Performance of the Westinghouse APF in Pilot Scale Test Facilities

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Abstract

Integrated Gasification Combined Cycles (IGCC) and Pressurized Fluidized Bed Combustion (PFBC) are being developed and demonstrated for commercial, power generation application. Hot gas particulate filters are key components for the successful implementation of IGCC and PFBC in power generation gas turbine cycles. The objective of this work is to develop and qualify through analysis and testing a practical hot gas ceramic barrier filter system that meets the performance and operational requirements for these applications.

This paper reports on the development and status of testing of the Westinghouse Advanced Hot Gas Particle Filter (W-APF) including:

- 4246 hours of testing that has now been completed at the Foster Wheeler 10 MW PCFB facility located in Karhula, Finland.
- Operation of the W-APF in conjunction with the Foster Wheeler Advanced HIPPS Test Program being conducted at their Livingston, New Jersey site.
- Approximately 2100 hours of operation of the W-APF at the SCS/PSDF site on the MWK transport reactor test loop.
- The design, installation and startup status of the W-APF unit supplied to the 95 MW Pinon Pine IGCC Clean Coal Demonstration, Reno, Nevada.
- The status of the Westinghouse development and testing of HGF's for Biomass Power Generation.

Results reported include operating history, operating characteristics and filter performance. Schedules and objectives for future testing are summarized. The status of the 200 MW_e PCFB Clean Coal Demonstration Project, City of Lakeland Florida and 75 MW_e. Minnesota Agriculture Biomass Power Project are summarized.

Research sponsored by the U.S. Department of Energy's Morgantown Energy Center, under contract DE-AC21-94MC311147 with Westinghouse Electric Corporation, Science & Technology Center, 1310 Beulah Road, Pittsburgh, PA 15235-5098; telefax: 412-256-2121.

Introduction

High temperature particulate filters are a key component in advanced, coal based gas turbine cycles (IGCC, Integrated Gasification Combined Cycle and PFBC, Pressurized Fluidized Bed Combustion) that are currently under development by DOE/FETC (Federal Energy Technology Center) for clean coal demonstration. In these applications the hot gas particulate filter protects the downstream heat exchanger and gas turbine components from particle fouling and erosion effects and cleans the gas to meet particulate emission requirements. Both PFBC and IGCC plants benefit because of lower cost downstream components, improved energy efficiency, lower maintenance and the elimination of additional and expensive flue gas treatment systems.

IGCC Systems

In IGCC systems, the hot gas particulate filter must operate in reducing gas conditions (i.e., presence of H_2, CH_4, CO), high system pressure (150 psi to 350 psi) and at operating temperatures usually determined by the method of sulfur removal, i.e., in bed, external or by cold gas scrubbing. Typically, these temperatures range around 1650°F (in bed), 900 to 1200°F (external) and 1000°F to 500°F (cold scrubbing).

In gasification applications, cold scrubbing of the fuel gas has been demonstrated as effective in cleaning the fuel gas to meet turbine and environmental requirements. However, with this process, plant energy efficiency is reduced, and higher capital costs are incurred. Incorporating a hot particulate filter upstream of the scrubbing unit reduces heat exchanger costs and provides for dry ash handling (partial hot gas cleaning).

Hot fuel gas cleaning concepts (in bed and external) have also been proposed that utilize reactive solid sorbents to remove gas phase sulfur and hot gas filters to collect the ash and sorbent particles. This approach in IGCC provides for highest energy efficiency and lowest cost of electricity.

IGCC systems may utilize air or oxygen blown entrained or fluid bed gasifiers. Specific operating conditions of the hot gas particulate filter will vary depending on these choices. In general, hot gas filter pilot plant test experience suggests that gasifier ash/char is noncohesive with relatively high flow resistance. Thus, the potential for fines re-entrainment and high filter pressure drop are reduced by selecting a relatively low design filter operating face velocity. Since the filter treats only the fuel gas component of the total gas flow, the choice of a low filter face velocity does not adversely impact economics. Typically, for a 100 MW_e IGCC system, the filter is required to treat only 6000 to 12,000 acfm, depending if the gasifier is oxygen or air blown. Inlet dust loadings may also vary widely, ranging from <1000 ppmw to 10,000 ppmw.

PFBC Systems

Bubbling bed PFBC technology is being demonstrated at commercial scale worldwide. Currently, these plants utilize high efficiency cyclones to remove greater than 95% of the ash and a ruggedized gas turbine to tolerate ash carried over from the upstream cyclones. Economic and performance improvements in these first generation type PFBC plants can be realized with the application of hot gas particulate filters. Both the secondary cyclone(s) and stack gas ESP(s) could be eliminated saving costs and providing lower system pressure losses. The cleaner gas (basically ash free) provided with the hot gas filter, also permits a wider selection of gas turbines with potentially higher performance.

The applicability of hot gas particulate ceramic filters to PFBC technology was demonstrated at the American Electric Powers' Tidd PFBC 70 MW_e Clean Coal Demonstration Plant. In this project, a 10 MW_e hot gas filter slipstream was operated for approximately 6000 hrs. over a range of conditions and configurations (Hoffman, J.D., 1955). The Tidd PFBC demonstration project was completed in March 1995. For these bubbling bed PFBC applications, the hot gas filter must operate at temperatures of 1580°F and system pressures of 175 psia (conditions typical of the Tidd PFBC plant). Inlet dust loadings to the filter are estimated to be about 500 to 1000 ppm with mass mean particle diameters ranging from 1.5 to 3 μm. However, it was demonstrated in the Tidd PFBC filter slipstream, better filter performance is achieved by eliminating the PFBC primary cyclone. Filter inlet loading increased to about 18,000 ppm and particle mass mean diameter to 27 μm.

For commercial applications typical of the 70 MW_e Tidd PFBC demonstration unit, the filter must treat up to 56,600 acfm of gas flow. Scale-up to about 310 MW_e would require filtering over 160,000 acfm gas flow. For these commercial scale systems, multiple filter vessels are required.

An alternative to the bubbling bed PFBC is the circulating bed design (PCFB). In this process the hot gas filter will be exposed to higher operating temperatures (1650°F) and higher (factor of 10 or more) particle loading. Although the inlet particle loading is high, it contains a significantly coarser fraction (mass mean generally >15 μm) which helps mitigate the effect of the higher mass loading. For a 75 MW_e commercial scale circulating bed PFBC plant, gas flow to the filter is approximately 70,000 acfm. At this scale multiple vessels with modular filter subassemblies are required.

