is first cooled using a water-cooled screw and then depressurized the through lock-hoppers. In the CPFBC system the ash is depressurized through a restricted pipe discharge (RPD) vessel as proposed in the Foster Wheeler study and then cooled using a water-cooled screw. In the carbonizer, the hot pressurized ash is fed directly into the PFBC according to the Foster Wheeler study.

Each of the two CPFBC's has a filter module composed of four candle filter vessels. Each filter vessel has an inside refractory diameter of 20'-6" and tubesheet diameter of 18'-0". The inlet gas flow to each filter vessel is 657,652 lb/hr at 1600°F and 188 psia. This inlet gas flow is slightly lower then for the CPFBC granular-bed filters by the amount of pulse air added to the CPFBC candle filters. This allows for equal outlet gas flow for both the CPFBC candle filters and granular-bed filters. The ash concentration in the inlet gas stream is 4,000 ppmw. A filter face velocity of 10 ft/min was specified for the CPFBC filter.

The candle filter for the carbonizer on each of the two CPFBC's has a single filter vessel in which the refractory inside diameter is 18'-0" and the tubesheet diameter is 15'-6". The inlet gas flow to each filter vessel is 244,650 lb/hr at 1500°F and 207.90 psia. The ash concentration in the inlet gas stream is 10,000 ppmw. A filter face velocity of 5 ft/min was specified for the carbonizer.



APPLICATIONS

	CPFBC	CARBON-IZER	KRW GASIFIER
CAPACITY, MWe	450	450	100
QUANITY	8	2	1
HEIGHT, FT	51	46	45
I.D., FT	20.5	18	16.5

Figure 3 Configuration of Candle Filters

The candle filter for the gasifier has a single filter vessel in which the refractory inside diameter is 16'-6" and the tubesheet diameter is 14'-0". The inlet gas flow to the filter vessel is 312,800 lb/hr at 1600°F and 385.00 psia. The ash concentration in the inlet gas stream is 8,500 ppmw. A filter face velocity of 5 ft/min was specified for the gasifier.

HEAT LOSSES AND PRESSURE DROP

Heat loss and pressure drop across each filter is accounted for in the calculation for the COE. Filter pressure drop represents a loss in power generation. Heat losses show up as temperature drop across the filter and can be accounted for by burning or gasifying more coal. These values are shown in Table 2. The candle filter pressure drop was predicted using filter cake resistivity measurements made by METC[4] researchers, and the GBF pressure drop was established by finite element (CFD) analysis as described above. Heat loss for the candle filters includes radiation and convection losses from the filter vessels and heat loss from cooling process gas for use as pulse gas. Since pulse air for the CPFBC candle filter is not cooled prior to usage, it does not represent a heat loss. For the granular bed filter, heat loss includes radiation and convection losses from the filter vessel and the media circulation system components, and heat loss from cooling filter media circulation gases. This heat could be used to heat boiler feedwater, but this is not proposed.

Table 2 Filter Pressure/Temperature Drop

Item	Granular-Bed Filters	Candle Filters
CPFBC Filter		
Pressure Drop, psi	3.0	2.66
Temperature Drop, °F	20	12
Carbonizer Filter		
Pressure Drop, psi	1.34	1.96
Temperature Drop, °F	34	27
KRW Gasifier Filter		
Pressure Drop, psi	1.31	1.99
Temperature Drop, °F	35	31

FILTER COSTS

Costs, in December, 1991 dollars, for the commercial size granular-bed and ceramic candle filter plants are presented in Tables 3, 4, and 5 for comparison. Filters for the CPFBC and the carbonizer in the second generation PFB combustion plant are presented in Tables 3 and 4, respectively. Gasifier filter costs are presented in Table 5. *Bare erected costs* include capital and installation costs for equipment. The granular-bed filter system includes: filter media circulation and cleaning, ash cooling, and ash discharge equipment. The candle filter system includes: pulse gas supply, ash cooling, and ash discharge equipment. The candle filter vessels are larger and heavier than the granular-bed filter vessels, accounting for the higher cost. Granular-bed filter internals are lighter than the candle filter internals (tubesheet and support); thus, costs are lower. For the granular-bed filter, the media circulation system separates ash from the filtration media, serving a similar function as the candle filter pulse cleaning system. For the granular-bed filter, the regenerative heat exchanger cools the ash; the candle filter uses a water-cooled ash screw (except for the carbonizer filter which feeds ash directly to the PFBC).

Annual maintenance costs are determined as a percentage of the *bare erected cost* of the filter system plus the cost of replacing systems expected to have a short life. The EPRI TAG recommends maintenance costs ranging from 3% to 6% of the *bare erected cost* for processes handling solids at high temperature and pressure. Four percent is used in this study since the maintenance cost of major pieces of equipment needing periodic replacement are added to this base maintenance cost.

For the granular-bed filter, three areas are identified that will require periodic replacement. The bags in the pressurized baghouse are recommended for replacement on a yearly basis by the vendor. The lift pipe liner is assumed to need replacement every three years, based on the limited data from testing at NYU, and the filter internals for the carbonizer and gasifier are assumed to need replacement every five years, based on corrosion rates for metals in high temperature, reducing atmospheres.

For the ceramic candle filters, four areas are identified that will require periodic replacement. It is assumed that filter elements will need replacement every three years. Solenoid pulse valve and isolating ball valve replacement is at 10% and 5% per year based on the high number of cycles. The filter internals for the carbonizer and gasifier are assumed to need replacement every five years, based on corrosion rates for metals in high temperature, reducing atmospheres.

Electrical requirements for the granular-bed filters include power for the boost blowers and for cooling water supply to the water-cooled heat exchanger. Most of the power is for the boost blowers. For the candle filter, power is required for pulse air/gas compressors and dryers, ash coolers, and miscellaneous cooling water needs. Most of the power is for the pulse air/gas compressors and dryers.

Table 3 CPFBC Filter Cost Comparison
(452 Mwe Basis)

Granular-Bed Filter System		Candle Filter System	
	$/1000		$/1000
Filter Vessels (8)	4,031	Filter Vessels (8)	5,385
Filter Internals (8)	2,121	Filter Internals (8)	7,142
Vessel Refractory	1,647	Vessel Refractory	2,135
Filter Media	2,070	Filter Elements	3,477
Circulation System		Pulse Back	
Vessels/Piping	2,476	Piping/Valves	5,847
Regen. Ht. Exch.	5,412	Compressors	1,108
Water-Cooled Hx.	81	Ash System	
Baghouse	412	Vessels/Piping	390
Boost/Maint. Blower	1,094	Ash Coolers	919
Instr/Controls	200	Ash Valves	1,436
Inlet/Outlet Ducting	3,062	Instr/Controls	196
Access/Support Steel	1,551	Inlet/Outlet Ducting	3,730
Foundation Mat'l	56	Access/Support Steel	1,486
Ash System	275	Foundation Mat'l	42
Erection	1,160	Erection	2,871
Engineering	949	Engineering	949
Freight	743	Freight	1,074
Bare Erected Cost, k$	27,339		38,187
Maintenance Cost, k$/yr	1,040		2,522
Electrical Load, kVa	349		318

Table 4 Carbonizer Filter Cost Comparison
(452 Mwe Basis)

Granular-Bed Filter System		Candle Filter System	
	$/1000		$/1000
Filter Vessels (2)	460	Filter Vessels (2)	972
Filter Internals (2)	186	Filter Internals (2)	761
Vessel Refractory	232	Vessel Refractory	489
Filter Media	237	Filter Elements	784
Circulation System		Pulse Back	
Vessels/Piping	1,182	Piping/Valves	1,181
Regen. Ht. Exch.	1,224	Compressors	771
Water-Cooled Hx.	32	Ash System	
Baghouse	137	Vessels/Piping	-
Boost/Maint. Blower	382	Ash Coolers	-
Instr/Controls	148	Ash Valves	-
Access/Support Steel	450	Instr/Controls	93
Foundation Mat'l	28	Access/Support Steel	450
Ash System	168	Foundation Mat'l	19
Erection	442	Erection	698
Engineering	377	Engineering	377
Freight	166	Freight	200
Bare Erected Cost	5,851		6,795
Maintenance Cost, k$/yr	286		619
Electrical Load, kVa	59		123

Table 5 KRW Gasifier Filter Cost Comparison
(100 Mwe Basis)

Granular-Bed Filter System		Candle Filter System	
	$/1000		$/1000
Filter Vessel	405	Filter Vessel	738
Filter Internals	99	Filter Internals	340
Vessel Refractory	116	Vessel Refractory	182
Filter Media	119	Filter Elements	314
Circulation System		Pulse Back	
Vessels/Piping	666	Piping/Valves	506
Regen. Ht. Exch.	873	Compressors/Coolers	542
Water-Cooled Hx.	19	Ash System	
Baghouse	78	Ash Coolers	570
Boost/Maint. Blower	137	Ash Hoppers	31
Instr/Controls	74	Ash Valves	74
Access/Support Steel	213	Instr/Controls	50
Foundation Mat'l	10	Access/Support Steel	113
Ash System	87	Foundation Mat'l	8
Erection	217	Erection	300
Engineering	561	Engineering	561
Freight	102	Freight	130
Bare Erected Cost, k$	3,775		4,458
Maintenance Cost, k$/yr	156		300
Electrical Load, kVa	22		84

FUTURE WORK

Determination of capital and operation costs for commercial size granular bed and ceramic candle filters, and comparison of the resultant COE's, is the first task of a program that has three other options. These options will be funded by the Department of Energy at its discretion.

Option I

Component Testing provides the opportunity to test and evaluate different granular bed filter designs and critical sub-systems determined from the base study described above.

Option II

Moving granular bed filter proof tests will be performed at a Gasification and PFBC Test Facility. The granular-bed filter has been proven to be feasible in the tests at NYU. The new filter design has the same basic configuration, but different proportions. A new test series needs to be arranged to prove that the design is practical. Presumably, this can be resolved at the Southern Company Services test facility that is being designed at this time.

OPTION III

Successful development of the granular bed filter for multi-contaminant control will make this equipment unique. Besides removing particulate, a granular-bed filter has the potential of removing other pollutants in the gas stream. The filter is an excellent gas/solids contactor; in that, it has gas residence times in the order of several seconds, solids residence times in the order of several hours, uniform gas flow across the media, and the gas and filter media flow in opposite directions for the maximum driving potential.

The contaminants of major concern, besides particulate in coal utilization processes, are sulfur compounds, nitrogen compounds, alkali compounds, halogenated compounds, tars, and trace contaminants such as cadmium and mercury[5]. A granular-bed filter which is able to capture particulate and one or more of these additional contaminants would have significant benefits over just a particulate removal system.

Many processes that are under development are able to meet current New Source Performance Standards, but may have trouble meeting more stringent requirements which could be promulgated in the future. As an example, pressurized fluidized bed combustors are able to meet New Source Performance Standards of 90% sulfur removal but probably will have difficulty obtaining 95-98% sulfur removal. A granular-bed filter with an SO_2 absorbing media may be able to increase the overall sulfur removal efficiency from 90% to 98% in a PFBC system while maintaining a cost effective calcium to sulfur ratio.

Having determined possible processes for multi-contaminant control, proof of concept testing will be required to establish feasibility of the proposed processes. In order to conduct the proof of concept testing, test plans and conceptual designs of the test equipment will be prepared. Actual testing will occur in the next phase of the program after approval of the test plans by DOE.

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SECTION 1

INTRODUCTION

1.1 Program Objectives

The U.S. Department of Energy is currently sponsoring programs to develop advanced coal fired, pressurized fluidized-bed combustors (PFBC's) and gasifiers to be used in combined-cycle, power generating systems. In these systems, a portion of the electricity is generated using a gas turbine driven by the high-temperature, high-pressure process gases. A hot gas cleanup train must be used before the gas turbine to remove the major portion of the particulate. This is necessary to prevent erosion of turbine materials and deposition of particles within the turbine. The granular-bed filter (GBF) has shown considerable promise to date and has been chosen for further investigation by the U.S. Department of Energy.

The objective of the base portion of the contract is to develop conceptual design(s) of moving granular-bed filter and ceramic candle filter technology for control of particles from integrated gasification combined cycle (IGCC) systems, pressurized fluidized-bed combustors (PFBC), and direct coal fueled turbine (DCFT) environments. The conceptual design(s) of these filter technologies are to be compared, primarily from an economic perspective. The results of the base contract are reported in this topical report.

The development of moving granular-bed filter technology for control of particles in gasification and PFBC environments is directly applicable and transferable to the employment of moving granular-bed filter technology in the reduction ("fuel rich") and oxidation ("fuel lean") DCFT systems.

After the completion of the base contract, the Department of Energy will fund at its discretion three Options. The objective of Option I is to identify and resolve technical issues associated with development of moving granular-bed filter technology through the use of a component test facility. The objective of Option II is to test and evaluate the GBF at a Government-furnished hot gas cleanup test facility. This facility has been identified as the Southern Company Services, Power Systems Development Facility in Wilsonville, Alabama. The objective of Option III is to develop moving GBF technology for multi-contaminant control of particles and other coal-derived contaminants such as sulfur and alkali.

1.2 General Approach

A technical work plan was developed to define the methodology which would be used to develop an improved granular-bed filter and determine the costs of GBF's and ceramic candle filters. The work plan is divided into the following steps.

1.2.1 Basis for Conceptual Designs

The Department of Energy (DOE) specified two existing system studies to be used as the basis for developing conceptual designs and economics for both filter systems. One is a study by Foster Wheeler on a 452 MWe, second-generation pressurized fluidized-bed combustion plant[1]. The other is a study by Westinghouse on a 100 MWe integrated gasification combined-cycle (IGCC) plant which uses a Kellogg-Rust-Westinghouse (KRW) air blown gasifier[2]. Ceramic cross-flow filters in both of these systems are replaced with moving granular-bed and ceramic candle filters designed based on current technology.

1.2.2 GBF Conceptual Designs

Four design approaches of a moving granular-bed filter were investigated.

1. Single Gas Entry: The first approach was to scale the single gas entry, counterflow, screenless GBF, which was tested at New York University (NYU) to a larger diameter filter. The filter diameter was scaled from 5 to 28 ft and has a filter bed depth based on scaling factors. As part of the scale-up effort, the media size was increased from 3 mm, tested at NYU, to 6 mm, the largest size commercially available. In order to investigate geometry changes, a computational fluid dynamics program was used to predict filter gas flow patterns and gas pressure drop.

2. Multiple Gas Entry: The second approach was to evaluate a large diameter, counterflow, screenless GBF with multiple gas entries. Some of the information gathered from testing at NYU was used in this conceptual design.

3. Screened Inlet and Outlet: The third type of filter evaluated was a screened or louvered type of granular-bed filter similar to that used commercially at low temperatures (up to 600°F) and low pressure(1 psig).

4. Screened Outlet: This filter concept is a hybrid between the single inlet filter and a screened outlet filter. Its potential advantage is a much higher gas capacity than concepts 1 and 2 and for this reason is called a "high-flow" granular-bed filter.

- **Relative Cost Analysis of GBF Conceptual Designs**

A relative cost analysis and technical assessment was used to evaluate the relative merits of the granular-bed filter designs. The overall most attractive design for PFBC and for IGCC was further developed to provide a better cost estimate.

For each application, a conceptual design was prepared consisting of:

- Filter Vessel(s)
- Filter media circulation system
- Ash cooling and removal system

1.2.3 Candle Filter Design

Combustion Power gathered background information on candle filter designs from published reports and DOE researchers. Vendors of ceramic candle filter elements were surveyed to determine design parameters and characteristics of filter elements. Based on current practice, a candle filter design was formulated for both Pressurized Fluidized Bed Combustion and Integrated Gasification Combined Cycle applications. Conceptual designs of candle filters were compared:

1. V-Support Tubesheet: Filter diameter limitations were explored utilizing a solid, V-support for the tubesheet.

2. Tiered Tubesheet: A large filter with multiple tiers to support the candles was compared with a filter with a single tubesheet.

3. Filter Quantities: The cost of numerous smaller filters was compared against fewer larger filters. Singles tubesheet were assumed for the comparison.

4. Modified Tubesheet Support: A unique conical tubesheet support was investigated. Tubesheet diameters up to 18'-0" were analyzed.

- **Comparison of Candle Filter Conceptual Designs**

A relative cost analysis and technical assessment was used to evaluate the relative merits of the ceramic candle filter designs. The overall most attractive design for PFBC and for IGCC was further developed to provide a better cost estimate.

The filter design consists of:

- Filter vessel(s)
- Pulse cleaning system
- Ash cooling and removal system
- Gas distribution system
- Filter element supports and pressure seals

1.2.4 Design and Cost Estimate

The design effort and cost estimate consisted of:

- **Design Package**

  - Supporting structure, ducting and foundations
  - Process flow diagrams
  - P & ID

- General arrangement drawings
- Utility requirements
- Major equipment specifications

- **Capital Cost**

We performed a Class II (preliminary) design and cost estimate as defined in the EPRI Technical Assessment Guide (TAG)®. Capital costs of major pressure vessels and refractory are based on estimates from fabricators. Major equipment cost of items such as blowers, heat exchangers, ash coolers, and baghouses are based on vendor quotations. Cost of instruments, controls, structural steel, piping and ducting are based on recent purchase costs adjusted for inflation. The installation cost of each filter is based on an itemized construction cost estimate by a certified cost engineer. Process and project contingency and other parameters used to establish the capital cost of the base plants were used in costing the filters.

- **Operating and Maintenance Costs**

Operating costs for the all filter systems are based on guidelines given by the EPRI Technical Assessment Guide (TAG). Since no filter configuration constituted a major portion of the power plant, no adjustment to operation labor was made from the base studies that included cross-flow filters. Filter pressure drop and heat loss are include in the comparison. Maintenance costs for the granular-bed and the candle filters are compared by using EPRI TAG guidelines, and augmenting with items unique to each filter.

- **Cost of Electricity (COE)**

COE is determined by using a Lotus 1-2-3 spreadsheet provided by the Department of Energy, and is based on EPRI's Technical Assessment Guide, Volume 1, December, 1986. The COE is the basis for economic comparison between the granular-bed filter and the ceramic candle filter. The COE for each application is updated to December, 1991 cost using the *Chemical Engineering Magazine Plant Cost Index*. For the gasifier application, the cost of the zinc ferrite plant section is updated using costs from the EG&G study[3] submitted to us by DOE.

1.2.5 Comparison of Granular-Bed Filter and Candle Filter

The granular-bed filter is compared with the candle filter in terms of capital cost, maintenance requirements, utility demands, pressure and temperature drop, and cost of electricity.

1.3 REFERENCES

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SECTION 2

OVERALL PLANT DESCRIPTIONS AND FILTER REQUIREMENTS

2.1 Plant Site Description

The plant site given for the second generation pressurized fluidized bed (PFB) combustion plant in the Foster Wheeler study is in the Ohio River Valley of southwestern Pennsylvania/eastern Ohio[1]. This site is considered within 15 miles of a medium-sized metropolitan area and with a well established infrastructure capable of supporting the required construction work force. The site is served by a river with adequate flow to serve as a navigable waterway suitable for shipping shop-fabricated major components to the site. The site is also considered to be served by a well developed road network capable of carrying AASHTO H-20 S-16[a] loads, with overhead restrictions not lower than 16 ft (Interstate Standard). No such assumptions were made in the study for the KRW gasifier based plant; so to simplify our task, we used the same assumptions for both plants.

All filter systems were designed to fit within the plant areas chosen by the original designers. For the second generation PFB combustion plant, layouts published in the report were used to define these areas. Elevations of the filters were set by the inlet ducting locations. For the KRW Gasification Plant, only process schematics were published. Layouts were prepared based on separately supported filters. Both sites are considered to be on relatively flat land with a maximum difference in elevation within the site of about 30 ft. The topography of the area surrounding the site is rolling hills with elevation within 2000 yd not more than 300 ft above the site elevation. Again, this is based on the second generation PFB combustion plant.

Site conditions, as defined by the Uniform Building Code, and ambient design conditions are:

Seismic	UBC, Zone 1
Wind	UBC, 70 mph
Barometric Pressure	14.4 psia
Dry Bulb Temperature	60°F
Wet Bulb Temperature	52.5°F

This generic work site includes a sufficient work force of well-trained construction labors within a 50-mile radius of the site. Labor conditions are such that suitable work agreements can be obtained from labor organizations and contractors. All necessary bulk construction materials are available locally and can be delivered within a reasonable period of time.

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a. American Association of State Highway and Transportation Officials.

Although this generic site was prepared for the second generation PFB combustion plant, it was used to prepare cost estimates for the KRW gasification based power plant. Although specific site conditions could dictate design and cost changes, the comparisons in this report should be valid.

2.2 Second Generation PFB Combustion Plant

Foster Wheeler Development Corporation is developing a second-generation fluidized bed combustion plant. In this concept, coal is fed to a pressurized carbonizer which produces a low BTU fuel gas and a char. The char from the carbonizer is burned in a circulating pressurized fluidized bed combustor (CPFBC) with high excess air. Hot gas clean up (HGCU) devices are used to remove the particulate from the carbonizer fuel gas and from the vitiated air from the combustor. The cleaned fuel gas is burned in a topping combustor with the cleaned vitiated air from the combustor. The high temperature, high pressure products of combustion from the topping combustor expand in a gas turbine which in turns drives an electric generator and a compressor which supplies air to the combustor and carbonizer. Steam generated in a heat recovery steam generator downstream of the gas turbine and in a fluidized bed heat exchanger, drives the steam turbine generator which supplies the balance of the plant electricity.

The proposed plant produces 452.8 MWe at a heat rate of 7822 Btu/kWh. The plant is divided into two modules with each module consisting of a carbonizer, a CPFBC, a HGCU and a gas turbine module. A 2400 psig/1000°F/1000°F/2-1/2 in. Hg steam turbine is supplied with steam from each module. The carbonizer operates at 1500°F, the CPFBC at 1600°F, and the topping combustor at 2100°F.

Table 6 shows the gas and solids flow rates, gas and solids compositions, and particle size for each of the two CPFBC modules. In the original study by Foster Wheeler, the PFB combustor had two ceramic cross-flow filters for each module and the carbonizer had one ceramic cross-flow filter. Figure 4 shows a simplified schematic of the second-generation PFB combustion plant with ceramic cross-flow filters as the HGCU devices. The ceramic cross-flow filters are replaced with moving granular-bed filters and for cost comparison purposes, with ceramic candle filters.

2.3 Gasification Based Power Plant

The KRW air blown gasifier[2] was designated as the second power cycle to be considered in the conceptual design of a granular-bed or ceramic candle filter. In this process, coal is gasified in a fluidized bed reactor using air as the oxidant. Fuel gas and recycle solids from the gasifier are quenched with cooled recycle gas. A primary cyclone returns recycle solids to the gasifier. A secondary cyclone removes additional solids from the fuel gas before the fuel gas enters the HGCU device. The gas is further cooled in a heat recovery boiler and then passes through a fixed bed of zinc ferrite for removal of H_2S. The fuel gas is burned in a gas turbine with air from the turbine driven compressor. Further heat is recovered in a heat recovery boiler which generates steam

Table 6 HGCU Filter Requirements for Each CPFBC Module

Operating Parameter	CPFB Combustor 1 Train	CPFB Carbonizer 1 Train
Plant Module (MWe)	225	225
Gas State:	Oxidizing	Reducing
Gas Flow Rate (ACFM):	175,800	15,800
Gas Temperature (F):	1600	1500
Gas Inlet Pressure (psia):	190	208
Gas Flow Rate (lb/hr)	2,644,236	244,650
Gas Composition (% volume)		
$C0_2$	7.1	12.4
H_20	3.2	11.2
N_2	77.4	54.4
0_2	12.3	0.0
C0	0.0	8.9
H_2	0.0	7.9
CH_4	0.0	3.7
C_2'S	0.0	1.8
H_2S	-	0.07
$S0_2$	0.002	-
Mol Wt.	29.44	26.4
Particulate Load (lbs/hr):	10,566	2,459
Particulate Load (ppmw)	4,000	10,000
Particulate Composition (% weight)		
Char	0.0	62.1
$CaS0_4$	52.7	0.0
Mg0	17.4	7.2
$CaC0_3$	0.0	15.4
Coal Ash	29.9	15.3
Particulate Size Distribution:		
Size Range (micron)	Fractional Distribution	Fractional Distribution
1.2	0.197	0.197
1.7	0.389	0.389
2.4	0.291	0.291
3.4	0.090	0.090
4.8	0.020	0.020
6.8	0.007	0.007
9.65	0.007	0.007
Mean Particle Dia. (micron)	2.1	2.1

for the steam turbine. The plant power output is 100 MWe with a net heat rate of 9000 Btu HHV/kWh. Figure 5 shows a schematic of the gasification and HGCU portion of the IGCC plant. In the schematic, ceramic cross-flow filters are shown as the HGCU device. As in the Foster Wheeler study, the ceramic cross-flow filters are replaced with moving granular-bed filters, and for cost comparison purposes, with ceramic candle filters. Table 7 shows the gas and solids flow rates, gas compositions, and particle size for the flow entering the HGCU device.

Table 7 HGCU Filter Requirements for IGCC Plant

Operating Parameter	Expected Value
Plant Module (MWe):	100
Gas State:	Reducing
Gas Flow Rate (ACFM):	12,600
Gas Temperature (F):	1600
Gas Inlet Pressure (psia):	385
Gas Flow Rate (lb/hr)	312,800
Gas Composition (% volume)	
$C0_2$	17.1
H_20	4.3
N_2	44.1
0_2	0.0
C0	9.2
H_2	24.5
CH_4	0.8
H_2S	0.07
Mol Wt.	23.2
Particulate Load (lbs/hr):	2660
Particulate Load (ppmw):	8,500
Particulate Size Distribution:	
Size Range (micron)	Fractional Distribution
1.2	0.197
1.7	0.389
2.4	0.291
3.4	0.090
4.8	0.020
6.8	0.007
9.65	0.007
Mean Particle Diameter (micron)	2.1

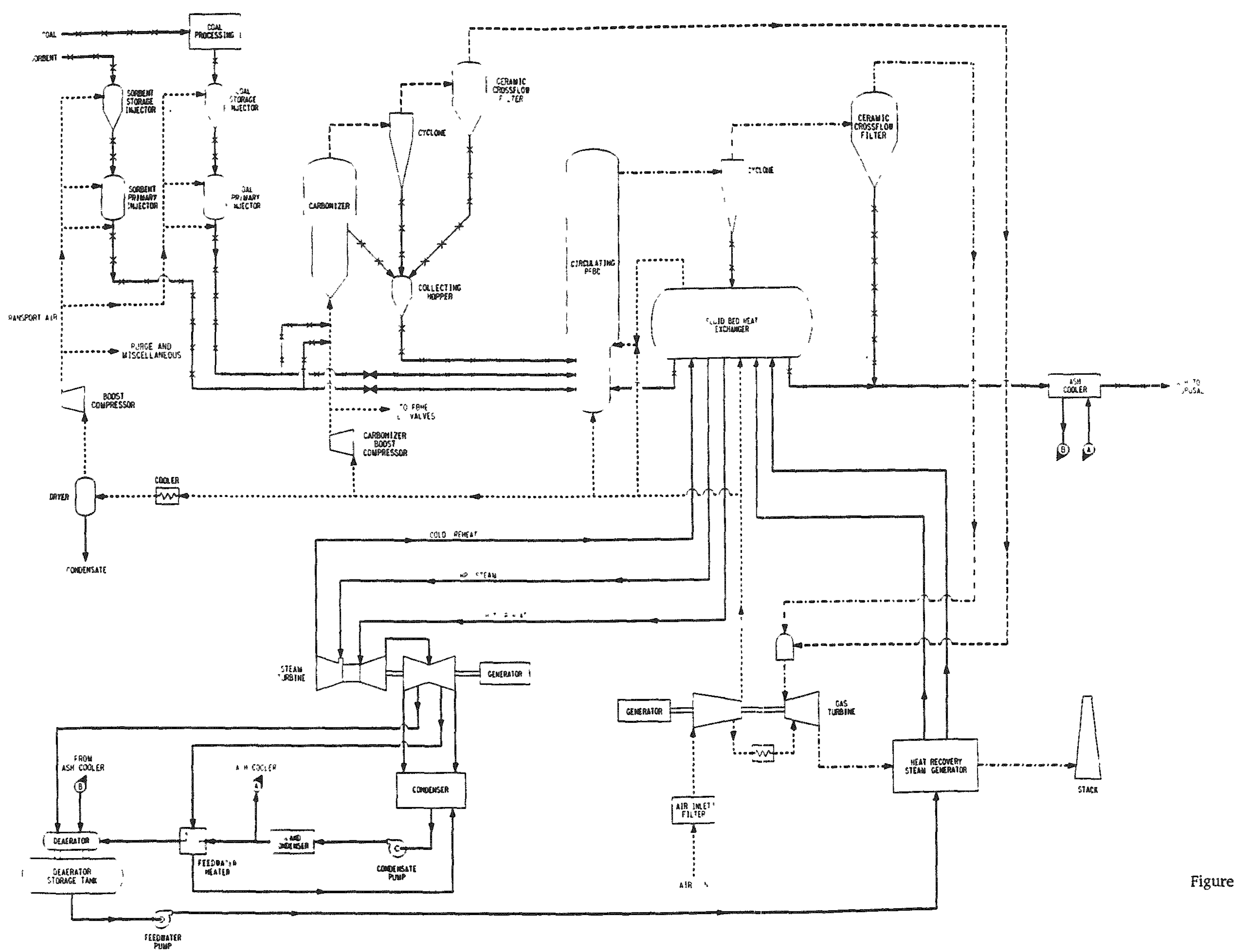

Figure 4 Simplified Schematic of Second-Generation PFB Combustion Plant [1]

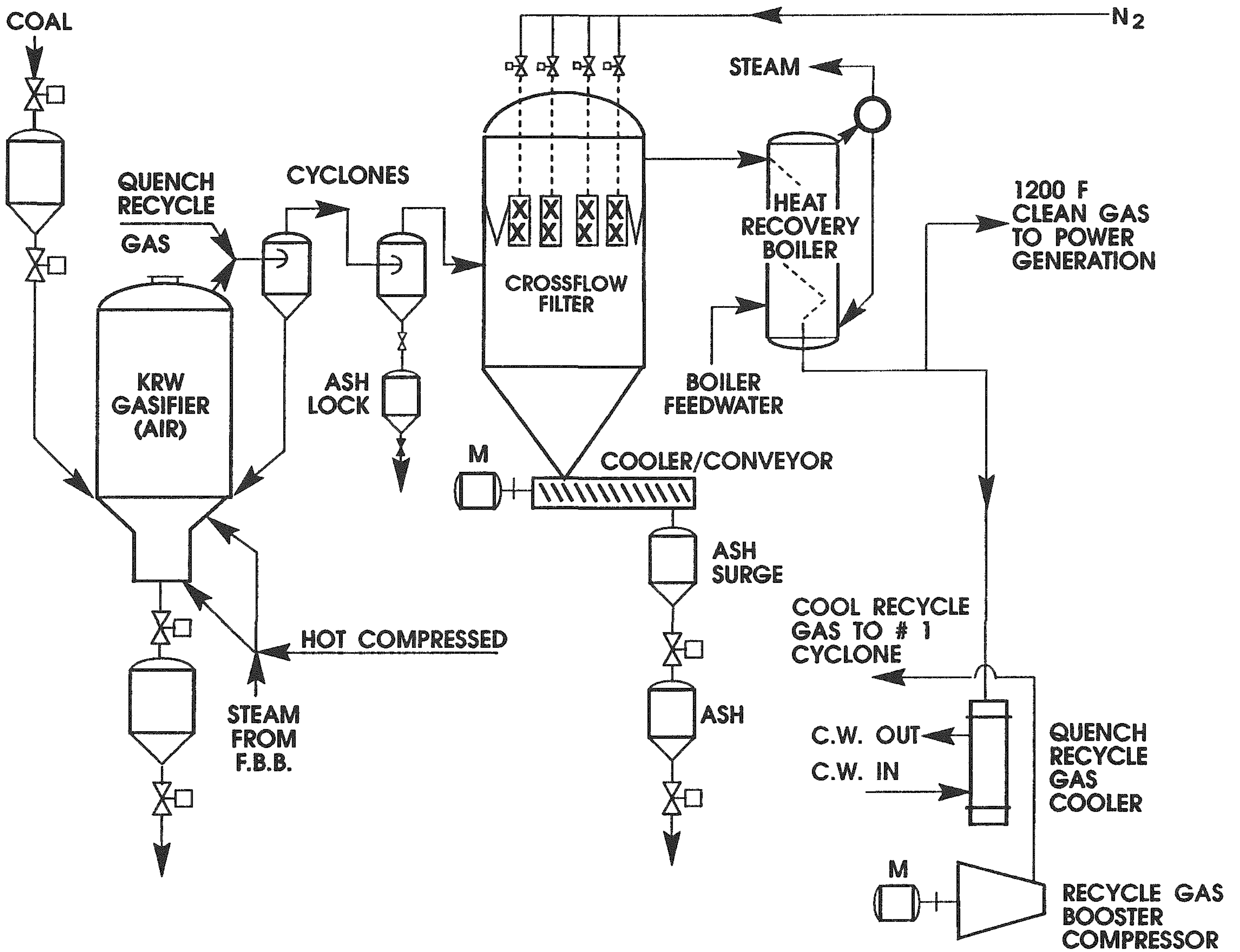

Figure 5 Simplified Schematic of KRW Air-Blown Gasification Process

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2.4 REFERENCES

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SECTION 3

GRANULAR-BED FILTERS

3.1 Previous Development Efforts

Initially, high temperature gas cleanup testing at Combustion power utilized the same technology developed for low to medium temperature applications; that is, 2 mm granular media was contained in the space between two concentric louvered screens[1]. Performance with this configuration was quite good, but continued difficulty was encountered with screen pluggage in low pressure tests and at temperatures above 1400°F. The design eventually evolved away from the screened configuration, hence the label "screenless".

Figure 6 shows a schematic of the screenless configuration developed at a result of initial efforts up to the early 1980's[2]. There are three zones of gas cleaning: a parallel-flow zone in which a high amount of ash is collected, a cross-flow zone, and a counterflow zone where the final ash collection and gas polishing takes place. Tests of this filter at atmospheric pressure and at a temperature of about 1600°F demonstrated successful operation over a 1500-hour test period. Collection efficiencies were 99% and no degradation of collection media occurred. The filter also operated successfully under upset conditions (inlet loadings 10 times normal and inlet flow rates 25% higher than normal).

Figure 7 shows the screenless filter essentials installed in a test pressure vessel at New York University (NYU). Particle laden gas entered the filter through a centrally located pipe submerged in a downward moving bed of 2 mm or 3 mm ceramic granules which act as the cleaning media. Fine particulate in the gas stream collected on the downward moving media. Clean media granules were distributed to the top of the filter and flowed downward through eight equally spaced pipes and the annulus formed around the central gas inlet. The particle-laden media was withdrawn at the bottom of the filter element and transported pneumatically for cleaning and reuse.

A schematic of the moving granular-bed filter tested at NYU is shown in Figure 8. The particle-laden media withdrawn from the bottom of the filter was conveyed in a lift pipe to a de-entrainment vessel where the filter media and the ash particles were separated. The clean media flowed by gravity to a media reservoir located above the filter vessel. From here, filter media was distributed back to the filter. The particles leaving the de-entrainment vessel were removed in a pressurized baghouse after the lift-pipe transport gas was cooled to 500°F. The lift pipe transport gas was boosted in pressure with a blower before it was reused to convey particle-laden media up the lift pipe. The NYU filter element had a diameter of 5 ft with a gas inlet diameter of 1 ft and a bed depth 2.5 ft.

NYU test equipment included a coal-fired, pressurized fluidized bed combustor (PFBC) with a fixed orifice to provide backpressure. This unit operated with a flue gas flows up 16,000 lb/hr at 60-135 psig and 1400-1650°F. Excess air was typically 20-30%

as heat was removed from the fluidized bed by water coils. Particulate generated by the PFBC was 100-3000 ppmw. For the test series involving the granular-bed filter, the PFBC was fired on Kittanning bituminous coal containing 5-8% ash. Sulfur sorbent was Ohio dolomite containing negligible amounts of alkali compounds. Five performance tests were run at NYU. Data from two of these tests is reported in Tables 8 and 9.

Table 8 compares low pressure GBF data with the contractual targets and actual results. The early prototype filter had the same critical dimensions as the NYU test module but was tested at low pressure; thus, not all parameters are directly comparable. The low pressure performance tests and some NYU tests including HG-204, used identical 2 mm media. These results compare closely except for pressure. Flows through the filters are best compared when referenced to minimum fluidizing velocity of the media. Temperatures reported for the NYU tests are typical for near steady state conditions, and indicate the heat loss experienced across the test module. These heat losses were anticipated as a result of the small pilot-plant scale. The lower heat loss on HG-205 was due to higher gas flow. In a commercial-scale unit, the temperature drop across the filter would be much less. Filter pressure drop depends mainly on gas flows, ash concentration and media circulation rate. It is normally steady since the media is circulated and cleaned continuously.

Table 8 GBF Operating Parameters, NYU

Parameter	Low Pressure GBF Tests	Contractual Target	Representative NYU Tests HG-204	HG-205
Media Size	2	2-3	2	3
Pressure, psig	1-4	90-135	90-115	105-115
Temperature				
GBF in (Typ)	1550	1550-1700	1550	1550
GBF out (Typ)	--	--	1350	1450
Flow				
Gas To GBF, lb/hr	2000	7200-14,400	7200	12,515
Gas to GBF, acfm	1550	700-1400	700	1250
% Min. Fluidization	28-33	25-50	25	31
Filter Pressure Drop, IWC	25-30	--	24-30	18-22
Media Circulation Rate lb/min	20-40	20-40	20-70	20-70

Particulate sampling results are shown on Table 9. The amount of ash entering the filter could be roughly controlled by adjusting sorbent feed to the PFBC. For HG-204 inlet loadings below 200 ppmw at the inlet were questionable; since, this data was not consistent with ash loadings estimated by the ash collected by the GBF. Therefore, the averages shown for HG-204 are for 18 of 26 samples during 74 hours of operation where inlet loadings were greater than 200 ppmw. For HG-205 there was 17 samples collected over 47 hours of operation. Having gained a general idea of how sorbent rates affected filter ash loadings, the ash input rate was raised to a high level during HG-204 (2800 ppmw) to observe the filter response. There was only a slight rise in pressure drop across the filter (1-2 IWC) during this one-hour period.

Table 9 Particulate Sampling Results, NYU

Parameter	Low Pressure GBF Tests	Contractual Target	Representative NYU Tests HG-204	Representative NYU Tests HG-205
Ash Concentration				
@ GBF Inlet, ppmw	1500-40,000	--	80-2800	160-1600
o Avg	--	≤ 1200	560	860
@ GBF Outlet ppmw	30-60	12	3-16	1-10
o Avg	--	~	7	4
Emissions lb/10^6 Btu	--	<.03 LB/10^6 BTU	.003-.013	.001-.010
o Avg		(NSPS)	.008	.004
Collection Eff %	98-99.2	99	94.3-99.9	98-99.8
o Avg	--	~	98.6	99.7
% Ash in Media	.1-4.3	6	.03-1.0	.1-1.0

Outlet loadings meet New Source Performance Standards (NSPS) of .03 lb/million Btu and also will most likely meet turbine tolerance limits which actually can be more restrictive at large particulate sizes. With 3 mm media (HG-205), the outlet loadings were expected to increase over that measured at 2 mm (HG-204). One explanation for the higher efficiency of 3 mm media is that it was composed of alumina spheres ranging between 2.4 and 4.0 mm. The 2 mm media was more uniform at 1.9 to 2.0 mm. More opportunity for ash collection (by impaction, etc.) could exist with the wider size range of media than with an evenly sized media bed. Another explanation is that the higher gas velocity permitted by the larger media increased particulate collection by impaction.

The percent of ash in the media compares the ash collection rate to the media circulation rate. Although anticipated at NYU, it was not possible to circulate media slow enough to challenge the contractual target of 6% ash in the media. Other testing on this parameter was carried out at Combustion Power Company and demonstrated 6% as achievable[3]. At NYU, some experiments involved no media circulation for various time periods, but this does not directly correlate to this parameter.

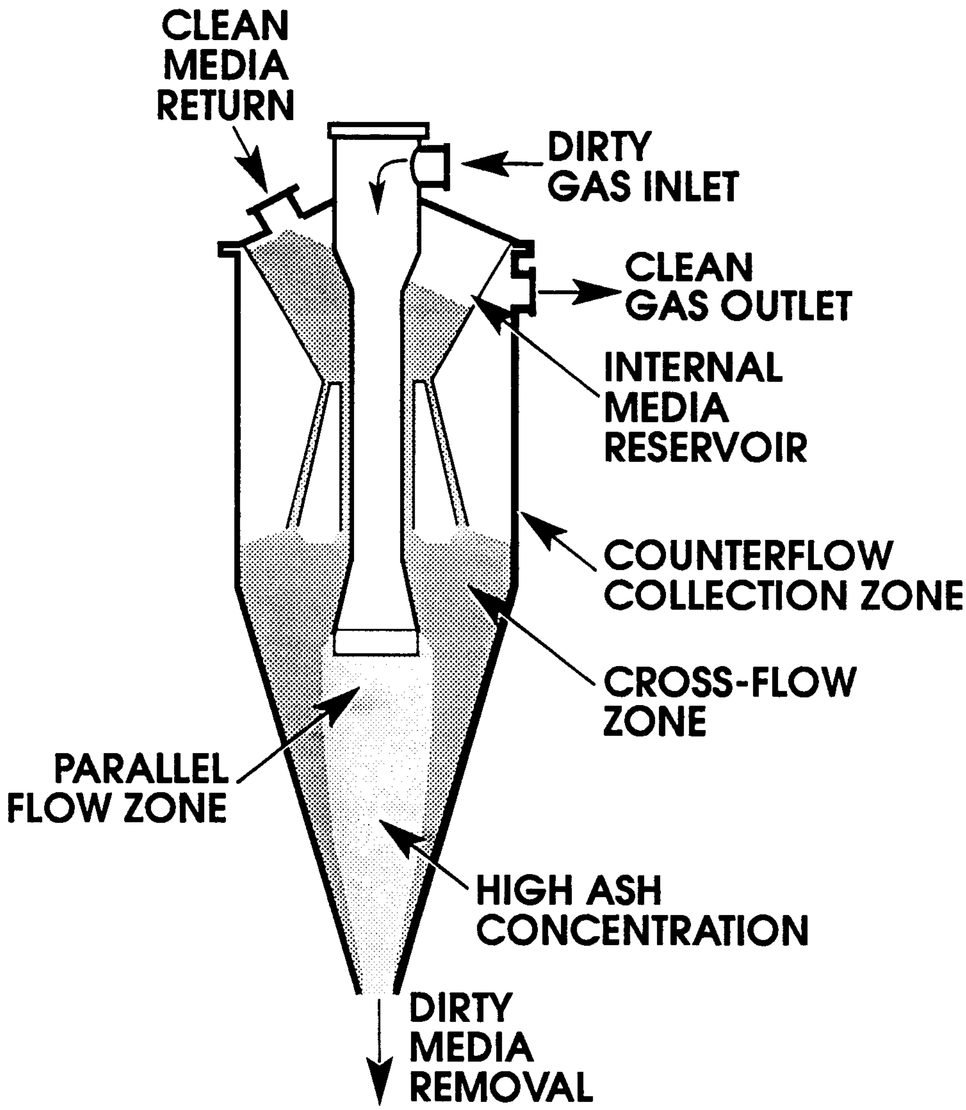

Figure 6 Screenless Counterflow Granular-Bed Filter

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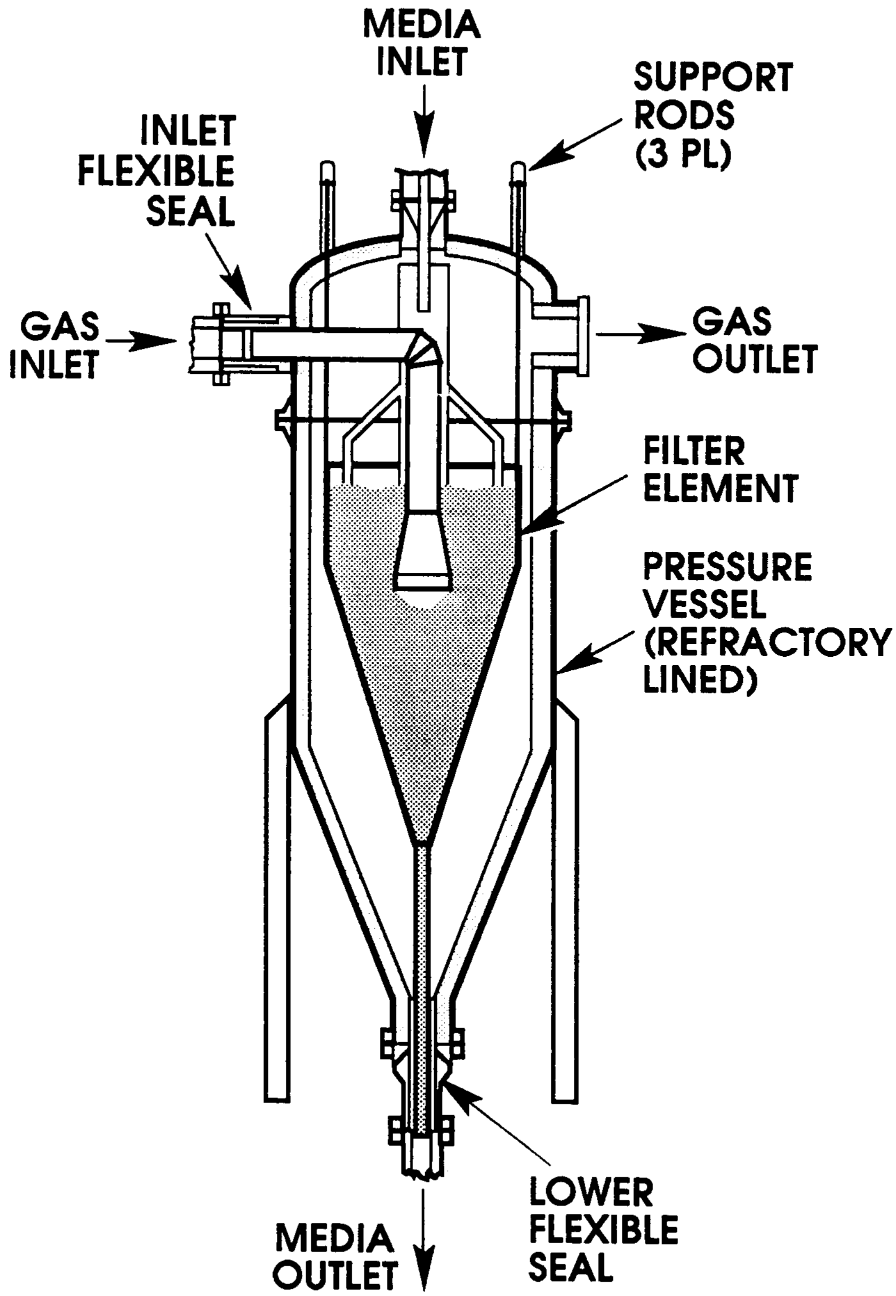

Figure 7 Granular-Bed Filter Installation at NYU

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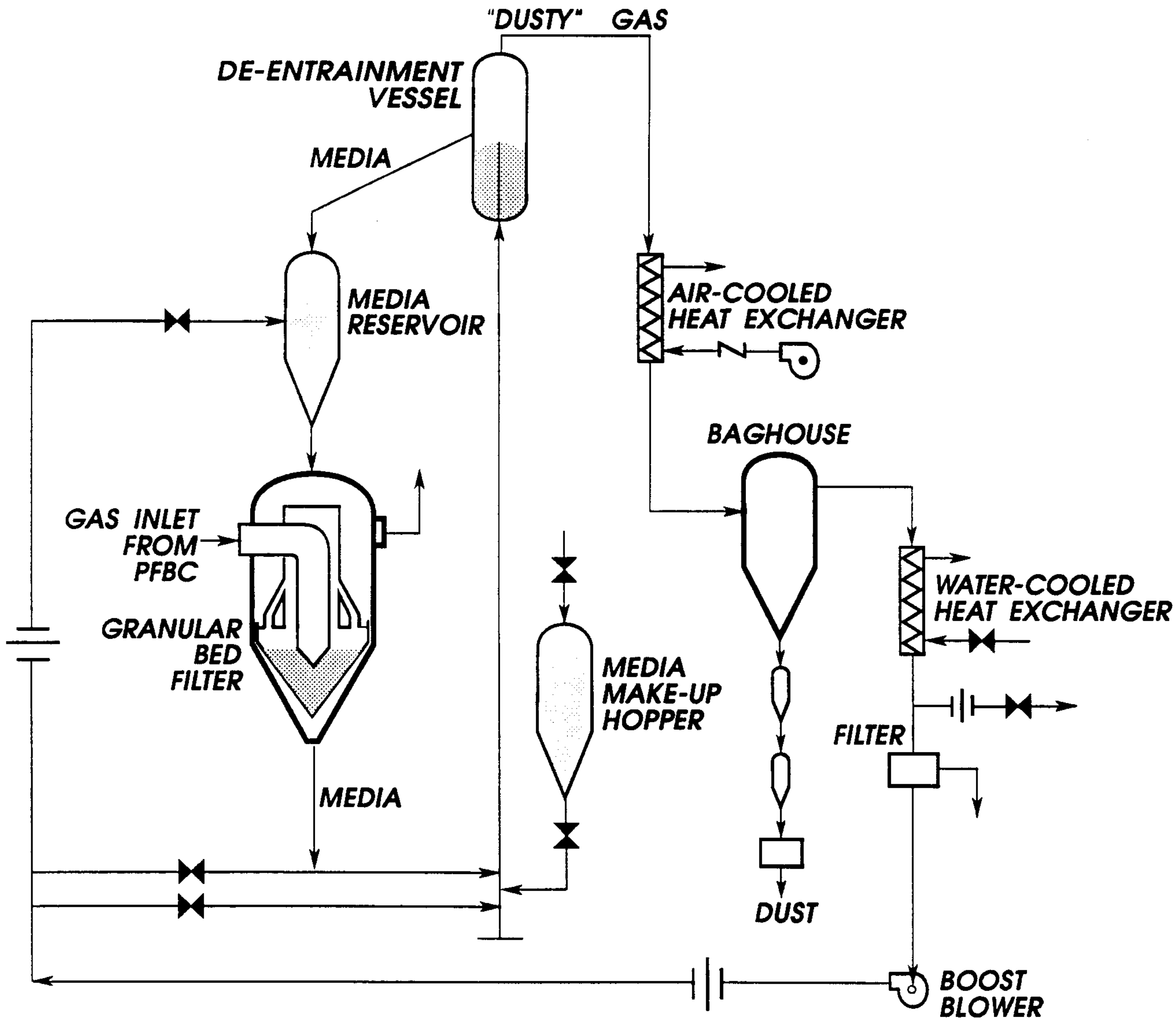

Figure 8 Schematic of Screenless Granular-Bed Filter Tested at NYU

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3.2 Conceptual Designs of Granular-Bed Filters

Although the filter tested at NYU was able to achieve high particulate removal efficiency and meet New Source Performance Standards, the multiple element approach proposed for commercial design[3] was perceived to be undesirable due to weight, complexity and cost. It was the goal of this study to improve the commercial design of the moving granular-bed filter, and show that it can be simpler and less costly. Four conceptual designs of moving granular-bed filters were considered. The first design was a screenless granular-bed filter configuration like that tested at New York University[4]. To simplify this design, and increase the throughput, we abandoned the multi-element approach in favor of simply increasing the single element size. The second type of filter considered was a screenless filter with multiple gas inlets instead of a single centrally located gas inlet. Next considered was a screened filter in which louvered screens retained the downward moving media while the gas passes horizontally through the screens and the media. The fourth design considered was a high throughput filter which features a screenless inlet and a screened outlet.

3.2.1 Single Entry Filter

The filter successfully tested at New York University (NYU) was a single element from a multi-element conceptual design. This filter element had an inside diameter of 5 ft with a process gas inlet diameter of 12". The filter bed depth was 2.5 ft for both 2 mm and 3 mm filter media. An option to the multi-element approach, is to increase the size of the single element to handle more gas flow.

For the Foster Wheeler, circulating pressurized bed combustor (CPFBC), granular-bed filter designs up to 24 feet in diameter were considered. The preliminary economic analysis discussed below, showed that the 20 foot diameter filter was the best choice for the CPFBC application. In addition to increasing the size of the filter element itself, the size of the media was increased to 6 mm. The use of larger media allows more gas to pass through the moving bed of media without danger of causing fluidization or channeling of the gas. Previous tests at Combustion Power Company showed that the particulate collection efficiency is proportional to the number of collectors over which the gas moves[5]. To maintain collection efficiency, the minimum bed depth of the filter needs to be doubled as the media sized is doubled.

The computational fluid dynamics analysis, discussed below, shows that gas inlet diameter relative to that of the filter diameter should be increased in order to reduce the pressure drop through the filter. The filter tested at NYU had a gas inlet area that was 4% of the filter area. When this percentage was input to the computational fluid dynamics (CFD) model for large diameter filters with large media, the pressure drop determined was very high. For the 20 foot diameter filter, the model showed that the gas inlet area could be increased up to 16% of the filter area with a corresponding lower pressure drop. A further increase in the inlet area caused the pressure drop through the filter to increase.

During testing at NYU it was confirmed that if the gas flow rate through the filter was too high, fluidization or gas channeling would result. This occurred at a gas velocity which was about 50% of that needed to fluidized a filter bed with ideal gas distribution. Subsequent analysis showed that for the test in which channeling occurred, the predicted pressure drop through the filter was nearly equal to the calculated pressure drop required to fluidized the media[a]. This indicates that the ratio of the predicted filter pressure drop to the pressure drop required to fluidize the media is an alternate filter capacity parameter to the percent minimum fluidization velocity. The single inlet filter for the CPFBC application is designed to have a pressure drop which is 80% of the pressure drop required to fluidize the bed and to operated at 54% of the minimum fluidization velocity.

The media circulation rate is determined by the ash loading to the filter. The ash loading from the PFB combustor is a moderate concentration of 4000 ppmw while that for the carbonizer is 10,049 ppmw and for the gasifier it is 8440 ppmw. The PFBC filter is designed to operate with an ash to media ratio of 0.02. The carbonizer and gasifier are both designed to operate with an ash to media ratio of 0.025. As a result of the high ash loading in the gasifier and carbonizer applications, the gas velocity through the filter is reduced to 37% of the minimum fluidization velocity.

Conceptually, the media circulation system for the new filter designs is very similar to that used for the NYU tests. The major difference is that a regenerative heat exchanger has been added to reheat the lift pipe circulation gas which helps to minimizes heat loss from the filter system.

3.2.2 Multiple Entry Filter

A filter with multiple gas entry points achieves gas distribution through the use of a complex gas distribution system, but it has the potential advantage over a single entry filter of lower pressure drop and smaller filter size.

The gas enters any type of granular-bed filter through a gas manifold imbedded in the filter media or through a manifold external to the bed. It is essential that the gas manifold system does not disturb the mass flow of media in the region of the bed above the gas inlet. If the media departs from mass flow in this region, the filter will suffer a loss of efficiency due to particle re-entrainment as the media shears due to the relative motion between the individual media[5]. Vertical gas entry generally satisfies this criteria as shown by the testing at NYU.

The use of multiple gas entry points with a counterflow granular-bed filter allows flexibility in deciding the size of a filter module. Once an appropriate ratio of gas distribution elements to filter area has been chosen, the filter can be scaled accordingly.

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a. The projected filter pressure drop was determined by the GBF model developed under contract AC21-77ET10373 which is specific to the filter geometry used at NYU. The predicted pressure drop required to fluidize the bed is equal to the weight of the media above the gas distributor divided by the area of the filter.

In choosing this ratio, the design tested at NYU was considered as a maximum. The 19 sq ft, single entry filter tested at NYU had one gas entry point.

There is a trade off between the complexity of the gas distributor and how effectively it is able to distribute the gas to the filter. One would like a large number of gas entry points, but as the number of entry points increases, the gas and media distribution systems become extremely complex. Eighty distribution points were chosen as the optimum number of gas inlets which could be reasonably connected in a 25 ft diameter filter. This corresponds to 6.1 sq ft of filter surface for each gas inlet, a considerable change from NYU.

CFD computer modeling was attempted for evaluating the placement of gas inlets and determining the influence of one gas distributor on neighboring distributors. The three dimensional CFD model necessary was not yielding useful results during initial trials; consequently, this effort was suspended.

Based on approximate relationships generated for sizing granular-bed filters, the multiple inlet filter was designed to operate at 68% of the minimum fluidization velocity. Bed depth chosen was 5.0 ft, the same as the single inlet filter, and based on scaling from NYU testing. The bed pressure drop is estimated to be about 60 IW. Table 10 shows the design parameters for the multiple gas inlet filter and Figure 9 shows the general arrangement.

A preliminary cost comparison between the single entry and the multiple entry filter showed that the multiple entry filter to have a slightly higher capital cost.

In order to have a more accurate comparison between a single inlet and multiple inlet filter, data will have to be collected during proof of concept testing. Comparison of performance data for the two design approaches will determine if the added complexity of multiple gas entry points is advantageous.

3.2.3 Screened Filter

The third filter concept explored is that of a screened filter. Past development efforts with a screened filter indicated problems with screen fouling[5]. Proper louver design or a change in characteristics of the gas to be cleaned could eliminate this potential problem. The objective of this part of the design phase was to determine if the screened filter has an economic advantage compared to the counterflow filter. The design of the screened filter was based on the previous experience of Combustion Power Company with this type of filter. Combustion Power developed a low temperature screened filter which used an electrical grid to enhance collection efficiency. There was also considerable work done on the development of a high efficiency, high temperature screened filter. The design criteria used for these filters was applied to the design of a filter for the Foster Wheeler CPFBC for comparison to the other approaches.

Table 10 Design Parameters for the Multiple Gas Entry Filter

Design Parameter	Expected Value
Number of Filters	4
Filter Diameter (ft)	25
Gas Flow Rate (acfm)	88700
% Inlet Area of Total Area	12.8
Velocity as a Percent of Minimum Fluidization Velocity	68
Projected Filter Pressure Drop (IW)	60
Media Size (mm)	6
Number of Gas and Media Distributors	80

The geometry of a cross-flow, or screened, GBF can be determined by five independent variables: volumetric gas flow, gas velocity at the outer screen, the dust to media ratio, bed thickness, and media velocity.

Previous experience has shown that at high exit gas velocities, the media is carried through the louvers and can not be retained in the moving bed. For this reason, the gas velocity at the outer screen of the filter is limited to 25% of the velocity which is capable of fluidizing the media.

The media for the filter will be 2 mm in diameter. Experience with larger media in a screened filter demonstrated that the high efficiency required for this application could not be obtained using 4.5 mm media in the screened configuration.

The proposed screened filter is designed to operate at a dust to media ratio of 0.005. The filter performance is sensitive to this ratio. The screened filter at higher dust to media ratios becomes saturated with dust such that voids between the media granules are filled with dust. At higher dust concentrations, the media releases captured dust with a resulting drop in filter efficiency. The screenless, counterflow filter is able to handle dust concentrations of 0.025 lb dust per lb of media, and perhaps up to .06 lb dust per lb media.

The media velocity used in the previous development for a high efficiency screened filter ranged from 0.5 in./min to 1.0 in./min. The proposed filter designs will use a media velocity of 1.0 in./min. Higher media velocities increase the possibility that dust particles will be dislodged due to media shear flow induced at high media velocities.

The bed thickness has a considerable affect on the aspect ratios of the filter. Once gas flow rate, dust to media ratio, gas approach velocity, and media velocity are determined, bed thickness determines the relation between filter height and diameter. Thicker beds lead to smaller diameter filters with increased screen height. The previous development efforts with a high efficiency screened filter used a 3.8 ft diameter filter with a 15 in. thick bed. The low temperature, electrostatically enhanced filters are 8.3 ft in diameter with a bed thickness ranging from 18 in. to 30 in. For the proposed screened filter, a 48 in. bed thickness was chosen to provide a reasonable ratio of filter height to filter diameter.

Table 11 shows the design parameters for the screened filter. The filter is housed in a pressure vessel with a 29 ft inside diameter and would be 70 ft tall. Four of these filters would be required for each 452 MWe module of two CPFBC's. The estimated pressure drop for the filter using 2 mm media is 41 IW.

3.2.4 High Flow Filter

The advantage of the screenless GBF, both the single entry and the multi-entry design, is high filtration efficiency and minimum ash fouling potential. The advantage of the screened filter is that media is trapped by mechanical barriers that prevent fluidization. These advantages can be combined in a hybrid type of filter that features a screen only at the outlet.

Figure 10 shows the schematic of such a filter. Gas enters through a single inlet pipe which delivers the gas to the center of the filter in a manner similar to the single entry filter. The gas turns and flows upward through downward moving media introduced at the top of the filter. The area of the outlet screen is sized for minimal restriction to gas flow and placed to obtain the desired collection efficiency. The bed of media continues some distance above the outlet screen. Little if any gas flows through this section of the filter. This upper section of media weighs down the media in the active filtration zone such that fluidization is not possible.

There are several advantages of a filter of this configuration. The filter can have very high gas throughput since the media is restrained from fluidizing by the media above the outlet screen. Since the gas flow exits below the top surface of the media, the contour of the top surface is no longer important. Therefore, this filter also has a simple, annular media distribution system as shown in Figure 10. Filter media spreads by gravity such that the top surface of the media is at the media angle of repose.

This filter design maintains counterflow filtration. The media at the filter inlet has the highest ash concentration because it does the initial filtration. The final filtration is accomplished with clean media, resulting in high efficiency particulate removal.

Table 11 Screened Filter Design

Design Parameter	Expected Value
Number of Filters	4
Bed Thickness (ft)	4
Gas Flow Rate (ACFM)	87,900
Estimated Pressure Drop (IW)	41
Velocity as a Percent of Minimum Fluidization velocity	25
Active Screen Height (ft)	26.7
Media Size (mm)	2
Number of Media Distributors	16
Filter Diameter (ft)	28.8

Another feature of a this filter is that it can function with smaller and/or less dense media than is used with the other filter configurations. This is possible because the it is not limited in capacity by the fluidization velocity of the media; which, increases with media density and size. This has advantages for a filter designed to control multi-contaminants if low density, high porosity media is needed for sorption of gas contaminants. The screened outlet design could allow operation at a filter velocity which would otherwise cause light weight media to fluidize.

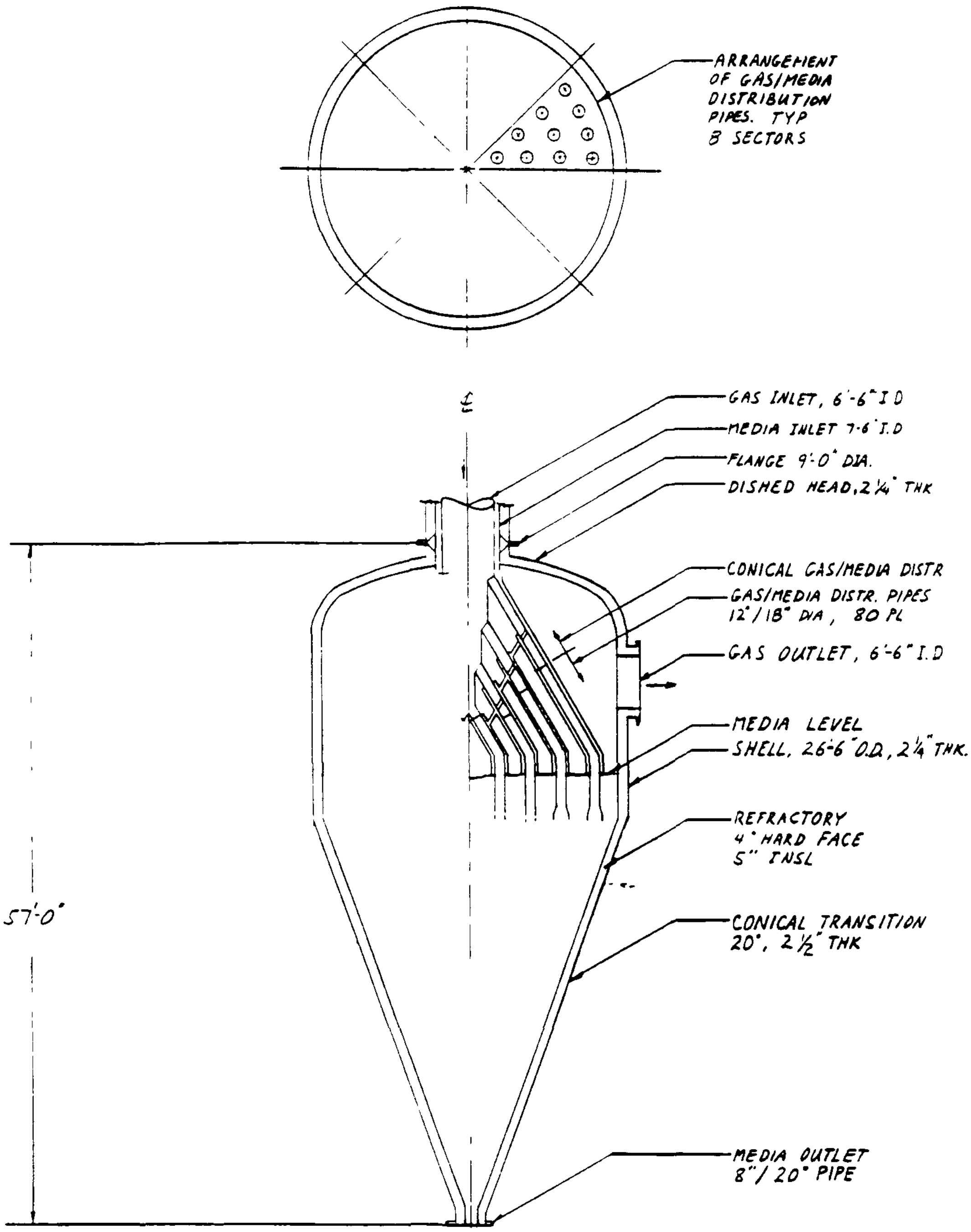

Figure 9 Multi-Entry Granular-Bed Filter

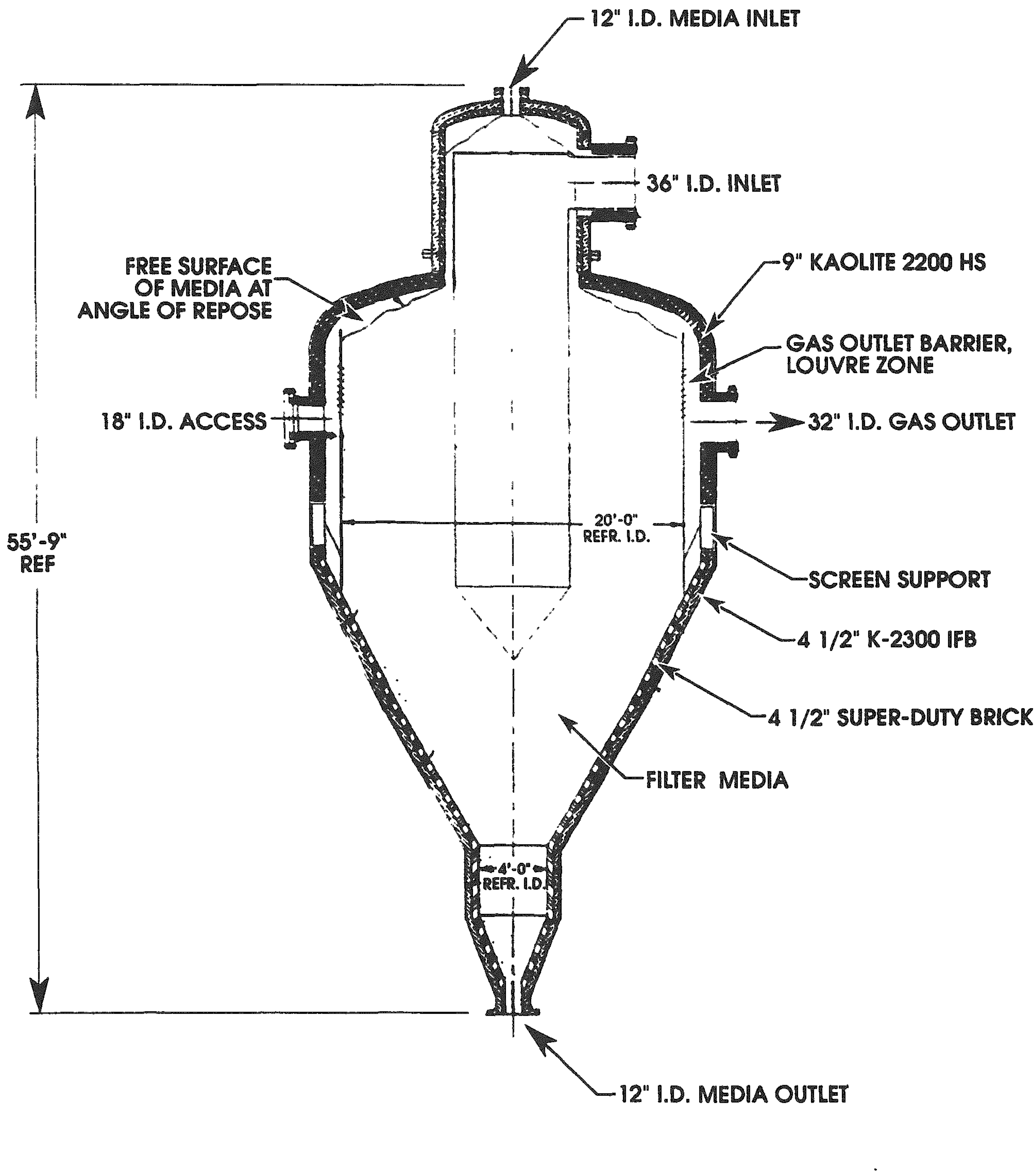

Figure 10 High Flow Granular-Bed Filter

3.3 Preliminary Cost Comparison

The conceptual designs proposed were evaluated in terms of their relative costs to determine which design is most promising. All cases are for a CPFBC associated with the 452 MWe Foster Wheeler second generation PFBC plant. The cost in each case is based on estimated capital cost of equipment plus an operating cost due to filter pressure drop. Capital costs were estimated on a preliminary, but consistent basis, and did not include all items that were duplicated in each system. Therefore these costs cannot be considered accurate to 20%.

An increase in filter pressure drop causes a reduction in the power produced by the plant. The cost of electricity (COE) program supplied by DOE was used to determine an equivalent capital cost associated with the incremental power production due to different filter pressure drops. This was accomplished by maintaining a constant COE by reducing the equipment cost to offset the reduction in power due to an increase in filter pressure drop above that used in the base study. The base study by Foster Wheeler used a filter pressure drop of 1.5 psi. Since GBF pressure drop exceeded this value in all cases but one, a cost penalty was added to all filter cases. More detail is given in Section 5.3.5 on the procedure for relating filter pressure drop to a change in net generated power and heat input.

Table 12 shows the results of the cost comparison. Cases A and B include an upstream (primary) cyclone to reduce the particle concentration to the filter; filter quantities were changed to observe the effect on size. All other cases do not utilize primary cyclones. Cases C through F are all single entry filters with costs evaluated at different quantities to observe the effect on economics. The high flow filter, in case G, has the lowest capital cost, but because of the high pressure drop, it is not the most economic approach. In systems where high pressure drop does not adversely affect the economics, this design may have a slight cost advantage. Cases H and I show how the multiple entry filter competes with the other approaches. Although the filters are smaller that their single inlet counterparts, costs are higher. This is mainly due to the additional stainless steel needed for filter internals. Finally, the screened filter results are presented in column J. While the pressure drop is the lowest of all the filters considered, the capital cost is high. This is mainly due to the high cost of the screens and screen supports.

The lowest cost filter system is case C, eight 20 ft diameter single entry filters without primary cyclones. In terms of actual capital cost, case G was the least expensive but the high pressure drop across the filter increased the effective cost of the filter. Case C is used in the rest of this study to develop more accurate cost and design data for the GBF. But note that many of the other arrangements are close enough in cost to Case C that further development of these designs could give different results.

Table 12 Cost Comparison of Filter Designs for 452 MWe Foster Wheeler CPFBC

Case		A	B	C	D	E	F	G	H	I	J
Type		SE(1)	SE	SE	SE	SE	SE	HF(2)	ME(3)	ME	SC(4)
Volume flow per filter	acfm	87900	43950	43950	21975	146650	10988	87900	87900	43950	87900
No. of filters		4	8	8	16	24	32	4	4	8	4
% Min fluidization	%	4	54	54	54	54	54	89	72	68	25
Filter I.D.	ft	28	20	20	14	12	10	22	25	18	28.2
Filter depth	ft	8	5	5	5	5	5	5	5	5	4
Primary cyclone eff	%	80	80	0	0	0	0	0	0	0	0
Total press drop	inch water	176	138	65	57	53	50	155	64	58	41
Power required for excess filter press drop	MWe	3.28	2.35	0.59	0.39	0.29	0.22	2.77	0.57	.41	0
Heat due to compression	MMBtu/hr	10.78	7.70	1.88	1.23	0.87	0.64	9.08	1.80	1.28	0
Equivalent capital cost due excess press drop	k$	4235	3035	765	505	380	290	3580	737	536	0
Capital cost (partial)	k$	170746	15517	15139	17941	17803	19781	14278	18700	20300	18700
Equivalent capital cost	K$	21281	18552	15904	18446	18183	20071	17858	19437	20836	18700
Ratio of filter cost to least cost filter system		1.34	1.17	1.00	1.16	1.14	1.26	1.12	1.22	1.31	1.18

(1) SE = Single Entry Filter
(2) ME = Multiple Entry Filter
(3) HF = High Flow Filter
(4) SC = Screened Filter

3.4 Computational Fluid Dynamics (CFD) Analysis

To better understand the fluid mechanics and flow patterns in a larger diameter single entry filter, a CFD model was created. The model provides data on the streamline pattern, the flow distribution, and the pressure drop through the filter. The use of the model provides a means of evaluating the effects of changes in filter geometry and flow conditions. No attempt was made to model particle collection in the filter. The model was developed under subcontract to Combustion Power.

Figure 11 shows an idealized arrangement of the single entry GBF tested at New York University. The filter gas inlet pipe was 12 inches in diameter and extended 2.5 ft. below the surface of the media in the 5 ft. diameter filter vessel. It was assumed that the media at the inlet pipe formed a cone with an angle determined by testing performed previously at Combustion Power Company[5]. To simplify the model without introducing significant error, it was assumed that the top surface of the media was level. After the model was developed, it was validated by comparing predicted flow rates with data collected at NYU.

The flow through the granular-bed filter was modelled by using the Ergun equation to predict the flow rate between nodes in a finite element grid. The ANSYS® finite element program generated the grid used to described a particular filter geometry. Coefficients from the Ergun equation were matched to the momentum equation in the FIDAP® computational fluid dynamics program. The FIDAP® program was then used to solve for the unknown flow conditions after the geometry and boundary conditions were specified. In order to insure that the FIDAP® program was giving the same results as the Ergun equation, a one dimensional porous media flow problem was solved. The flow rate predicted by the Ergun equation matched the flow predicted by the FIDAP® program.

The next step in establishing the validity of using the FIDAP® program was to show that a two dimensional axisymmetric model could match data collected at NYU. Data points from the operation at NYU were extracted for periods in which no particulate was entering the filter, and for a period of stable operation with particulate entering the filter. The void fraction used in the model was adjusted until the model predictions matched the data from NYU. Using a sphericity of 0.930 and a void fraction of 0.50, the flow predicted by the model, on the average, was within 5.8% of the measured flow rate. Given that the media is moving, a void fraction of 0.50 appears to be reasonable and a sphericity of 0.93 also appears to be reasonable for the spherical media used at NYU. The data is summarized in Table 13. The close agreement between the NYU data and the CFD flow predictions indicate that the CFD model is a useful tool for predicting flow characteristics for the new filter geometries and operating conditions.

Having verified the general approach, the model was used to predict flow through a 20 ft. I.D. filter using the 6 mm media planned for the commercial cases and the 3 mm media used at NYU. The 20 ft. I.D. filter modelled was geometrically similar to the filter used at NYU. Initial modelling efforts showed that the pressure drop through the filter could be significantly reduced by increasing the diameter of gas inlet duct where it meets the filter media. A larger inlet reduces the gas velocity at the gas-media interface where a majority of the pressure drop was found to occur. Figure 12 is a plot of the flow rate at a constant pressure drop through the filter, as function of the gas inlet diameter. In this case, the filter I.D. is 20 ft., the bed depth is 10 ft., and the media diameter is 6 mm. The maximum flow rate in the filter corresponds to a gas inlet duct diameter of 108 inches. Any further increase in gas inlet duct diameter reduces the filter flow rate because of the increase velocity and pressure drop in the upper portion of the filter.

Table 13 Comparison of NYU Data with CFD Model Prediction

Date Data Taken	6/7/88	6/7/88	6/7/88	Typical
Time	03:29	07:38	7:09	None
Filter Condition	Clean	Clean	Clean	Dirty
Gas Flow (lb/hr)	10,400	11,490	10,900	12,515
Avg. Filter Temp (F	1261	1005	958	1400
Outlet Press. (PSIG)	80.4	80.0	80.3	110
Measured Pres. Drop (IW)	14.2	14.2	12.7	20.0
Calculated Valves				
Viscosity X 10^5 (lbm/ft/s)	2.76	2.49	2.44	3.00
Density (lbm/ft^3)	0.151	0.184	0.183	0.174
Void Fraction	0.50	0.50	0.50	0.50
Flow Rate (lbm/hr)	9,522	10,750	10,109	12,362
Model Run #	Clh	Cli	Clj	Clk

Results with the 10 ft. bed depth indicated that further improvements could be made to reduce the filter pressure drop and lower the filter cost. The filter configuration was subsequently changed to include a 5 ft. deep bed. The filter inlet duct was also moved to a position lower in the filter compared to the previous cases. Figure 13 shows a sketch of this geometry. For a gas inlet duct diameter of 90 in., the CFD model predicts that the pressure drop through the filter will be 82 IW. Figure 14 shows the stream lines through the filter. The streamlines in the upper section of the filter are very parallel and uniform. Figure 15 shows the isobars in the filter. At the outlet end of the filter, the pressure is uniform across the filter and the pressure gradient is constant in the axial direction. Figure 16 shows the flow distribution at the outlet of the filter. There is a reduction of flow along the wall and a corresponding increase in flow slightly away from the wall;otherwise, the flow rate across the filter is fairly uniform. The figures indicate a favorable gas distribution pattern which is necessary for high particle collection efficiency. Figures like these were prepared for all other cases, including the NYU verification cases, and compare favorably.

Once the modelling procedure were completed for the CPFBC, similar techniques were applied to the carbonizer and the IGCC gasifier. For both these filters, the diameter was 14 ft., the bed depth was 5 ft., and the gas-media interface diameter (gas inlet duct) was varied between 48 and 78 inches. For both applications, the minimum pressure drop occurred with a gas inlet diameter of 78 inches. With this gas inlet diameter, the pressure drop in the carbonizer filter is 31.5 IW and in the gasifier the pressure drop is 34.8 IW. The flow patterns for each application are similar to those shown for the CPFBC filter.

3.5 Preliminary Design of Granular-Bed Filter

Four different approaches to filter design were considered from the cost standpoint. The cost analysis indicated that the single entry filters were the lowest cost design, and established the most economic quantities. The CFD study, performed in parallel to the cost analysis, yielded guidelines for determining optimum single entry filter dimensions. In this section, the preliminary designs for these filters are presented.

3.5.1 Process Description

For the CPFBC, the carbonizer, and the KRW gasifier, the GBF process is nearly identical. Furthermore, this process is scaled up from the system tested at NYU. The major change from NYU is the inclusion of a recuperative heat exchanger and an automatic filter media make-up system. Figure 17 shows the process flow diagram for the CPFBC granular-bed filter. In this filter, there are four filter vessels that are serviced by a single media circulation system. The following description for the CPFBC filter also applies to the granular-bed filters used with the carbonizer and the KRW gasifier.

Particle laden gas enters each of four filter vessels, stream 1, through a centrally located duct submerged in filter media. The media moves continuously downward toward the cone section of the filter. Particles are removed as the gas turns and flows upward through the filter media. The particle-laden media from each filter is withdrawn at the bottom of the filter element, stream 3, and transported pneumatically in a lift pipe, stream 6, to a de-entrainment vessel where the filter media and the ash particles are separated. The clean media flows by gravity back to each filter vessel, stream 9. The media is distributed in the filter vessel through numerous distribution pipes and an annulus around the central inlet pipe. The lift gas and the particles leaving the de-entrainment vessel, stream 11, are cooled to 500°F in a regenerative heat exchanger.