Second generation or topping PCFB is being developed and planned for demonstration and commercialization. In this plant, higher (than first generation PFBC) turbine inlet temperatures are achieved by partially devolatilizing the coal in a carbonizer unit producing a fuel gas. The char produced is transferred and burned in a circulating PFBC unit with high excess air. The hot (1600°F) vitiated air produced is used to combust the hot fuel gas to raise the combustion gas temperature to as high as 2350°F (Robertson, et al., 1989). With second generation PFBC, two hot gas filters are required. One filter is used to collect the ash and char material carried over from the carbonizer unit with the hot fuel gas. The second filter is used to remove ash and sorbent particles carried over with the hot vitiated air leaving the circulating pressurized fluidized bed combustor (CPFBC). Both filter units are required to operate at high temperatures (1200 to 1600°F) and high particle loading. The fuel gas filter will operate in reducing gas while the CPFBC filter operates in oxidizing conditions. A nominal 200 MW_e second generation CPFBC plant would require one filter module for the carbonizer while two filter modules (vessels) would likely be used on the combustor leg of the process.

Objectives

The objective of this work is to develop and qualify through analysis and testing a practical hot gas ceramic barrier filter system that meets the performance and operational requirements of Advanced, Solid Fuel Power Generation Cycles, Table 1.

Table 1 - Hot Gas Filter Application Requirements

- Effective Filter
  - Meet NSPS
  - Protect Downstream Equipment
- Operate Reliably
  - Cleanable
  - Stable Pressure Drop Characteristics
- Robust
  - Oxidizing/Reducing Environments
  - Alkali/Acid Gas
  - Thermal Cycling

The hot gas filter must remove sufficient particulate to protect the gas turbine from erosion damage, corrosion and particle deposition and meet power plant environmental standards (NSPS). Turbine tolerance estimates and current NSPS requirements are shown in Figure 1. Also shown are ceramic barrier filter outlet particle loading data from subpilot and pilot plant test facilities. This data shows the high performance potential of the hot gas ceramic filter device relative to power generation application.

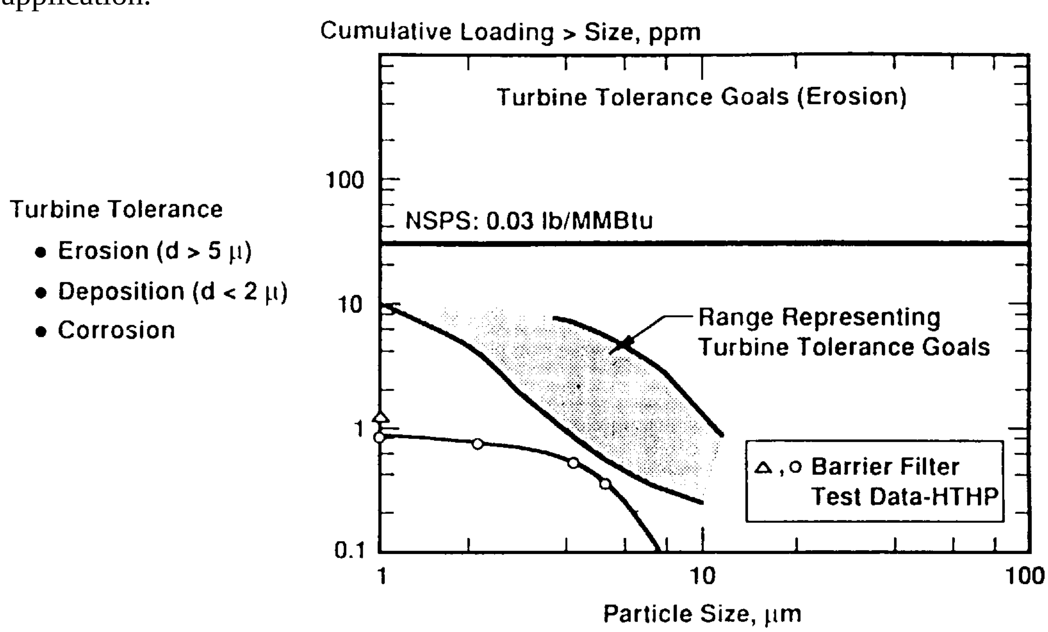

Figure 1 - Turbine Tolerance and Particulate Emission Requirements in Coal Fueled Gas Turbine Applications

Candle, crossflow and tube filters are examples of ceramic barrier filter devices being developed for high temperature particle filtration. These filter devices are basically absolute filters on ash materials, can be operated at high throughput and can be cleaned by simple pulse jet methods.

Project Description

Background

The Westinghouse hot gas filter system development is being supported through key sub-pilot, pilot and demonstration programs, Table 2. This testing has included approximately 3290 hours of operation in reducing gas environments (gasification) and 13,000 hours in combustion (oxidizing) conditions. In addition to this field experience, over 28,000 hours of test experience has been compiled in the Westinghouse HGF, high temperature, high pressure simulators.

Table 2 - Westinghouse IGCC and PFBC Hot Gas Cleaning Testing Experience

Application	Facility	Pressure (psi)	Temperature Range (^oF)	Flow (ACFM)	Dust Load (ppmw)	Test Hours
Gasification (IGCC)	Fluid bed (KRW)	131-231	1050	50-300	1,000-25,000	1300
	Texaco Gasifier	350	1000-1400	50-110	300-25,000	700
	Biomass (NREL) IGT/WHBGP	195-260	1000-1650	125	1,000-2,500	50-IGT *(Continuing)*
	SPPC, Pinon Pine IGCC (95 MW_e)	260	1000	13,391	18,000	Startup
Combustion (PFBC)	SCS Wilsonville (MWK)	200-350	700-1500	1000-1700	4,000-40,000	2100 *(Continuing)*
	AEP Tidd, PFBC	135	1200-1500	7,500	600-10,000	5,800
	Ahlstrom Karhula, PCFB	160	1550-1650	3,070	4,000-18,000	4,246 *(Continuing)*
Advanced PFBC and Indirect Cycles	FWDC Livingston	150-200	1100-1500	100-400	5,000-35,000	
	• Carbonizer					400 (700)*
	• Combustor					900 (700)*
	• HIPPS	60-120	1200-1400	100-400	40,000 and higher	142 *(Continuing)*
	SCS/PSDF (FW-7MW_t)	200-350	1200-1650	2,000	11,000	Startup - 1998

**Integrated Operation, 1995*

Hot Gas Filter System

The Westinghouse hot gas filter design, schematically shown in Figure 2, consists of stacked arrays of filter elements supported from a common tubesheet structure. In this design, the arrays are formed by attaching individual candle elements (Item 1) to a common plenum section (Item 2). All the dirty gas filtered through the candles comprising this single array is collected in the common plenum section and discharged through a pipe to the clean side of the tubesheet structure. Each array of filter elements is cleaned from a single pulse nozzle source. The individual plenum assemblies (or arrays) are stacked vertically from a common support structure (pipe), forming a filter cluster (Item 3). The individual clusters are supported from a common, high alloy tubesheet structure and expansion assembly (Item 4) that spans the pressure vessel and divides the vessel into its “clean” and “dirty” gas sides. Each cluster attaches to the tubesheet structure by a specially designed split ring assembly. The cluster is free to grow down at temperatures. The plenum discharge pipes ducting the filtered gas to the clean gas side of the tubesheet structure are contained within the cluster support pipe and terminate at the tubesheet. Each discharge pipe contains an eductor section. Separate pulse nozzles are positioned over each eductor section. The eductors assist pulse cleaning. During cleaning, the pulse gas is contained within and ducted down the discharge pipe and pressurizes the respective plenum section.

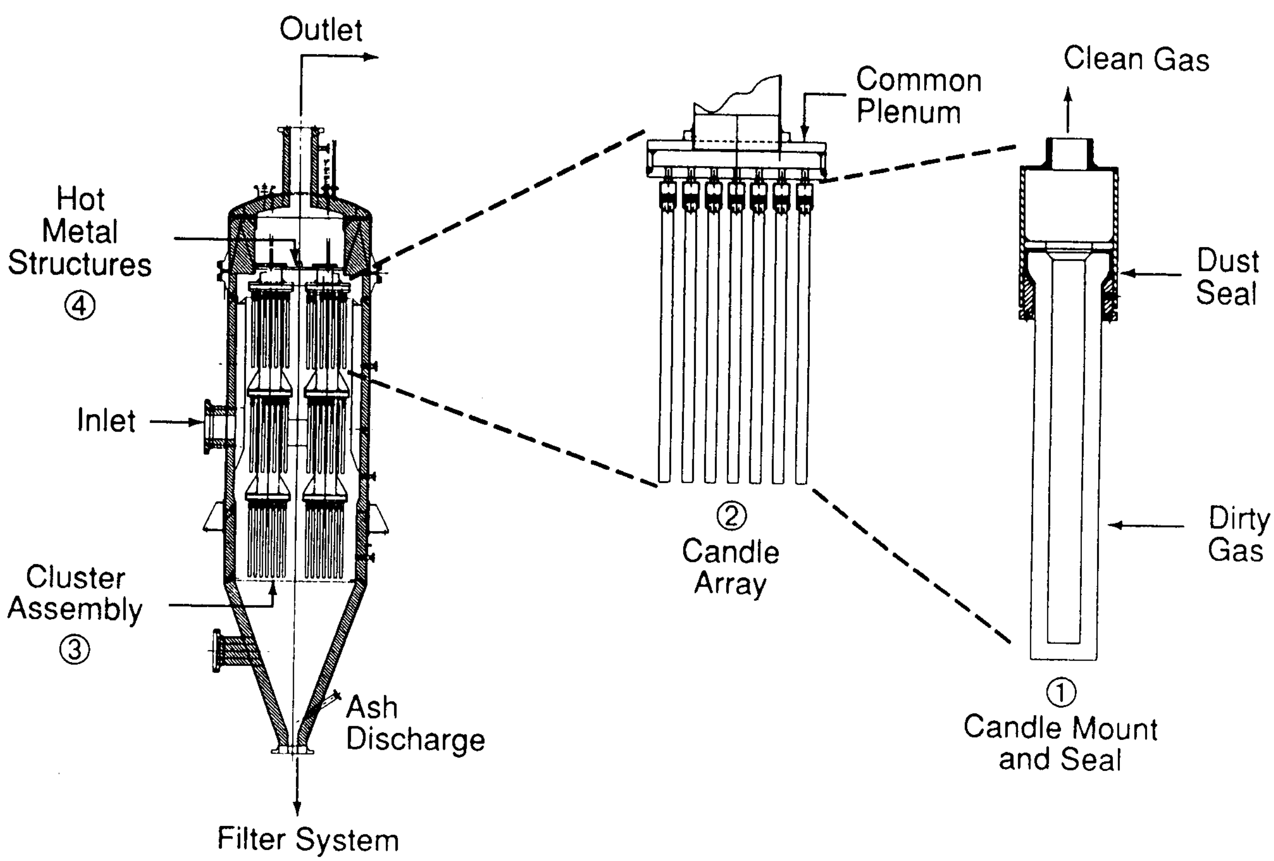

Figure 2 - Westinghouse Candle Filter System Design

The plenum assembly and cluster (stacked plenums) form the basic modules needed for constructing large filter systems indicative of PFBC requirements. The scale-up approach is:

- Increasing plenum diameter (more filter elements per array)
- Increasing the number of plenums per cluster
- Increasing the vessel diameter to hold more clusters

In general, vessel diameter will be limited by the tubesheet structure and desire to shop fabricate the vessel. Larger PFBC plants would utilize multiple vessels.

Filter Element Technology

Ceramic barrier filter devices, such as candles and cross flow filters, are under development for hot gas filter application. These devices have been shown to be basically absolute filters on ash material, can be operated at relatively high gas throughput with acceptable pressure drop and cleanable by simple reverse pulse jet methods. Clay bonded silicon carbide (SiC) candle filters are commercially available. The structure of these elements is mainly a coarse-grained SiC bonded by a clay-based binder. Each element is provided with a fine grained SiC or aluminosilicate fiber outer skin that serves as the filtration surface. Alternate, oxide-based ceramic materials are also being developed for ceramic barrier filter application. Both first generation, full-scale cross flow and candle filter elements have been constructed using a homogeneous structure that is an alumina/mullite (A/M) matrix containing a small percentage of amorphous (glass) phase. Over the past several years, Westinghouse working with DOE and various suppliers, have helped to develop and qualify alternative, advanced ceramic filter materials and candle elements. This development has included both dense and lightweight monolithic, vapor infiltrated and Sol-Gel fiber reinforced and filament wound constructions. Laboratory and field evaluation of these and other materials are being conducted to identify, characterize and compare their respective chemical and thermal stability for IGCC and PFBC applications. The status of this work is presented in a companion paper entitled “Filter Component Assessment.”

This paper updates the assessment of the Westinghouse hot gas filter design based on ongoing testing and analysis.

Approach

The development and qualification of the Westinghouse hot gas filter is being supported through key sub-pilot, pilot and demonstration projects, as outlined in Table 2. Test sites include government furnished and industrial facilities.

Results

Entrained Gasification

In this program, a sub-pilot scale hot gas filter was integrated with a 15 tpd Texaco entrained gasifier. The facility is located in Montebello California. The filter test program was conducted from

April 1989 through August 1992 and reported (Lippert et al., 1993). Filter testing was in support of a base program that was focused on evaluating hot desulfurization technologies. In this testing, the filter was used to protect the external sulfur sorbent beds from ash plugging. This work showed that in the entrained gasification application, stable pressure drop operation can be achieved but the ceramic barrier filter system must be sized and designed for relatively low face velocity (<4 ft/min) and high operating pressure drop (>3 or 4 psi). The potential for particle re-entrainment is a key consideration in selecting the hot gas filter design and operating conditions.