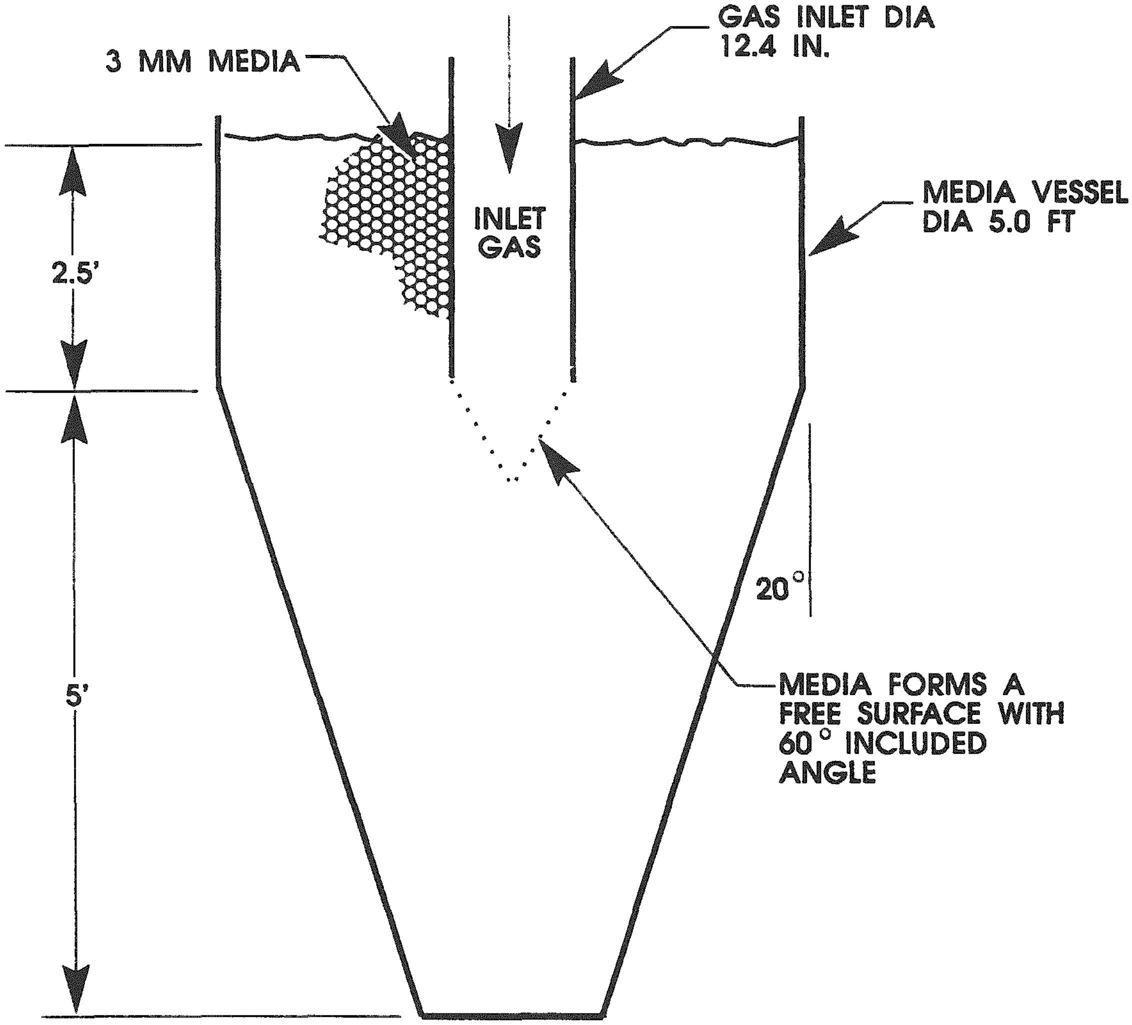

Figure 11 Idealized Sketch of the GBF Tested at NYU

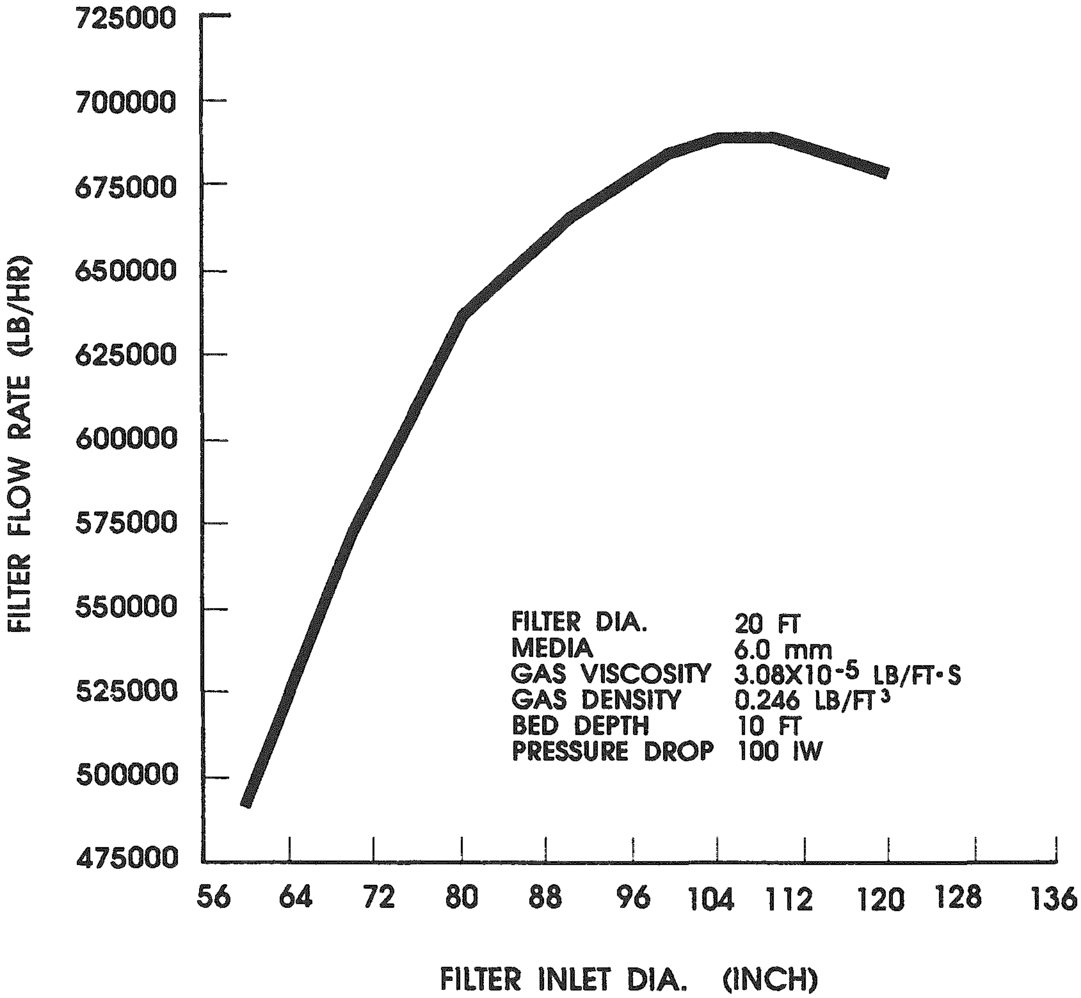

Figure 12 Effect of Filter Inlet Diameter on Filter Flow Rate

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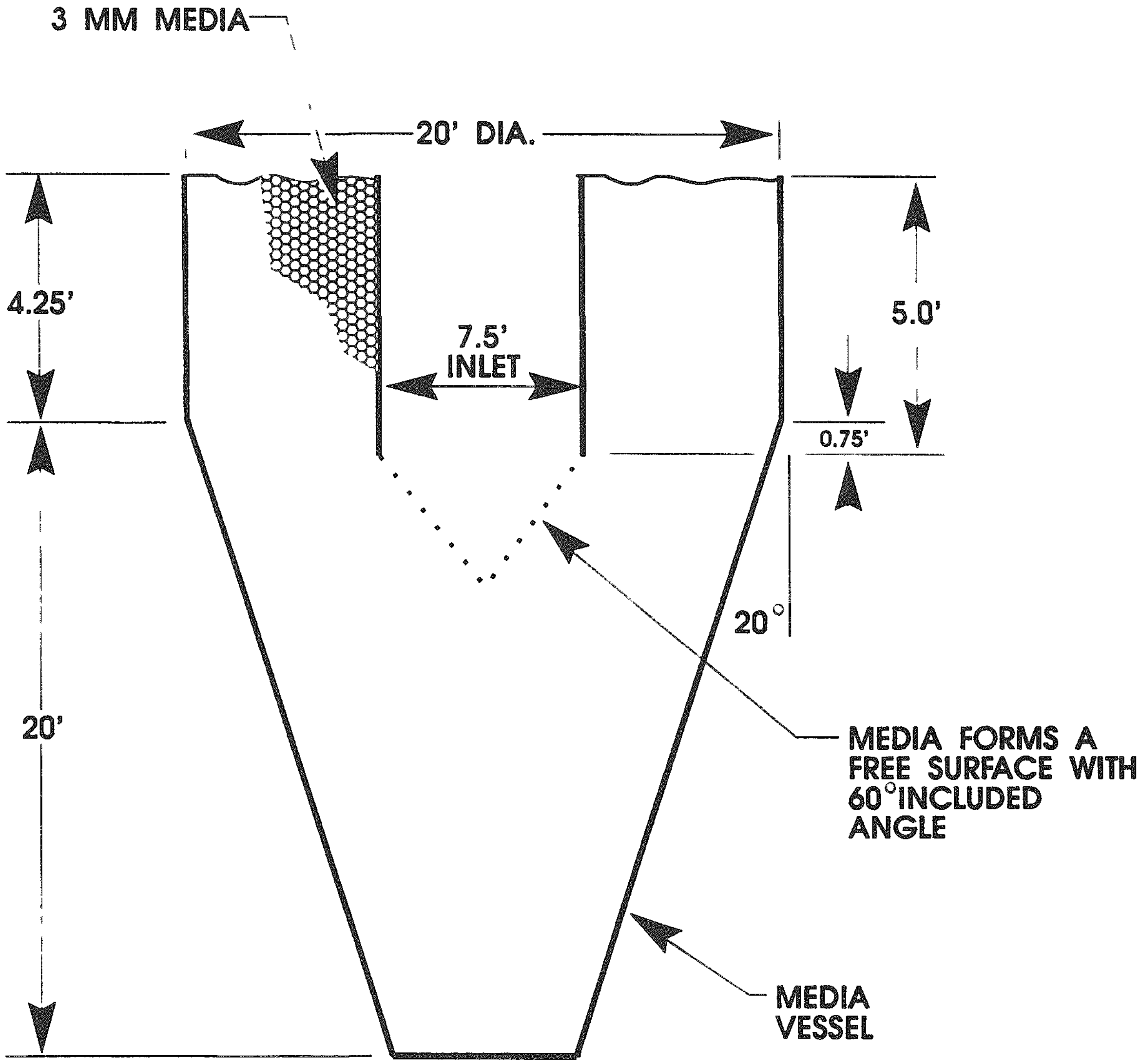


Figure 13 Schematic of the Geometry of 20 ft Diameter Filter with a 5 ft Deep Bed

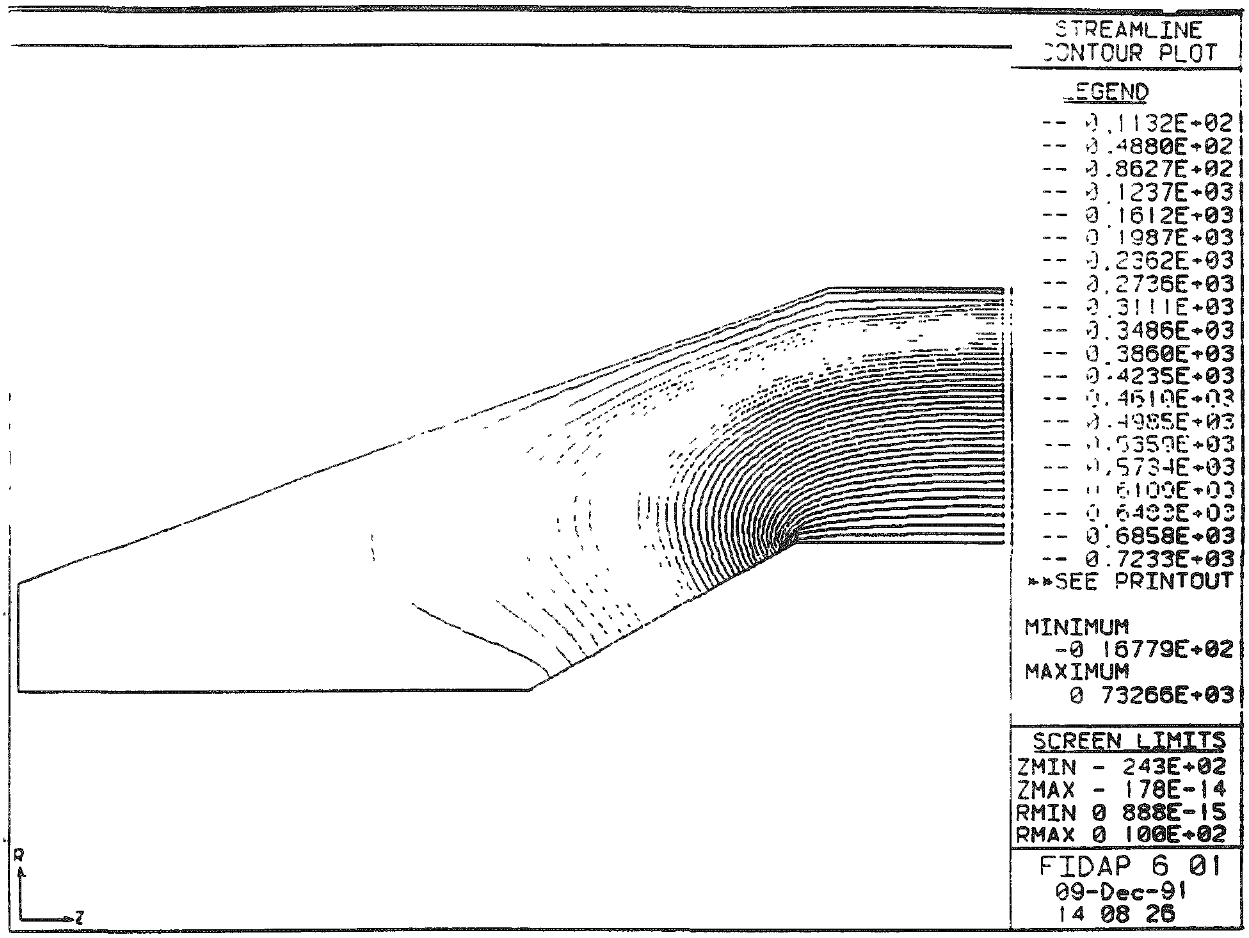


Figure 14 Streamlines for 20 ft Diameter GBF with a 5 ft Deep Bed

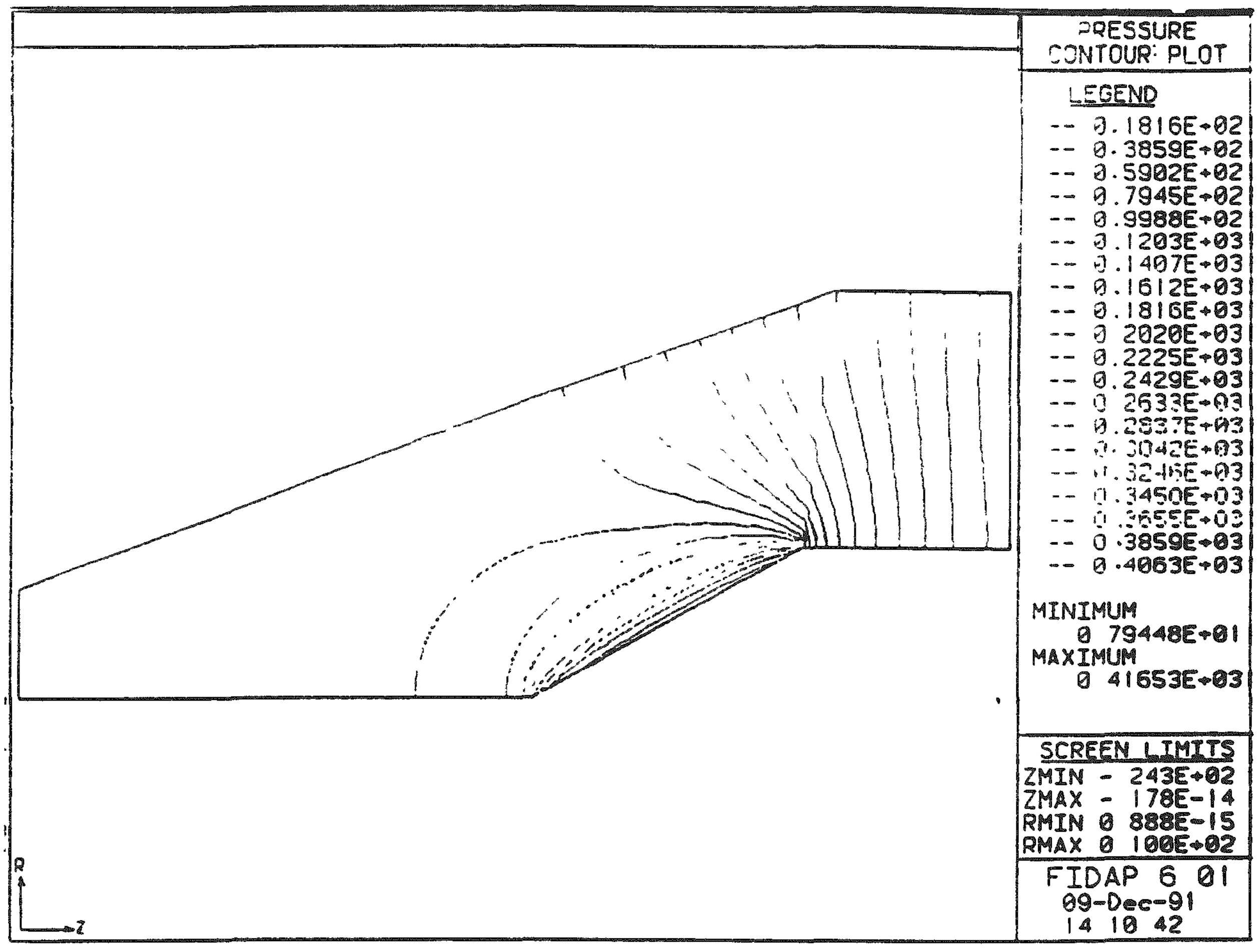


Figure 15 Pressure contours for 20 ft Diameter GBF with a 5 ft Deep Bed

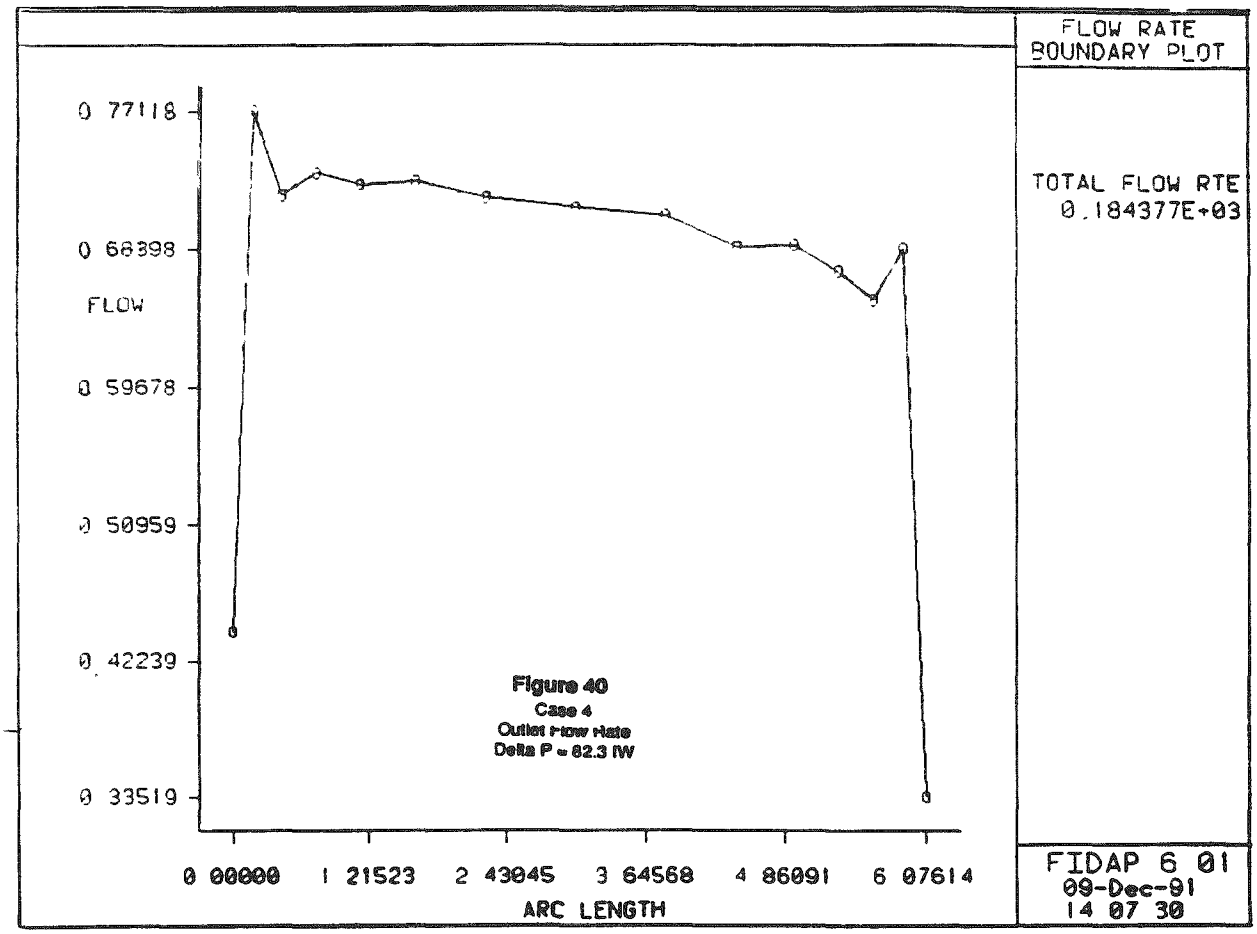


Figure 16 Outlet Flow Profile for 20 ft Diameter GBF with a 5 ft Deep Bed

Ash is removed from the cooled lift gas in a pressurized baghouse, stream 21. The lift pipe transport gas is further cooled to 250°F in a water-cooled heat exchanger, boosted in pressure with a blower, reheated in the regenerative heat exchanger,and recycled to convey particle-laden media up the lift pipe. Pressure is balanced between the filter and the lift pipe, insuring that seepage gas flows down the lower seal leg in the same direction as the ash/media mix.

The recuperative heat exchanger serves two function: it reduces the temperature of the gas in the baghouse and it reheats the gas exiting the boost blower. The gas from the boost blower needs some degree of reheat to insure that any condensed liquids which may have formed during the gas compression in the boost blower are vaporized. An alternative to the recuperative heat exchanger would be to use a waste heat steam generator to reduce the temperature of the recirculation gas going to the baghouse. Although this would be a less expensive capital cost alternative, it would adversely impact the plant heat rate and would not provide for the potential problem of entrained liquids.

The baghouse is designed to operate at 500°F with standard fiberglass felt bags. For the CPFBC, the baghouse uses air as the pulse gas. For the carbonizer and KRW gasifier, the baghouse uses nitrogen as pulse gas. For the CPFBC, the ash discharges from the baghouse through a restricted pipe discharge (RPD) vessel as proposed in the Foster Wheeler study[6]. In the KRW gasification process, the ash from the baghouse discharges through lock hoppers.

The function of the water-cooled heat exchanger located after the baghouse is to reduce the temperature of the gas entering the boost blower. The heat from this exchanger could be recovered by incorporating the cooling stream into the feed water heating loop. No credit was taken for recycling the heat back into the power cycle.

Several types of compressors were evaluated for use as a boost blower. Lobe-type blowers were chosen, but single stage centrifugal blowers are an option.

The media used in the filter are 6 mm, manufactured spheres composed mainly of aluminum oxide and mullite. Bulk density is 110 lb/ft^3. Based on experience with 2 mm and 3 mm media at NYU and Combustion Power, it is expected to be very tough and wear resistant. Wear rates on similar 3 mm media used in the testing at NYU were too low to be measured.

Table 14 shows the gas composition entering the filters for each application.

3.5.1.1 Process Flow for GBF - CPFBC

Each of the two CPFBC's has a granular-bed filter module composed of four 20'-0" ,inside diameter, filter vessels; such that, the gas flow to each vessel is 661,000 lb/hr, 1600°F, 188 psia. The ash concentration is 4000 ppmw. The projected filter pressure drop, based on the CFD model, is 82 IW assuming a 5' deep filtering bed. Figure 17 shows the mass and energy balance for the filters used with the CPFBC. Based on the test results from NYU, the filters are expected to have a particle collection efficiency of greater then 99%.

Table 14 Gas Composition for Each Filter Application (% by Volume)

Gas	CPFBC	Carbonizer	Gasifier
CO_2	7.1	12.4	17.1
H_2O	3.2	11.2	4.3
N_2	77.4	54.4	44.1
O_2	12.3	0.0	0.0
CO	0.0	8.9	9.2
CH_4	0.0	3.7	0.8
C_2's	0.0	1.8	0.0
H_2S	0.0	700 PPM	700 PPM
SO_2	20 PPM	0.0	0.0

The ash to media weight ratio used in sizing the media circulation system is 0.02. In component testing associated with the NYU test program, ratios up to .06 were demonstrated in a media circulation system. Due to operating restrictions at NYU, this ratio could not be duplicated. The amount of ash which is allowed to accumulate in the filter has a critical effect on the design of the filter and its performance. A high ash concentration allows for a smaller media circulation system which favorably impacts filter cost and the filter temperature drop, but may adversely impact filter efficiency. The combination of the gas velocity and ash concentration chosen for this design is based on our experience previous to NYU operation. Testing will be required to confirm these values.

The data given on particulate size distribution indicates that a pre-collection cyclone would not effectively remove a significant portion of the ash to the filter. The expected mean diameter of the ash particles to the filter is 2.1 microns[7]. Our initial economic evaluation showed that the penalty associated with the additional cost and pressure drop of pre-collection cyclones would not be offset by lower filter costs. This is because the pre-collection cyclone does not have a high collection efficiency on such small size particles. Should the size of the particles to the filter be such that a pre-collection cyclone could remove 85 to 90% of the ash, then the use of pre-collection cyclones would have to be reviewed.

Heat loss calculations for the CPFBC GBF are shown in Appendix B. Using the heat loss from each vessel, an energy balance is used to determine the temperature of the streams leaving each piece of equipment; the results of these calculations are shown in Figure 17. Due to the heat loss from the vessels and the heat rejected in the water-cooled heat exchanger, the CPFBC off-gas drops 20°F as it flows through the filter. If a recuperative heat exchanger were not used, the temperature drop through the filter would be about 60°F. If unheated, once-through media were used, the temperature drop through the filter would be about 400°F for the media circulation rate shown.

3.5.1.2 Process Flow for Carbonizer GBF

The carbonizer will use one 14'-0" diameter single entry filter for each PFBC module. The gas flow to each filter is 244,650 lb/hr at 1501°F and 208 psia. The ash concentration in the inlet gas stream is 10,000 ppmw. Because of the relatively high ash concentration, the gas velocity through the filter is 37% of the minimum fluidization velocity, and the ash to media weight ratio is 0.025. The filter bed depth is 5 feet and the expected pressure drop through the filter is 37 IW. Figure 18 shows the process flow diagram for the carbonizer filter.

The temperature drop through the filter is 35°F. Heat loss calculations for the carbonizer GBF are shown in Appendix B. Both the size of the filter and the temperature drop through the filter are directly affected by the quantity of ash flowing to the filter. As with the CPFBC filter, a pre-collection cyclone was rejected because of the low collection efficiency expected due to small particle size. Nevertheless, any modification to the process which would reduce the ash concentration to the filter would reduce the capital cost of the filter and its operational cost. The gas flow rate through the filter was reduced from the 54% of minimum fluidization velocity used with the filter on the CPFBC to 37% to accommodate the high ash concentration. The high heat loss associated with the filter is a direct result of the higher ash concentration which requires a larger media recirculation system. If the inlet ash concentration were the same as that of the CPFBC, the diameter of the filter would be reduced from 14 feet to 11.6 feet. The temperature drop through the carbonizer filter would then be about the same as through the CPFBC filter, 20°F.

Table 14 shows the composition of the reducing gas from the carbonizer. The Foster Wheeler model of the carbonizer predicts the presence of 2.4 lb/hr of coal tars[6]. The tars or other high molecular compounds may crack and form coke as the reducing gas passes through the filter. It is not expected that the formation of coke in the GBF will cause an operation problem due to the movement of the media. Coking in a porous ceramic, candle filter could cause temporary blinding of the filter elements which would require periodic burnout to remove coke deposits.

3.5.1.3 Process Flow for KRW Gasifier GBF

The KRW gasifier[8] will use a 14'-0" diameter filter similar to that used for the carbonizer. The gas flow to the filter is 312,800 lb/hr at 1600°F and 385 pisa. The ash concentration in the inlet gas stream is 8,500 ppm. The gas velocity through the filter is 37% of the minimum fluidization velocity, and the ash to media ratio is 0.025. The bed depth is 5 feet and the expected pressure drop through the filter is 36 IW. Figure 19 shows the process flow diagram for the KRW gasifier filter.

	1	2	3	4	5	6	7•	8	9	10	11
	GBF INLET	TURBINE INLET PIPING	LOWER SEAL LEG	LIFT PIPE SUPPLY	INJECTOR VALVE	LIFT PIPE	INJECTOR VALVE	COUNTER-FLOW AIR	RETURN LEG	DEV OUTLET	EXCH #1 INLET GAS
FLOW											
SOLID, LB/MIN	44		2245			8981			2201	176	
LIQUID, LB/HR											
GAS, LB/MIN	11018	22035	4	2785	60	2800	30	20	2	2826	2826
GAS, ACFM	44042	88635		9134	197	10678	98	66	6	10833	10842
TEMPERATURE, F	1600	1580	1580	1248	1248	1501	1248	1248	1483	1481	1480
PRESSURE PSIA	187 70	184 73	187 70	189 69	189 03	187 30	189 69	189 89	184 73	184 41	184 23

	12	13	14	15	16	17	18	19	20	21	22
	EXCH #1 OUTLET GAS	BAGHOUSE OUTLET	EXCH #2 OUTLET GAS	BLOWER OUTLET	EXCH #1 CLEAN GAS INLET	EXCH #1 CLEAN GAS OUTLET	GBF EXIT	EXCH #2 WATER IN	EXCH #2 WATER OUT	ASH	BLEED LINE
FLOW											
SOLID, LB/MIN										176	
LIQUID, LB/HR								149576	149576		
GAS, LB/MIN	2826	2826	2826	2826	2826	2826	11018				22
GAS, ACFM	5415	5435	4034	3832	3836	9278	44321				73
TEMPERATURE, F	500	500	250	250	250	1251	1580	110	180	500	1251
PRESSURE PSIA	182 49	181 83	181 17	190 73	190 55	189 87	184 71	50 00	20 00	181 83	184 73

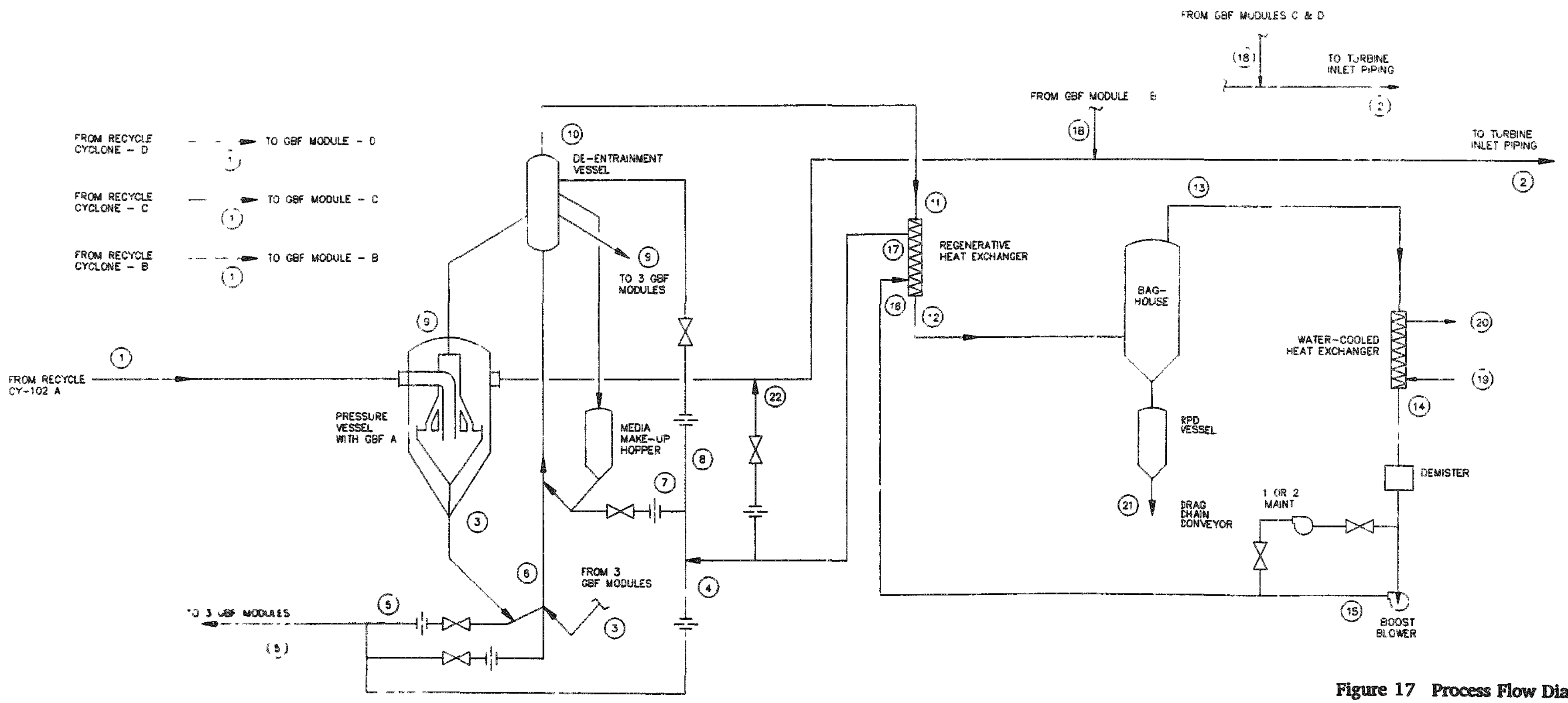


Figure 17 Process Flow Diagram, GBF for CPFBC

• INTERMITTENT

NOTE. FLOWS SHOWN FOR EACH OF TWO CPFBC'S

	1 GBF INLET	2 TURBINE INLET PIPING	3 LOWER SEAL LEG	4 LIFT PIPE SUPPLY	5 INJECTOR VALVE	6 LIFT PIPE	7* INJECTOR VALVE	8 COUNTER-FLOW AIR	9 RETURN LEG	10 DEV OUTLET	11 EXCH #1 INLET GAS
FLOW											
SOLID, LB/MIN	41		1680			1680			1639	41	
LIQUID, LB/HR											
GAS, LB/MIN	4078	4078	4	471	60	475	30	20	11	506	506
GAS, ACFM	15911	15734		1483	189	1744	94	63	40	1863	1864
TEMPERATURE, F	1501	1468	1468	1137	1137	1384	1137	1137	1365	1363	1362
PRESSURE, PSIA	207 90	206 56	207 90	209 89	209 23	207 78	209 89	209 89	206 56	204 87	204 69

	12 EXCH #1 OUTLET GAS	13 BAGHOUSE OUTLET	14 EXCH #2 OUTLET GAS	15 BLOWER OUTLET	16 EXCH #1 CLEAN GAS INLET	17 EXCH #1 CLEAN GAS OUTLET	18 GBF EXIT	19 EXCH #2 WATER IN	20 EXCH #2 WATER OUT	21 ASH	22 BLEED LINE
FLOW											
SOLID, LB/MIN										41	
LIQUID, LB/HR								31134	31134		
GAS, LB/MIN	506	506	506	506	506	506	4063				15
GAS, ACFM	990	994	737	705	705	1596	15686				48
TEMPERATURE, F	500	500	250	250	250	1142	1468	110	180	500	1142
PRESSURE, PSIA	202.95	202 29	201 63	210 93	210 75	210 07	206 56	50 00	20 00	202 29	206 56

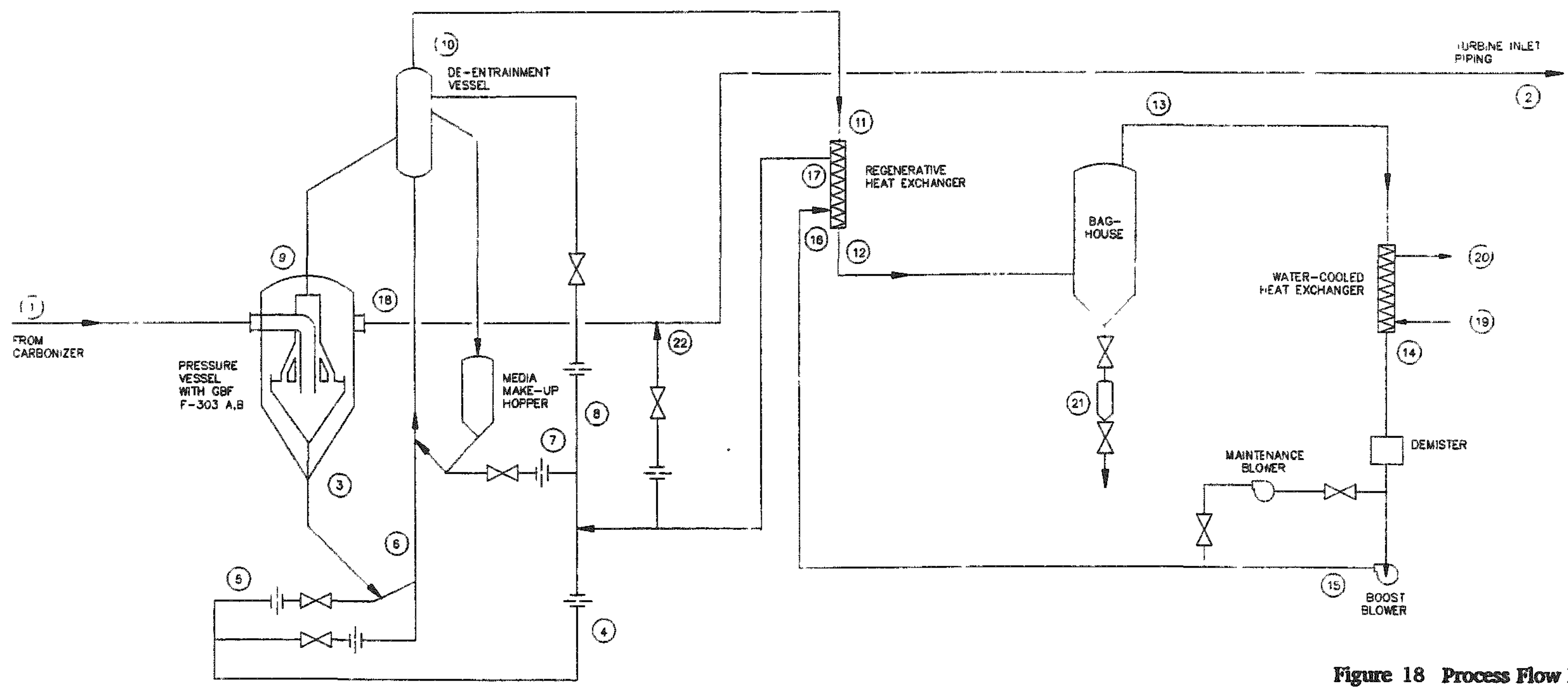


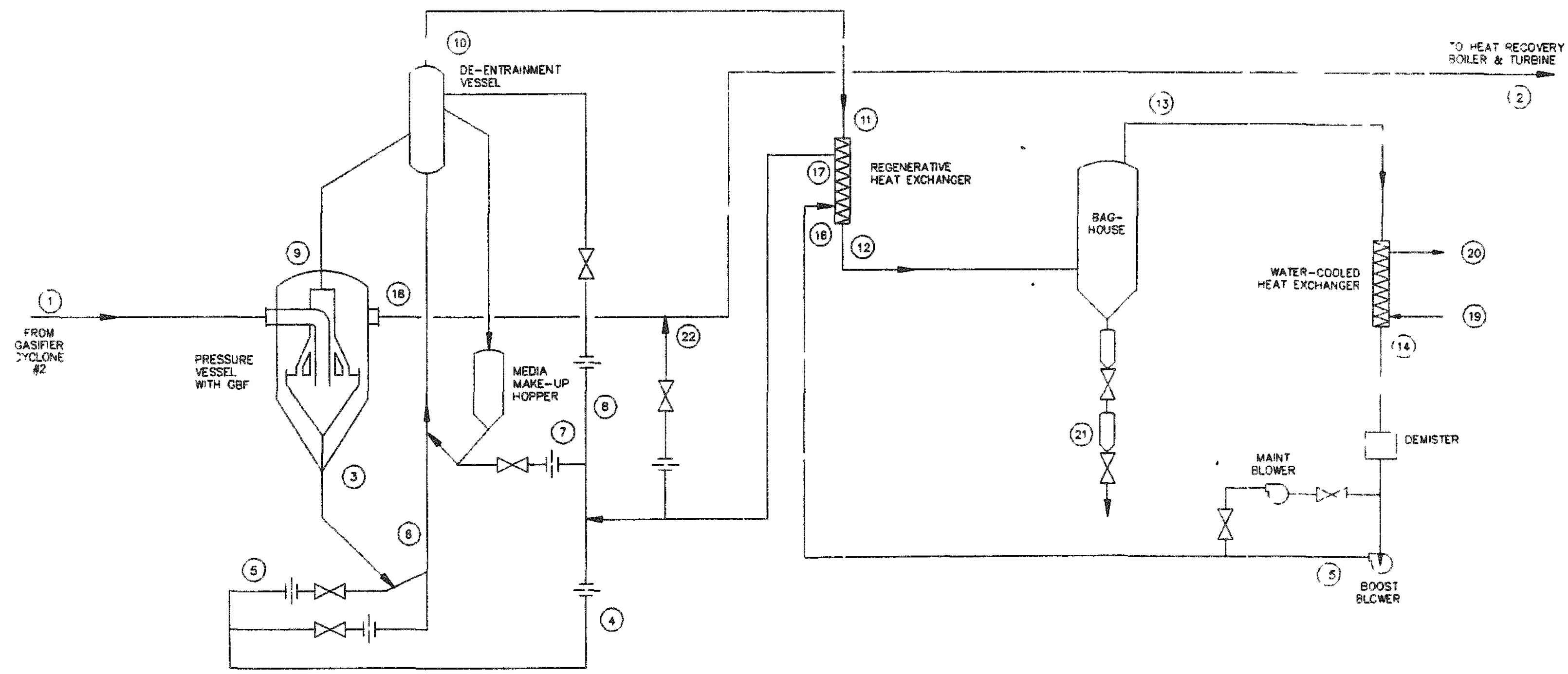
Figure 18 Process Flow Diagram, GBF for Carbonizer

* INTERMITTENT

NOTE: FLOWS SHOWN FOR EACH OF TWO CARBONIZERS

	① GBF INLET	② TURBINE INLET PIPING	③ LOWER SEAL LEG	④ LIFT PIPE SUPPLY	⑤ INJECTOR VALVE	⑥ LIFT PIPE	⑦* INJECTOR VALVE	⑧ COUNTER-FLOW AIR	⑨ RETURN LEG	⑩ DEV OUTLET	⑪ EXCH #1 INLET GAS
FLOW											
SOLID LB/MIN	44		1818			1818			1773	44	
LIQUID LB/HR											
GAS, LB/MIN	5213	5213	9	641	60	650	30	20	17	687	687
GAS, ACFM	12628	12458		1241	116	1454	58	39	38	1534	1535
TEMPERATURE F	1600	1565	1567	1195	1195	1442	1195	1195	1423	1422	1422
PRESSURE, PSIA	385 00	383 66	385 00	386 99	386 33	384 86	386 99	386 99	383 66	381 50	381 32

	⑫ EXCH #1 OUTLET GAS	⑬ BAGHOUSE OUTLET	⑭ EXCH #2 OUTLET GAS	⑮ BLOWER OUTLET	⑯ EXCH #1 CLEAN GAS INLET	⑰ EXCH #1 CLEAN GAS OUTLET	⑱ GBF EXIT	⑲ EXCH #2 WATER IN	⑳ EXCH #2 WATER OUT	㉑ ASH	㉒ BLEED LINE
FLOW											
SOLID LB/MIN										44	
LIQUID LB/HR								47368	47368		
GAS, LB/MIN	687	687	687	687	687	687	5187				26
GAS, ACFM	787	788	584	569	569	1332	12407				51
TEMPERATURE F	500	500	250	250	250	1198	1567	110	180	500	1198
PRESSURE, PSIA	379 58	378 92	378 26	388 03	387 85	387 17	383 66	50 00	20 00	380	384



* INTERMITTENT

Figure 19 Process Flow Diagram, GBF for KRW Gasifier

The temperature drop through the filter is 35°F. As is the case for the carbonizer, the high heat loss is a result of the high ash concentration to the filter. Table 14 shows the composition of the gas entering the filter. Heat loss calculations for the gasifier GBF are shown in Appendix B.

In the KRW process, the gasification products are cooled after the HTHP gas cleanup device before entering the zinc ferrite H_2S removal process. There may be some benefits to partial cooling the gasification products before the gas cleanup equipment. A lower temperature gas stream would allow lower cost materials to be used for the filter internals, would reduce the size of the filter. Presently the GBF is designed to handle the high temperature gasification products, and the benefits of a lower temperature gas entering the filter were not evaluated.

3.5.2 Instrumentation and Control

An automatic control system maintains the system process parameters at specified set-points, provides system status and safe operation, and adjust filter operating conditions to match changes in the process gas stream. The automatic control system for each of the filter applications is nearly the same. Figures 20, 21, and 22 show the Piping and Instrumentation Diagrams for each application.

Flow, temperature and pressure requirements are arranged to give complete definition of system operation at all times. Some redundant measurements are provided to cross check data. Computer control is utilized with a programmable logic controller.

The control system has four major control loops. They are:

- Filter pressure drop

This loop adjust the media circulation rate to maintain the filter pressure drop at a predetermined set point. The set point for the filter pressure drop is a function of the gas flow through the filter and is determined from tests during the initial startup of the filter. If the filter pressure drop is above the set point, the gas flow to the lift pipe "ell" valve is increased to increase the media circulation rate. The increased media circulation rate will lower the ash concentration in the filter which will reduce the filter pressure drop. An opacity meter or other solids monitoring device in the cooled turbine exhaust is used as a trim function for the filter pressure drop set point. If the opacity meter indicates poor filter efficiency, the filter pressure drop set point is increased to reduce the media circulation rate and increase filter efficiency.

- Lift gas flow

This loop maintains the gas flow through the lift pipe at the specified set-point by adjustment of the boost blower speed. The set-point for this loop is selected to minimize the media velocity in the lift pipe and is a function of the lift pipe pressure drop, pressure and temperature.

- Pressure balancing

Flow control valve FCV-170 maintains the pressure balance between the filter element and the lift pipe by bleeding gas from the high pressure side of the boost blower to the process gas stream exiting the filter.

When large pressure excursion occur such as during startup or shutdown, PDCV-006 and PDCV-006-2 automatically bleed gas into or out of the lift gas circulation system allowing the pressure in the media recirculation system to rapidly follow system pressure.

- Ash removal system

The CPFBC will use restricted pipe discharge (RPD) hoppers as proposed in the Foster Wheeler study to remove the ash captured in the baghouse. The ash drains from the baghouse hopper through a standpipe to the RPD hopper. A description of the operation and control of the RPD system can be found in the Foster Wheeler report[6].

The KRW gasifier filter will use a lock hopper system to discharge high pressure ash from the baghouse hopper to the low pressure ash conveying system. The steps are:

A. Both ball valves start off closed while ash accumulates in the upper ash holding vessel.

B. At a preset time interval or at operator initiation, a pressure balancing valve opens to bleed system pressure into the lower ash holding vessel. A pressure switch proves status.

C. The upper ball valve opens and ash falls at equal pressure into the lower ash holding vessel.

D. After the upper ball valve closes to isolate the lower ash holding vessel, a bleed valve opens to vent pressure. Desired pressure is proven by a switch.

E. The lower ball valve opens to discharge ash at atmospheric pressure into the ash conveying line

F. The sequence ends after the lower ball valve closed.

- Computer Control System

The computer control system is based on a programmable logic controller (PLC). It is constructed on a modular basis using plug-in printed circuit cards installed in a control rack. See Figure 23 for the granular-bed filter for the CPFBC. Figure 24 shows the system for the carbonizer and the gasifier granular-bed filters. A central processing unit scans the user program and generates logic commands. Data collection is performed through the device called a "Genius I/O" (Input/Output) connected to the PLC.

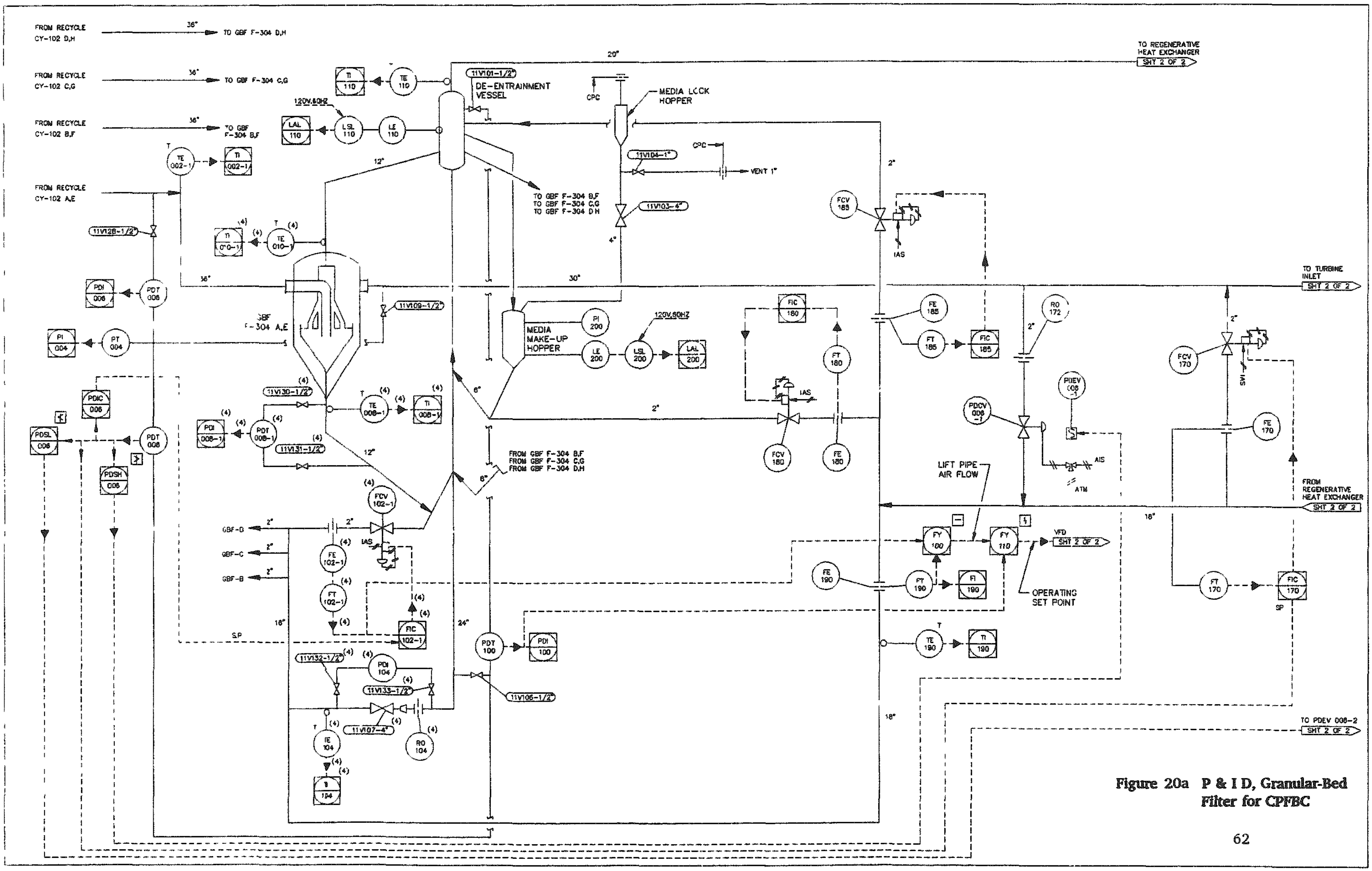


Figure 20a P & I D, Granular-Bed Filter for CPFBC

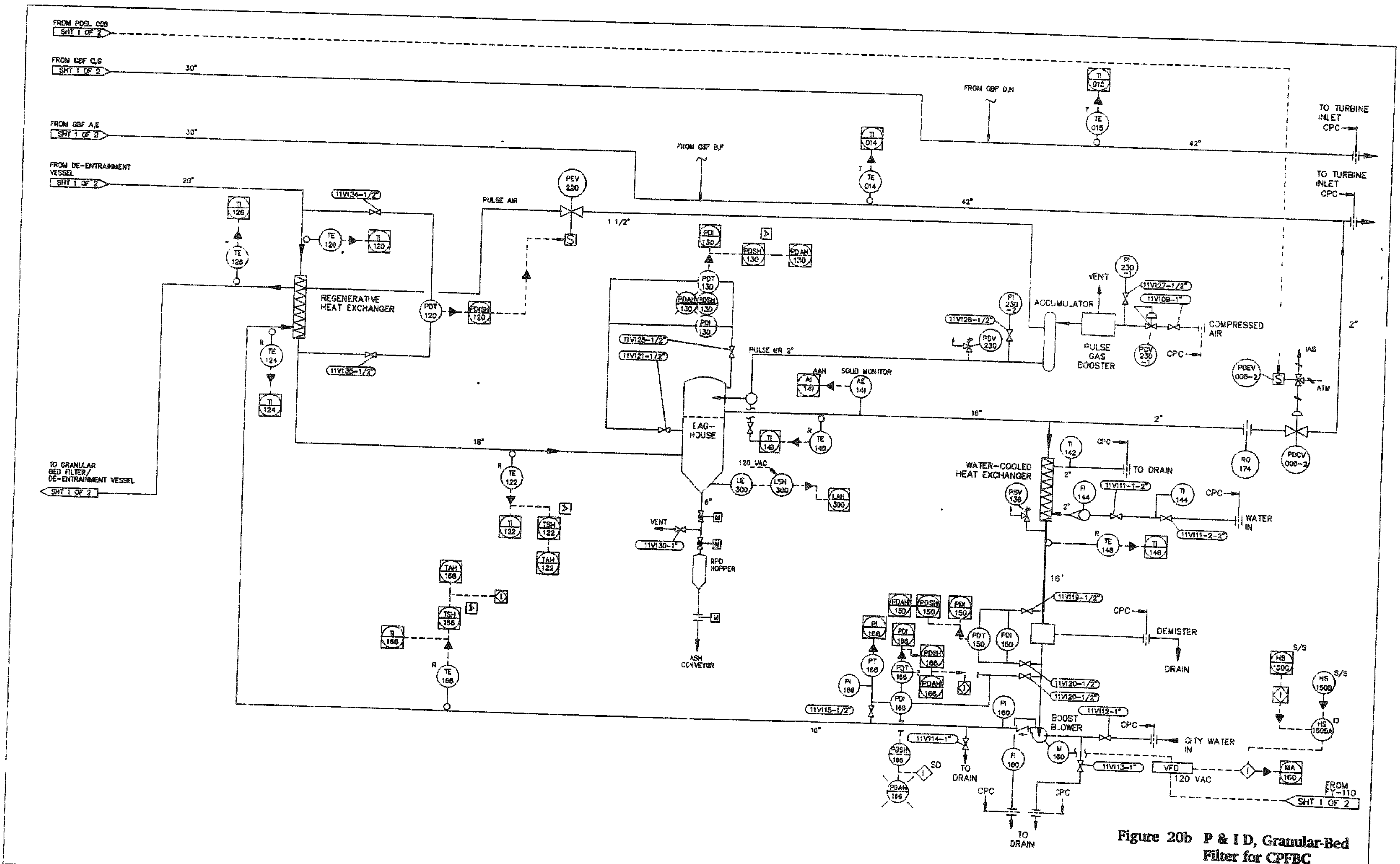


Figure 20b P & I D, Granular-Bed Filter for CPFBC

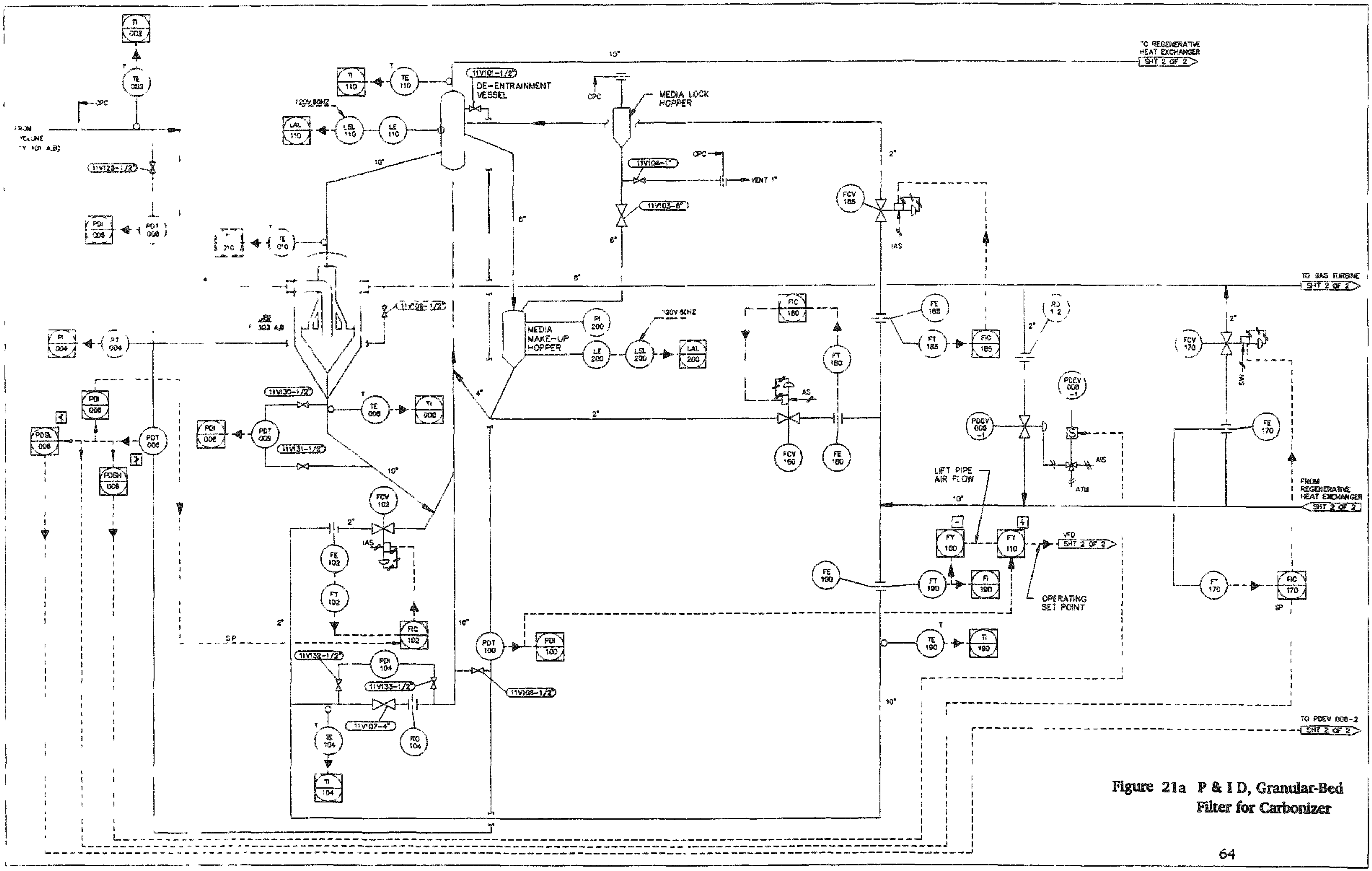


Figure 21a P & I D, Granular-Bed Filter for Carbonizer

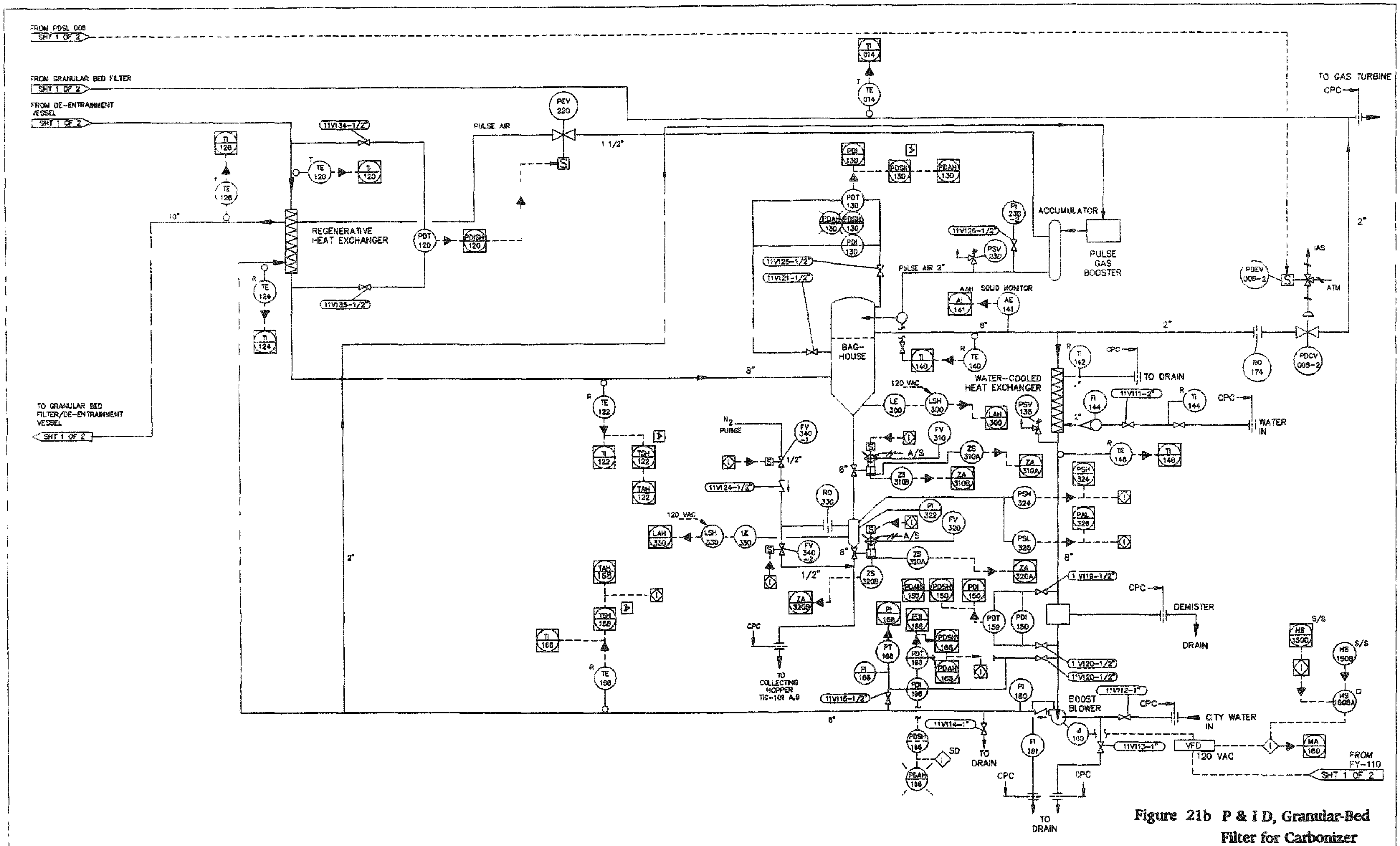


Figure 21b P & I D, Granular-Bed Filter for Carbonizer

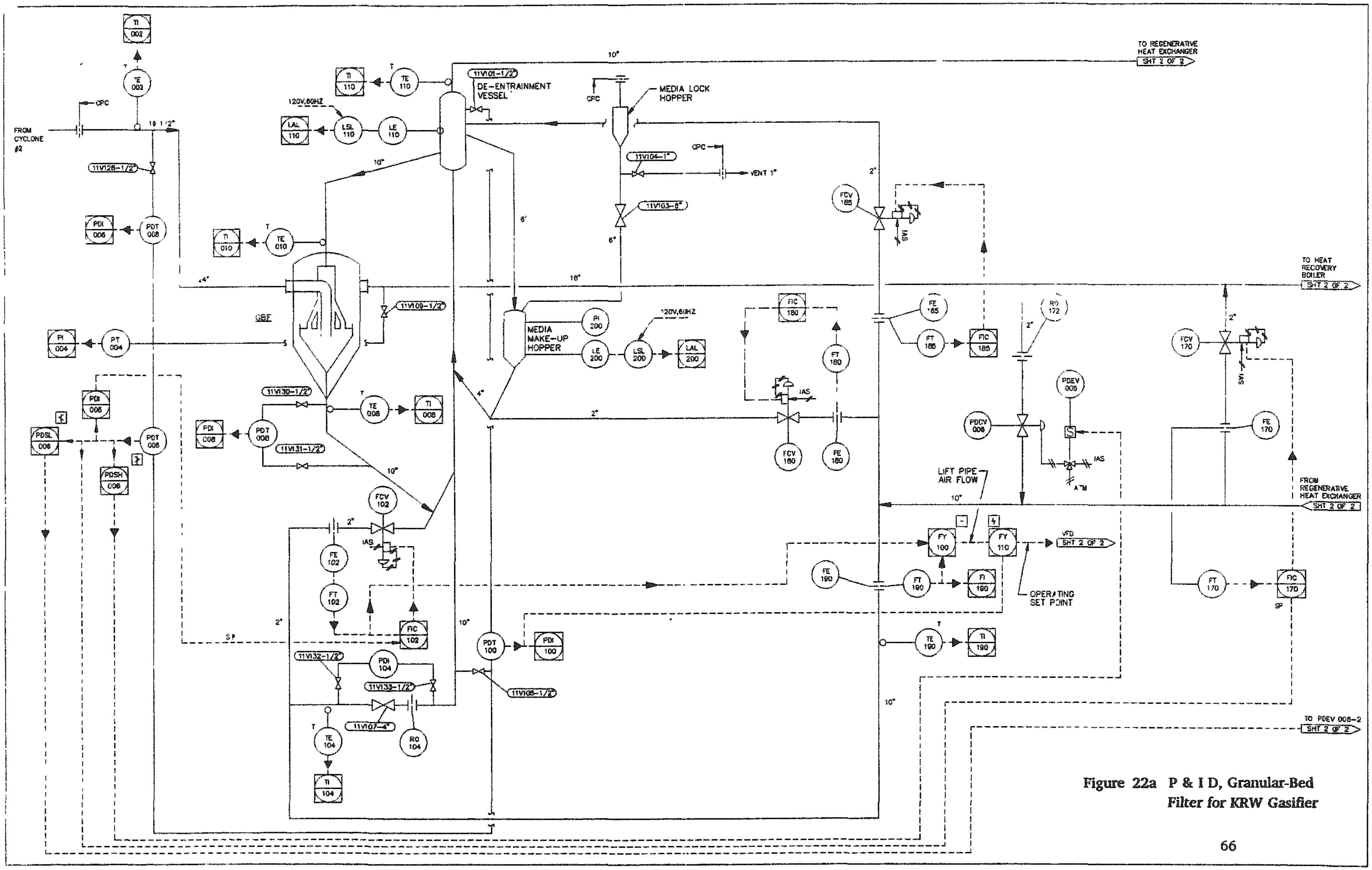


Figure 22a P & I D, Granular-Bed Filter for KRW Gasifier

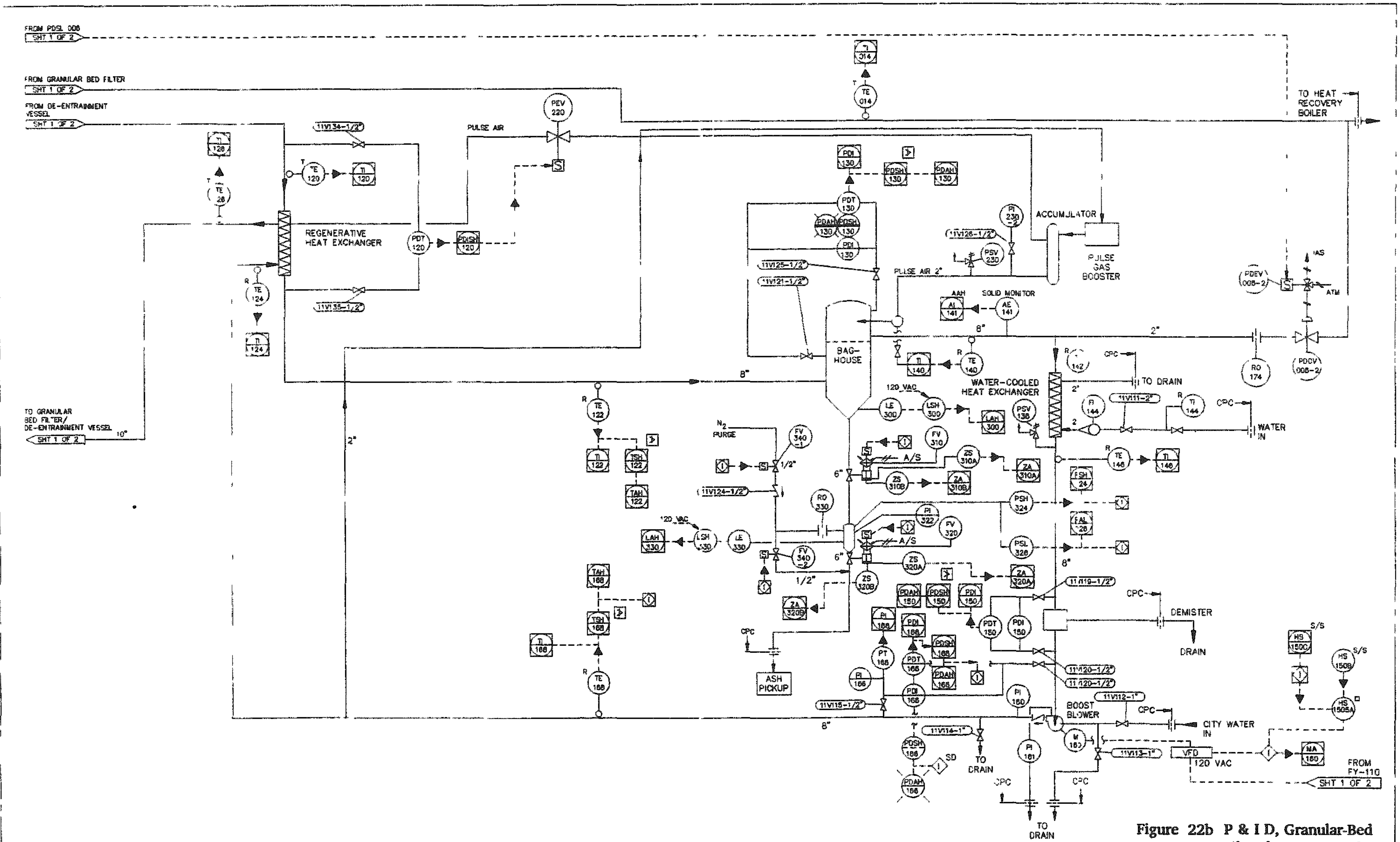


Figure 22b P & I D, Granular-Bed Filter for KRW Gasifier

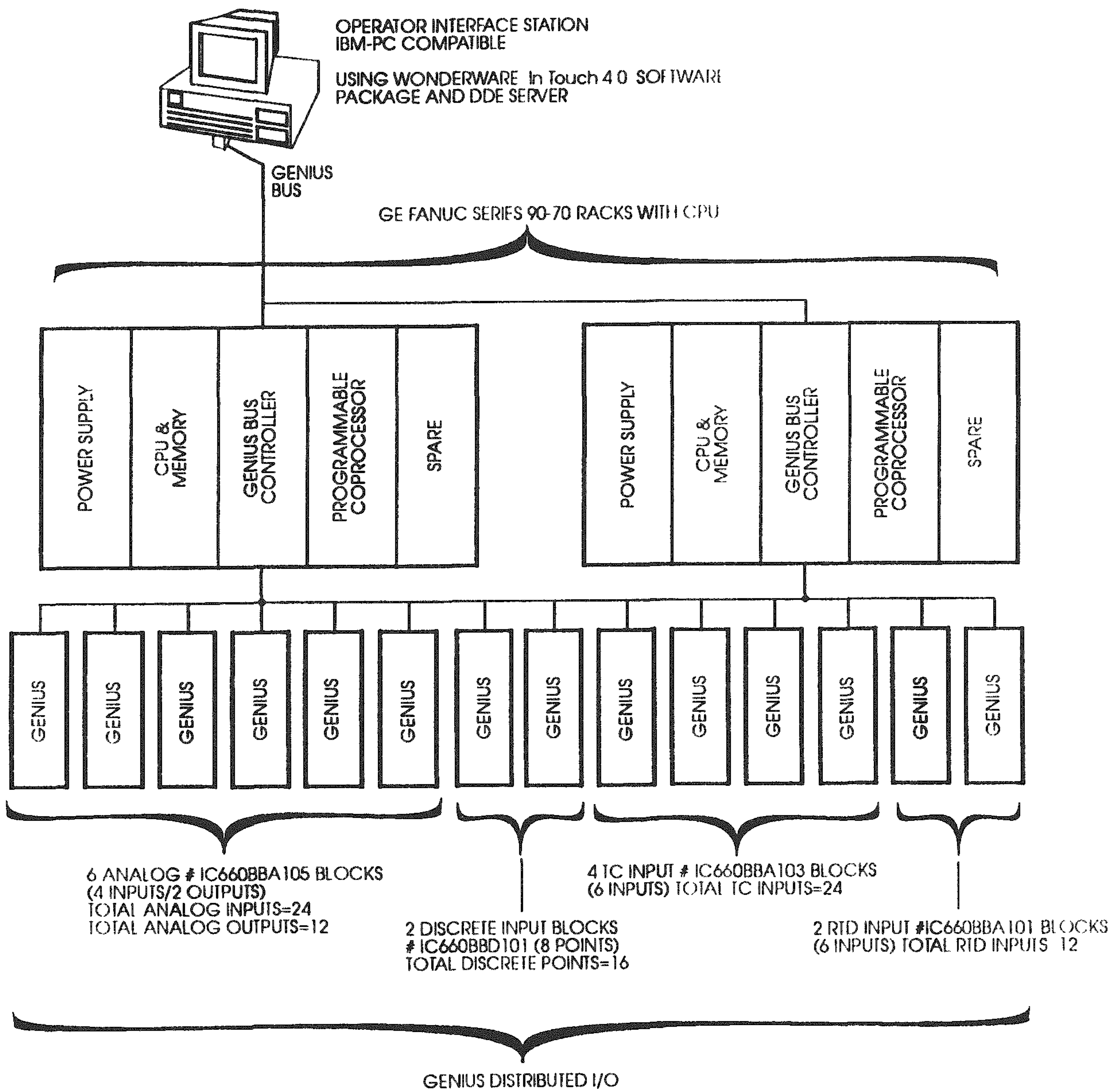


Figure 23 Control System Architecture, GBF for CPFBC

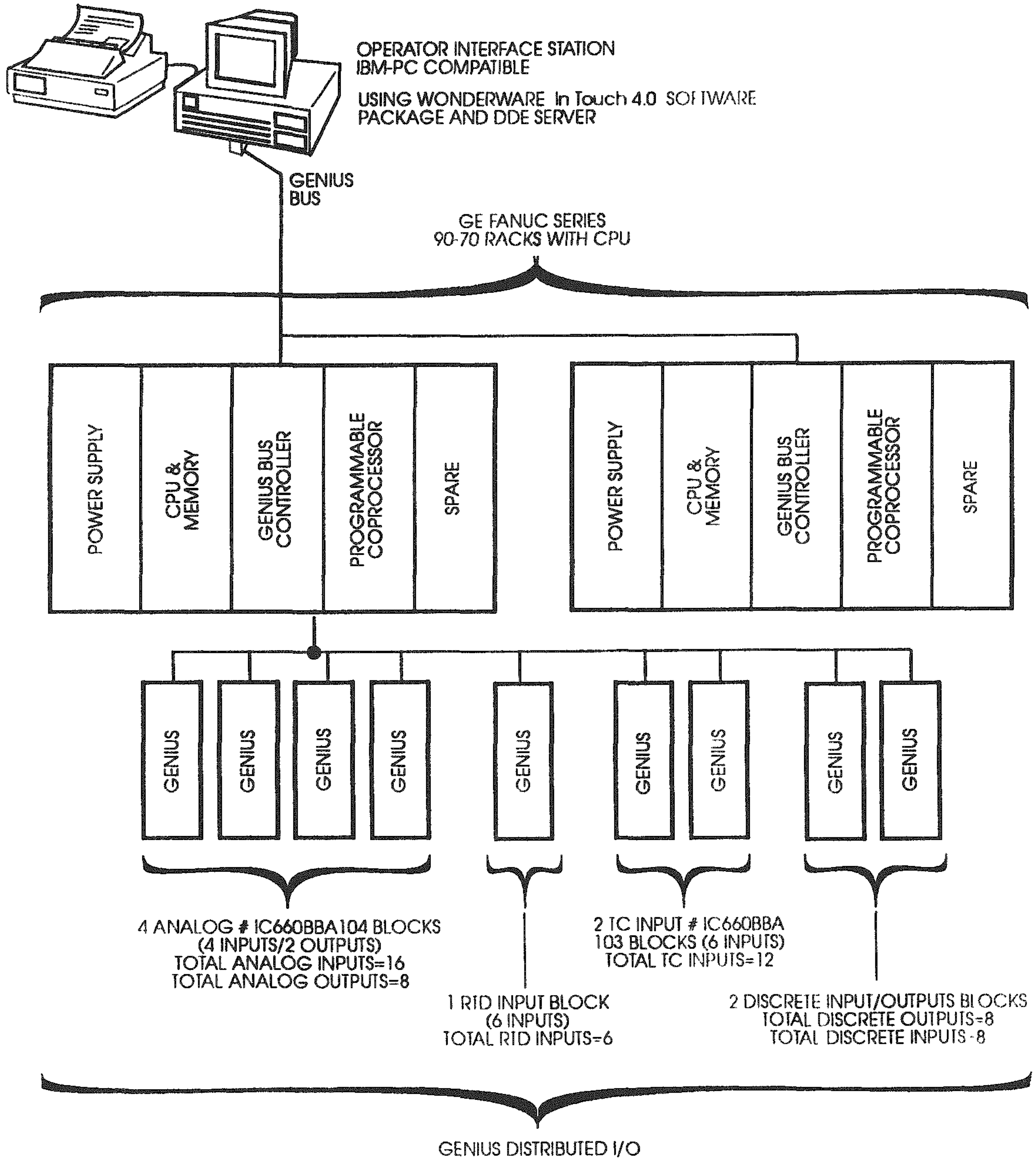


Figure 24 Control System Architecture, GBF for Carbonizer and Gasifier

Unlike conventional remote I/O, this arrangement requires no central I/O control cabinets, no racks, and no separate power supply. These I/O devices are installed close to field instruments. Genius I/O automatically provides diagnostic information of field wiring and power conditions. This troubleshooting capability reduces time needed for control system debugging.

This mode of local computer control also cuts down on maintenance costs and system downtime because it eliminates the need for destructive fuses. When overloads and short circuits are detected, output circuits turn off immediately, protecting circuitry and wiring.

The software package provides monitoring, control, data acquisition, alarms, and graphics. All process data can be transferred in common data base programs; such as, Microsoft's data base program called EXCEL, to take advantage of data conversion capabilities. Using the proficiency of the software package, user programmed management reports can be prepared and printed at anytime, during operation or downtime. Selected data can be stored in computer memory for a predetermined amount of time, allowing historical review of operation.

Included with the computer control package are: analog transmitters, thermocouple inputs, RTD inputs, and analog outputs. The local computer control module includes: redundant CPU with memory, redundant rack, redundant power supply, redundant bus controller, redundant coprocessor with software, and required input and output blocks. Software includes programming to allow: standard displays, dynamic graphics and trending, configuration changes, alarming, and report generation. For monitoring the operation, a caliber 486SX personal computer is included with two serial ports, one parallel port, 105 Megabyte hard drive, 3.5" floppy drive, Super VGA monitor, keyboard, mouse, color printer, and interconnecting cables. Personal computer software includes MS DOS 5.0 and Windows 3.1.

3.5.3 Granular-Bed Filter Configurations

The 452 MWe, second generation PFB combustion plant is arranged in two identical trains of equipment, each sized for 226 MWe. Each train includes a CPFBC and a carbonizer. There are four granular-bed filter vessels for each CPFBC and one granular-bed filter vessel for each carbonizer. These filter vessels replace two cross-flow filter vessels for each CPFBC and one cross-flow filter vessel for each carbonizer. For the 100 MWe, KRW, air blown gasifier, a single granular-bed filter vessel replaces the cross-flow filter originally utilized. Figure 25 shows the basic configuration of these granular-bed filters. The filters are enclosed in refractory-lined pressure vessels. Dirty gas enters through a nozzle incorporated into an vessel extension on top of the filter vessel. This gas is dispersed by metal ducting into the filter media at the gas/media interface. Clean filter media enters at the top of the filter and is distributed across the filter by numerous pipes and an annular distribution duct in the center. Ash is removed by the spherical, ceramic, filter media moving in the opposite direction of the ash-ladened process gases. Clean gas exits the open area above the filter bed and ash ladened media exits at the bottom of the filter.

3.5.3.1 Refractory

Several approaches to lining the filter with refractory were considered.

- Cast insulation and hardface in the filter cone and partial sidewalls, and ceramic fiber product in the gas space above the filter media.
- Castable-type refractory applied by pneumatic gunning techniques installed in regions described above.
- Insulating and hardface brick in the filter cone with gunite insulation/hardface in the space above the filter media.

In the granular-bed filter vessel above the filter bed, conditions for the refractory are fairly mild, even in the reducing atmospheres for the carbonizer and the gasifier. There is virtually no ash, gas velocity is very low (< 10 ft/sec) and operating temperatures are 1500°F to 1600°F. Under these conditions, the most important refractory properties to consider are thermal conductivity to minimize heat loss and refractory stability to resist any kind of deterioration that could add particles to the gas stream leaving the filter.

Ceramic fiber products have very low thermal conductivity (.5 to 1 Btu-in/hr ft^2 °F) and are available in a number of forms that could be suitable for lining this zone. Even though manufactures and installers claim otherwise, these products could deteriorate and add particles, in the form of ceramic fibers or chunks, to the gas stream exiting towards the gas turbine. Metal liners can be used to protect this material, but this is costly. Consequently, these materials are not proposed; although, consideration would be given in an actual application. Instead our choice is a lightweight, insulating gunning mix. These materials have slightly less insulating value when compared to ceramic fiber products, but are much stronger and more resistant to deterioration and chemical attach. A 60 to 70 lb/ft^3 gunning mix could be applied as a combination insulating and hardface layer in the granular-bed filter operating in an oxidizing or reducing environment. Thermal conductivity is in the range of 1.3 to 1.6 Btu-in/hr ft^2 °F and good strength is indicated by a cold crushing strength of 300 to 500 psi after heating to 1500°F.

In the granular-bed filter area that houses filtration media in the form of 6 mm ceramic spheres, requirements are different. A hardface material must be fairly smooth to allow the filter media to move with minimal friction. Furthermore, the material must have good strength to hold the media weight and moderate abrasion resistance for long life. At New York University, the media reservoir was lined with A.P. Green Lo-Abrade castable hardface and a very lightweight, low strength insulating castable. This approach was satisfactory from both the process and strength standpoint. For small granular-bed filters, casting the cone and sidewall areas that enclose the media would be the preferred technique. Pneumatic gunning would not be suitable because the resulting surface tends to be very rough in comparison to formed castables. In larger granular-bed filters, forms for installing castables (similar to forms for installing concrete) are very large, bulky and expensive. There will be an economic break-point where alternate techniques are more suitable. Super-duty refractory brick can be installed in these larger diameters to achieve a smooth surface that we feel is equivalent to a cast refractory surface. Abrasion resistance and strength are also comparable to castable refractory hardfaces. Bricking is chosen for the large (14-20' diameter) granular-bed filters. For an insulation layer under the hardface bricks, we have also chosen an insulating brick of moderate strength and good thermal conductivity.

Insulating refractory brick comes in many grades, differentiated by suitability for temperature, thermal conductivity, and strength. In this case, temperature is not a factor, as typical insulating firebrick is rated to at least 2000°F. Requirements for strength may govern the choice of brick as the weight of the filter media must be supported off the filter wall and cone. Thermal conductivities of insulating firebrick range from 1 to 2.5 Btu-in/hr ft^2 °F. Higher thermal conductivities are associated with higher strength materials.

3.5.3.2 Metal Internals

The life of the metallic internals used in the filters will greatly depend on the operating temperature and gas environment. For the CPFBC granular-bed filter operating at 1600°F with a high oxygen and a low sulfur dioxide environment, we expect that the loss of metal will be less than 5 mils/year. This corresponds to a service life of about 25 years. In candle filters for service in PFBC applications (oxidizing atmospheres) RA333 and 310 SS have been used with satisfactory results[9]. RA333 has been used in regions of high stress, and 310 SS has been used in regions of low stress. Therefore, for the candle filter in the oxidizing atmosphere, the CPFBC candle filter, these materials are proposed as referenced in the section describing the ceramic candle filters. A different alloy, RA253MA has also shown good strength and corrosion resistance in oxidizing atmospheres[10]. The granular-bed filter internals are under minimal stress in the CPFBC filter, and since the additional high temperature strength of RA333 is not necessary, the bulk of the internals are proposed to be made from RA253MA. Minimally stressed internals for auxiliary granular-bed filter equipment are proposed in 310 SS.

The carbonizer and gasifier environments will be significantly more corrosive. In a 1500-1600°F reducing gas environment, the corrosion rate could be as high as 20 mils/year[11]. The expected service life in this situation could be only 5 years; less if "breakaway" corrosion occurs. Breakaway corrosion is a suddenly increasing corrosion rate occurring after a long period of relatively stable behavior. As the corrosion information available on metals in the reducing environments is limited, we believe that one of the functions of any future development program should be to collect corrosion data on promising alloys which can be used in this type of service.

Since sulfur is captured in the gasifier, sulfidation potential due to H_2S is considerably reduced downstream in the filter. Strength is an important factor for the candle filter tubesheet, but primary stresses in the granular-bed filter internals are low because the internals hang from the top of the vessel and basically support only their own weight. Welding must be sound from the standpoint of strength and corrosion. Consideration must be given to metal toughness, creep, creep fatigue, thermomechanical fatigue, and all types of corrosion, both low and high temperature. Primary stresses at 1500-1600°F must be low; 600-2500 psi depending on the material choice. This design stress is typically determined by ASME Boiler Code guidelines even though the Code does not specifically apply to the internals of the filters or auxiliary equipment. The Code gives a number of criteria for the determining design stress. For the 1500-1600°F range, the criteria is usually based on some percentage of the average stress to produce rupture in 100,000 hours; or less, depending on the source and requirements. Candidate metals for carbonizer and KRW gasifier granular-bed filter systems are: 310 SS. RA85H, Haynes 556, Haynes HR-160, and Haynes 188. The choice is RA85H for both granular-bed and ceramic candle filter internals[12] and 310 SS for other lightly-stressed components such as duct liners. This choice is made somewhat based on costs; since, other choices are considerably more expensive. Table 15 summarizes the materials chosen for the different components, and Table 16 lists the compositions of these materials. The first choice of materials is marked with an "X" in Table 15. In some cases the material choice is limited by its availability in the forms utilized in the granular-bed or the ceramic candle filter. Prices listed are for purchased plate, 1/4" to 1" thick, and are rounded off the nearest dollar in most cases.

See Figures 26 and 27 for the configuration and dimensions of the CPFBC filter. Dimensions and pressure vessel design data are given on Figure 26. Information on the design of refractory and internals is given on Figure 27. The carbonizer, granular-bed filter is shown on Figures 28 and 29, and the IGCC (KRW, air blown gasifier) granular-bed filter is shown on Figures 30 and 31.

3.5.4 Granular-Bed Filter Plant Arrangements

Included with the moving granular-bed filter (GBF) is a media circulation and ash removal system as shown in Figures 32, 33, and 34. In all three systems, the particle-laden media from the filter is withdrawn at the bottom and transported pneumatically in a lift pipe to a de-entrainment vessel where the filter media and the ash particles are separated. The clean media flows by gravity back to the filter vessel. The media is distributed in the filter vessel through distribution pipes and an annulus around the central inlet pipe. The lift gas and particles leaving the de-entrainment vessel are cooled to 500°F in a regenerative heat exchanger. Ash is removed from the cooled lift gas in a pressurized baghouse and depressurized through a restricted-pipe discharge (RPD) or lock-hopper system. The lift pipe, transport gas is further cooled to 250°F in a water-cooled heat exchanger, boosted in pressure with a blower, reheated in the regenerative heat exchanger, and reused to convey particle-laden media up the lift pipe.

Table 15 Granular-Bed Filter Materials

Application/ Mat'l	Highly Stressed Plt/Sht	Lightly Stressed Plt/Sht	Pipe (1)	Flats (1)	Sr (2)	Approx. Plt Cost ($/lb)
CPFBC						
RA333**	Option				1800	8-9
RA253MA**	X		Option		1450	4
310		X	X	X	800	2.5
Carbonizer/ Gasifier						
310		X	X	X	800	2.5
RA85H**	X		Option		1300	4
556TM*	Ref				3000	14
HR-160TM*	Ref				2500	20
188TM*	Ref				4000	28

(1) Use 'Option' for highly stressed pipe.
(2) Average stress to rupture for 100,000 hours, psi.
* Haynes International, Inc (Haynes alloys 556, 188, HR-160)
** Rolled Alloys, Inc.