Biomass IGCC/HGF Testing

A 14 candle-element HGF unit was integrated and operated with the Institute of Gas Technology's (IGT) RENUGAS biomass gasification process. The RENUGAS process is a pressurized fluidized bed, air or oxygen blown gasifier. The development and operation of the IGT's 10 ton per day process development unit (PDU) is described by Wiant, et al., 1993 and Lau, et al., 1993. The testing program at IGT utilized bagasse and alfalfa feed and was conducted in support of the DOE Biomass Power Program, and specifically the Biomass Gasification Facility Demonstration in Paia, Hawaii.

The IGT/PDU included a tar cracker that was first operated and characterized. It was concluded from this work that the majority of the oil and tar from the RENUGAS process would not crack within the pores of the filter elements if the filter temperature is maintained below 1500°F (815°C), but above the condensation temperature of the highest boiling-point components (approximately 950°F (510°C)).

The hot gas filter testing was conducted in two, one week test campaigns resulting in about 50 operational hours at conditions. A summary of the testing conditions is given in Table 3. Test Series 1 was conducted with the full 14-element complement of candle elements. In this test series, the upstream cyclone was disabled to increase particle size and solid loading to the filter unit. Particle analysis showed a 10.8 micron mass mean. This short duration test showed no operational issues, with stable baseline pressure drop. Visual inspection, following testing confirmed filter integrity and high performance level (high collection efficiency).

Test series 2 was conducted utilizing ten candle elements and with the upstream cyclone fully operational. Again, particle analysis showed that the mass mean size, 3.8 microns, now entering the filter decreased significantly compared to Test Series 1. Initially, in the Test Series 2 testing, steady filter pressure drop characteristics were observed but in the latter portion of this testing, a steady rise in the baseline pressure drop was observed, likely reflecting re-entrainment because of the smaller particle mean size. Post test inspection confirmed the filter integrity and no dust was found on the clean gas side. These test results show that better performance will be achieved with larger particle size, thus eliminating the need for the upstream cyclone.

Following the IGT testing, this 14-element HGF Test Unit was removed from the IGT/PDU and installed into the slipstream off the DOE's 100 ton per day Biomass Gasification Facility (BGF) located in Paia Hawaii.

Table 3. Biomass/IGT Hot Gas Filter Testing Summary

	Test 1	**Test 2**	**PAIA - 1997**
Feed Stock	Bagasse	Bagasse	Bagasse
Filter Pressure	260 psig	195 to 245 psig	25 to 100 psig
Filter Gas Temperature	1580 to 1650°F	1000 to 1230°F	1300F
No. of Candle Elements	14	10	14
Dust Loading	2900 ppm	980 to 2500 ppm	ND
Operating Hours	21	30	170
Outlet Dust Loading	Not Detectable	Not Detectable	Not detectable
Alkali	--	0.7 to 1.0 ppm	---

Westinghouse is the prime contractor for the DOE's Hawaiian Biomass Gasification Commercialization Program. The program is facilitating the commercialization of pressurized biomass gasification combined cycle power plants. The BGF was modified to operate at pressures up to 300 psig and at throughputs of up to 100 tons per day of dry bagasse. The Westinghouse HGF system is installed in a slipstream that filters approximately one tenth of the bagasse product gas flow from the gasifier. In 1997, the initial shakedown and operation of the Paia BGF and hot gas filter slipstream was completed, Table 3. Approximately 170 hours of startup and steady state operation was achieved. At steady state conditions, the operating pressure drop remained stable, indicating effective cleaning. No dust sampling was conducted, however at disassembly, inspection showed no evidence of dust on the clean filter side. Further inspection revealed no mechanical issues or failed elements.

Sierra Pacific, Pinon Pine IGCC/HGF Project

Westinghouse has designed and supplied the HGF unit for the Department of Energy's Clean Coal Technology Demonstration, Pinon Pine IGCC project. The coal gasification process uses the KRW fluid bed technology owned by The M.W. Kellogg Co. who specified and purchased the filter. The final filter design evolved to satisfy the project requirements of both The M.W. Kellogg Co. and the Sierra Pacific Power Co. The plant is located at the Sierra Pacific Power Company's Tracy station near Reno, Nevada. The plant will gasify approximately 880 tons/day of coal using the KRW air blown gasification process to produce about 100 MWe.

Table 4 summarizes the design basis for the HGF unit. The unit is schematically shown in Figure 3. The filter consists of 784 candle elements, arrayed on four clusters. Each cluster contains 187 candles distributed over four plenums.

Table 4 - SPPC -Pinon Pine HGF Design Basis

Gas Environment:	Reducing
Gas Flow:	307,800 lb/hr
Pressure:	260 psi
Gas Temperature:	1011°F
Inlet Dust Loading:	18,400 ppm
Max. Pressure Drop:	9 psi (max.)

For commercial operation, the Filter is designed for maintainability. Access into the filter body is provided by four, 36 inch diameter manways. Two diametrically opposite manways are positioned between clusters to access the top level of plenums. Similarly, two diametrically opposite manways are positioned between clusters to access the lower middle level of plenums. Platforms were designed to bolt to the manway flanges to provide staging for personnel to stand inside the vessel for in-situ service work. Below each manway a set of vertically oriented rails are provided. Ladders treads are strung between the rails to provide access to the lower plenum service area. Personnel climb down the ladder and work off a second platform. The arrangement is illustrated in Figure 4. At any given platform location, all filters for two adjacent plenums are accessible by rotating the associated cluster. Such rotation is accomplished by entering the vessel head above the tubesheet, disengaging the cluster top flange from the tubesheet and with standard manual rigging attached between the vessel head and cluster top flange, lifting and rotating the cluster.

The first application of the maintenance hardware was demonstrated at the initial filter installation. Four teams of boilmakers were trained. They worked simultaneously inside the filter vessel and accomplished assembly of all the 748 candle elements, demonstrating the overall approach to maintainability.

Shakedown and commissioning of the gasification island, including the hot gas filter, was initiated in 1997. Although coal gasification operation has been achieved operational hours have been limited due to various mechanical issues (mostly fines removal) not directly related to the filter unit. As a result of the fines removal issues, ash on two separate occasions filled the hot gas filter vessel hopper to levels at or above the lowest candle plenums; causing candle damage and breakage. Candle replacement was achieved using the insitu vessel maintenance approach described above.

Pressurized Fluidized Bed Combustion and Topping Cycle

Westinghouse has conducted hot gas filter testing at two different PFBC facilities: at the American Electric Power (AEP) 70Mwe Tidd-PFBC demonstration plant located in Brilliant Ohio, and

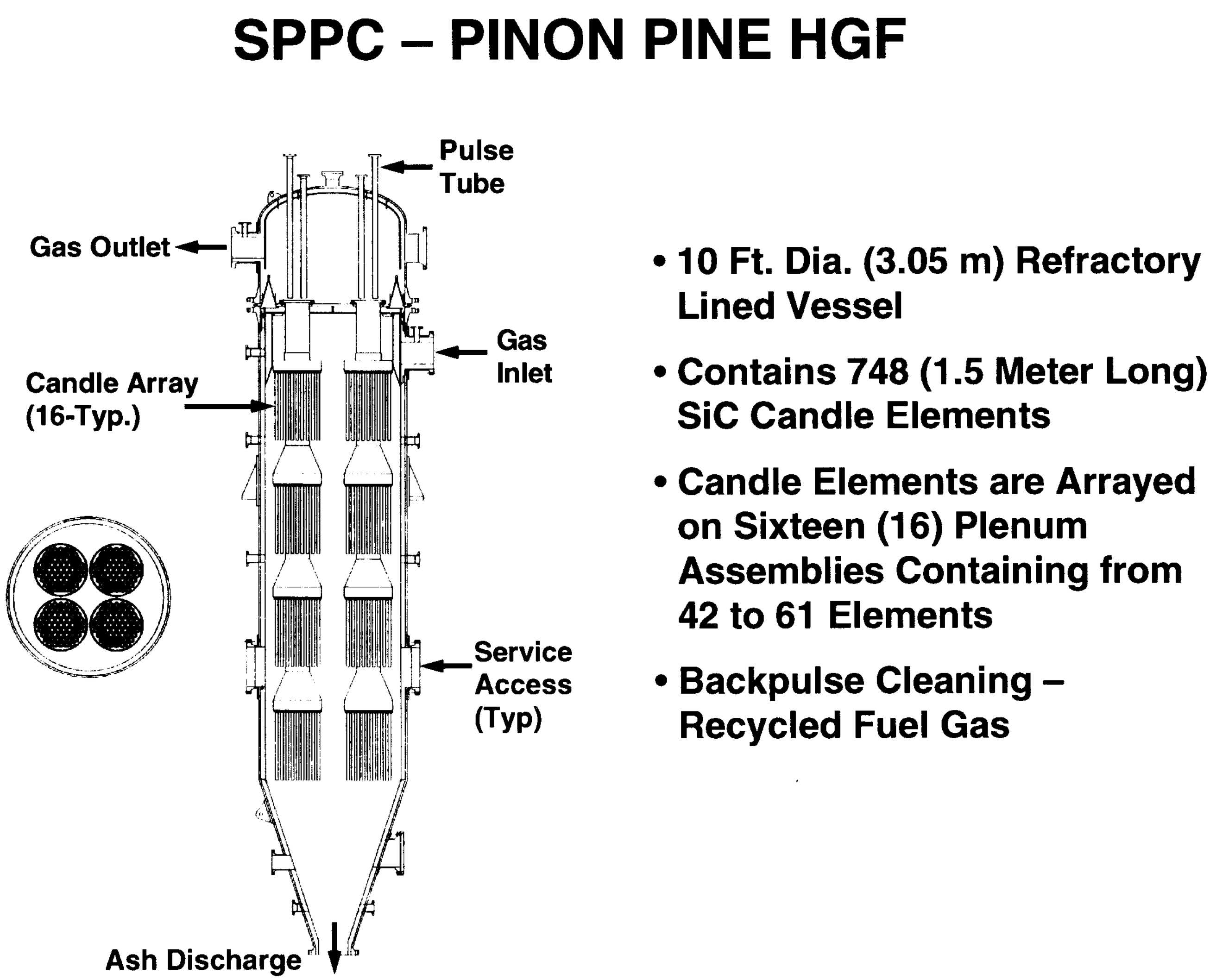

Figure 3 - SPPC - Pinon Pine HGF

at the Foster Wheeler (formally Ahlstrom) 10 MWt circulating PCFB facility located in Karhula Finland. In addition, testing has continued at the Foster Wheeler Livingston facility on the carbonizer unit and testing on the Kellogg Transport Reactor test leg of the Southern Companies Services/DOE Power Systems Development Facility (PSDF). Testing at the AEP/TIDD plant has been completed and reported (Hoffman, 1995). Hot Gas Filter testing at the SCS/PSDF is reported in a comparison paper (Davidson, 1998). An update is given of the Karhula PCFB filter testing at Foster Wheeler Livingston (Carbonizer) below.