Table 16 Nominal Composition of Heat-Resistant Alloys (wt %)

Alloy	UNS	Fe	Cr	Ni	Mo	Co	Others
RA333**	N06333	Bal	26	46	3.3	3.3	3.3 W 1.0 Si
RA253MA**	S30815	Bal	21	11			1.7 Si 0.06Ce
310 SS	S31000	Bal	25	20			
RA85H**	S30615	Bal	19	15			3.6 Si 1.0 Al
556™*	R30556	Bal	22	21	3.3	19	2.8 W 0.8 Ta 0.3 Al
188™*	R30188	3	22	22		Bal	14 W
HR-160™*		2	29	37		29	2.8 Si 0.5 Ti

* Haynes International, Inc (Haynes alloys 556, 188, HR-160)
** Rolled Alloys, Inc.

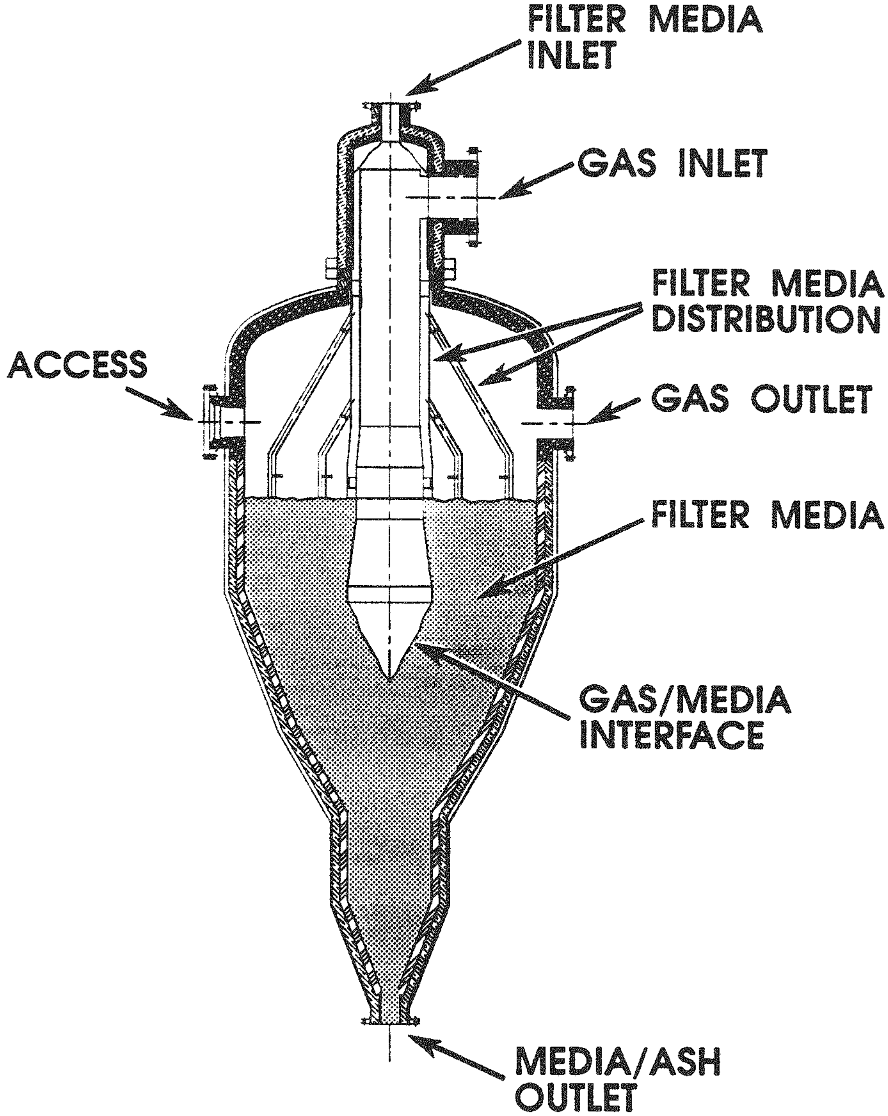
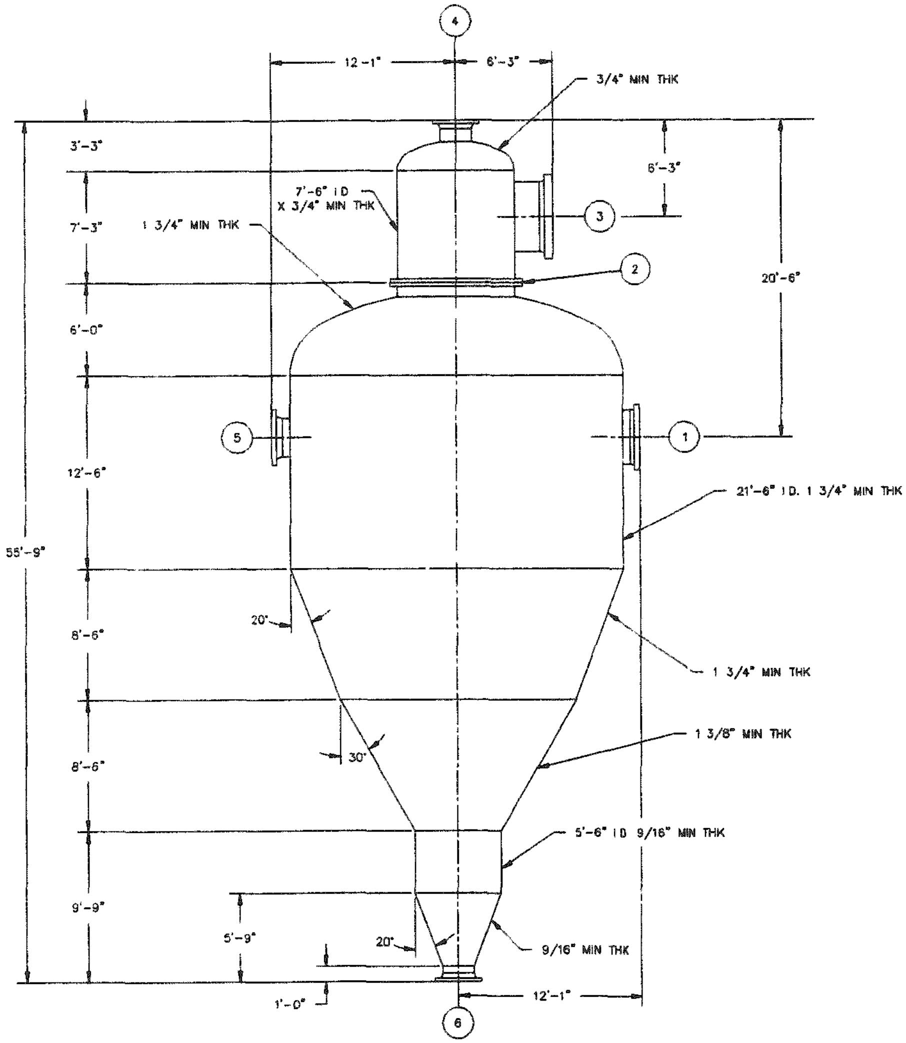


Figure 25 Granular-Bed Filter Configuration

92901BKW.CDR



VESSEL DATA

SERVICE:	CPFBC OUTLET FILTER
OPERATING PRESS:	185 PSIA
DESIGN PRESS:	200 PSIG
MAX. OPERATING TEMP:	1600°F (INTERNAL)
DESIGN TEMP:	650°F (METAL)
WIND DATA:	UBC (70 MPH, EXP.C)
EARTHQUAKE DATA:	UBC (ZONE 1)
CODE:	ASME SECT VIII DIV. 1
CODE STAMP:	YES
P.W.H T. FOR CODE:	PARTIAL
P W.H.T. FOR PROCESS:	NO
JOINT EFF:	100%
RADIOGRAPHED:	FULL
CORROSION ALL.	1/8'
MAT'L SHELL.	SA-516 GR 70
MAT'L HEADS:	SA-516 GR 70 (2:1 ELLIPTICAL)
MAT'L SUPPT'S:	SA-516 GR 70
MAT'L NOZZLES:	SA-516 GR 70
MAT'L FLANGES:	SA-105
EMPTY WEIGHT:	185000 LBS (METAL ONLY)
WATER ONLY WEIGHT:	560000 LBS
FILTER MEDIA:	580000 LBS
REFRACTORY LINING:	140000 LBS
SHIPMENT:	1 PIECE

NOZZLES

NO.	SIZE	ANSI RATING	SERVICE	I.D LINING	QTY
1	42"	CL 300 RF	OUTLET	30"	1
2	90"	CL 300 RF	ACCESS	72"	2
3	54"	CL 300 RF	INLET	36"	1
4	24"	CL 300 RF	MEDIA IN	12"	1
5	30"	CL 300 RF	MANWAY/BLIND	18"	1
6	24"	CL 300 RF	MEDIA OUT	12"	1

1. SEE SHEET 2 FOR REFRACTORY INSTALLATION NOTES.

Figure 26 Granular-Bed Filter Pressure Vessel, CPFBC

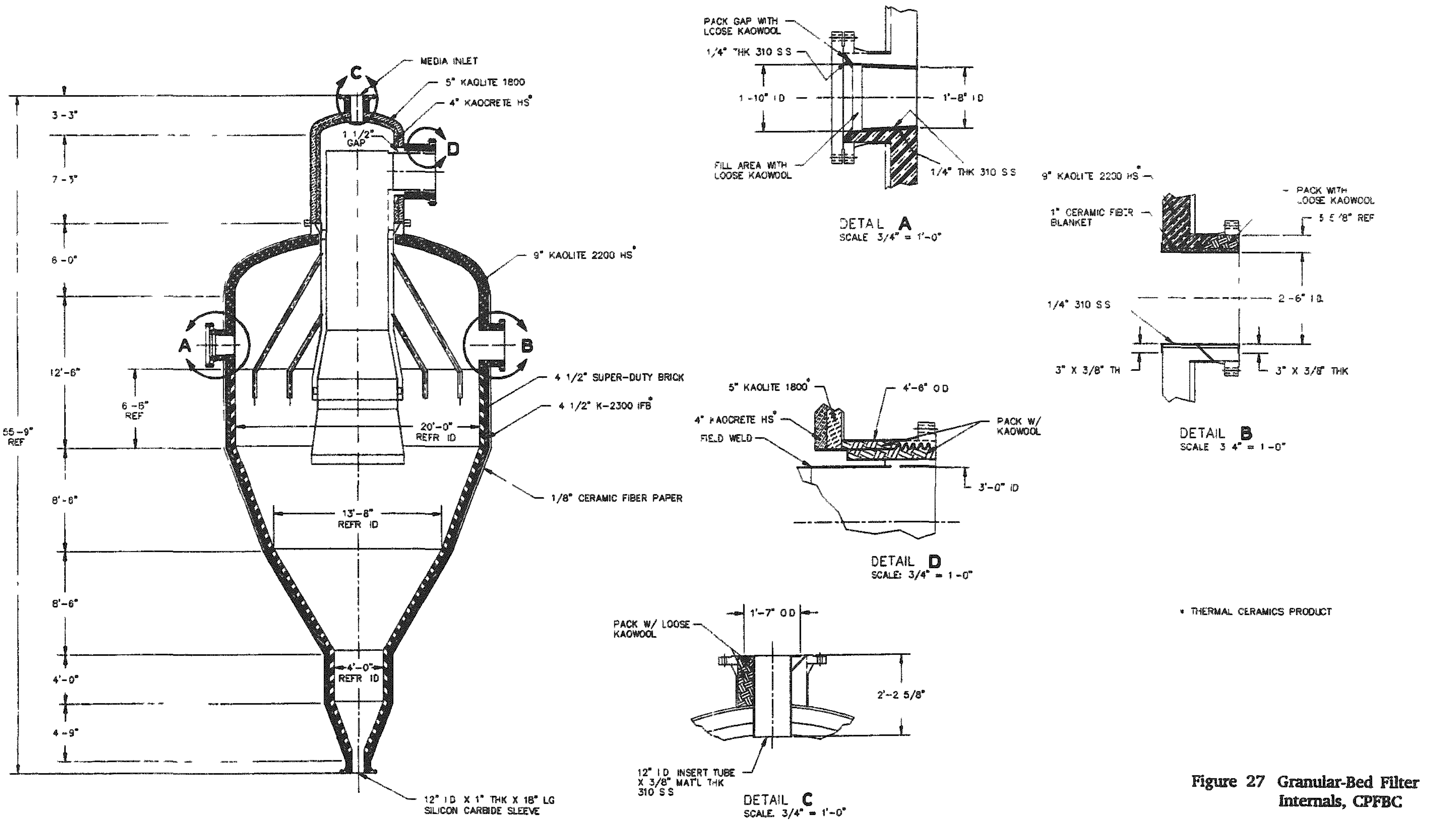
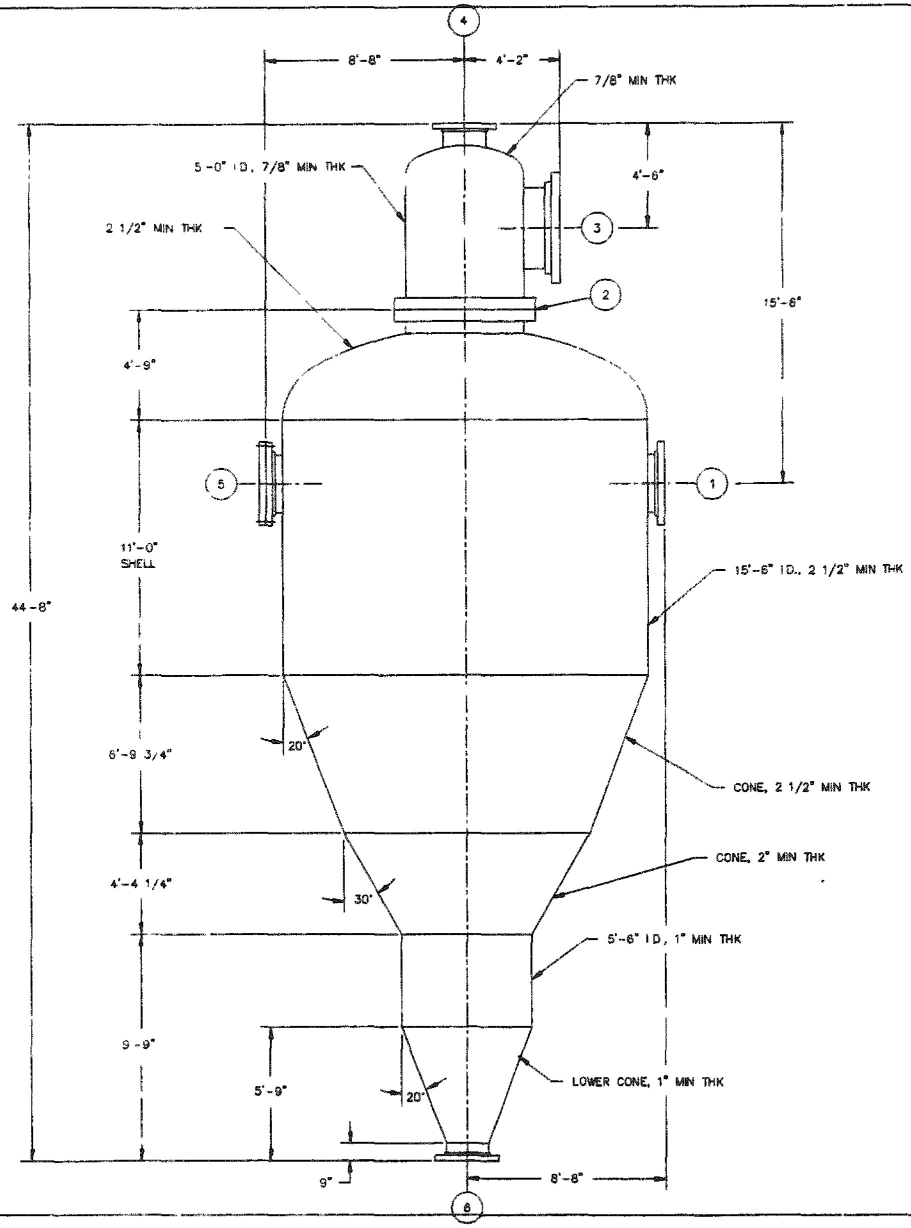


Figure 27 Granular-Bed Filter Internals, CPFBC



VESSEL DATA

SERVICE	GASIFIER OUTLET FILTER
OPERATING PRESS	385 PSIA
DESIGN PRESS	410 PSIG
MAX OPERATING TEMP	1600°F (INTERNAL)
DESIGN TEMP	650°F (METAL)
WIND DATA	UBC (70 MPH, EXP C)
EARTHQUAKE DATA:	UBC (ZONE 1)
CODE:	ASME SECT VIII DIV 1
CODE STAMP:	YES
P.W.H.T. FOR CODE:	PARTIAL
P.W.H.T. FOR PROCESS	NO
JOINT EFF:	100%
RADIOGRAPHED	FULL
CORROSION ALL:	1/8"
MAT'L SHELL:	SA-516 GR 70
MAT'L HEADS:	SA-516 GR 70 (2:1 ELLIPTICAL)
MAT'L SUPPT'S:	SA-516 GR 70
MAT'L NOZZLES:	SA-516 GR 70
MAT'L FLANGES:	SA-105
EMPTY WEIGHT:	138000 LBS (METAL ONLY)
WATER ONLY WEIGHT:	240000 LBS
FILTER MEDIA:	195000 LBS
REFRACTORY LINING:	80000 LBS
SHIPMENT:	1 PIECE

NOZZLES

NO.	SIZE	ANSI RATING	SERVICE	I.D. LINING	QTY
1	30"	CL 300 RF	OUTLET	18"	1
2	60"	CL 300 RF	ACCESS	42"	2
3	42"	CL 300 RF	INLET	24"	1
4	22"	CL 300 RF	MEDIA IN	10"	1
5	30"	CL 300 RF	MANWAY/BLIND	18"	1
6	22"	CL 300 RF	MEDIA OUT	10"	1

1 SEE SHEET 2 FOR REFRACTORY INSTALLATION NOTES.

Figure 28 Granular-Bed Filter Pressure Vessel, Carbonizer

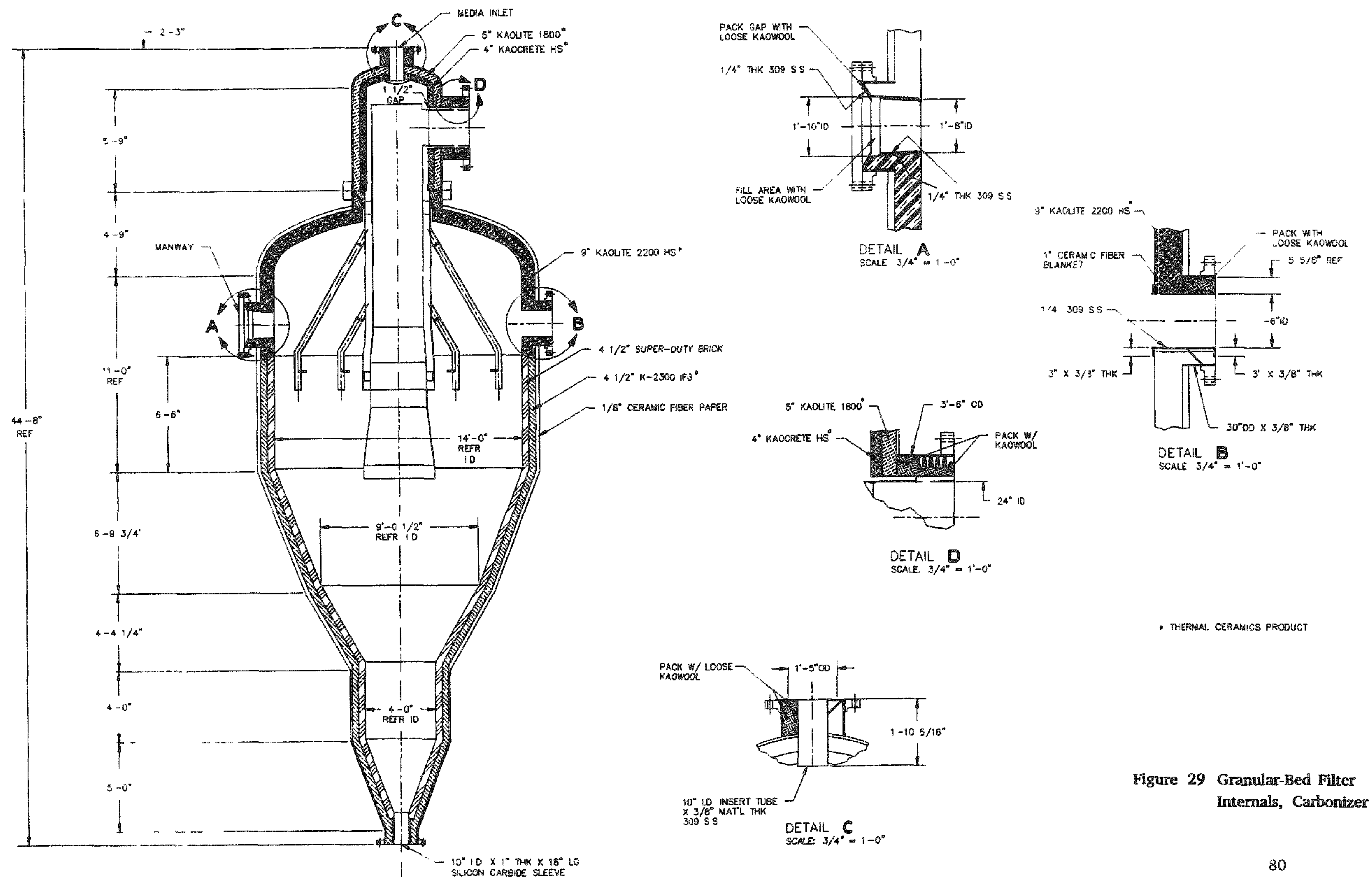
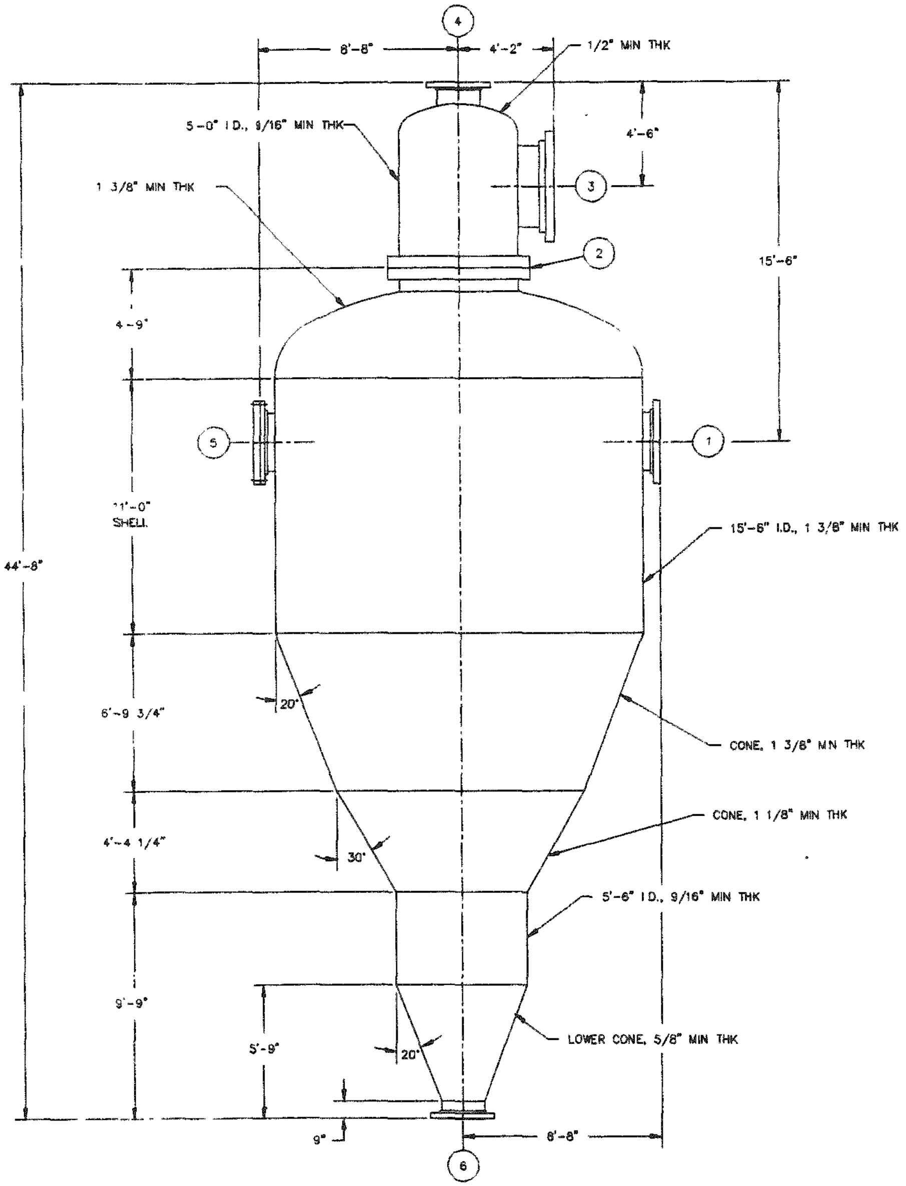


Figure 29 Granular-Bed Filter Internals, Carbonizer



VESSEL DATA

SERVICE:	CARBONIZER OUTLET FILTER
OPERATING PRESS:	208 PSIA
DESIGN PRESS:	218 PSIG
MAX. OPERATING TEMP	1500°F (INTERNAL)
DESIGN TEMP:	650°F (METAL)
WIND DATA:	UBC (70 MPH, EXP.C)
EARTHQUAKE DATA:	UBC (ZONE 1)
CODE:	ASME SECT VIII DIV. 1
CODE STAMP:	YES
P.W.H.T. FOR CODE:	NO
P.W.H.T. FOR PROCESS:	NO
JOINT EFF:	100%
RADIOGRAPHED:	FULL
CORROSION ALL:	1/8"
MAT'L SHELL:	SA-516 GR 70
MAT'L HEADS:	SA-516 GR 70 (2:1 ELLIPTICAL)
MAT'L SUPPT'S:	SA-516 GR 70
MAT'L NOZZLES:	SA-516 GR 70
MAT'L FLANGES:	SA-105
EMPTY WEIGHT:	78500 LBS (METAL ONLY)
WATER ONLY WEIGHT:	240000 LBS
FILTER MEDIA:	195000 LBS
REFRACTORY LINING:	80000 LBS
SHIPMENT:	1 PIECE

NOZZLES

NO.	SIZE	ANSI RATING	SERVICE	I.D. LINING	QTY
1	30"	CL 300 RF	OUTLET	18"	1
2	60"	CL 300 RF	ACCESS	42"	2
3	42"	CL 300 RF	INLET	24"	1
4	22"	CL 300 RF	MEDIA IN	10"	1
5	30"	CL 300 RF	MANWAY/BLIND	18"	1
6	22"	CL 300 RF	MEDIA OUT	10"	1

1 SEE SHEET [illegible] FOR REFRACTORY INSTALLATION

NOTES:

Figure 30 Granular-Bed Filter Pressure Vessel, KRW Gasifier

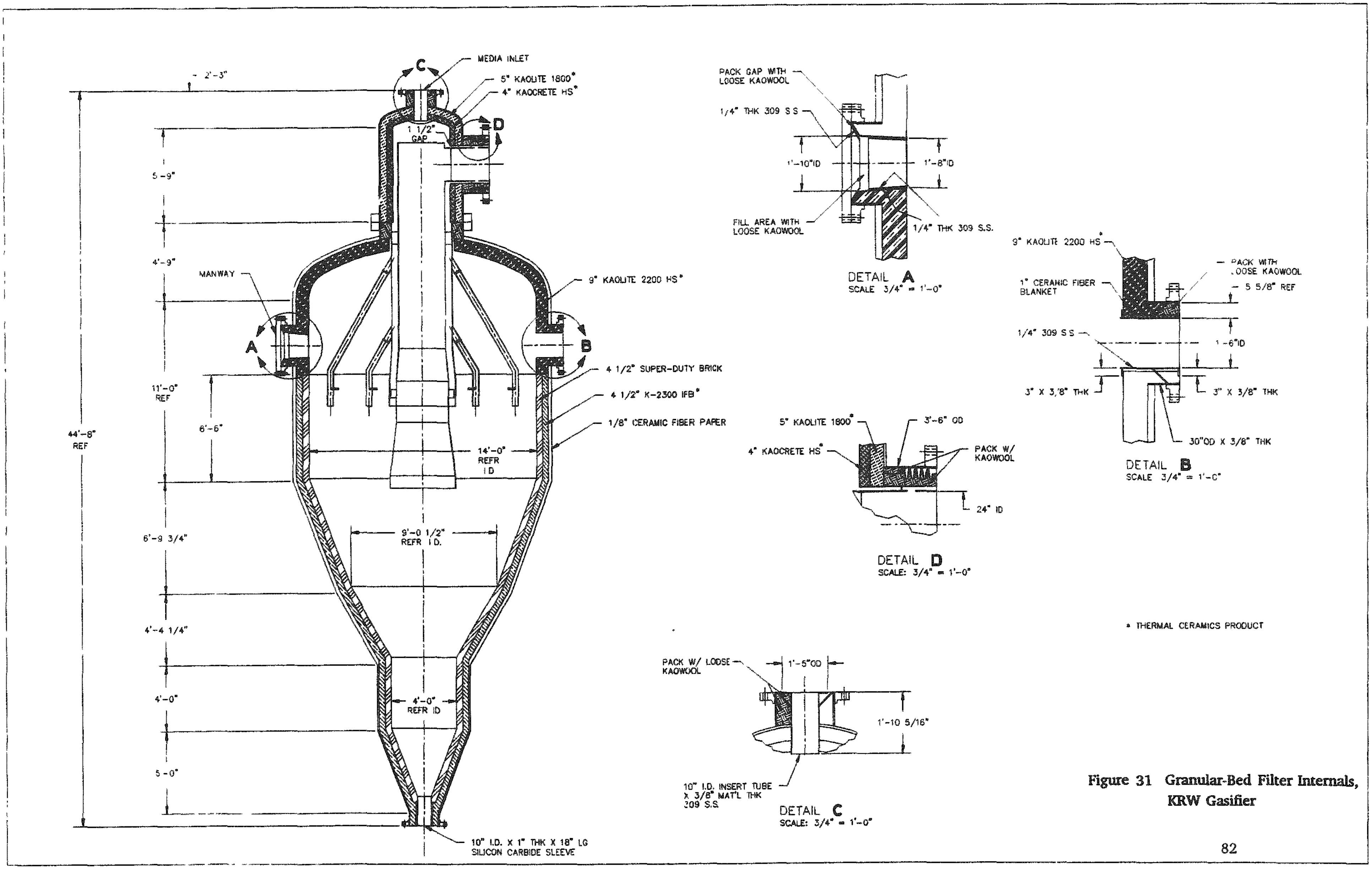


Figure 31 Granular-Bed Filter Internals, KRW Gasifier

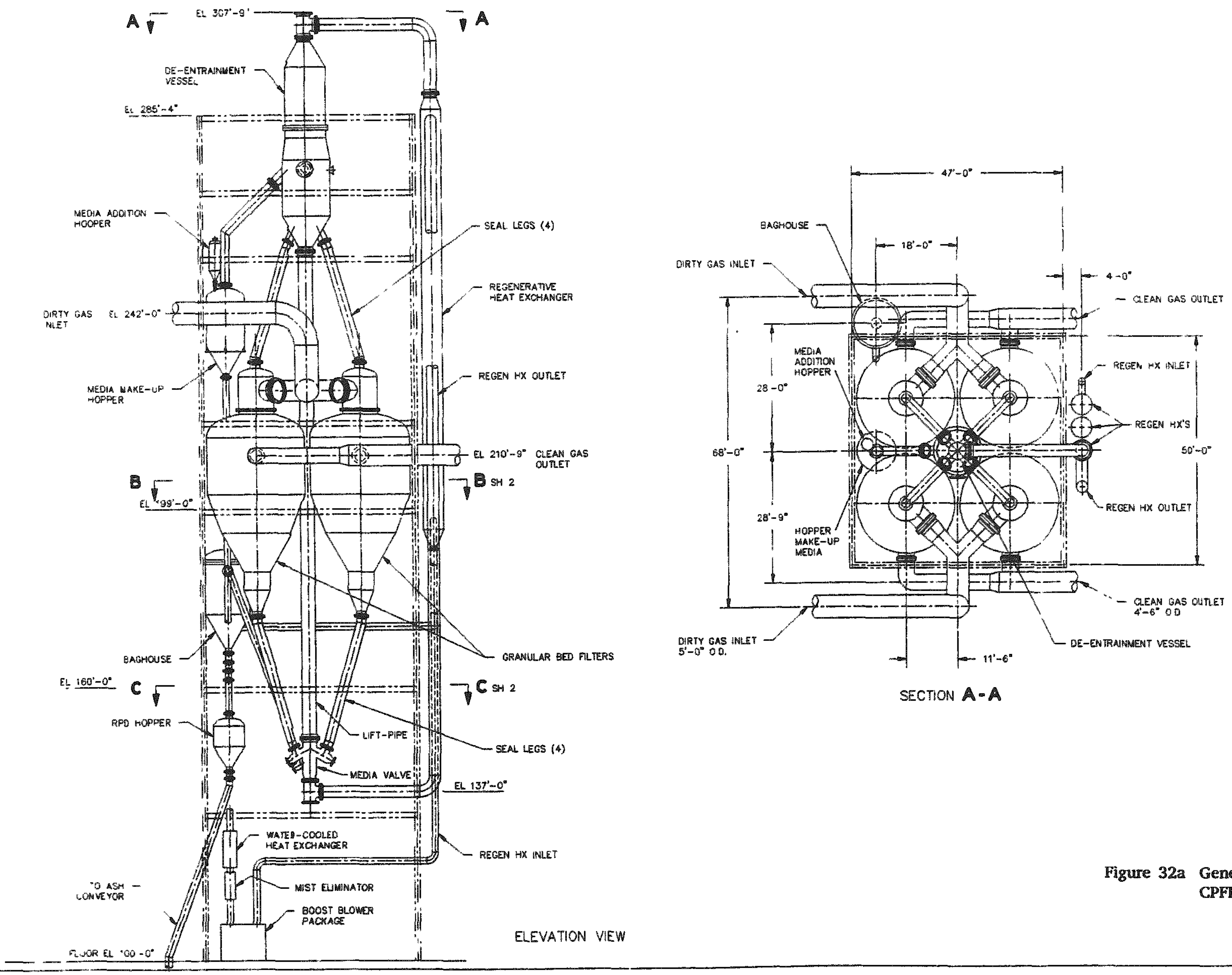
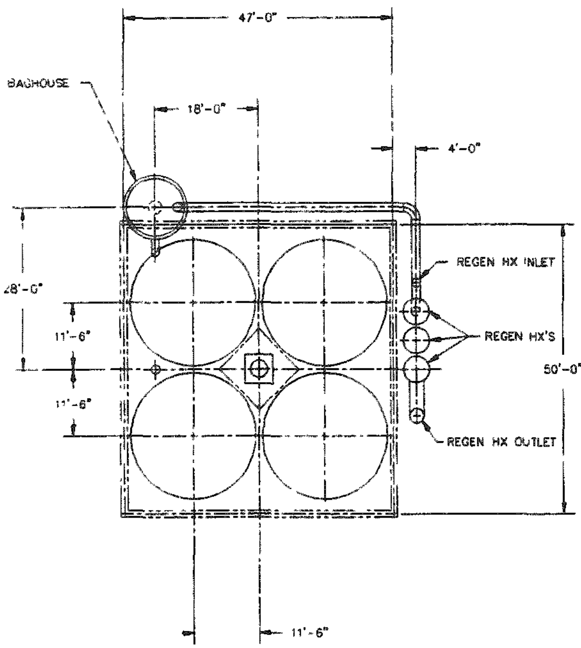
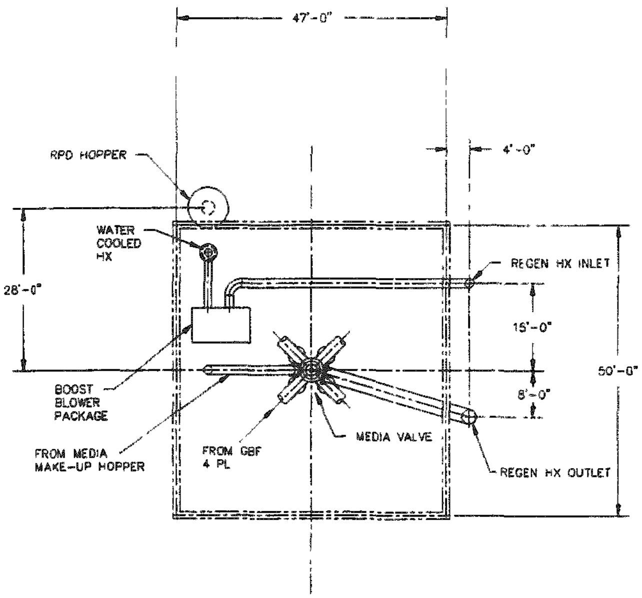


Figure 32a General Arrangement, CPFBC GBF



SECTION **B-B** SH 1



SECTION **C-C** SH 1

Figure 32b General Arrangement, CPFBC GBF

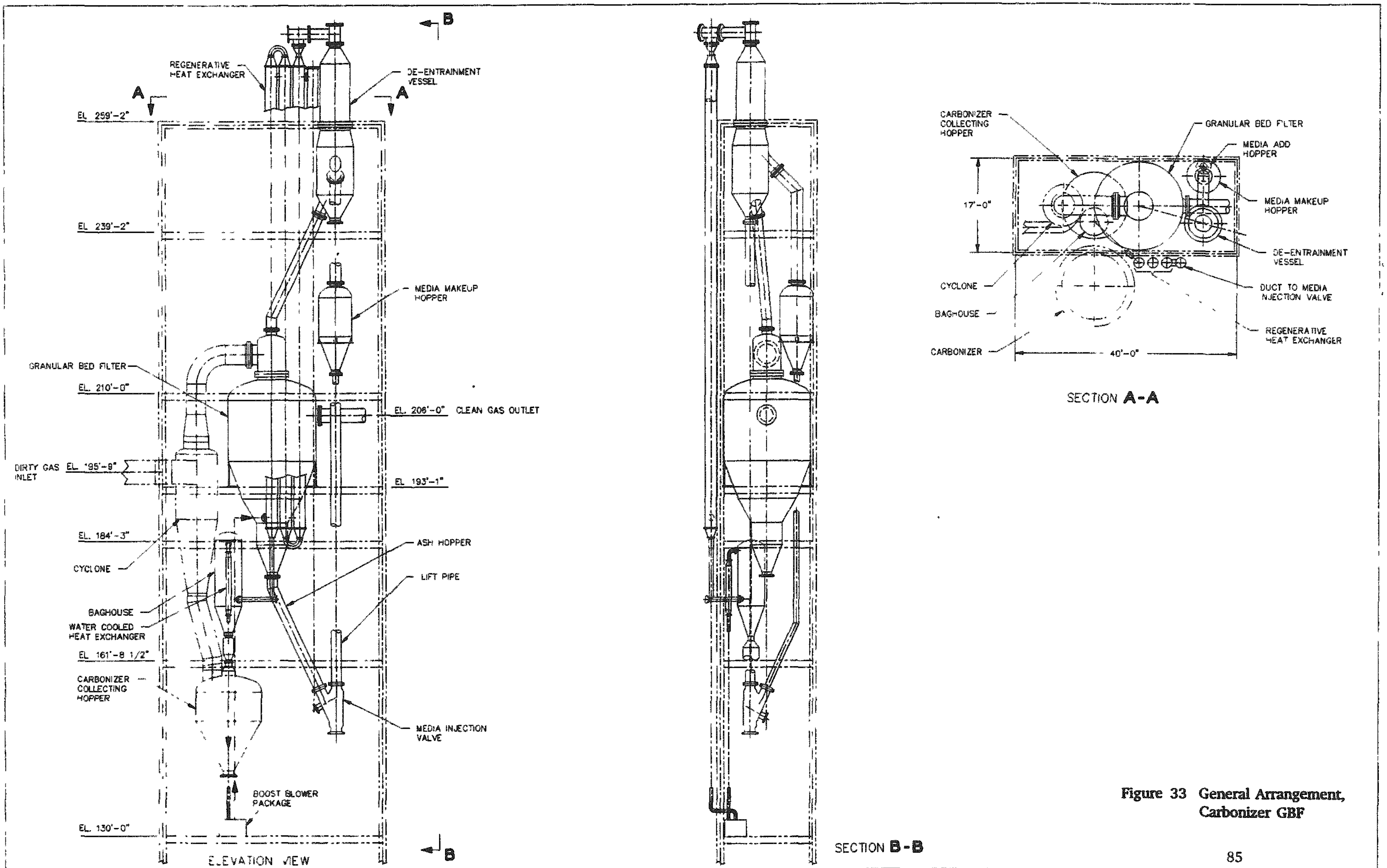


Figure 33 General Arrangement, Carbonizer GBF

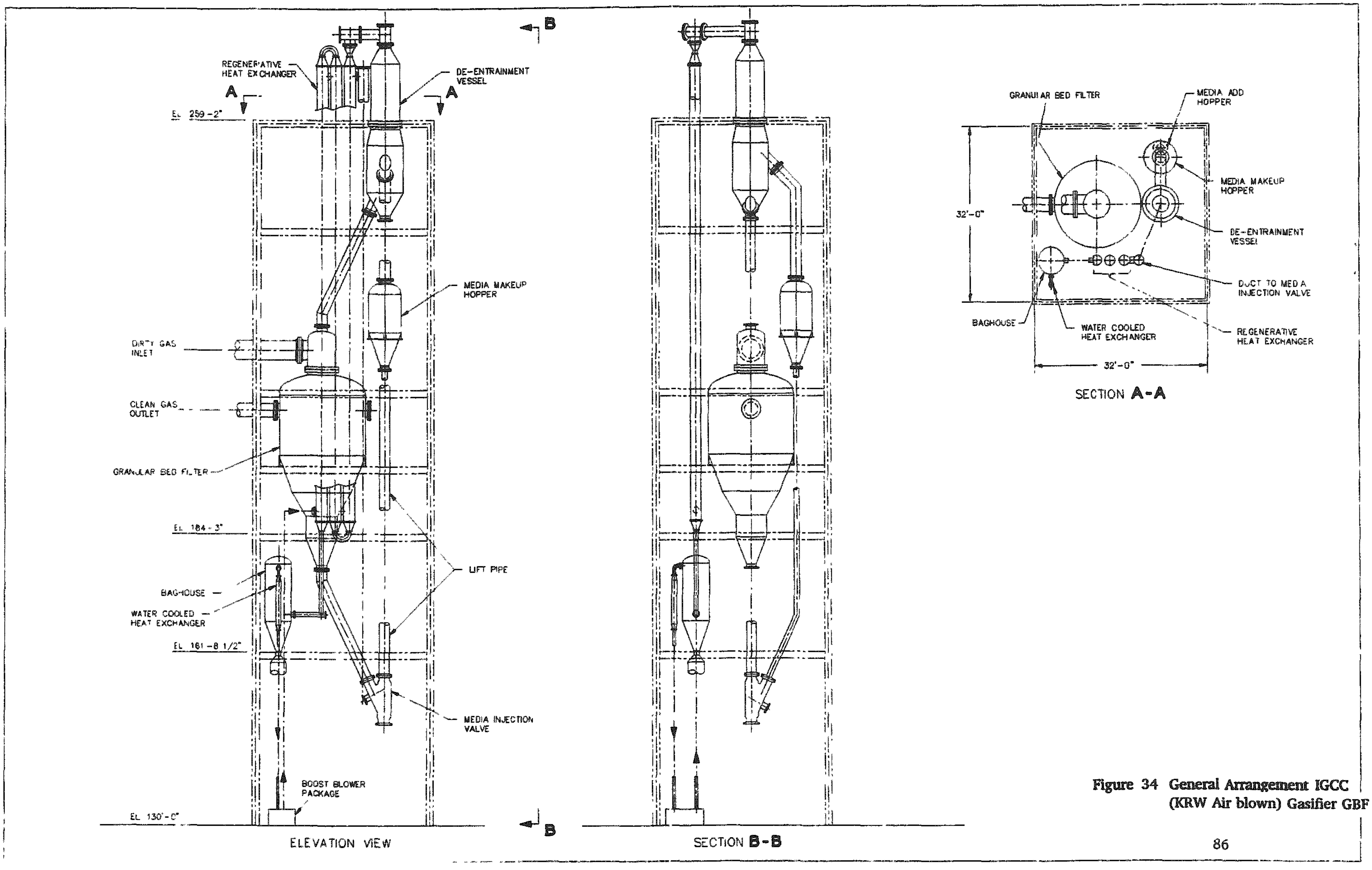


Figure 34 General Arrangement IGCC (KRW Air blown) Gasifier GBF

3.6 Granular-Bed Filter Auxiliary Equipment/Specs

3.6.1 De-Entrainment Vessels

Filter media and ash are separated in the de-entrainment vessels shown in Figures 35, 36,and 37. These figures show the de-entrainment vessel configurations for the CPFBC, carbonizer, and KRW gasifier filter, respectively. Filter media falls out of the gas stream and collects in a reservoir at the bottom of the vessel. Ash follows the gas stream out the top of the vessel and continues to the ash handling components. The media reservoir in the bottom of the de-entrainment operates in an overflow mode to maintain a conservative excess volume of filter media in the system. During periods in which media is heating up or accumulating ash, the volume of the media increases. The increased media volume is accommodated by allowing excess media to overflow from the media reservoir to the media make-up hopper. During periods of operation when the media occupies less volume, media from the media make-up hopper is circulated to refill the reservoir. Temperatures in the de-entrainment vessels are 100-200°F lower than in the filter vessels, so even though the gas composition is the same, corrosive conditions are less severe. These temperatures range from 1380°F to 1500°F for the three applications studied.

The enclosures of the de-entrainment vessels are pressure vessels. These carbon steel enclosures are lined with a two component refractory system to minimize heat loss and to withstand the action of the process gases and filter media. Insulating refractory maintains the outside wall temperature to the range of 180-200°F. The refractory hot face lining is erosion resistant to withstand the filter media movement, and will easily contend with the oxidizing and reducing gas atmospheres at de-entrainment vessel temperatures. In the top part of the de-entrainment vessel, the hot face lining is 6" to provide extra durability. A flange is included in the body of the de-entrainment vessel to allow installation of refractory, metal internals, and to allow inspection, if necessary.

Metals in the de-entrainment vessels, type 310 stainless steel, are under minimal stress that is mainly thermal in nature. This metal was chosen as the most economic choice for corrosion resistance against the process gas stream components at process temperatures.

3.6.2 Media Make-up Hoppers

The media make-up hoppers serve a dual function. This is the location in the system where the media volume changes occur, and this is the place where media is added to make-up for attrition. These hoppers are shown of figures 38, 39, and 40 for the CPFBC, the carbonizer, and the KRW gasifier filters, respectively. During periods of media volume change, a small amount of media circulation is maintained from the media make-up hopper. If this media is not needed in the filter, a similar amount overflows the reservoir in the de-entrainment vessel. If more media is needed than is being provided, the low level switch is activated in the de-entrainment reservoir. If less media is needed, the excess overflows to the make-up hopper. During stable operation, the make-up hopper may only be operated once a shift or once a day for a short period. When the low level switch is energized in the media reservoir, media is added through the small media add hopper. Access for refractory installation and inspection is through manways.

These hoppers are pressure vessels lined on the inside with refractory. Pressure levels and gas compositions are nearly the same as in the respective filters, but temperatures are less by at least 100°F. Refractory choices are the same as for the de-entrainment vessel reservoirs for the same reasons. Nozzles for media flow are lined with ceramic sleeves for wear resistance.

3.6.3 Media Valves, Seal Legs, Lift Pipes

Refractory-lined piping items that contain moving filter media are all designed similarly. Carbon steel piping components are utilized to contain the pressure, and refractory linings provide insulation and erosion resistance.

Ash-ladened media from one or four filter vessels, depending on the application, is metered to a lift pipe by a media valve. In addition, an inlet nozzle is provided for the media from the media make-up hopper. Media valves are shown on Figures 41, 42 and 43 for the CPFBC, carbonizer, and KRW gasifier filters, respectively. Pressure and temperature in each media valve is almost the same as in the filter vessel. Refractory lining consists of silicon carbide sleeves for wear resistance against moving media with a backing of light weight castable refractory for insulation. The castable insulation also provides some structural support for the silicon carbide sleeves. Metals internals are non-structural but do experience thermal stresses.

The seal legs that convey ash-ladened media away from the filter and return clean media, are made in 10 ft long spools. Lift pipe segments are also made in 10 ft long spools. Each spool is lined with 1" thick silicon carbide for wear resistance, and light weight castable insulation to minimize heat loss. These piping spools are bolted together during installation. Seal legs for the CPFBC filter are 24" pipe lined to 12" I.D. refractory. The lift pipe is 36" pipe lined to 24" I.D. refractory. Seal legs for the carbonizer and KRW gasifier filter are 22" pipe lined to 10" I.D. refractory. The lift pipes are also 22" pipe lined to 10" I.D. refractory.

3.6.4 Media Addition Hoppers

A small, carbon steel media addition hopper is mounted on the top of each media make-up hopper. These hoppers are sized to hold about one pallet of bagged media, or about 3000 lbs. They are 30" O.D. and 9' 6" long including the conical bottom. The media inlet is 8" for ease of loading and the media outlet is 4". Media is added to the hopper while the hopper is at atmospheric pressure. The hopper is then closed and pressurized. When the hopper is at system pressure, a valve underneath the hopper is opened to unload the contents into the media make-up hopper. Since the media addition hopper is always at atmospheric temperature, it is not refractory lined.

3.6.5 Baghouses

A baghouse is used as part of the filter media circulation and ash removal system for the granular-bed filter. Ash separated from the granular-bed filter media is cooled to 500°F in the regenerative heat exchanger, and conveyed to a pressurized baghouse for removal. A baghouse was chosen because it operates reliably at moderate temperatures (500°F), utilizes standard filter bags, and delivers dry ash to an ash handling system. Baghouse design criteria is given on Table 17. Design gas flow rates allow for 15% margin over the operating values. Table 18 summarizes the baghouse equipment.

Table 17 Baghouse Design Criteria

Parameter	CPFBC Filter	Carbonizer Filter	Gasifier Filter
Gas flow Rate (lb/hr)	195,000	35,000	48,000
(acfm @ 500°F and operating pressure)	6,230	1,123	935
Inlet Gas Temp. (°F)	500	500	500
Inlet Pressure (psig)			
Design	200	218	410
Operating	167	188	365
Dust Loading (lb/hr)			
Design	6,800	2,830	3,036
Operating	3,435	2,460	2,640
Design (gr/acf)	171	294	379

The particle outlet loading from each baghouse (gr/acf) is expected to be about 0.2 gr/acf, which requires better than 99.9% ash removal efficiency.

The baghouses proposed for these applications are designed for access to the filter bags by unbolting the top head. ASME Code construction is used. Each baghouse is complete with insulation stubs, an access port, and a hinged, lift-off dished head. The filter assemblies include filter bags, carbon steel bag retainers, and stainless steel bag clamps. Ash removal hoppers have a 60° side slope, gas inlet diffuser, and bag catch grid. Pulse cleaning assemblies include a solid state design cyclic timer (NEMA 4 enclosure), pulse gas supply header, pulse gas distribution pipes, right angle diaphragm valves and solenoid valves (NEMA 4). Filter bags are 4 1/2" in diameter, 8' long and made from 27 oz. fiberglass felt, a commonly used material in commercial and utility applications. See Figure 44 for a typical drawing of the baghouse used with the KRW gasifier, granular-bed filter. Baghouses utilized with the CPFBC filter and the carbonizer filter are similar.

Table 18 Baghouse Equipment Selection

Parameter	CPFBC Filter	Carbonizer Filter	Gasifier Filter
Filter Area (ft^2)	1678	395	395
Filter Rate ($acfm/ft^2$)	2.80:1	2.84:1	2.37:1
Filter Bags/Module	178	42	42
Bag Material	Fiberglass	Fiberglass	Fiberglass
Housing Thickness	1"	1/2"	1"
Estimated Weight (lbs)	30,000	8,750	14,650
Pulse Gas (scfm)	35	20	20
Pulse Pressure	267	288	465

3.6.6 Regenerative Heat Exchangers

The function of the recuperative heat exchanger is to exchange heat between the hot gas stream leaving the lift pipe and the cool gas stream entering the lift pipe. The hot gas steam needs to be cooled to 500°F so that the suspended ash particles can be removed in a conventional baghouse. The gas stream entering the lift pipe is reheated in order to minimize heat loss and; consequently, the temperature drop through the filter.

The heat exchanger design proposed utilizes a "flue gas through the tubes" concept which has been proven on sludge incineration and carbon black processes throughout the world. The heat exchanger has hot gas flowing within the tubes while the heated gas moves over the outside of the tubes in multiple passes. The velocity of the gas inside the tubes along with the ash which is entrained tends to constantly scrub the surface of the tubes and consequently keep them from fouling. The hot gas flow is parallel to the tube walls, as opposed to normal, so that the high velocities do not cause erosion as can occur with standard convective coils. Ferrules are placed at the flue gas inlet of each tube of the heat exchanger in order to further protect the refractory covered tube sheet from erosion and the high heat flux expected.

Table 19 shows the design criteria for the recuperative heat exchanger. Figure 45 shows a typical arrangement for the regenerative heat exchangers used with the granular-bed filter.

Table 19 Regenerative Heat Exchanger Design Criteria

	CPFBC Filter	Carbonizer Filter	Gasifier Filter
Hot Gas Side			
Inlet Temperature,°F	1480	1362	1422
Outlet Temperature,°F	500	500	500
Gas Flow, lbm/hr	168,500	30,060	40,560
Design Pressure, psia	200	218	410
Max. Pressure Drop, psi	<2	<2	<2
Cold Gas Side			
Inlet Temperature, °F	250	250	250
Outlet Temperature, °F	1251	1142	1198
Gas Flow, lbm/hr	168,500	30,060	40,560
Design Pressure, psia	200	218	418
Max Pressure Drop, psi	<1	<1	<1
Log Mean Temp. Diff., °F	239	250	250
Heat Transferred, MMBtu/hr	45.0	8.1	13.5

3.6.7 Boost Blowers

Boost blowers are used in the granular-bed filter media circulation systems to convey the media and ash mixture. These blowers must generate 6 to 10 psi above the system inlet pressure. They must be capable of providing a variable amount of gas flow for conveying at a range of pressures and temperatures. The range of flow is shown in Table 20.

Several types of machines were considered for this application. A rotary vane compressor was used for the 2" lift system at New York University. This type of blower is limited in size, and has the disadvantage of needing lubricating oil added directly to the blower internals. While the lubricating oil can be dealt with, the limitation in size makes this type of blower unsuitable for the commercial systems defined above. Multi-stage, centrifugal blowers have the advantage of operating at inlet temperatures in the 500 to 750 F range. This is an attractive characteristic, but these machines are very expensive, starting at about $750,000. Some single stage, centrifugal blowers are available, and will operate with an inlet temperature of up to 500°F. These blowers are more competitively priced with the options selected.

Table 20 Boost Blower Sizing Criteria

Parameter	CPFBC Filter	Carbonizer Filter	Gasifier Filter
Design Pres., psig	200	218	410
Operating Inlet pres., psig	167	188	65
Operating Flow, acfm @ 250°F	4,670	833	694
Startup Flow, acfm @ 70°F	6,500	1160	930
Operating pressure rise, psi	10	10	10
Maintenance Operation, acfm @ 70°F, 15 psia	17,100	3,185	3,160
Maint. pres. rise, psi	8	8	8

The boost blowers proposed are rotary-lobe type, positive displacement blowers. The blowers utilize two figure-eight impellers rotating in opposite directions to move entrapped air or gas around the case to the outlet port. Timing gears accurately position the impellers in relation to each other, maintaining the minute clearances which give high volumetric efficiency without metal-on-metal friction. For the CPFBC and the carbonizer, since the design pressure is 200 and 218 psig, respectively, the blowers can be housed in reinforced casings and supplied with suitable seals. Blowers are commercially available in high pressure casings. Drive motor sizes are 500 hp and 60 hp for the CPFBC and the carbonizer filter, respectively, based on start-up operation as defined in Table 20 above. Operating power usage is much less. For the gasifier filter, the inlet pressure of 410 psig requires that the blower be enclosed in a pressure vessel. A shaft protruding through the pressure vessel is supported on both ends with bearings. The blower inside the pressure vessel is connected to the shaft with a flexible coupling, and the 40 hp motor outside the pressure vessel is connected to the other end of the shaft with a flexible coupling. Shaft seals are purged with nitrogen to keep the process gases from leaking to the atmosphere.

Boost blower packages include a mounting base, high pressure mechanical seals, electric motor, variable frequency drive, check valve, expansion joints, inlet and discharge silencers or sound enclosure, and protective instrumentation for the blower.

Separate blower packages are provided to allow for circulation of filter media during maintenance outages (atmospheric pressure circulation of filter media). These are standard, low pressure, single speed, rotary-lobe type, positive displacement blower packages. They are on standby to be connected to the circulation system when the pressure is atmospheric. For the CPFBC filter, there are two blowers, each rated at 8550 acfm at 15 psia, and each driven by a 400 hp motor. For each carbonizer and gasifier filter, one blower is included, driven by a 175 hp motor. These blower packages include: blower, motor, baseplate, v-belt drive and guard, check valve, inlet and outlet expansion joints, inlet and outlet silencers, and safety switches for the blower.

3.6.8 Water-Cooled Heat Exchangers

The water-cooled heat exchanger cools the filter media transport gas just prior to the boost blower. The heat exchanger is needed because the boost blower cannot handle gas above about 250°F and the regenerative heat exchanger needs a reasonable differential temperature at the cold gas inlet to operate efficiently. The water-cooled heat exchangers are installed downstream of the pressurized baghouse in each application. The particle loading into each heat exchanger is less than 0.2 gr/acf as a result of baghouse cleaning efficiency.

For all water-cooled heat exchangers, moisture should not condense from the process gas as a result of being cooled to 250 F. On the other hand, since the tube wall temperatures will be somewhat less than 250 F, there may be some condensation formed on these walls. Table 21 shows the design parameters for the water-cooled heat exchangers.

The water-cooled heat exchangers are shell-and-tube construction with the gas flowing inside the tubes. The 5/8" x 18 Gage tubes are made of type 316 stainless steel. The exchangers are a straight tube design with a fixed tube sheet and with removable channel and bonnet construction. The exchangers are designed to conform to the requirements of: ASME Code, Section VIII Div. 1, TEMA "B" or "C", and ANSI B78.

3.6.9 Mist/Particle Eliminators

A mist/particle eliminator is installed downstream of each water-cooled heat exchanger, and is intended to protect the boost blower from liquids which may condense. The particle loading into each mist/particle eliminator will be less than 0.2 gr/acf as a result of the upstream baghouse cleaning efficiency. The particle size will be small enough to pass through the particle separator under normal circumstances. In addition, the small particles passing through the separator will not effect the boost blower.

A centrifugal type, in-line gas/ liquid separator is used. The separator is designed to remove 99% of all liquids and solids 10 micron and larger from the gas stream. The separation is accomplished by curved stationary blades causing the gas stream to enter into controlled centrifugal flow. This action forces the entrained liquids and solids to the outer wall for collection. The de-entrained liquids and solids are collected in a trap.

Table 21 Water-Cooled Heat Exchanger Design Criteria

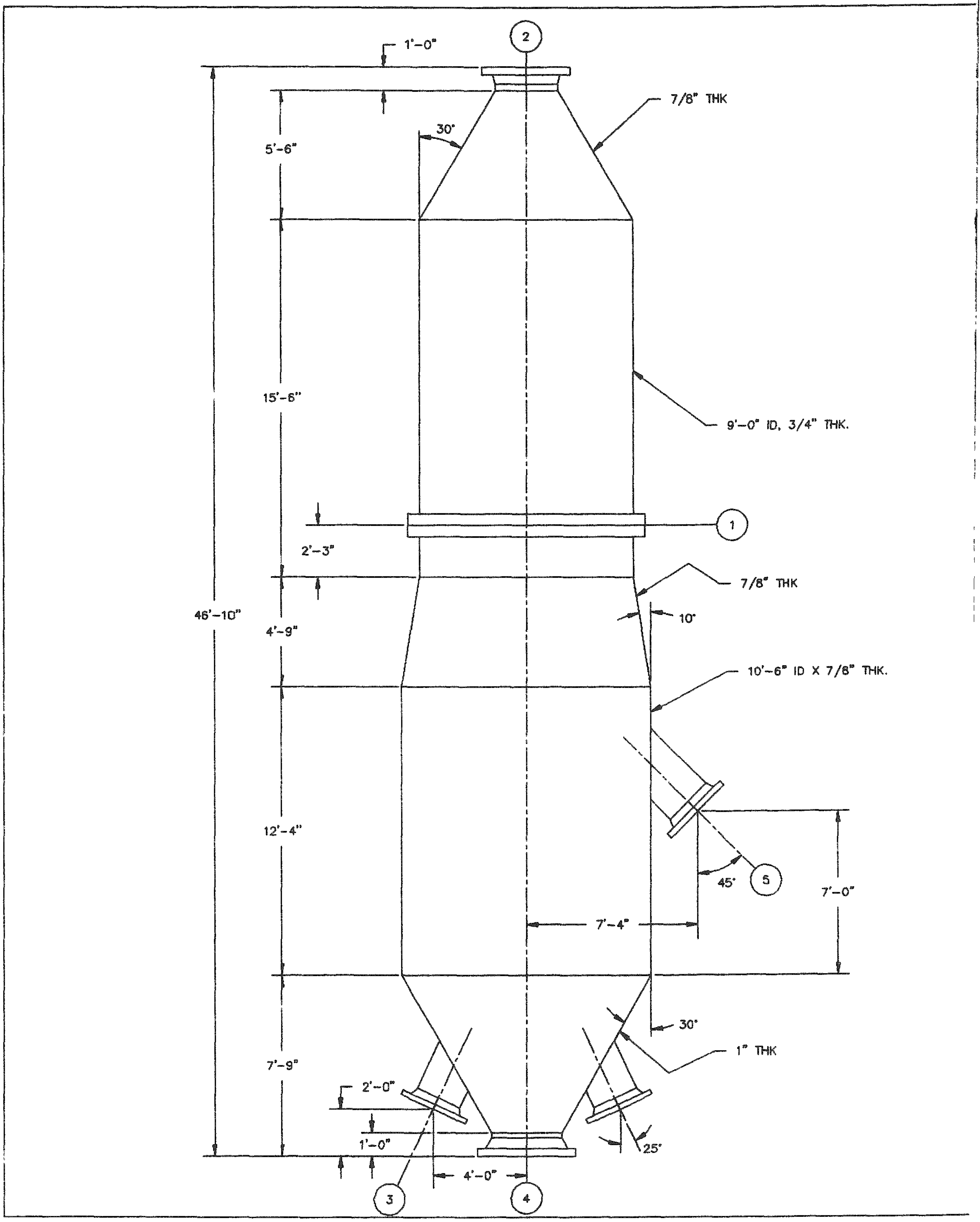
Application:	CPFBC Filter	Carbonizer Filter	Gasifier Filter
Gas flow, lb/hr	195,000	35,000	48,000
Design pressure, psia	200	218	410
Gas inlet temperature, °F	500	500	500
Gas outlet temperature, °F	250	250	250
Gas pressure drop, psi	<1	<1	<1
Heat given up, MMBtu/hr	12.2	2.6	4.0
Water supply, °F	110	110	110

3.7 Filter Plant Construction

The Foster Wheeler study notes that considerable utility experience in barge-shipping and erection of large steam generator vessels exists as a result of the expanding nuclear industry in the 1960's and 1970's. Several vessels weighing up to 800 tons have been shipped and erected. Several contractors in the United States specialize in transporting and rigging this heavy equipment. Thus there appear no major obstacles to supplying the much smaller filter vessels in a similar way. Filter vessels are assumed to be moved from a barge to the construction site by crawler/transporters as shown in the Foster Wheeler report[6].

- CPFBC Granular-bed filters

Table 22 lists the equipment for this plant. Each GBF plant consists of four filters as shown on Figure 32a. There are two identical GBF modules as the entire plant is divided into two identical trains of equipment, each sized for, nominally, 226 MWe.



2
1'-0"
7/8" THK
30°
5'-6"
15'-6"
9'-0" ID, 3/4" THK.
1
2'-3"
7/8" THK
46'-10"
4'-9"
10°
10'-6" ID X 7/8" THK.
12'-4"
5
45°
7'-0"
7'-4"
30°
1" THK
7'-9"
2'-0"
1'-0"
25°
4'-0"
3
4

VESSEL DATA

SERVICE:	ASH/MEDIA SEPARATION
OPERATING PRESS:	185 PSIA
DESIGN PRESS:	200 PSIG
MAX. OPERATING TEMP:	1600°F (INTERNAL)
DESIGN TEMP:	650°F (METAL)
WIND DATA:	UBC (70 MPH, EXP.C)
EARTHQUAKE DATA:	UBC (ZONE 1)
CODE:	ASME SECT VIII DIV. 1
CODE STAMP:	YES
P.W.H.T. FOR CODE:	NO
P.W.H.T. FOR PROCESS:	NO
JOINT EFF:	100%
RADIOGRAPHED:	FULL
CORROSION ALL:	1/8"
MAT'L SHELL:	SA-516 GR 70
MAT'L HEADS:	
MAT'L SUPPT'S.	SA-516 GR 70
MAT'L NOZZLES:	SA-516 GR 70
MAT'L FLANGES:	SA-105
EMPTY WEIGHT:	63000 LBS (METAL ONLY)
WATER ONLY WEIGHT:	180000 LBS
FILTER MEDIA:	83000 LBS
INSL/REFR:	80000 LBS

NOZZLES

NO.	SIZE	ANSI RATING	SERVICE	I.D LINING	QTY
1	108"	CL 300 RF	ACCESS	7'-0"	2
2	32"	CL 300 RF	OUTLET	20"	1
3	24"	CL 300 RF	MEDIA OUT	12"	4
4	36"	CL 300 RF	INLET	24"	1
5	26"	CL 300 RF	MEDIA OUT	12"	1

WALL THICKNESSES GIVEN ARE MINIMUM

Figure 35a De-Entrainment Vessel, CPFBC GBF

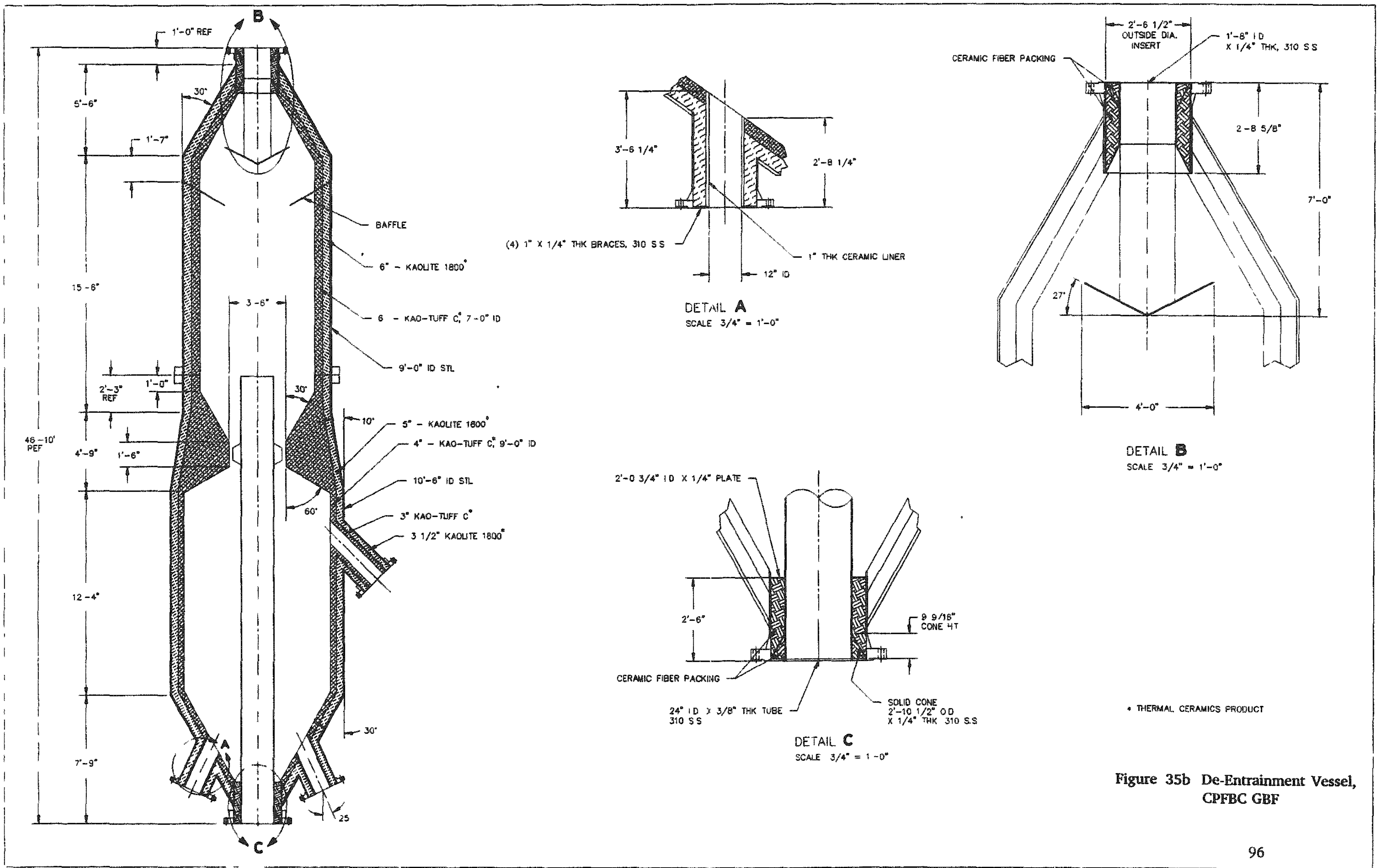
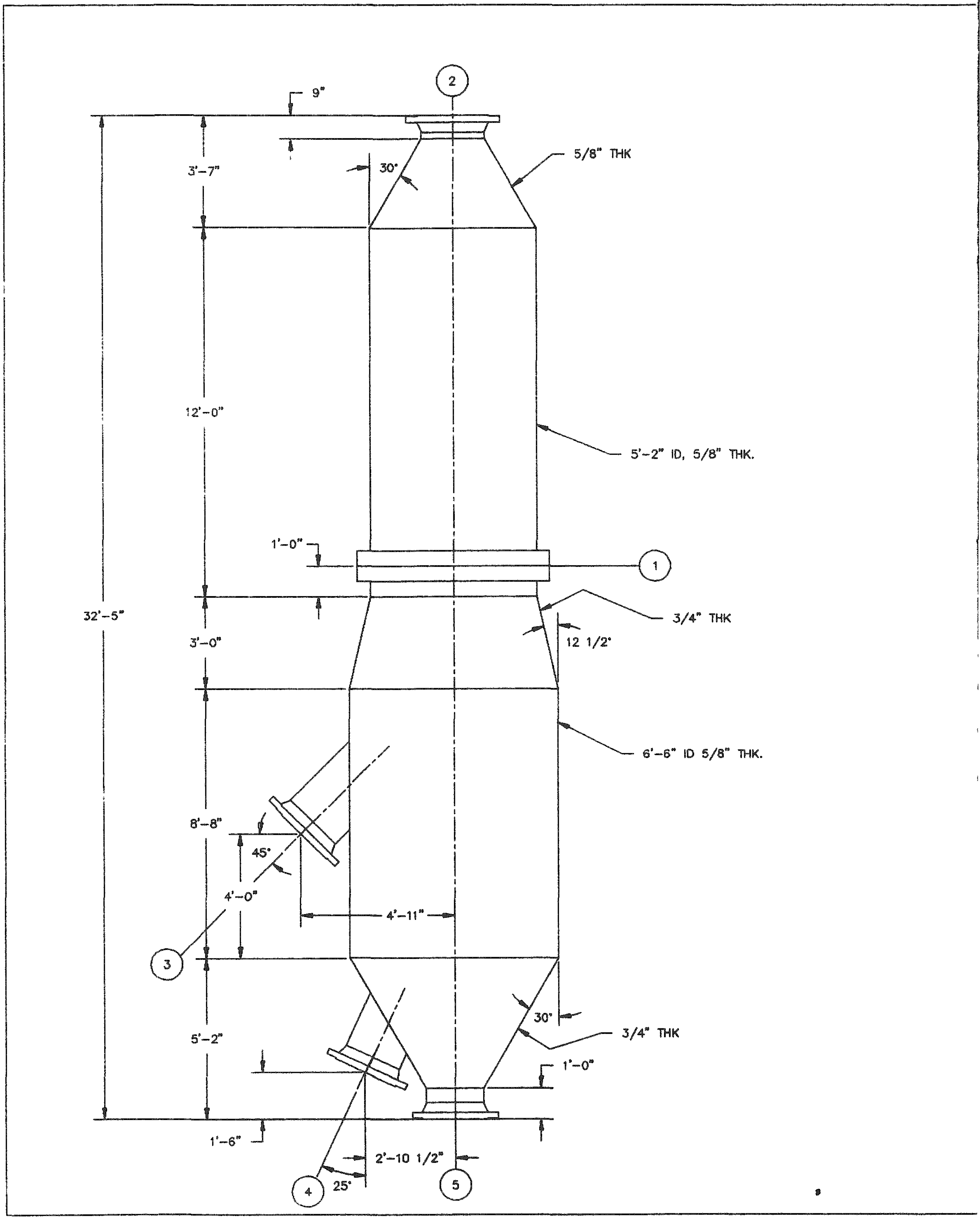


Figure 35b De-Entrainment Vessel, CPFBC GBF



2
9"
3'-7"
30°
5/8" THK
12'-0"
5'-2" ID, 5/8" THK.
1'-0"
1
32'-5"
3/4" THK
3'-0"
12 1/2°
6'-6" ID 5/8" THK.
8'-8"
45°
4'-0"
4'-11"
3
30°
3/4" THK
5'-2"
1'-0"
1'-6"
2'-10 1/2"
4
25°
5

VESSEL DATA

SERVICE:	ASH/MEDIA SEPARATION
OPERATING PRESS:	208 PSIA
DESIGN PRESS:	218 PSIG
MAX. OPERATING TEMP:	1485°F (INTERNAL)
DESIGN TEMP:	650°F (METAL)
WIND DATA:	UBC (70 MPH, EXP.C)
EARTHQUAKE DATA:	UBC (ZONE 1)
CODE:	ASME SECT VIII DIV. 1
CODE STAMP:	YES
P.W.H.T. FOR CODE:	NO
P.W.H.T. FOR PROCESS:	NO
JOINT EFF:	100%
RADIOGRAPHED:	FULL
CORROSION ALL.	1/8"
MAT'L SHELL:	SA-516 GR 70
MAT'L HEADS:	
MAT'L SUPPT'S:	SA-516 GR 70
MAT'L NOZZLES:	SA-516 GR 70
MAT'L FLANGES:	SA-105
EMPTY WEIGHT:	21000 LBS (METAL ONLY)
WATER ONLY WEIGHT:	46000 LBS
FILTER MEDIA:	13000 LBS
INSL/REFR:	33000 LBS

NOZZLES

NO.	SIZE	ANSI RATING	SERVICE	I.D. LINING	QTY.
1	62"	CL 300 RF	ACCESS	3'-2"	2
2	24"	CL 300 RF	OUTLET	10"	1
3	24"	CL 300 RF	MEDIA OUT	10"	1
4	22"	CL 300 RF	MEDIA OUT	10"	1
5	22"	CL 300 RF	INLET	10"	1

WALL THICKNESS GIVEN ARE MINIMUM

Figure 36a De-Entrainment Vessel, Carbonizer GBF

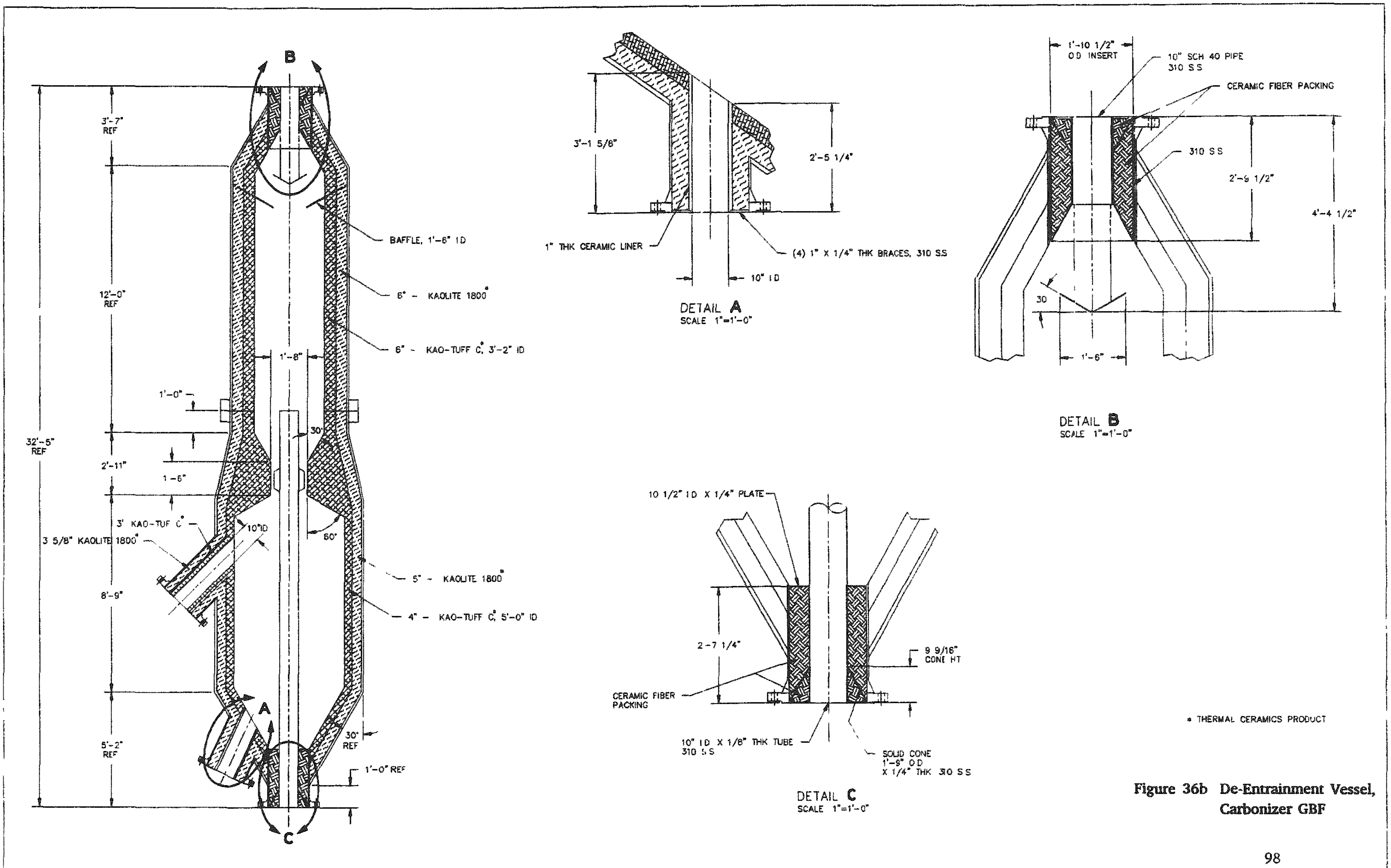
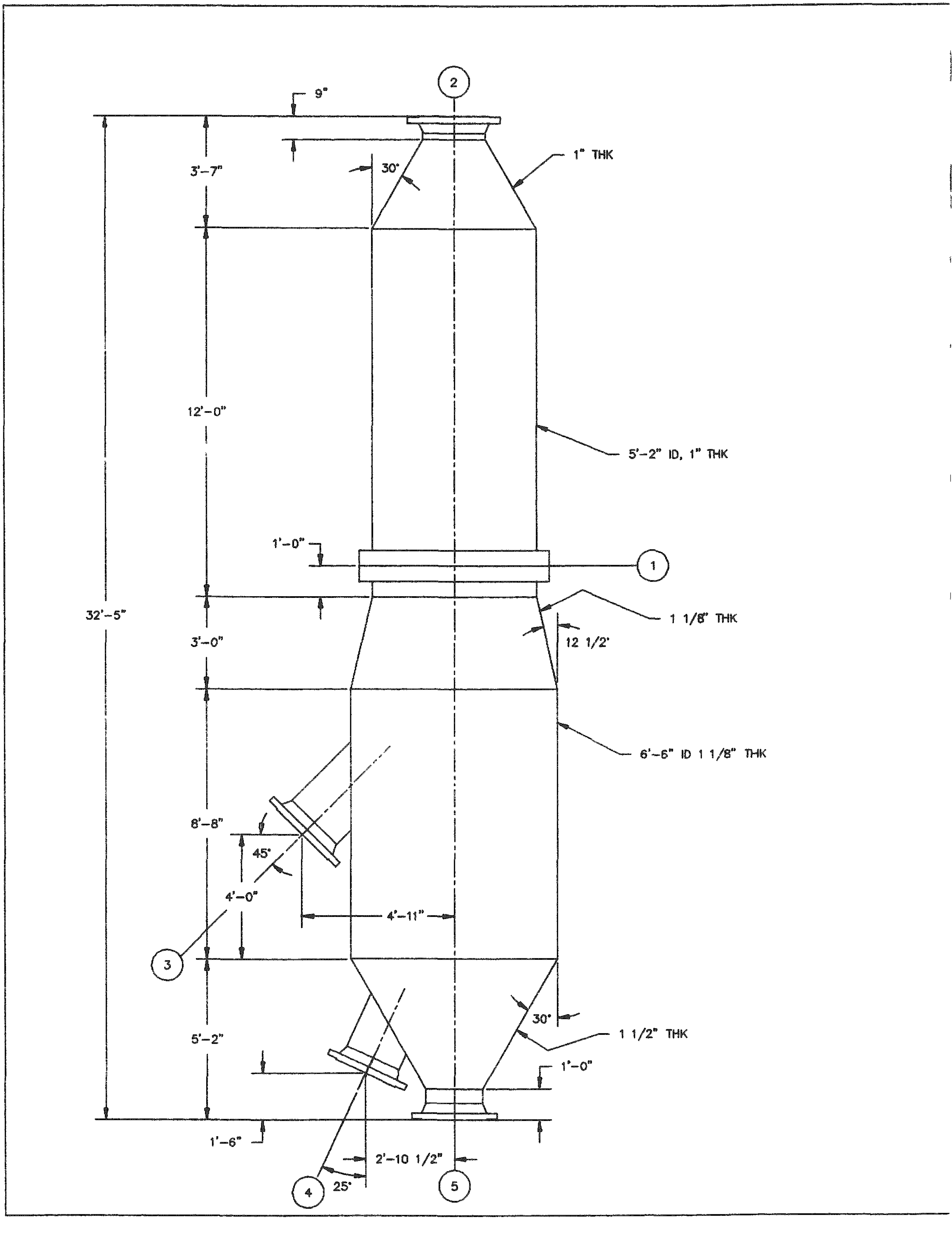


Figure 36b De-Entrainment Vessel, Carbonizer GBF


2
9"
3'-7"
30°
1" THK
12'-0"
5'-2" ID, 1" THK
1'-0"
1
32'-5"
1 1/8" THK
3'-0"
12 1/2'
6'-6" ID 1 1/8" THK
8'-8"
45°
4'-0"
4'-11"
3
5'-2"
30°
1 1/2" THK
1'-0"
1'-6"
2'-10 1/2"
25°
4
5

VESSEL DATA

SERVICE:	ASH/MEDIA SEPARATION
OPERATING PRESS:	382 PSIA
DESIGN PRESS:	410 PSIG
MAX. OPERATING TEMP:	1485°F (INTERNAL)
DESIGN TEMP:	650°F (METAL)
WIND DATA:	UBC (70 MPH, EXP.C)
EARTHQUAKE DATA:	UBC (ZONE 1)
CODE:	ASME SECT VIII DIV. 1
CODE STAMP	YES
P.W.H.T. FOR CODE:	NO
P.W.H.T. FOR PROCESS:	NO
JOINT EFF:	100%
RADIOGRAPHED:	FULL
CORROSION ALL:	1/8"
MAT'L SHELL	SA–516 GR 70
MAT'L HEADS:	
MAT'L SUPPT'S:	SA–516 GR 70
MAT'L NOZZLES:	SA–516 GR 70
MAT'L FLANGES:	SA–105
EMPTY WEIGHT:	32000 LBS (METAL ONLY)
WATER ONLY WEIGHT:	46000 LBS
FILTER MEDIA:	13000 LBS
INSL/REFR:	33000 LBS

NOZZLES

NO.	SIZE	ANSI RATING	SERVICE	I.D. LINING	QTY.
1	62"	CL 300 RF	ACCESS	3'–2"	2
2	24"	CL 300 RF	OUTLET	10"	1
3	24"	CL 300 RF	MEDIA OUT	10"	1
4	22"	CL 300 RF	MEDIA OUT	10"	1
5	22"	CL 300 RF	INLET	10"	1