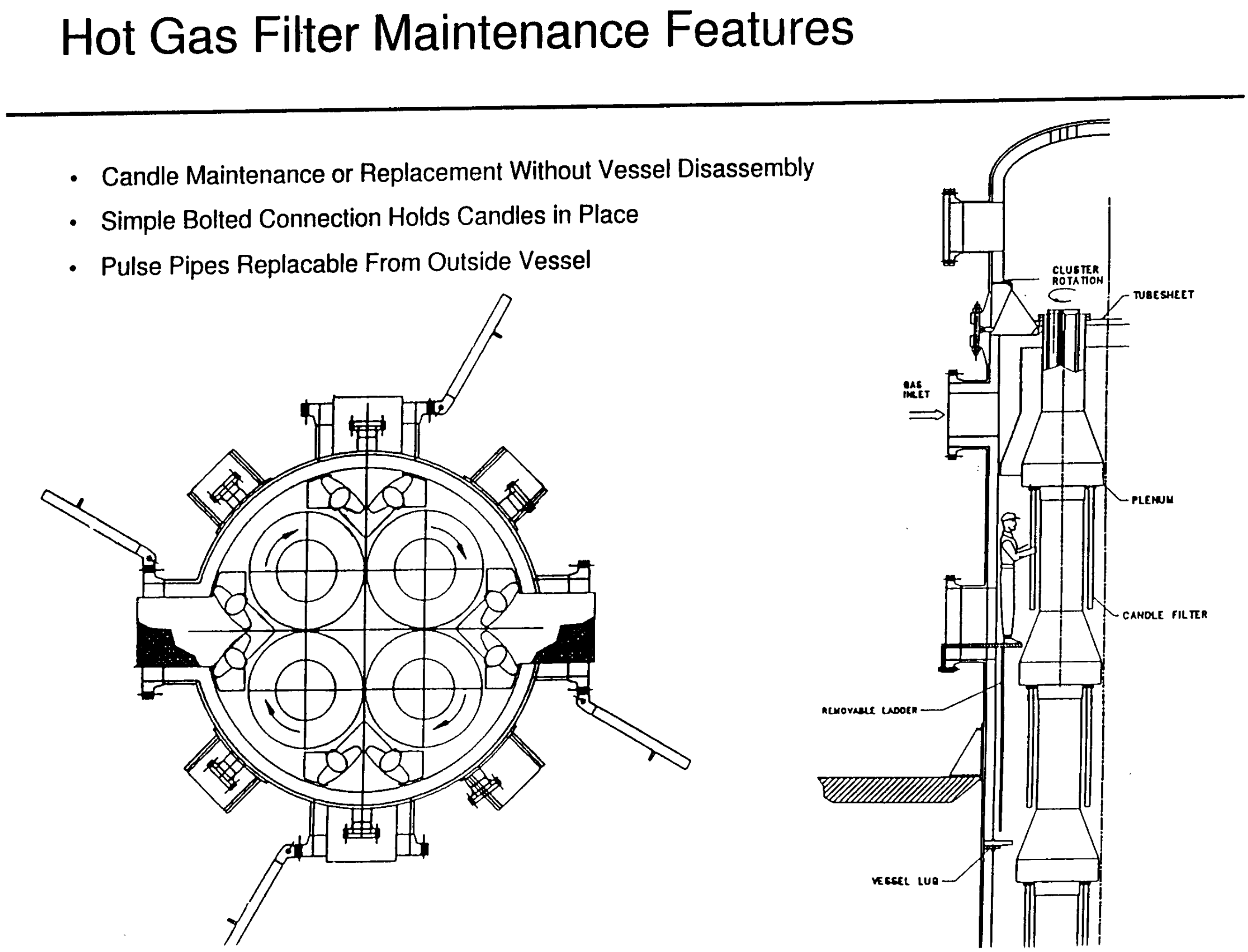

Figure 4 - Hot Gas Filter Maintenance Features

1. Karhula PCFB Testing

The hot gas filter testing conducted at the Foster Wheeler Karhula 10 MWt PCFB Facility is divided into three test periods:

1. Nov. 1992 through June 1994
2. Nov. 1995 through Oct. 1996
3. April 1997 - through Nov. 1997

Table 5 summarizes the cumulative testing hours and coals used. A description of the Karhula facility and results from the earlier Nov. 1992 through June 1994 testing and November 1995 through October 1996 have been reported (Lippert, T.E., et al, 1995, and 1997). A summary of the 1997 testing is given below.

Table 5 - Summary of Westinghouse Hot Gas Filter Operation at the Foster Wheeler PCFB - Karhula

	Hours (Oct. '92 - Feb. '94)	Hours (Nov. '95 - Oct. 96)	Hours April '97
Illinois No. 6	306		
Iowa Rawhide	61		
Newland	300		
Kentucky	270		
Black Thunder	804		
Bituminous	170		
Pennsylvania	135		
Sparta		1166	
E. Kentucky			1034
Total Coal (Period)	2046	1166	1034
Total Coal (Cumulative)		3212	4246

The objectives of the 1997 testing was to evaluate the PCFB boiler emissions and hot gas filter ash characteristics using the coal and sorbent currently anticipated for the DOE PCFB Clean Coal Demonstration Plant planned for the City of Lakeland Florida at the Lakeland Electric McIntosh Unit 4 Station.

Testing was conducted in two test segments, Table 6, focusing primarily on operating temperature level and its effect on ash behavior, continuing the exposure of commercially available SiC and alumina mullite candle elements, to gain initial operating experience on advanced oxide based candle elements and establishing the overall operating and performance characteristics of the HGF unit under steady state conditions.

HGPF Operation

Over Test Segments 1 and 2 the operation of the HGPF remained steady with effective pulse cleaning. Cleaning cycles ranged from 20 to 30 minutes. Baseline pressure drop was stable under steady state conditions. No abnormal process events occurred.

Figure 5 compares the relative hot gas filter permeance values for various test runs between the earlier Tidd PFBC and Karhula PCFB testing. The testing reflects different feedstock, and different operating conditions. Filter permeance is calculated from pressure drops measured across the filter unit

Table 6 - Summary of PCFB Hot Gas Filter Testing - 1997

Operating Parameters	Test Segment 1 April/July - 97	Test Segment 2 Sept/Nov. - 97
Coal	Eastern Kentucky	Eastern Kentucky
Sorbent	Gregg Limestone	Gregg Limestone
Number of Candles	128	90-112
Operating Temperature	820 to 850C	700 to 750C
Operating Pressure	10-11 bar	9.5 to 11 bar
Inlet Dust Loading	6600 to 10,800 ppmw	5700 to 9000 ppmw
Operating Hours (Coal)	454 hrs.	581 hrs.

and include both V (Velocity) and V^2 effects. Under any given set of operating conditions, filter permeance appears relatively constant, suggesting stable long term filter pressure drop.

E. Kentucky Coal and Gregg Limestone Behavior in PCFB Testing

Periodic inspection of the filter unit following extended operating periods in both Test Segment 1 (850C operation) and Test Segment 2 (730C operation) showed no indication of ash sintering or bridging issues. Filter visual inspections were conducted after extended test runs of 256 hours (Segment 1) and 199 and 148 hours (Segment 2). Previous test experience suggests that ash bridges can form in less than 100 hours. Based on this testing, the E. Kentucky Coal and Gregg Limestone combination appear to have little or no tendency for sintering or forming ash bridges under PCFB temperature conditions. Other potential coal/sorbent combinations should also be tested that may be considered for the Lakeland Demonstration Project.

PCFB Exposure of SiC and Aluminum Mullite Candle Elements

Both the commercially available SiC (Schumacher FT20 and Pall 326) with reformulated binder for high temperature operation and Coors Alumina Mullite candle elements types were utilized. Both element types were used in the 1996/1996 testing conducted at Karhula achieving cumulative exposure times ranging up to 1620 hrs (SiC) and 2720 hours (Alumina Mullite). The Alumina Mullite elements had 1100 hours of previous exposure in the Tidd PFBC hot gas filter slipstream test conducted from 1993 into 1995.