WALL THICKNESS GIVEN ARE MINIMUM

Figure 37a De-Entrainment Vessel, KRW Gasifier GBF

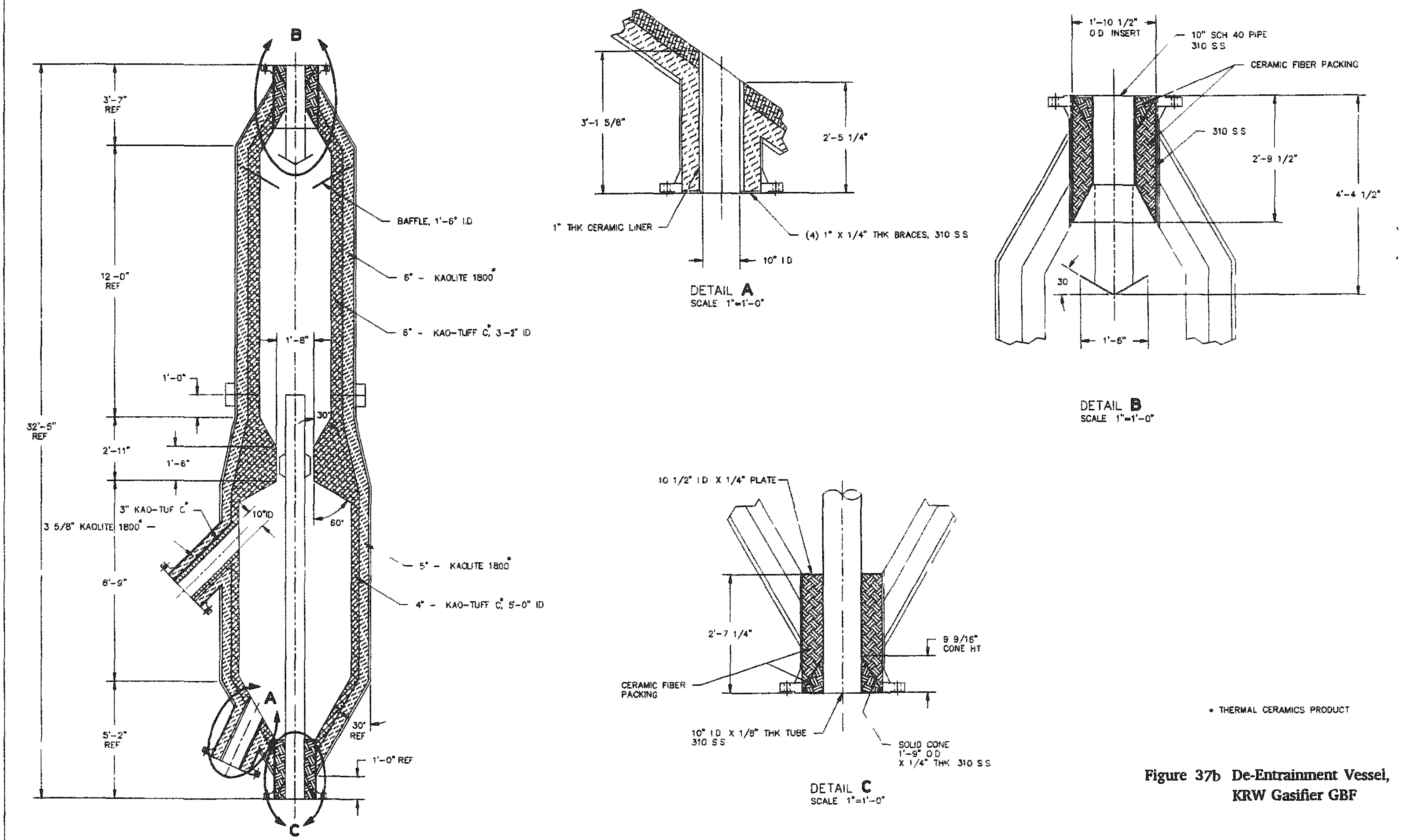
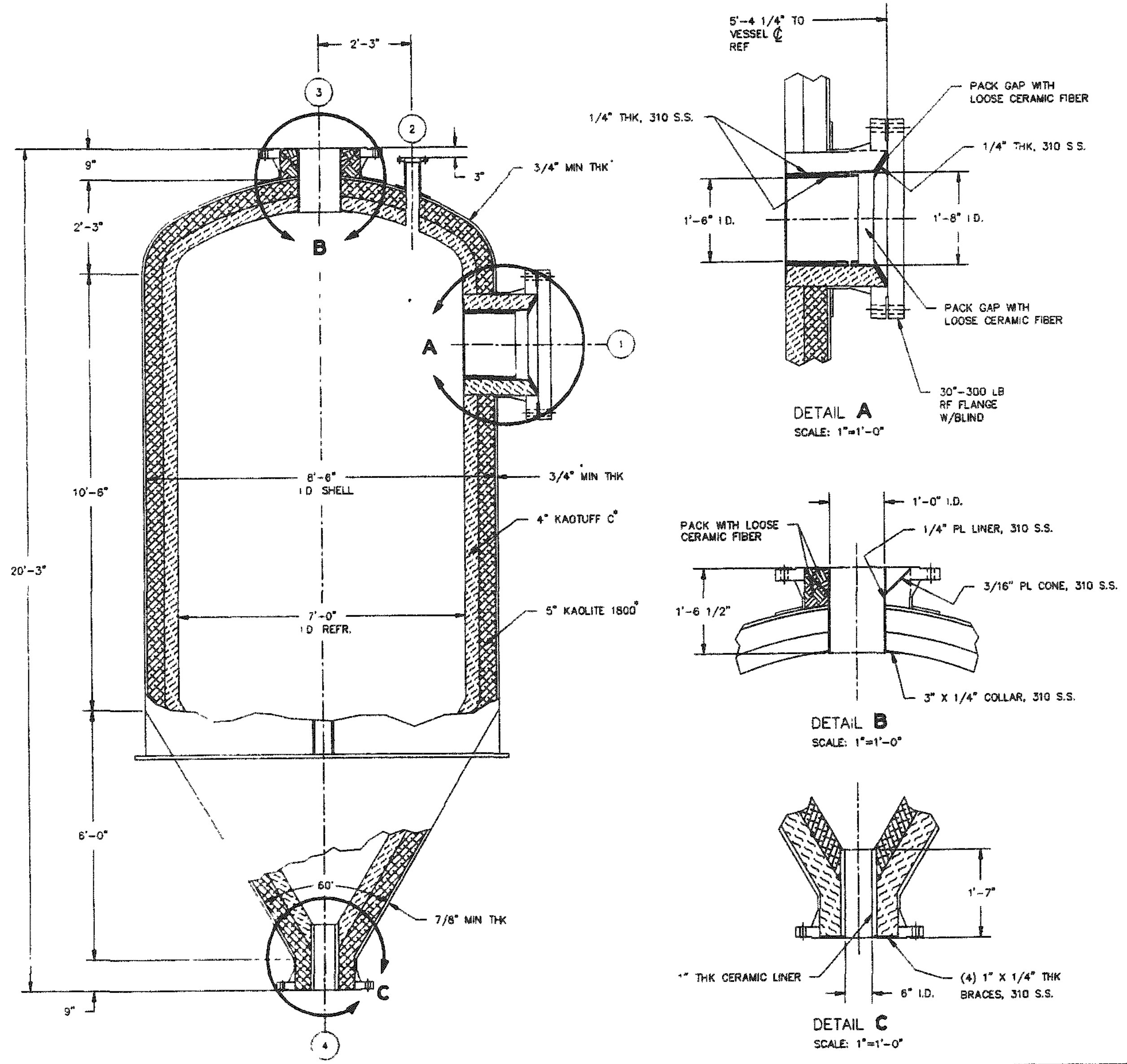


Figure 37b De-Entrainment Vessel, KRW Gasifier GBF



VESSEL DATA

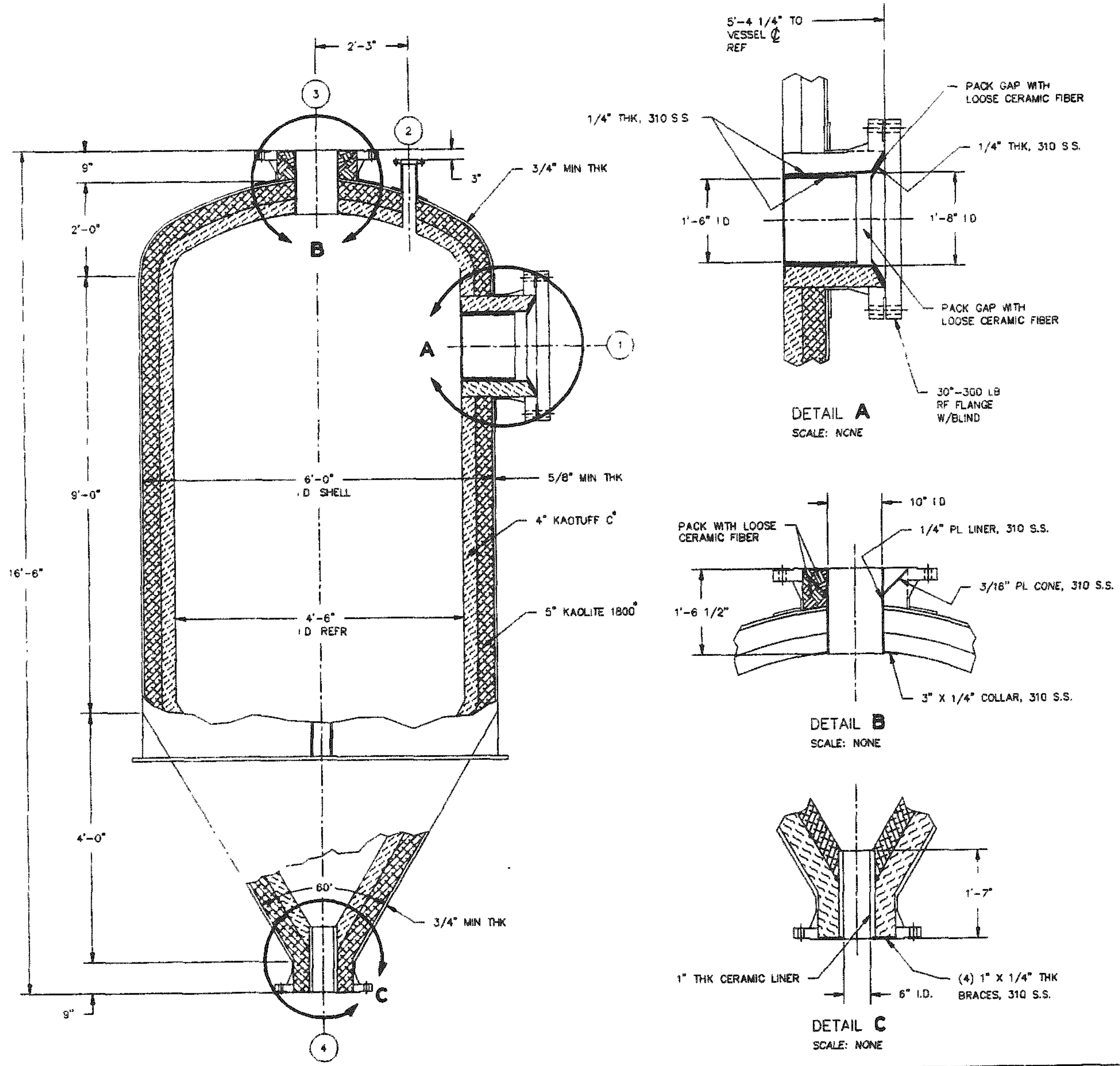
SERVICE:	FILTER MEDIA STORAGE/ADD
OPERATING PRESS:	185 PSIA
DESIGN PRESS:	200 PSIG
MAX. OPERATING TEMP:	1500°F (INTERNAL)
DESIGN TEMP:	650°F (METAL)
WIND DATA:	UBC (70 MPH, EXP.C)
EARTHQUAKE DATA:	UBC (ZONE 1)
CODE:	ASME SECT VIII DIV 1
CODE STAMP:	YES
P.W.H.T. FOR CODE:	NO
P.W.H.T. FOR PROCESS:	NO
JOINT EFF:	100%
RADIOGRAPHED:	FULL
CORROSION ALL.	1/8"
MAT'L SHELL:	SA-516 GR 70
MAT'L HEADS.	SA-516 GR 70 (2:1 ELLIPTICAL)
MAT'L SUPP'T'S:	SA-516 GR 70
MAT'L NOZZLES:	SA-516 GR 70
MAT'L FLANGES:	SA-105
EMPTY WEIGHT:	16500 LBS (METAL ONLY)
WATER ONLY WEIGHT:	50000 LBS
FILTER MEDIA:	65000 LBS
REFR. LINING:	24000 LBS
SHIPMENT:	1 PIECE

NOZZLES

NO.	SIZE	ANSI RATING	SERVICE	I.D. LINING	QTY.
1	30"	CL 300 RF	MANWAY/BLIND	18"	1
2	4"	CL 300 RF	MEDIA ADD	4"	1
3	24"	CL 300 RF	MEDIA IN	12"	1
4	18"	CL 300 RF	MEDIA OUT	6"	1

* THERMAL CERAMICS PRODUCTS

Figure 38 Media Make-up Hopper, CPFBC



VESSEL DATA

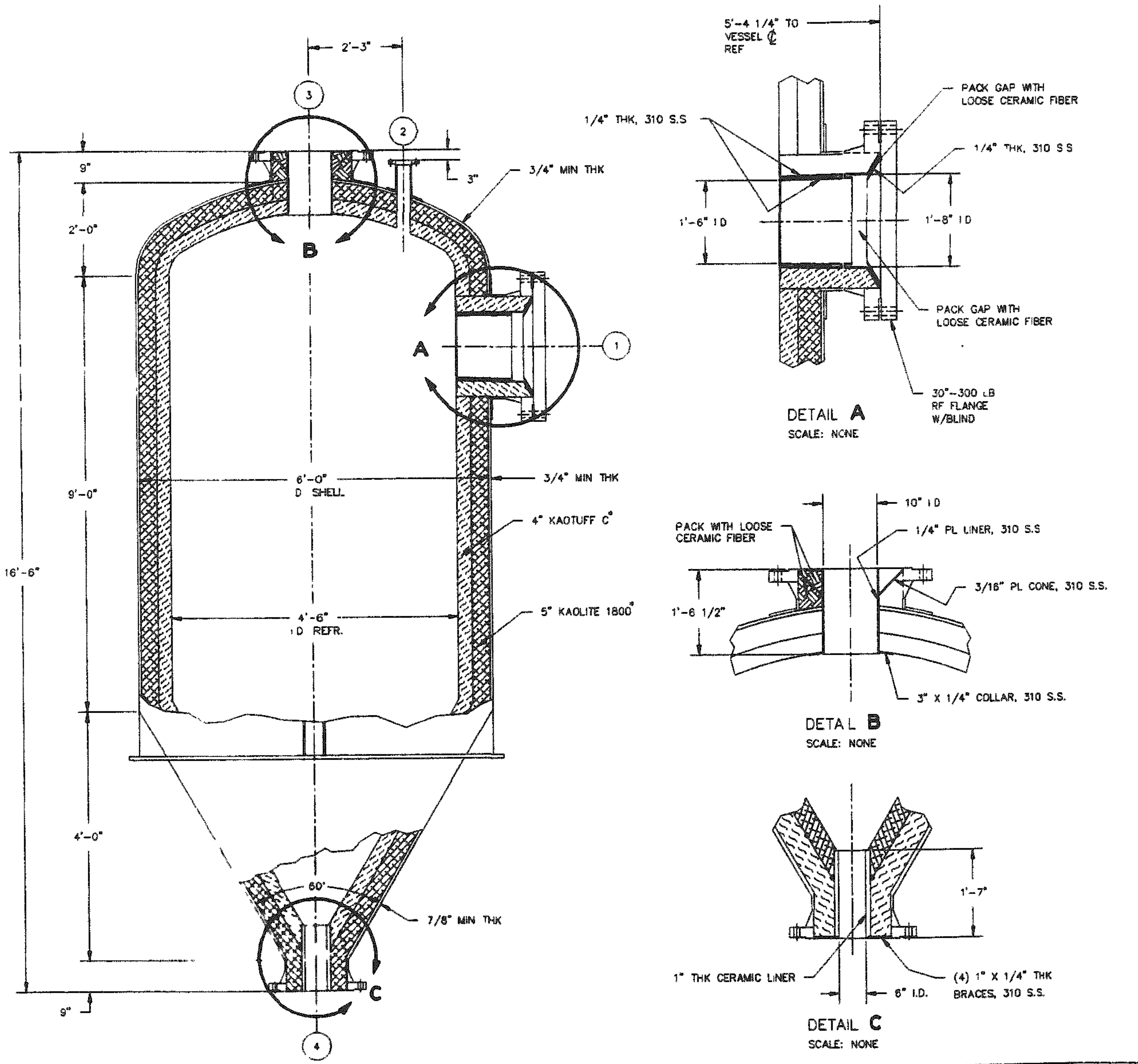
SERVICE:	FILTER MEDIA STORAGE/ADD
OPERATING PRESS:	208 PSIA
DESIGN PRESS:	218 PSIG
MAX. OPERATING TEMP:	1550°F (INTERNAL)
DESIGN TEMP:	650°F (METAL)
WIND DATA:	UBC (70 MPH, EXP.C)
EARTHQUAKE DATA.	UBC (ZONE 1)
CODE:	ASME SECT VIII DIV 1
CODE STAMP	YES
P.W.H.T. FOR CODE:	NO
P.W.H.T. FOR PROCESS:	NO
JOINT EFF:	100%
RADIOGRAPHED:	FULL
CORROSION ALL:	1/8"
MAT'L SHELL	SA-516 GR 70
MAT'L HEADS.	SA-516 GR 70 (2:1 ELLIPTICAL)
MAT'L SUPPT'S:	SA-516 GR 70
MAT'L NOZZLES:	SA-516 GR 70
MAT'L FLANGES.	SA-105
EMPTY WEIGHT:	8500 LBS (METAL ONLY)
WATER ONLY WEIGHT:	21500 LBS
FILTER MEDIA:	18000 LBS
REFR. LINING:	14000 LBS
SHIPMENT:	1 PIECE

NOZZLES

NO.	SIZE	ANSI RATING	SERVICE	I.D. LINING	QTY.
1	30"	CL 300 RF	MANWAY/BLIND	18"	1
2	4"	CL 300 RF	MEDIA ADD	4"	1
3	24"	CL 300 RF	MEDIA IN	10"	1
4	18"	CL 300 RF	MEDIA OUT	6"	1

* THERMAL CERAMICS PRODUCTS

Figure 39 Media Make-up Hopper, Carbonizer



VESSEL DATA

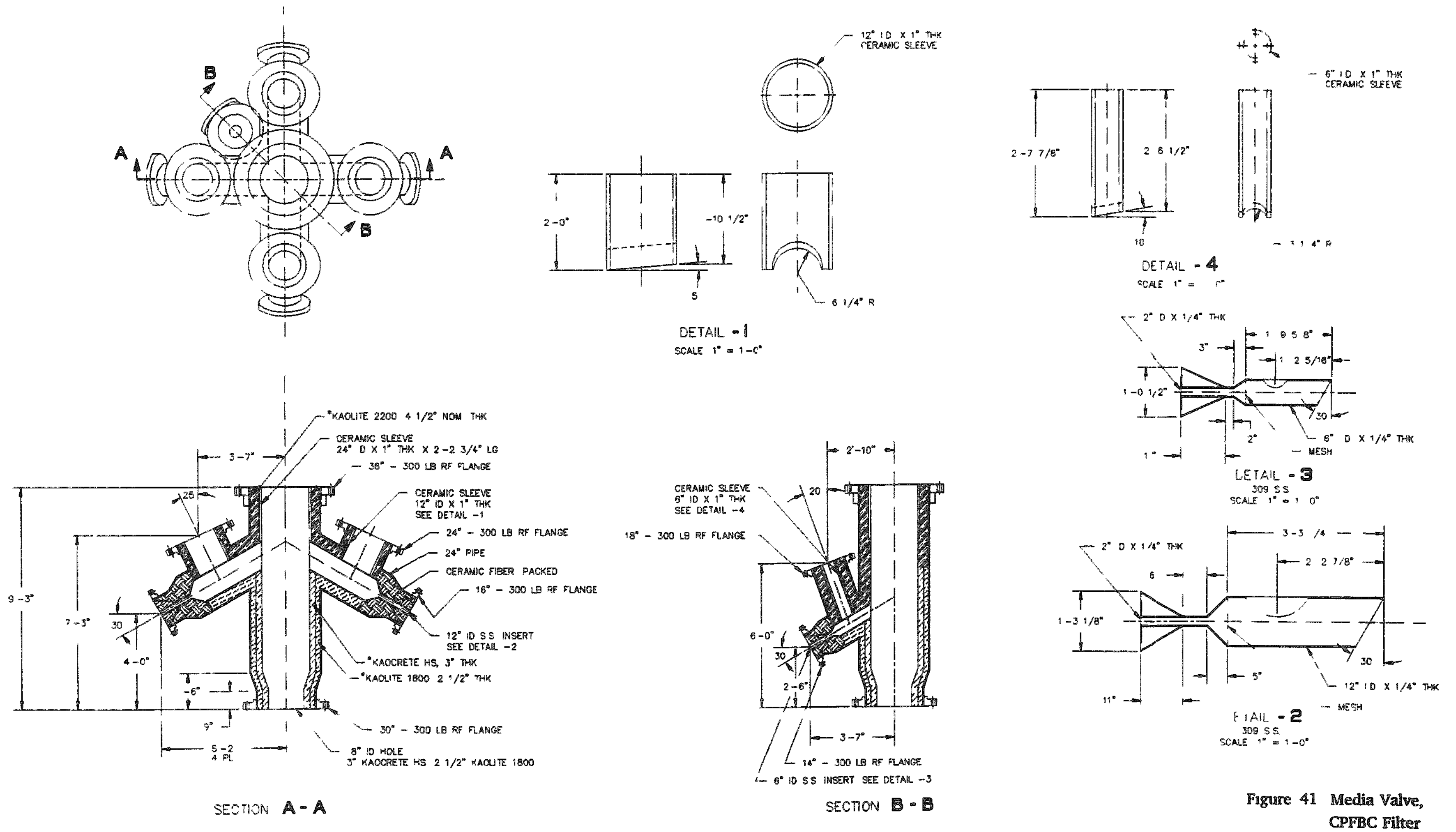
SERVICE:	FILTER MEDIA STORAGE/ADD
OPERATING PRESS:	381 PSIA
DESIGN PRESS:	410 PSIG
MAX. OPERATING TEMP:	1550°F (INTERNAL)
DESIGN TEMP:	650°F (METAL)
WIND DATA:	UBC (70 MPH, EXP C)
EARTHQUAKE DATA	UBC (ZONE 1)
CODE:	ASME SECT VIII DIV 1
CODE STAMP:	YES
P.W.H.T. FOR CODE:	NO
P.W.H.T. FOR PROCESS:	NO
JOINT EFF:	100%
RADIOGRAPHED:	FULL
CORROSION ALL.	1/8"
MAT'L SHELL	SA-516 GR 70
MAT'L HEADS	SA-516 GR 70 (2:1 ELLIPTICAL)
MAT'L SUPPT'S:	SA-516 GR 70
MAT'L NOZZLES	SA-516 GR 70
MAT'L FLANGES:	SA-105
EMPTY WEIGHT:	12500 LBS (METAL ONLY)
WATER ONLY WEIGHT:	21500 LBS
FILTER MEDIA:	18000 LBS
REFR. LINING:	14000 LBS
SHIPMENT:	1 PIECE

NOZZLES

NO.	SIZE	ANSI RATING	SERVICE	I.D. LINING	QTY.
1	30"	CL 300 RF	MANWAY/BLIND	18"	1
2	4"	CL 300 RF	MEDIA ADD	4"	1
3	24"	CL 300 RF	MEDIA IN	10"	1
4	18"	CL 300 RF	MEDIA OUT	6"	1

* THERMAL CERAMICS PRODUCTS

Figure 40 Media Make-up Hopper, KRW Gasifier



* THERMAL CERAMICS REFRACTORIES

Figure 41 Media Valve, CPFBC Filter

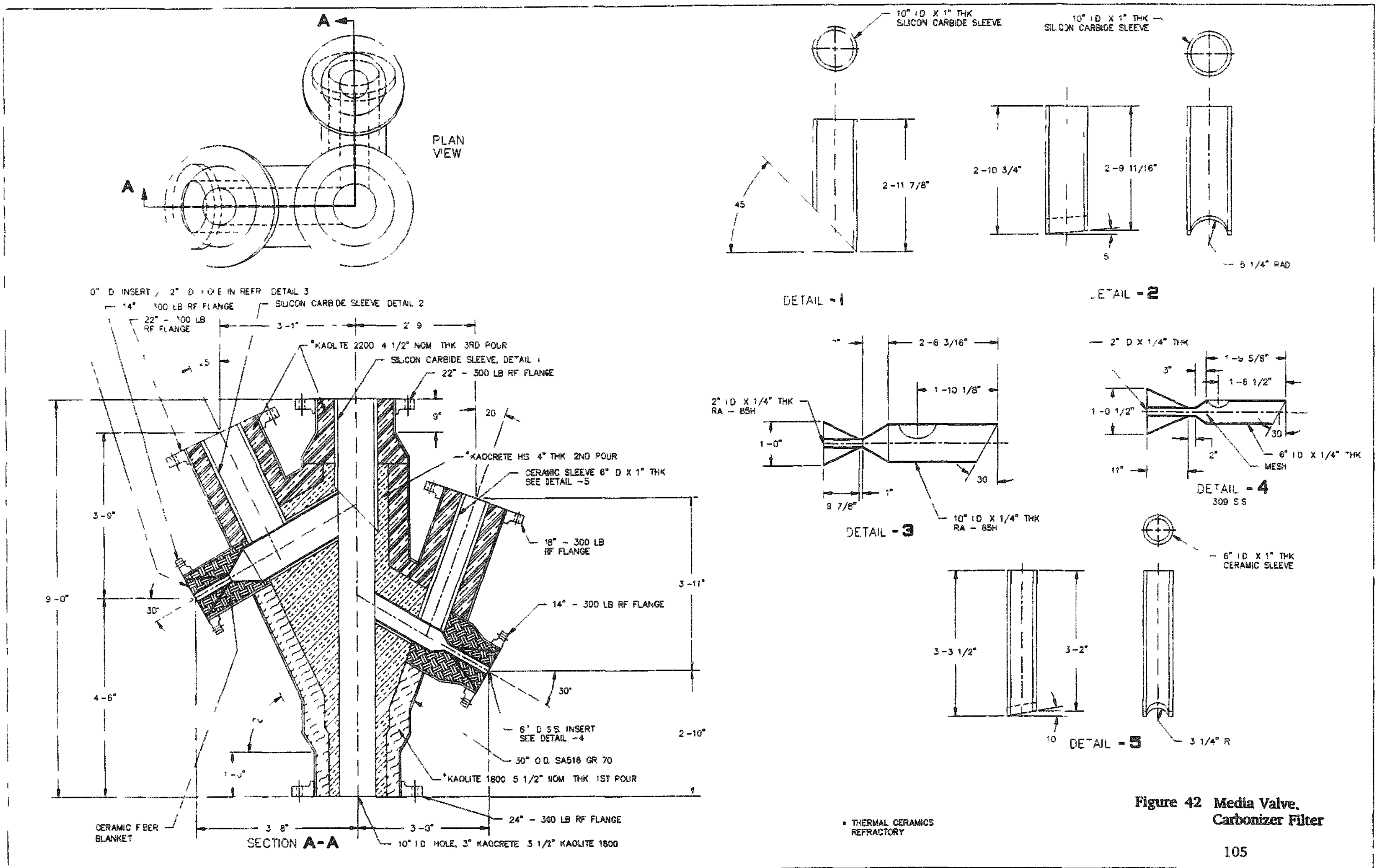


Figure 42 Media Valve, Carbonizer Filter

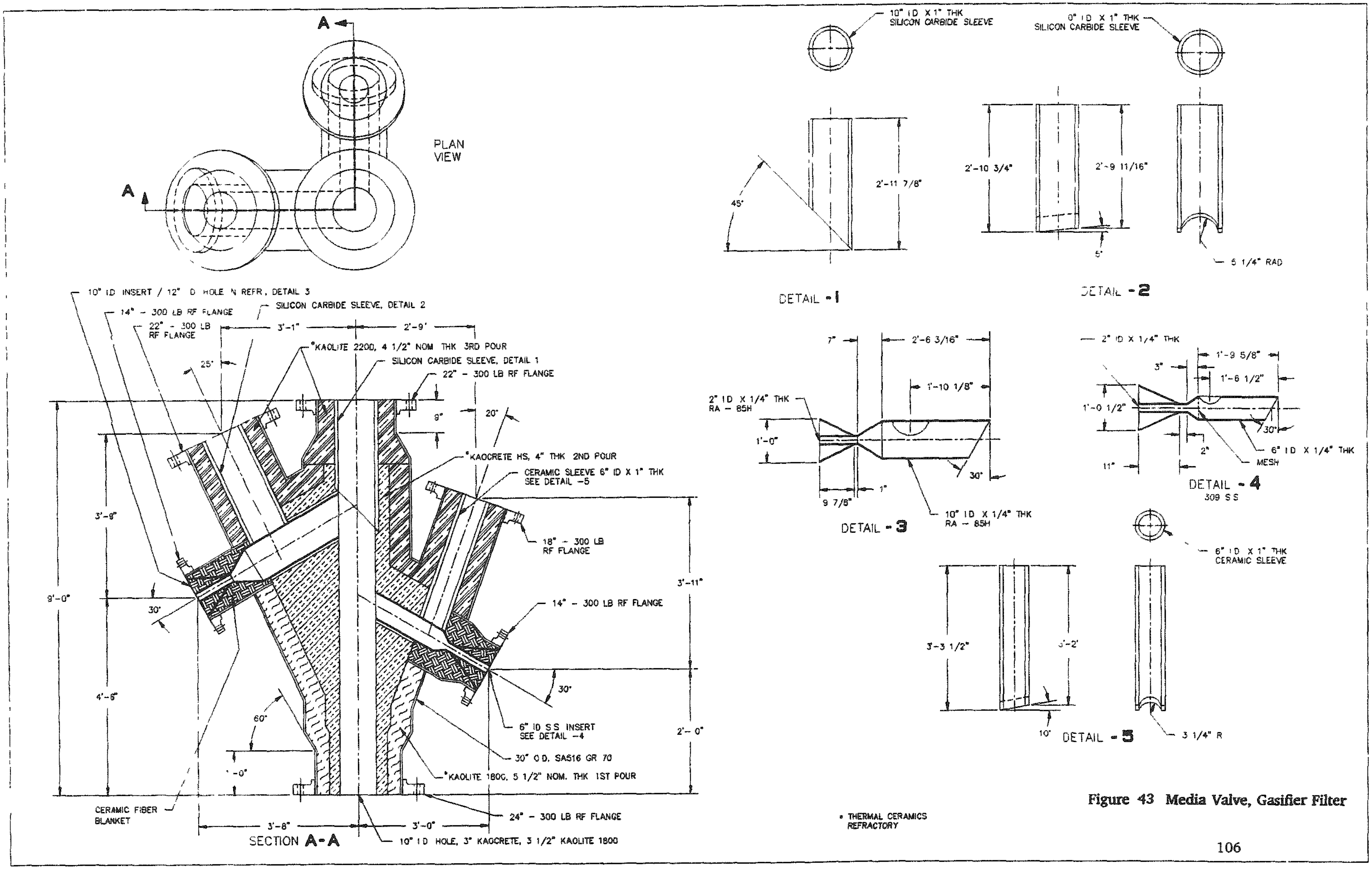


Figure 43 Media Valve, Gasifier Filter

PROPOSAL ONLY
NOT FOR APPROVAL

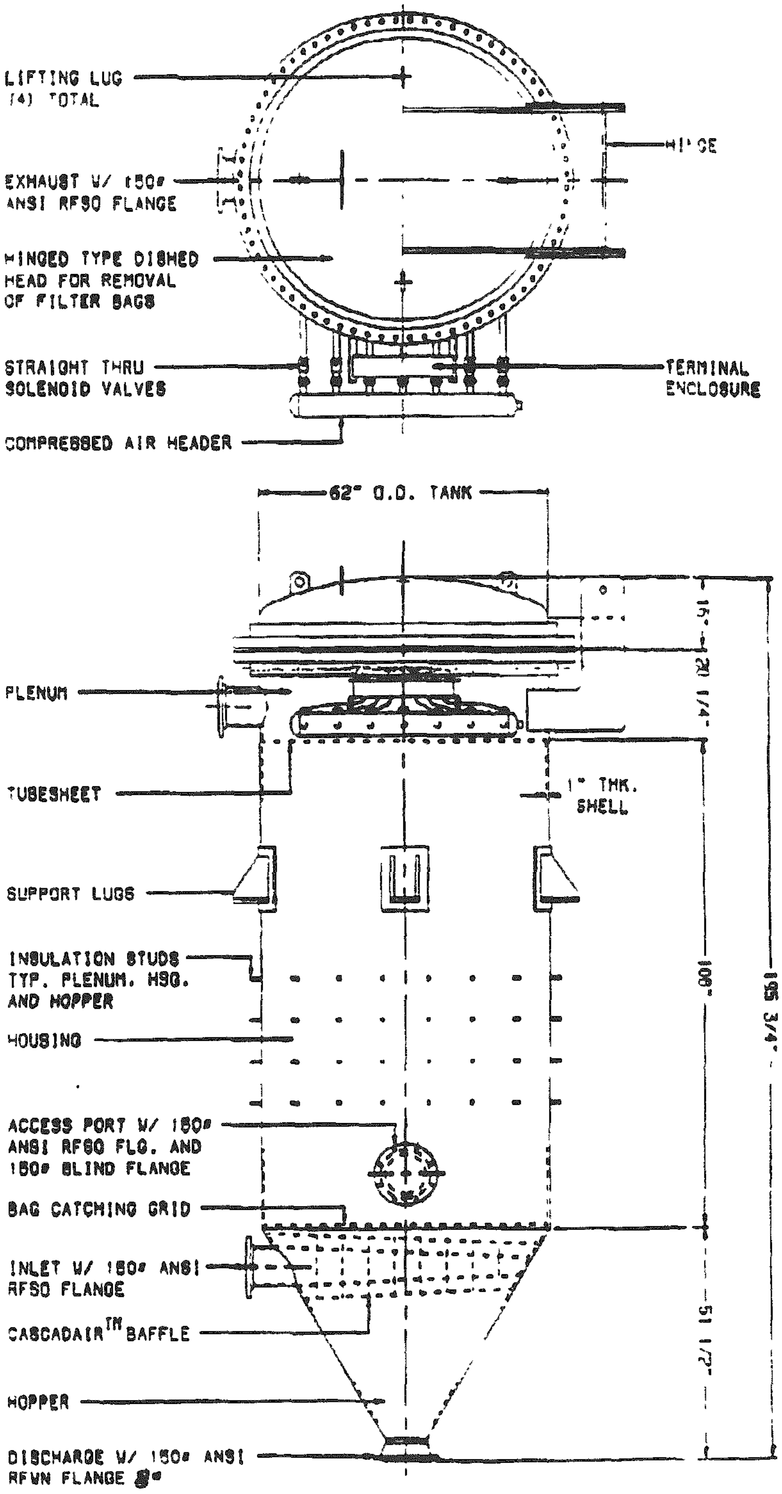


Figure 44 Typical Baghouse Configuration

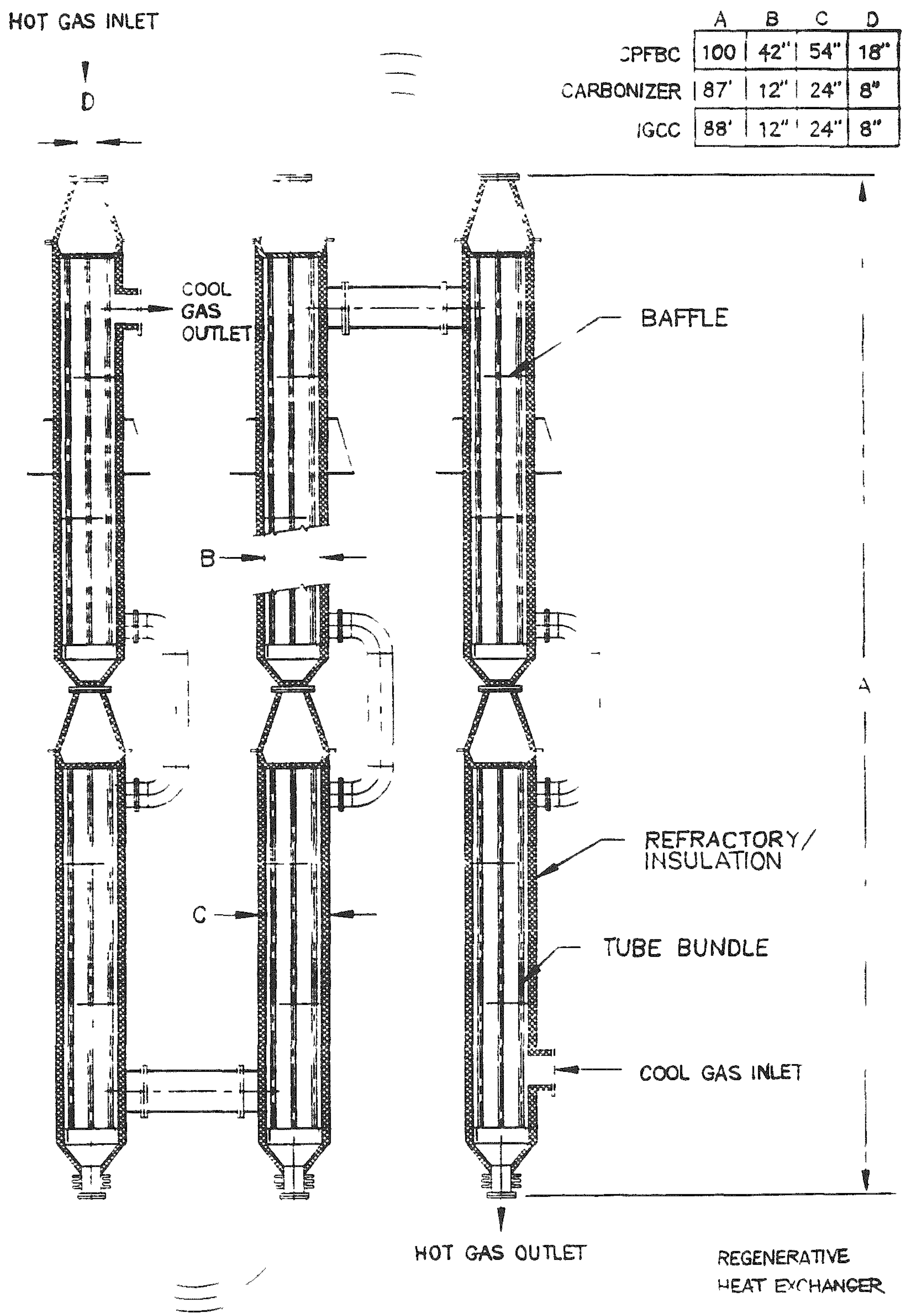


Figure 45 Arrangement for Regenerative Heat Exchangers

Some costs are not included in the erection estimate. For example, refractory costs include installation. The filter vessel will have refractory installed on site, in place. The other, smaller items will have refractory installed off site. Filter media is installed by others during start-up. Installation costs for inlet and outlet ducting, instruments and controls, and filter media were estimated by Combustion Power based on factoring from the material costs.

Installation of the granular-bed filter vessel will require some field welding and handling. The filter vessel cap, at flange "2", Figure 26, ships separate. As shown on Figure 27, in details A, B, and C, the stainless components are field welded into place. This will occur prior to installation of refractory. After refractory is installed in the major vessel and the cap, filter internals are installed. There is a field butt weld just below flange "2" to attach the major filter internals. Care will need to be taken to assure that the internals are centered inside the vessel. After the vessel cap is installed, the expansion joint assembly, shown on Figure 27, Detail D, is installed. Kaowool blanket is fitted into the expansion joint assembly and a single butt weld attaches the assembly to the major bulk of the internals.

The installation of refractory lined pipe (lift pipe and seal legs) involves exact fit-up; since there are no expansion joints. The assembly allows for field fit and welding of 6, 24"-300# weld neck flanges and includes extra handling to allow installation of a small amount of refractory at the tip of six 10' long pipe spools. The remaining installation of pressure vessels and piping is routine. All piping and fittings were itemized to assist in the erection cost estimate.

- Carbonizer Granular-Bed Filter

Table 23 lists the equipment for this plant. Each filter module consists of one filter vessel with a media circulation system as shown on Figure 33. The cyclone and the carbonizer collecting hopper, shown phantom, are not part of the installation. There are two identical filter modules as the entire plant is divided into two identical trains of equipment, each sized for, nominally, 226 MWe.

Some costs are not included in the construction estimate. As with the CPFBC filter, this includes: installation of refractory, filter media, and instruments/controls. Inlet and outlet ducting is similar to that needed for the other filters considered for this plant, so it cancels out of the cost estimate. The filter will have refractory installed on site, in place. The other, smaller items will have refractory installed off site.

Installation of the granular-bed filter vessel with internals and refractory is accomplished the same as for the CPFBC filter. As with the CPFBC filter, the filter vessel cap, at flange "2", Figure 28, ships separate to assist installation. The reference drawings are Figures 28 and 29.

The installation of refractory lined pipe (lift pipe and seal legs) involves exact fit-up; since there are no expansion joints. The assembly allows for field fit and welding of 1, 22"-300# weld neck flange and includes extra handling to allow installation of a small amount of refractory at the tip of one 10' long pipe spool. The remaining installation of pressure vessels and piping is routine. All piping is itemized for the plant to assist in the erection cost estimate.

- KRW Gasifier Granular-Bed Filter

Table 24 lists the equipment for this plant. Each filter module consists of one filter vessel with a filter media circulation system as shown on the general arrangement drawing, Figure 34. There is one filter vessel, sized for 100 MWe.

Some costs are not included in the construction estimate. As with the CPFBC, and carbonizer filter, this includes: refractory, filter media, inlet/outlet ducting, instruments, and controls. The filter will have refractory installed on site, in place. The other, smaller items will have refractory installed off site.

The arrangement of the cost estimating model allows all installation costs to be lumped together. No breakdown is needed for direct and indirect cost.

Installation of the granular-bed filter vessel with internals and refractory is accomplished the same as for the CPFBC filter. As with the CPFBC filter, the filter vessel cap, at flange "2", Figure 30, ships separate to assist installation. The reference drawings are Figures 30 and 31.

The installation of refractory lined pipe (lift pipe and seal legs) involves exact fit-up; since there are no expansion joints. As with the carbonizer, the assembly allows for field fit and welding of 1, 22"-300# weld neck flange and includes extra handling to allow installation of a small amount of refractory at the tip of one 10' long pipe spool. The remaining installation of pressure vessels and piping is routine.

Table 22 CPFBC Granular-Bed Filter Equipment - 226 MWe Module

Filter Components	Qty	Unit Weight (lbs)	Size or Capacity, (each)	Installed/ Operating Hp
Filter Vessels	4	171,327	21' 6" OD X 56'	-
Vessel Refractory	4	139,709		-
Filter Internals	4	8,027		-
Filter Auxiliaries				-
Filter Media	4	484,406		-
De-Entrain. Ves.	1	58,196	10' 6" OD X 47'	-
Internals	1	5,040		-
Refractory	1	81,414		-
Media Valve	1	8,422	24" ID	-
Internals	1	860		-
Refractory	1	3,132		-
Media Makeup Hpr.	1	16,456	8' 6" OD X 20'	-
Refractory	1	24,150		-
Refr Lined Pipe	1	108,101	24" ID Refr	-
Refractory	1	104,215		-
Regen. Ht. Exch.[1]	8	100,000	54" OD X 50' ea	-
Water-cooled Hx	1	18,000	34" OD X 13'	-
Baghouse	1	30,000	97.5" OD X 16.5'	-
Boost Blower	1	12,500	6500 acfm	500/290
Maintenance Blower	2	10,000	8550 acfm	400/370
Piping/Valves	1 Lot	23,868		-
Media Add Hopper	1	1,056	30" OD X 9.5'	-
Insulation	1 Lot	-		-
Access/Support Stl.	1 Lot	620,000		-
Instr/Controls	1 Lot	-		-
Inlet/Outlet Ducting	1 Lot	400,000		-
Ash System for CPFBC Granular-Bed Filter:				
500°F Ball Valve	2	100	6"	-
500°F Bleed Valve	1	50	2"	-
Throt'lng Slide Gate	1	100	6"	-
RPD Vessel-C'Stl[2]	1	8,810	7' OD X 12.5'	-

Notes:
1. Eight section at 54" OD x 50' long for 100,000 lbs total.
2. Restricted-Pipe Discharge hopper.

Table 23 Carbonizer Granular-Bed Filter Equip. - 226 MWe Module

Filter Components	Qty	Unit Weight (lbs)	Size or Capacity, (each)	Installed/ Operating Hp
Filter Vessel	1	78,264	15' 6" OD X 45'	-
Vessel Refractory	1	79,703		-
Filter Internals	1	6,329		-
Filter Auxiliaries				-
Filter Media	1	221,875		-
De-Entrain. Ves.	1	20,850	6' 6" OD X 32'	-
Refractory	1	32,298		-
Internals	1	2,081		-
Media Valve W/Refr	1	7,923	10" ID	-
Internals	1	200		-
Media Makeup Hopper	1	8,642	6' OD X 16.5'	-
Refractory	1	13,994		-
Refr Lined Pipe	1	56,487	10" ID Refr	-
Refractory	1	52,954		-
Regen. Ht. Exch.[1]	8	30,000	24" OD X 44' ea	-
Water-Cooled Hx	1	1,955	16" OD X 13'	-
Baghouse	1	8,750	60" OD X 16.5'	-
Boost Blower	1	15,000	1160 acfm	60/48
Maintenance Blower	1	5,000	3185 acfm	175/165
Piping/Valves	1 Lot	6,522		-
Insulation	1 Lot	-		-
Media Add Hopper	1	1,081	30" OD X 9.5'	-
Instr/Controls	1 Lot	-		-
Access/Support Stl.	1 Lot	180,000		-

Ash System for Carbonizer Granular-Bed Filter:

500°F Ball Valve	2	100	6"	-
500°F Bleed Valve	1	50	2"	-
Ash Hopper	1	3939	4' OD X 9' 9"	-

Notes:
1. Eight section at 24" OD x 44' long for 30,000 lbs total.

Table 24 KRW Gasifier Granular-Bed Filter Equip. - 100 MWe Plant

Filter Components	Qty	Unit Weight (lbs)	Size or Capacity, (each)	Installed/ Operating Hp
Filter Vessel	1	137,863	15' 6" OD X 45'	-
Vessel Refractory	1	78,962		-
Filter Internals	1	6,749		-
Filter Auxiliaries				-
Filter Media	1	221,875		-
De-Entrain. Ves.	1	30,153	6' 6" OD X 32'	-
Refractory	1	32,298		-
Internals	1	2,081		-
Media Valve W/Refr	1	8,590	10" ID	-
Internals	1	200		-
Media Makeup Hopper	1	12,627	6' OD X 16.5'	-
Refractory	1	13,994		-
Refr Lined Pipe	1	61,678	10" ID Refr	-
Refractory	1	52,954		-
Regen. Ht. Exch	8	40,000	24" OD X 44'	-
Water-Cooled Hx	1	2,310	14" OD X 13'	-
Baghouse	1	14,650	62" OD X 16.5'	-
Boost Blower	1	20,000	930 acfm	100/64
Maintenance Blower	1	5,000	3160 acfm	175/166
Piping/Valves	1 Lot	6,533		-
Insulation	1 Lot	-		-
Media Add Hopper	1	1,564	30" OD X 9.5'	-
Instr/Controls	1 Lot	-		-
Access/Support Stl	1 Lot	170,000		-

Ash System for KRW Gasifier Granular-Bed Filter:

500°F Ball Valve	2	100	6"	-
500°F Bleed Valve	1	50	2"	-
Ash Hopper	1	3,939	4' OD X 9' 9"	-

Notes:
1. Eight Sections at 24" OD X 44' long for 40,000 lbs total.

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12. Kelly, J. September, 1991. RA-85H Performance in Hot Corrosion. In *Heat Resistance Materials*. Proceedings of the First International Conference, Fontana, Wisconsin, USA, ed. K. Natesan and D.J. Tillack, 653-658. Materials Park, Ohio: ASM International.

SECTION 4

CERAMIC CANDLE FILTERS

4.1 Candle Filter Development Status

Interest in ceramic barrier filters has increased over the last 15-20 years. Development of the cross-flow filter has received a lot of attention because of the possibility of packaging a high amount of filter area in a small filter element. Cross-flow filters consist of thin, porous ceramic plates that contain troughs formed by ribbed segments. These plates are stacked and fired to form a continuous, porous structure in the shape of a rectangular cube. A flange is included on the element to provide a connection interface to metal exhaust ducting. Cross-flow filter systems have been field tested in both combustion and gasification, pilot test facilities. Typically, failure in the cross-flow filter element has been the result of either seam trough delamination, or crack formation along the flanged section. Modifications made in both fabrication and production of the cross-flow filter bodies, as well as redesign of the flange clamping arrangement has reduced these modes of failure. Nevertheless, increased interest has been shown in alternate shapes of ceramic, barrier filter elements.

Ceramic candle filter elements are commercially available from a few sources. These filter elements are rigid tubes, closed at the bottom and flanged at the top. They are formed by bonding ceramic fibers and/or grains with an aluminosilicate binder. Lengths are typically 1 to 1.5 m and outside diameters are 60 mm with a wall thickness of 10 to 15 mm. Candle filter elements are mounted in tubesheets, utilizing a variety of arrangements to clamp and seal the filter element flanges. Tubesheets not only support the candle filters but seal the clean gas plenum from dirty gases. Candle filters (and cross-flow filters) are cleaned periodically by high pressure bursts of gas delivered near the filter element outlets. In combustion systems, high pressure air is used to clean the filter elements. In gasifiers, nitrogen or process gas is used. Candle filter elements have been vulnerable to cracking, especially near the flange portion. This has generally been attributed to problems that can be solved once understood. These problems are: excessive mechanical and thermal stresses that developed from improper mounting techniques, tubesheet design, pulse cleaning, candle design, or system transients.

Table 25 summarizes some of the relevant field test experience with both cross-flow and candle filters[1]. Both types of filters have been successfully tested; although, some failures have occurred as noted. Furthermore, a variety of materials have been tested; many of which are not listed. Materials used for cross-flow filter construction include alumina/mullite, cordierite, aluminosilicate foam, cordierite-silicon nitride (CSN), and reaction-bonded silicon nitride (RBSN). Silicon carbide-based materials are currently used in the commercial manufacture of candle filters. Alternate candle filter materials include fireclay, aluminosilicate fibers, alumina, alumina/mullite, or chemical vapor infiltration of silicon carbide (CVI-SiC) matrices.

Table 25 Ceramic Barrier Filter Experience

Location	Year	Gasif(G) Comb(C)	Mat'ls	Operating Hours	Experience
<u>Ceramic Cross-Flow Filters</u>					
DOE/METC	1970-80's	G	Al/M	250	Delamination, but no performance
degradation					
KRW	1985-87	C	Al/M	168	2/8 elements delamination or cracked
NYU	1988	C	Al/M	83	5/15 delaminated or cracked
Texaco	1989-90	G	Al/M	250	
WH-LTDTF	1989-91	C	Al/M	1,300	Failure along flange section
<u>Ceramic Candle Filters</u>					
CRE	1984-85	G/C	FC		
Grimethorpe	1987	C	SiC	800	1 breakage after 300 h; 4 breakages due to system problems
KRW	1985-87	G	SiC	6-50	Failure due to system problems
DOE-METC	Current	C	SiC		Pressurized, entrained combustor
Solar Turbine	1990	C	SiC	50	
IGT	1983-85	G	SiC	150	
Calvert		C		700	2 tiers, 6 candles/tier
U. Aachen		C	SiC	5,800	
Deusche Babcock		C	SiC	3,500 cycles	2 candles in parallel; 700°C
Rheinbraun-Berrenrath		G	SiC		9 elements
Rheinbraun-Wesselery		G	SiC		90 elements
EPDC, Japan		C	SiC & Cor		
Ahlstrom		C	Cor		
ABB-Carbon		C	Cor & others		

Al/M - Alumina/mullite
FC - Filter coupons
SiC - Clay-bonded SiC
Cor - Cordierite

Based on the experience summarized above, the ceramic candle filter represents the approach in which there is the most interest; therefore, the granular-bed filter is compared to the most economic commercial approach believed suitable for the applications studied in this effort. From the experience presented and some of the more recent endeavors, four filters (or filter groups) influenced the candle filter design proposed by Combustion Power. This includes the experience at the Grimethorpe PFBC Establishment, Barnsley, South Yorkshire, United kingdom; the Tidd PFBC Demonstration Plant, Brilliant, Ohio; Aachen Technical University (RWTH), Aachen, Germany; and Industrial Filter and Pump, Cicero, Illinois.

4.1.1 Pilot Plant Filter at Grimethorpe

The candle filter installed and tested at the Grimethorpe plant in the United Kingdom in 1987 was significant because it was one of the largest filters constructed and operated as of that date. This filter housed 130 filter elements inside an internally insulated filter vessel with a carbon steel enclosure 2.6 m (8.5 ft) in diameter and 8.9 m (29 ft) long. Filter elements were the Diaschumalith type manufactured by Schumacher GmbH. These tubular filter elements were 1.5 m long, 60 mm outside diameter with a wall thickness of 15 mm. The filter elements consisted of an inner, high porosity support layer made from silicon carbide granules; with a thin, low porosity, outer layer composed of fine alumina fibers and silicon carbide grains. The bonding agent used for the filter element materials was clay.

The tubesheet was a flat plate drilled to accept the filter elements and attached to the filter housing by a V-type support. Filter elements were held in place by a counterweighted venturi. A cylinder shaped shroud of constructed of alloy steel is installed around the filter elements in order to protect the elements from direct impingement of the dirty incoming flue gas onto the elements and to force the dirty flue gas to flow in an upward direction on the outside of the shroud. After the gas flows over the top of the shroud it turns and flows in a downward direction as it comes in contact with the filter elements. This downward flow of dirty flue gas is co-current with falling particulate filter cake and helps to keep reintrainment of particles to a minimum. High pressure air was used to remove ash accumulated on the outside of the candle filter elements by generating a periodic reversal of air flow inside the candle filter element. In the literature on the Grimethorpe filter[2,3,4], there was sufficient information presented on the design and operation of the filter and on the pulse system that extrapolation of certain aspects of the design to commercial size was possible.

4.1.2 Tidd Candle Filter Design

The candle filter at the Tidd PFBC Demonstration Plant is currently undergoing testing, so actual performance data on the filter is not available; but literature[5] on the candle filter design was useful in confirming many aspects of our candle filter design. The Tidd filter uses a candle filter element of 1.5 m length and 60 mm outside diameter constructed of two layers of sintered silicon carbide consisting of a thin outer layer of fine porosity material over a much thicker layer of courser porosity material. According to the literature, the elements used at Tidd are very similar in size and construction to those tested at Grimethorpe. The Tidd filter contains 384 candle filter elements arranged in three tiered clusters containing 128 elements each. Each tier cluster has three levels with the upper and middle tier of each cluster supporting 38 elements and the lower tier of each cluster supporting 52 elements.

A flat tubesheet with a V-type support similar to that used at Grimethorpe is used to support the three tiered element clusters. The filter element clusters are surrounded by a cylindrical, alloy steel shroud similar to the one used at Grimethorpe. This shroud serves the same functions in the Tidd filter as in the Grimethorpe filter described above. The three tiered element clusters and surrounding shroud are housed in an internally insulated carbon steel vessel of 10 ft. in diameter and 44 ft. length. Figure 47 shows a general arrangement of the Tidd candle filter vessel.

The pulse air system at Tidd consists of an air compressor system, refrigerated air dryer, primary air accumulator tank, duplex air filters, secondary air accumulator tanks, dual Atkomatic solenoid pulse valves (presumably, one is a spare), and automated ball valves. The outlet of each pulse valve feeds three different pulse manifolds, each isolate with an automated ball valve. Only when the manifold is being pulsed is the automated ball valve opened; thus, one pulse valve can service three manifolds sequenced as desired. This feature allows for multiple usage of the very costly pulse valves. The automated ball valves also serve as shut off valves in case the pulse valve fails in the open position. The pulse air system used at Grimethorpe is almost the same configuration as that used at Tidd except each pulse valve supplied pulse air to one single manifold, and there were no automated ball valves downstream of the pulse valves.

4.1.3 Pilot Plant Testing at Aachen, Germany

The filter unit installed and tested at Aachen Technical University (RWTH) Aachen, Germany in 1988 and 1989 was a small unit with only six candle filter elements. The six candle filter elements tested were Diaschumalith type elements manufactured by Schumacher GmbH similar to those used at Grimethorpe but only 1 meter in length. The six candle filter elements where supported in a flat tube sheet and arranged in a circular pattern. The sealing of the candle filter element flange and the tubesheet was provided by a ceramic fiber gaskets and a weighted element retainer. This retainer was similar to the counterweighted venturi used at Grimethorpe except it had a straight bore. The candle filter vessel was made of carbon steel with internal refractory lining. The dirty flue gas entered the vessel below the filter elements and was directed upward to near the underside of the tube sheet by a center duct so that the dirty flue gas flowed downwards along the filter elements. This arrangement serves the same function as the peripheral baffle used in the Grimethorpe and the Tidd filters. That is, the filter cake dislodged from the elements falls into the cone shaped ash hopper section of the filter vessel aided by co-current flow of the dirty flue gases.

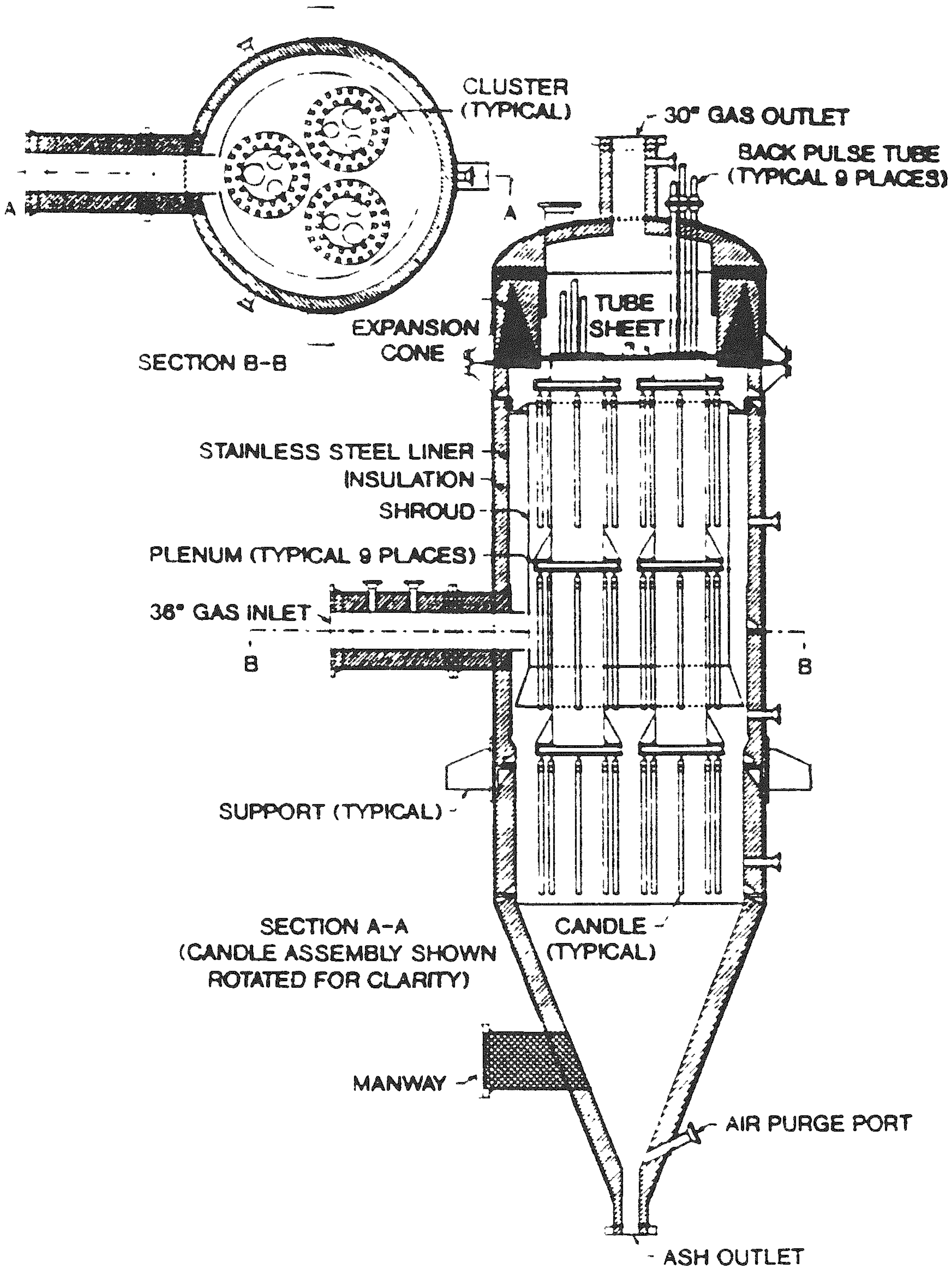


Figure 46 Candle Filter at Tidd [5]

The pulse air system for this filter consisted of a compressed air reservoir located above the filter vessel with a quick opening solenoid pulse valve connected to each of the six filter elements. In this filter each filter element was pulsed by a single solenoid pulse valve; unlike, the Grimethorpe and Tidd filters were multiple filter elements are pulsed by a single solenoid pulse valve. Literature[6,7] on the design and performance of this filter provided background information that was useful in confirming pulse air pressures and capacities.

4.1.4 Candle Filters With Vacuum Formed Ceramic Fiber Components

In the three candle filter units discussed above, a non-cooled, alloy steel tube sheet supports candle filter elements made of hard sintered ceramic materials. Most of the candle filter units tested and reported in the literature to this date, have used this same approach. In addition to their work on these types of filters described above, Industrial Filter & Pump Mfg. Co. (I.F.& P.) of Cicero, Illinois is developing candle filter designs using lightweight vacuum formed ceramic fiber components. In these designs, the components such as the tubesheet, and the candle filter elements are made of vacuum formed ceramic fiber materials which are lightweight and suitable for high temperature serice[8] according to I.F.& P. It is also proposed to incorporate the pulse air distribution system into the vacuum formed hold-down plate. One possible candle filter arrangement uses a steam cooled alloy steel tubesheet and components, such as candle elements and element hold-down plates, made from lightweight vacuum formed ceramic fiber materials. While use of ceramic fiber filter elements and components is an intriguing, and potentially inexpensive, alternative to other more conventional designs, there is limited information on large scale design, testing and performance of candle filters using these components. Information provided by I.F.& P. in other areas of more traditional candle filter design was useful in confirming other aspects of the commercial approach.

4.2 Conceptual Candle Filter Designs

In our literature search, design variables and potential configurations for candle filters were identified. The most critical design variable was filter face velocity, expressed in ft/min (or cm/sec). This is the average velocity at which the process gas approaches the candle filter elements. Although a data base is forming, there are considerable, and varying, opinions on this variable.

Ash from the process collects on one side of the filter element. Periodically, the ash is removed by back flushing with a high pressure pulse of air or gas. The amount of pulse air, or gas, needed to clean each filter element is another important design parameter. There in quite a divergence between early design values, lab measured quantities, and field measured quantities. This flow is significant because it lowers the process gas temperature, can be a source of heat loss, and requires equipment of considerable capital cost. The number of filter elements that can be back-pulsed by singlemanifold is another difficult tradeoff. A large quantity of filter elements serviced by a single manifold results in fewer manifolds and a less bulky supply system. The drawback is in attenuation of the air or gas pulse as it is spread through a higher volume manifold. Intuitively, this will result in a higher pulse volume required because of the pulse energy is dissipated. The capacity of available pulsing valves is also a practical limit. Other design parameters can also have a profound effect on the filter design. These are: Filter element size, filter element spacing, and pulse gas pressure.

There is similarity between some ceramic candle filters arrangements and industrial baghouses. Filter elements in both devices are tubular in nature and are supported by a structural plate separating the dirty gas plenum from the clean gas plenum. In baghouses, flexible cloth bags are held in a tubular shape by internal metal cages. Candle filter elements have the tubular structure built into the ceramic matrix. Ash buildup on the filter elements in both devices is removed by a reverse flow of gas. In "pulse jet" baghouses as in candle filters, the reverse flow of gas is generated by quick blasts of high pressure air. Pulse air distribution systems for baghouses are similar to those used in some candle filter pilot plant facilities. There is, although, a difference in the effect of the pulse air in a baghouse bag and in a candle filter element; since, the baghouse bag flexes and the ceramic candle remains essentially rigid.

The design parameter known as face velocity for candle filters is the same as the industrial baghouse filter design parameter known as air-to-cloth ratio. In the baghouse industry, this parameter is calculated by dividing the inlet gas flow in actual cubic feet per minute (acfm) by the area of filter cloth in square feet (ft^2). The result is the velocity of the gases approaching the filter bags in ft/min; which is the same as face velocity. For baghouses, the air-to-cloth ratio is based on the application. Users and manufactures have collected a vast amount of data to set this parameter. The value typically varies between baghouse manufactures. It is sometimes specified by the user.

4.2.1 Candle Filter Specification

Using information from current documents on candle filter technology, a mechanical design specifications was prepared for the commercial size, ceramic candle filter. Design guidelines from test filters were used directly or extrapolated to commercial size. Some of the candle filter design features were pushed beyond the tested limits on the assumption that these parameters could eventually be achieved. This specification forms the foundation for the commercial candle filter design.

• Candle Filter Elements: Although the candle filter tubesheet can be designed to accept any filter element, for the purpose of costing the filter, a description is needed. The most common filter element is a two layer element of silicon carbide with overall length of 1.5 meters and outside diameter of 60 mm. Elements of these same dimensions and materials were used in the candle filters at Grimethorpe[2] and Tidd[5]. These elements are commercially available from manufacturers in thicknesses of 10 mm and 15 mm. The outer layer of silicon carbide is made from fine material, for filtration, with a mean pore size of 22-30 micron (Grade 5-10). The inner layer of course material adds structural rigidity. Mean pore size is 125 micron (Grade 50). Quotes were received based on this description.

• Filter Face Velocity: After a literature search and subsequent review by the Morgantown Energy Technology Center, we used a face velocity of 10 ft/min for the CPFBC filter (oxidizing atmosphere) and 5 ft/min for the carbonizer and gasifier filters (reducing atmospheres). For all filters, the particulate loading is fairly high at 4000 ppmw for the CPFBC filter, 10,000 ppmw for the carbonizer filter and 8500 ppmw for the gasifier filter. Face velocity has to be balanced against pulse requirements. Filter face velocities used in other filter testing are listed in Table 26.

• Spacing of Elements on Tubesheet: Based mainly on the information published on the candle filter used at Grimethorpe, a 4 3/8" center to center spacing was used[2]. Although filter elements were spaced on a square, non-staggered, pattern at Grimethorpe, we found that a staggered patten resulted in a more efficient use of the available space on the tubesheet. Six open lanes were included on each tubesheet, giving them a pie-shaped pattern, so gas could penetrate to the central filter elements.

• Number of Elements per Pulse: Not more then 15 filter elements are pulsed at once. This is based mainly on industrial baghouse practice. There is a limit on how far a gas pulse can be spread before it dissipates. To keep the amount of pulse gas to a minimal amount, we felt it would be best to mimic the pulse distribution practice used in similar equipment. To confirm this selection, we verified that the flow capability of the pulse valve chosen would be adequate. At Grimethorpe, the test filter had 10-13 filter elements per pulse[2,4]. Industrial Filter & Pump proposes pulsing up to 36 filter elements with a single pulse valve[10]. At Tidd, it is proposed to pulse up to 52 candles with a single pulse valve[5]. Some more development is needed in this area as it would simplify the candle filter to utilize fewer parallel pulse paths.

• Pressure of Pulse Gas: The pulse gas system for each candle filter application was designed to supply pulse gas at pressures that range from 100 psi (7 Bar) to a maximum of 300 psi (21 Bar) above filter pressure. This is based on our literature search regarding testing of candle filter pulse systems. At Grimethorpe, the pulse pressure was 20 bar (290 psi) over system pressure mainly to improve operation of the pulse valves[4]. The Department of Energy at the Morgantown Energy Test Facility tested at 13.8 bar (200 psi) above filter pressure[9]. RWTH Aachen tests were run at 1-6 bar (15-87 psi) over filter pressure[7]. I.F.& P. proposes 6-8 bar (87-116) above filter pressure[10]. At Tidd, compressor capability is 1500 psig for a 150 psig filter system[5]. A pulse gas pressure of 100 psi over filter pressure is considered normal pulse gas system operating pressure for this report and this pressure is shown on the process flow sheets for each candle filter application but the pulse gas pressure can be adjusted upward to the maximum design value as needed. This flexibility is needed due to possible changes in the properties of the ash cake that may effect the cleaning of the candle filter elements.

• Pulse Valves: Use 2" Atkomatic quick opening, pilot actuated solenoid valves; with actuated, quick closing ball valves as a safety shutoff valve downstream of solenoid valve.

Table 26 Filter Face Velocities

Test Site	Face Vel. ft/min	Notes
Grimethorpe[4]	2.0-13.8	
Grimethorpe[4]	11.8	longest Test, 230 hrs
RWTH Aachen[7]	7-19	3700 test hours
DOE/METC[9]	13	single element
I F & P[10]	15-28	recommendation
Wakamatsu, Japan[11]	11.9-16.7	
KRW Gasifier[12,13]	1.5-5.2	gasification conditions
Commercial Filter Study:		
CPFBC Filter	10	oxidizing atm.
Carbonizer Filter	5	reducing atm.
Gasifier Filter	5	reducing atm.

At this time the Atkomatic valve is the most widely used pulse valve in candle filter service. Atkomatic pulse valves have been reported to have been used at the Grimethorpe filter[4], EPRI tier filter[14], and the Tidd filter[5].

Several solenoid valve manufacturers were contacted regarding quick opening solenoid valves suitable for high pressure service (450-750 psig) as a pulse valve on a candle filter. The pulse valve is required to open and close in one second or less. The only company identified to date that manufactures this type of valve in the required 2" size is the Atkomatic Valve Company of Indianapolis, IN. Atkomatic has a standard valve that meets the requirements identified for a candle filter pulse valve. It is rated to 400°F. Because these valves are expensive, one solenoid actuated valve is utilized to service three pulse air manifolds. These manifolds are isolated by automated ball valves.

• Pulse Air Element Venturi: The fixture we proposed to hold the filter element does not include a venture; although, to add one would not increase the cost substantially.

• Tubesheet and Tubesheet Support Design: The intent was to choose the most economic tubesheet design. Various sizes and shapes were considered, including: thick, flat tubesheets; thinner, braced, flat tubesheets; and spherical segments. Single tubesheets were compared with tiered tubesheets. A "V-type" support similar to that used at Grimethorpe[4] and Tidd[5] was considered, but this limited the tubesheet diameter. Another design was chosen based on results of finite element analysis that was not as limited on diameter.

• Filter Element Sealing Material: Filter element sealing materials used in candle filter tests to date were reviewed. One type of candle element seal uses 3M Company "Interam" heat expanding type gasket material. This material is reported to have been used as the candle filter element gasket in candle filter test units by Industrial Filter & Pump Mfg. Co.[15] and at the Department of Energy Morgantown Energy Test Facility[9,16]. The 3M Company was contacted for design information on "Interam" gasket material. Although this material is limited to use up to 1500 F, we are assuming this material or one of similar cost and form will be suitable for use on a commercial size candle filter.

4.2.2 Pulse Gas Requirements

The pulse gas requirement for a candle filter depends on the application, face velocity, and desired pressure drop. Candle filter pressure drop varies considerably according to available sources. A review paper[17] on high temperature, high pressure gas filtration states that the pressure drop across a ceramic barrier filter is expected to be 6 psi. A report on testing ceramic filter elements on a atmospheric fluidized bed[14] relates a pressure drop of 0.75 psi. British Coal[18] determined that the steady state permeance during three consecutive test periods for PFBC gas at 830°C was about 0.25 m/s/bar. (Permeance is defined as the ratio of filtration face velocity to filter pressure drop.) Using this value of permeance, a 10 ft/min face velocity, used in the CPFBC filter, would cause a filter pressure drop of 2.92 psi and a 5 ft/min face velocity, used in the carbonizer and in the gasifier filters, would cause a filter cake pressure drop of 1.46 psi. Added to this pressure drop would be the pressure drop from the flow through the filter housing and from the flow past the venturi. A limitation of Hudson data is that it does not account for the effect of pulse cleaning cycle time on filter pressure drop.

METC researchers[9] collected data on the specific cake resistance, K_2, for ash from an atmospheric fluidized bed combustor. Specific cake resistance ranged from 33.0 to 40.7 (in H_2O ft min/lb) for filter cakes formed from ash which had passed through a pre-collection cyclone. This data can be used to estimate the pressure drop through the cake for each application. The total pressure drop through the filter system is 50% of the pressure drop through the cake plus the pressure drop through the candle filter itself and through the filter housing. We used 50% of the cake resistance because filter elements are continuously being cleaned, and at any particular time, some filter elements have just been cleaned and some are ready to be cleaned. The steady state pressure drop through the cleaned filter for the two METC tests with pre-collection cyclones was about 75 IW at a face velocity of 13.1 ft/min. If one assumes that the pressure drop through the cleaned filter is linearly proportional to the gas flow through the filter, the cleaned pressure drop through the filter can be calculated for the face velocities used in the the assigned applications. Table 27 summarizes parmeters used in estimating pulse air requirements for the CPFBC. For a specific cake resistance of 33, the pressure drop is 2.7 psi.

Even less data is available on properties of filter cakes generated in a gasification environment. Texaco reports[19] that their filter cakes had a high cake resistance, low cohesivity, and low density. Typical cleaning times for filter cakes from both the Texaco and the Shell process were about 5 minutes. Juhani Isaksson of Ahlstrom found that filter cakes from gasification processes have a permeability 1/3 of cakes formed in a combustion process[19]. For the carbonizer and the gasifier, a specific cake resistance of 99 is used in the calculation results shown in Table 27. In order to keep the overall filter pressure drop less than 2 psi, the pulse gas cycle time is 8 minutes for the carbonizer and 6 minutes for the gasifier.

Based on the METC data, we designed the CPFBC filter for a pressure drop of 2.7 psi and the carbonizer and gasifier for a pressure drop of 2.0 psi. The results agree reasonably well with the data of Hudson.

As is the case for filter pressure drop, there is considerable variation reported in the quantity of pulse gas necessary to clean a filter element. Michael Durst of Schumacher[19] indicated that 0.2 ft^3 of gas is required per element for pulse cleaning. An EPRI test on a atmospheric, tiered filter[14], reported pulse gas quantities ranging from 0.2 to 0.76 ft^3 per pulse, with the pulse reservoir 4 bar above the filter pressure. The RWTH Aachen tests[7] reported pulse gas quantities between 0.27 to 0.5 ft^3 with the pulse reservoir 4 bar above the filter pressure. Mattie Nieminen of the Technical Research Center of Finland found that a pulse reservoir pressure of 4 bar above filter pressure provided sufficient pressure in the pulse gas system.[19] Researches at Grimethorpe[3] report using 1.29 ft^3 of gas per pulse. As a design value CPC uses 0.40 ft^3 of pulse gas per element. Table 27 also shows the total quantity of pulse gas required for each application.

4.2.3 Tubesheet/Support Specification

A general specification for the tubesheets applied to the CPFBC and the carbonizer filter was prepared. This specification defined the commercial operating environment. Tubesheet operating conditions were described for the hot gas cleanup facility proposed for the second generation PFB combustion plant[20]. Although there are filters for the circulating pressurized fluidized bed combustor (CPFBC), the carbonizer, and the gasifier, only the CPFBC filter was analyzed based on this specification. The carbonizer filter and the gasifier filter are both smaller; the assumption was that it would be easier for conditions to be met in smaller sizes. Furthermore no operating conditions were given for the gasifier filter.

The hot gas filter vessels operate near 1600°F for the CPFBC and the gasifier, and near 1500°F for the carbonizer. The pressure inside these filters is around 200-400 psig and the pressure vessel enclosures are protected by insulating refractory such that conventional design practices apply.

Table 27 Candle Filter Pressure Drop/Pulse Gas Parameters

Operating Parameter	CPFBC Filter	Carbonizer Filter	Gasifier Filter
Plant Capacity, MWe	226	226	100
Gas State	Oxidizing	Reducing	Reducing
Gas Flow, lb/hr	2,644,236	244,650	312,800
Gas Flow, acfm	175,800	15,800	12,600
Ash Loading, ppmw	4,000	10,000	8,500
Face Velocity, fpm	10	5	5
No. of Elements	6,288	1,130	906
Specific Cake Res., in H20 ft min/lb	33	99	99
Pulse Gas Rate acf/Pulse/Element	0.40	0.40	0.40
Cycle time min	10	8	6
Filter Press. Drop psi	2.66	1.96	1.99
Pulse Gas Density, lb/cf at Operating Cond.	0.969	0.948	1.61
Pulse Gas Rate lb/pulse/element	0.39	0.38	0.64
Pulse Gas Rate lb/hr	13,628	2,995	5,410
% of Filter Gas Flow percent	0.52	1.22	1.73
Pulse Gas Pressure, psia (100 psi above filter)	290	308	485

The tubesheet support provides the transition between the hot tubesheet and the cold pressure vessel shell. For heat transfer purposes, the tubesheets operate at 1500-1600°F and environment external to the pressure vessel is 70°F.

Because of the high temperature environment, design of the tubesheet support is sensitive to the elevated temperature properties of the selected materials of construction. A suitable material must be able to withstand extended exposure to temperatures in the thermal creep domain and to withstand creep-fatigue damage due to temperature cycling.

Information on the thermal transients is taken from the report on the second generation PBFC where available, and supplemented by information prepared for the 70-MWe Tidd PFBC Demonstration Plant located in Brilliant, Ohio[21]. The material of construction for the CPFBC filter tubesheet is RA333, and for the carbonizer and gasifier tubesheet, RA85H stainless steel.

The tubesheet is not within the scope of the ASME Code. However, the design, analysis, and construction philosophy of Section VIII, Division 2 of the Code was applied, supplemented by appropriate elevated temperature design rules.

Transient and steady state thermal analysis, and linear and nonlinear structural analysis were considered using finite element analysis techniques. Design criteria based upon nonlinear analysis was used in evaluating the adequacy of the tubesheet. An erosion/corrosion allowance of 1/8" was assumed for the CPFBC tubesheet.

In Table 28, tubesheet design conditions are summarized. A design life of 100,000 hours was chosen to allow the CPFBC tubesheet a nominal 20 year life. This is based on the projected operating hours per year and capacity factor proposed for the second generation PFBC plant. The number of heatups, cooldowns, and load change transients is increased from that projected for a mature, commercial facility to assure a reasonable conservative design.

In Table 29, the load change transient temperatures and flows are those reported for the second generation PFBC. The rate of change of 2% per minute comes from the Tidd study, since there is no information on this subject for the second generation PFBC. The temperature change due to load change is minimal.

Figure 47, the heat-up transient[22], is based on actual start-up data from the Tidd Plant. A gas turbine trip, while recognized as a transient, is not defined for the second generation PFBC and was not included in this analysis. While the report on the second generation PFBC does not include this level of detail, there is a statement that heating rates will be controlled to 200-300 F/hr based on refractory limitations. This limitation also applies to refractory cooling rates. The heat-up rate shown for Tidd on Figure 47 exceeds this limit during some intervals, and in general, but is a reasonable and conservative estimate as far as the tubesheet is concerned. Controlled cooldown can be assumed to occur at rates less than 300°F/hr; so for the purpose of this study, we assume 300 F/hr.

This specification for the tubesheet operation basically defines long term operation as the governing design criteria. Load change transients do not create enough of a temperature change to be significant. There are not enough start-ups in the life of the plant to make thermal fatigue a factor. The analysis, therefore, keys on limits to rupture, creep, and yield stresses at temperature.

TABLE 28 Tubesheet Design and Operation Conditions

Design Conditions	CPFBC	Carbonizer	Source
Life, hours	100,000	30,000	1
Temperature, °F	1600	1500	2
Pressure, psig	200	218	2
Tubesheet Pressure Differential, psi	3	3	3
Operating Conditions			
Temperature, °F	1546-1596	1403-1488	2
Pressure, psia	145-186	160-206	2
Heatups & Cooldowns	30 first 2 years	30 first 2 years	1 & 2
	100 each 10 years	100 each 10 years	1 & 2
Load Change Transients (100-50-100%)	40 first year	40 first year	
(See Table 29)	30/year thereafter	30/year thereafter	1 & 2
Gas Turbine Trip Transient	1 per year	1 per year	3
Tubesheet Pressure Differential			
• Normal, psi	1	1	3
• Commence Pulse Cleaning, psi	3	3	3
Off Normal or Other Mechanical Loads			
Non Considered			

Sources: 1 - Combustion Power, 2 - Second Generation PFBC report, 3 - Tidd study.

Table 29 Tubesheet Load Change Transients* (100-50-100)

Firing Rate (%)	Pressure (psia)	Temp (°F)	Gas Flow (lb/hr)	acfm
CPFBC Filter Inlet Conditions				
100	186.2	1596	661,059	43,950
50	145.7	1546	642,938	41,705
Carbonizer Filter Inlet Conditions				
100	206.3	1488	244,650	15,800
50	160.1	1403	80,216	4,955

* For load change transient, assume a change of 2% (firing rate) per minute between the above listed conditions. Sufficient time between transients shall be allowed for temperature equilibrium to be reached.

4.2.4 Tiered vs. Single Tubesheet

A tiered tubesheet contains multiple levels of candle filter elements, such as that supplied at Tidd[5]. In this approach, the main tubesheet is structural in nature and typically contain no candle filter elements. The advantage is in packaging a large quantity of candle filter elements in a small diameter pressure vessel. Many types of supports have been proposed for support of candle filter tubesheets[23]. Some have undergone preliminary analysis, and some have undergone more detailed analysis. The design utilized most, to date, is the V-type support. Because of structural limitations, the V-support it is limited in diameter to 8-10 ft. Therefore tiered candle filters are characterized by a fairly elaborate alloy metal structure to arrange the filter elements in multiple levels. Pulse piping and manifolds must be built into this structure. This complicates access for inspection, maintenance, modifications, and repairs.

A single tubesheet design, such as that tested at Grimethorpe is similar in arrangement to an industrial baghouse. All filter elements are installed in the same tubesheet and the pulse system is installed on top of the tubesheet. Access to the top of the tubesheet is easily arranged for direct inspection and maintenance of filter elements and pulse components. Limitation on the diameter of the tubesheet support is the major drawback. With a workable alternative, large diameter tubesheets could be built and, according to our estimate, a less expensive candle filter system could be proposed.

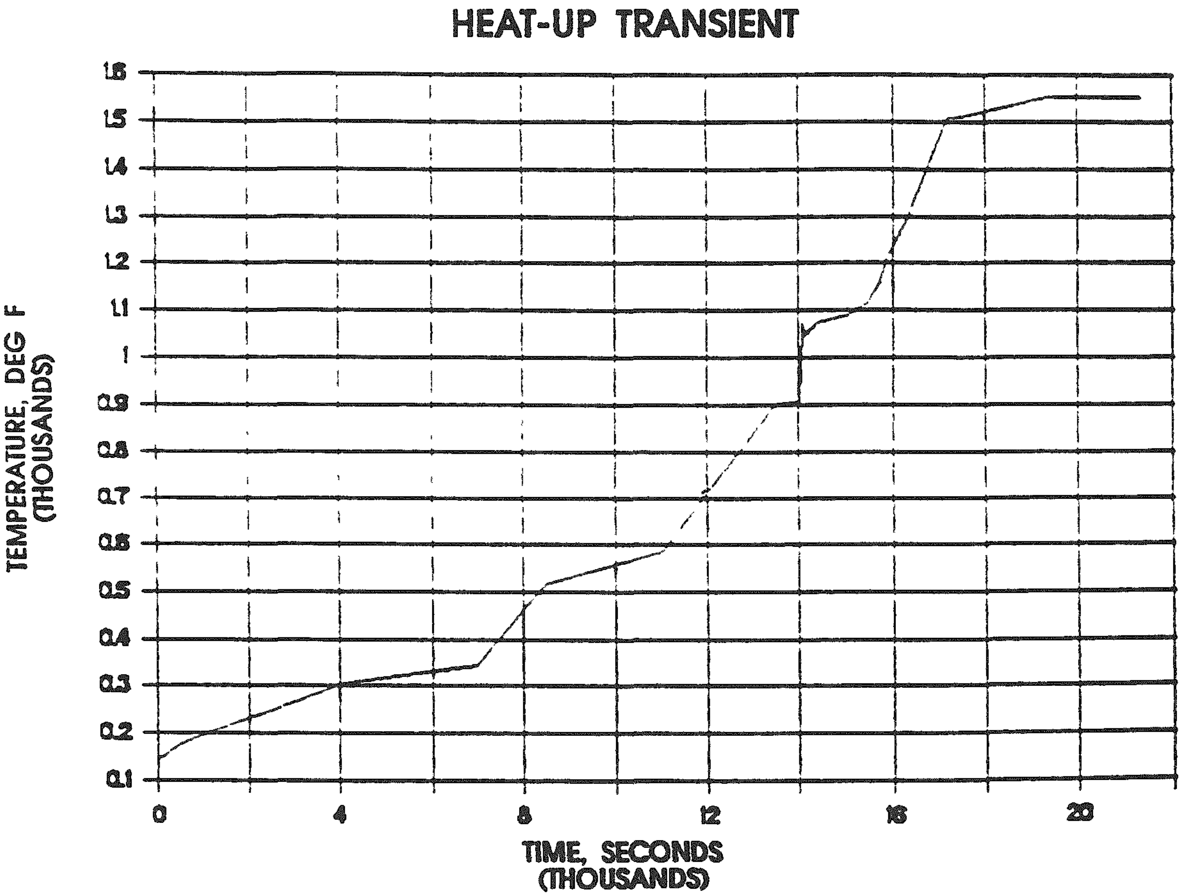


Figure 47 Heat-up Transient, Commercial Design [22]

4.2.5 Tubesheet/Support Structural Analysis

Allowable stress levels in the tubesheet and tubesheet support were found to be based on isothermal operation, as opposed to repeated thermal transients. This is because operating philosophy for commercial plants minimizes start-ups, and load changes for the assigned combustion and gasification processes are not accompanied by wide temperature changes. Therefore, thermal fatigue is not expected to be a limiting factor. During operation, primary stresses depend on the pressure drop across the tubesheet, but are offset by the weight of the tubesheet plus the candle filter elements. During a hot shutdown, the tubesheet and tubesheet support must support its weight. Primary stresses at 1500-1600°F must be low; 600-2500 psi depending on the material choice. This is dictated by guidelines influenced by the ASME Boiler Code. Since creep and stress rupture govern the design at these high temperatures, the Code recommends that the maximum allowable stress value for materials must not exceed the lowest of the following:

- 100% of the average stress to produce a creep rate of 0.01% in 1000 hours at use temperature.

- 67% of the average stress to cause rupture at the end of 100,000 hours.

- 80% of the minimum stress to cause rupture at the end of 100,000 hours.

In the case of the tubesheet and support where finite element analysis is utilized, the guidelines for minimum allowable stress in elastic analysis were somewhat broadened. The membrane stress intensity at all parts of the component due to pressure and dead weight were not to exceed the lower of 1) 90% of the tabulated yield strength at the average temperature of the cross section for the average strain rate of the loading, and 2) 100% of the tabulated S_{mt} value at the average temperature of the cross section and for a time duration equal to the total duration of this loading/temperature combination. Under these guidelines, S_{mt} is the lower of one-half the ultimate strength, two-thirds the mininum value to cause rupture, or the average stress for 1% creep. At temperatures in the creep range, stress-rupture or creep governs the allowable stress. This criteria allows the choice of design life; although, for CPFBC tubesheet analysis, 100,000 hours was chosen as suggested by the ASME Boiler Code. The other criteria utilized to assess the design of the internals was the value of the membrane plus bending stress. This stress at all parts of the component due to pressure and dead weight loadings was not allowed to exceed the lower of 1) 135% of the tabulated yield strength at the average temperature of the cross section for the average strain rate of the loading, and 2) 110% of the tabulated S_{mt} value at the average temperature of the cross section and for a time duration equal to the total duration of this loading/temperature combination. S_{mt} is defined above, and was chosen based on a time duration of 100,000 hours. In addition to the above criteria, which sets limits to the primary stresses, a limit was set for the primary-plus-secondary stresses. Secondary stresses are those caused by thermal expansion. This limit was the yield strength at temperature. For these criteria, the limit for membrane stress due to pressure and dead weight for Rolled Alloys, RA333 at 1600°F for 100,000 hours operation is about 950 psi. The ASME Boiler Code limit is about 30% higher. For membrane plus bending stress due to pressure and dead weight, the limit is about 1050 psi for RA333 at 1600°F for 100,000 hours operation. The limit for primary-plus-secondary stresses is about 17,800 psi for RA333 at 1600°F.

First analyzed was an 18' diameter tubesheet formed from 2" thick flat plate reinforced by ribs perpendicular to the plate. Material assumed was RA333. It appeared that by manipulation of the reinforcing rib design, that this approach could meet the stress criteria. The other tubesheet configuration considered was a segment of a sphere. This configuration was analyzed only at the connection to the tubesheet support. The spherical segment is well suited for pressure containment and is a very stable shape at high temperature; it will inherently resist deformation if its temperature is uneven. Preliminary calculations indicated that a flat plate, stiffened to maintain the same stress level, could weigh more than twice that of the spherical segment. A few shops in the USA were approached about building a spherical segment up to 18' diameter and; since this is similar to a pressure vessel head, we found that was feasible.

The "V" type support similar to that utilized at Grimethorpe and Tidd was analyzed in an 18' diameter configuration. At the steady state temperature conditions that govern the commercial design, primary and primary-plus-secondary stresses exceeded the design criteria. Modifications to the "V" type support were made to lower stresses to acceptable levels. A conical type support was also analyzed using similar modifications, and found to have acceptable stresses. Although these calculations were only made for RA333 material, it was assumed that a similar approach would be feasible for smaller diameter tubesheet supports in other materials, such as RA85H.

The analysis made was preliminary as described, and did not take all criteria into account. In a detailed design other details must be considered. Welding must be sound from standpoint of strength and corrosion. Other items to consider are metal toughness, creep, creep fatigue, thermomechanical fatigue, and all types of corrosion, both low and high temperature.

4.2.6 Preliminary Cost Comparisons

Early in our design effort it became apparent that a CPFBC candle filter module for 226 MWe would require more filter vessels then the two proposed for the cross-flow filters in the Foster Wheeler study[20]. Assuming a single tubesheet approach, we considered candle filter vessels of two different diameters: first a larger diameter vessel that would require four candle filter vessels for a 226 MWe CPFBC module, and second, a smaller diameter vessel that would require use of eight candle filter vessels for a 226 MWe CPFBC module. We found that while the smaller vessels needed thinner vessel walls, which relates to less weight and less cost, the smaller vessels also had increased surface area that meant additional costs for refractory. When the cost for the alloy metal tubesheets and baffles where added, it was found that there was little or no cost advantage of having eight smaller diameter vessels verses four larger vessels. On the other hand, an eight vessel module incurred additional complication, and cost, for the process gas ducting and the ash discharge system. Consequently, the base configuration chosen for CPFBC candle filters was a four filter vessel module for 226 MWe capacity.

A cost estimate for a tiered candle filter module for 226 Mwe capacity was prepared based on the candle filter installed at Tidd. The Tidd candle filter vessel contains a total of 384 elements supported by three plenums with each plenum containing 128 elements on three different tiered levels. The lower level of each plenum contains 52 elements (156 total elements for lower level of three plenums) while each of the two higher levels contain 38 elements per plenum (114 elements total for each upper level of three plenums). For our cost estimate we added four additional upper tier levels by lengthening the vessels and plenums so that a total of eight (8) Tidd style vessels with seven (7) levels of tiers (one lower and 6 upper tiers) contained the required number of elements needed for a 226 MWe CPFBC module (6288). When the costs for carbon steel pressure vessels, alloy metal internals, and refractory where compared with four, larger diameter, single tubesheet vessels, it was found that the single tubesheet configuration was about two-thirds the cost of the tiered configuration. The majority of the cost difference is in the value of the alloy metal internals that make up the tubesheet, tubesheet support, plenums and baffle. The savings in carbon steel pressure vessels costs, for the smaller tiered vessels, are overshadowed by the much higher costs of the alloy metal internals. It was concluded from this excersize that a large, single tubesheet configuration was the least cost alternate for a candle filter.

4.3 Preliminary Design of Candle Filters

4.3.1 Process Description

The candle filter configuration shown on Figure 48 is based on utilizing the largest tubesheet possible. All filter elements are attached to the tubesheet to simplify the filter element layout and the pulse gas piping. In this configuration, filter elements can be inspected and maintained from inside the filter vessel.

Hot process gases and particulate enter at a single port on the side of the vessel below the tubesheet and, are distributed by a cylindrical baffle around the outer edge of the candle filter array near the upper end of the filter elements. The particulate loaded gases pass through the filter elements leaving the particulate on the outside surface of the filter elements in the form of an ash cake. The clean process gases enter the inside of each candle filter element, collect in the chamber above the tubesheet, and exit through an outlet port. The ash cake collected on the outside surface of the elements is dislodged by periodic high pressure bursts of pulse gas. For filters in oxidizing atmospheres, air is used for pulse cleaning of the filter elements. For filters in reducing gas environments, either process gas or nitrogen may be used for pulse gas. The ash cake dislodged from the filter elements is collected in the conical hopper below the tubesheet and is discharged into a suitable ash handling system. In the gasifier filter, the ash is first cooled using a water-cooled screw and then depressurized through lock-hoppers. In the CPFBC system, the ash is depressurized through a restricted pipe discharge (RPD) vessel as proposed in the Foster Wheeler study[20] and then cooled using a water-cooled screw. In the carbonizer, the hot pressurized ash is used directly in another operation.

Filter elements are 1.5 meters long, 60 mm outside diameter and made with two layer construction to minimize the possibility for ash to penetrate into the ceramic matrix.

4.3.1.1 Process Flow for CPFBC Candle Filter

Each of the two CPFBC's has a filter module composed of four candle filter vessels. Each filter vessel has an inside refractory diameter of 20'-6" and tubesheet diameter of 18'-0". The inlet gas flow to each filter vessel is 657,652 lb/hr at 1600°F and 187.70 psia. This inlet gas flow is slightly lower then for the CPFBC granular-bed filters by the amount of pulse air added to the CPFBC candle filters. This allows for equal outlet gas flow for the candle filter module and the granular-bed filter module; since, the granular-bed filter process does not require any appreciable amounts of additional gases. The ash concentration in the inlet gas stream is 4,000 ppmw. A filter face velocity of 10 ft/min was specified for the CPFBC filter. The filter pressure drop is calculated to be 2.66 psi (74 IW) based on a 0.40 ACF/Pulse/Element pulse gas flow rate and a pulse cycle time of every 10 minutes as presented in sections 4.2.1 and 4.2.2. Figure 49 shows the process flow sheet for the CPFBC candle filter.

The process gas temperature drop through the filter is 12°F. This temperature drop is due to both radiation heat loss through the shell of the filter and dilution of the process gases by the cooler pulse air. Heat loss calculations for the CPFBC candle filter are shown in Appendix B.

Pulse air for cleaning the candle elements is 13,628 lb/hr for the four filter module serving each 226 MWe CPFBC module. This pulse air supply is taken from the outlet stream of the transport air boost compressor at 176°F and 267.60 psia. This pulse air is precooled, compressed, aftercooled, dried and filtered before being supplied to the pulse air reservoirs 290 psia or approximately 100 psi above the candle filter internal pressure. Pulse air at a pressure of 100 psi above the candle filter pressure is considered a normal operating pulse air pressure for this study. The pulse air compressor system is designed to supply compressed air at up to 300 psi above filter pressure or 490 psia. This ability to supply higher pressure pulse air may be needed for proper cleaning of the candle element depending on the properties of the ash cake.

Ash from two of the each four filter vessel module is collected in a small candle filter ash vessel. There are two candle filter ash vessels per CPFBC module. From the outlet of each candle filter ash vessel, the ash is depressurized through a restricted pipe discharge (RPD) vessel as it enters the same ash handling equipment proposed for the candle filter in the Foster Wheeler study[20]. The depressurized ash from each of the two RPD vessels per CPFBC module is combined in an ash collecting hopper. The outlet of the ash collecting hopper is split into two streams each feeding the inlet of ash screw coolers. Each ash screw cooler is sized for 100% ash capacity from a 226 MWe CPFBC module as proposed in the Foster Wheeler study. This allows for 100% backup of ash screw coolers at design ash rates. If both cooling screws are operated, this also allows for cooling of increased ash loads in the event of reduction of CPFBC cyclone collection efficiency.

4.3.1.2 Process Flow for Carbonizer Candle Filter

The candle filter for the carbonizer on each of the two CPFBC's has a single filter vessel in which the refractory inside diameter is 18'-0" and the tubesheet diameter is 15'-6". The inlet gas flow to each filter vessel is 244,650 lb/hr at 1500°F and 207.90 psia. The ash concentration in the inlet gas stream is 10,000 ppmw. A filter face velocity of 5 ft/min was specified for the carbonizer. The filter pressure drop is calculated to be 1.96 psi (54 IW) based on a 0.40 ACF/Pulse/Element pulse gas flow rate and a pulse cycle time of every 8 minutes as presented in sections 4.2.1 and 4.2.2. Figure 50 shows the process flow sheet for the carbonizer candle filter.

The process gas temperature drop through the filter is 27°F. This temperature drop is due to both radiation heat loss through the shell of the filter and from the cooling of process gas that is reinjected into the filter as pulse gas. Heat loss calculations for the carbonizer candle filter are shown in Appendix B.

Pulse gas for cleaning the candle filter elements is 2,995 lb/hr total for each candle filter serving a CPFBC module. This pulse gas is recycled, clean process gas taken from the outlet of the carbonizer candle filter. The hot process gas is first cooled from 1474°F to 400°F using a simple fire tube boiler which produces low pressure saturated steam. The process gas is then further precooled, compressed, aftercooled, dried, and filtered before being supplied to the pulse gas reservoirs 307 psia or approximately 100 psi above the candle filter internal pressure. Pulse gas at a pressure of 100 psi above the candle filter pressure is considered a normal operating pulse gas pressure for this study. The pulse gas compressor is designed to supply compressed process gas at pressures up to 300 psi above the filter pressure or 508 psia.

The ash collected by the carbonizer is returned to the second-generation fluidized bed process according to the Foster Wheeler study.

4.3.1.3 Process Flow for KRW Gasifier Candle Filter

The candle filter for the gasifier has a single filter vessel in which the refractory inside diameter is 16'-6" and the tubesheet diameter is 14'-0". The inlet gas flow to the filter vessel is 312,800 lb/hr at 1600°F and 385.00 psia. The ash concentration in the inlet gas stream is 8,500 ppmw. A filter face velocity of 5 ft/min was specified for the gasifier. The filter pressure drop is calculated to be 1.99 psi (55 IW) based on a 0.40 ACF/Pulse/Element pulse gas flow rate and a pulse cycle time of every 6 minutes as presented in above sections 4.2.1 and 4.2.2. Figure 51 shows the process flow sheet for the gasifier candle filter.

The process gas temperature drop through the filter is 31°F. This temperature drop is due to both radiation heat loss through the shell of the filter and from the cooling of process gas that is reinjected into the filter as pulse gas. Heat loss calculations for the gasifier candle filter are shown in Appendix B.

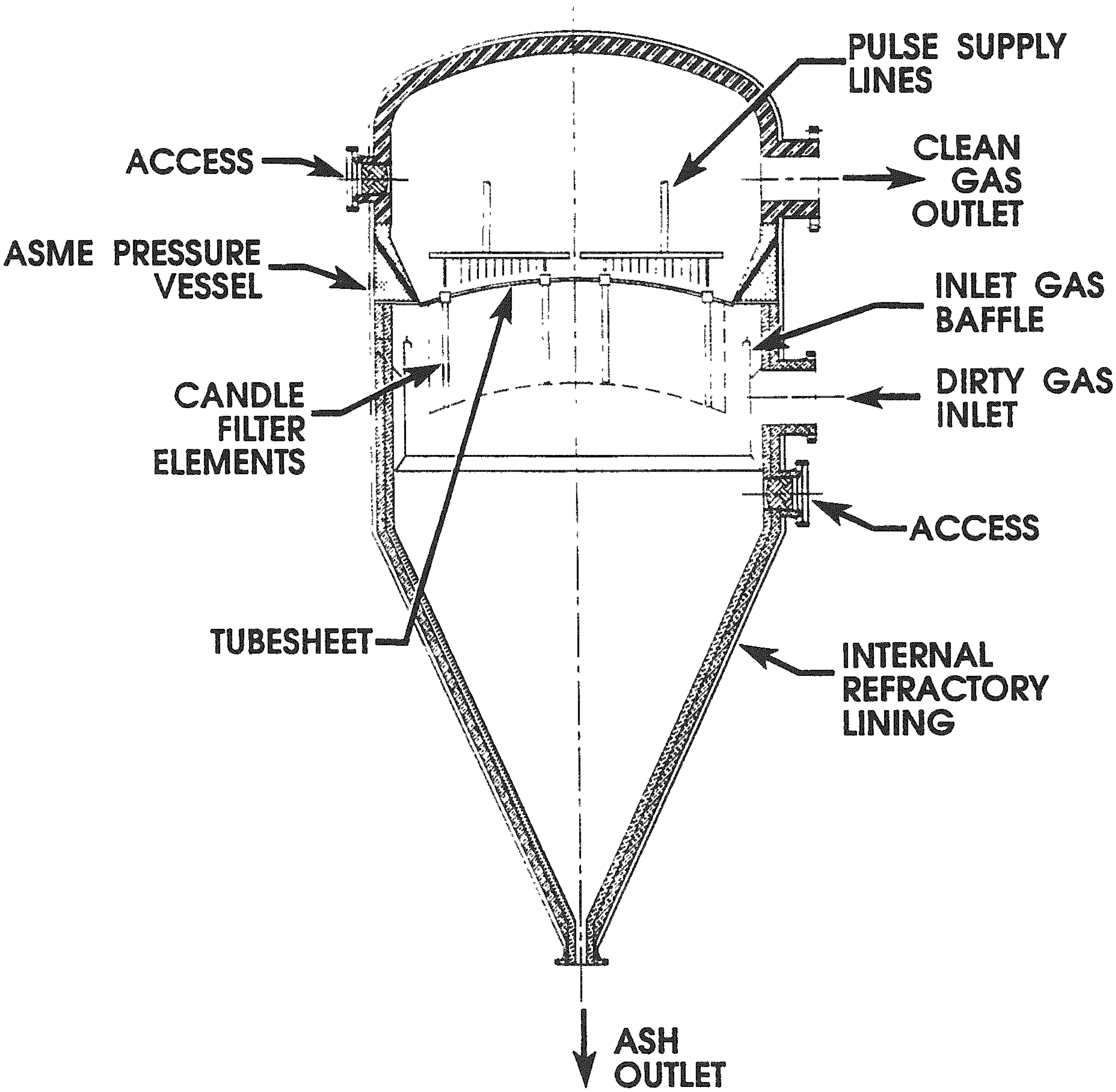


Figure 48 Candle Filter Configuration

	① CANDLE FILTER INLET	② TURBINE INLET PIPING	③ CANDLE FILTER OUTLET	④ CANDLE FILTER ASH	⑤ RPD HOPPER INLET	⑥ RPD HOPPER OUTLET	⑦ ASH COOLER INLET	⑧ ASH COOLER OUTLET	⑨ ASH COOLER WATER IN	⑩ ASH COOLER WATER OUT	⑪ PULSE AIR COMPRESSOR INLET	⑫ PULSE AIR COMPRESSOR OUTLET	⑬ PULSE AIR COMPRESSOR WATER IN	⑭ PULSE AIR COMPRESSOR WATER OUT
FLOW														
SOLID, LB/MIN	44			44	88	88	88	88						
LIQUID, LB/MIN									305	305			240	240
GAS, LB/MIN	10961	22036	11018								227	227		
GAS, ACFM	43816	88830	44415								200	143		
TEMPERATURE, F	1600	1588	1588	1600	1600	1600	1600	300	110	200	176	35	90	110
PRESSURE, PSIA	187.70	185.04	185.04	187.70	187.70	14.40	14.40	14.40	135.00	20.00	267.60	290.00	50.00	30.00

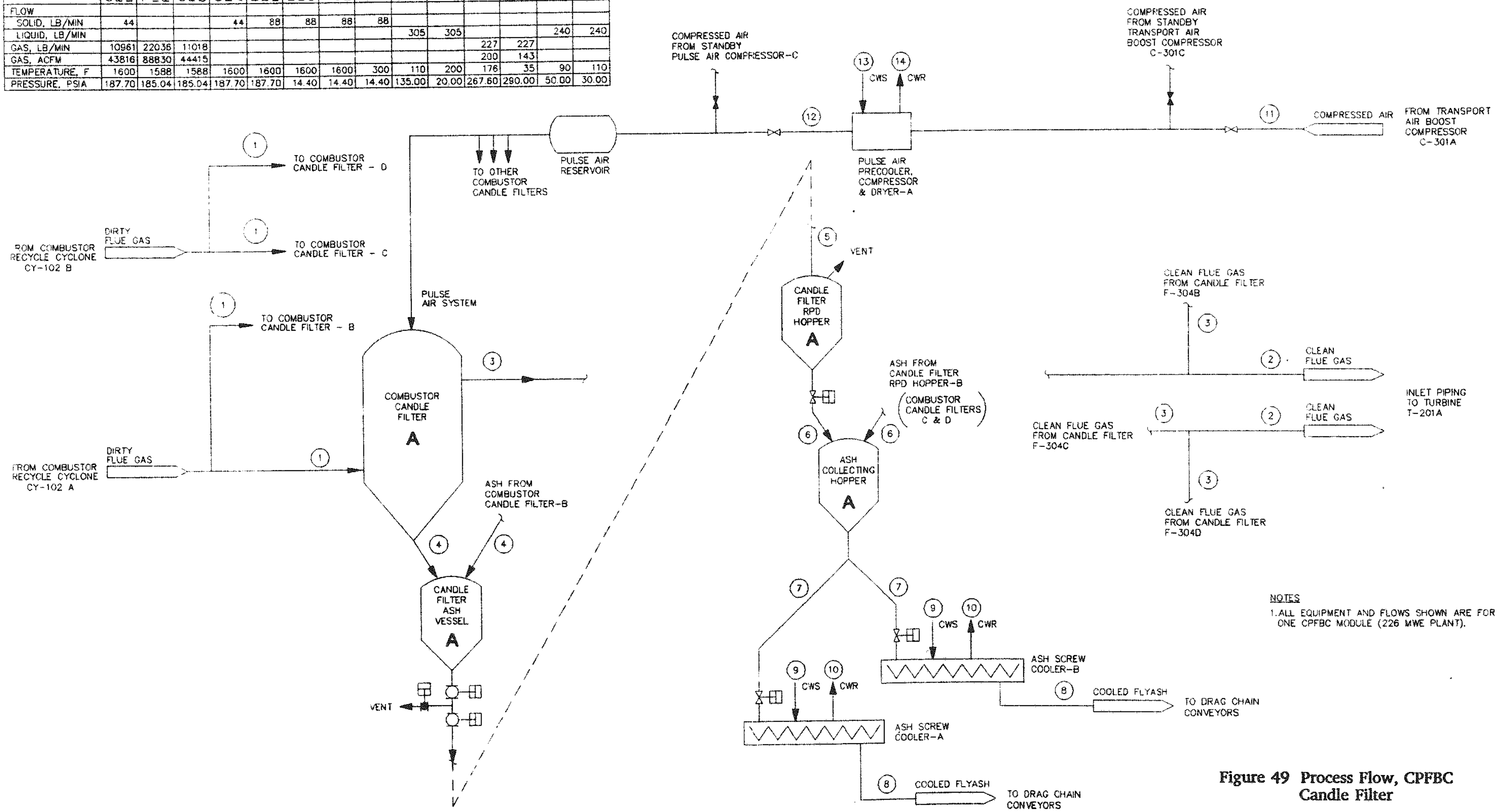


Figure 49 Process Flow, CPFBC Candle Filter

	1 CANDLE FILTER INLET	2 CANDLE FILTER OUTLET	3 CARBONIZER SOLIDS	4 RECYCLED PULSE GAS	5 PULSE GAS BOILER/COOLER INLET	6 PULSE GAS COMPRESSOR OUTLET	7 BOILER FEEDWATER	8 SATURATED STEAM	9 COMPRESSOR WATER INLET	10 COMPRESSOR WATER OUTLET
FLOW										
SOLID, LB/MIN	41		41							
LIQUID, LB/MIN							19		283	283
GAS, LB/MIN	4078	4078		50	50	50		19		
GAS, ACFM	15911	15847		192	86	33				
TEMPERATURE, F	1501	1474	1501	1474	400	35	228	287	90	110
PRESSURE, PSIA	207.90	205.94	207.90	207.90	206.90	306.90	85.00	55.00	50.00	30.00

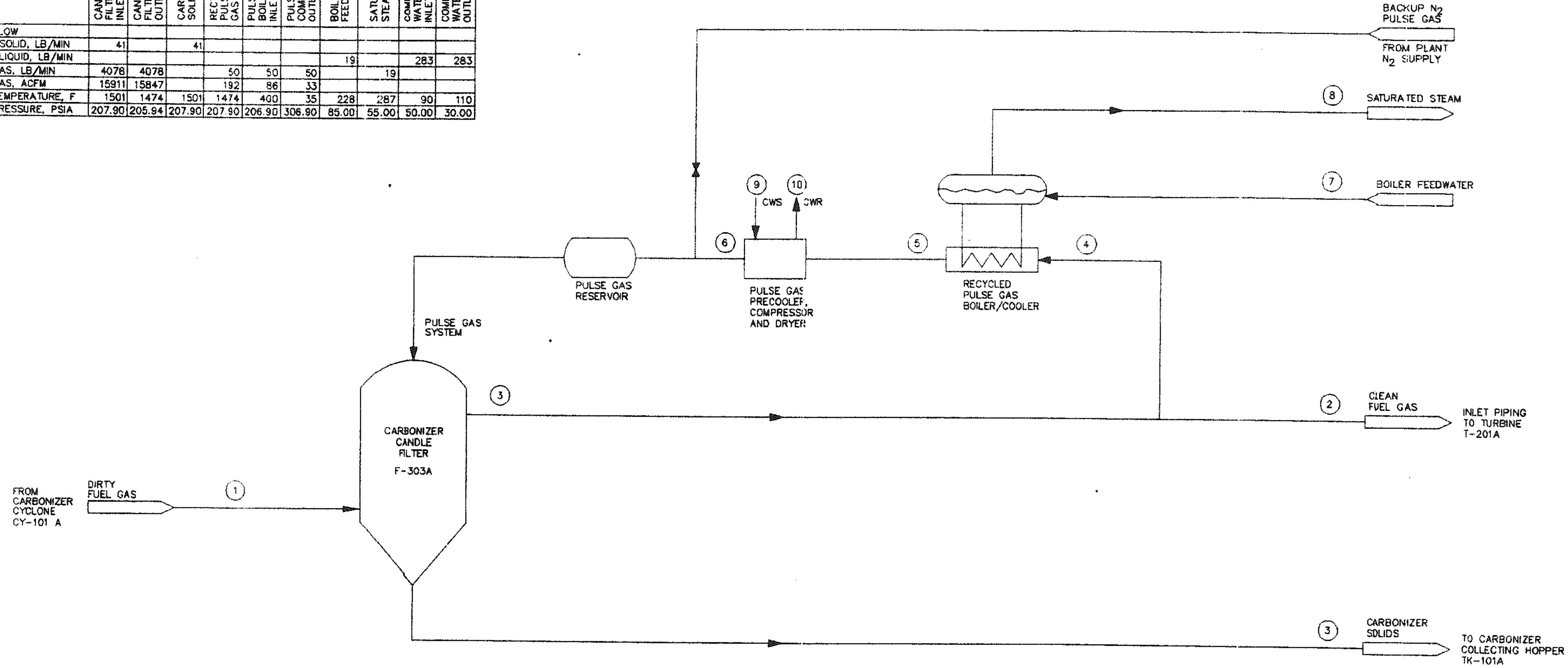


Figure 50 Process Flow, Carbonizer Candle Filter

	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮	⑯
	CANDLE FILTER INLET	TURBINE INLET PIPING	CANDLE FILTER ASH OUTLET	RECYCLED PULSE GAS	PULSE GAS BOILER/COOLER OUTLET	PULSE GAS COMPRESSOR OUTLET	BOILER FEEDWATER	SATURATED STEAM	COMPRESSOR WATER INLET	COMPRESSOR WATER OUTLET	ASH COOLER OUTLET	LOCK HOPPER OUTLET	ASH COOLER WATER INLET	ASH COOLER WATER OUTLET	ASH COOLER CWS INLET	ASH COOLER CWR OUTLET
FLOW																
SOLID, LB/MIN	44		44								44	44				
LIQUID, LB/MIN							39		476	476			425	425	638	638
GAS, LB/MIN	5213	5213		90	90	90		39								
GAS, ACFM	12628	12503		216	92	42										
TEMPERATURE, F	1600	1569	1600	1569	400	35	228	287	90	110	412	412	350	380	90	110
PRESSURE, PSIA	385.00	383.01	385.00	383.01	381.01	485.00	85.00	55.00	50.00	30.00	385.00	14.40	200.00	189.00	50.00	30.00

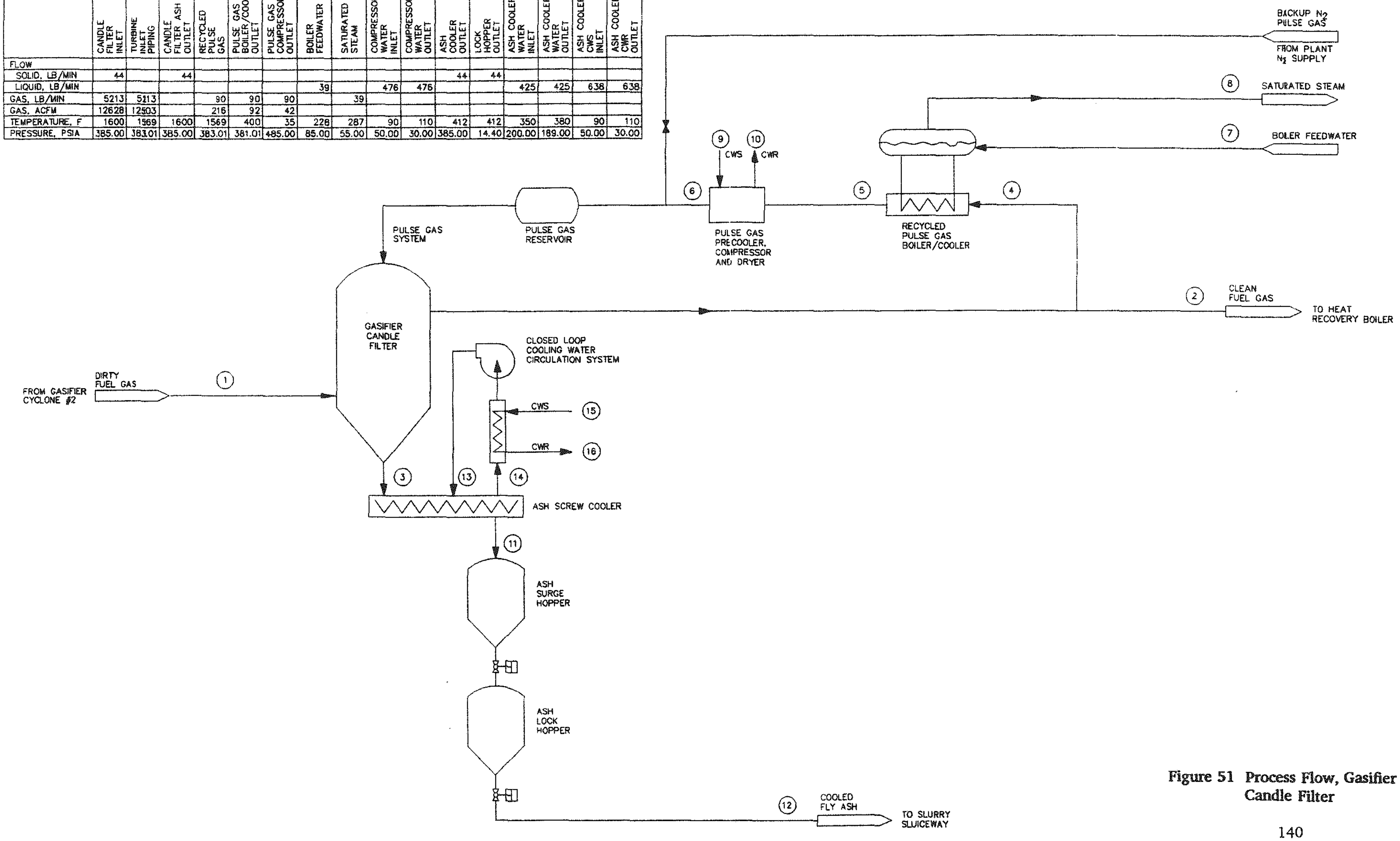


Figure 51 Process Flow, Gasifier Candle Filter

Pulse gas for cleaning the candle filter elements is 5,410 lb/hr for the gasifier candle filter. This pulse gas is recycled clean process gas taken from the outlet of the gasifier candle filter. The hot process gas is first cooled from 1569°F to 400°F using a simple fire tube boiler which produces low pressure saturated steam. The process gas is then further precooled, compressed, aftercooled, dried, and filtered before being supplied to the pulse gas reservoirs at 485 psia or approximately 100 psi above the candle filter internal pressure. Pulse gas at a pressure of 100 psi above the candle filter pressure is considered the normal operating pulse gas pressure for this study. The pulse gas compressor is designed to supply compressed process gas at pressures up to 300 psi above the filter pressure or 685 psia.

Ash from the gasifier candle filter is first cooled from 1600°F to about 400°F using a pressurized water-cooled screw conveyor. In order to prevent condensation of hot process gases on the metal surfaces of the screw cooler, a closed loop cooling water circulation system is provided for the ash screw cooler. This closed loop circulation system allows the metal surfaces of the ash screw cooler to be maintained at temperatures of 350°F to 380°F. After the ash is cooled, it is depressurized using lock hoppers.

4.3.2 Instrumentation and control

An automatic computer control system maintains the filter operating parameters at specified set-points, provides indication of system status, provides alarms of abnormal process variables, and alarms indication of failed equipment. This allow for safe and steady operation of the filter with minimum plant personnel supervision. The automatic control system for each of the candle filter applications is nearly the same. All of the candle filter applications monitor or control:

- Process gas temperatures at filter inlet and outlet
- Filter pressure drop and pulse valve operation
- High ash level in candle filter hoppers
- Pulse gas compressor systems

The main differences between the control systems for the candle filter applications is the number of pulse valves operated and the ash system control. Figures 52, 53, and 54 show the Piping and Instrumentation Diagrams (P & ID's) for the CPFBC filter, carbonizer filter, and gasifier filter, respectively. A description of monitoring functions and main control loops follows:

- Process gas temperatures at filter inlet and outlet

Local thermocouples monitor process gas inlet and outlet temperatures of each candle filter vessel. These analog inputs are used for information on system operation. On the CPFBC application where there are multiple filter vessels, inlet and outlet temperatures are useful in comparing operation and gas flows between filter vessels. Temperature data will be recorded and stored. This historical data is useful in troubleshooting changes in filter operation over longer periods of operation.

• Filter pressure drop and pulse valve control

Control of the pulse valve system has three main control parameters, 1) the time duration between pulsing a filter element, which is the cycle time between opening of each pulse valve and is often referred to as valve "off-time"; 2) the time duration that the pulse valve is actually open allowing flow of pulse gas, referred to as valve "on-time"; and 3) the pressure of the pulse gas supplied to the reservoir upstream of the pulse valve. Adjustments in all three of these parameters can be utilized to vary the cleaning of the candle filter elements; which in turn, effects the filter pressure drop. It is assumed that the primary control parameter will be the valve off-time, with valve on-time and pulse gas pressure being secondary or cascaded control parameters. The cost estimate allows for programming the control of all three parameters in several different ways, with the flexibility for operator intervention.

The control system will also cause the opening of one of the three ball valves downstream of the pulse valve just prior to the pulse valve actuation, and then cause the closing of the ball valve after the pulse is completed. The control system will monitor the position of each ball valve and alarm any valve movement failures.

This portion of control system also includes instruments to monitor pulse gas flow into each secondary pulse air reservoir. Controls would be used to alarm the condition where a pulse value and ball valve fail in the open position. This part of the loop could function as follows: Since pulse gas only flows into the secondary reservoir to refill the reservoir directly after a pulse valve is actuated, there is exists a short time of high flow rate and then a quick drop-off of flow rate as the reservoir comes back up to operating pressure. Since this high pulse gas flow rate should only last for a short time the control loop could be programmed to alarm a condition of excessive time duration of high pulse gas flow rate. If this alarm occurs, the last pulse valve actuated could be electronically identified. The defective pulse valve could then be removed from the control loop pulsing sequence, and manual isolation valve upstream of the valve closed. The valve train is designed so a defective pulse valve can be manually isolated, then repaired or replaced.

• High ash level in candle filter hoppers

Ash level detection devices are installed each candle filter hopper to alarm high ash level.

• Pulse gas compressor system control

The reciprocating compressor package and refrigerated gas drier package will be supplied with an integrated control system. Each piece of equipment can be operated from a local control panel, with some overriding controls from the main control panel. Each package will have various discrete and analog inputs and outputs such as start/stop controls, output set points, and alarms. All of these inputs and outputs from each separate equipment package will be integrated into the candle filter computer control system so control of the entire pulse gas compressor system can be monitored and controlled as part of the candle filter system.

On the carbonizer and gasifier filter there is a fire tube boiler for cooling the hot process gases for pulse gases. This boiler will use a two element feedwater control system. This two element feedwater control loop and other instruments that are part of the boiler will be controlled as part of the candle filter computer control system.

- Ash removal systems

The CPFBC candle filter systems will use the same basic ash system proposed in the Foster Wheeler study[20]. This includes restricted pipe discharge (RPD) hoppers for ash decompression, and ash cooling screws to cool the hot ash. A description of the operation and control of this ash system can be found in the Foster Wheeler study.

The gasifier candle filter will use a pressurized ash cooling screw to cool the ash before depressurizing. The lock hopper system utilized for depressurizing is the same for the granular-bed filter and is described in section 3.5.2. The pressurized ash cooling screw used on the gasifier candle filter will have two control loops, one for control of screw speed, and one for control of the closed loop cooling water circulation system. The controls for the closed loop cooling water circulation system includes: controls for system water level, operation of circulation pumps, flow of plant cooling water supply, operation of pressure maintaining boost pumps, operation of electric heater for heating the cooling water startup, and use of backup emergency water supply. In addition there are instruments for monitoring water flow to the ash screw cooler as well as instruments for monitoring and alarming pressures and temperatures throughout the system.

- Computer Control System

The computer control system is based on a programmable logic controller (PLC). It is constructed on a modular basis using plug-in printed circuit cards installed in a control rack. Figures 55, 56, and 57 show the control system architecture layout for the CPFBC filter, carbonizer filter, and gasifier filter, respectively. A central processing unit scans the user program and generates logic commands. Data collection is done through the device called a "Genius I/O" (Input/Output) connected to the PLC. Unlike conventional remote I/O, this arrangement requires no central I/O control cabinets, no racks, no separate power supply. These I/O devices are installed close to field instruments. Genius I/O automatically provides diagnostic information of field wiring and power conditions. This troubleshooting capability reduces time needed for control system debugging.

This mode of local computer control also cuts down on maintenance costs and system downtime because it eliminates the need for destructive fuses. When overloads and short circuits are detected, output circuits turn off immediately, protecting circuitry and wiring.

The software package provides monitoring, control, data acquisition, alarms, and graphics. All process data can be transferred in common data base programs; such as, Microsoft's data base program called EXCEL, to take advantage of data conversion capabilities. Using the proficiency of the software package, user programmed management reports can be prepared and printed anytime, during operation or downtime.

Selected data can be stored in computer memory for a predetermined amount of time, allowing historical review of operation.

Included with the computer control package are: analog transmitters, thermocouple inputs, RTD inputs, and analog outputs. The local computer control module includes: redundant CPU with memory, redundant rack, redundant power supply, redundant bus controller, redundant coprocessor with software, and required input and output blocks. Software includes programming to allow: standard displays, dynamic graphics and trending, configuration changes, alarming, and report generation. For monitoring the operation, a caliber 486SX personal computer is included with two serial ports, one parallel port, 105 Megabyte hard drive, 3.5" floppy drive, super VGA monitor, keyboard, mouse, color printer, and interconnecting cables. Personal computer software includes MS DOS 5.0 and Windows 3.1.

4.3.3 Candle Filter Configurations

The 452 MWe, second generation PFBC plant is arranged in two identical trains of equipment, each sized for 226 MWe. Each train includes a CPFBC and a carbonizer. There are four candle filter vessels for each CPFBC and one candle filter vessel for each carbonizer. As with the granular-bed filters, these candle filter vessels replace two cross-flow filter vessels for each CPFBC and one cross-flow filter vessel for each carbonizer. For the 100 MWe KRW gasifier, a single candle filter vessel replaces the single cross-flow filter vessel originally utilized. Above Figure 48 shows the basic configuration of the candle filter used for all applications. The filters are refractory-lined with a single tubesheet supporting the candle filter elements. The dirty process gas enters the vessel through a single inlet nozzle located on the side of the vessel cylinder below the tubesheet. Inside the vessel is a cylinder shaped, alloy metal baffle that distributes the dirty gas around the outer edge of the filter element array near the upper end of the candle filter elements. The particulate loaded dirty gas passes through the porous filter element leaving the particulate on the outside surface of the filter element in the form of a ash cake. The clean gas exits each filter element, collects in the chamber above the tubesheet, and exits the vessel through an outlet nozzle on the side of the vessel. The clean side plenum of the vessel contains many manifolds for delivery of pulse air or gas to each candle filter element. Ash collected on the candle filter elements is dislodged by the pulse air or gas and falls into a conical hopper for exit into the ash handling system. Access doors are provided both above and below the tubesheet.

Figures 58, 60, and 62 show the pressure vessels and list the design criteria for the candle filter vessels for the CPFBC filter, carbonizer filter, and gasifier filter, respectively. Figures 59, 61, and 63 show the internal refractory and nozzle details for the candle filter vessels for the CPFBC filter, carbonizer filter, and gasifier filter, respectively.

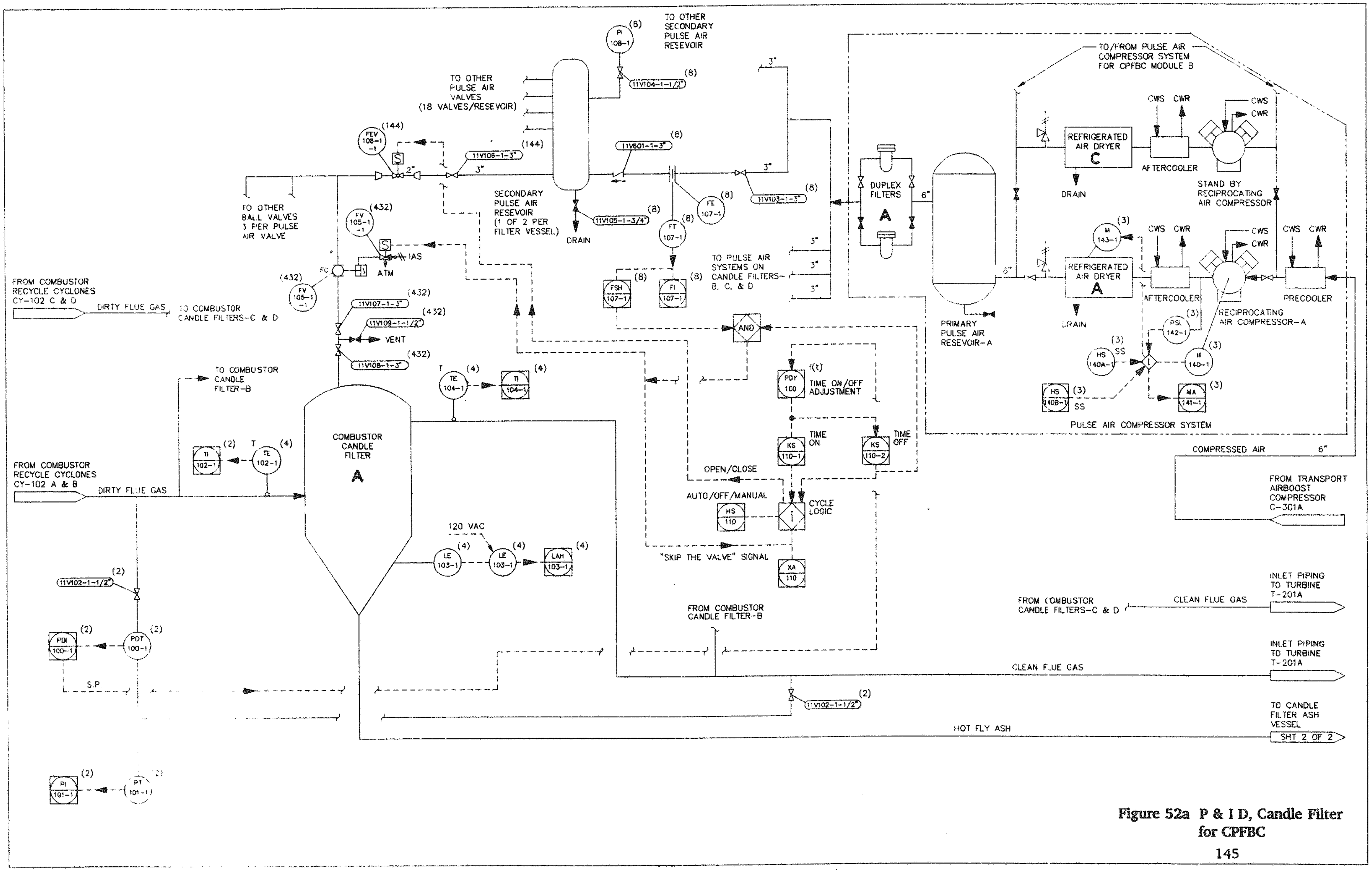


Figure 52a P & I D, Candle Filter for CPFBC

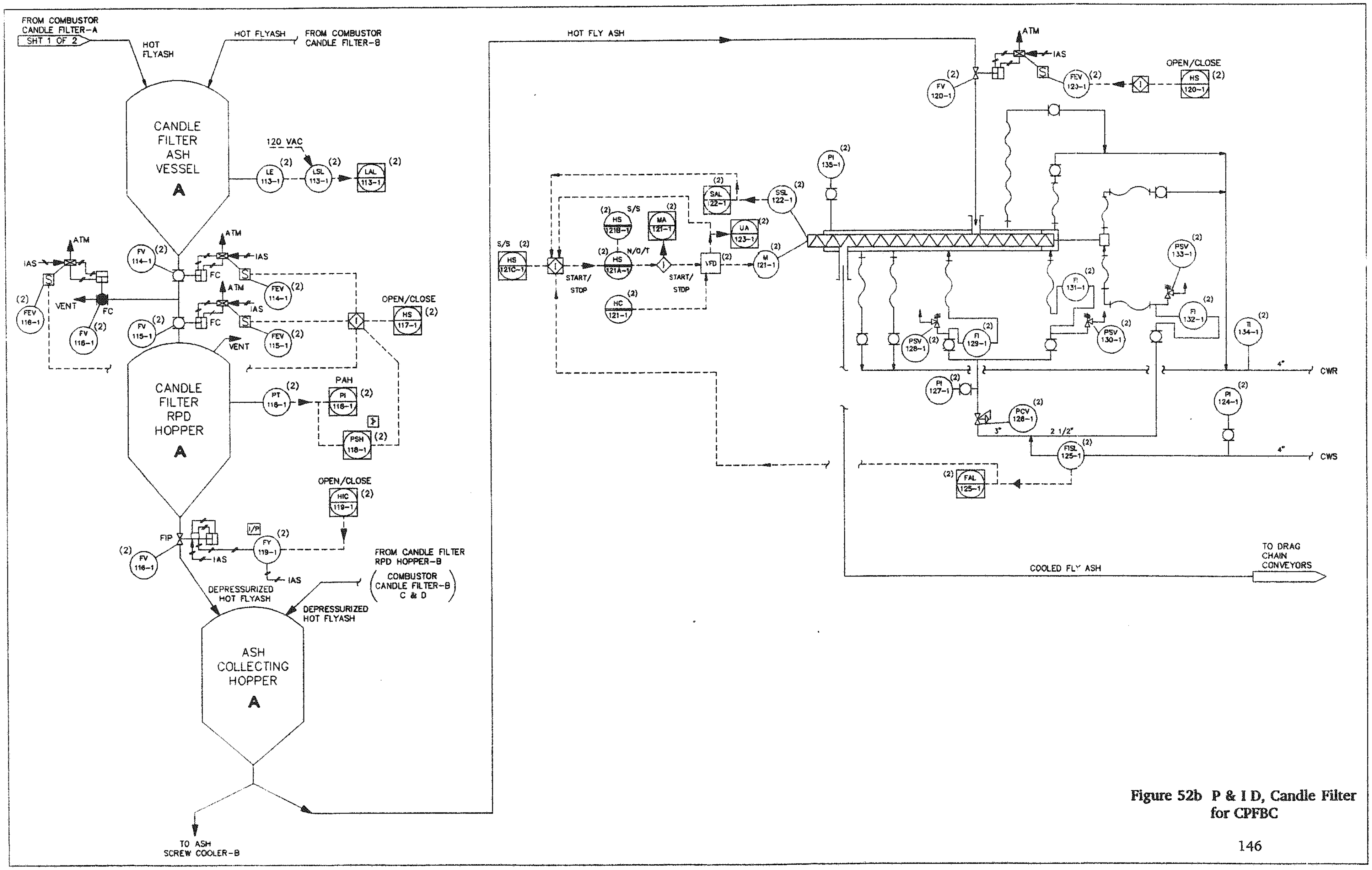


Figure 52b P & I D, Candle Filter for CPFBC

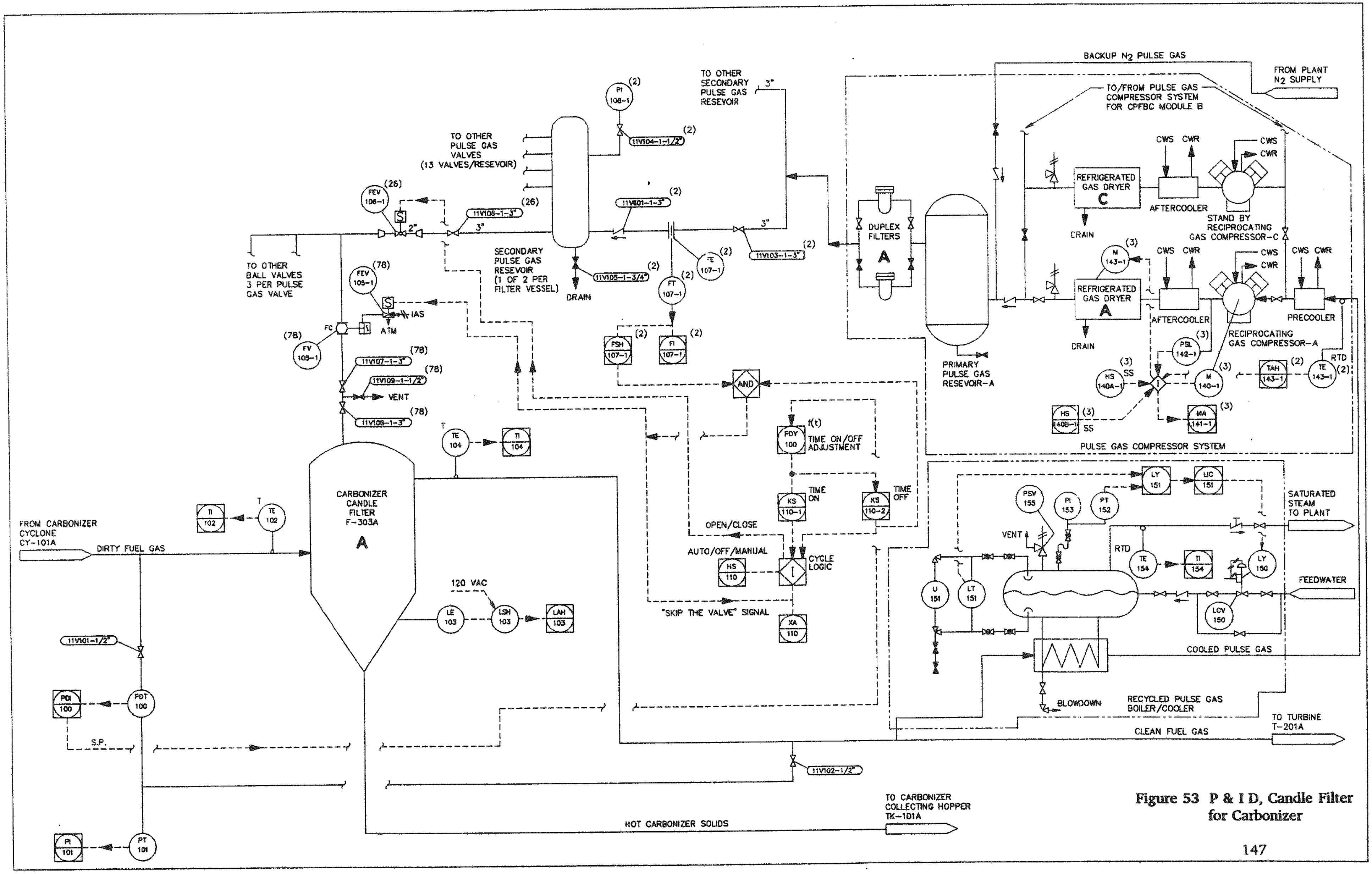


Figure 53 P & I D, Candle Filter for Carbonizer

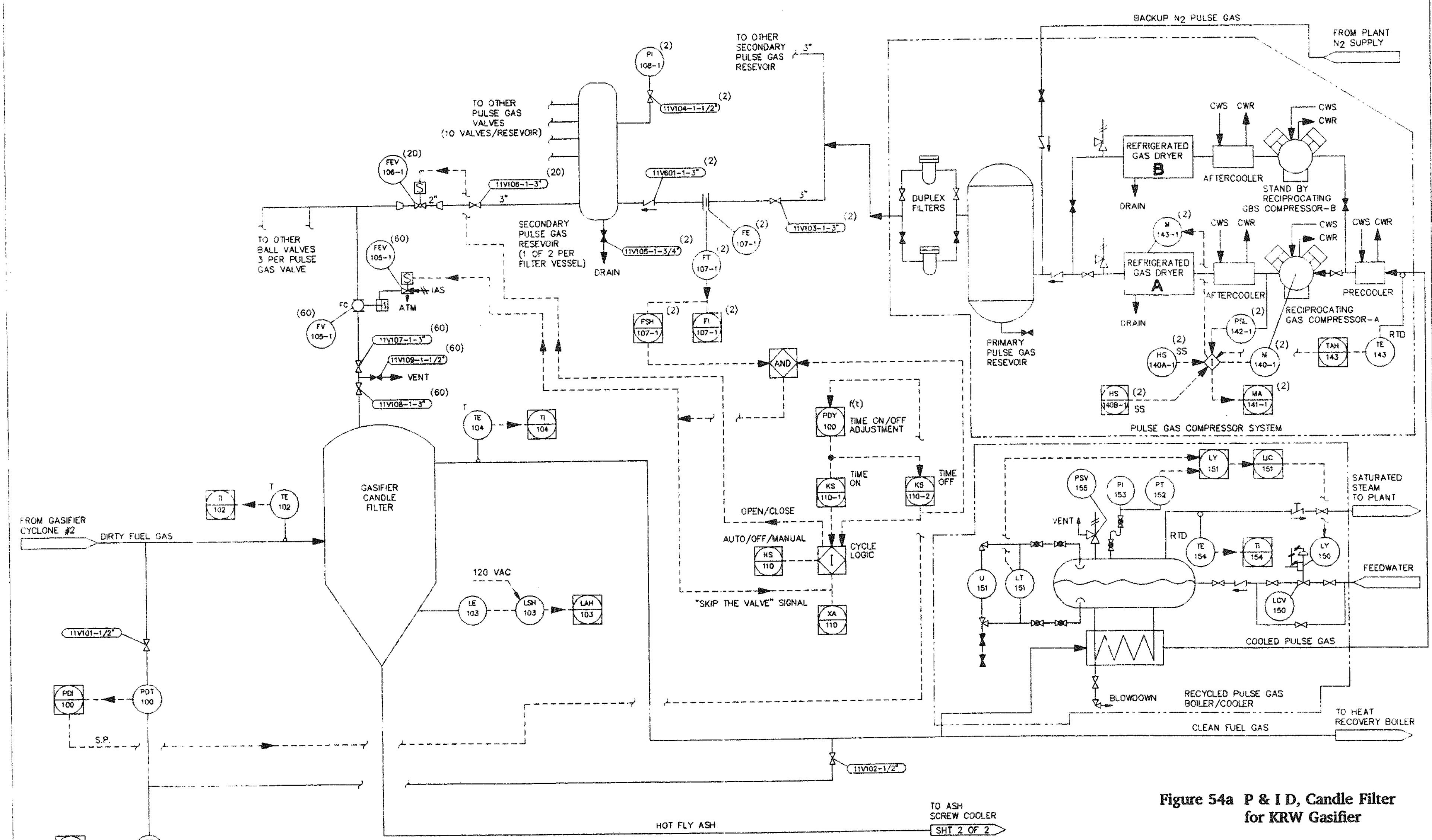


Figure 54a P & I D, Candle Filter for KRW Gasifier

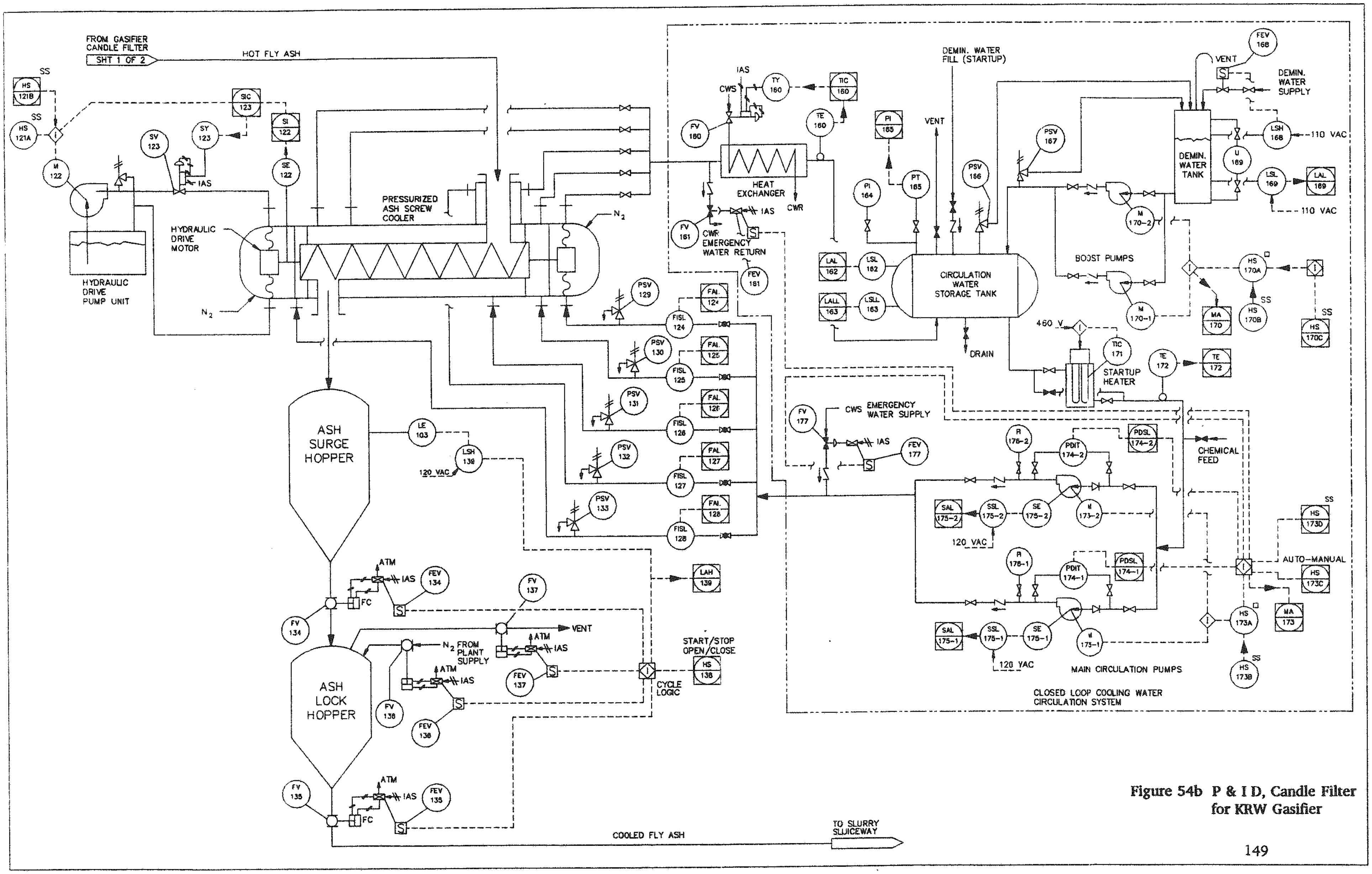


Figure 54b P & I D, Candle Filter for KRW Gasifier

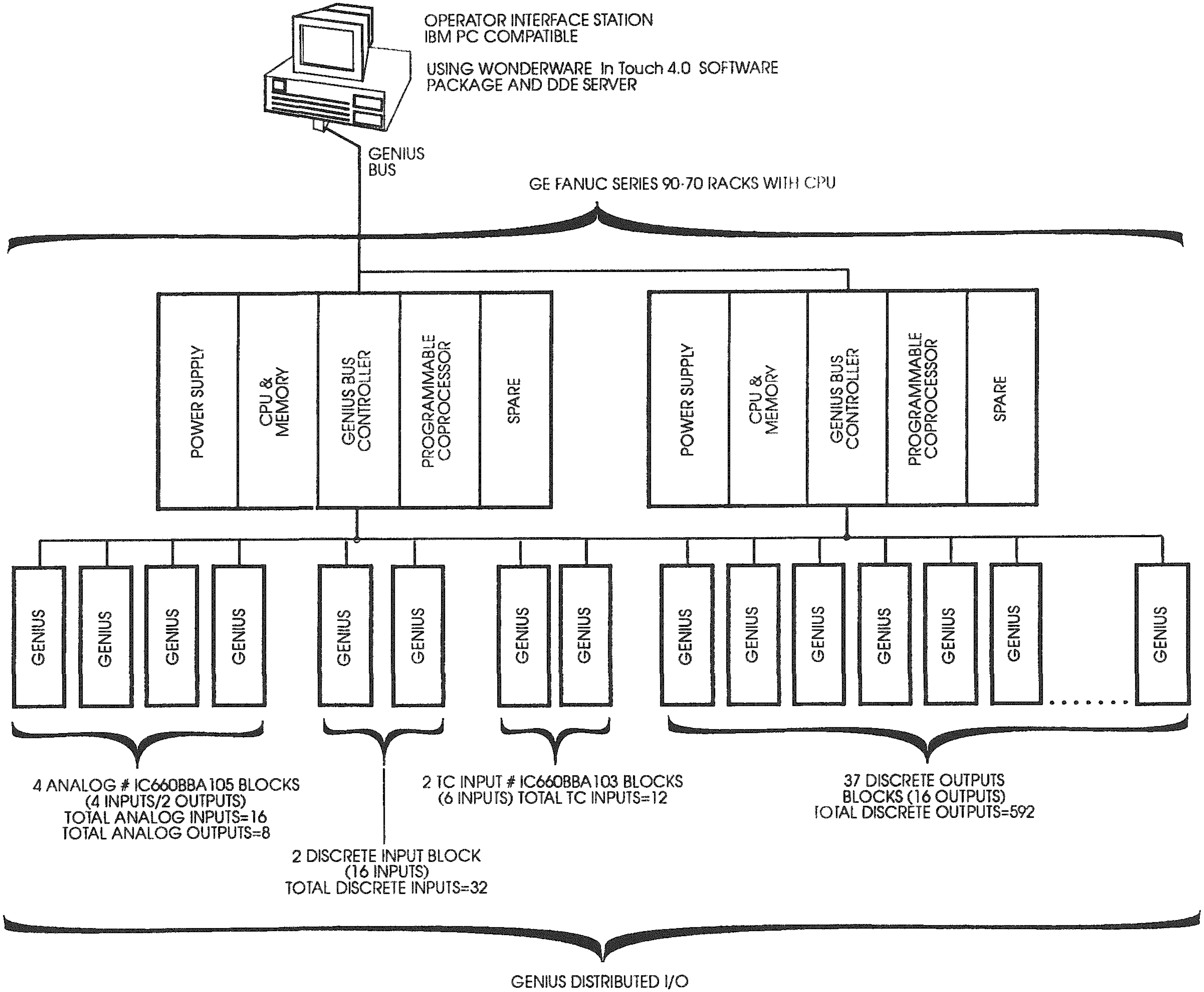


Figure 55 Control System Architecture, Candle Filter for CPFBC

921210IK.CDR

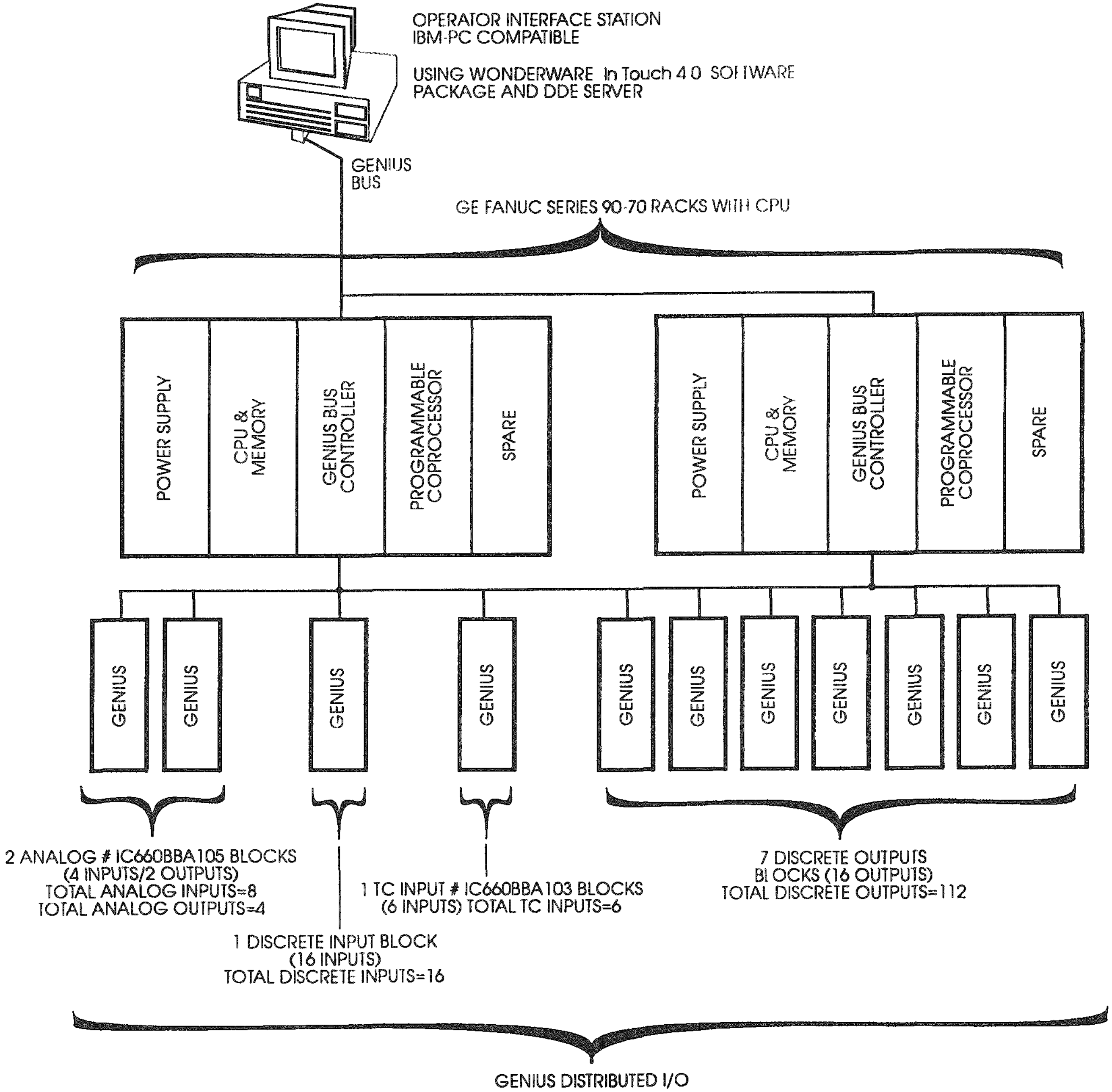


Figure 56 Control System Architecture, Candle Filter for Carbonizer

921202IK.CDR

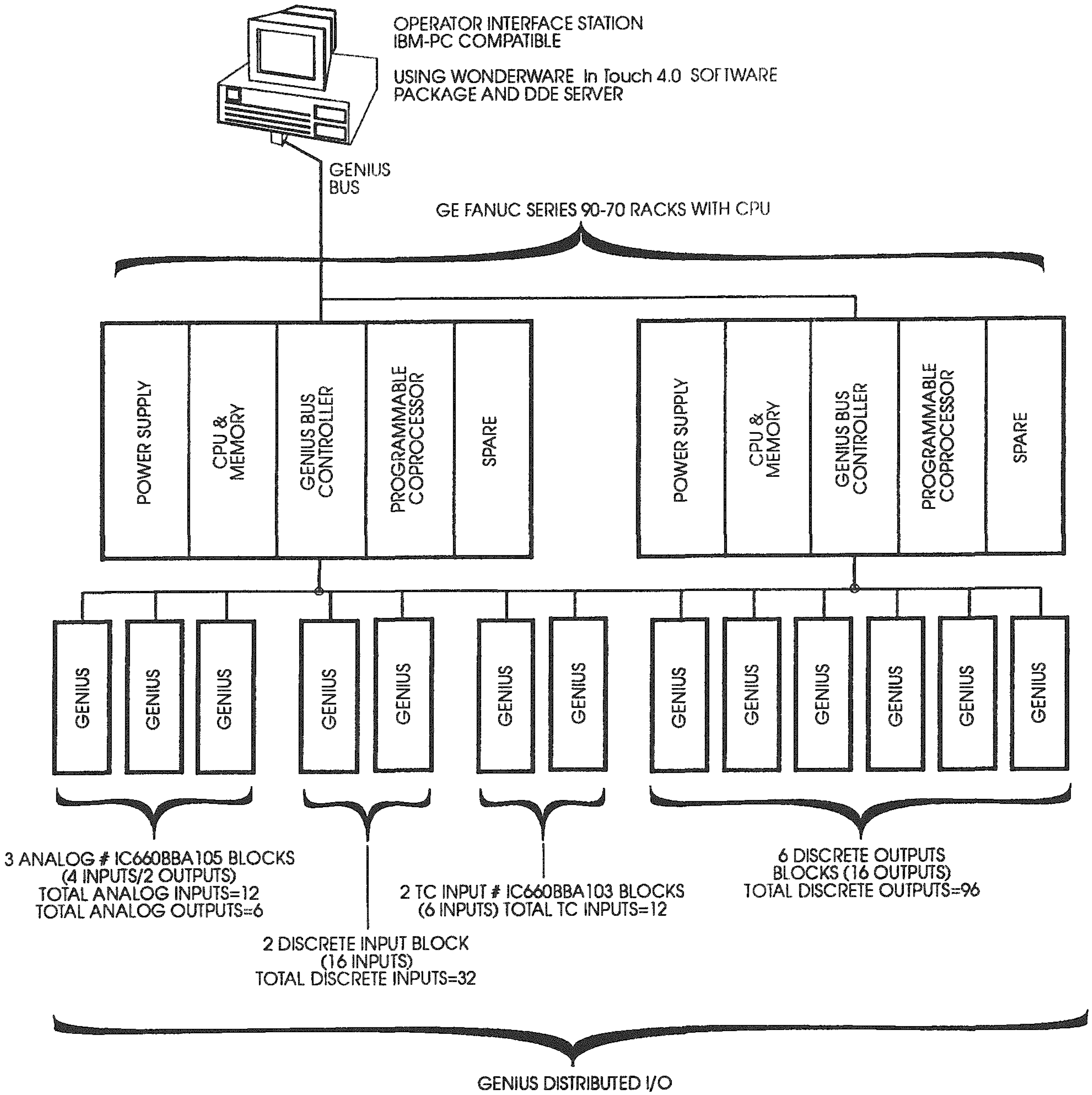
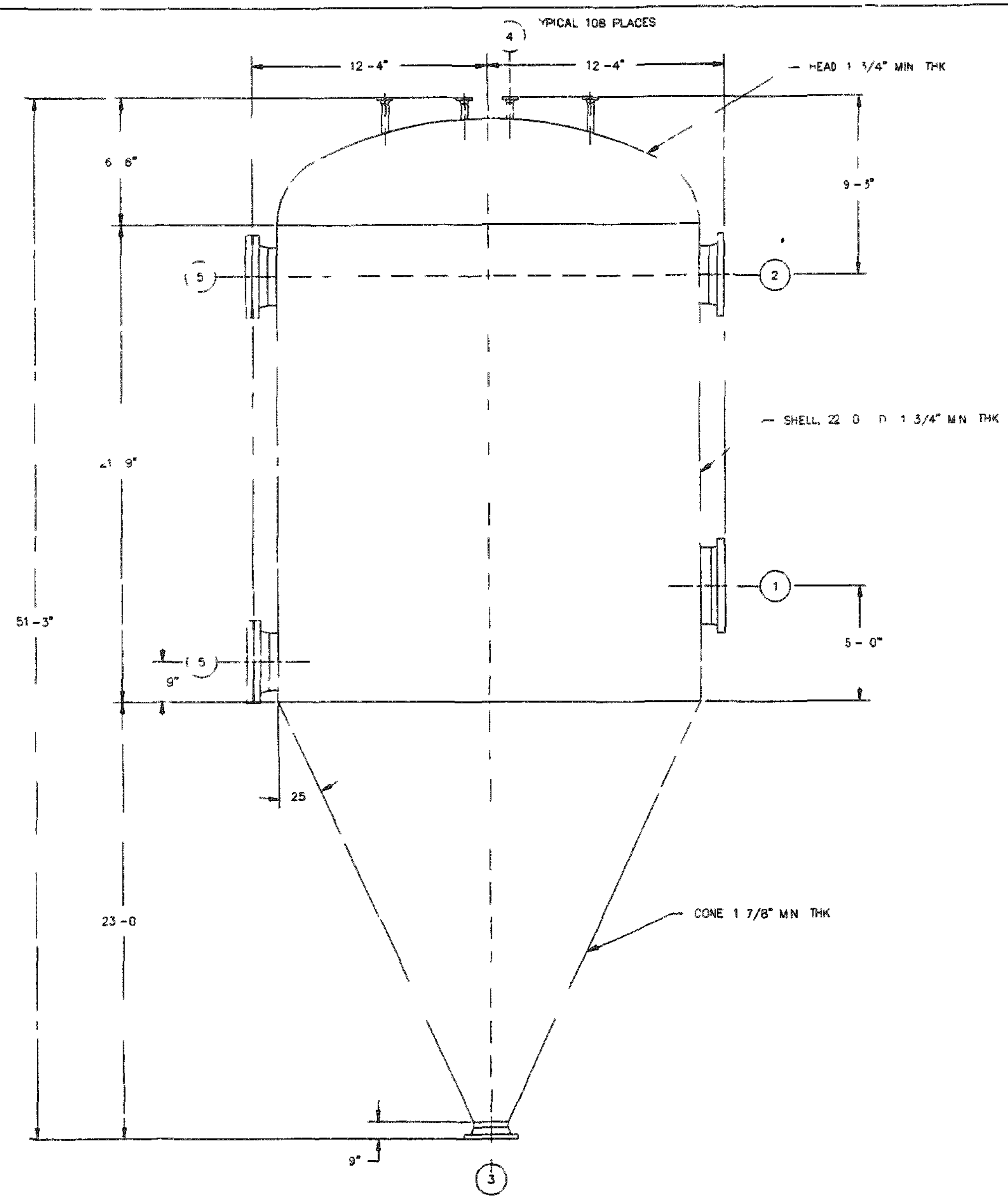


Figure 57 Control System Architecture, Candle Filter for KRW Gasifier

921211IK.CDR



VESSEL DATA

SERVICE	COMBUSTOR OU LET FILTER
OPERATNG PRESS	85 PSIA
DES GN PRESS	200 PSIG
MAX OPERATING TEMP	600°F (INTERNAL)
DESGN TEMP	650°F (META)
WIND DATA	BC (70 MPH EXP C)
EARTHQUAKE DATA	BC (ZONE 1)
CODE	ASME SECT VIII DIV 1
CODE STAMP	YES
P W H T FOR CODE	PARTIAL
P W H T FOR PROCESS	NO
JOINT EFF	00%
RADIOGRAPHED	FULL
CORROSION ALL	/8"
MAT'L SHELL	SA-516 GR 70
MAT'L HEADS	SA-516 GR 70 (2 1 ELLIPTICAL)
MAT'L SUPPT'S	SA-516 GR 70
MAT'L NOZZLES	SA-516 GR 70
MAT'L FLANGES	SA-105
EMPTY WEIGHT	221000 LBS (METAL ONLY)
WATER ONLY WEIGHT	790000 LBS
REFRACTORY LINING	138000 LBS
SHIPMENT	1 PIECE

NOZZLES

NO	SIZE	ANSI RATING	SERVICE	LINING	QTY
1	60"	CL 300 RF	INLET	48"	
2	42"	CL 300 RF	OUTLET	30"	1
3	18	CL 300 RF	ASH OUTLET	6"	
4	3"	CL 300 RF	PULSE AIR	N A	108
5	30"	CL 300 RF	MANWAY/BLIND	18"	2

Figure 58 Candle Filter Pressure Vessel, CPFBC

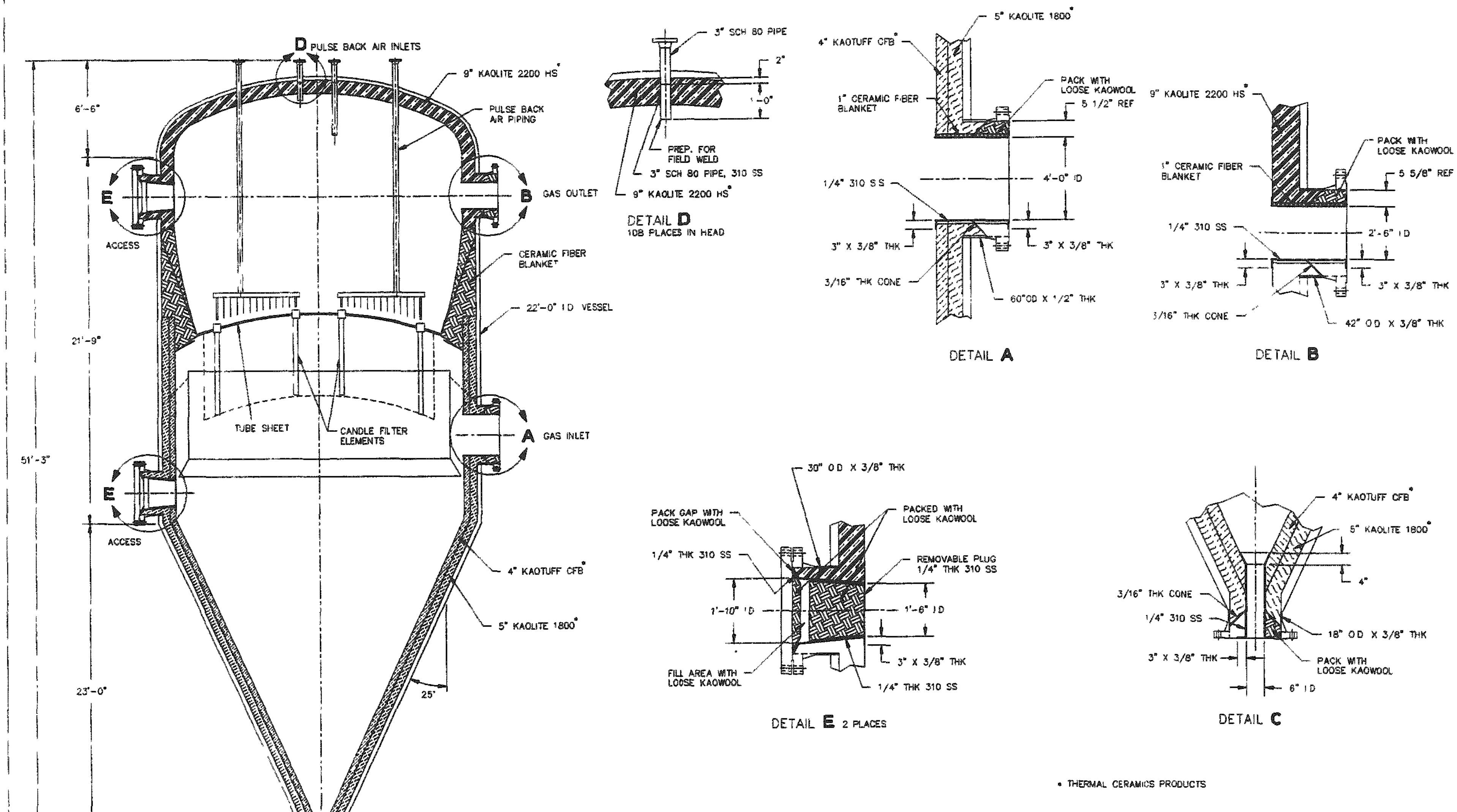
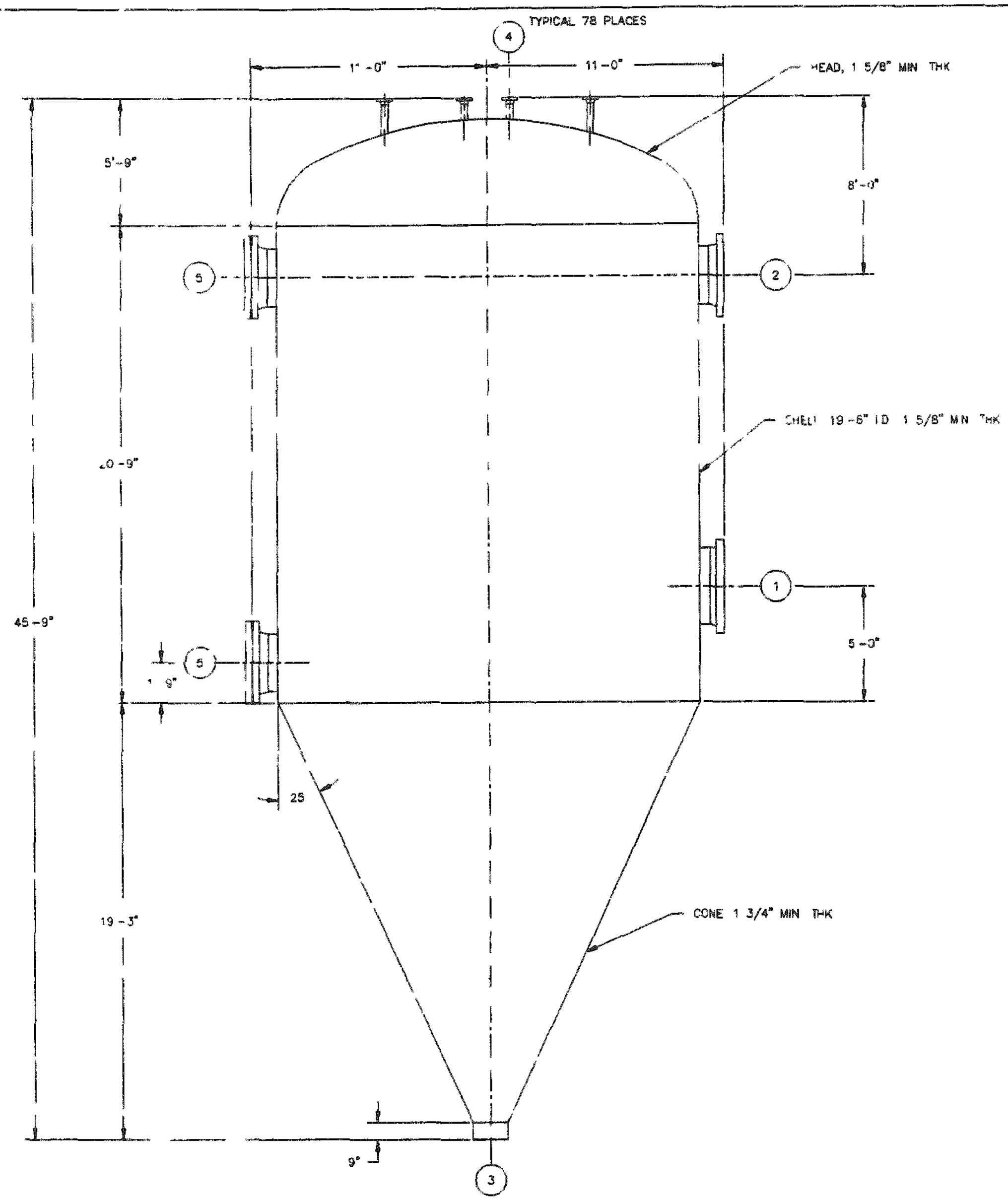


Figure 59 Candle Filter Internals, CPFBC



<u>VESSEL DATA</u>

SERVICE	CARBONIZER OUTLET FILTER
CPERATING PRESS	208 PSIA
DESGN PRESS	218 PSIG
MAX. OPERATING TEMP	1500°F (INTERNAL)
DESIGN TEMP	650°F (METAL)
WIND DATA	UBC (70 MPH, EXP C)
EARTHQUAKE DATA	UBC (ZONE 1)
CODE	ASME SECT VIII DIV 1
CODE STAMP	YES
P WH T FOR CODE	PARTIAL
P WH T FOR PROCESS	NO
JOINT EFF	100%
RADIOGRAPHED	FULL
CORROSION ALL	1/8"
MAT'L SHELL	SA-516 GR 70
MAT'L HEADS	SA-516 GR 70 (2 1 ELLIPTICAL)
MAT'L SUPPT'S	SA-516 GR 70
MAT'L NOZZLES	SA-516 GR 70
MAT'L FLANGES	SA-105
EMPTY WEIGHT	168000 LBS (METAL ONLY)
WATER ONLY WEIGHT	580000 LBS
REFRACTORY LINING	112000 LBS
SHIPMENT	1 PIECE

<u>NOZZLES</u>

NO	SIZE	ANSI RATING	SERVICE	I D LINING	QTY
1	42"	CL 300 RF	NLET	30"	1
2	30"	CL 300 RF	OUTLET	18"	1
3	30"		ASH OUTLET	12"	1
4	3"	CL 300 RF	PULSE GAS	N A	78
5	30"	CL 300 RF	MANWAY/BLIND	18"	2

Figure 60 Candle Filter Pressure Vessel, Carbonizer

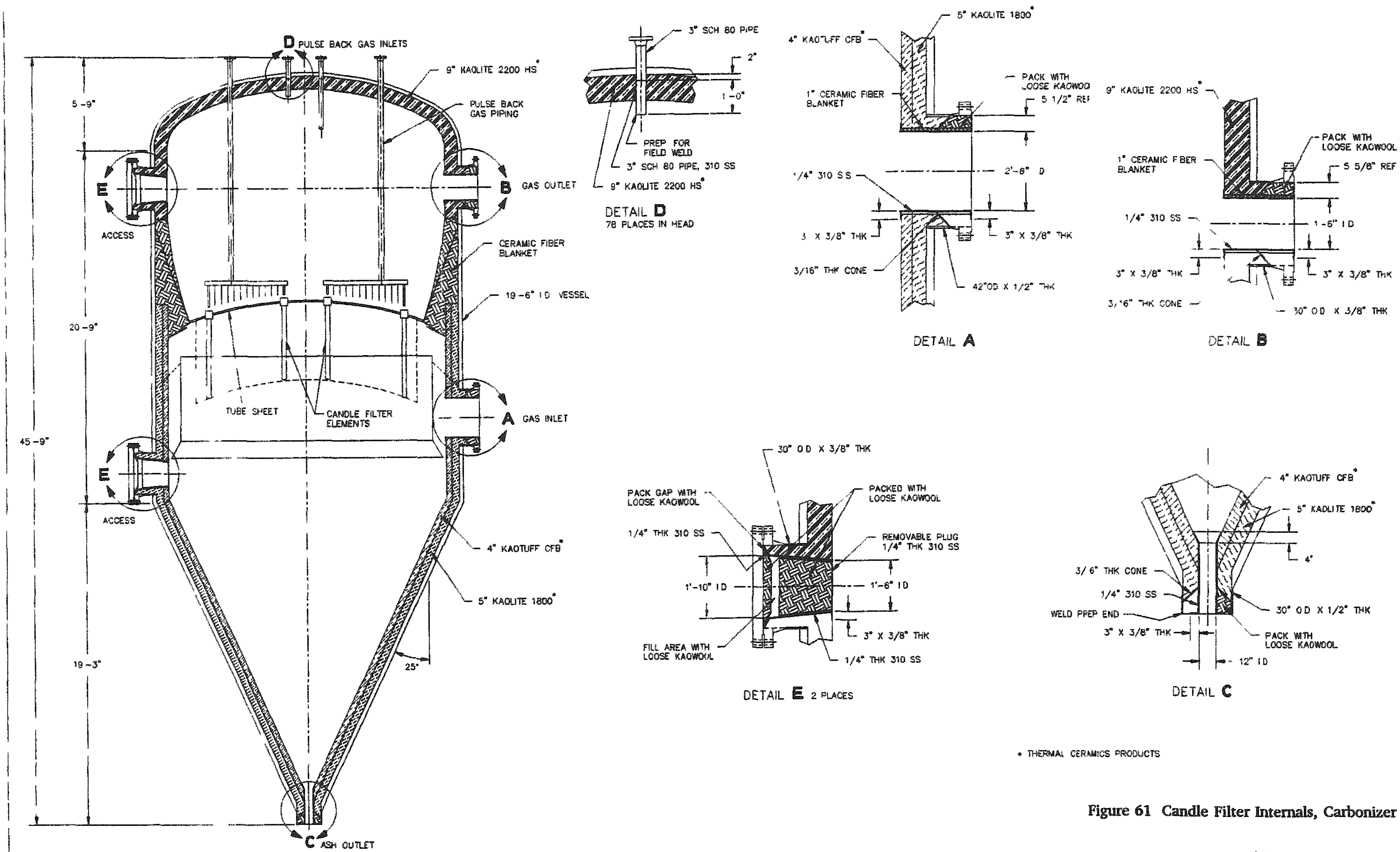
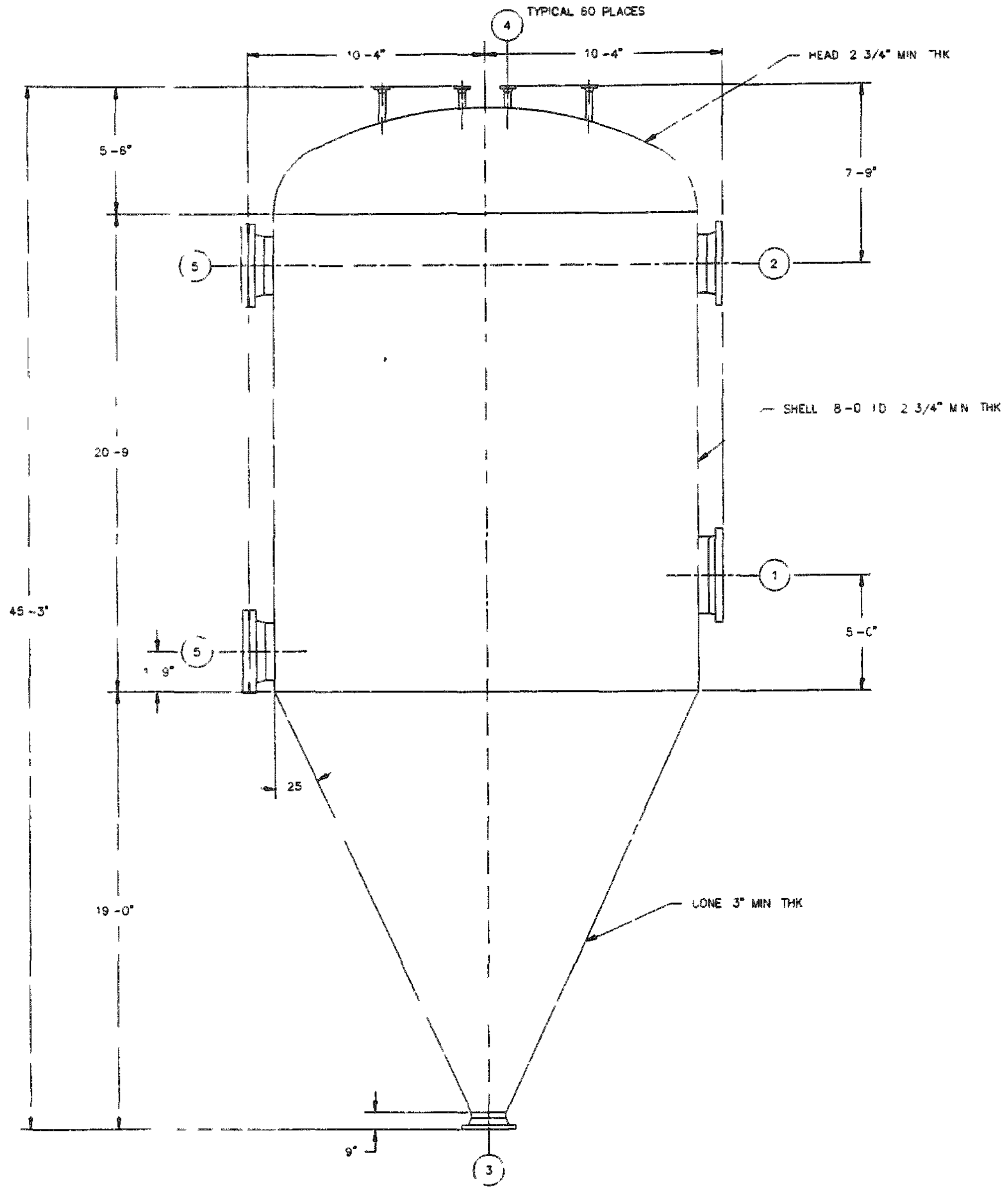


Figure 61 Candle Filter Internals, Carbonizer



VESSEL DATA

SERVICE	GASIFIER OUTLET FILTER
OPERATING PRESS	385 PSIA
DESIGN PRESS	410 PSIG
MAX OPERATING TEMP	1600°F (INTERNAL)
DESIGN TEMP	650°F (METAL)
WIND DATA	UBC (70 MPH EXP C)
EARTHQUAKE DATA	UBC (ZONE 1)
CODE	ASME SECT VIII DIV 1
CODE STAMP	YES
P W H T FOR CODE	PARTIAL
P W H T FOR PROCESS	NO
JOINT EFF	100%
RADIOGRAPHED	FULL
CORROSION ALL	/8"
MAT'L SHELL	SA-516 GR 70
MAT'L HEADS	SA-516 GR 70 (2 1 ELLIPTICAL)
MAT'L SUPPTS.	SA-516 GR 70
MAT'L NOZZLES	SA-516 GR 70
MAT'L FLANGES	SA-105
EMPTY WEIGHT	251000 LBS (METAL ONLY)
WATER ONLY WEIGHT	483000 LBS
REFRACTORY LINING	99000 LBS
SHIPMENT	1 PIECE

NOZZLES

NO	SIZE	ANSI RATING	SERVICE	D LINING	QTY
1	40"	CL 300 R	INLET	28"	1
2	30"	CL 300 R	OUTLET	18"	1
3	18	CL 300 R	ASH OUTLET	6"	1
4	3"	CL 300 R	PULSE GAS	N A	60
5	30"	CL 300 R	MANWAY/BLIND	18"	2

Figure 62 Candle Filter Pressure Vessel, KRW Gasifier

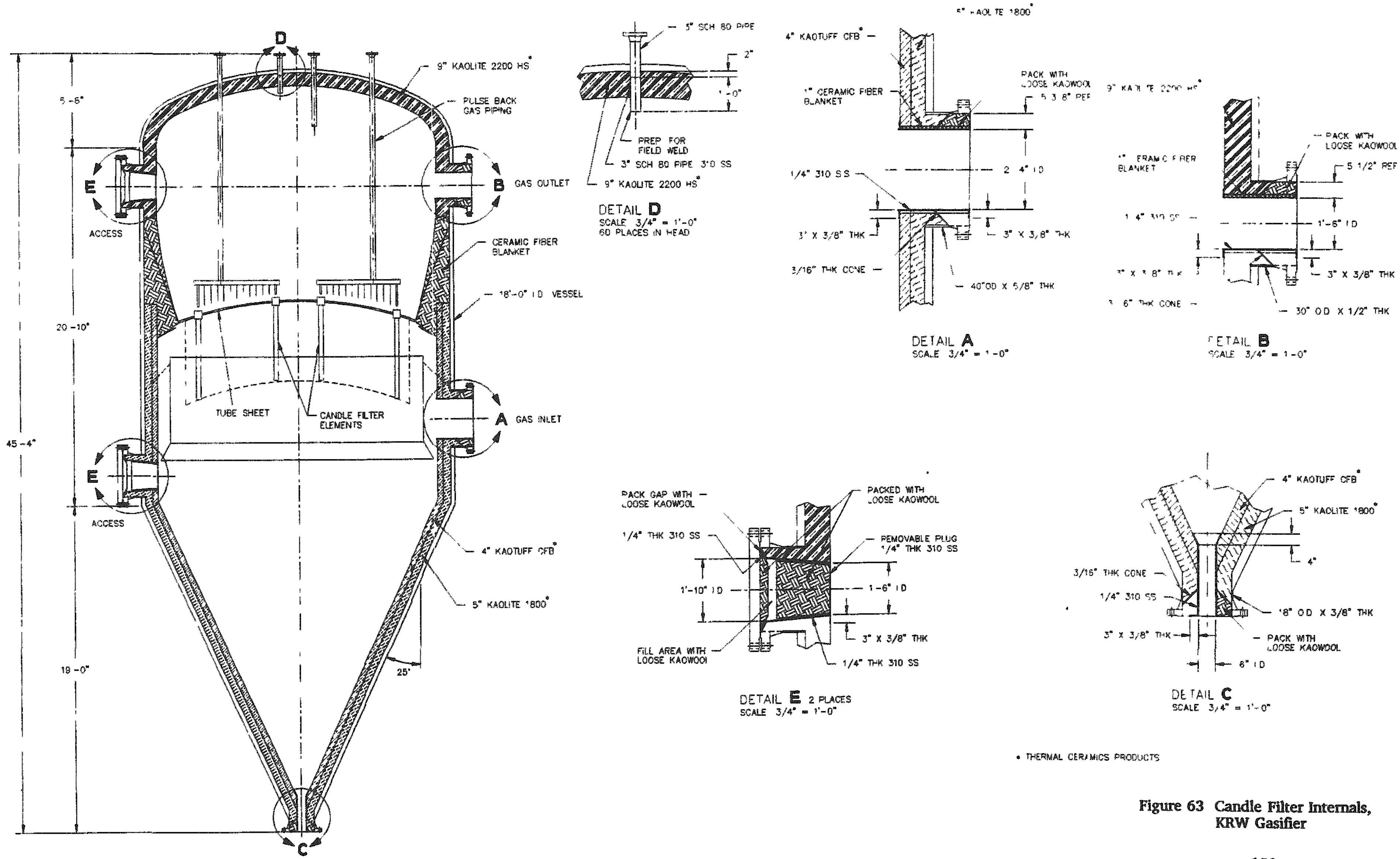


Figure 63 Candle Filter Internals, KRW Gasifier

4.3.3.1 Refractory

Several approaches for lining of the candle filter vessel with refractory were considered.