The earlier PCFB 1620 hour exposure of the SiC elements at 850C identified significant elongation occurring resulting from oxidation. In the 1997 testing both the used and new SiC candle elements were used. Test Segment 1 (850C operation) confirmed continued elongation effects in both

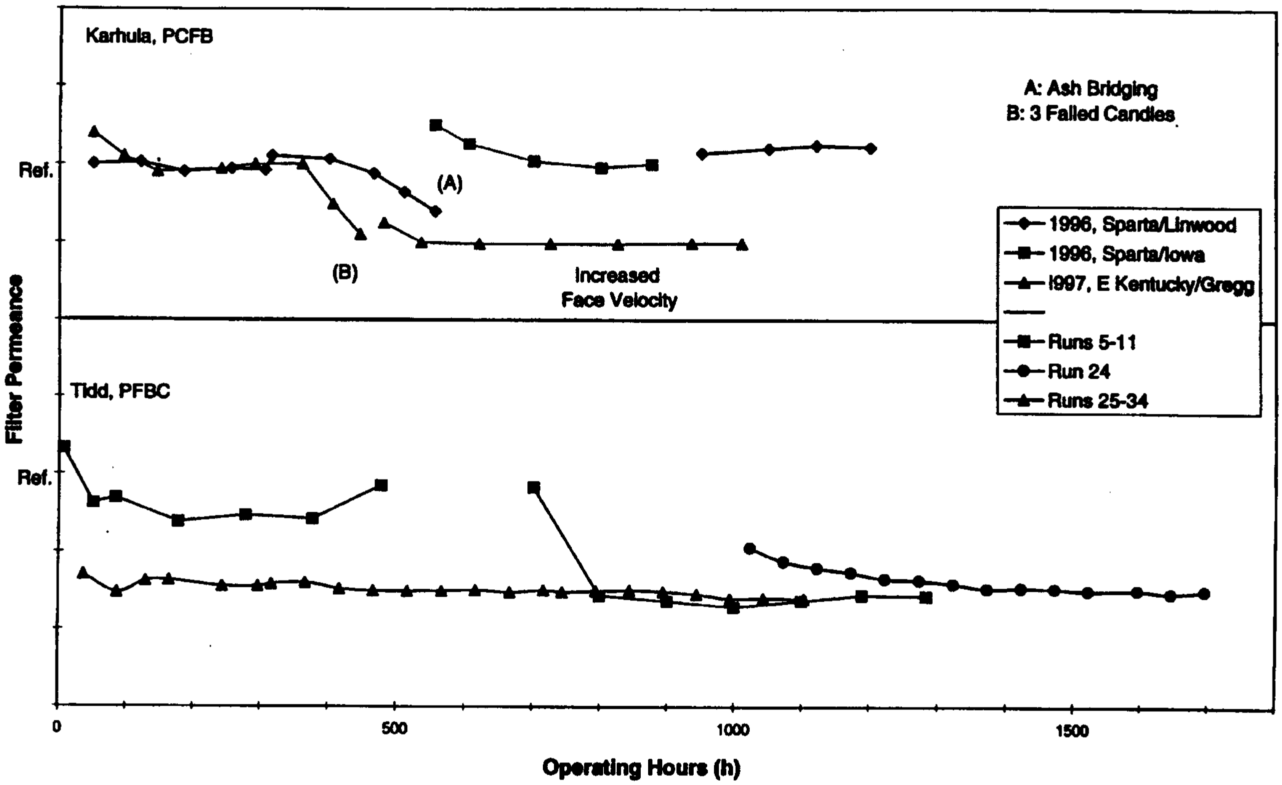

Figure 5 - Westinghouse Hot Gas Particulate Filter Development Filter Permeance, Pilot Plant Testing

the used and new elements. Based on these results, the viability of the SiC elements in commercial PCFB operation at the 850C condition appears problematical. In Test Segment 2 (730C operation), the lower operating temperature significantly reduced the effects (by a factor or 4). Although more exposure time at the 730C condition is needed to confirm the lower temperature effect, Test Segment 2 results suggest that the SiC elements should be considered for the currently planned Lakeland PCFB Project.

The oxide based Alumina Mullite candles (unlike the SiC compositions) are stable at the 850C (and higher) temperature conditions and having achieved over 2700 hours testing prior to the 1997 Karhula program, were candidates for PCFB application. Three element failures (out of some 46 total installed) occurred in Test Segment. The installed number of Alumina Mullite elements in Test Segment 2 was reduced to 28, eliminating what may have been previously damaged elements. No additional failures occurred in Test Segment 2. Alumina Mullite remain a candidate for PCFB application, but a better understanding of statistical behavior, failure modes and accumulated damage is needed.

Advanced Oxide Candle Elements

Six different advanced oxide candle filter elements were tested during Segment 2 operation. These elements represented different suppliers (3M Co., DuPont, McDermott, Techniweave, Ensto and Blasch) and ranged from monolithic construction to fiber reinforced (CFCC). Two of the element types (3M and Techniweave) suffered damage in the early part of testing and were removed. The incurred damage is attributed to first time manufacturing and the overall nature of their respective constructions. Manufacturing modifications are expected to be implemented that will make these elements more robust to filter operating conditions. In general, all remaining advanced candle elements survived intact Test Segment 2 operations. It is currently planned to continue testing these elements in other available PCFB type facilities to gain additional exposure. Testing at higher operating temperatures (850C) is needed to fully evaluate the potential of these materials for first generation PFBC and PCFB application.

HGPF Performance - Outlet Dust Loading

Isokinetic sampling was conducted throughout the testing program. Outlet dust loading responded to candle failure events that occurred in Test Segment 1 and to both the damaged candle event and leaky blanked holders in Test Segment 2. In Test Segment 1 with a full candle array and prior to any candle failure events, dust could not be detected in the outlet samples.

HGPF - Metal Structures

The Karhula filter test unit was first installed and operated in October 1992 and since has experienced over 5000 hours of high temperature operation including 4246 hours on coal. The unit has experienced over 300 significant thermal cycle events (start-up/shutdown and reduced operation to standby). Inspection of the metal structures has indicated no issues with the major structural components of the assembly that would compromise the commercial system. The hot seal plate connecting the cluster assembly to the existing Karhula water cooled tube sheet (unique to the Karhula test unit) has deformed during operation. Inspection following the 1997 Test Segment 2 operation showed no further deformation occurring with the lower operating temperature (730C) conditions.

Following the 1996 operation, major effort was expended to repair several cracked (but non structural) welds in the exit flow pipes connecting clean side to clean side. This required removal and disassembly of the metal clusters. Modifications to the clean side gas piping were made to prevent occurrence of weld cracking. Inspection following the current 1997 program has confirmed the effectiveness of the modifications.

Based on the Karhula test experience, it would appear that commercially viable hot metal structures can be designed and utilized in PCFB.

2. FWDC/Livingston HGF Testing

Testing supporting the development of Topping-PFBC, as well as the Foster Wheeler advanced pulverized coal-fired electric utility HIPPs concept has taken place at the Foster Wheeler Development

Corporation (FWDC) pilot plant facility located at the John Blizzard Research Center in Livingston, New Jersey. As part of this program, separate carbonizer filter and combustor filter testing was conducted, followed by integrated operation of the test facility.

Recently the operation of the 22-element Carbonizer/Filter has been continued as part of the Foster Wheeler/ DOE HIPPs program. In the concept, an air-fluidized sand-bed pyrolyzer, with injected pulverized coal and limestone, generates a low-Btu fuel gas, and a char-sorbent mixture. The fuel gas and most of the char-sorbent mixture flows directly into a hot gas filter. The cleaned fuel gas is then fired in a combustion turbine, and the char-sorbent mixture is burned in a conventional PC-furnace.