- Cast insulation and hardface in the vessel ash cone and cylinder sidewalls below the tubesheet and ceramic fiber product in the space above the tubesheet.

- Castable-type refractory applied by pneumatic gunning techniques installed in both regions above and below the tubesheet.

- A combination gunite insulation/hardface in the entire candle filter vessel.

In the candle filter vessel space above the tubesheet, conditions for the refractory are fairly mild, even in the reducing atmospheres for the carbonizer and the gasifier. There is virtually no ash, gas velocity is very low (< 10 ft/sec) and operating temperatures are 1500°F to 1600°F. Under these conditions, the most important refractory properties to consider are thermal conductivity to minimize heat loss and refractory stability to resist any kind of deterioration that could add particles to the cleaned gas stream exiting the filter.

Ceramic fiber products have very low thermal conductivity (.5 to 1 Btu-in/hr ft^2 °F) and are available in a number of forms that could be suitable for lining the zone above the tubesheet. Although manufactures and installers claim otherwise, these products could deteriorate and add particles in the form of ceramic fibers or chunks to the gas stream exiting towards the gas turbine. Metal liners can be used to protect this material, but this is costly. Consequently, these materials are not proposed; although, consideration would be given in an actual application. Instead our choice is a lightweight, insulating gunning mix. These materials have slightly less insulating value when compared to ceramic fiber products, but are much stronger and more resistant to deterioration and chemical attach. A 60 to 70 lb/ft^3 gunning mix could be applied as a combination insulating and hardface layer in the candle filter operating in an oxidizing or reducing environment. Thermal conductivity is in the range of 1.3 to 1.6 Btu-in/hr ft^2 °F, and good strength is indicated by a cold crushing strength of 300 to 500 psi after heating to 1500°F.

In the candle filter area below the tubesheet where the ash is collected, the requirements are different. The hard face refractory must have good strength to hold the ash weight and moderate abrasion resistance for long life. The insulating refractory must minimize heat loss to the surroundings.

For small candle filters, casting the cone and sidewall areas that enclose the ash would be the preferred technique. In larger candle filters, forms for installing castables (similar to forms for installing concrete) are very large, bulky, and expensive. There will be an economic break-point where pneumatic gunning is more suitable. Abrasion resistance and strength is comparable to castable refractory hardfaces. Gunning is chosen for the large (16-20' diam.) candle filters. For the insulation layer under the gunned hardface, a light-weight, gunned refractory material is proposed.

4.3.3.2 Metal Internals

The life of the metallic internals used in the filters will greatly depend on the operating temperature and gas environment. For the CPFBC candle filter operating at 1600°F with a moderate oxygen and a low sulfur dioxide environment, we expect that the loss of metal will be less than 5 mils/year. This corresponds to a service life of about 25 years. In candle filters for service in PFBC applications (oxidizing atmospheres) RA333 and 310 SS have been used with satisfactory results[5]. RA333 has been used in regions of high stress, and 310 SS has been used in regions of low stress. Therefore, for the candle filter in the oxidizing atmosphere, the CPFBC candle filter, these materials are proposed.

Since sulfur is captured in the carbonizer and gasifier, sulfidation potential due to H_2S is considerably reduced downstream in the filter. Regardless, the carbonizer and gasifier environments will be corrosive. In a 1500-1600°F reducing gas environment, the corrosion rate could be as high as 20 mils/year[24]. The expected service life in this situation could be only 5 years; less if "breakaway" corrosion occurs. Breakaway corrosion is a suddenly increasing corrosion rate occurring after a long period of relatively stable behavior. As the corrosion information available on metals in the reducing environments is limited, we believe that one of the functions of any future development program should be to collect corrosion data on promising alloys which can be used in this type of service. For the reducing atmospheres, we could find no precedent. Options are: 310, RA85H, Haynes 556, Haynes HR-160, and Haynes 188, in order of material cost from \$2.5/lb to \$28/lb. The choice for reducing atmospheres is RA85H for the candle filter tubesheet[25] and 310 SS for other lightly-stressed components such as duct liners. This choice is made somewhat based on costs; since, other choices are considerably more expensive.

Table 15, Section 3, summarizes the materials chosen for the different components, and Table 16, Section 3, lists the compositions of these materials. The first choice of materials is marked with an "X" in Table 15. In some cases the material choice is limited by its availability in the forms utilized in the ceramic candle filter. Prices listed are for purchased plate, 1/4" to 1" thick, and are rounded off the nearest dollar in most cases.

4.3.4 Candle Filter Plant Arrangements

The CPFBC and carbonizer filters were arranged to fit into the existing plant layout and replace the originally proposed cross-flow filters for the Foster Wheeler, second generation PFB combustion plant[20]. Figure 64 shows the general arrangement of the CPFBC candle filter plant for one of two identical 226 MWe modules. The arrangement of the four candle filter vessels replaces the two cross-flow filters originally proposed with minimal increase in plan area and installed elevation. Inlet and outlet ducting is revised to accommodate the proposed candle filter module. The location, arrangement, and elevations of the ash handling equipment remain almost unchanged from the positions as shown for the cross-flow filter in the Foster Wheeler study.

Figure 65 shows the general arrangement of the carbonizer candle filter plant for one of the two identical 226 MWe modules. Since a single carbonizer candle filter vessel replaces a single cross-flow filter vessel of nearly the same size and shape there are very minor changes in the plant layout. The carbonizer candle filter vessel was arranged to connect with the carbonizer cyclone and ash collecting hopper without changing the position of these existing pieces of equipment. Locations of the inlet and outlet nozzles for the candle filter vessel are only slightly different than for the cross-flow filter vessel. These resulting gas ducting changes are considered irrelevant to the cost estimate.

In the Foster Wheeler study[20], all of the pulse gas compressor systems for the cross-flow filters are located at ground floor level, which is ideal for easy access and maintenance. The pulse gas compressor systems for the candle filters will also be located at ground floor level, and are not shown in our general arrangements for the CPFBC and gasifier candle filters.

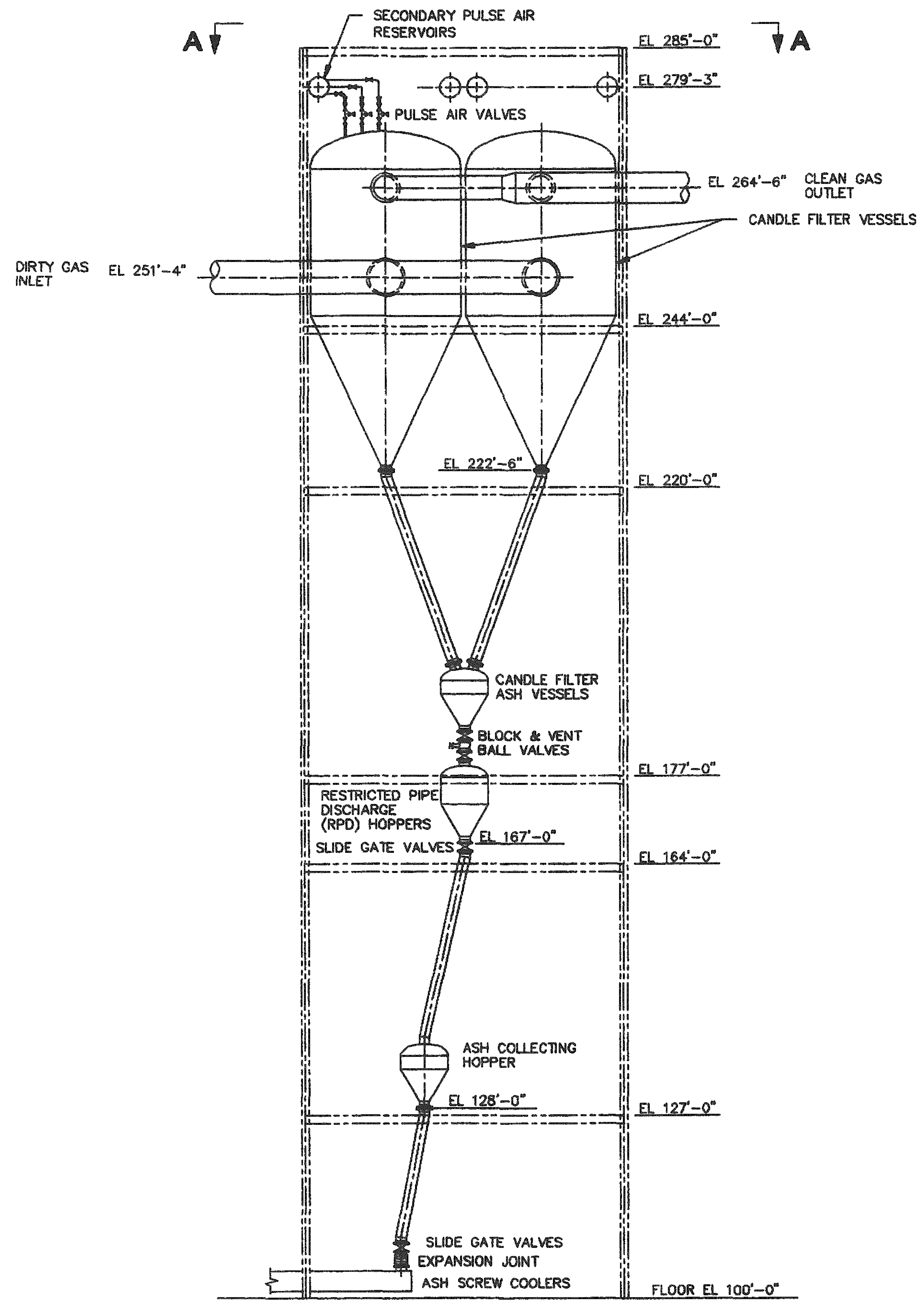
Figure 66 shows the general arrangement of the gasifier candle filter plant. In the study by Westinghouse on the gasifier plant, no general arrangement drawings where prepared. Our arrangement of the gasifier candle filter plant was designed to be as compact as possible while still allowing space for access and maintenance. The structure for the gasifier candle filter and auxiliary equipment is a free standing unit that could be easily integrated into the layout of the complete gasifier plant. As with the CPFBC and carbonizer candle filters, the pulse gas compressor system is assumed to be located on the ground floor and is not shown in the general arrangement.

4.4 Candle Filter Auxiliary Equipment/Specifications

Auxiliary equipment for the candle filters includes: pulse gas supply equipment, ash handling equipment, and ducting. Pulse gas supply is fairly straightforward for the CPFBC filter because it is in an oxidizing atmosphere. Compressed air can be bypassed from the CPFBC supply, boosted in pressure and utilized. For the carbonizer and the gasifier, because of the reducing atmosphere, pulse systems utilizing process gas and nitrogen are compared. Since the least costly system uses process gas, it is chosen. Ash handling is accomplished as proposed for the filters in the base plants.

4.4.1 Pulse System, CPFBC

Equipment specified in each pulse air compressor system for the CPFBC candle filters consists of a inlet air cooler, single stage reciprocating compressor, refrigerated air dryer system, primary accumulator tank, and duplex air filters. In addition to each complete compressor system, there is a single standby boost compressor that can supply air to either of the two main systems. This compressor system approach is consistent with



ELEVATION VIEW

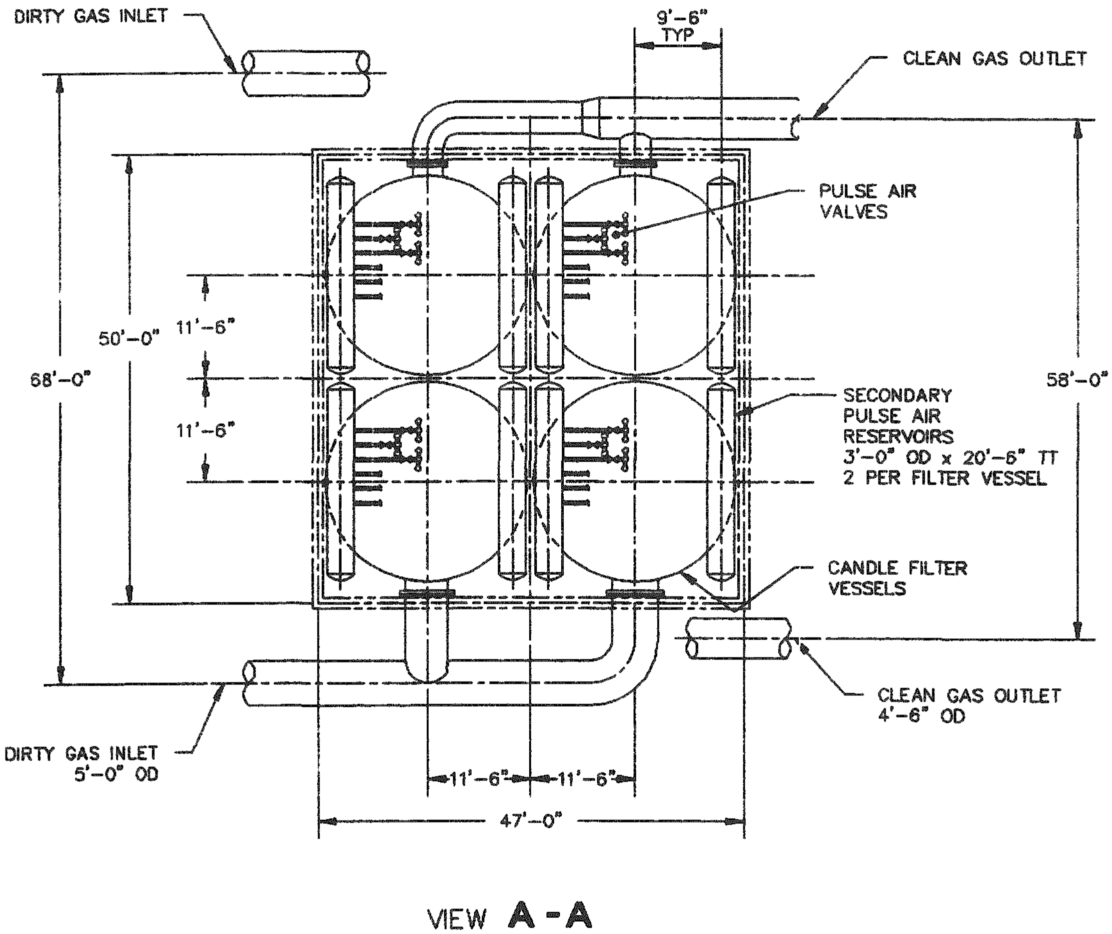


Figure 64 General Arrangement, CPFBC Candle Filter

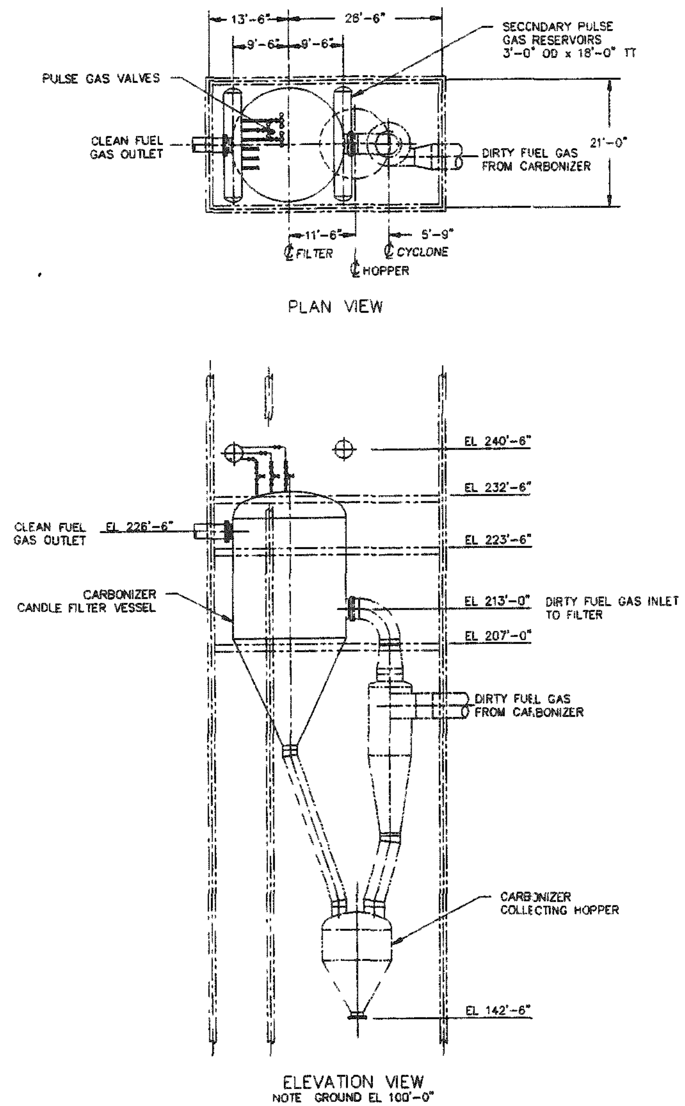
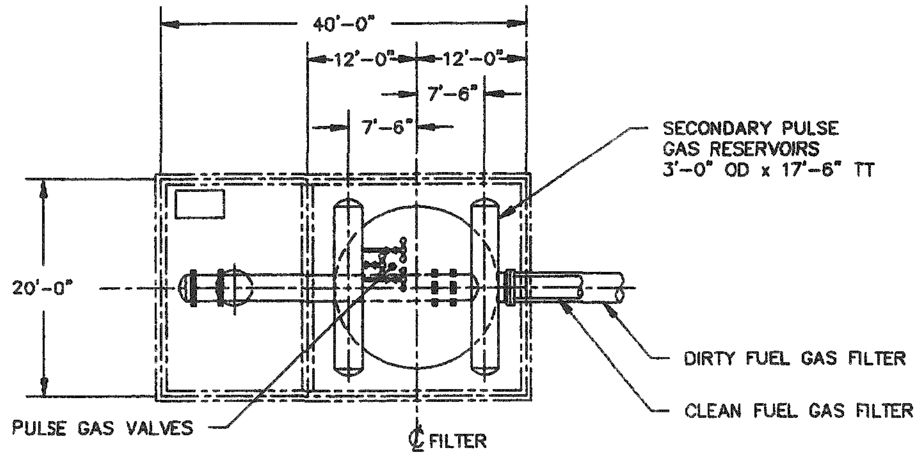
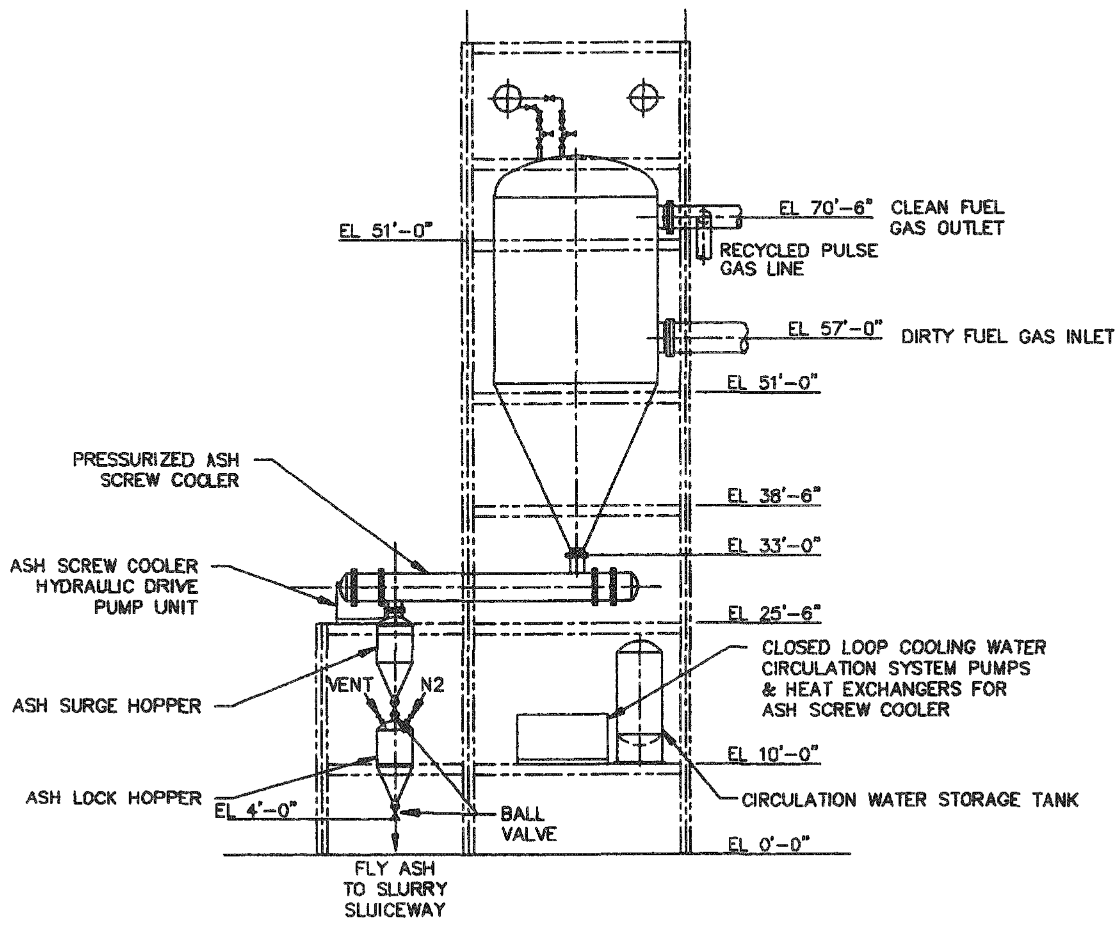


Figure 65 General Arrangement, Carbonizer Candle Filter



PLAN VIEW



ELEVATION VIEW

Figure 66 General Arrangement KRW Gasifier Candle Filter

the pulse compressed air system described in the Foster Wheeler second generation PFBC study[20], and the compressed air system being installed at the Tidd PFBC hot gas cleanup test facility[5]. Pulse air systems are supplied inlet compressed air from the transport air, boost compressor of the applicable CPFBC.

Each reciprocating compressor system has an unlimited source of pressurized air at the inlet at 268 psia and 176°F. The outlet pressure is determined at the outlet of the duplex filters. See Table 30 for summary of pulse air design data.

In addition to the two identical and complete, reciprocating compressor trains, a third standby compressor and refrigerated air dryer is included. (See CPFBC P&ID, Figure 52 above). Capacity of standby compressor and dryer are the same as listed in Table 30. The air dryer system for each compressor is designed for a +35°F dew point at the compressor design air flow. Cooling water is assumed to be 90°F for the precoolers, aftercoolers, and oil cooler. An accumulator tank is supplied with each compressor train. This tank is sized using standard industry practices. A duplex type filter that allows servicing of the filter with the compressor system on line is provided on each compressor train. Filters remove particles down to three (3) micron in size. Maximum total oil or hydrocarbon content in the compressed air outlet does not exceed one (1) ppm w/w or v/v under normal operating conditions.

Table 30 CPFBC Pulse Air System
(226 MWe Basis)

	Flow		Pressure
	lb/hr	scfm*	psia
Design	17,035	3786	490
Normal Operation	13,628	3028	390
Minimum Operation	6,814	1514	290
Inlet	As Nec.	-	268

* Standard Air Density is 0.075 lb/cu.ft @ 14.7 psia and 70°F

The driver supplied with each reciprocating compressor is a 250 hp, 460V/3Ph/60hz, induction type motor. At a discharge pressure of 490 psia and full capacity, 237 bhp is utilized. Electric controls and instruments are included in a NEMA 4 panel enclosure with local wiring and sense lines connected.

4.4.2 Pulse System, Carbonizer/Gasifier

In the base studies for the Foster Wheeler second generation PFBC plant[20] and the KRW air blown gasifier[26], pulse gas for cleaning the candle filter elements was supplied by stored nitrogen. This approach was investigated for the candle filters based on the estimated pulse gas quantities calculated. Equipment initially defined for these applications consisted of liquid nitrogen storage tanks, a liquid nitrogen compressor, and a liquid nitrogen vaporizer system. This is the basic system proposed for the cross-flow filter that was originally part of the 100 MWe KRW air blown gasifier[26]. Because of the large capacity of nitrogen specified, all suppliers contacted declined to quote based on liquid nitrogen storage. Instead, these suppliers recommended on-site generation. Two types of nitrogen producing plants were considered. Cryogenic plants produce nitrogen of very high purity, in the range of 99.9% or better, while pressure swing adsorption (PSA) type plants produce nitrogen with purity of 95 to 99%. Our requirement for nitrogen purity for the candle filter back pulse gas was estimated at a minimum of 98%. Since very high purity nitrogen (i.e. 99.9% or above) was not required, PSA type nitrogen generating plants were utilized for both applications.

Nitrogen is produced from air in the PSA process. The key components of this system are carbon molecular sieve beds which are exposed to compressed air, the only feedstock. The system is comprised of a compressor, refrigerated dryer, and pressure vessels charged with molecular sieves and controls. A microprocessor and sensing devices monitor, regulate, and control the adsorption and desorption nitrogen production cycle.

PSA nitrogen generating plants do not include any type of backup system to supply compressed nitrogen to the candle filter in the event of nitrogen generating plant failure. Since pulse gas usage is continuous, the loss of pulse gas would quickly curtail the operation of the candle filter. Consequently, a reliable standby source of nitrogen is included. A specification for a standby nitrogen gas system was prepared, based on the system described for the gasifier cross-flow filter in the Westinghouse gasifier study[26]. The liquid nitrogen tanks were sized to store only a 12-hour supply of nitrogen based on normal full load operation as opposed to a multi-day supply in the Foster Wheeler second generation PFBC. A 12-hour supply of nitrogen should allow ample time to repair the main PSA nitrogen generating system should this be necessary. If the PSA nitrogen generating system cannot be repaired in 12 hours, the standby liquid storage tank can be refilled as needed to keep the carbonizer or gasifier plant operational.

- Process Gas for pulse cleaning

Review of the quotations for the on-site nitrogen generating plant indicated that the capital costs and operating costs were quite high. In addition to the high cost of generating nitrogen, the injection of inert nitrogen in quantities of up to nearly 2% of total gas flow through the candle filter will dilute the fuel gas supplied to the turbine. As an option, process gas can be conditioned to serve as pulse gas. Conditioning would include cooling, cleaning, drying, and pressurizing.

Process gas from downstream of the candle filter can be cooled from 1500°F or 1600°F, depending on the application, down to 120-250°F which is suitable for the inlet of a compressor system. Several types of heat exchangers and heat exchanger combinations are possible for this application. The least cost approach utilizes a small heat recovery boiler followed by water-cooled heat exchanger. With this approach, it is possible to cool to 120°F. The simplest, but more costly, approach utilizes a single, natural draft type convection heat exchanger. With this approach, cooling to 250°F is more typical, and a compressor precooler is needed to reach 120°F. Once cooled to 120°F, the process gas enters a compressor system consisting of a duplex filter/mist eliminator, boost compressor, refrigerated gas dryer system, and accumulator tank.

The capital costs and operating costs for these alternatives were compared, and the results are presented on Table 31. Clearly for these alternatives, it is less costly to use process gas for pulse cleaning of the candle filter elements. The use of a heat recovery boiler instead of a air cooled natural convection heat exchanger will probably not effect the overall economics of the filter plant, but is also less expensive. This study does not consider implications beyond the cost and data presented. There may be significant costs associated with matters that were not taken into account; such as disposal of waste condensate from process gas cooling.

The heat recovery boiler is sized to cool flue gas from the carbonizer filter outlet from 1500°F to 400°F. It is followed by a water-cooled heat exchanger (trim cooler) which further reduces the flue gas temperature to 120°F. For the gasifier, candle filter outlet gas is cooled from 1600°F to 400°F in the boiler, then to 120°F in the trim cooler. At 120°F, the gas can be filtered and compressed without any further precooling. Steam produced is saturated at 40 psig with a feedwater inlet temperature of 240°F. Pricing for the boiler includes all standard boiler trim, and valves, from the feedwater control valve station through the steam outlet stop check valve. The optional, air-cooled, natural draft convection air heater contains no moving parts or controls. Hot flue gas is passed through heat exchanger tubing and is cooled by ambient air drawn through the unit by natural draft. Air is typically heated from ambient to 500°F. At the high temperature flue gas inlet of the heat exchanger, the allowable tube stresses are very low, requiring heavy wall thicknesses. From the natural draft heat exchanger, the flue gas is typically cooled to 250°F requiring a precooler prior to the boost compressor.

Downstream of the heat recovery boiler and trim cooler is a packaged compressor system. For the carbonizer filter, process gas is boosted in pressure from 204 psia to a maximum of 508 psia, see Table 31. For the gasifier filter, the pressure rise is from 381 psia to a maximum of 685 psia. Reciprocating compressors fitted with suitable materials to resist corrosion from the fuel gas are motor driven through v-belt drives. Motor sizes are 125 HP and 150 HP, 1800 RPM, 460 V, TEFC for the carbonizer and the gasifier respectively. Compressor system auxiliaries include refrigerated dryer systems for +35°F dew point gases, water-cooled aftercoolers, duplex air filters with switching valves, main air receivers tanks, and controls locally tubes or wired to a local panel. For the carbonizer, there is one complete compressor system for each 226 MWe filter module. A spare compressor, aftercooler, and refrigerated dryer is also supplied that can be valved into either filter module. For the gasifier, one complete compressor system is included with a spare compressor, aftercooler, and refrigerated gas dryer.

Table 31 Pulse Gas Parameters - Carbonizer/Gasifier

Parameter	Carbonizer	Gasifier
Capacity Basis, MWe	226	100
Operating Flow, lb/hr	2,995	5,410
Inlet Operating Pres., psia*	204	381
Outlet Operating Pres., psia	408	585
Outlet Design Pres, psia	508	685
Process Gas Flow, Design		
Wet, Inlet, lb/hr	4,300	7,150
Nitrogen Gas Flow, Design		
lb/hr	4,079	8,030
<u>Pulse Gas Supply Alternatives</u>		
Nitrogen Storage	No Quote	No Quote
Nitrogen Generation, PSA	$993,000	$1,946,000
Power Usage, hp	640	980
Process Gas Conditioning	$327,500	$405,000
Power Usage, hp	105	134
Nitrogen Backup, 12-hr	$90,000	$270,000
Power Supply, hp	10	25
<u>Process Gas Cooling Alternatives</u>		
Nat. Conv. Ht. Exchr.	$65,000	$95,000
Heat Recovery Blr	$39,000	$55,000

* Applies to process gas only: +/- 10 psi. Inlet operating pressure for nitrogen generating equipment is atmospheric.

4.4.3 Pulse Gas Distribution

The Tidd candle filter[5] utilizes one solenoid valve to pulse three separate manifolds. These manifolds are isolated by actuated ball valves downstream of each solenoid valve. Assuming the extra piping and bends required to service these manifolds from one solenoid valve is not excessive, this arrangement should not degrade the pulse gas cleaning effectiveness. We are proposing a similar design; since, the number of solenoid valves is reduced by two-thirds and the cost of the solenoid valves is much greater than the ball valves used to isolate them. Each solenoid valve will pulse a maximum of three manifolds by branching to the three lines directly downstream of the solenoid valve. A normally closed, actuated ball valve will be installed in each manifold supply line. The ball valve at the inlet to each manifold will be opened a few seconds before the solenoid valve actuates. The ball valves on the other two lines will remain closed. After the manifold is pulsed, the ball valve will be closed. Since the normal position of the ball valves will be closed, the chance for leakage of pulse gas into the filter is minimized. Figure 67 shows the proposed distribution of pulse gas from the secondary reservoirs installed local to the filter vessels. There is no back-up solenoid valve as provided at Tidd because these are all large systems, and the temporary loss of a single pulse circuit can be temporarily compensated for by pulsing the other circuits more often. The pulse valves proposed are 2" Atkomatic quick opening pilot actuated solenoid valve.

4.4.4 Ash Handling, CPFBC/Carbonizer

The CPFBC candle filter ash handling system uses the same components and configuration as proposed in the Foster Wheeler study[20] except for the addition of one small refractory lined vessel for each two candle filter vessels. This small refractory lined vessel, called a candle filter ash vessel, is required because there are two candle filter vessels to replace each cross-flow filter vessel. This vessel combines the ash from two candle filter vessels so that the ash system equipment beyond the outlet of this vessel is identical to the equipment described in the Foster Wheeler study[20]. The ash is depressurized using restricted pipe discharge (RPD) vessels and then cooled using water-cooled screw conveyors. A detailed description of the CPFBC ash system is given in the Foster Wheeler report.

The carbonizer candle filter does not have any ash handling equipment because the ash from the filter is discharged directly into the carbonizer collecting hopper. A detail description of this equipment is given in the Foster Wheeler report.

4.4.5 Ash Handling, Gasifier

The ash system proposed for the gasifier in the Westinghouse study[26] consists of a pressurized water-cooled screw conveyor to cool the ash then a series of lock hoppers for depressurizing the cooled ash. The information and description of this ash system given in the Westinghouse report consists of a process flow diagram mearly showing a concept of the equipment. Incidently, both the Grimethorpe[4] and Tidd[5] candle filter plants use this ash system approach. To obtain current costs and design information for the ash system for the gasifier candle filter, specifications were prepared for a pressurized water-cooled screw conveyor and required lock hopper valves and submitted to vendors for quotation. Information from reports on the ash systems at Grimethorpe and Tidd served as basis for these specifications.

• Pressurized Ash, Screw Cooler

The function of the pressurized ash, screw cooler is to reduce the candle filter ash temperature from 1600°F to approximately 400°F while the ash is still at full system pressure. In this arrangement, the inlet of the ash cooler is connected directly to the outlet of the gasifier candle filter, so the it must be designed for the same pressure conditions as the candle filter vessel, or 410 psig. There are advantages to cooling the ash from 1600°F down to 400°F before it is depressurized through lock hoppers. The first advantage is in cost savings on the lock hopper valves. A valve designed for operation in ash at 410 psig and 1600°F has a high capital and maintenance cost. If the ash temperature is reduced to 400°F prior to depressurizing, both the capital and maintenance costs of the valves are greatly reduced. Information obtained from one valve manufacturers indicates that capital cost for the low temperature valves for a gasifier plant would be a 1/4 of the cost for high temperature valves of the same size and pressure rating. The vendor also estimated that valve repair costs for the lower temperature valves over a 5 year period would be 1/8 that of the high temperature valves, not including costs for down time. An estimate of the total savings in capital and repair costs for low temperature valves verses high temperature valves for the gasifier ash system is over $500,000 in a 5 year period. In addition, the low temperature lock hoppers can be made from carbon steel without a refractory lining.

Figure 68 shows a typical arrangement of a pressurized ash screw cooler. It is comprised of a cylindrical outer shell, the cooling screw and the hydraulic drive unit. The ash cooler is similar to a standard water-cooled screw conveyor except the outer, water-cooled shell is a pressure vessel. The unique feature of this equipment is the separate chambers on each end of the screw that house the cooling water transfer flexible coupling at one end and the hydraulic drive motor at the other. Both of these chambers are purged with nitrogen to keep these areas free of ash.

Since the screw cooler is directly connected to the gasifier filter, there could be condensation from the process gases on the cool metal surfaces of the screw if standard plant cooling water of approximately 90°F was utilized. In order to prevent this condensation from forming, causing ash flow problems, the water circulated through the screw remains heated in a separate, closed loop cooling water system. This closed loop circulation system allows the metal surfaces of the ash screw cooler to be maintained at temperatures of 350°F to 380°F.

This closed loop cooling water circulation system consists of:

- a main water storage tank
- a electric heater for preheating the loop during startup
- two 100% capacity main circulation pumps each with 5 hp motors
- flow meters, psv valves, and flow control valves
- water-cooled heat exchanger cooled with plant cooling water
- small water storage tank to feed boost pumps
- two small, 100% capacity boost pumps with 1 hp motors that maintain the loop at desired pressure at all times
- actuated valves to allow flow of plant cooling water through the screw cooler to protect the unit in case of complete failure of the closed loop system
- instruments and controls

For a compete schematic of the closed loop circulation system, the pressurized ash screw, and the ash look hoppers see Figure 54, the piping and instrumentation diagram for the gasifier.

4.5 Filter Plant Construction

The Foster Wheeler study[20] notes that considerable utility experience in barge-shipping and erection of large steam generator vessels exists as a result of the expanding nuclear industry in the 1960's and 1970's. Several vessels weighing up to 800 tons have been shipped and erected. Several contractors in the United States specialize in transporting and rigging this heavy equipment. Thus there appears to be no major obstacle to supplying the much smaller filter vessels in a similar way. Filter vessels are assumed to be moved from a barge to the construction site by crawler/transporters as shown in the Foster Wheeler report.

• General Installation Information

The following is installation information that applies to all three candle filter applications.

Candle Filter Vessel(s): Each candle filter vessel will be shipped to the site with the tubesheet and tubesheet support installed. Since the baffle when installed would interfere with the refractory installation it is shipped inside the vessel in three 120 degree sections. The internal refractory will be field installed after the vessel is positioned. Once the refractory is installed, the baffle will be assembled inside the vessel.

Candle Filter Element Installation: Each element is about 5 feet in length and weights about 9 pounds. Each element is supported in the tubesheet in a support fixture with ring gaskets on both sides of the element flange. All of the candle filter elements will have to be installed inside the vessel in the field after the internal refractory is installed. There is a total of 1572 elements per filter vessel in the CPFBC, 1130 elements per filter vessel in the carbonizer, and 906 elements per filter vessel in the gasifier. Installation of the filter elements is similar to installing bags in a pulse jet type baghouse in that care must be taken to prevent damage to the filter elements.

Pulse Piping Inside Vessels: Once the candle filter elements are installed, pulse air or gas manifolds and piping must be installed inside the vessel. All of the these manifolds and pipe spools will be shop fabricated to the greatest extent to reduce field installation labor.

Secondary Pulse Reservoirs: Each filter vessel has two of these reservoirs which have a number of nozzles to connect air or gas to the pulse piping. These reservoirs will be shop fabricated and lifted into place.

Pulse Valve Piping: This is the installation of valves and piping spools that supply air or gas from the secondary reservoirs to the nozzles in the head of the filter vessel. Figure 67 shows the typical installation details of this piping and valves.

Compressor Skids and Refrigerated Dryer Skids: Each filter installation includes air or gas compressor and refrigerated dryer equipment. This equipment will be shipped to the site skid mounted and assembled to the greatest extend possible. Piping between skids will be installed in the field.

- CPFBC Candle Filters

Table 32 lists the equipment for this plant. Each candle filter plant consists of four filters as shown on Figure 64. There are two identical candle filter modules as the entire plant is divided into two identical trains of equipment, each sized for, nominally, 226 MWe.

Some costs are not included in the construction estimate, these are: refractory and instruments/controls. The candle filter vessels will have refractory installed in the vessels once they are in place at the site. Other smaller refractory lined vessels and piping for the ash system will have refractory installed off site. Refractory costs include installation.

The ash system installation for the CPFBC candle filters consists of installing block and vent valves, restricted pipe discharge hoppers, ash collecting hopper, ash screw coolers, and connecting refractory lined pipe.

- Carbonizer Candle Filter

Table 33 lists the equipment for this plant. Each filter module consists of one filter vessel with pulse gas reservoirs and piping as shown on above Figure 65. The cyclone and the carbonizer collecting hopper, shown in phantom are not part of the installation. There are two identical filter modules as the entire plant is divided into two identical trains of equipment, each sized for, nominally, 226 MWe.

- Gasifier Candle Filter

Table 34 lists the equipment for this plant. Each filter module consists of one filter vessel with ash cooling and depressurization equipment as shown in above Figure 66. There is one filter vessel, sized for 100 MWe.

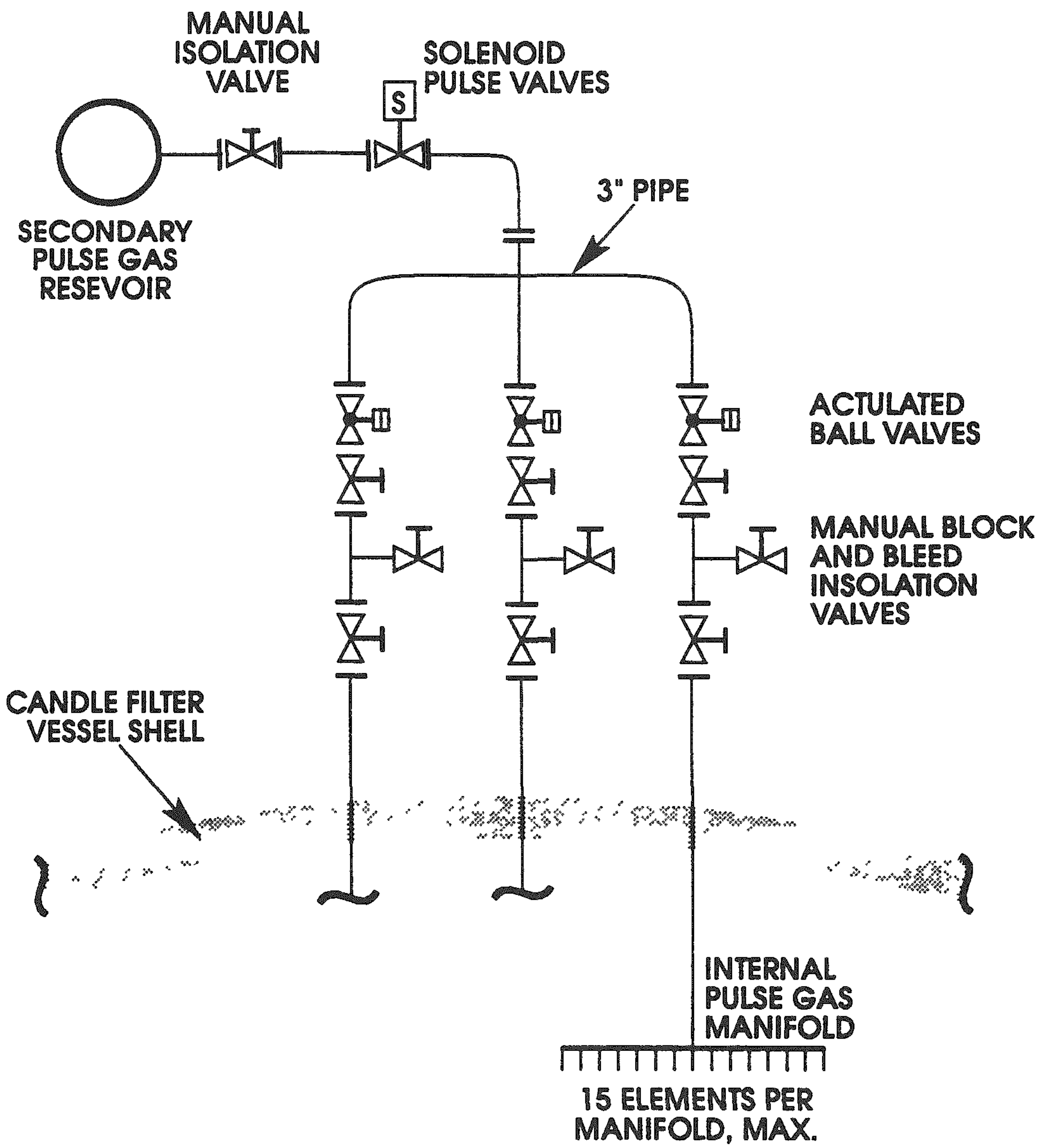


Figure 67 Pulse Gas Piping

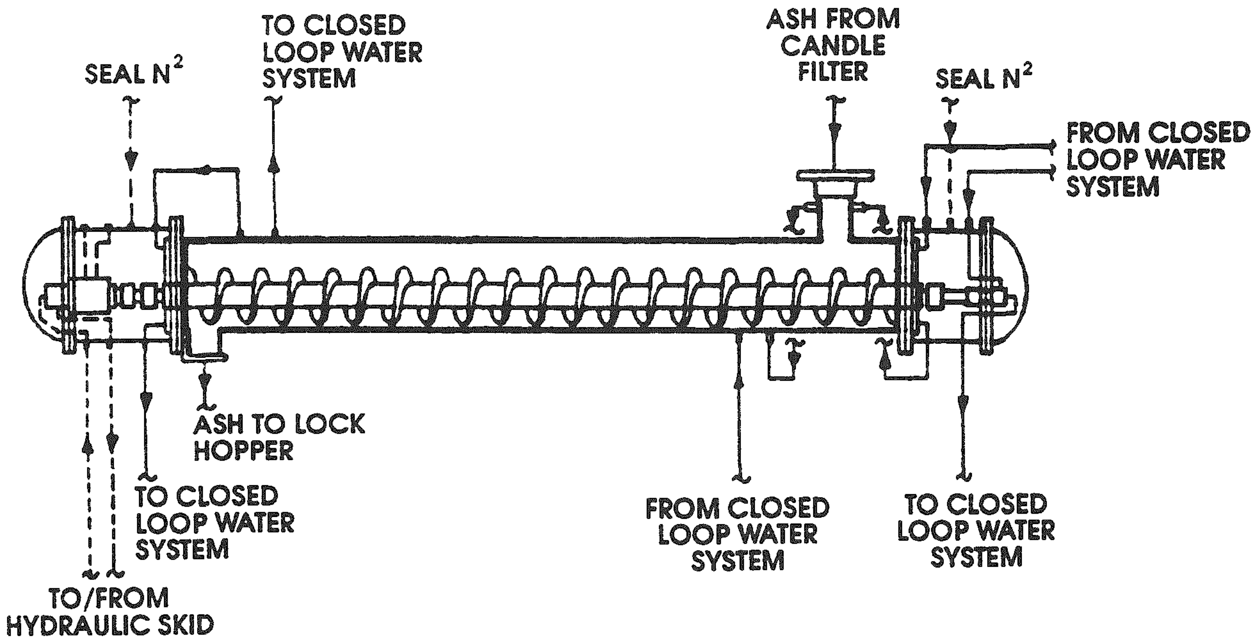


Figure 68 Water-Cooled Screw

930419ME CDR

Table 32 CPFBC Candle Filter Equipment - 226 MWe Module

Filter Components	Qty	Unit Weight (lbs)	Size or Capacity, (each)	Installed/ Operating Hp
Filter Vessels	4	232,000	22' Dia X 51'	-
includes tubesheet and baffle				
Vessel Refractory	4	138,000		-
Candle Elements	6288	9	60 mm OD X 1.5 m	-
Pulse Air System				
Air Compressor Skid	1.5[1]	25,000	15'L X 10'W X 8'H	250/237
Refr. Dryer Skid	1.5[1]	3,500	10'L X 5'W X 10'H	25/20
Main Receiver Tank and Filter Skid	1	30,000	12'L X 6'W X 12'H	-
Sec. Reservoir Tank	8	6,000	3' Dia X 22'	-
Piping/Valves	1 Lot	236,000		-
Insulation	1 Lot	-		-
Access/Support Stl.	1 Lot	594,000		-
Instr/Controls	1 Lot	-		-
Inlet/Outlet Ducting	1 Lot	470,000		-
Ash System for CPFBC Candle Filter				
C/F Ash Vessels	2	5,600	7' Dia X 10'	-
Refractory	2	10,200		-
500°F Ball Valve	4	200	6"	-
500°F Bleed Valve	2	50	2"	-
RPD Vessel-C'Stl[2]	2	8,810	7' Dia X 12.5'	-
Refractory	2	12,900		-
Throt'lg Slide Gate	2	200	6"	-
Ash Coll. Hopper	1	5,300	7' Dia X 10'	-
Refractory	1	5,100		-
Refr Lined Pipe	1 Lot	18,700	18' Pipe X 230'	-
Refractory	1	12,200		-
Slide Gate Valve	2	200	6"	-
Ash Screw Coolers	2	28,000	25'L X 4'W X 3'H	30/15

Notes:
1. Includes stand-by compressor equipment shared by each module.
2. Restricted-Pipe Discharge ash hopper.

Table 33 Carbonizer Candle Filter Equipment - 226 MWe Module

Filter Components	Qty	Unit Weight (lbs)	Size or Capacity, (each)	Installed/ Operating Hp
Filter Vessel	1	180,000	19'-6" Dia X 46'	-
includes tubesheet and baffle				
Vessel Refractory	1	110,000		-
Candle Elements	1130	9	60 mm OD X 1.5 m	-
Pulse Gas System				
Refr Lined Pipe	1	11,000	18" Pipe X 135'	-
Refractory	1	7,200		-
Boiler/Cooler Skid	1	10,000	15'L X 5'W X 8'H	-
Gas Precooler Skid	1	4,000	10'L X 2'W X 2'H	-
Gas Compressor Skid	1.5[1]	20,000	15'L X 10'W X 8'H	125/100
Refr. Dryer Skid	1.5[1]	3,500	8'L X 4'W X 8'H	10/5
Main Receiver Tank and Filter Skid	1	22,000	12'L X 6'W X 12'H	-
Sec. Reservoir Tank	2	6,000	3' Dia X 19'-6"	-
Piping/Valves	1 Lot	46,400		-
Insulation	1 Lot	-		-
Access/Support Stl.	1 Lot	180,000		-
Instr/Controls	1 Lot	-		-

Notes:
1. Includes stand-by compressor equipment shared by each module.

Table 34 Gasifier Candle Filter Equipment - 100 MWe Plant

Filter Components	Qty	Unit Weight (lbs)	Size or Capacity, (each)	Installed/ Operating Hp
Filter Vessel includes tubesheet and baffle	1	265,000	18' Dia X 46'	-
Vessel Refractory	1	99,000		-
Candle Elements	906	9	60 mm OD X 1.5 m	-
Pulse Gas System				
Refr Lined Pipe	1	9,300	18" Pipe X 75'	-
Refractory	1	4,000		-
Boiler/Cooler Skid	1	10,000	15'L X 5'W X 8'H	-
Gas Precooler Skid	1	4,000	10'L X 2'W X 2'H	-
Gas Compressor Skid	2[1]	20,000	15'L X 10'W X 8'H	150/126
Refr. Dryer Skid	2[1]	3,500	8'L X 4'W X 8'H	10/8
Main Receiver Tank and Filter Skid	1	22,000	12'L X 6'W X 12'H	-
Sec. Reservoir Tank	2	7,000	3' Dia X 19'	-
Piping/Valves	1 Lot	38,000		-
Insulation	1 Lot	-		-
Access/Support Stl.	1 Lot	90,000		-
Instr/Controls	1 Lot	-		-
Ash System for Gasifier Candle Filter				
Ash Screw Cooler	1	90,000	25'L X 3'W X 3'H	-
Ash Screw Cooler Hyd. Drive Unit Skid	1	2,000	5'L X 3'W X 3'H	5/5
Closed Loop Water System Pump Skid	1	9,000	10'L X 6'W X 6'H	5/2
Closed Loop Water System Water Tank	1	5,000	4'-6" Dia X 14'	-
Ash Lock Hoppers	2	4,000	4' Dia X 10'	-
500°F Ball Valves	2	200	6"	-

Notes:
1. Includes stand-by compressor equipment

4.6 References

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SECTION 5

FILTER PLANT ECONOMIC ANALYSIS

In this section the basis, approach, and outcome of the economic evaluation are described. Costs for the commercial size granular-bed and ceramic candle filter plants are presented in various forms for comparison. The cost of electricity (COE) is the key parameter and is calculated based on EPRI guidelines. These guidelines were incorporated into a Lotus 1-2-3 spreadsheet program by the Morgantown Energy Technology Center (METC). Upon completion of data entry in the form of capital costs, operating costs and fuel costs, the cost of electricity is automatically calculated and displayed. The calculation methodology is patterned after the method developed by the Electric Power Research Institute (EPRI) in their Technical Assessment Guide (TAG), Volume I, EPRI-4463-SR, December, 1986[1]. The cost of electricity is stated in terms of 10^{th} year levelized dollars.

Costs presented by Foster Wheeler for the 452 MWe, second generation pressurized fluidized bed combustion (PFBC) plant[2] are updated to December 1991 costs to compare on an equivalent basis with the filters. Similarly, costs presented by Westinghouse for a 100 MWe integrated gasification combined-cycle (IGCC) plant which uses a Kellogg-Rust-Westinghouse (KRW) air blown gasifier[3] are updated to December 1991 dollars. To the gasifier plant, the zinc ferrite system is revised according to guidelines issued by METC[4], and results are also presented. Both these commercial sized plant had cross-flow filters as part of the original technology.

5.1 Cost Estimating Procedures

Costs reported by Foster Wheeler and Westinghouse for the referenced base plants were input into the Lotus 1-2-3 spreadsheet program and manipulated to reproduce the costs of electricity reported in the source documents. This involved overriding many default values provided in the program. In the second step, the spreadsheet program was allowed to use the spreadsheet calculated financial parameters to calculate the cost of electricity. A levelizing factor is used as a financial parameter to spread costs over the 30 year life of each plant. This parameter is calculated as a different number in the spreadsheet than is reported by Foster Wheeler or Westinghouse. It is a major source of difference in the calculations by these sources. In the third step, costs for equipment, labor, fuel, and utilities were updated to December 1991 dollars. In the case of the gasifier plant, the zinc ferrite plant was updated based on information provided by METC. Costs associated with the cross-flow filters were then extracted from the plant costs and replaced with granular-bed filter costs and then with candle filter costs. The granular-bed filters required much simpler and less costly ash handling equipment than the cross-flow filters; consequently, this portion of the original cost estimates was revised. The candle filters required considerably more pulse gas than the cross-flow filters; consequently, these systems were resized and new estimates were obtained.

Equipment specifications for major filter components were prepared and sent to qualified suppliers for quotations. Where possible, multiple quotations were received so a bid analysis could be made to identify the best response. A sampling of the new filter pressure vessels and stainless steel components were sent out for quotation. Quotations received were reduced to terms of cost-per-pound and used to estimate costs of all other similar pressure vessels and vessel internals. Refractory cost guidelines were prepared by a licensed refractory contractor familiar with these types of installations. Costs per unit area were submitted by the contractor based on the type of refractory, thicknesses, and logistics involved in applying the lining. For correlation, these costs were compared to the cost of refractory materials needed for each item, in dollars per ton, multiplied by a factor to allow for installation.

Annual operation and maintenance costs were reviewed for each power generation facility. Operating labor, based on the entire power plant, was left unchanged. The unit cost was updated for escalation. Maintenance was expressed as a percentage of each major category of equipment as proposed by the EPRI TAG. This percentage was left unchanged for all equipment except for the filters. Special consideration was given to the maintenance needed for the granular-bed and the ceramic candle filters, and separate calculations were made. Costs for fuel and other consumables were updated based on the best available information.

Erection costs were estimated by a Certified Cost Engineer that is president of a company specializing in construction cost estimating and planning. He has over 35 years of experience in engineering, construction, purchasing and cost estimating for firms like Dow Chemical, USA. Equipment details and piping material listings, prepared for each plant were used to prepare the erection estimates. Wage rates for the Ohio River Valley were used for both the PFBC[2] and the gasifier[3] based plant; which, is the location given for the Foster Wheeler second generation PFB combustion plant.

Other general estimate basis and assumptions are identified below:

- The plant site given for the second generation PFB combustion plant in the Foster Wheeler study is in the Ohio River Valley of southwestern Pennsylvania/eastern Ohio. This location was also used for the gasifier; since, no other location was given.

- All filter systems were designed to fit within the plant areas chosen by the original designers. For the second generation PFB combustion plant, layouts published in the report were used to define these areas. For the KRW gasification plant, only process schematics were published; therefore, layouts were prepared based on separatable ely supported filters.

- Plant costs are expressed in December 1991 dollars.

- Estimates represent a mature technology plant, as opposed to a first-of-a-kind plant.

- Costs are presented consistent with the source documents, transferred to Lotus 1-2-3 spreadsheet format with as much accuracy as possible. For more information on the origin of other costs presented, refer to the source documents.

Each capital cost and annual cost category is determined on a first-year basis and levelized over the life of the plant through application of a levelizing factor to determine the significance as part of the COE. These costs and expenses are examined for the granular-bed and the ceramic candle filter in detail.

- **EPRI Technical Assessment Guide**

In order to provide a standard economic methodology, uniform cost estimating premises, and equivalent financial assumptions for evaluating electric utility technologies, the Technical Assessment Guide (TAG) is utilized for the basis of the cost of estimate. The cost estimate performed for these filters is classified by the TAG as Class II. In a Class II estimate, the design effort performed is preliminary, requiring the general site conditions, plant layouts, process flow diagrams, major equipment specifications, and preliminary piping and instrument diagrams. Costs for major and minor materials were determined by techniques normally characteristic of a Class III, or detailed, cost estimate; that is, quotations were received for equipment, and installation labor was estimated by determining manhours and labor rates for each job classification. It would have required a data base of information on equipment and labor to have performed a Class II estimate. Because of the developmental nature of this equipment, this data base is not available. Accuracy for these types of estimates is expressed by including a *project contingency*, which is a capital cost contingency factor covering the cost of additional equipment or other costs that would result from a more detailed design. For a Class II estimate the *project contingency* recommended by the TAG is 15-30%, and for a Class III estimate it is 10-20%. The cost estimate presented for the filter equipment is considered in the 20% accuracy category. Project contingency utilized was 15% for the second generation PFB combustion plant and 18% for the KRW gasifier plant, as proposed in the base studies.

In the TAG methodology, costs are divided into three categories for which the contribution to COE is calculated. Costs associated with building the plant are totaled to yield the *total capital requirement* (TCR). Fuel costs to run the plant are broken out separately; since, this is a major operating cost. Operation and maintenance is the third category of expenses reported. The cost totaled to give the TCR are summarized in Table 35.

5.2 Base Cost of Electricity Calculations

In order to compare the cost of competing hot gas clean-up technologies, the Cost of Electricity (COE) for power plants incorporating a granular-bed filter are compared to the COE for the same plant using a ceramic candle filter. The COE is calculated using the

"Lotus Cost of Electricity" spreadsheet by T. J. Hand, December 1988 which was supplied by METC. This spreadsheet is based on methodology developed in the 1986 TAG, published by EPRI.

Table 35 Components of Capital Cost

TAG Cost Category	Components	Explanation
Bare erected cost	Factory equipment	
	Direct field labor	
	Indirect field labor	supervision, payroll burden
	Field mat'l & supplies	
	Tools and facilities	
	Field engineering	
Total Plant Cost (TPC)	Bare Erected Cost +	Process capital & general facilities
	Engineering &	
	Home office	overhead & fee
	Process Contingency	
	Project Contingency	
Total Plant Investment (TPI)	Total Plant Cost +	
	Interest & escal. during construction	Allowance for funds used during construction
Total Capital Requirement (TCR)	Total Pl. Investm't +	at in service date
	Prepaid royalties	
	Preproduction costs	Start-up costs
	Inventory capital	Working capital
	Initial catalyst	
	Chemical charges	
	Land	

5.2.1 Second Generation PFB Combustion Plant

Table 36 shows the base COE comparisons for the 452 MWe second generation pressurized fluidized bed (PFB) combustion plant incorporating ceramic cross-flow filters.

Table 36 Second Generation PFB Combustion Plant
Base Cost of Electricity - Comparisons

Parameter	Foster Wheeler Base Cost (Dec 1987)	Adjusted to EPRI TAG 10th yr. Levelize	Escalation Included (Dec 1991)
Total Capital Req'mt, K$	469,504	464,668	508,866
Fuel Cost, K$	36,095	36,095	41,786
Operating & Maint., K$	25,904	34,891	37,659
Levelizing Factors[1]			
Capital Carrying Chrg	0.173	0.175	0.175
Fuel	1.9	1.375	1.244
Oper. & Maint.	1.75	1.321	1.202
Cost of Electricity[1], mills/kWh			
Capital Charges, mills/kWh	31.5	31.6	35.0
Fuel Costs, mills/kWh	26.6	19.2	20.2
Oper. & Maint., mills/kWh	17.6	17.9	17.6
Total Cost of Electricity, (COE)[1]	75.7	68.7	72.7
COE, Constant $, (Reference)	-	46.7	52.0

Note 1. Expressed in current $ in columns two and three.

The COE calculated by Foster Wheeler in the first column follows EPRI TAG methodology, but was accomplished without the benefit of the spreadsheet supplied by METC. Values for *total capital requirement, fuel cost,* and *operation & maintenance* are those determined by Foster Wheeler. Levelizing factors and the resultant COE are also exactly as determined by Foster Wheeler. The COE calculation summarized in the second column is the same data adjusted to spreadsheet methodology as is described in this section. In column three, the costs presented in column two are adjusted for escalation per EPRI TAG guidelines. Detail spreadsheet output for each COE calculation summary above are given in Appendix A.

This COE information presented in the second and third columns is in *Current $* from the spreadsheets. *Current dollar* analysis includes the effect of inflation and *real escalation*. *Real escalation* is the annual rate of increase, or decrease, of an expenditure due to factors such as resource variation, demand fluctuation, and changes in design or manufacturing. Real escalation does not include inflation. The main reasons for the differences between the costs given by Foster Wheeler for the base costs, column 1 above, and the costs calculated by the spreadsheet, column 2 above, are given below.

- *Project contingency* is 15% of *process plant cost* plus *general plant facilities* plus *engineering* plus *process contingency* in the Foster Wheeler study. In the Lotus spreadsheet, based on the 1986 EPRI TAG, *project contingency* is a percentage of *process plant cost* plus *general plant facilities* only.

- Capital cost for spares was not detailed in the Foster Wheeler, base costs, but added into subsequent costing at 0.5% of the *total plant cost* per the spreadsheet.

- The cost for *operation & maintenance* in column 2, above, is increased by the cost of *insurance & local taxes* at 2% of the *total plant cost* ($8,086,000) and by *other operating costs* ($901,000) which is a function of *operation labor* and *maintenance costs* in the spreadsheet.

- Although there is difference in tax life and tax rates between the Foster Wheeler study and the spreadsheet, this does not account for the different levelizing factors used in the calculation of the COE. Tenth year levelized dollars is used in the spreadsheet calculation: whereas, the Foster Wheeler study uses first year levelized costs.

Escalated plant costs, summarized in Table 36, column 3, were attained by applying the *Chemical Engineering Plant Cost Index* to applicable plant sections and by applying escalation factors recommended by the 1989 EPRI TAG to portions of the annual operating costs. The *Chemical Engineering Plant Cost Index* for December, 1987 is 332.5 and the value for December, 1991 is 359.3. Not all items in the *total capital requirement* (TCR) are adjusted by this index, as some items are factored from other costs. Inflation used in the calculation of levelizing factors is 4%, and the *real escalation rate* (over inflation) for fuel is 0.7% per year as recommended in the spreadsheet.

The annual operating costs are taken from the 1989 EPRI TAG if listed, and from the Foster Wheeler report otherwise. Inflation applied to the operating costs is 5% as recommended by the 1989 EPRI TAG. Note that while the methodology used in the calculation of the COE is based on the 1986 EPRI TAG, escalation of some of the operation costs and fuel costs is based on the 1989 edition of the EPRI TAG. The operating costs are summarized on Table 37.

5.2.2 KRW Gasifier Based Power Plant

On Table 38, the COE results are compared for the 100 MWe, KRW air blown gasifier. These values are based on the gasifier plant utilizing a ceramic cross-flow filter. The base costs derived by Westinghouse, in 1986 dollars, are presented for the gasifier in the first column. In the second column, the Westinghouse costs are adjusted to comply with 1986 EPRI TAG methodology programmed into the spreadsheet. The third column presents costs adjusted for escalation to December, 1991. The COE information presented is in *current dollars* from the spreadsheets.

Table 37 Second Generation PFB Annual Operating Costs

Item	Base Unit Cost $	Source	No. Years Inflation @ 5%/yr	Unit Cost Dec, 1991 $
Plant Labor	20.0/hr	EPRI TAG	3	23.15/hr
Coal[1]	44.57/ton	F-W/ TAG	3	51.60/ton
Raw Water	0.60/kgal	EPRI TAG	3	0.69/kgal
Dolomite	17.90/ton	F-W	4	21.76/ton
H20 Makeup/Trt.	0.14/lb	F-W	4	0.17/lb
Liquid Effluent	0.10/lb	F-W	4	0.12/lb
Fuel oil	0.53/gal	EPRI TAG	3	0.61/gal
Gases, N2 etc.	0.29/100 scf	F-W	4	0.35/100 scf
Waste Disposal	8.00/ton	EPRI TAG	3	9.26/ton

Note 1. Pittsburgh No. 8 coal. F-W = Foster Wheeler.

The COE calculated by Westinghouse in the first column follows EPRI TAG methodology, but was accomplished without the benefit of the spreadsheet supplied by METC. Values for *total capital requirement*, *fuel cost*, and *operation & maintenance* are those determined by Westinghouse. Levelizing factors and the resultant COE are also exactly as determined by Westinghouse. The COE calculation summarized in the second column uses the same data adjusted to appropriate spreadsheet methodology as is described in this section. In column three, the costs presented in column two are adjusted for escalation per EPRI TAG guidelines. Detail spreadsheet output for each COE calculation summary above are given in Appendix A.

The main reasons for the differences between the costs given by Westinghouse for the base costs, column 1, Table 38, and the costs calculated by the spreadsheet, column 2, are given below.

- Adjusting the *total capital requirement* between the Westinghouse base costs and the EPRI TAG methodology involves separate calculations for some items grouped together by Westinghouse. A single value is reported by Westinghouse for *allowance for funds used during construction* (AFUDC), *working capital*, etc. ($22,005,000). The spreadsheet breaks out costs for *royalties, start-up costs, spare parts*, and *working capital*. Also the spreadsheet uses a separate calculation for AFUDC and lists this as *adjustment for interest and inflation* during the construction period. The total of these values is calculated by the spreadsheet ($26,935,000).

Table 38 KRW Gasifier Power Plant
Cost of Electricity - Comparisons

Parameter	Westinghouse Base Cost (Dec 1986)	Adjusted to EPRI TAG 10th yr. Levelize	Escalation Included (DEC 1991)
Total Capital Req'mt, K$	203,514	208,253	245,745
Fuel Cost, K$	9,685	6,508	7,534
Operating & Maint., K$	11,090	15,016	18,234
Levelizing Factors[1]			
Capital Carrying Chrg	0.223	0.175	0.175
Fuel	1.0	1.244	1.244
Oper. & Maint.	1.75	1.202	1.202
Cost of Electricity[1], mills/kWh			
Capital Charges, mills/kWh	79.7	65.1	76.8
Fuel Costs, mills/kWh	17.0	14.2	16.5
Oper. & Maint., mills/kWh	19.5	31.7	38.5
Total Cost of Electricity, (COE)[1]	116.2	111.0	131.7
COE, Constant $, (Reference)	-	76.4	90.8

Note 1. Expressed in current $ in columns two and three.

- Coal cost used by Westinghouse was \$1.89/MMBtu for Illinois No. 6. This was changed the \$1.27/MMBtu as listed in the 1989 EPRI TAG.

- The spreadsheet adds funds for *insurance & local taxes* (\$3,385,000), *royalties* (\$65,000), and *other operation costs* (\$603,000) which do not appear in the Westinghouse estimate.

- Different levelizing factors are used by the calculation of COE as shown in Table 38. The spreadsheet used 10th year levelized dollars.

Escalated plant costs for the gasifier plant, summarized in Table 38, column 3, were attained by applying the *Chemical Engineering Plant Cost Index* to applicable plant sections, and by applying escalation factors recommended by the EPRI TAG to the annual cost parameters. First, escalation added in the Westinghouse study to adjust costs from 1981 to 1986, was deducted, then these costs were adjusted to 1991. The *Chemical Engineering Plant Cost Index* for December, 1981 is 297.0 and the value for December, 1991 is 359.3. Not all items in the *total capital requirement* (TCR) are adjusted by this index, as some items are factored from other costs.

The annual costs are taken from the 1989 EPRI TAG. Inflation applied is 5% as generally recommended by the 1989 EPRI TAG. Inflation used in the calculation of levelizing factors is 4% and the *real escalation rate* (over inflation) for fuel is 0.7% per year as recommended in the spreadsheet. These operating costs are summarized in Table 39.

5.3 Granular-Bed Filter Costs

Costs for granular-bed filters for the 452 MWe, second generation PFB combustion plant[2] and the 100 MWe, KRW air blown gasifier plant[3] are presented in this section. The second generation PFBC plant consists of two identical trains of equipment, each having a capacity of 226 MWe and including a CPFBC and a carbonizer. For each CPFBC, there is a granular-bed filter module consisting of four filter vessels serviced by a single media circulation system. There is a granular-bed filter module for each carbonizer consisting of a single filter vessel with a circulation system. The KRW gasifier plant consists of one gasifier serviced by a single granular-bed filter vessel.

5.3.1 Capital Costs of Granular-Bed Filters

Table 40 presents a summary of granular-bed filter equipment for each plant with costs in thousands of dollars. Costs for the circulation system, pressure vessels and piping are grouped together under the single classification "vessels/piping". For the CPFBC filter, ducting is included within the envelope of the equipment. Ducting for the other filters was judged equivalent to the ducting for the cross-flow filters in the original studies and for the candle filters. Therefore it cancels out of the comparison. Ash systems are presented in more detail in another section. For reference, sizes and weights of this equipment is given is Section 3, Tables 22, 23, and 24.

Table 39 KRW Gasifier Plant Annual Operating Costs

Item	Base Unit Cost $	Source	No. Years Inflation @ 5%/yr	Unit Cost Dec, 1991 $
Plant Labor	20.0/hr	EPRI TAG	3	23.15/hr
Coal[1]	1.27/MMBtu	EPRI TAG	3	1.47/MMBtu
Raw Water	0.60/k gal	EPRI TAG	3	0.69/k gal
Catalyst & Chem	100/ton	Note 2	4	$127.63/ton
Sulfur	81.8/ton	EPRI TAG	3	94.69/ton
Waste Disposal	8.00/ton	EPRI TAG	3	9.26/ton

Notes:

1. Illinois No. 6 coal.
2. A variable operating cost of $455,000 was given by Westinghouse which was arbitrarily priced at $100/ton for this spreadsheet. This manipulation was done so some of this material would be recognized by the spreadsheet as "consumable inventory" which is part of "Working Capital". The unit cost chosen does not affect the COE unless it is zero.

5.3.2 Maintenance Costs

Annual maintenance costs are determined as a percentage of the *total installed cost* of the filter system plus the cost of replacing systems expected to have a short life. The EPRI TAG procedure recommends maintenance costs ranging from 3% to 6% of the installed cost for processes handling solids at high temperature and pressure. Four percent is used in this study since the maintenance cost of major pieces of equipment needing periodic replacement are added to this base maintenance cost. For the granular-bed filter, three areas are identified that will require periodic replacement. The bags in the pressurized baghouse are recommended for replacement on a yearly basis by the vendor. The lift pipe liner is assumed to need replacement every three years, based on the limited data from testing at NYU, and the filter internals for the carbonizer and gasifier are assumed to need replacement every five years, based on corrosion rates for metals in high temperature, reducing atmospheres. Table 41 shows the maintenance costs for each filter application. The basis for the yearly maintenance cost includes capital and installation costs for the base maintenance but only capital cost for lift pipe lining, baghouse bags, and filter internals. The rational is that labor for these additional items is accounted for in the percentage for base maintenance. A 40/60 split between maintenance labor and materials is shown as proposed by the EPRI TAG.

Table 40 Granular-Bed Filter Capital Costs

Filter Plant	CPFBC Filter		Carbonizer Filter		Gasifier Filter	
Plant Capacity, MWe	452		452		100	
Filter Components	Qty	Cost k$	Qty	Cost k$	Qty	Cost k$
Filter Vessels	8	4,031	2	460	1	405
Filter Internals	8	2,121	2	186	1	99
Vessel Refractory	2 Lot	1,647	2 Lot	232	1 Lot	116
Filter Media	2 Lot	2,070	2 Lot	237	1 Lot	119
Circulation System						
Vessels/Piping	-	2,476	-	1,182	-	666
De-Entrain. Ves.	2	incl	2	incl	1	incl
Refr./Internals	2	incl	2	incl	1	incl
Media Valve	2	incl	2	incl	1	incl
Refr./Internals	2	incl	2	incl	1	incl
Media Makeup Hpr.	2	incl	2	incl	1	incl
Refractory	2	incl	2	incl	1	incl
Refr Lined Pipe	2	incl	2	incl	1	incl
Piping/Valves	2 Lot	incl	2 Lot	incl	1 Lot	incl
Media Add Hopper	2	incl	2	incl	1	incl
Insulation	2 Lot	incl	2 Lot	incl	1 Lot	incl
Regen. Ht. Exch.[1]	16	5,412	16	1,224	8	873
Water-cooled Hx	2	81	2	32	1	19
Baghouse	2	412	2	137	1	78
Boost Blower	2	595	2	284	1	88
Maintenance Blr	4	499	2	98	1	49
Access/Support Stl.	2 Lot	1,551	2	450	1	213
Foundation Mat'l	2 Lot	56	2 Lot	28	1 Lot	10
Instr/Controls	2 Lot	200	2 Lot	148	1 Lot	74
Inlet/Outlet Duct	2 Lot	3,062	N/A	-	N/A	-
Ash System	2 Lot	275	2 Lot	168	1 Lot	87
Erection	2 Lot	1,160	2 Lot	442	1 Lot	217
Engineering Fee	-	949	-	377	-	561
Freight	2 Lot	743	2 Lot	166	1 Lot	102
Total		27,340		5,851		3,775

Note 1. Eight sections for each 226 MWe module for the CPFBC and carbonizer filter.

Table 41 Annual GBF Maintenance Costs
(in Thousands of Dollars)

Maintenance Item	CPFBC Filter	Carbonizer Filter	KRW Gasifier Filter
Plant Output (Ref), MWe	452	452	100
Base Maintenance Cost (4% of Installed Cost)	969	232	129
Lift Pipe Replacement (Assumes Lift Pipe Liner is Replaced Every 3 Years)	35	14	7
Yearly Bag Replacement	36	8	4
Metal Filter Internals (Assumes Replacement Every 5 Yrs. in reducing atm.)	-	32	17
Total Yearly Maintenance, k$	1040	286	156
Labor Maintenance Cost, k$	416	114	62
Mat'ls Maintenance Cost, k$	624	172	94

5.3.3 Operating Labor Costs

Both the Foster Wheeler CPFBC study and the Westinghouse gasifier study determine the total number of personnel needed to operate the entire plant. No differentiation is made regarding which equipment and duties are assigned to a given operator so that is not possible to determine the number of personnel assigned to the hot gas clean up equipment.

Combustion Power Co. has extensive experience with a commercial product line of granular-bed filters in applications operating around 450°F. In our many contacts with plants that have operated these devices, it was never considered that the number of personnel needed to operate these filter was any different from that required to operate a baghouse or an electrostatic precipitator. Consequently, no change will be made to number of plant operating personnel because the ceramic cross-flow filter is exchanged for a granular-bed filter. We assumed that the cross-flow filter, the granular-bed, and the candle filter require the same number of operating personnel.

5.3.4 Utility Requirements

The Table 42 shows the utility requirements and media replacement rates for granular-bed filter modules for the CPFBC, carbonizer and gasifier. Electric power is used by the boost blowers and water circulation pumps. Compressed air is used to back-pulse the baghouse used with the CPFBC filter (35 scfm each baghouse, per vendor[5]) and for instrument air. Nitrogen is used to back-pulse the baghouse used with the carbonizer and gasifier filters (20 scfm each baghouse, per vendor[5]) and to purge pressure sense lines in dirty gas streams. Nitrogen is also used to purge the ash depressurizing vessel on the gasifier filter (60 scfm). Cooling water is used in the water-cooled heat exchanger to cool the recirculation gas before entering the boost blower. It is assumed that the plant circulating water system handles this utility. This cooling water could be incorporated into the steam cycle; although this is not the assumption in this study.

Table 42 Granular-Bed Filter Utility Requirements

Utility	CPFBC Filter	Carbonizer Filter	KRW Gasifier Filter
Plant Output (Ref), MWe	452	452	100
Operating Hp			
Boost Blowers, bhp	584	98	35
Electrical Load, kVa			
Boost Blowers[1]	335	56	20
Cooling Water[2]	14.4	3	2.3
Hopper Heaters[3]	3	2	2
Compressed air, scfm	78	8	4
Cooling water[1], gpm	600	124	95
Media (estimate), lb/hr	22	4	2
Nitrogen, scfm	none	80	100

Notes:

1. Assuming 460-3-60, 0.80 power factor, 0.94 efficiency.
2. Water-cooled heat exchangers.
3. During start-up only.

5.3.5 Consumables Operating Costs

Costs for power plant consumables are shown on Table 37 for the second generation PFB combustion plant and on Table 39 for the KRW gasifier based plant. The granular-bed filter uses relatively few consumables. Table 42 shows the utility requirements which also corresponds to the consumable for the GBF. The replacement media costs $.45 per pound. The compressed air requirements are so low that they are included as part of the general compressed air requirements of the plant. Cooling water flows are low compared to the condenser requirements so that the only charge for cooling water is the pumping cost to deliver the cooling water. It was assumed that the cooling water would be pumped to 50 psi. The power consumption in Table 42 may be added to power requirements to overcome filter pressure drop, giving the following total parasitic power for the combustor, carbonizer and gasifier filters.

Attempts have been made to measure the attrition of the dense ceramic filter media utilized in the granular-bed filter. These attempts have been unsuccessful; mainly, because the attrition rate is so small that no values have been produced in the test periods undertaken. Nevertheless, an initial estimate has been made equal to 10% of the media replacement rate which occurred in Combustion Power's commercial granular-bed filters which used natural occurring stone as media. It is expected that the attrition rate for the ceramic media used in the high temperature filter will be much lower than the river gravel used in the low temperature granular-bed filters.

A comparison of the operating cost of different filter types requires a means of accounting for the effects of different filter pressure drops and heat losses. The assumption is made that the process can be adjusted to maintain a constant turbine inlet pressure and temperature regardless of the pressure drop or heat loss from a filter. The cost of different filter pressure drops would be accounted for by the change in compressor power needed to provide for filter pressure drop. Filter heat loss is made up for by firing additional coal. Adjusting the amount of fuel gas produced by the carbonizer or the gasifier provides a means of maintaining a constant turbine inlet temperature.

The pressure drop for the filters used in the second generation PFB combustion plant is compared to the pressure drop of the Westinghouse cross-flow filter. The difference in compressive power corresponding to the difference in pressure drop is either added or subtracted from the net power generated, thus accounting for filter pressure drop on cycle performance. In addition to the change in power due to filter pressure drop, there is also a change of heat input because of the heat associated with the gas compression. Both the change in power and heat input associated with different filter pressure drops are taken into account.

Heat losses are accounted for by firing additional coal to make up for the heat loss by the filter. The calculations use the lower heating value of the coal, 11970 Btu/lb, in determining the amount of coal to be fired to make up for the lost heat. Since the filter heat loss is a small fraction of the total heat input, the additional coal firing will not significantly effect mass flow or equipment size. Secondary effects associated with the firing of additional coal are not be taken into account. The firing of additional coal to make up for filter heat losses is factored into the cost of electricity.

- **CPFBC Granular-Bed Filter**

The pressure drop of the CPFBC granular-bed filter (GBF) is 2.97 psi. The cross-flow filter has a projected pressure drop of 1.5 psi so that the outlet pressure of the turbine compressor must be increased by 1.47 psi. The efficiency of the turbine compressor used in the PFBC study was calculated by matching the compressor inlet and outlet conditions assuming an adiabatic compression. The compressor efficiency is 87.835%. Corresponding to the 1.47 psi increase in pressure, the compressor power increases 1.007 MWe. The heat associated with the additional compression is 3.255 MMBtu/hr. As result of the higher pressure drop through the combustor GBF, the net power is reduced by 1.007 MWe and the coal consumption is reduced by .135 tons/hr.

The temperature drop through the CPFBC granular-bed filter is expected to be 20°F. This is due to radiation heat loss through the shell of the filter and auxiliary equipment, and due to heat lost from the system from the water-cooled heat exchanger. This corresponds to a heat loss of 15.1 MMBtu/hr. In order to make up for the heat loss an additional 0.630 tons/hr of coal will need to be fired. This is offset by the heat due to additional compression; such that, the net additional coal firing is 0.495 ton/hr.

- **Carbonizer Granular-Bed Filter**

The carbonizer has a boost compressor which raises the pressure of the gas which flows through the carbonizer train. The boost compressor is supplied with air from the turbine compressor which also supplies air for the PFB combustor. If the turbine compressor raises the pressure of the main air flow because of the additional pressure drop through the PFB combustor filter, then the boost compressor on the carbonizer will provide a lower increase in pressure because its supply is at a higher pressure. The expected pressure drop through the GBF associated with the carbonizer is 1.34 psi. The pressure drop through the cross-flow carbonizer filter was 1.5 psi. As a result of the lower pressure drop through the carbonizer GBF and the increased inlet pressure to the boost compressor, the pressure drop across the boost compressor is reduced by 1.63 psi. The power consumed by the boost compressor is reduced by 0.173 MWe and the corresponding loss of heat of compression is 0.56 MMBtu/hr. Corresponding to the loss of heat of compression, 0.023 tons/hr of additional coal will be needed to be fired.

The temperature drop through the GBF associated with the carbonizer is 34°F. The corresponding heat loss is 2.72 MMBtu/hr which correspond to an increase in coal rate of 0.113 tons/hr. This is offset by the heat due to additional compression such that the net additional coal firing is 0.137 ton/hr.

- **Combined Effects for CPFB Combustor and Carbonizer**

In order to account for the heat loss and pressure drop of the GBF's used with the PFBC filters when compared to the cross-flow filter, the net power should be reduce by 0.835 MWe and the coal firing rate increased by 0.632 tons/hr.

- **KRW Gasifier Granular-Bed Filter**

The air flow to the gasifier is raised in pressure by a boost compressor which provides for the pressure drop through the gasifier and for the hot gas clean-up (HGCU) system. The Westinghouse study did not provide complete information on the gasifier based power plant; therefore, several assumptions were made to evaluate the effects of filter pressure drop on system performance. It was assumed that the pressure drop through the gasifier is 10% of the system pressure. Correspondingly, the boost compressor will boost the air to the gasifier from 385 psia to 425 psia plus the pressure drop through the hot gas cleanup device. Based on the nitrogen content of the gas entering the filter, the air flow through the boost compressor is estimated to be 146,000 lb/hr. In addition to the boost compressor for the process air to the gasifier there is also a boost compressor for the recycle gas which recycles 49,700 lb/hr of gas. The recycle boost compressor must make up for the pressure drop through the cyclones, the hot gas filter and the zinc ferrite system. It is estimated that the pressure drop through the recycle boost compressor is 7.5 psi plus the pressure drop through the hot gas filter.

The pressure drop through the gasifier GBF is estimated to be 1.31 psi. The incremental power to the air boost blower is 0.007 MWe and the incremental power to the recycle compressor is 0.003 MWe. The heat of compression for the two compressors is 0.032 MMBtu/hr, reducing the coal input by 0.001 tons/hr.

The temperature drop through the GBF associated with the gasifier is 35°F which corresponds to a heat loss of 3.90 MMBtu/hr or 0.163 tons/hr of coal. The net result of the pressure drop and heat loss from the GBF when compared to the cross-flow filter proposed for the gasifier, is a reduction of power of 0.010 MWe and a 0.162 tons/hr increase in coal usage.

5.4 Ceramic Candle Filters Costs

Costs for candle filters for the 452 MWe, second generation PFB combustion plant and the 100 MWe, KRW air blown gasifier plant are presented in this section. The second generation PFB combustion plant consists of two identical trains of equipment, each having a capacity of 226 MWe and including a CPFBC and a carbonizer. For each CPFBC, there is a ceramic candle filter module consisting of four filters that dispenses ash to the same ash collecting system proposed for the cross-flow filters. There is a ceramic candle filter module for each carbonizer consisting of a single filter vessel with no ash handling system; since, the downstream equipment processes the hot ash at pressure according to the Foster Wheeler study. The KRW gasifier plant consists of a gasifier serviced by a ceramic candle filter vessel.

5.4.1 Capital Costs of Candle Filters

Table 43 presents candle filter equipment for each plant with costs in thousands of dollars. Filter internals includes the tubesheet, tubesheet support, gas baffling, element hold downs and gaskets. The pulse gas system is broken into two categories, "piping & valves" and "compressors". The items included in each category is listed under each heading. Note that the CPFBC filter does not need a pulse gas boiler/cooler because the source air is at a suitable temperature. For the CPFBC filter, ducting is included within the envelope of the equipment. Ducting for the other filters was judged equivalent to the ducting for the cross-flow filters in the original studies and for the candle filters.

Table 43 Ceramic Candle Filter Capital Costs

Filter Plant	CPFBC Filter		Carbonizer Filter		Gasifier Filter	
Plant Capacity, MWe	452		452		100	
Filter Components	Qty	Cost k$	Qty	Cost k$	Qty	Cost k$
Filter Vessels	8	5,385	2	972	1	738
Filter Internals	8	7,142	2	761	1	340
Tubesheet/Suppt.	8	incl	2	incl	1	incl
Baffling	8	incl	2	incl	1	incl
Elem't Holddown	12,576	incl	2,260	incl	906	incl
Vessel Refractory	2 Lot	2,135	2 Lot	489	1 Lot	182
Filter Elements	12,576	3,447	2,260	784	906	314
Pulse Gas System						
Piping/Valves	1 Lot	5,847	1 Lot	1,181	1 Lot	506
High Alloy Pipe	8 Lot	incl	2 Lot	incl	1 Lot	incl
Carbon Stl Pipe	2 Lot	incl	2 Lot	incl	1 Lot	incl
Pulse Valves	288	incl	52	incl	20	incl
Auto Isolat'n Vlvs	864	incl	156	incl	60	incl
Hand Valves	2 Lot	incl	2 Lot	incl	1 Lot	incl
Secondary Reserv.	16	incl	4	incl	2	incl
Compressors	2 Lot	1,108	2 Lot	771	1 Lot	542
Pulse Gas Blr/Clr	N/A	-	2	incl	1	incl
Pulse Gas Compr.	2	incl	2	incl	1	incl
Std-by Compr.	1	incl	1	incl	1	incl
Instr/Controls	2 Lot	196	2 Lot	93	1 Lot	50
Inlet/Outlet Duct	2 Lot	3,730	-	-	-	-
Access/Support Stl.	2 Lot	1,486	2	450	1	113
Foundation Mat'l	2 Lot	42	2 Lot	19	1 Lot	8
Ash System[1]			None			
Vessels/Pipe	2 Lot	390	-	-	1 Lot	31
Ash Coolers	4	919	-	-	1	570
Ash Valves	2 Lot	1,436	-	-	1 Lot	74
Erection	2 Lot	2,871	2 Lot	698	1 Lot	300
Freight	2 Lot	1074	2 Lot	200	1 Lot	130
Engineering	-	949	-	377	-	561
Total		38,187		6,795		4,458

Therefore it cancel out of the comparison. In the estimate for the KRW gasifier, all engineering for individual systems in included in the equipment price. The amount for engineering is the same as estimated for the granular-bed filter. For reference, sizes and weights of this equipment is given is Section 4, Tables 32, 33, and 34.

5.4.2 Maintenance Costs

Annual maintenance costs are determined as a percentage of the total installed cost of the filter system plus the cost of replacing systems expected to have a short life. The EPRI TAG procedure recommends maintenance costs ranging from 3% to 6% of the installed cost for processes handling solids at high temperature and pressure. Four percent is used in this study since the maintenance cost of major pieces of equipment needing periodic replacement are added to this base maintenance cost.

For the ceramic candle filters, three areas are identified that will require periodic replacement. It is assumed that filter elements will need replacement every three years. This is based on knowledge of the types of guarantees that suppliers of candle filter elements will offer (1 year) and the statistical study presented by Westinghouse for the cross-flow filter elements in the Foster Wheeler report (5 years). Solenoid pulse valve and isolating ball valve replacement is at 10% and 5% per year based on the high number of cycles. The filter internals for the carbonizer and gasifier are assumed to need replacement every five years, based on corrosion rates for metals in high temperature, reducing atmospheres. Table 44 shows the maintenance costs for each filter application. The basis for the yearly maintenance cost includes capital and installation costs for the base maintenance but only capital cost for filter elements, tubesheet components, and valves. The rational is that labor for these additional items is accounted for in the percentage for base maintenance. A 40/60 split between maintenance labor and materials is shown as proposed by the EPRI TAG.

5.4.3 Operating Labor Costs

Both the Foster Wheeler CPFBC study and the Westinghouse gasifier study determine the total number of personnel needed to operate the entire plant. No differentiation is made to which equipment and duties are assigned to a given operator, so that is not possible to determine the number of personnel assigned to the hot gas clean up equipment. Consequently, no change will be made to number of plant operating personnel because the ceramic cross-flow filter is exchanged for a candle filter. We assumed that the cross-flow filter, the granular-bed, and the candle filter require the same number of operating personnel.

5.4.4 Utility Requirements

The Table 45 shows the utility requirements for candle filter modules for the CPFBC, carbonizer and gasifier. Equipment vendors provided the electric power consumption for the pulse gas compressors and pulse gas refrigerated dryers for the

CPFBC, carbonizer and gasifier filters. Ash cooling screws used in the CPFBC and gasifier candle filter systems are the same as proposed for the cross-flow filters in the base studies. Electric power consumption for the ash screws were provided by qualified vendors based on specifications prepared from the base studies. The ash cooling screw on the gasifier candle filter has a closed loop water circulation system that requires use of a water circulation pump that is included with the ash screw.

Table 44 Annual Candle Filter Maintenance Costs (in Thousands of Dollars)

Maintenance Item	CPFBC Filter	Carbonizer Filter	KRW Gasifier Filter
Plant Output (Ref), MWe	452	452	100
Base Maintenance Cost (4% of Installed Cost)	1,377	271	156
Ceramic Filter Elements (Assumes 1/3 Elements are Replaced Each Year)	985	222	89
Pulse Valves (@ 10% per year)	82	15	6
Ball Valves, Isolation (@ 5% per year)	78	14	5
Metal Filter Internals (Assumes Replacement Every 5 Yrs. in reducing atm.)	-	97	44
Total Yearly Maintenance, k$	2522	619	300
Labor Maintenance Cost, k$	1009	248	120
Mat'ls Maintenance Cost, k$	1513	371	180

Cooling water is used in the pulse gas compressors of all three filter systems and in the ash cooling screws of the CPFBC and carbonizer filters. It is assumed that the plant cooling water system handles this utility. Boiler feedwater is used to cool process gas for use as pulse gas on the carbonizer and gasifier filters. It is assumed that the plant boiler water system handles this utility. No attempt was made to incorporate the heat lost in the cooling water or the boiler into the steam cycle.

5.4.5 Consumables Operating Costs

Costs for power plant consumables are shown on Table 37 for the second generation PFB combustion plant and on Table 39 for the KRW gasifier based plant. The ceramic candle filter uses relatively small amounts of various consumables. Table 45 shows the utility requirements which also corresponds to the consumables for the candle filter. The compressed air requirements are so low that they are included as part of the general compressed air requirements of the plant. Cooling water and boiler feedwater flows are low compared to the condenser requirements so that the only charge for cooling water is the pumping cost to deliver the cooling water. Assumptions for cooling water pressure are included on Table 45. The power consumption in Table 45 may be added to power requirements to overcome filter pressure drop, giving the following total parasitic power for the CPFBC, carbonizer and gasifier candle filters.

A comparison of the operating cost of different filter types requires a means of accounting for the effects of different filter pressure drops and heat losses. The assumption is made that the process can be adjusted to maintain a constant turbine inlet pressure and temperature regardless of the pressure drop or heat loss from a filter. The cost of different filter pressure drops can be accounted for by the change in compressor power needed to provide for filter pressure drop. Filter heat loss is made up for by firing additional coal. Adjusting the amount of fuel gas produced by the carbonizer or the gasifier provides a means of maintaining a constant turbine inlet temperature.

The pressure drop for the candle filters used in the second generation PFBC is compared to the pressure drop for the Westinghouse cross-flow filter. The difference in compressive power corresponding to the difference in pressure drop is either added or subtracted from the net power generated, thus accounting for filter pressure drop on cycle performance. In addition to the change in power due to filter pressure drop, there is also a change of heat input because of the heat associated with the gas compression. Both the change in power and heat input associated with different filter pressure drops are taken into account.

Heat losses are accounted for by firing additional coal to make up for the heat loss by the filter. The calculations use the lower heating value of the coal, 11970 Btu/lb, in determining the amount of coal to be fired to make up for the lost heat. Since the filter heat loss is a small fraction of the total heat input, the additional coal firing will not significantly effect mass flow or equipment size. Secondary effects associated with the firing of additional coal will not be taken into account. The firing of additional coal to make up for filter heat losses is factored into the cost of electricity.

- **CPFBC Candle Filter**

The pressure drop of the CPFBC candle filter is 2.66 psi. The cross-flow filter has a projected pressure drop of 1.5 psi so that the outlet pressure of the turbine compressor must be increased by 1.16 psi. The efficiency of the turbine compressor used in the PFBC study was calculated by matching the compressor inlet and outlet conditions assuming an adiabatic compression. The compressor efficiency is 87.835%. Corresponding to the

1.16 psi increase in pressure, the compressor power increases 0.799 MWe. The heat associated with the additional compression is 2.56 MMBtu/hr. As result of the higher pressure drop through the CPFBC candle filter, the net power is reduced by 0.799 MWe and the coal consumption is reduced by .107 tons/hr.

Table 45 Candle Filter Utility Requirements

Utility	CPFBC Filter	Carbonizer Filter	KRW Gasifier Filter
Plant Output (Ref), MWe	452	452	100
Operating Hp			
Pulse Gas Compr., bhp	474	200	126
Ash Screw, bhp	30	-	5
H20 Circ. Pump, bhp[4]	-	-	1.2
Pulse Gas Dryer, bhp	40	10	8
Electrical Load, KVa			
Pulse Gas Compr.[1]	272	115	72
Cooling Water[2]	1.4	1.6	1.4
Ash Screw[1]	17	-	3
H20 Circ. Pump[4]	-	-	0.7
Cooling Water	4.7[(3)]	-	1.8[(2)]
Pulse Gas Dryer	23	6	4.5
Boiler Feedwater	-	.2	.2
Compressed air, scfm	-	8	4
Cooling water			
Compressors, gpm[5]	58	68	57
Boiler, gpm	-	5	5
Ash Screw, gpm	73	-	76
Nitrogen, scfm	-	8[(6)]	67[(7)]

Notes:

1. Assuming 460-3-60, 0.80 power factor, 0.94 efficiency.
2. Assuming 50 psig, 70% pump eff; see also note 1.
3. Assuming 135 psig, 70% pump eff; see also note 1.
4. Assuming 25 psi, 380°F water, 70% pump eff; see also note 1.
5. Precoolers, compressors & aftercoolers
6. Purging of instrument pressure taps only
7. Purging of instrument pressure taps and pressurizing ash lock hopper during ash depressurization cycle

The temperature drop through the CPFBC candle filter is expected to be 12°F. This is due to radiation heat loss through the shell of the filter, and due to dilution of the combustion gases by pulse air. Heat loss is due to the radiation heat losses only, and amounts to 3.94 MMBtu/hr. Pulse air simply enters the system as excess combustion air in a different location. In order to make up for the heat loss, an additional 0.165 tons/hr of coal will need to be fired. This is offset by the heat due to additional compression such that the net additional coal firing is 0.058 ton/hr.

- **Carbonizer Candle Filter**

The carbonizer has a boost compressor which raises the pressure of the gas which flows through the carbonizer train. The boost compressor is supplied with air from the turbine compressor which also supplies air for the CPFB combustor. If the turbine compressor raises the pressure of the main air flow because of the additional pressure drop through the CPFB combustor filter, then the boost compressor on the carbonizer will provide a lower increase in pressure because its supply is at a higher pressure. The expected pressure drop through the candle filter associated with the carbonizer is 1.96 psi. The pressure drop through the cross-flow carbonizer filter was 1.5 psi. As a result of the higher pressure drop through the carbonizer candle filter and the increased inlet pressure to the boost compressor, the pressure drop across the boost compressor is reduced by 0.70 psi. The power consumed by the boost compressor is reduced by 0.123 MWe and the corresponding loss of heat of compression is 0.398 MMBtu/hr. Corresponding to the loss of heat of compression, 0.017 tons/hr of additional coal will be needed to be fired.

The temperature drop through the candle filter associated with the carbonizer is 27°F. This is due to radiation heat loss through the shell of the filter vessel and from cooling process gas for use as pulse gas. The corresponding heat loss is 2.19 MMBtu/hr which correspond to an increase in coal rate of 0.091 tons/hr. This is increased by the heat due to additional compression such that the net additional coal firing is 0.108 ton/hr.

- **Combined Effects for CPFB Combustor and Carbonizer**

In order to account for the heat loss and pressure drop of the candle filters used with the second generation PFB combustion plant in comparison to the cross-flow filters, the net power should be reduce by 0.676 MWe and the coal firing rate increased by 0.166 tons/hr.

- **KRW Gasifier Candle Filter**

The air flow through the gasifier is increased in pressure by a boost compressor which provides for the pressure drop through the gasifier and the HGCU system. The Westinghouse study did not provide complete information on the gasifier based power plant; therefore, several assumptions were made to evaluate the effects of filter pressure drop on system performance. It is assumed that the pressure drop through the gasifier is 10% of the system pressure. Correspondingly, the boost compressor will boost the process air to the gasifier from 385 psia to 425 psia plus the pressure drop through the hot gas cleanup device. Based on the nitrogen content of the gas entering the filter, the air flow through the boost compressor is estimated to be 146,000 lb/hr. In addition to the boost compressor for the air to the gasifier there is also a boost compressor for the recycle gas which recycles 49,700 lb/hr of gas. The recycle boost compressor must make up for the pressure drop through the cyclones, the hot gas filter and the zinc ferrite system. It is estimated that the pressure drop through the recycle boost compressor is 7.5 psi plus the pressure drop through the hot gas filter.

The pressure drop through the candle filter for the gasifier is estimated to be 1.99 psi. The incremental power to the air boost blower is 0.009 MWe and the incremental power to the recycle compressor is.004 MWe. The heat of compression for the two compressors is 0.043 MMBtu/hr, reducing the coal input by 0.002 tons/hr.

The temperature drop through the candle filter associated with the gasifier is 31°F which corresponds to a heat loss of 3.73 MMBtu/hr or 0.156 tons/hr of coal. The net result of the pressure drop and heat loss from the GBF used with the gasifier is a reduction of power of 0.013 MWe and a 0.154 tons/hr increase in coal usage.

5.5 COE Comparison, Second Generation PFBC Combustion Plant

In the Foster Wheeler report on the 452 MWe, second generation PFB combustion plant, equipment costs are broken down by account numbers for cost of electricity (COE) calculations. Hot gas cleanup equipment and piping is summarized in account number 5, and includes the CPFBC filter, carbonizer filter, hot gas ducting, and foundations. Ash handling equipment is contained in cost account number 10 which includes items for the ash and spent sorbent recovery system connected to the filters and connected to other equipment. There is also a separate cost account for instrumentation/control, but since this item was such a small amount for each filter, it was included with the filters. The *bare erected costs* for these items include equipment costs, material costs, and direct and indirect installation labor. Costs for all filter related equipment can be compared at this level, but must be segregated by cost account for further COE calculations because different contingencies apply.

5.5.1 Bare Erected Costs, CPFBC and Carbonizer Filters

Bare erected costs established for the granular-bed and the ceramic candle filters for the CPFBC outlet are compared in Tables 46 and 47 for the CPFBC and the carbonizer filters, respectively. These costs were originally presented separately in sections 5.3 and 5.4. Filter vessels are all estimated at $2.50/lb based on quotes received for shop fabrication. The candle filter vessels are larger, and heavier, than the granular-bed filter vessels. GBF internals are lighter than candle filter internals and are based on fabrication from RA253MA instead of RA333 for the CPFBC filters; although the sensitivity is analyzed in the COE calculation. Costing is at $10.50/lb for the GBF internals and at $20/lb for the candle filter, for the CPFBC based on analysis of quotes received. For the carbonizer filters, internals for the granular-bed and candle filter are estimated assuming fabrication from RA85H. Costing for both sets of internals is assumed at $15/lb, based on analysis of quotes received. Pressure vessel steelwork for all smaller vessels is included at $3.50/lb for both filters. Small fabricated items made from 310 SS sheet or plate for the items such as de-entrainment vessel internals and media valve internals for the granular-bed filter are included at $7.50/lb, again based on quotes. Carbon steel fabricated piping and ducting is $2.50/lb and stainless steel fabricated piping is $10.50/lb. Filter media for the both the CPFBC and carbonizer granular-bed filters is

Table 46 Bare Erected Cost Comparison
CPFBC Filters, 452 Mwe

Granular-Bed Filter System		Candle Filter System	
	$/1000		$/1000
Filter Vessels (8)	4,031	Filter Vessels (8)	5,385
Filter Internals (8)	2,121	Filter Internals (8)	7,142
Vessel Refractory	1,647	Vessel Refractory	2,135
Filter Media	2,070	Filter Elements	3,477
Circulation System		Pulse Back	
Vessels/Piping	2,476	Piping/Valves	5,847
Regen. Ht. Exch.	5,412	Compressors	1,108
Water-Cooled Hx.	81	Ash System	
Baghouse	412	Vessels/Piping	390
Boost/Maint. Blower	1,094	Ash Coolers	919
Instr/Controls	200	Ash Valves	1,436
Inlet/Outlet Ducting	3,062	Instr/Controls	196
Access/Support Steel	1,551	Inlet/Outlet Ducting	3,730
Foundation Mat'l	56	Access/Support Steel	1,486
Ash System	275	Foundation Mat'l	42
Erection	1,160	Erection	2,871
Engineering	949	Engineering	949
Freight	743	Freight	1,074
Bare Erected Cost, k$	27,339	Bare Erected Cost, k$	38,187
Breakdown:		Breakdown:	
Filter Equipment	23,946	Filter Equipment	31,670
Inlet/Outlet Ducting	3,062	Inlet/Outlet Ducting	3,730
Ash System	275	Ash System	2,745
Foundation Mat'l	56	Foundation Mat'l	42

Table 47 Bare Erected Cost Comparison
Carbonizer Filters, 452 Mwe

Granular-Bed Filter System		Candle Filter System	
	$/1000		$/1000
Filter Vessels (2)	460	Filter Vessels (2)	972
Filter Internals (2)	186	Filter Internals (2)	761
Vessel Refractory	232	Vessel Refractory	489
Filter Media	237	Filter Elements	784
Circulation System		Pulse Back	
Vessels/Piping	1,182	Piping/Valves	1,181
Regen. Ht. Exch.	1,224	Compressors	771
Water-Cooled Hx.	32	Ash System	
Baghouse	137	Vessels/Piping	-
Boost/Maint. Blower	382	Ash Coolers	-
Instr/Controls	148	Ash Valves	-
Access/Support Steel	450	Instr/Controls	93
Foundation Mat'l	28	Access/Support Steel	450
Ash System	168	Foundation Mat'l	19
Erection	442	Erection	698
Engineering	377	Engineering	377
Freight	166	Freight	200
Bare Erected Cost	5,851	Bare Erected Cost	6,795
Breakdown:		Breakdown:	
Filter Equipment	5,823	Filter Equipment	6,776
Inlet/Outlet Ducting	-	Inlet/Outlet Ducting	-
Ash System	incl	Ash System	none
Foundation Mat'l	28	Foundation Mat'l	19

estimated at $0.45/lb. Filter elements for the CPFBC and carbonizer candle filters are priced at $235/element and $295/element, respectively. These costs are based on quotations from candle element manufacturers in quantities for each filter application. Other buyout equipment is priced based on quotes from qualified suppliers. Freight is estimated at 4% of the cost of filter items. The refractory contractors estimating factors include freight and installation. Erection for all filters was evaluated by an independent contractor specializing in construction cost estimating. General and administrative costs and allowance for profit is included for all items by dividing costs by 0.85.

5.5.2 Ducting & Foundations

Hot gas piping for the granular-bed, ceramic candle, and cross-flow filter systems was estimated within equivalent envelopes. Identical cost factors were used. The *bare erected cost* for cross-flow filter ducting was estimated at $3,431,000; for the granular-bed filter, $3,062,000; and for the ceramic candle filter $3,730,000. One reason that the ceramic candle filter ducting is the most costly is that the gas outlet elevation is higher in comparison to the granular-bed filter, and it must eventually reach grade level for the gas turbine. The difference between ducting costs in comparison to the cross-flow filter was used as a credit or debit to the hot gas cleanup and piping cost (account no. 5).

The *bare erected cost* for hot gas piping in the Foster Wheeler study was $12,716,000 in December, 1987 dollars. This cost was escalated to December, 1991 by the *Chemical Engineering Plant Cost Index* (359.30/332.50) then adjusted for difference in ducting cost. This value is $13,382,000 for the granular-bed filter plant and $14,050,000 for the candle filter plant.

In a similar manner, the value estimated by Foster Wheeler for foundations was escalated to December, 1991 and adjusted for the difference between the granular-bed and the ceramic candle filter. In this case, mostly because the numbers were fairly small in comparison to others in account no. 5, the cost of the candle filter foundations was assumed equal to the cross-flow filter foundations. The difference between foundations for the granular-bed filters and ceramic candle filters, for both the CPFBC and the carbonizer, was applied to the granular-bed filter plant cost. The bare erected cost for foundations in the Foster Wheeler study was $457,000 in December, 1987 dollars. This was escalated to $494,000 for the candle filter plant, and increased to $516,000 for the granular-bed filter plant.

5.5.3 Ash Systems

The ash handling system for the CPFBC candle filter is almost the same as for the cross-flow filter originally included in Foster Wheeler's pricing. The equipment includes the restricted pipe discharge (RPD) vessels; the downstream, connected ash collecting vessels; the ash coolers; and the associated isolation and control valves. The difference is that because there are eight candle filters where there were four cross-flow filters, four extra ash collection vessels with connecting refractory lined piping are needed to complete the connection with the initial ash handling equipment. Therefore the CPFBC candle filter vessels and ash piping to the first set of ash collecting hoppers (see Figure 64, Section 4) is included with the account number 5, "Hot Gas Cleanup and Piping". There is no ash handling equipment for the carbonizer candle filter; since, it empties directly into a downstream processing vessel. The ash handling equipment for the carbonizer granular-bed filter is a small percentage of the cost; therefore, it is included with the filter (account no. 5) for simplicity. Under these circumstances, the ash handling equipment assigned to account number 10 remains unchanged between the cross-flow and the candle filter. This equipment is simply escalated by the *Chemical Engineering Plant Cost Index.*

For the granular-bed filter, ash cooling screws and hot valving is not needed; since, ash is cooled in the regenerative heat exchanger and discharged at low temperature (500°F). Consequently, ash handling equipment (account no. 10 for the cross-flow filter) is escalated, then reduced by the value of the items needed for the cross-flow/candle filter ($2,745,000) and then increased by the value of the items needed for the granular-bed filter ($275,000). Account number 10 for "Ash/Spent Sorbent Recovery and Handling" includes the ash coolers for the cross-flow or candle filters and the fluidized bed heat exchanger (FBHE), ash depressurization equipment for the FBHE and filters, ash storage silos, ash transport and feed equipment, and associated foundations. The bare erected cost was $7,335,000 in 1987 dollars for the cross-flow filter, and was escalated to $7,926,000 in 1991 dollars. The value of $7,926,000 was used for the account number 10 for the candle filter. This was reduced to $5,456,000 for the granular-bed filter as credit was applied for items not needed. The value of the ash handling equipment for the candle filter was determined by preparing specifications based on the Foster Wheeler study and obtaining quotes from qualified vendors.

5.5.4 Power Plant Maintenance

The Foster Wheeler report used EPRI TAG methodology to estimate the cost of power plant maintenance. For each item in the power plant, maintenance is estimated at a percentage of bare erected cost. Maintenance for the ash/spent sorbent handling system was proposed by Foster Wheeler at 3.2%. With the exception of the value for hot gas cleanup equipment, this value and others proposed by Foster Wheeler were utilized in this study.

Results from maintenance calculations were presented for the CPFBC and the carbonizer filters in Tables 41 and 44 for the granular-bed and ceramic candle filter, respectively. The base maintenance cost of 4% of the bare erected cost is also applied to the remaining items in the hot gas cleanup and piping account; namely, hot gas piping and foundation. For the second generation PFB Combustion plant with granular-bed filters, the maintenance items for account number 5 include the CPFBC filter ($1,040,000), the carbonizer filter ($286,000), the hot gas piping ($535,000), and the HGCU foundations ($21,000). This totals to $1,881,000. Maintenance items for the same plant with ceramic candle filters include the CPFBC filters ($2,522,000), the carbonizer filter ($623,000), the hot gas piping ($562,000), and the HGCU foundations ($19,000). This totals to $3,726,000. These values for maintenance were used to calculate COE.

5.5.5 Cost of Electricity

Costs for HGCU equipment and piping are summarized in Table 48. To the *bare erected cost*, percentages are added for engineering, *process contingency* and *project contingency* to arrive at the *total plant cost* (TPC). Percentages are those proposed by Foster Wheeler. Engineering is added at 6.5% of *bare erected costs*. *Project contingency* is added at 15% of the sum of *bare erected cost* and *general plant facilities*. *Process contingency* is added at 20% of filter costs, but presented as a percentage of *bare erected* *costs* of all items in account number 5. Engineering (6.5%) is for PFBC plant engineering and includes construction management, and home office fees. The cost for engineering services provided by the equipment manufacturers and vendors is included directly in the equipment costs. *Process contingency* is a factor added to account for the uncertainty in technical performance and cost of new technology. Foster Wheeler proposed 20% for the developmental cross-flow filter. This factor was also applied to portions of the granular-bed and the candle filter. In both cases the factor was taken as a percentage of the filter vessel, filter refractory, internals, and filtration elements/media.

In a similar manor, the *bare erected costs* for ash/spent sorbent handling system is factored up to TPC. Engineering is added at 6.5% of bare erected costs. *Project contingency* is added at 15% of *the sum of bare erected cost* and *general plant facilities*. *Process contingency* is added at 50% of items involved with ash depressurization, which apparently averages to 11.8% of the total cost account for ash systems according to the Foster Wheeler report. For simplicity, 11.8% is utilized for both the ceramic candle and the granular-bed filter.

Clearly, the addition of engineering fees and contingencies adds significantly to the cost of the filter plants and the ash handling facilities. The addition to the granular-bed filter module is $25.6/kW, or 26.6% of the bare erected cost. For the candle filter the addition cost is $34.5/kW or 29.5% of the bare erected cost.

To the TPC, additions are made for interest charges and inflation during the construction period, sometimes called allowance for funds used during construction. This yields the value for *total plant investment* (TPI). Foster Wheeler estimated a construction period of 3-1/2 years with an interest rate of 12.5%. These values were used in the updated calculation of COE. To the TPI, values were added according to the Foster Wheeler report for royalties, initial catalyst and chemical inventory, start-up costs, spare parts, working capital, and land. This resulted in the *total capital requirement* (TCR). If a value was included by Foster Wheeler, it was escalated and utilized. Otherwise the default value in the Lotus 1-2-3 program was used. Annual costs include consumables, ash disposal, plant labor, maintenance, insurance, local taxes, royalties, and by-product credits. The annual cost of fuel (coal) is calculated and listed separately. See Section 5.2 for additional explanation on the use of the Lotus 1-2-3, COE calculation program and on the origin of annual cost values. The results presented in Table 49 show that the constant dollar COE for the second generation PFB combustion plant is 52.8 mills/kWh based on granular-bed filters and 54.5 mills/kWh based on ceramic candle filters. This assumes that the parasitic power presented in Tables 42 and 45 is accounted for in the base calculations that arrived at 452.8 MWe because of the cross-flow filter analysis.

If the net power output is adjusted for the parasitic power calculated for the filters there is a slight increase in COE of 0.1 mills/kWh. This increase applies to the second generation PFB combustion plant based on either granular-bed or ceramic candle filters and to either the current or constant dollar COE.

If RA253MA is used for the CPFBC candle filter internals instead of RA333, the COE in both current and constant dollars drops by 0.2 mills/kWh.

If process gas is replaced by nitrogen for candle filter pulse cleaning, the COE increases to 54.8 mills/kWh in constant dollars and 76.9 mills/kWh in current dollars. This change includes capital and operating costs associated with replacing the process gas cooling/compressing equipment with the PSA nitrogen generating system. A 12-hour nitrogen supply is included with the PSA generation system for backup. Values for this adjustment are presented on Table 31, Section 4.

Table 48 Cost Summary, HGCU/Piping & Ash Handling System (1991 Costs in Thousands of Dollars, 452.8 MWe Plant)

Cost Item	Plant with Granular-Bed Filters	Plant with Candle Filters
Hot Gas Cleanup and Piping		
CPFBC Filter Module	23,946	31,670
Carbonizer Filter Module	5,823	6,776
Hot Gas Piping	13,382	14,050
HGCU Foundations	516	494
Bare Erected Cost	43,667	52,989
in $/kW	96.4	117.0
Engineering Fee, 6.5%	2,838	3,444
Process Contingency	2,197	4,229
Project Contingency, 15%	6,550	7,948
Total Plant Cost (TPC), k$	55,252	68,610
Total Plant Cost, $/kW	122.0	151.5
Ash/Spent Sorbent Handling System		
Bare Erected Cost	7,926	5,456
in $/kW	17.5	12.0
Engineering Fee, 6.5%	515	355
Process Contingency	935	644
Project Contingency, 15%	1,189	818
Total Plant Cost (TPC), k$	10,565	7,273
Total Plant Cost, $/kW	23.3	16.1

Table 49 Cost of Electricity Comparison
Second Generation PFB Combustion Plant, 452 MWe

Cost of Electricity - Levelized	Current $ mills/kWh	Constant $ mills/kWh
Granular-Bed Filter		
Capital Charges	36.2	21.3
Fuel Charges	20.3	16.9
Operation & Maintenance	17.6	14.7
Total Cost of Electricity	74.1	52.8
Candle Filter		
Capital Charges	37.2	22.0
Fuel Charges	20.2	16.8
Operation & Maintenance	18.8	15.7
Total Cost of Electricity	76.5	54.5

Tables 50 and 51 present the summary printouts from the Lotus 1-2-3 COE calculation with the assumption presented.

Table 50 COE Calculation, PFB Combustion Plant with GBF

05/07/93 ELECTRIC POWER GENERATION COST - Version 1.12

2ND GENERATION PFB 452 MW POWER PLANT
BASED ON GRANULAR BED FILTERS

CAPITAL REQUIREMENTS (Dec 1991 Dollars)

Total Plant Investment

AREA NO	PLANT SECTION DESCRIPTION	PROCESS CONT, %	COST, K$ W/O CONT
1	COAL AND SORBENT HNDLG	0	$35,404
2	COAL AND SORBENT PREP	3	$22,339
3	FEEDWATER AND MISC BOP SYSTEMS	0	$19,774
4	CARBONIZER, CPFBC & CPFBC FBHE	17	$50,670
5	HOT GAS CLEANUP AND PIPING, GBF	5	$43,667
6	COMBUSTION TURBINE /ACCESSORIES	9	$55,681
7	HRSG, DUCTING AND STACK	13	$26,959
8	STEAM TURBINE GENERATOR	0	$37,050
9	COOLING WATER SYSTEM	0	$9,775
10	ASH / SPENT SORBENT HNDL SYSTEM	12	$5,457
11	ACCESSORY ELECTRIC PLANT	0	$14,131
12	INSTRUMENTATION AND CONTROL	0	$11,502
13	IMPROVEMENTS TO SITE	0	$9,492
14	BUILDINGS AND STRUCTURES	0	$12,283

Subtotal, Process Plant Cost	$354,184
General Plant Facilities	$0
Engineering Fees	$23,022
Process Contingency (Using contingencies listed above)	$21,136
Project Contingency, 15 % Proc Plt & Gen Plt Fac	$53,128
Total Plant Cost (TPC)	$451,470
Plant Construction Period, 3.5 Years (1 or more)	
Construction Interest Rate, 12.5 %	
Adjustment for Interest and Inflation	$48,028
Total Plant Investment (TPI)	$499,498
Prepaid Royalties	$0
Initial Catalyst and Chemical Inventory	$0
Startup Costs	$14,864
Spare Parts	$2,257
Working Capital	$13,527
Land, 200 Acres	$1,500
Total Capital Requirement (TCR)	$531,646

Table 50 COE Calculation, PFB Combustion Plant with GBF (continued)

ANNUAL OPERATING COSTS

Capacity Factor = 65 %

COST ITEM		QUANTITY		UNIT $ PRICE		ANNUAL COST, K$
PITTS NO.8 COAL	Fuel Type	3428.7	T/D	$51.60	/T	$41,971
Consumable Materials						
WATER		5575.0	1000 GAL/	$0.69	/1000 GAL	$919
DOLOMITE		987.8	T/D	$21.76	/T	$5,099
H20 MAKEUP/TREAT		5110.0	LB/D	$0.17	/LB	$206
LIQUID EFF		13520	LB/D	$0.12	/LB	$390
FUEL OIL		4175.0	GAL/D	$0.61	/GAL	$608
GASES N2, ect.		5040	100 SCF/D	$0.35	/100 SCF	$421
Ash/Sorbent Disposal Costs		1093.7	T/D	$9.26	/T	$2,403
Plant Labor						
Oper Labor (incl benef)		26	Men/shift	$23.15	/Hr.	$5,273
Supervision & Clerical						$2,750
Maintenance Costs						$9,734
Insurance & Local Taxes						$9,029
Royalties						$0
Other Operating Costs						$917
	Total Operating Costs					$79,720
By-Product Credits						
____		____	T/D	____	/T	$0
____		____	T/D	____	/T	$0
____		____	T/D	____	/T	$0
____		____	T/D	____	/T	$0
	Total By-Product Credits					$0
	Net Operating Costs					$79,720

Table 50 COE Calculation, PFB Combustion Plant with GBF (continued)

BASES AND ASSUMPTIONS

A. CAPITAL BASES AND DETAILS

	QUANTITY	UNIT $ PRICE	COST, k$
Initial Catalyst Inventory			
________________	_____ lb.	_____ /lb.	$0
________________	_____ lb.	_____ /lb.	$0
________________	_____ lb.	_____ /lb.	$0
________________	_____ lb.	_____ /lb.	$0
Initial Chemicals Inventory			
________________	_____ lb.	_____ /lb.	$0
________________	_____ lb.	_____ /lb.	$0
________________	_____ lb.	_____ /lb.	$0
________________	_____ lb.	_____ /lb.	$0
Total Catalyst and Chemical Inventory			$0
Startup costs			
Plant modifications,	2 % TPI		$9,990
Operating costs			$3,547
Fuel			$1,327
Total Startup Costs			$14,864
Working capital			
Fuel & Consumables inv,	60 days supply		$12,547
By-Product inventory,	30 days supply		$0
Direct expenses,	30 days		$979
Total Working Capital			$13,527

Table 50 COE Calculation, PFB Combustion Plant with GBF (continued)

B. ECONOMIC ASSUMPTIONS

Project life	30 Years
Book life	30 Years
Tax life	20 Years
Federal and state income tax rate	38.0 %
Tax depreciation method	ACRS
Investment Tax Credit	0.0 %

Financial structure

Type of Security	% of Total	Current Dollar Cost, %	Current Dollar Ret, %	Constant Dollar Cost, %	Constant Dollar Ret, %
Debt	50	11.0	5.5	4.6	2.3
Preferred Stock	15	11.5	1.7	5.2	0.8
Common Stock	35	15.2	5.3	8.7	3.0
Discount rate (cost of capital)			12.5		6.1

Inflation rate, % per year	4.0
Real Escalation rates (over inflation)	
Fuel, % per year	0.7
Operating & Maintenance, % per year	0.0

C. COST OF ELECTRICITY

The approach to determining the cost of electricity is based upon the methodology described in the Technical Assessment Guide, published by the Electric Power Research Institute, Volume I, EPRI-4463-SR, December 1986. The cost of electricity is stated in terms of 10th year levelized dollars. Insurance and local taxes are accounted for explicitly in cell H87, rather than including it in Capital Charges as does EPRI TAG.

	Current $	Constant
Levelizing Factors		
Capital Carrying Charge, 10th year	0.175	0.103
Fuel, 10th year	1.244	1.036
Operating & Maintenance, 10th year	1.202	1.000
	mills/kWh	mills/kW
Cost of Electricity - Levelized		
Capital Charges	36.2	21.3
Fuel costs	20.3	16.9
Operating & Maintenance	17.6	14.7
Total Cost of Electricity	74.1	52.8

Table 51 COE Calculation, PFB Combustion Plant with Candle Filter

05/07/93 ELECTRIC POWER GENERATION COST - Version 1.12
BASED ON CANDLE FILTERS
2ND GENERATION PFB 452 MW POWER PLANT

CAPITAL REQUIREMENTS (Dec 1991 Dollars)

Total Plant Investment

AREA NO	PLANT SECTION DESCRIPTION	PROCESS CONT, %	COST, K$ W/O CONT
1	COAL AND SORBENT HNDLG	0	$35,404
2	COAL AND SORBENT PREP	3	$22,339
3	FEEDWATER AND MISC BOP SYSTEMS	0	$19,774
4	CARBONIZER, CPFBC & CPFBC FBHE	17	$50,670
5	HOT GAS CLEANUP AND PIPING, CNDL	8	$52,989
6	COMBUSTION TURBINE /ACCESSORIES	9	$55,681
7	HRSG, DUCTING AND STACK	13	$26,959
8	STEAM TURBINE GENERATOR	0	$37,050
9	COOLING WATER SYSTEM	0	$9,775
10	ASH / SPENT SORBENT HNDL SYSTEM	12	$7,926
11	ACCESSORY ELECTRIC PLANT	0	$14,131
12	INSTRUMENTATION AND CONTROL	0	$11,502
13	IMPROVEMENTS TO SITE	0	$9,492
14	BUILDINGS AND STRUCTURES	0	$12,283

Subtotal, Process Plant Cost	$365,976
General Plant Facilities	$0
Engineering Fees	$23,788
Process Contingency (Using contingencies listed above)	$23,460
Project Contingency, 15 % Proc Plt & Gen Plt Fac	$54,896
Total Plant Cost (TPC)	$468,120
Plant Construction Period, 3.5 Years (1 or more)	
Construction Interest Rate, 12.5 %	
Adjustment for Interest and Inflation	$49,799
Total Plant Investment (TPI)	$517,919
Prepaid Royalties	$0
Initial Catalyst and Chemical Inventory	$0
Startup Costs	$15,438
Spare Parts	$2,341
Working Capital	$13,574
Land, 200 Acres	$1,500
Total Capital Requirement (TCR)	$550,773

Table 51 COE Calculation, PFB Combustion Plant with Candle Filter (continued)

ANNUAL OPERATING COSTS

Capacity Factor = 65 %

COST ITEM		QUANTITY	UNIT $ PRICE	ANNUAL COST, K$
PITTS NO.8 COAL	Fuel Type	3417.5 T/D	$51.60 /T	$41,834
Consumable Materials				
WATER		5575.0 1000 GAL/	$0.69 /1000 GAL	$919
DOLOMITE		987.8 T/D	$21.76 /T	$5,099
H2O MAKEUP/TREAT		5110.0 LB/D	$0.17 /LB	$206
LIQUID EFF		13520 LB/D	$0.12 /LB	$390
FUEL OIL		4175.0 GAL/D	$0.61 /GAL	$608
GASES N2, ect.		5040 100 SCF/D	$0.35 /100 SCF	$421
Ash/Sorbent Disposal Costs		1093.7 T/D	$9.26 /T	$2,403
Plant Labor				
Oper Labor (incl benef)		26 Men/shift	$23.15 /Hr.	$5,273
Supervision & Clerical				$2,980
Maintenance Costs				$11,653
Insurance & Local Taxes				$9,362
Royalties				$0
Other Operating Costs				$993
	Total Operating Costs			$82,142
By-Product Credits				
______		____ T/D	____ /T	$0
______		____ T/D	____ /T	$0
______		____ T/D	____ /T	$0
______		____ T/D	____ /T	$0
	Total By-Product Credits			$0
	Net Operating Costs			$82,142

Table 51 COE Calculation, PFB Combustion Plant with Candle Filter (continued)

BASES AND ASSUMPTIONS

A. CAPITAL BASES AND DETAILS

	QUANTITY	UNIT $ PRICE	COST, K$
Initial Catalyst Inventory			
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
Initial Chemicals Inventory			
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
Total Catalyst and Chemical Inventory			$0
Startup costs			
Plant modifications,	2 % TPI		$10,358
Operating costs			$3,758
Fuel			$1,322
Total Startup Costs			$15,438
Working capital			
Fuel & Consumables inv,	60 days supply		$12,513
By-Product inventory,	30 days supply		$0
Direct expenses,	30 days		$1,061
Total Working Capital			$13,574

Table 51 COE Calculation, PFB Combustion Plant with Candle Filter (continued)

B. ECONOMIC ASSUMPTIONS

Project life	30 Years
Book life	30 Years
Tax life	20 Years
Federal and state income tax rate	38.0 %
Tax depreciation method	ACRS
Investment Tax Credit	0.0 %

Financial structure

Type of Security	% of Total	Current Dollar Cost, %	Current Dollar Ret, %	Constant Dollar Cost, %	Constant Dollar Ret, %
Debt	50	11.0	5.5	4.6	2.3
Preferred Stock	15	11.5	1.7	5.2	0.8
Common Stock	35	15.2	5.3	8.7	3.0
Discount rate (cost of capital)			12.5		6.1

Inflation rate, % per year	4.0
Real Escalation rates (over inflation)	
Fuel, % per year	0.7
Operating & Maintenance, % per year	0.0

C. COST OF ELECTRICITY

The approach to determining the cost of electricity is based upon the methodology described in the Technical Assessment Guide, published by the Electric Power Research Institute, Volume I, EPRI-4463-SR, December 1986. The cost of electricity is stated in terms of 10th year levelized dollars. Insurance and local taxes are accounted for explicitly in cell H87, rather than including it in Capital Charges as does EPRI TAG.

	Current $	Constant
Levelizing Factors		
Capital Carrying Charge, 10th year	0.175	0.103
Fuel, 10th year	1.244	1.036
Operating & Maintenance, 10th year	1.202	1.000
	mills/kWh	mills/kW
Cost of Electricity - Levelized		
Capital Charges	37.5	22.0
Fuel costs	20.2	16.8
Operating & Maintenance	18.8	15.7
Total Cost of Electricity	76.5	54.5

5.6 COE Comparison, KRW Gasifier Based Power Plant

In the Westinghouse report on the 100 MWe, KRW air blown gasifier based power plant, filter costs are broken down into four categories. These categories included the cross-flow filter vessel with internals, nitrogen supply for pulse cleaning, nitrogen accumulator, and ash cooling and depressurizing. Labor and materials for erection are in another category and include instrumentation, controls, piping, structure, foundations, insulation, and engineering fees. These cost items generally fit the definition of *bare erected costs* for the filter based on EPRI TAG methodology. Another item of *bare erected cost* of the plant is the zinc/ferrite system for sulfur removal. Part of our contract was to update the cost of this plant based on published METC guidelines and include this in the COE calculation.

5.6.1 Zinc Ferrite Plant Cost Update

The KRW air blown gasification plant is described in the Westinghouse report comparing numerous gasification plants[3]. Subsequent to this report, in 1989, EG&G Washington Analytical Services Center issued "Conceptual Design and Cost Estimate for Zinc Ferrite Plant Section."[4] The plant cost determined by the EG&G report needed to be adjusted to match the plant size and operating conditions described in the Westinghouse report and then adjusted to December, 1991 dollars. The updated cost are incorporated into the cost of electricity for the KRW gasifier based power generation plant.

The plant used in the EG&G study is a two train, zinc ferrite facility with a common sorbent handling system. The volumetric flow rate of a single train is close that of the flow through the zinc ferrite plant to be used in the GBF study. Table 52 shows the flow conditions for the two plants. The temperature of the gas entering the zinc ferrite section of both plants is nearly equal. The plants differ in three significant ways. The plant used in the EG&G study operates at 600 psia while the plant in the GBF study operates at 385 psia. The EG&G plant uses water quench to cool the gases from the hot gas particulate cleanup equipment while the plant in the GBF study uses a heat recovery boiler. The plant with the GBF is a single train plant. The cost analysis makes adjustments to the cost to account for the plant differences.

It was assumed that the reactors in both plants should operate at the same space velocity of 2000 reactor volumes per hour so that the gases will have the same residence time in the reactors. Consequently, the volumetric flow rate is used as the scaling factor between the two plants. Equipment cost are scaled by the ratio of the flow through the reactors of each plant raised to an exponential power. The exponential powers depend on the type of equipment being priced, and are given in handbooks on cost estimating. Fortunately the two plants have similar volumetric flow rates so that corrections for capacity are less than 5%.

Table 52 Relative Plant Capacities for Zinc Ferrite Plant

	EG&G Report Single Train Plant Used in Zinc Ferrite Cost Estimate	Plant Used, GBF Development Study
Mass Flow, lb/hr	534,769	312,800
Volumetric Flow, acfm	10,916	10,153
Temperature, °F	1,140	1,200
Pressure, psia	600	385

The pressure vessel costs are adjusted to account for the difference in operating pressure as well as capacity. The cost of the pressure vessel without nozzles was adjusted by 110% of the pressure ratio between the two plants. The revised cost is then adjusted for capacity differences.

Table 53 shows the material cost breakdown for the EG&G study and the revised cost for the GBF study. The comments after each itemized piece of equipment provide the basis for adjusting the EG&G cost to obtain the revised cost. The revised costs are then adjusted by the ratio of the *Chemical Engineering Plant Equipment Cost Index* for Dec. 1991 to that of 3rd quarter 1988 to obtain Dec. 1991 costs.

The EG&G plant cost estimate uses a factored cost method. Once the cost of the equipment is determined, other costs are then factored from this value. The same approach is used to determine the cost of the zinc ferrite equipment used in this study. The same factors are used in both cases. Table 54 shows the factored cost summary. The installed cost of the zinc ferrite plant to be used in the GBF study is $8,952,641.

Table 53 Material Cost Breakdown for Zinc Ferrite Plant

Description	EG&G Report Mat'l Cost Two Trains @600 PSIA @ 10,916 ACFM 3rd Quarter 1988 $	GBF Study Mat'l Cost One Train @385 PSIA @ 10,153 ACFM 3rd Quarter 1988 $	GBF Study Mat'l Cost One Train @385 PSIA @ 10,153 ACFM Dec 1991 $	Notes
Humidifiers	$176,000	N/A	N/A	
Desulfurizing Reactor	$4,044,000	$1,586,838	$1,650,796	1
Steam/Air Regen Hx	$162,000	$78,458	$81,621	2
Regenerative Gas Cooler	$154,000	$74,584	$77,590	3
Valves	$2,291,000	$1,145,500	$1,191,670	4
Sorbent Handling System.	$316,700	$267,096	$277,861	5
Shutdown Regen Coolers	$81,600	$39,520	$41,113	6
Recycle N2 Compressor	$232,000	$220,526	$229,401	7
Instrumentation	$403,400	$254,822	$265,092	8
Sample Coolers	$81,600	$40,800	$42,444	9
Piping	$392,000	$247,660	$2576013	10
Total Factored Mat'l	$1,568,700		$773,154	11
	$9,903,000		$4,888,357	

NOTE: Chemical Engineering, Plant Equipment Cost Index:
Dec. 1991 - 394.9 3rd Quarter 1988 - 379.6

Notes for Table 53

1. Costs halved, then adjusted for pressure then adjusted by (Volumetric Capacity Ratio)$^{.68}$ See Table 54.
2. Cost halved, then adjusted by (Volumetric Capacity Ratio)$^{.44}$
3. Cost halved, then adjusted by (Volumetric Capacity Ratio)$^{.44}$
4. Valve cost assumed to be evenly Split between two trains.
5. Cost reduced by cost of 2nd spent sorbent conveyor and feeder ($39,750) then adjusted by (Volumetric Capacity Ratio)$^{.5}$
6. Cost halved, then adjusted by (Volumetric Capacity Ratio)$^{.44}$
7. Cost adjusted by (Volumetric Capacity Ratio)$^{.70}$
8. Cost adjusted by (Two Train Volumetric Capacity Ratio)$^{.6}$
9. Cost halved.
10. Cost adjusted by (Two Train Volumetric Capacity Ratio)$^{.6}$.
11. 18% of (Material Less Sorbent Handling and Piping) + 50% of Piping.

Volumetric Capacity Ratio = 10153/10916
Two Train Volumetric Capacity Ratio = 10153/(2*10916)
Exponents of Capacity Factor are from Perry & Clinton "Chemical Engineers Handbook". 5th ed. Table 25-14.

Table 54 Factored Cost Summary for Zinc Ferrite Plant - Dec. 1991 Dollars

	Material Factor	Material Dollars Jan 1992	Labor Factor	Labor Dollars	Subcontract Factor	Total Dollars	Dollars
Equipment	100	$3,579,741	8	$286,379			$3,866,120
Civil	4	$143,190	10	$357,974			$501,164
Sorbent Handling System		$277,861		$69,465			$347,326
Piping		$386,401		$270,481			$656,883
Building (Control House)	3	$107,392	3	$107,392			$214,784
Structures	5	$178,987	2	$71,595			$250,582
Instrumentation Install.	2	$71,595	2	$71,595			$143,190
Insulation					7	$250,582	$250,582
Fireproofing					1	$35,797	$35,797
Electrical	4	$143,190	5	$178,987			$322,177
Painting					2	$71,595	$71,595
		---------------		---------------		--------------	--------------
Total Direct Costs		$4,888,357		$1,413,868		$357,974	$6,660,199

Testing (6.5% Labor)	$91,901
Labor Fringes (32% Labor)	$452,438
Field Indirects (54% Labor)	$763,489
home office services (11% labor)	$984,614

Total Installed Cost (Excluding Contingency and Fee)	$8,952,641

5.6.2 Bare Erected Costs, Gasifier Filters

Bare erected costs established for the granular-bed and the ceramic candle filters for the gasifier are compared on Table 55. These costs were originally presented separately in sections 5.3 and 5.4. As in the original cost estimate for the cross-flow filter, all costs associated with the filter are included as follows: filter, ash removal (media circulation or pulse cleaning), and ash handling. Filter vessels are all estimated at $2.50/lb based on quotes received for shop fabrication. The candle filter vessels are larger, and heavier, than the granular-bed filter vessels. GBF internals are lighter and less complex than candle filter internals; but since they are based on fabrication from the same material, RA85H, costing is at $15/lb for both, based on analysis of quotes received. Pressure vessel steelwork for all smaller vessels is included at $3.50/lb for both filters. Small fabricated items made from 310 SS sheet or plate, for items such as the de-entrainment vessel internals and the media valve internals for the granular-bed filter, are included at $7.50/lb, again based on quotes. Carbon steel fabricated piping and ducting is $2.50/lb and stainless steel fabricated piping is $10.50/lb. Filter media for the granular-bed filter is priced at $0.45/lb. Candle filter elements are priced at $295/element based on quotations from manufacturers. Other buyout equipment is priced based on quotes from qualified suppliers. Freight is estimated at 4% of the cost of filter items. The contractors estimating factors for refractory include freight and installation. Erection for all filters was evaluated by an independent contractor specializing in construction cost estimating. General and administrative costs and allowance for profit is included for all items by dividing costs by 0.85.

5.6.3 Power Plant Maintenance

The Westinghouse report used 2.7% of total plant, *bare erected cost* for power plant maintenance. For this study, this factor was applied to all capital cost items except the filter equipment. Results from maintenance calculations were presented for the gasifier filters in Tables 41 and 44 for the granular-bed and ceramic candle filter, respectively. These costs ($156,400 for the granular-bed filter and $300,200 for the candle filter) were used in the calculation of COE.

5.6.4 Cost of Electricity

Costs for hot gas cleanup equipment and piping are summarized in Table 56. To the *bare erected cost*, percentages are added for *process contingency* and *project contingency* to arrive at the *total plant cost* (TPC). Engineering is included with the filter. Percentages are those proposed in the Westinghouse report. *Project contingency* is added at 18% of the sum of *bare erected cost* and *general plant facilities*. *Process contingency* is added at 5.5% of *bare erected costs* of the entire plant. Engineering for the filters includes construction management, and home office fees in addition to the cost for engineering services provided by the filter manufacturers.

Clearly, the addition of engineering fees and contingencies add significantly to the cost of the filter plants and the ash handling facilities. The addition to the granular-bed filter module is $7.7/kW, or 20.4% of the *bare erected cost*. For the candle filter the addition cost is $9.1/kW or 20.4% of the *bare erected cost*.

Table 55 Bare Erected Cost Comparison
Gasifier Filters, 100 Mwe

Granular-Bed Filter System		Candle Filter System	
	$/1000		$/1000
Filter Vessel	405	Filter Vessel	738
Filter Internals	99	Filter Internals	340
Vessel Refractory	116	Vessel Refractory	182
Filter Media	119	Filter Elements	314
Circulation System		Pulse Back	
Vessels/Piping	666	Piping/Valves	506
Regen. Ht. Exch.	873	Compressors/Coolers	542
Water-Cooled Hx.	19	Ash System	
Baghouse	78	Ash Coolers	570
Boost/Maint. Blower	137	Ash Hoppers	31
Instr/Controls	74	Ash Valves	74
Access/Support Steel	213	Instr/Controls	50
Foundation Mat'l	10	Access/Support Steel	113
Ash System	87	Foundation Mat'l	8
Erection	217	Erection	300
Engineering	561	Engineering	561
Freight	102	Freight	130
Bare Erected Cost, k$	3,775	Bare Erected Cost, k$	4,458

To the TPC, additions are made for interest charges and inflation during the construction period, sometimes called allowance for funds used during construction (AFUDC). This yields the value for *total plant investment* (TPI). Westinghouse estimated 13% of total investment for AFUDC, working capital, etc. Since this value is very close to the spreadsheet calculation assuming 12.5% construction interest and a 4 year construction period, the substitution was made. These values were used in the updated

Table 56 Cost Summary, KRW Gasifier Based Power Plant (1991 Costs in Thousands of Dollars, 100 MWe Plant)

Cost Item	Plant with Granular-Bed Filters	Plant with Candle Filters
Filter Module		
Bare Erected Cost	3,775	4,458
in $/kW	37.8	44.6
Engineering Fee,	incl	incl
Process Contingency, 5.5%	208	245
Project Contingency, 15%	566	669
Total Plant Cost (TPC), k$	4,549	5,372
Total Plant Cost, $/kW	45.5	53.7

calculation of COE. To the TPI, values were added according to the Westinghouse report for royalties, initial catalyst and chemical inventory, start-up costs, spare parts, working capital, and land. This resulted in the *total capital requirement* (TCR). If a value was included by Westinghouse, it was escalated and utilized. Otherwise the default value in the Lotus 1-2-3 program was used. Annual costs include consumables, ash disposal, plant labor, maintenance, insurance, local taxes, royalties, and by-product credits. The annual cost of fuel (coal) is calculated and listed separately. See Section 5.2 for additional explanation on the use of the COE calculation program and on the origin of annual cost values. The results presented in Table 57 show that the constant dollar COE for the KRW gasifier based plant is 91.8 mills/kWh based on granular-bed filters and 92.4 mills/kWh based on ceramic candle filters. This assumes that the parasitic power presented in Tables 42 and 45 is accounted for in the base calculations that arrived at 100 MWe because of the cross-flow filter analysis.

If the net power output is adjusted for the parasitic power calculated for the filters there is a slight increase in COE of 0.1 mills/kWh. This increase applies to the KRW gasifier based power plant based on either granular-bed or ceramic candle filters and to either the current or constant dollar COE.

If process gas is replaced by nitrogen for pulse cleaning, the COE increases 2.1 mills/kWh and 1.4 mills/kWh in constant dollars and current dollars, respectively. This change includes capital and operating costs associated with replacing the process gas cooling/compressing equipment with the PSA nitrogen generating system. A 12-hour nitrogen supply is included with the PSA generation system for backup. Values for this adjustment are presented on Table 31, Section 4.

Table 57 Cost of Electricity Comparison
KRW Gasifier Based Power Plant, 100 MWe

Cost of Electricity - Levelized	Current $ mills/kWh	Constant $ mills/kWh
Granular-Bed Filter		
Capital Charges	77.8	45.7
Fuel Charges	16.5	13.8
Operation & Maintenance	38.9	32.4
Total Cost of Electricity	133.2	91.8
Candle Filter		
Capital Charges	78.1	45.9
Fuel Charges	16.5	13.8
Operation & Maintenance	39.4	32.7
Total Cost of Electricity	134.0	92.4

Tables 58 and 59 present the summary printouts from the Lotus 1-2-3 COE calculation with the assumption presented.

Table 58 COE Calculation, KRW Gasification Plant with GBF

05/07/93 ELECTRIC POWER GENERATION COST - Version 1.12
BASED ON CANDLE FILTERS
KRW GASIFIER(AIR) 100 MW POWER PLANT

CAPITAL REQUIREMENTS (Dec 1991 Dollars)

Total Plant Investment

AREA NO	PLANT SECTION DESCRIPTION	PROCESS CONT, %	COST, K$ W/O CONT
1	Store/Dry/Grind/FBC		$10,044
2	Air Booster Compressors		$5,140
3	Gasifier		$17,021
4	Heat Recovery		$2,811
5	Filtration, Candle Filters		$4,458
6	METC Zn/Fe SO2 Adsorbers		$7,968
7	Allied Chem. SO2->H2S->S		$13,598
8	BFW, Cond., etc.		$1,591
9	Combined Cycle		$74,213
10	Other Facilities		$35,422
11	Cat. and Chem.		$1,170
12	Process Contingency	5.5	
	Subtotal, Process Plant Cost		$173,437

General Plant Facilities		$0
Engineering Fees, Zn/Fe System only		$985
Process Contingency (Using contingencies listed above)		$9,464
Project Contingency,	18 % Proc Plt & Gen Plt Fac	$32,075
Total Plant Cost (TPC)		$215,961
Plant Construction Period,	4 Years (1 or more)	
Construction Interest Rate,	12.5 %	
Adjustment for Interest and Inflation		$27,948
Total Plant Investment (TPI)		$243,909
Prepaid Royalties		$867
Initial Catalyst and Chemical Inventory		$0
Startup Costs		$6,532
Spare Parts		$1,080
Working Capital		$1,250
Land, ____ Acres		$0
Total Capital Requirement (TCR)		$253,638

Table 58 COE Calculation, KRW Gasification Plant with GBF (continued)

ANNUAL OPERATING COSTS

Capacity Factor = 65 %

COST ITEM		QUANTITY		UNIT $ PRICE		ANNUAL COST, K$
Ill. No. 6 Coal	Fuel Type	903.9	MM Btuh	$1.47	/MM Btu	$7,566
Consumable Materials						
	Raw water	1525.7	1000 GAL	$0.69	/1000 G	$251
	Catalysts & Chem.	18.8	T/D	$127.63	/T	$568
	____	____	T/D	____	/T	$0
	____	____	T/D	____	/T	$0
Ash/Sorbent Disposal Costs		82.2	T/D	$9.26	/T	$181
Plant Labor						
	Oper Labor (incl benef)	24	Men/shift	$23.15	/Hr.	$4,868
	Supervision & Clerical					$2,182
Maintenance Costs	(GBF =	$300)				$6,011
Insurance & Local Taxes						$4,319
Royalties						$76
Other Operating Costs						$727
	Total Operating Costs					$26,748
By-Product Credits						
	Sulfur	24.7	T/D	$94.69	/T	$556
	____	____	T/D	____	/T	$0
	____	____	T/D	____	/T	$0
	____	____	T/D	____	/T	$0
	Total By-Product Credits					$556
	Net Operating Costs					$26,193

Table 58 COE Calculation, KRW Gasification Plant with GBF (continued)

BASES AND ASSUMPTIONS

A. CAPITAL BASES AND DETAILS

		QUANTITY	UNIT $ PRICE	COST, K$
Initial Catalyst Inventory				
	________	_____ lb.	_____ /lb.	$0
	________	_____ lb.	_____ /lb.	$0
	________	_____ lb.	_____ /lb.	$0
	________	_____ lb.	_____ /lb.	$0
Initial Chemicals Inventory				
	________	_____ lb.	_____ /lb.	$0
	________	_____ lb.	_____ /lb.	$0
	________	_____ lb.	_____ /lb.	$0
	________	_____ lb.	_____ /lb.	$0
	Total Catalyst and Chemical Inventory			$0
Startup costs				
Plant modifications,		2 % TPI		$4,878
Operating costs				$1,644
Fuel				$10
	Total Startup Costs			$6,532
Working capital				
Fuel & Consumables inv,		60 days supply		$333
By-Product inventory,		60 days supply		$140
Direct expenses,		30 days		$777
	Total Working Capital			$1,250

Table 58 COE Calculation, KRW Gasification Plant with GBF (continued)

B. ECONOMIC ASSUMPTIONS

Project life	30 Years
Book life	30 Years
Tax life	20 Years
Federal and state income tax rate	38.0 %
Tax depreciation method	ACRS
Investment Tax Credit	0.0 %

Financial structure

Type of Security	% of Total	Current Dollar Cost, %	Current Dollar Ret, %	Constant Dollar Cost, %	Constant Dollar Ret, %
Debt	50	11.0	5.5	4.6	2.3
Preferred Stock	15	11.5	1.7	5.2	0.8
Common Stock	35	15.2	5.3	8.7	3.0
Discount rate (cost of capital)			12.5		6.1

Inflation rate, % per year	4.0
Real Escalation rates (over inflation)	
Fuel, % per year	0.7
Operating & Maintenance, % per year	0.0

C. COST OF ELECTRICITY

The approach to determining the cost of electricity is based upon the methodology described in the Technical Assessment Guide, published by the Electric Power Research Institute, Volume I, EPRI-4463-SR, December 1986. The cost of electricity is stated in terms of 10th year levelized dollars. Insurance and local taxes are accounted for explicitly in cell H87, rather than including it in Capital Charges as does EPRI TAG.

	Current $	Constant $
Levelizing Factors		
Capital Carrying Charge, 10th year	0.175	0.103
Fuel, 10th year	1.244	1.036
Operating & Maintenance, 10th year	1.202	1.000
	mills/kWh	mills/kWh
Cost of Electricity - Levelized		
Capital Charges	78.1	45.9
Fuel costs	16.5	13.8
Operating & Maintenance	39.4	32.7
Total Cost of Electricity	134.0	92.4

Table 59 COE Calculation, KRW Gasifier Plant with Candle Filter

05/07/93 ELECTRIC POWER GENERATION COST - Version 1.12
BASED ON GRANULAR BED FILTERS
KRW GASIFIER(AIR) 100 MW POWER PLANT

CAPITAL REQUIREMENTS (Dec 1991 Dollars)

Total Plant Investment

AREA NO	PLANT SECTION DESCRIPTION	PROCESS CONT, %	COST, K$ W/O CONT
1	Store/Dry/Grind/FBC		$10,044
2	Air Booster Compressors		$5,140
3	Gasifier		$17,021
4	Heat Recovery		$2,811
5	Filtration, GBF System		$3,775
6	METC Zn/Fe SO2 Adsorbers		$7,968
7	Allied Chem. SO2->H2S->S		$13,598
8	BFW, Cond., etc.		$1,591
9	Combined Cycle		$74,213
10	Other Facilities		$35,422
11	Cat. and Chem.		$1,170
12	Process Contingency	5.5	
	Subtotal, Process Plant Cost		$172,753

General Plant Facilities	$0
Engineering Fees, Zn/Fe System only	$985
Process Contingency (Using contingencies listed above)	$9,427
Project Contingency, 18 % Proc Plt & Gen Plt Fac	$31,948
Total Plant Cost (TPC)	$215,114
Plant Construction Period, 4 Years (1 or more)	
Construction Interest Rate, 12.5 %	
Adjustment for Interest and Inflation	$27,838
Total Plant Investment (TPI)	$242,952
Prepaid Royalties	$864
Initial Catalyst and Chemical Inventory	$0
Startup Costs	$6,497
Spare Parts	$1,076
Working Capital	$1,244
Land, ____ Acres	$0
Total Capital Requirement (TCR)	$252,632

Table 59 COE Calculation, KRW Gasifier Plant with Candle Filter (continued)

ANNUAL OPERATING COSTS

Capacity Factor = 65 %

COST ITEM		QUANTITY		UNIT $ PRICE		ANNUAL COST, K$
Ill. No. 6 Coal	Fuel Type	904.0	MM Btuh	$1.47	/MM Btu	$7,568
Consumable Materials						
	Raw water	1525.7	1000 GAL	$0.69	/1000 G	$251
	Catalysts & Chem.	18.8	T/D	$127.63	/T	$568
	________	____	T/D	____	/T	$0
	________	____	T/D	____	/T	$0
Ash/Sorbent Disposal Costs		32.2	T/D	$9.26	/T	$181
Plant Labor						
	Oper Labor (incl benef)	24	Men/shift	$23.15	/Hr.	$4,868
	Supervision & Clerical					$2,164
Maintenance Costs	(GBF =	$156.4)				$5,863
Insurance & Local Taxes						$4,302
Royalties						$76
Other Operating Costs						$721
	Total Operating Costs					$26,561
By-Product Credits						
	Sulfur	24.7	T/D	$94.69	/T	$556
	________	____	T/D	____	/T	$0
	________	____	T/D	____	/T	$0
	________	____	T/D	____	/T	$0
	Total By-Product Credits					$556
	Net Operating Costs					$26,005

Table 59 COE Calculation, KRW Gasifier Plant with Candle Filter (continued)

BASES AND ASSUMPTIONS

A. CAPITAL BASES AND DETAILS

	QUANTITY	UNIT $ PRICE	COST, K$
Initial Catalyst Inventory			
______	______ lb.	______ lb.	$0
______	______ lb.	______ /lb.	$0
______	______ lb.	______ /lb.	$0
______	______ lb.	______ /lb.	$0
Initial Chemicals Inventory			
______	______ lb.	______ /lb.	$0
______	______ lb.	______ /lb.	$0
______	______ lb.	______ /lb.	$0
______	______ lb.	______ /lb.	$0
Total Catalyst and Chemical Inventory			$0
Startup costs			
Plant modifications,	2 % TPI		$4,859
Operating costs			$1,628
Fuel			$10
Total Startup Costs			$6,497
Working capital			
Fuel & Consumables inv,	60 days supply		$333
By-Product inventory,	60 days supply		$140
Direct expenses,	30 days		$771
Total Working Capital			$1,244

Table 59 COE Calculation, KRW Gasifier Plant with Candle Filter (continued)

B. ECONOMIC ASSUMPTIONS

Project life	30 Years
Book life	30 Years
Tax life	20 Years
Federal and state income tax rate	38.0 %
Tax depreciation method	ACRS
Investment Tax Credit	0.0 %

Financial structure

Type of Security	% of Total	Current Dollar Cost, %	Current Dollar Ret, %	Constant Dollar Cost, %	Constant Dollar Ret, %
Debt	50	11.0	5.5	4.6	2.3
Preferred Stock	15	11.5	1.7	5.2	0.8
Common Stock	35	15.2	5.3	8.7	3.0
Discount rate (cost of capital)			12.5		6.1

Inflation rate, % per year	4.0
Real Escalation rates (over inflation)	
Fuel, % per year	0.7
Operating & Maintenance, % per year	0.0

C. COST OF ELECTRICITY

The approach to determining the cost of electricity is based upon the methodology described in the Technical Assessment Guide, published by the Electric Power Research Institute, Volume I, EPRI-4463-SR, December 1986. The cost of electricity is stated in terms of 10th year levelized dollars. Insurance and local taxes are accounted for explicitly in cell H87, rather than including it in Capital Charges as does EPRI TAG.

	Current $	Constant $
Levelizing Factors		
Capital Carrying Charge, 10th year	0.175	0.103
Fuel, 10th year	1.244	1.036
Operating & Maintenance, 10th year	1.202	1.000
	mills/kWh	mills/kWh
Cost of Electricity - Levelized		
Capital Charges	77.8	45.7
Fuel costs	16.5	13.8
Operating & Maintenance	38.9	32.4
Total Cost of Electricity	133.2	91.8

5.7 References

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SECTION 6

DEVELOPMENT OF MULTI-CONTAMINANT CONTROL GRANULAR-BED FILTERS

6.1 Objective

The objective of this study is to develop conceptual designs of granular-bed filters (GBF) that are capable of removing a combination of pollutants in high temperature and high pressure (HTHP) gas streams from processes being developed for advanced coal utilization.

6.2 Combustion Power's Approach to Multi-Contaminant Control

Although we are still in the initial stages of our study, we have narrowed the many possible approaches down to the following concept. The media used in the granular-bed filter could be composed of two distinct size distributions. Larger, six mm diameter, spheres could be the same inert media used for particulate control. In addition to this media, a smaller (2 to 3 mm diameter) media could be supplied which would be chemically reactive and have a finite life. The smaller media could be separated pneumatically from the larger media in the lift pipe or removed by gradual attrition in the pneumatic conveying system. The frequency of removal and replacement of the chemically reactive media would depend on its reactivity and the extent of conversion in a single pass through the filter. There are several reasons for the dual media approach. The quantity of media which passes through the filter is so great that to be economically feasible the majority of the media has to pass through the filter millions of times. The larger media serves this purpose. A reactive media would no longer be active after passing through the filter so many times and is unlikely to have the attrition resistance required for a large number of passes through the filter. Secondly it is much more difficult to make a large, stable, attrition resistant particle than a smaller one. The large size media is necessary to maintain a high gas flow through the filter at a low pressure drop.

There are many possible materials which could be incorporated in a chemically reactive media. The initial work performed in this study has narrowed the field to three types of media. One is a reactive media composed of limestone and clay which could be used for control of sulfur, alkali, and some trace metals. The limestone /clay media would be used either with gasification or combustion processes at temperatures of 850°C to 950°C. Another reactive media is composed of calcium oxide or nahcolite ($NaHCO_3$) and could be used for the removal of chlorides in coal gasification streams at temperatures of 600°C. The reactive media could be pelletized from fine grain materials forming a 2-3 mm pellets. The pelletized material has a large pore structure which allows high conversion rates. Cements are used to bind the grains of the pellets producing spheres with relatively high attrition resistance. The third type of media could be a catalyst for the decomposition of ammonia in coal gasification gas. The most promising of these are nickel based catalyst operating at 800-900°C. The catalytic material would be incorporated in the larger 6 mm diameter media as either a coating or as separate material mixed with the bulk media.

6.3 Background

Previous work at New York University demonstrated that a granular-bed filter is capable of removing particulate from a high pressure and high temperature gas stream and meeting New Source Performance Standards[1]. The current contract has allowed Combustion Power Co. to improve on the design of the granular-bed filter so that it is cost competitive with ceramic candle filters for the removal of particulate from high temperature, high pressure (HTHP) gas streams. Besides removing particulate, a granular-bed filter has the potential of removing other pollutants in the gas stream. The filter is an excellent gas/solids contactor; in that, it has gas residence times in the order of several seconds, solids residence times in the order of several hours, uniform gas flow across the media, and the gas and filter media flow in opposite directions for the maximum driving potential.

The contaminants of major concern, besides particulate in coal utilization processes, are sulfur compounds, nitrogen compounds, alkali compounds, halogenated compounds, tars, and trace contaminants such as cadmium and mercury[2]. A granular-bed filter which is able to capture particulate and one or more of these additional contaminants would have significant benefits over just a particulate removal system.

Many processes that are under development are able to meet current New Source Performance Standards, but may have trouble meeting more stringent requirements which could be promulgated in the future. As an example, pressurized fluidized bed combustors are able to meet New Source Performance Standards of 90% sulfur removal but probably will have difficulty obtaining 95-98% sulfur removal. A granular-bed filter with an SO_2 absorbing media may be able to increase the overall sulfur removal efficiency from 90% to 98% in a PFBC system while maintaining a cost effective calcium to sulfur ratio.

6.3.1 Control of Sulfur Emissions

The control of sulfur emissions has historically been the major thrust of pollution control systems and still remains a primary focus of innovative technology. In combustion systems, the need is for the removal of SO_2, and for gasification, the need is for the removal of H_2S. There are several potential materials which may be suitable as a sorbent in a GBF for the control of sulfur emissions.

6.3.1.1 SO_2 Control

For the control of SO_2 at high temperature, the following materials could be used as sorbents in a granular-bed filter: limestone, dolomite, calcium silicates formed from Type III Portland cement[3], and ground and pelletized fluid bed ash. Work by Spitsbergen of the University of Twente showed that agglomerates made from ground limestone are considerably more reactive that similar sized particles of naturally occurring stone[4]. Such agglomerates could be used as filter media. Inexpensive media made from limestone or recycled bed ash could be used in a once through process. More expensive calcium silicate material would probably be used in a regenerative cycle.

The pelletized agglomerates made from ground limestone tested at the University of Twente[5] had an internal pore volume which was 50% greater than that of natural occurring limestones. The mean pore radius in the agglomerates was 20 to 40 times the mean pore radius of natural limestones. The pellets had good attrition resistance compared to hard natural limestones and far superior attrition resistance compared to soft limestone. TGA experiments showed 90% sulfidation conversion for the pelletized limestone compared to 60% conversions of naturally occurring limestones. For sulfation, the pelletized limestone had a conversion of 60% compared to 20% and 30% for two naturally occurring limestones. The agglomerated pellets were 0.85-1.00 mm in diameter and had higher conversions than naturally occurring limestones 1/5 the size. The reason for the high conversions rates is the porosity created by the macro pores. These studies are encouraging in that they suggest that limestone pellets 2-3 mm in diameter can be made which would be attrition resistant and have a high conversion rate in either combustion or gasification environments.

Copper oxide has proved effective as an SO_2 absorber and as a catalyst for the reduction of NOX with ammonia[6]. The optimum temperature for the absorption of SO_2 is 750-800°F. At 1200°F, copper sulfate decomposes to copper oxide. Consequently, this material could not be used for sulfur removal at temperatures above 1000°F and would not be suitable for sulfur removal from the higher temperature gas stream leaving a PFBC.

Amoco Oil Company has developed SO_2 sorbents which they believe would be suitable for capturing SO_2 and particulate in a granular-bed filter[7]. The sorbent also contains catalytic material for the reduction of NOX. It is unknown whether or not such sorbents would remain active when contacting the trace species which are present in coal combustion products. Combustion Power Co. worked with Amoco on the development of a filter for the simultaneous removal of SO_2 and particulate from the off-gas stream of a catalytic cracker in the early 1980's.

6.3.1.2 H_2S Control

The primary candidates for the sorption of H_2S are metal oxides such as iron oxide, zinc ferrite and zinc titinate. General Electric Co. demonstrated a moving bed process using a zinc ferrite sorbent[8]. They reported particulate removal efficiency of 82% for their initial trials. Sorbents such as zinc ferrite or zinc titinate require regeneration. The regeneration of the these compounds has to be carefully controlled because of the exothermic reactions and the temperature limits involved. These sorbents tend to be fragile and have a limited life even in a fixed bed configuration.