FWDC has tested the fluidized bed pyrolyzer pilot unit with a hot gas filter supplied by Westinghouse. The filter pressure vessel contained 22 filter elements, 11 on each of two side-by-side plenum chambers. The filter elements were 1-1/2 m long ceramic elements, 2 supplied by Coors and 10 each by Schumacher and Pall. Filter test results have been compiled in one shakedown test (HSD-2, March 1997), and in the first test run (TR-1, April 1997). Six set points were established during the TR-1 campaign. The test conditions and performance results are summarized in Table 7.

Table 7 - FWDC HIPPS Pyrolyzer Filter Test Conditions and Performance

Test Period	HSD-2	TR-1
Filter pressure, bara (psig)	3.8-5.7 (40-60)	5.7-11.3 (60-120)
Filter temperature, °C (°F)	649 (1200)	760 (1400)
Inlet dust loading, ppmw	40,000-120,000	40,000-180,000
Baseline DP, mbar (in-wg)	25-62 (10-25)	100-150 (40-60)
Pulse interval (min.)	10-12	9-10
Continuous test time (hr)	62	80

The hot gas filter commercial temperature is about 537°C (1000°F), and the FWDC testing has operated at filter temperatures up to 760°C (1400°F). No cyclone is used in the plant, and the ash loading to the filter is very high. The filter internals were inspected by boroscope following the testing and found to have no damaged candles and to be free of bridging and deposits. No significant difficulties with ash drainage from the vessel were observed during the testing. The FWDC pyrolyzer filter testing has shown that the Westinghouse hot gas filter can operate well even with inlet dust loadings greater than 100,000 ppmw. The high dust loading of coarse particles, 30-50 µm in mass-mean diameter, may minimize problems with bridging and vessel drainage. The filter cake permeability is comparable to previous measurements made during carbonizer filter testing in the Topping-PFBC program.

Subsequent to the HIPPs testing, FWDC conducted a series of carbonizer filter tests with the Lakeland coal/sorbent feedstocks to support the Lakeland Clean Coal Program. If the precleaning cyclone upstream of the carbonizer filter in the Lakeland plant could be eliminated, there would be a potentially substantial capital investment savings resulting from the elimination of the cyclone and its char handling equipment, as well as a simplification of the plant piping and structures. FWDC operated the carbonizer filter with and without the precleaning cyclone in place. This test data provided an opportunity to generate a preliminary, quantitative assessment of the performance and design tradeoffs to be made if the cyclone is to be eliminated. The test conditions, filter features, and performance results are summarized in Table 8. The major difference between the tests with and without the cyclone is the filter face velocity, with the tests with the cyclone in place being at about twice the face velocity of the no-cyclone tests.

Table 8 - FWDC Lakeland Carbonizer Filter Tests

	With Cyclone			Without Cyclone	
Test No.	TR07			TR04	TR05
Test Dates	12/97			9/97	9/97
No. candles	10			22	22
Operating time > 450°C (hr)	18			62	43
Filter temperature, °C (°F)	650-700 (1200-1300)			720-760 (1330-1400)	700-790 (1300-1450)
Inlet char load (1000 ppmw)	20 (estimated)			100-200	100-250
Trigger DP, mbar (in-wg)	100-107 (40-43)	548 (220)	149-174 (60-70)	75-110 (30-44)	87-164 (35-66)
Baseline DP, mbar (in-wg)	37-45 (15-18)	62 (25)	70-95 (28-38)	20-50 (8-20)	32-70 (13-28)
Pulse frequency (1/hr)	3.5-10	1.2	4.5-7	2-4	1.5-3

Two tests were completed with the cyclone in place, but only one has been evaluated. In the tests with the cyclone in place there was no measure of the char feed rate to the filter since the cyclone catch and filter catch were mixed into the same collection hopper. An estimated char loading of 20,000 ppmw has been assumed based on past test experience, but the actual char loading might have been substantially different (probably in the range of 5,000 to 35,000 ppmw). The char feed rate for the tests with no cyclone were directly measured by weighing the char hopper material removed periodically.

The tabulation compares trigger pressure drop, baseline pressure drop, and pulse frequency for the two sets of tests. The tests with no cyclone operated with lower pulse frequency than the tests with the cyclone installed, this being possible primarily because of the lower face velocity in the no-cyclone tests. The no-cyclone tests also operated at a higher gas inlet temperature than the cyclone tests, with the cyclone tests having a temperature close to the proposed Lakeland carbonizer filter temperature. Overall, all of the FWDC tests were very successful, with no ash bridging observed, no char drainage difficulties, and no ceramic candle damage.

3. Power Systems Development Facility (PSDF)

Westinghouse designed and supplied two particle control devices (PCD-301 and PCD-352) for installation and operation at the Southern Companies Service PSDF located in Wilsonville Alabama. The PCD-301 unit has been installed into the MWK Transport Reactor (TR) test loop. The TR is designed to operate in either a gasification or combustion mode. Testing to date has been in the combustion mode.

PCD-301 hot gas filter system is a two-plenum, single cluster unit containing 91 candle elements. The filter installation, and pressure and pulse-skid check-outs were completed in July 1996. Over 2100 hours of testing has now been completed. These results are discussed in a companion paper given by SCS (Davidson, 1998).

Application

The successful development and demonstration of hot gas particulate filters will enable achieving higher energy efficiencies and lower costs in Advanced Power Generation cycles such as IGCC, PFBC and Advanced PFBC. The technology has application for a wide range of solid fuels, including coal and biomass. In addition, many industrial applications could benefit from HGF technology application.

Future Activities

Power Systems Development Facility

Operation of the KRW TR and PCD-301 is continuing under the combustion mode. Plans for operation in the gasification mode are being developed.

PCD-352 unit has been completely fabricated and delivered to site. This unit will serve as the HGF for the Combustion Leg of the FWDC/APFB test loop. Installation is ongoing, with operation expected in 1999. The PCD-352 is a 3-Cluster, 2-Plenum unit that can hold up to 273 candle elements. Clusters from the PCD-301 are interchangeable with clusters from the PCD-352 unit. Candles for the PCD-352 have not been selected.

Acknowledgments

We wish to acknowledge the DOE/FETC CTO's involved in the various programs related to the hot gas particulate filter development for their technical guidance and support during the conduct of these programs; Mr. Richard Dennis, Mr. James Longanbach, Mr. Donald Bonk and Mr. Theodore McMachon. Also, the following organizations are recognized: Foster Wheeler Development Company; Southern Company Services; Electric Power Research Institute; M. W. Kellogg Company.

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