Other possible H_2S sorbents are limestone or dolomite. Scott Lynn of Lawrence Berkeley Laboratory is investigating the kinetics of limestone and dolomite in the absorption of H_2S[9]. In bench scale equipment, he was able to achieve 10-12% sulfur absorption and as high as 50% utilization under ideal conditions. The reactions are sensitive to temperature and are carried out just under the calcination temperature of the limestone. Work at Brookhaven National Laboratory has also shown that calcium silicate is capable of absorbing H_2S as well as SO_2[10]. Kawasaki Heavy Industries has developed a granular-bed filter which uses iron oxide as a coating on ceramic spheres to remove H_2S and particulate from gasification products[11].

One possible mode of operation for a granular-bed filter using limestone or dolomite as a media would be as second stage absorber for H_2S. Primary H_2S absorption would occur in the gasifier. The partially sulfided stone from the filter could be returned to the gasifier for further H_2S absorption or it could be oxidized for disposal with the spent sorbent from the gasifier. In this mode of operation, the filter would be used to remove the some remnants of H_2S with primary H_2S removal occurring in the gasifier. In a similar manner, a granular-bed filter with a limestone sorbent could be used as second stage SO_2 removal device with a PFBC.

6.3.2 Control of Nitrogen Compounds

When gasifying coal, the fuel bound nitrogen is partially converted to ammonia and to a lesser extent, to cyanide. When the fuel gas is used as a heat source to a gas turbine, these nitrogen compounds are converted to oxides of nitrogen in the turbine combustor. Catalytic decomposition of ammonia and cyanide before the turbine combustor would significantly reduce the emissions of nitrogen oxides from the gas turbine. Several investigators have evaluated several catalytic materials for this purpose.

SRI Int. performed screening test on possible catalyst[12]. A proprietary nickel catalyst developed by Haldor Topsøe AG, Copenhagen, Denmark was found to be a suitable catalyst at temperatures above 750°C. At lower temperatures, the presence of H_2S poisoned the catalyst. The catalyst was also effective in cracking tar simulant into CO and H_2. In a high steam environment (27% H_2O), the ammonia conversions were over 90%; in a low steam environment, (7% H_2O) ammonia conversion was 70%.

A study of the decomposition of ammonia over dolomite and limestone[13] found that ammonia was decomposed at 800°C when present in an inert carrier. In the presence of a simulated gasification process gas, no ammonia reduction occurred. The reason for the deactivation of the dolomite's catalytic activity was believed to be from the cracking of hydrocarbons such that a carbonaceous residue formed on the stone.

Two nickel catalyst from Ingelhard, Ni-0301 and Ni-1621, proved to be suitable catalyst for the reduction of ammonia[14]. A slip stream from a commercial peat gasifier was passed through beds of test catalysts. At 900°C, the nickel catalysts were extremely effective, yielding nearly complete decomposition of the ammonia. Ferrous dolomite, containing 4.5% iron, reduced ammonia concentrations by 75%, and sintered iron pellets reduced the ammonia concentration by 86% at a temperature of 900°C. At 800°C, these two compounds increased the concentration of ammonia.

From these studies, it is evident that there are catalytic materials which can be used to reduce ammonia in coal gasification streams. The catalysts are most effective at a temperature of 800-900°C. It is likely that a catalytic material could be incorporated into filter media as either a coating on media or as separate media mixed in with the bulk media.

6.3.3 Alkali Control

The presence of alkali species in PFBC or IGCC gas streams is of concern because of the potential corrosion which alkali species can cause in a gas turbine. Alkali species are also associated with low melting compounds which can provide the "glue" for forming deposits on turbine and heat exchanger surfaces. For these reasons, turbine manufactures have placed restrictions on the amount of alkali (sodium and potassium) that can enter a gas turbine. The acceptable levels of alkali in the fuel gas stream entering the turbine combustor ranges from 50 to 200 ppbw[15] depending on the gas temperature and the turbine manufacture. More recent studies give the permissible inlet concentration to the gas turbine itself as 24 ppbw[2,16]. These levels are below expected alkali levels in processed coal streams.

Several investigators have reported that the alkali vapor concentration in PFBC gas range from 0.1 to 10.0 ppmw[17]. Using an extractive technique to pass a slip stream through a bed of activated bauxite, Lee[18,19] found sodium levels of 1.3 to 1.5 ppmw and potassium levels of 0.10 ± 0.01 ppmw from the combustion of Buelah lignite at 9.2 atm and 850-750°C. Ciliberti reported alkali concentration of 0.3 to 16 ppm in the product gas from the Westinghouse pilot scale coal gasifier.

Using an in-situ mass spectrometer, researchers at SRI Int.[20] report vapor concentrations of 0.08 and 0.04 ppm for NaCl and Na_2SO_4 respectively when burning Beulah lignite at 900°C and 1 atm. They also found the sodium vapor concentration was very sensitive to the chlorine content of the coal. Buelah lignite has a chlorine content of <0.01%. When the chlorine content was raised by doping with NaCl, such that the sodium level was raised from 0.042% to 0.062% and the chlorine concentration was raised from <.01% to 0.3%, the NaCl (g) concentration increased from 0.08 ppm to 6.0 ppm. The effect of chlorides on sodium levels found in the SRI study are substantiated by a General Electric study[21]. Combustion results from Illinois #6 coal showed NaCl concentration of less than 0.02 ppm and a $NaSO_4$ of about 0.04 ppm. Initial gasification runs with Buelah lignite showed sodium concentrations of 5.0 ppm. These results are in line with non-equilibrium studies[22] that showed at 823°C the non-equilibrium partial pressure of NaCl vapor is an order of magnitude higher than the equivalent result under combustion conditions. Mojthaedi[23] found that the sodium and potassium levels from the gasification or combustion of peat were above acceptable turbine inlet levels especially during gasification.

At lower temperatures (600°C and less) used in some hot gas clean up systems for gasification processes, the alkali species are completely condensed so that they can be removed with the particulate filter.

The inference from these works is that alkali will need to be controlled from coal combustion streams resulting from coals which have more than a minimum chlorine content and from gasification streams which are not cooled below 800°C.

Various aluminum and silicate compounds have been found to be absorbers of alkali vapors[24]. Figure 69[25] shows the alkali aluminosilicates which can form. The alkali compounds are listed in descending order of their vapor pressure. At fluidized bed conditions, the sulfates are usually present as liquids. The types of aluminum silicates which are effective getters or absorbers of alkali are: activated bauxite, attapulgus clay, calcium montmorillonite clay, diatomaceous earth, and kaolin clay and emathlite clay.[26,27]. Lee[28] tested six possible alkali getters in an experiment in which NaCl vapors were passed through fixed beds of the getters. Activated bauxite and diatomaceous earth effectively capture NaCl, KCl, and K_2SO_4. About 10% of the captured alkali on the activated bauxite were irreversibly, chemically absorbed while the remainder was physically absorbed as a water soluble alkali. Because the activated bauxite captures alkali as a water soluble material, it can be regenerated by a simple water leaching. In contrast the diatomaceous earth was found to capture alkali by chemical reactions. The sorption of alkali by diatomaceous earth increased with temperature while sorption with activated bauxite decreased with temperature. Lee[19] demonstrated the capture of alkali in fixed beds of activated bauxite and diatomaceous earth from a flue gas stream generated by the combustion of Buelah lignite. A small fixed bed of activated bauxite or diatomaceous earth can be used with a gas slip stream to measure the time average alkali concentration, and large fixed bed can be used for the removal and control of alkali in the process stream. Lee developed a mathematical model which can be used to design a fixed bed reactor for the removal of alkali using activated bauxite.

Jain[29] performed sorbent screening experiments by passing sodium chloride vapor through a fixed bed of sorbent particles. The amount of NaCl captured by the sorbent was determined by analysis of the sodium content of the sorbent before and after the experiments. Thirteen sorbents were screened. In terms of weight gain, diatomaceous earth was the most effective followed by attapulgus clay and activated bauxite. Fullers Earth had negligible sorption capacity. Larger scale rate experiments were conducted in a single stage dry plate granular-bed scrubber operated in spouting bed and fixed bed modes using diatomaceous earth, activated bauxite and dolomite. Results showed that either diatomaceous earth or activated bauxite could be used for 99% removal of alkalies using 0.6 to 1.0 mm diameter sorbent with a contact times greater than 0.2 seconds.

Bachovchin[30] found emathlite, a type of fullers earth, to be a leading getter of alkali. The clay has a high capacity for sodium and binds the sodium irreversibly. Water vapors were found to accelerate the reaction but not to be stoichiometrically involved. A wet extrusion process was used to make cylindrical pellets. The commercially produced pellets were considerably less reactive than the laboratory pellets[30]. A kinetic rate expression was developed in which the reaction rate is proportional to the alkali concentration and independent of temperature between 775°C and 900°C.

REACTIVE ALKALI COMPOUNDS		ALUMINOSILICATE ADDITIVE		ALKALI ALUMINOSILICATES*		BYPRODUCTS	
KOH/K_2O				$KAlSi_3O_8$		H_2O	(g)
NaOH/Na_2O				$NaAlSi_3O_8$		O_2	(g)
KCl						HCl	(g)
NaCl	+	$\{xAl_2O_3 \cdot ySiO_2\}$	→	$KAlSi_2O_6$ $NaAlSi_2O_6$	+	SO_x	(g)
K_2CO_3						SiO_2	(s)
Na_2CO_3				$KAlSiO_4$		$3Al_2O_3$ $2SiO_2$	(s)
K_2SO_4				$NaAlSiO_4$			
Na_2SO_4				Plus calcium & mixed alumino-silicates			
(Gas/Vapor & Liquids)		(Solids)		(Solids)		(Gases and/or Solids)	

* Commonly found as feldspars and related compounds in nature, (e.g., orthoclase/sanidine/microcline, albite, leucite, kaliophyllite, nepheline, with anorthite/plagioclase, perthite, etc.)

Figure 69 General Reactions of Alkali Vapors with Aluminosilicate Additives [25] at 1500°-1800°F

Except for fresh pellets, the rate limiting step was found to the diffusion through the glassy reactants. The sorption of alkali was demonstrated in a fixed bed in which 12 kg of pellets were exposed to 500 m^3/hr of gas containing 10 ppmv NaCl at 11 atm and 827°C for up to 102 hours. Sorbent bed depth of 40 cm was able to reduce gas phase NaCl concentrations to 0.2 ppm. It was determined, at extreme conversions, that the sorbent can become sticky; thus causing problems in the operation of the fixed bed. Using the kinetic model, it was predicted that a bed of 1.2 cm diameter pellets with a 3.5 m bed depth would have a life of 4000 hours.

Uberoi[27] found that kaolin, bauxite and emathlite were all capable of removing alkali from coal conversion streams. All sorbents experienced a decrease in absorption rate as the loading increased until the sorbents maximum capacity was reached and the sorption dropped to zero. Kaolin had the highest increase in mass, and bauxite had the highest initial sorption rate. The kaolin and emathlite sorption of alkali is an irreversible process while 10% of the total weight gain of the bauxite was due to physisorption. The maximum sorption capacity of the kaolin was about 25%, while that of the bauxite and emathlite was about 15%.

McLaughlin[26] used a TGA & DTA micro balance to screen alkali sorbents. Thirteen reactive sorbents were found. Calcium montmorillonite was chosen for further investigation. Similar to the finding of Bachovchin[30], water vapor has a significate effect on the amount of alkali which is adsorbed. With a water concentration increase from 0 to 5%, the saturation sorption capacity of the calcium montmorillonite increased from 5 to 12.6%. The presence of HCl vapors reduced the rate and the saturation level of absorption. A 160 ppmv of HCl reduced the saturation capacity of the calcium montmorillonite to 5.5% Na.

These studies indicate that there are several possible getters which can be used for the sorption of alkali from coal process streams. The choice of getter for use with a granular-bed filter will depend on cost and availability of the sorbent and the ability to incorporate the alkali getter into a sulfur sorbent granule.

6.3.4 Trace Species Control

Besides the control of sulfur, alkali, and ammonia, a granular-bed filter has the potential to control other contaminants such as tars and heavy metals. In a gasification environment, activated carbon may be suitable for the capture of heavy metals and possibly the cracking of tars. The 1100-1200°F temperature used in the zinc ferrite process for the absorption of H_2S would be at the upper temperature limit for the use of activated carbon. It may be possible to incorporate activated carbon into granular-bed filter media or use it as an additive to the gas stream before the filter.

Recent work by Uberoi at the University of Arizona indicates the potential of porous solids such as bauxite, kaolin or activated alumina for the absorption of heavy metals such as lead or cadmium[31]. These same materials have proven effective in the capture of alkali metals from flue gas streams; so that, a system designed for alkali removal may also be effective in the removal of heavy metals.

Screening tests showed that bauxite was considerably more effective than kaolinite for the sorption of cadmium vapors[32]. Examination of the kaolinite particles showed that the surface of the kaolinite was almost completely reacted but that interior was un-reacted, indicating pore blocking by the product layer. The use of kaolinite in a agglomerated pellet with large micro-pores may allow higher utilization just as it does for the sorption of sulfur species by limestone agglomerates. The theoretical sorption capacity of cadmium by kaolinite is a 51% weight increase which can be compared to a 19% weight gain of kaolin flakes which were only reacted on their surface. The kaolinite had a lower water soluble fraction of sorbed cadmium than the bauxite which is desirable from the point of view of ultimate disposal.

Uberoi[33] also studied the sorption of lead vapors by various sorbents. Kaolinite proved to be the most effective sorbent evaluated. Theoretically the kaolinite can sorb 94% of its weight, forming in-soluble lead compounds. The measured weight gains were close to this value, indicating high utilization of the kaolinite.

Mojtahedi[23] studied the removal of zinc and lead vapors from simulated flue gases. Limestone removed 81% of the zinc vapors and 41% of lead vapors. Dolomite with its more open pore structure removed 82% of lead vapors and 19% of the Zinc vapors.

These studies show that a limestone/clay pellet has excellent potential for the removal of lead, cadmium and zinc from either gasification or combustion streams.

6.3.5 Halogen Control

Chlorine and fluorine are present in coal as trace quantities; and as such, are found in coal gasification streams in concentrations ranging from 50 to 1000 ppm. These elements form acidic compounds which can cause acidic corrosion in downstream equipment such as gas turbine components and heat exchangers and cause poisoning of molten carbonate fuel cell electrodes[34]. They also represent the release of acidic compounds to the environment. For these reasons it would be desirable to remove halogen contamination from coal gasification streams before the gas turbine.

Researchers at SRI Int. found that Nahcolite, the natural occurring mineral form of NaHCO3, is an effective sorbent of HCl[35]. The nahcolite was pelletized and calcined at 600°C, and had an eighty percent conversion in 250 minutes. The inlet concentration of 300 ppm of HCl was reduced to 1.0 ppm before break through occurred.

Researchers at Twente University[5] found that calcined pellets of limestone were effective in absorbing HCl. The CaO reacts with HCl to form $CaCl_2$. At 600°C, a 70% conversion of CaO was obtained after 25 minute exposure and 80% conversion was obtained after 66 minutes. While both CaO and Na_2CO3 are both capable of reacting with HCl, equilibrium calculations show that the equilibrium partial pressure of HCl with Na_2CO3 is $1.5x10^{-6}$ atm while that of CaO is $9.5x10^{-4}$ atm[35], so that Na_2CO3 has the potential to obtain lower concentrations of HCl.

Either of the above approaches utilize pelletized material which could be used as a reactive media in a granular-bed filter. The work at Twente University demonstrated that the limestone pellets have good attrition characteristic after calcining.

6.4 Developmental Work Plan for Multi-Contaminant GBF

6.4.1 Literature Review and Definition of Contaminant Levels

In this work step, which has already been started, a detailed review of the literature will be completed. The purpose of the review will be to identify and rank candidate sorbents for control of contaminants. Particular emphasis will be on gathering data that can be used to design a process using the candidate sorbents. The review of literature on alkali control is nearly complete and as a result the background section on alkali is considerable more detailed than the other section.

6.4.2 Process Definition

Based on the literature review and the potential conceptual designs already described, candidate processes for multi-contaminant control which could be incorporated into a granular-bed filter will be identified. To large extent this has already occurred, with preliminary results described in section 6.2. The concepts may change as more detailed information is collected. Flow sheets for potential processes will be developed. Primary emphasis will be on the development of processes for the further reduction of SO_2 and alkali from a pressurized fluidized-bed combustor and for the removal of H_2S, alkali and ammonia from gasification streams or halogen removal from lower temperature gasification streams.

In terms of filter configurations, both single and dual media filters will be evaluated. Once through media and regenerating media will be evaluated for the control of SO_2, H_2S, ammonia, alkali, tars, and heavy metals. Both mixed media and dual function single media will be evaluated.

A consultant, will be used to analyze the flow patterns through filter configurations with dual media. Previous work using computational fluid mechanics, was useful in predicting the flow field and pressure in the granular-bed filter designed for particulate collection. A chemical engineering consultant will be used to help design the chemical reactors used in the multi-contaminant control, granular-bed filter (GBF).

6.4.3 Basis of Conceptual Design

The conceptual designs of a multi-contaminant control, GBF will be based on the same size power plants that are being used in this program. The multi-contaminant control GBF will be applied to a second generation Pressurized Fluidized Bed Combustor (PFBC) being developed by Foster Wheeler[36]. For this application , we proposed using 10 granular-bed filters for particulate control. Eight filters are used on the flue gas from the PFB combustors with each filter having a capacity of 44,000 ACFM at 190 psia and 1600°F. Two filters are used on the fuel gas from the carbonizers with each filter having a capacity of 15,800 ACFM at 208 psia and 1500°F. In addition to the PFBC application, a multi-contaminant control GBF will be used in the KRW integrated combined cycle[37]. The IGCC filter will have a capacity of 12,600 ACFM at 385 psia and 1600°F. It is our goal that the multi-contaminant control GBF's have the same capacity as the GBF's proposed for particulate control.

6.4.4 Test Plans for Proof of Concept Testing

Having determined possible processes for multi-contaminant control, proof of concept testing will be required to establish feasibility of the proposed processes. In order to conduct the proof of concept testing, test plans and conceptual designs of the test equipment will be prepared. Actual testing will occur in the next phase of the program after approval of the test plans by DOE.

Test plans and test equipment designs will focus on the following areas:

- Manufacture and procurement of candidate sorbents
- Determination of size and chemical composition of candidate sorbents
- Thermal shock, crush strength, and dynamic attrition resistance of candidate sorbents
- Sorption capacity and kinetics of sorbent reactions
- For each filter configuration, control and distribution of media, media flow patterns, gas flow patterns and filter pressure drop.
- potential impact of multi-contaminant control on particulate removal efficiency

Test descriptions will include: objectives, experimental procedures, operating conditions, test duration, number of tests, experimental data to be collected during tests and post test inspections. An estimated cost of the experimental facilities and the proposed test programs will be determined.

6.4.5 Topical Report

The results of the conceptual design study for a multi-contaminant GBF and the proposed test plans for proof of concept testing will be reported in a topical report.

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SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

This economic study shows that the granular-bed filter compares favorably with the ceramic candle filter from an economic standpoint. For the granular-bed filters, the capital costs are less, the projected maintenance costs are less, the costs of electricity are less. To illustrate, see Table 60.

The granular-bed filter was proven to be feasible in the tests at NYU. The new filter design has the same basic configuration, but different proportions. A new test series needs to be arranged to show that the design is practical. Presumably, this can be resolved at the Southern Company Services test facility that is being designed at this time.

- CPFBC Filters

For the 452 MWe second generation PFB combustion plant, the savings in capital cost for the CPFBC, granular-bed filter instead of the candle filter is about 28%.

Capital costs for the candle filter include the eight filters vessels, pulse air compressor system, and ash depressurizing and cooling equipment. Capital costs for the granular-bed filter include the eight filter vessels, filter media circulation system, and ash cooling and depressurizing equipment. In EPRI TAG terminology, these are the *bare erected costs* as they include equipment, suppliers engineering, and installation, but none of the *process or project contingencies*. Costs are in December, 1991 dollars.

The estimated savings in yearly maintenance for the granular-bed filter is 59%. The major component of maintenance for the filters is the 4% of the capital cost applied according to EPRI TAG guidelines. For the CPFBC candle filter, the major contributor to the additional expense is the cost of replacement filter elements at $985,000/yearly assuming 1/3 candles per year.

Electrical loads for both filter plants are within 10%, with the candle filter lowest. The comparison is for all electrical loads associated with the filter equipment, and includes, pulse compressors for the candle filters, boost blowers for the granular-bed filters, and ash cooling equipment for both filters.

- Carbonizer Filters

For the 452 MWe second generation PFB combustion plant, the savings in capital cost for the carbonizer, granular-bed filter instead of the candle filter is about 14%.

Capital costs for the candle filter include the two filters vessels, pulse air compressor system, but no ash system; since, the Foster Wheeler study assumes the filter discharges hot ash directly to adjacent combustion equipment. Capital costs for the granular-bed filter include two filter vessels, filter media circulation system, and ash cooling and depressurizing equipment.

Table 60 Filter Comparisons

Cost Item	Plant with Granular-Bed Filters	Plant with Candle Filters
452.8 Second Generation PFB Combustion Plant		
CPFBC Filters		
Capital Cost, k$	27,339	38,187
$/kW	60.4	84.3
Filter Maint., k$/yr	1,040	2,522
Electric Load, kVa	349	318
Carbonizer Filters		
Capital Cost, k$	5,851	6,795
$/kW	12.9	15.0
Filter Maint., k$/yr	286	619
Electric Load, kVa	59	123
Cost of Electricity		
Current $, mills/kWh	74.1	76.5
Constant $, mills/kWh	52.8	54.5
100 MWe KRW Gasifier Plant		
Hot Gas Filters		
Capital Cost, k$	3,775	4,458
$/kW	37.8	44.6
Filter Maint., k$/yr	156	300
Electric Load, kVa	22	84
Cost of Electricity		
Current $, mills/kWh	133.2	134.0
Constant $, mills/kWh	91.8	92.4

The estimated yearly maintenance for the carbonizer granular-bed filter is 46% of the candle filter maintenance. The major component of maintenance for both filters is the 4% of the capital cost applied according to EPRI TAG guidelines. For the candle filter, the major contributor to the additional expense is the cost of replacement filter elements at $222,000/yearly assuming 1/3 candles per year. Another significant cost is the replacement of filter internals due to corrosion in the reducing atmosphere. The yearly allocation for this item is $32,000 for the granular-bed filter and $97,000 for the candle filter.

Electrical loads for the granular-bed filter plant is estimated at slightly less than 50% than that of the candle filter plant. The main reason is that the boost blower horsepower drops considerably in comparison to the CPFBC filters due to the smaller media circulation system; because the flow varies as the square of the lift pipe size. On the other hand, the pulse gas flow for the candle filter does not decrease as dramatically, because is depends on other parameters. The comparison is for all electrical loads associated with the filter equipment, and includes ash cooling equipment for both filters.

- Cost of Electricity for Second Generation PFB Combustion Plant

Both the CPFBC and the carbonizer filters are included in the values for cost of electricity (COE). The COE is for the entire power generation plant and varies by 1.7 mills/kWh in constant dollars; the lower COE is for the plant with granular-bed filters. The values given in Table 60 include the capital costs and maintenance costs listed above. When the electrical loads are taken into account, the COE values listed above, all increase by 0.1 mills/kWh.

- KRW Gasifier Filters

For the 100 MWe KRW gasifier plant, the savings in capital cost for the granular-bed filter instead of the candle filter is about 15%.

Capital cost for the candle filter includes one filter vessel, pulse air compressor system, and ash depressurizing and cooling equipment. Capital cost for the granular-bed filter includes one filter vessel, filter media circulation system, and ash cooling and depressurizing equipment. Costs are in December, 1991 dollars.

The estimated savings in yearly maintenance for the granular-bed filter is 48%. The major component of maintenance for the filters is the 4% of the capital cost applied according to EPRI TAG guidelines. For the candle filter, the major contributor to the additional expense is the cost of replacement filter elements at $89,000/yearly assuming 1/3 candles per year. Another significant cost is the replacement of filter internals due to corrosion in the reducing atmosphere. The yearly allocation for this item is $17,000 for the granular-bed filter and $44,000 for the candle filter.

Electrical loads for the granular-bed filter plant is estimated at slightly less than 30% than that of the candle filter plant. The explanation is similar to that for the carbonizer filters; in that, the boost blower horsepower for the granular-bed filter diminishes with filter capacity more significantly than the pulse gas for the candle filter. The comparison is for all electrical loads associated with the filter equipment, and includes ash cooling equipment for both filters.

- Cost of Electricity for KRW Gasifier Plant

The COE is for the entire power generation plant and varies by 0.6 mills/kWh in constant dollars with the lower value associated with the plant including granular-bed filters. The values given in Table 60 include the capital costs and maintenance costs listed above. When the electrical loads are taken into account, the COE values listed all increase by 0.1 mills/kWh.

- Multi-Contaminant Granular-Bed Filter

Besides removing particulate, a granular-bed filter has the potential of removing other pollutants in the gas stream. The filter is an excellent gas/solids contactor; in that, it has gas residence times in the order of several seconds, solids residence times in the order of several hours, uniform gas flow across the media, and the gas and filter media flow in opposite directions for the maximum driving potential. The contaminants of major concern, besides particulate in coal utilization processes, are sulfur compounds, nitrogen compounds, alkali compounds, halogenated compounds, tars, and trace contaminants such as cadmium and mercury.

The objective is to develop granular-bed filters that are capable of removing a combination of pollutants in high temperature and high pressure (HTHP) gas streams from processes being developed for advanced coal utilization. Although we are still in the initial stages of our study on multi-comtaminant control, we have narrowed the many possible approaches down to a single concept. The media used in the granular-bed filter could be composed of two distinct size distributions. Larger, six mm diameter, spheres could be the same inert media used for particulate control. In addition to this media, a smaller (2 to 3 mm diameter) media could be supplied which would be chemically reactive and have a finite life.

Having determined possible processes for multi-contaminant control, proof of concept testing will be required to establish feasibility of the proposed processes. In order to conduct the proof of concept testing, test plans and conceptual designs of the test equipment will be prepared. Actual testing will occur in the next phase of the program after approval of the test plans by DOE.

SECTION 8

ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CPC	Combustion Power Company
CPFBC	Circulating Pressurized Fluidized Bed Combustion
COE	Cost of Electricity
DCFT	Direct Coal-Fired Turbine
DOE	Department of Energy
EPRI	Electric Power Research Institute
FWDC	Foster Wheeler Development Corporation
FWEC	Foster Wheeler Energy Corporation
GBF	Granular-Bed Filter
HGCU	Hot Gas Clean Up
HHV	Higher Heating Value
HTHP	High Temperature High Pressure
I & C	Instrumentation and Control
IGCC	Integrated Gasification Combined-Cycle
KRW	Kellogg-Rust-Westinghouse
LHV	Lower Heating Value
LMTD	Log Mean Temperature Difference
METC	Morgantown Energy Technology Center
NPHR	Net Plant Heat Rate
NSPS	New Source Performance Standards
NYU	New York University
PFB	Pressurized Fluidized Bed
PFBC	Pressurized Fluidized Bed Combustion
RPD	Restricted Pipe Discharge
TAG	Technical Assessment Guide (EPRI)
TCR	Total Capital Requirement
TPC	Total Plant Cost
TPI	Total Plant Investment

APPENDIX

APPENDIX A

Lotus 1-2-3 Spreadsheet Results

The COE is calculated using the "Lotus Cost of Electricity Spreadsheet" by T. J. Hand, December 1988 which was supplied by the Morgantown Energy Technology Center (METC). This spreadsheet is based on methodology developed in the Technical Assessment Guide (TAG), published by the Electric Power Research Institute (EPRI), Volume I, EPRI-4463-SR, December, 1986.

In Tables 1, 2, and 3, the spreadsheet calculations are displayed for the 452 MWe, Foster Wheeler, second generation pressurized fluidized bed combustion (PFBC) plant. These values are based on the PFBC plant utilizing a ceramic cross-flow filter. The COE calculated by Foster Wheeler in Table 1, follows EPRI TAG methodology, but was accomplished without the benefit of the spreadsheet supplied by METC. Values for *total capital requirement*, *fuel cost*, and *operation & maintanence* are those detemined by Foster Wheeler. Levelizing factors and the resultant COE were also determined by Foster Wheeler. The COE calculatation shown in Table 2 is the same information adjusted to appropriate spreadsheet methodology. In Table 3, the costs presented in Table 2 are adjusted for escalation to Dec 1991 per EPRI TAG guidelines.

The main reasons for the differences between the costs given by Foster Wheeler for the base costs, Table 1, and the costs calculated by the spreadsheet, Table 2, are given below:

- *Project contingency* is 15% of *process plant cost* plus *general plant facilities* plus *engineering* plus *process contingency* in the Foster Wheeler study. In the Lotus spreadsheet, based on the 1986 EPRI TAG, *project contingency* is a percentage of *process plant cost* plus *general plant facilities* only.

- Capital cost for spares was not detailed in the Foster Wheeler, base costs, but added into subsequent costing at 0.5% of the *total plant cost* per the spreadsheet.

- The cost for *operation & maintenance* in Table 2, is increased by the cost of *insurance & local taxes* at 2% of the *total plant cost* ($8,086,000) and by *other operating costs* ($901,000) which is a function of *operation labor* and *maintenance costs* in the spreadsheet.

- Although there is difference in tax life and tax rates between the Foster Wheeler study and the spreadsheet, this does not account for the different levelizing factors used in the calculation of the COE. Tenth year levelized dollars is used in the spreadsheet calculation: whereas, the Foster Wheeler study uses first year levelized costs.

In Table 1, the Foster Wheeler results are shown in the spreadsheet format, but many of the spreadsheet calculations are overridden by inserting constants from the Foster Wheeler report. Furthermore a third column was added to Table 1, spreadsheet part "C. Cost Of Electricity", to input the levelizing factors used by Foster Wheeler. The Foster Wheeler report on the second generation pressurized fluidized bed combustion (PFBC) plant reports a total cost of electricity of 75.7 mills/kWh.

Table 2 presents the base costs of the second generation PFBC. The values presented are calculated by the spreadsheet methodology, and are based on the 1986 EPRI TAG. For this reason there are minor differences in the values for *startup costs* and *working capital*. In some cases where Foster Wheeler has presented information that differs with the assumptions made in the spreadsheet, the Foster Wheeler values are used. A 3.5 year *plant construction period* is assumed for this reason as is a 6.0%/yr inflation rate and the 0.8%/yr *real escalation rate* (over inflation) for fuel. Levelizing factors calculated by the spreadsheet are in tenth year levelized dollars.

Escalated plant costs, in Table 3, were attained by applying the *Chemical Engineering Plant Cost Index* to applicable plant sections and by applying escalation factors recommended by the 1989 EPRI TAG to portions of the annual operating costs. The *Chemical Engineering Plant Cost Index* for December, 1987 is 332.5 and the value for December, 1991 is 359.3. Not all items in the *total capital requirement* (TCR) are adjusted by this index, as some items are factored from other costs. Inflation used in the calculation of levelizing factors is 4%, and the *real escalation rate* (over inflation) for fuel is 0.7% per year as recommended in the spreadsheet. The annual operating costs are taken from the 1989 EPRI TAG if listed, and from the Foster Wheeler report otherwise. Inflation applied to the operating costs is 5% as recommended by the 1989 EPRI TAG. Note that while the methodology used in the calculation of the COE is based on the 1986 EPRI TAG, escalation of some of the operation costs and fuel costs is based on the 1989 edition of the EPRI TAG.

Table 1. Base Costs of the Second Generation PFBC Combustion Plant

05/07/93 ELECTRIC POWER GENERATION COST - Version 1.12

2ND GENERATION PFB 453 MW POWER PLANT

CAPITAL REQUIREMENTS (Dec 1987 Dollars)

Total Plant Investment

AREA NO	PLANT SECTION DESCRIPTION	PROCESS CONT, %	COST, K$ W/O CONT
1	COAL AND SORBENT HNDLG	0	$32,763
2	COAL AND SORBENT PREP	3	$20,673
3	FEEDWATER AND MISC BOP SYSTEMS	0	$18,299
4	CARBONIZER, CPFBC & CPFBC FBHE	17	$46,891
5	HOT GAS CLEANUP AND PIPING	5	$27,314
6	COMBUSTION TURBINE /ACCESSORIES	9	$51,528
7	HRSG, DUCTING AND STACK	13	$24,948
8	STEAM TURBINE GENERATOR	0	$34,286
9	COOLING WATER SYSTEM	0	$9,046
10	ASH / SPENT SORBENT HNDL SYSTEM	12	$7,335
11	ACCESSORY ELECTRIC PLANT	0	$13,077
12	INSTRUMENTATION AND CONTROL	0	$10,644
13	IMPROVEMENTS TO SITE	0	$8,784
14	BUILDINGS AND STRUCTURES	0	$11,367

Subtotal, Process Plant Cost	$316,955
General Plant Facilities	$0
Engineering Fees	$20,602
Process Contingency (Using contingencies listed above)	$19,189
Project Contingency, 15 % Proc Plt & Gen Plt Fac	$53,512
Total Plant Cost (TPC)	$410,258
Plant Construction Period, 3.5 Years (1 or more)	
Construction Interest Rate, 12.5 %	
Adjustment for Interest and Inflation	$33,702
Total Plant Investment (TPI)	$443,961
Prepaid Royalties	$0
Initial Catalyst and Chemical Inventory	$0
Startup Costs	$12,585
Spare Parts	$0
Working Capital	$11,458
Land, 200 Acres	$1,500
Total Capital Requirement (TCR)	$469,504

Table 1. Base Costs of the Second Generation PFBC Combustion Plant (Continued)

ANNUAL OPERATING COSTS

Capacity Factor = 65 %

COST ITEM		QUANTITY	UNIT $ PRICE	ANNUAL COST, K$
PITTS NO.8 COAL	Fuel Type	3413.5 T/D	$44.57 /T	$36,095
Consumable Materials				
DOLOMITE		987.8 T/D	$17.90 /T	$4,195
WATER		23136.3 T/D	$0.17 /T	$946
FUEL OIL		15.2 T/D	$205.48 /T	$743
MISC.ITEMS		3529.0 T/D	$1.00 /T	$837
Ash/Sorbent Disposal Costs		1093.7 T/D	$7.60 /T	$1,972
Plant Labor				
Oper Labor (incl benef)		26 Men/shift	$23.55 /Hr.	$5,350
Supervision & Clerical				$2,704
Maintenance Costs				$9,157
Insurance & Local Taxes				$0
Royalties				$0
Other Operating Costs				$0
Total Operating Costs				$61,999
By-Product Credits				
____		____ T/D	____ /T	$0
____		____ T/D	____ /T	$0
____		____ T/D	____ /T	$0
____		____ T/D	____ /T	$0
Total By-Product Credits				$0
Net Operating Costs				$61,999

Table 1. Base Costs of the Second Generation PFBC Combustion Plant (Continued)

BASES AND ASSUMPTIONS

A. CAPITAL BASES AND DETAILS

	QUANTITY	UNIT $ PRICE	COST, K$
Initial Catalyst Inventory			
______________	_____ lb.	_____ /lb.	$0
______________	_____ lb.	_____ /lb.	$0
______________	_____ lb.	_____ /lb.	$0
______________	_____ lb.	_____ /lb.	$0
Initial Chemicals Inventory			
______________	_____ lb.	_____ /lb.	$0
______________	_____ lb.	_____ /lb.	$0
______________	_____ lb.	_____ /lb.	$0
______________	_____ lb.	_____ /lb.	$0
Total Catalyst and Chemical Inventory			$0
Startup costs			
Plant modifications,	2 % TPI		$8,879
Operating costs			$2,514
Fuel			$1,141
Total Startup Costs			$12,534
Working capital			
Fuel & Consumables inv,	60 days supply		$10,828
By-Product inventory,	30 days supply		$0
Direct expenses,	30 days		$965
Total Working Capital			$11,793

Table 1. Base Costs of the Second Generation PFBC Combustion Plant (Continued)

B. ECONOMIC ASSUMPTIONS

Project life	30 Years
Book life	30 Years
Tax life	15 Years
Federal and state income tax rate	40.0 %
Tax depreciation method	ACRS
Investment Tax Credit	0.0 %

Financial structure

Type of Security	% of Total	Current Dollar Cost, %	Current Dollar Ret, %	Constant Dollar Cost, %	Constant Dollar Ret, %
Debt	50	11.0	5.5	4.6	2.3
Preferred Stock	15	11.5	1.7	5.2	0.8
Common Stock	35	15.2	5.3	8.7	3.0
Discount rate (cost of capital)			12.5		6.1

Inflation rate, % per year	6.0
Real Escalation rates (over inflation)	
Fuel, % per year	0.8
Operating & Maintenance, % per year	0.0

C. COST OF ELECTRICITY

The approach to determining the cost of electricity is based upon the methodology described in the Technical Assessment Guide, published by the Electric Power Research Institute, Volume I, EPRI-4463-SR, December 1986. The cost of electricity is stated in terms of 10th year levelized dollars. Insurance and local taxes are accounted for explicitly in cell H87, rather than including it in Capital Charges as does EPRI TAG.

	Current $	FW $	Constant $
Levelizing Factors			
Capital Carrying Charge, 10th year	0.178	0.173	0.104
Fuel, 10th year	1.375	1.9	1.041
Operating & Maintenance, 10th year	1.321	1.75	1.000
	mills/kWh	->	mills/kWh
Cost of Electricity - Levelized			
Capital Charges	32.4	31.5	19.0
Fuel costs	19.2	26.6	14.6
Operating & Maintenance	13.3	17.6	10.0
Total Cost of Electricity	64.9	75.7	43.6

Table 2. Second Generation PFBC Costs Adjusted to EPRI TAG

05/07/93 ELECTRIC POWER GENERATION COST - Version 1.12

2ND GENERATION PFB 453 MW POWER PLANT

CAPITAL REQUIREMENTS (Dec 1987 Dollars)

Total Plant Investment

AREA NO	PLANT SECTION DESCRIPTION	PROCESS CONT, %	COST, K$ W/O CONT
1	COAL AND SORBENT HNDLG	0	$32,763
2	COAL AND SORBENT PREP	3	$20,673
3	FEEDWATER AND MISC BOP SYSTEMS	0	$18,299
4	CARBONIZER, CPFBC & CPFBC FBHE	17	$46,891
5	HOT GAS CLEANUP AND PIPING	5	$27,314
6	COMBUSTION TURBINE /ACCESSORIES	9	$51,528
7	HRSG, DUCTING AND STACK	13	$24,948
8	STEAM TURBINE GENERATOR	0	$34,286
9	COOLING WATER SYSTEM	0	$9,046
10	ASH / SPENT SORBENT HNDL SYSTEM	12	$7,335
11	ACCESSORY ELECTRIC PLANT	0	$13,077
12	INSTRUMENTATION AND CONTROL	0	$10,644
13	IMPROVEMENTS TO SITE	0	$8,784
14	BUILDINGS AND STRUCTURES	0	$11,367

Subtotal, Process Plant Cost	$316,955
General Plant Facilities	$0
Engineering Fees	$20,602
Process Contingency (Using contingencies listed above)	$19,189
Project Contingency, 15 % Proc Plt & Gen Plt Fac	$47,543
Total Plant Cost (TPC)	$404,289
Plant Construction Period, 3.5 Years (1 or more)	
Construction Interest Rate, 12.5 %	
Adjustment for Interest and Inflation	$31,947
Total Plant Investment (TPI)	$436,236
Prepaid Royalties	$0
Initial Catalyst and Chemical Inventory	$0
Startup Costs	$13,118
Spare Parts	$2,021
Working Capital	$11,793
Land, 200 Acres	$1,500
Total Capital Requirement (TCR)	$464,668

Table 2. Second Generation PFBC Costs Adjusted to EPRI TAG (Continued)

ANNUAL OPERATING COSTS

Capacity Factor = 65 %

COST ITEM		QUANTITY	UNIT $ PRICE	ANNUAL COST, K$
PITTS NO.8 COAL	Fuel Type	3413.5 T/D	$44.57 /T	$36,095
Consumable Materials				
DOLOMITE		987.8 T/D	$17.90 /T	$4,195
WATER		23136.3 T/D	$0.17 /T	$946
FUEL OIL		15.2 T/D	$205.48 /T	$743
MISC.ITEMS		3529.0 T/D	$1.00 /T	$837
Ash/Sorbent Disposal Costs		1093.7 T/D	$7.60 /T	$1,972
Plant Labor				
Oper Labor (incl benef)		26 Men/shift	$23.55 /Hr.	$5,350
Supervision & Clerical				$2,704
Maintenance Costs				$9,157
Insurance & Local Taxes				$8,086
Royalties				$0
Other Operating Costs				$901
	Total Operating Costs			$70,986
By-Product Credits				
________		____ T/D	____ /T	$0
________		____ T/D	____ /T	$0
________		____ T/D	____ /T	$0
________		____ T/D	____ /T	$0
	Total By-Product Credits			$0
	Net Operating Costs			$70,986

Table 2. Second Generation PFBC Costs Adjusted to EPRI TAG (Continued)

BASES AND ASSUMPTIONS

A. CAPITAL BASES AND DETAILS

	QUANTITY	UNIT $ PRICE	COST, K$
Initial Catalyst Inventory			
DOLOMITE	59268 lb.	$17.90 /lb.	$0
SECONDARY FUEL,GAL	250000 lb.	$0.75 /lb.	$0
GASES,N2,/100SCF	302400 lb.	$0.29 /lb.	$0
______	______ lb.	______ /lb.	$0
Initial Chemicals Inventory			
______	______ lb.	______ /lb.	$0
______	______ lb.	______ /lb.	$0
______	______ lb.	______ /lb.	$0
______	______ lb.	______ /lb.	$0
Total Catalyst and Chemical Inventory			$0
Startup costs			
Plant modifications,	2 % TPI		$8,725
Operating costs			$3,252
Fuel			$1,141
Total Startup Costs			$13,118
Working capital			
Fuel & Consumables inv,	60 days supply		$10,828
By-Product inventory,	30 days supply		$0
Direct expenses,	30 days		$965
Total Working Capital			$11,793

Table 2. Second Generation PFBC Costs Adjusted to EPRI TAG (Continued)

B. ECONOMIC ASSUMPTIONS

Project life	30 Years
Book life	30 Years
Tax life	20 Years
Federal and state income tax rate	38.0 %
Tax depreciation method	ACRS
Investment Tax Credit	0.0 %

Financial structure

Type of Security	% of Total	Current Dollar Cost, %	Current Dollar Ret, %	Constant Dollar Cost, %	Constant Dollar Ret, %
Debt	50	11.0	5.5	4.6	2.3
Preferred Stock	15	11.5	1.7	5.2	0.8
Common Stock	35	15.2	5.3	8.7	3.0
Discount rate (cost of capital)			12.5		6.1

Inflation rate, % per year	6.0
Real Escalation rates (over inflation)	
Fuel, % per year	0.8
Operating & Maintenance, % per year	0.0

C. COST OF ELECTRICITY

The approach to determining the cost of electricity is based upon the methodology described in the Technical Assessment Guide, published by the Electric Power Research Institute, Volume I, EPRI-4463-SR, December 1986. The cost of electricity is stated in terms of 10th year levelized dollars. Insurance and local taxes are accounted for explicitly in cell H87, rather than including it in Capital Charges as does EPRI TAG.

	Current $	Constant
Levelizing Factors		
Capital Carrying Charge, 10th year	0.175	0.103
Fuel, 10th year	1.375	1.041
Operating & Maintenance, 10th year	1.321	1.000
	mills/kWh	mills/kWh
Cost of Electricity - Levelized		
Capital Charges	31.6	18.6
Fuel costs	19.2	14.6
Operating & Maintenance	17.9	13.5
Total Cost of Electricity	68.7	46.7

Table 3. Second Generation PFBC Costs with Escalation to Dec, 1991

05/07/93 ELECTRIC POWER GENERATION COST - Version 1.12

2ND GENERATION PFB 453 MW POWER PLANT

CAPITAL REQUIREMENTS (Dec 1991 Dollars)

Total Plant Investment

AREA NO	PLANT SECTION DESCRIPTION	PROCESS CONT, %	COST, k$ W/O CONT
1	COAL AND SORBENT HNDLG	0	$35,404
2	COAL AND SORBENT PREP	3	$22,339
3	FEEDWATER AND MISC BOP SYSTEMS	0	$19,774
4	CARBONIZER, CPFBC & CPFBC FBHE	17	$50,670
5	HOT GAS CLEANUP AND PIPING	5	$29,516
6	COMBUSTION TURBINE /ACCESSORIES	9	$55,681
7	HRSG, DUCTING AND STACK	13	$26,959
8	STEAM TURBINE GENERATOR	0	$37,050
9	COOLING WATER SYSTEM	0	$9,775
10	ASH / SPENT SORBENT HNDL SYSTEM	12	$7,926
11	ACCESSORY ELECTRIC PLANT	0	$14,131
12	INSTRUMENTATION AND CONTROL	0	$11,502
13	IMPROVEMENTS TO SITE	0	$9,492
14	BUILDINGS AND STRUCTURES	0	$12,283

Subtotal, Process Plant Cost	$342,502
General Plant Facilities	$0
Engineering Fees	$22,263
Process Contingency (Using contingencies listed above)	$20,736
Project Contingency, 15 % Proc Plt & Gen Plt Fac	$51,375
Total Plant Cost (TPC)	$436,876
Plant Construction Period, 3.5 Years (1 or more)	
Construction Interest Rate, 12.5 %	
Adjustment for Interest and Inflation	$46,475
Total Plant Investment (TPI)	$483,351
Prepaid Royalties	$0
Initial Catalyst and Chemical Inventory	$0
Startup Costs	$14,528
Spare Parts	$2,184
Working Capital	$13,487
Land, 200 Acres	$1,500
Total Capital Requirement (TCR)	$515,051

Table 3. Second Generation PFBC Costs with Escalation to Dec, 1991 (Continued)

ANNUAL OPERATING COSTS

Capacity Factor = 65 %

COST ITEM	QUANTITY	UNIT $ PRICE	ANNUAL COST, K$	
PITTS NO.8 COAL Fuel Type	3413.5 T/D	$51.60 /T	$41,786	
Consumable Materials				
WATER	5575.0 1000 GAL/	$0.69 /1000 GAL	$919	
DOLOMITE	987.8 T/D	$21.76 /T	$5,099	
H2O MAKEUP/TREAT	5110.0 LB/D	$0.17 /LB	$206	
LIQUID EFF	13520 LB/D	$0.12 /LB	$390	
FUEL OIL	4175.0 GAL/D	$0.61 /GAL	$608	
GASES N2, ect.	5040 100 SCF/D	$0.35 /100 SCF	$421	
Ash/Sorbent Disposal Costs	1093.7 T/D	$9.26 /T	$2,403	
Plant Labor				10046.15
Oper Labor (incl benef)	26 Men/shift	$23.15 /Hr.	$5,273	
Supervision & Clerical			$2,771	
Maintenance Costs			$9,908	
				17952.13
Insurance & Local Taxes			$8,738	
Royalties			$0	
Other Operating Costs			$924	
Total Operating Costs			$79,445	
By-Product Credits				
____	____ T/D	____ /T	$0	
____	____ T/D	____ /T	$0	
____	____ T/D	____ /T	$0	
____	____ T/D	____ /T	$0	
Total By-Product Credits			$0	
Net Operating Costs			$79,445	

Table 3. Second Generation PFBC Costs with Escalation to Dec, 1991 (Continued)

BASES AND ASSUMPTIONS

A. CAPITAL BASES AND DETAILS

		QUANTITY	UNIT $ PRICE	COST, k$
Initial Catalyst Inventory				
	______	______ lb.	______ /lb.	$0
	______	______ lb.	______ /lb.	$0
	______	______ lb.	______ /lb.	$0
	______	______ lb.	______ /lb.	$0
Initial Chemicals Inventory				
	______	______ lb.	______ /lb.	$0
	______	______ lb.	______ /lb.	$0
	______	______ lb.	______ /lb.	$0
	______	______ lb.	______ /lb.	$0
Total Catalyst and Chemical Inventory				$0
Startup costs				
Plant modifications,		2 % TPI		$9,667
Operating costs				$3,540
Fuel				$1,321
Total Startup Costs				$14,528
Working capital				
Fuel & Consumables inv,		60 days supply		$12,500
By-Product inventory,		30 days supply		$0
Direct expenses,		30 days		$987
Total Working Capital				$13,487

Table 3. Second Generation PFBC Costs with Escalation to Dec, 1991 (Continued)

B. ECONOMIC ASSUMPTIONS

Project life	30 Years
Book life	30 Years
Tax life	20 Years
Federal and state income tax rate	38.0 %
Tax depreciation method	ACRS
Investment Tax Credit	0.0 %

Financial structure

Type of Security	% of Total	Current Dollar Cost, %	Current Dollar Ret, %	Constant Dollar Cost, %	Constant Dollar Pet, %
Debt	50	11.0	5.5	4.6	2.3
Preferred Stock	15	11.5	1.7	5.2	0.8
Common Stock	35	15.2	5.3	8.7	3.0
Discount rate (cost of capital)			12.5		6.1

Inflation rate, % per year	4.0
Real Escalation rates (over inflation)	
Fuel, % per year	0.7
Operating & Maintenance, % per year	0.0

C. COST OF ELECTRICITY

The approach to determining the cost of electricity is based upon the methodology described in the Technical Assessment Guide, published by the Electric Power Research Institute, Volume I, EPRI-4463-SR, December 1986. The cost of electricity is stated in terms of 10th year levelized dollars. Insurance and local taxes are accounted for explicitly in cell H87, rather than including it in Capital Charges as does EPRI TAG.

	Current $	Constant $
Levelizing Factors		
Capital Carrying Charge, 10th year	0.175	0.103
Fuel, 10th year	1.244	1.036
Operating & Maintenance, 10th year	1.202	1.000
	mills/kWh	mills/kWh
Cost of Electricity - Levelized		
Capital Charges	35.0	20.6
Fuel costs	20.2	16.8
Operating & Maintenance	17.6	14.6
Total Cost of Electricity	72.7	52.0

In Tables 4, 5, and 6, the spreadsheet calculations are displayed for the 100 MW, KRW air blown gasifier. These values are based on the gasifier plant utilizing a ceramic cross-flow filter. The base costs derived by Westinghouse, in 1986 dollars, are presented for the gasifier in Table 4. In Table 5, the Westinghouse costs are adjusted to comply with 1986 EPRI TAG methodology programmed into the spreadsheet. In Table 6, costs are adjusted for escalation to December, 1991.

The main reasons for the differences between the costs given by Westinghouse for the base costs, Table 4, and the costs calculated by the spreadsheet, Table 5, are given below.

- Adjusting the *total capital requirement* between the Westinghouse base costs and the EPRI TAG methodology involves separate calculations for some items grouped together by Westinghouse. A single value is reported by Westinghouse for *allowance for funds during construction* (AFDC), *working capital*, etc. ($22,005,000). The spreadsheet breaks out costs for *royalties, startup costs, spare parts*, and *working capital*. Also the spreadsheet uses a separate calculation for AFDC and lists this as *adjustment for interest and inflation* during the construction period. The total of these values is calculated by the spreadsheet ($26,935,000).

- Coal cost used by Westinghouse was $1.89/MMBtu for Illinois No. 6. This was changed the $1.27/MMBtu as listed in the 1989 EPRI TAG.

- The spreadsheet adds funds for *insurance & local taxes* ($3,385,000), *royalties* ($65,000), and *other operation costs* ($603,000) which do not appear in the Westinghouse estimate.

- Different levelizing factors are used by the calculation of COE as shown in Tables 4, 5, and 6. The standard spreadsheet used 10th year levelized dollars.

Table 4 presents the Westinghouse derived values with many of the spreadsheet calculations nullified. A third column was added for the COE calculation, on the fourth page of Table 4, to input the levelizing factors used by Westinghouse. The Westinghouse report on the KRW (Air) gasifier, reports a total cost of electricity of 116.2 mills/kWh. The financial information presented in Table 4 provides the basis for the levelizing factors shown.

Table 5 presents the gasifier costs adjusted to 1986 EPRI TAG methodology. The 4 year *plant construction period* is the spreadsheet default value. Westinghouse used a factor of 1.064% for escalation from 1981 to 1986. No information on land requirements was given, so this was left blank. The by-product credit for sulfur is $90/long ton in the 1989 EPRI TAG. This was adjusted to $81.80/(short)ton. Levelizing factors calculated by the spreadsheet are in 10th year levelized dollars.

Escalated plant costs for the gasifier plant, shown on Table 6, were attained by applying the *Chemical Engineering Plant Cost Index* to applicable plant sections, and by applying escalation factors recommended by the EPRI TAG to portions of the annual operating costs. First, escalation added in the Westinghouse study to adjust costs from 1981 to 1986, was deducted, then these costs were adjusted to 1991. The *Chemical Engineering Plant Cost Index* for December, 1981 is 297.0 and the value for December, 1991 is 359.3. Not all items in the *total capital requirement* (TCR) are adjusted by this index, as some items are factored from other costs. The annual operating costs are taken from the 1989 EPRI TAG. Inflation applied is 5% as generally recommended by the 1989 EPRI TAG. Inflation used in the calculation of levelizing factors is 4% and the *real escalation rate* (over inflation) for fuel is 0.7% per year as recommended in the spreadsheet.

Table 4. Base Costs of the KRW Gasifier (Air) Plant

05/07/93 ELECTRIC POWER GENERATION COST - Version 1.12

KRW GASIFIER(AIR) 100 MW POWER PLANT

CAPITAL REQUIREMENTS (Dec 1986 Dollars)

Total Plant Investment

AREA NO	PLANT SECTION DESCRIPTION	PROCESS CONT, %	COST, k$ W/O CONT
1	Store/Dry/Grind/FBC		$8,238
2	Air Booster Compressors		$4,216
3	EGGCP Air/O2 Invest. ratio		$13,961
4	Heat Recovery		$2,306
5	Filtration X-Flow Systems		$1,292
6	METC Zn/Fe SO2 Adsorbers		$3,207
7	Allied Chem. SO2->H2S->S		$11,153
8	BFW, Cond., etc.		$1,305
9	Combined Cycle		$60,870
10	Other Facilities - 150(CW Sys)		$29,053
11	Cat. and Chem. - 145 (Selexol)		$960
12	Process Contingency	7452	

Subtotal, Process Plant Cost		$136,561
General Plant Facilities		$0
Engineering Fees		$0
Process Contingency (Using contingencies listed above)		$7,452
Project Contingency,	18 % Proc Plt & Gen Plt Fac	$25,255
Total Plant Cost (TPC)		$169,268
Plant Construction Period,	4 Years (1 or more)	
Construction Interest Rate,	12.5 %	
Adjustment for Interest and Inflation		$22,005
Escallation to mid-'86, 1-Mult'plr	0.064	
Total Plant Investment (TPI)		$203,514
Prepaid Royalties		$0
Initial Catalyst and Chemical Inventory		$0
Startup Costs		$0
Spare Parts		$0
Working Capital		$0
Land, ____ Acres		$0
Total Capital Requirement (TCR)		$203,514

Table 4. Base Costs of the KRW Gasifier (Air) Plant (Continued)

ANNUAL OPERATING COSTS

Capacity Factor = 65 %

COST ITEM		QUANTITY	UNIT $ PRICE	ANNUAL COST, K$
Coal	Fuel Type	882.7 T/D	$46.25 /T	$9,685
Consumable Materials				
Raw water		1525.7 T/D	$0.82 /T	$295
Catalysts & Chem.		____ T/D	____ /T	$445
____________		____ T/D	____ /T	$0
____________		____ T/D	____ /T	$0
Ash/Sorbent Disposal Costs		82.2 T/D	$6.00 /T	$117
Plant Labor				
Oper Labor (incl benef)		24 Men/shift	$20.00 /Hr.	$4,205
Supervision & Clerical				$1,810
Maintenance Costs				$4,570
Insurance & Local Taxes				$0
Royalties				$0
Other Operating Costs				$0
Total Operating Costs				$21,127
By-Product Credits				
Sulfur		24.7 T/D	$60.00 /T	$352
____________		____ T/D	____ /T	$0
____________		____ T/D	____ /T	$0
____________		____ T/D	____ /T	$0
Total By-Product Credits				$352
Net Operating Costs				$20,775

Table 4. Base Costs of the KRW Gasifier (Air) Plant (Continued)

BASES AND ASSUMPTIONS

A. CAPITAL BASES AND DETAILS

		QUANTITY	UNIT $ PRICE	COST, K$
Initial Catalyst Inventory				
	____________	____ lb.	____ /lb.	$0
	____________	____ lb.	____ /lb.	$0
	____________	____ lb.	____ /lb.	$0
	____________	____ lb.	____ /lb.	$0
Initial Chemicals Inventory				
	____________	____ lb.	____ /lb.	$0
	____________	____ lb.	____ /lb.	$0
	____________	____ lb.	____ /lb.	$0
	____________	____ lb.	____ /lb.	$0
Total Catalyst and Chemical Inventory				$0
Startup costs				
Plant modifications,		2 % TPI		$0
Operating costs				$0
Fuel				$0
Total Startup Costs				$0
Working capital				
Fuel & Consumables inv,		0 days supply		$0
By-Product inventory,		0 days supply		$0
Direct expenses,		0 days		$0
Total Working Capital				$0

Table 4. Base Costs of the KRW Gasifier (Air) Plant (Continued)

B. ECONOMIC ASSUMPTIONS

Project life	30 Years
Book life	30 Years
Tax life	20 Years
Federal and state income tax rate	38.0 %
Tax depreciation method	ACRS
Investment Tax Credit	0.0 %

Financial structure

Type of Security	% of Total	Current Dollar Cost, %	Current Dollar Ret, %	Constant Dollar Cost, %	Constant Dollar Ret, %
Debt	50	11.0	5.5	4.6	2.3
Preferred Stock	15	11.5	1.7	5.2	0.8
Common Stock	35	15.2	5.3	8.7	3.0
Discount rate (cost of capital)			12.5		6.1

Inflation rate, % per year	4.0
Real Escalation rates (over inflation)	
Fuel, % per year	0.7
Operating & Maintenance, % per year	0.0

C. COST OF ELECTRICITY

The approach to determining the cost of electricity is based upon the methodology described in the Technical Assessment Guide, published by the Electric Power Research Institute, Volume I, EPRI-4463-SR, December 1986. The cost of electricity is stated in terms of 10th year levelized dollars. Insurance and local taxes are accounted for explicitly in cell H87, rather than including it in Capital Charges as does EPRI TAG.

	Current $		Constant $
Levelizing Factors			
Capital Carrying Charge, 10th year	0.175	0.223	0.103
Fuel, 10th year	1.244	1	1.036
Operating & Maintenance, 10th year	1.202	1	1.000
	mills/kWh		mills/kWh
Cost of Electricity - Levelized			
Capital Charges	62.6	79.7	36.8
Fuel costs	21.2	17.0	17.6
Operating & Maintenance	23.4	19.5	19.5
Total Cost of Electricity	107.2	116.2	73.9

Table 5. KRW Gasifier (Air) Costs Adjusted to EPRI TAG

05/07/93 ELECTRIC POWER GENERATION COST - Version 1.12

KRW GASIFIER(AIR) 100 MW POWER PLANT

CAPITAL REQUIREMENTS (Dec 1986 Dollars)

Total Plant Investment

AREA NO	PLANT SECTION DESCRIPTION	PROCESS CONT, %	COST, K$ W/O CONT
1	Store/Dry/Grind/FBC		$8,238
2	Air Booster Compressors		$4,216
3	Gasifier		$13,961
4	Heat Recovery		$2,306
5	Filtration X-Flow Systems		$1,292
6	METC Zn/Fe SO2 Adsorbers		$3,207
7	Allied Chem. SO2->H2S->S		$11,153
8	BFW, Cond., etc.		$1,305
9	Combined Cycle		$60,870
10	Other Facilities		$29,053
11	Cat. and Chem.		$960
12	Process Contingency	5.5	

Subtotal, Process Plant Cost	$136,561
General Plant Facilities	$0
Engineering Fees	$0
Process Contingency (Using contingencies listed above)	$7,452
Project Contingency, 18 % Proc Plt & Gen Plt Fac	$25,255
Total Plant Cost (TPC)	$169,268
Plant Construction Period, 4 Years (1 or more)	
Construction Interest Rate, 12.5 %	
Adjustment for Interest and Inflation	$21,905
Escallation to mid-'86, 1-Mult'plr 0.064	
Total Plant Investment (TPI)	$203,409
Prepaid Royalties	$683
Initial Catalyst and Chemical Inventory	$0
Startup Costs	$5,403
Spare Parts	$846
Working Capital	$1,051
Land, ____ Acres	$0
Total Capital Requirement (TCR)	$211,392

Table 5. KRW Gasifier (Air) Costs Adjusted to EPRI TAG (Continued)

ANNUAL OPERATING COSTS

Capacity Factor = 65 %

COST ITEM		QUANTITY	UNIT $ PRICE	ANNUAL COST, K$
Coal	Fuel Type	900.0 MM Btuh	$1.27 /MM Btu	$6,508
Consumable Materials				
Raw water		1525.7 T/D	$0.82 /T	$295
Catalysts & Chem.		18.8 T/D	$100.00 /T	$445
______		______ T/D	______ /T	$0
______		______ T/D	______ /T	$0
Ash/Sorbent Disposal Costs		32.2 T/D	$6.00 /T	$117
Plant Labor				
Oper Labor (incl benef)		24 Men/shift	$20.00 /Hr.	$4,205
Supervision & Clerical				$1,810
Maintenance Costs				$4,570
Insurance & Local Taxes				$3,385
Royalties				$65
Other Operating Costs				$603
	Total Operating Costs			$22,004
By-Product Credits				
Sulfur		24.7 T/D	$81.80 /T	$480
______		______ T/D	______ /T	$0
______		______ T/D	______ /T	$0
______		______ T/D	______ /T	$0
	Total By-Product Credits			$480
	Net Operating Costs			$21,524

Table 5. KRW Gasifier (Air) Costs Adjusted to EPRI TAG (Continued)

BASES AND ASSUMPTIONS

A. CAPITAL BASES AND DETAILS

	QUANTITY	UNIT $ PRICE	COST, K$
Initial Catalyst Inventory			
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
Initial Chemicals Inventory			
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
________	____ lb.	____ /lb.	$0
Total Catalyst and Chemical Inventory			$0
Startup costs			
Plant modifications,	2 % TPI		$4,068
Operating costs			$1,326
Fuel			$9
Total Startup Costs			$5,403
Working capital			
Fuel & Consumables inv,	60 days supply		$285
By-Product inventory,	60 days supply		$121
Direct expenses,	30 days		$645
Total Working Capital			$1,051

Table 5. KRW Gasifier (Air) Costs Adjusted to EPRI TAG (Continued)

B. ECONOMIC ASSUMPTIONS

Project life	30 Years
Book life	30 Years
Tax life	20 Years
Federal and state income tax rate	38.0 %
Tax depreciation method	ACRS
Investment Tax Credit	0.0 %

Financial structure

Type of Security	% of Total	Current Dollar Cost, %	Current Dollar Ret, %	Constant Dollar Cost, %	Constant Dollar Ret, %
Debt	50	11.0	5.5	4.6	2.3
Preferred Stock	15	11.5	1.7	5.2	0.8
Common Stock	35	15.2	5.3	8.7	3.0
Discount rate (cost of capital)			12.5		6.1

Inflation rate, % per year	4.0
Real Escalation rates (over inflation)	
Fuel, % per year	0.7
Operating & Maintenance, % per year	0.0

C. COST OF ELECTRICITY

The approach to determining the cost of electricity is based upon the methodology described in the Technical Assessment Guide, published by the Electric Power Research Institute, Volume I, EPRI-4463-SR, December 1986. The cost of electricity is stated in terms of 10th year levelized dollars. Insurance and local taxes are accounted for explicitly in cell H87, rather than including it in Capital Charges as does EPRI TAG.

	Current $	Constant $
Levelizing Factors		
Capital Carrying Charge, 10th year	0.175	0.103
Fuel, 10th year	1.244	1.036
Operating & Maintenance, 10th year	1.202	1.000
	mills/kWh	mills/kWh
Cost of Electricity - Levelized		
Capital Charges	65.1	38.2
Fuel costs	14.2	11.8
Operating & Maintenance	31.7	26.4
Total Cost of Electricity	111.0	76.4

Table 6. KRW Gasifier (Air) Costs with Escalation to Dec, 1991

05/07/93 ELECTRIC POWER GENERATION COST - Version 1.12

KRW GASIFIER(AIR) 100 MW POWER PLANT

CAPITAL REQUIREMENTS (Dec 1991 Dollars)

Total Plant Investment

AREA NO	PLANT SECTION DESCRIPTION	PROCESS CONT, %	COST, K$ W/O CONT
1	Store/Dry/Grind/FBC	____	$10,044
2	Air Booster Compressors	____	$5,140
3	Gasifier	____	$17,021
4	Heat Recovery	____	$2,811
5	Filtration X-Flow Systems	____	$1,575
6	METC Zn/Fe SO2 Adsorbers	____	$7,968
7	Allied Chem. SO2->H2S->S	____	$13,598
8	BFW, Cond., etc.	____	$1,591
9	Combined Cycle	____	$74,213
10	Other Facilities	____	$35,422
11	Cat. and Chem.	____	$1,170
12	Process Contingency	5.5	____

Subtotal, Process Plant Cost	$170,554
General Plant Facilities	$0
Engineering Fees, Zn/Fe System only	$985
Process Contingency (Using contingencies listed above)	$9,307
Project Contingency, 18 % Proc Plt & Gen Plt Fac	$31,542
Total Plant Cost (TPC)	$212,387
Plant Construction Period, 4 Years (1 or more)	
Construction Interest Rate, 12.5 %	
Adjustment for Interest and Inflation	$27,486
Total Plant Investment (TPI)	$239,873
Prepaid Royalties	$853
Initial Catalyst and Chemical Inventory	$0
Startup Costs	$6,419
Spare Parts	$1,062
Working Capital	$1,238
Land, ____ Acres	$0
Total Capital Requirement (TCR)	$249,444

Table 6. KRW Gasifier (Air) Costs with Escalation to Dec, 1991 (Continued)

ANNUAL OPERATING COSTS

Capacity Factor = 65 %

COST ITEM		QUANTITY		UNIT $ PRICE		ANNUAL COST, K$
Ill. No. 6 Coal	Fuel Type	900.0	MM Btuh	$1.47	/MM Btu	$7,534
Consumable Materials						
	Raw water	1525.7	1000 GAL	$0.69	/1000 G	$251
	Catalysts & Chem.	18.8	T/D	$127.63	/T	$568
	______	______	T/D	______	/T	$0
	______	______	T/D	______	/T	$0
Ash/Sorbent Disposal Costs		82.2	T/D	$9.26	/T	$181
Plant Labor						
	Oper Labor (incl benef)	24	Men/shift	$23.15	/Hr.	$4,868
	Supervision & Clerical					$2,148
Maintenance Costs						$5,734
Insurance & Local Taxes						$4,248
Royalties						$75
Other Operating Costs						$716
	Total Operating Costs					$26,324
By-Product Credits						
	Sulfur	24.7	T/D	$94.69	/T	$556
	______	______	T/D	______	/T	$0
	______	______	T/D	______	/T	$0
	______	______	T/D	______	/T	$0
	Total By-Product Credits					$556
	Net Operating Costs					$25,768

Table 6. KRW Gasifier (Air) Costs with Escalation to Dec, 1991 (Continued)

BASES AND ASSUMPTIONS

A. CAPITAL BASES AND DETAILS

	QUANTITY	UNIT $ PRICE	COST, K$
Initial Catalyst Inventory			
____________	_____ lb.	_____ /lb.	$0
____________	_____ lb.	_____ /lb.	$0
____________	_____ lb.	_____ /lb.	$0
____________	_____ lb.	_____ /lb.	$0
Initial Chemicals Inventory			
____________	_____ lb.	_____ /lb.	$0
____________	_____ lb.	_____ /lb.	$0
____________	_____ lb.	_____ /lb.	$0
____________	_____ lb.	_____ /lb.	$0
Total Catalyst and Chemical Inventory			$0
Startup costs			
Plant modifications,	2 % TPI		$4,797
Operating costs			$1,611
Fuel			$10
Total Startup Costs			$6,419
Working capital			
Fuel & Consumables inv,	60 days supply		$332
By-Product inventory,	60 days supply		$140
Direct expenses,	30 days		$765
Total Working Capital			$1,238

Table 6. KRW Gasifier (Air) Costs with Escalation to Dec, 1991 (Continued)

B. ECONOMIC ASSUMPTIONS

Project life	30 Years
Book life	30 Years
Tax life	20 Years
Federal and state income tax rate	38.0 %
Tax depreciation method	ACRS
Investment Tax Credit	0.0 %

Financial structure

Type of Security	% of Total	Current Dollar Cost, %	Current Dollar Ret, %	Constant Dollar Cost, %	Constant Dollar Ret, %
Debt	50	11.0	5.5	4.6	2.3
Preferred Stock	15	11.5	1.7	5.2	0.8
Common Stock	35	15.2	5.3	3.7	3.0
Discount rate (cost of capital)			12.5		6.1

Inflation rate, % per year	4.0
Real Escalation rates (over inflation)	
Fuel, % per year	0.7
Operating & Maintenance, % per year	0.0

C. COST OF ELECTRICITY

The approach to determining the cost of electricity is based upon the methodology described in the Technical Assessment Guide, published by the Electric Power Research Institute, Volume I, EPRI-4463-SR, December 1986. The cost of electricity is stated in terms of 10th year levelized dollars. Insurance and local taxes are accounted for explicitly in cell H87, rather than including it in Capital Charges as does EPRI TAG.

	Current $	Constant $
Levelizing Factors		
Capital Carrying Charge, 10th year	0.175	0.103
Fuel, 10th year	1.244	1.036
Operating & Maintenance, 10th year	1.202	1.000
	mills/kWh	mills/kWh
Cost of Electricity - Levelized		
Capital Charges	76.8	45.1
Fuel costs	16.5	13.7
Operating & Maintenance	38.5	32.0
Total Cost of Electricity	131.7	90.8

APPENDIX B

HEAT LOSS CALCULATIONS

Heat losses for each granular-bed filter and candle filter application were calculated using a spreadsheet program. The results of these calculations are summarized in the following six tables. Each table has two sheets, Part 1 and Part 2. Part 1 of each table shows the thickness and conductivity of the heat loss per unit surface area of each vessel. Part 2 of each table defines the size, total surface area, and total heat loss from each vessel. In Part 2 of each table the total heat loss from the entire filter for each application is summed. Following is a listing of tables by application:

- Table 1: CPFBC Granular-bed Filter
- Table 2: Carbonizer Granular-bed Filter
- Table 3: KRW Gasifier Granular-bed Filter
- Table 4: CPFBC Candle Filter
- Table 5: Carbonizer Candle Filter
- Table 6: KRW Gasifier Candle Filter

The symbols used in Part 1 of each table are defined as follows:

R1 Inside Radius of vessel, duct, or pipe (FT)

R2 Outside Radius of first refractory layer (FT)

R3 Outside Radius of second refractory layer (FT)

R4 Outside Radius of vessel, duct, or pipe (FT)

K1 Thermal conductivity of inside layer of refractory (BTU/HR/FT/°F)

K2 Thermal conductivity of middle layer of refractory (BTU/HR/FT/°F)

K3 Thermal conductivity of outside layer of refractory (BTU/HR/FT/°F)

Ho Convective Coefficient of outside surface (BTU/HR/FT^2/F)

Hi Convective Coefficient of inside surface (BTU/HR/FT^2/F)

To Ambient Temperature (F)

APPENDIX B
TABLE 1, PART 1
HEAT LOSS CALCULATIONS FOR CPFBC GRANULAR-BED FILTER

	R1	R2	R3	REFR. WIDTH	R4	R5	K1	K2	K3	K4	Hi	Hc	E	Hr	Ho	Ti	To	HEAT LOSS BTU/ HOUR/ FT^2
	(FT)	(FT)	(FT)	(IN)	(FT)	(FT)												
LIFT PIPE	1.00	1.08	1.50	5.00	1.53	1.53	10.8	0.07	26		80	0.88	1	1.24	2.12	1544	70	193
GBF TOP HAT	3.00	3.33	3.75	5.00	3.81	3.81	0.51	0.10	26		62	0.96	1	1.32	2.28	1592	70	265
GBF TOP CYC	10.08	10.08	10.75	8.00	10.92	10.92	0.08	0.08	26		10	0.85	1	1.21	2.06	1592	70	169
GBF PRESSURE VESSEL	10.00	10.38	10.75	4.5	10.76	10.93	1.33	0.09	0.05	26	10	0.98	1	1.35	2.33	1592	70	288
TOP SEAL LEG	0.50	0.58	1.00	5.00	1.03	1.03	10.8	0.07	26		80	0.85	1	1.21	2.06	1503	70	169
BOTTOM SEAL LEG	0.50	0.58	1.00	5.00	1.03	1.03	10.8	0.07	26		80	0.86	1	1.22	2.09	1583	70	179
BOTTOM DEV	4.42	4.75	5.25	6.00	5.29	5.29	0.63	0.10	26		80	0.92	1	1.28	2.19	1505	70	225
TOP DEV	5.50	6.00	6.50	6.00	6.54	6.54	0.63	0.10	26		60	0.91	1	1.27	2.18	1503	70	217
DEV TO HEAT EXCH	0.83	0.85	1.27	5.00	1.27	1.27	16.6	0.06			60	0.85	1	1.21	2.06	1500	70	167
HEAT EXCH TO LIFT PIPE	0.75	0.77	1.10	4.00	1.10	1.10	16.6	0.06			60	0.87	1	1.23	2.09	1315	70	182

APPENDIX B
TABLE 1, PART 2
HEAT LOSS CALCULATIONS FOR CPFBC GRANULAR-FILTER

EQUIPMENT	OD	LENGTH	AREA	RATE OF	HEAT	NO.	TOTAL
				HEAT LOSS	LOSS	OF	HEAT LOSS
	(IN)	(FT)	(FT^2)	(BTU/HR/FT^2)	(BTU/HR)	UNITS	(BTU/HR)
GBF							
TOP HAT			57	265	15103	4	60412
TOP HAT SIDE	91.5	8	192	265	50777	4	203109
TOP CYLINDER	262.0	12	823	169	139362	4	557448
BOTTOM CYLINDER	262.3	9	601	288	172718	4	690873
CONE	262.3	22	938	288	269680	4	1078720
TOP			472	169	79916	4	319665
TOP SEAL LEG	24.8	25	162	169	27422	4	109690
LOWER SEAL LEG	24.8	30	194	179	34747	4	138986
LIFT PIPE	36.8	125	1203	193	232547	1	232547
LIFT PIPE TO HEAT EXCH	30.5	10	80	166	13293	1	13293
HEAT EXCH TO LIFT PIPE	26.5	125	867	182	157550	1	157550
BOTTOM DEV	127.0	20	676	225	152071	1	152071
TOP DEV	157.0	26	1069	217	231431	1	231431
WATER COOLED HX					9113483	1	9113483
TOTAL HEAT LOSS							13059279

APPENDIX B
TABLE 2, PART 1
HEAT LOSS CALCULATIONS FOR CARBONIZER GRANULAR-BED FILTER

	R1	R2	R3	REFR. WIDTH	R4	R5	K1	K2	K3	K4	Hi	Hc	E	Hr	Ho	Ti	To	HEAT LOSS BTU/ HOUR/ FT^2
	(FT)	(FT)	(FT)	(IN)	(FT)	(FT)												
LIFT PIPE	0.50	0.58	1.00	5.00	1.03	1.03	10.8	0.07	26		80	0.83	1	1.20	2.03	1395	70	156
GBF TOP HAT	0.80	0.80	1.30	6.00	1.36	1.36	16.7	0.12	26		62	0.93	1	1.29	2.22	1470	70	238
GBF TOP CYC	6.75	6.75	7.54	9.50	7.71	7.71	0.1	0.12	26		10	0.87	1	1.23	2.10	1470	70	185
GBF PRESSURE VESSEL	6.75	7.13	7.50	4.50	7.54	7.71	1.3	0.09	0.12	26	10	0.95	1	1.32	2.27	1470	70	253
TOP SEAL LEG	0.46	0.54	1.04	6.00	1.07	1.07	10.8	0.07	26		80	0.78	1	1.15	1.92	1336	70	120
BOTTOM SEAL LEG	0.46	0.54	1.04	6.00	1.07	1.07	10.8	0.07	26		80	0.79	1	1.16	1.96	1451	70	131
BOTTOM DEV	1.58	1.59	2.09	6.00	2.14	2.14	16.7	0.06	26		80	0.79	1	1.16	1.95	1336	70	129
TOP DEV	1.33	1.66	2.16	6.00	2.21	2.21	0.4	0.10	26		60	0.85	1	1.21	2.06	1335	70	169
DEV TO HEAT EXCH	0.17	0.19	0.60	5.00			16.6	0.06			60	0.75	1	1.13	1.88	1333	70	106
HEAT EXCH TO LIFT PIPE	0.17	0.19	0.52	4.00			16.6	0.06			60	0.76	1	1.14	1.90	1083	70	111

APPENDIX B
TABLE 2, PART 2
HEAT LOSS CALCULATIONS FOR CARBONIZER GRANULAR-BED FILTER

EQUIPMENT	OD	LENGTH	AREA	RATE OF HEAT LOSS	TOTAL HEAT LOSS
	(IN)	(FT)	(FT^2)	($BTU/HR/FT^2$)	(BTU/HR)
GBF					
TOP HAT	32.7	6.0	4.3	238	1019
TOP CYLINDER	185.0	7.0	339.0	185	62641
BOTTOM CYLINDER	185.0	7.0	339.0	253	85674
CONE	185.0	13.0	441.1	253	111467
TOP			180.8	185	33412
BOTTOM	54.0	5.0	70.7	253	17862
TOP SEAL LEG	25.8	15.0	101.1	120	12087
LOWER SEAL LEG	25.8	20.0	134.8	131	17595
LIFT PIPE	24.8	100.0	648.0	156	101308
LIFT PIPE TO HEAT EXCH	14.5	10.0	38.0	106	4027
HEAT EXCH TO LIFT PIPE	12.5	125.0	409.1	111	45542
BOTTOM DEV	51.3	6.0	80.5	129	10345
TOP DEV	52.9	15.0	207.8	169	35124
HX					2179350
TOTAL HEAT LOSS					2717452

APPENDIX B
TABLE 3, PART 1
HEAT LOSS CALCULATIONS FOR KRW GASIFIER GRANULAR-BED FILTER

	R1	R2	R3	REFR. WIDTH	R4	R5	K1	K2	K3	K4	Hi	Hc	E	Hr	Ho	Ti	To	HEAT LOSS BTU/ HOUR/ FT^2
	(FT)	(FT)	(FT)	(IN)	(FT)	(FT)												
LIFT PIPE	0.50	0.58	1.00	5.00	1.03	1.03	10.8	0.07	26		80	0.85	1	1.21	2.06	1493	70	168
GBF TOP HAT	0.80	0.80	1.30	6.00	1.36	1.36	16.7	0.12	26		62	0.95	1	1.32	2.26	1581	70	257
GBF TOP CYC	6.75	6.75	7.54	9.50	7.71	7.71	0.1	0.12	26		10	0.89	1	1.25	2.14	1581	70	200
GBF PRESSURE VESSEL	6.75	7.13	7.50	4.50	7.54	7.71	1.3	0.09	0.1	26	10	0.97	1	1.34	2.31	1581	70	273
TOP SEAL LEG	0.46	0.54	1.04	6.00	1.07	1.07	10.8	0.07	26		80	0.79	1	1.16	1.95	1421	70	128
BOTTOM SEAL LEG	0.56	0.54	1.04	6.00	1.07	1.07	10.8	0.07	26		80	0.81	1	1.18	1.99	1562	70	141
BOTTOM DEV	1.58	1.59	2.09	6.00	2.14	2.14	16.7	0.06	26		80	0.80	1	1.17	1.98	1421	70	137
TOP DEV	1.33	1.66	2.16	6.00	2.21	2.21	0.4	0.10	26		60	0.87	1	1.23	2.09	1420	70	181
DEV TO HEAT EXCH	0.17	0.19	0.60	5.00			16.6	0.06			60	0.76	1	1.14	1.91	1419	70	113
HEAT EXCH TO LIFT PIPE	0.17	0.19	0.52	4.00			16.6	0.06			60	0.78	1	1.15	1.93	1168	70	121

APPENDIX B
TABLE 3, PART 2
HEAT LOSS CALCULATIONS FOR KRW GASIFIER GRANULAR-BED FILTER

EQUIPMENT	OD	LENGTH	AREA	RATE OF HEAT LOSS	TOTAL HEAT LOSS
	(IN)	(FT)	(FT^2)	($BTU/HR/FT^2$)	(BTU/HR)
GBF					
TOP HAT	32.7	6	4	257.4	1102
TOP CYLINDER	185.0	7	339	199.7	67715
BOTTOM CYLINDER	185.0	7	339	273.3	92653
CONE	185.0	7	441	273.3	120547
TOP			181	199.7	36118
BOTTOM	54.0	5	71	273.3	19318
TOP SEAL LEG	25.8	15	101	127.6	12905
LOWER SEAL LEG	25.8	20	135	141.1	19031
LIFT PIPE	24.8	100	648	168.1	108892
LIFT PIPE TO HEAT EXCH	14.5	10	38	113.3	4302
HEAT EXCH TO LIFT PIPE	12.5	125	409	120.9	49442
BOTTOM DEV	51.3	6	81	137.2	11046
TOP DEV	52.9	15	208	180.6	37525
HX					2940600
TOTAL HEAT LOSS					3521196

APPENDIX B
TABLE 4, PART 1
HEAT LOSS CALCULATIONS FOR CPFBC CANDLE FILTER

	R1	R2	R3	REFR. WIDTH	R4	R5	K1	K2	K3	K4	Hi	Hc	E	Hr	Ho	Ti	To	HEAT LOSS BTU/ HOUR/ FT^2
	(FT)	(FT)	(FT)	(IN)	(FT)	(FT)												
ABOVE TUBE SHEET	10.25	10.25	11.00	9.0	11.17	11.17	1.16	0.16	26		10	0.97	1	1.34	2.31	1599	70	279.2
BELOW TUBE SHEET	10.25	10.58	11.00	9.0	11.17	11.17	0.46	0.11	26		10	0.97	1	1.34	2.30	1599	70	293.3

APPENDIX B
TABLE 4, PART 2
HEAT LOSS CALCULATIONS FOR CPFBC CANDLE FILTER

EQUIPMENT	OD	LENGTH	AREA	RATE OF	HEAT	NO.	TOTAL
				HEAT LOSS	LOSS	OF	HEAT LOSS
	(IN)	(FT)	(FT^2)	(BTU/HR/FT^2)	(BTU/HR)	UNITS	(BTU/HR)
ABOVE TUBESHEET CYLINDER	268.0	11.0	771.8	279.2	215447	4	861788
BELOW TUBESHEET CYLINDER	268.0	18.3	1280.5	293.3	375564	4	1502256
CONE	268.0	22.8	890.8	293.3	261262	4	1045048
TOP			472.0	279.2	131761	4	527044
TOTAL HEAT LOSS							3936136

APPENDIX B
TABLE 5, PART 1
HEAT LOSS CALCULATIONS FOR CARBONIZER CANDLE FILTER

	R1	R2	R3	REFR. WIDTH	R4	R5	K1	K2	K3	K4	Hi	Hc	E	Hr	Ho	Ti	To	HEAT LOSS BTU/ HOUR/ FT^2
	(FT)	(FT)	(FT)	(IN)	(FT)	(FT)												
ABOVE TUBE SHEET	9.00	9.00	9.75	9.0	9.92	9.92	0.16	0.16	26		10	0.97	1	1.34	2.30	1599	70	277.4
BELOW TUBE SHEET	9.00	9.33	9.75	9.0	9.92	9.92	0.46	0.11	26		10	0.97	1	1.34	2.30	1599	70	291.9

APPENDIX B
TABLE 5, PART 2
HEAT LOSS CALCULATIONS FOR CARBONIZER CANDLE FILTER

EQUIPMENT	OD	LENGTH	AREA	RATE OF HEAT LOSS	TOTAL HEAT LOSS
	(IN)	(FT)	(FT^2)	($BTU/HR/FT^2$)	(BTU/HR)
ABOVE TUBESHEET CYLINDER	238.0	11.0	685.4	277.4	190137
BELOW TUBESHEET CYLINDER	238.0	18.3	1137.1	291.9	331893
CONE	238.0	20.3	702.5	291.9	205038
TOP			472.0	277.4	130940
TOTAL HEAT LOSS					858008

APPENDIX B
TABLE 6, PART 1
HEAT LOSS CALCULATIONS FOR KRW GASIFIER CANDLE FILTER

	R1	R2	R3	REFR. WIDTH	R4	R5	K1	K2	K3	K4	Hi	Hc	E	Hr	Ho	Ti	To	HEAT LOSS BTU/ HOUR/ FT^2
	(FT)	(FT)	(FT)	(IN)	(FT)	(FT)												
ABOVE TUBE SHEET	8.33	8.33	9.08	9.0	9.25	9.25	0.16	0.16	26		10	0.97	1	1.34	2.30	1599	70	276.3
BELOW TUBE SHEET	8.33	8.67	9.08	9.0	9.25	9.25	0.46	0.11	26		10	0.97	1	1.34	2.30	1599	70	290.9

APPENDIX B
TABLE 6, PART 2
HEAT LOSS CALCULATIONS FOR KRW GASIFIER CANDLE FILTER

EQUIPMENT	OD	LENGTH	AREA	RATE OF HEAT LOSS	TOTAL HEAT LOSS
	(IN)	(FT)	(FT^2)	($BTU/HR/FT^2$)	(BTU/HR)
ABOVE TUBESHEET CYLINDER	222.0	11.0	639.3	276.3	176637
BELOW TUBESHEET CYLINDER	222.0	18.3	1060.7	290.9	308600
CONE	222.0	18.9	611.2	290.9	177831
TOP			472.0	276.3	130409
TOTAL HEAT LOSS					793477

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Granular-Bed and Ceramic Candle Filters in Commercial Plants - A Comparison

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