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Subpilot Scale Gasifier Evaluation of Ceramic Cross Flow Filter

**Final Report
February 1, 1988 - December 31, 1992**

**T. E. Lippert
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E. E. Smeltzer
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J. H. Meyer**

August 1993

Work Performed Under Contract No.: DE-AC21-88MC24021

**For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia**

**By
Westinghouse Electric Corporation
Science and Technology Center
Pittsburgh, Pennsylvania**

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ABSTRACT

The operating characteristics, performance and durability of a hot gas cross flow filter system were evaluated at the Texaco 15 tpd, entrained-bed gasifier pilot plant facility that is located at their Montebello Research Facilities (MRL) in California. A candle filter unit was also tested for comparative purposes. A wide range of operating test conditions were experienced. This report summarizes the results of eleven different test runs that occurred from April 1989 through August 1992. Differences between filter operation on the entrained gasifier and prior experience on fluid bed combustion are discussed.

1. INTRODUCTION

High temperature and pressure (HTHP) particulate control is an essential component of advanced coal-fired power generation systems that are under development by the DOE Morgantown Energy Technology Center for clean coal programs and future commercialization. These systems include gasification combined cycles (IGCC), pressurized fluidized-bed combustion (PFBC), and direct coal fueled turbines (DCFT). All of these systems rely on a gas turbine to generate all (or a portion of) the electrical power.

The Texaco coal gasification process is a second generation coal conversion process that utilizes a slagging entrained flow gasifier. This technology has been successfully demonstrated in a 100 MW integrated gasification combined cycle (IGCC) electric power generating plant, as well as in three other commercial installations to produce ammonia and petrochemicals. The use of an advanced gasification system, which is integrated with a combined cycle power plant, results in one of the most promising processes which utilizes fossil fuels in an environmentally acceptable manner. Using coal to generate a fuel gas, however, requires removal of particulates and other gas phase contaminants that could lead to erosion and corrosion of downstream gas turbine components.

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. Hot gas particulate filters can be used with cold gas scrubbing to reduce the capital costs of this approach. Incorporating a hot particulate filter upstream of the scrubbing unit reduces heat exchanger

costs and provides for dry ash handling. Hot fuel gas cleaning concepts have also been proposed that utilize reactive sorbents to remove gas phase sulfur (H_2S , etc.) and hot gas filters to collect particulate. This approach provides for highest energy efficiency and lowest cost of electricity.

A schematic representation of one scheme for a Texaco Integrated Gasification Combined Cycle (IGCC) process utilizing hot gas cleaning is shown in Figure 1.1. Hot fuel gases generated during coal gasification are first desulfurized in the in situ cleanup module located either in the gasifier, or in a downstream radiant cooling section. Fuel gas then enters the first filter module which removes the gasifier fly ash and spent sorbent which is released from the primary desulfurizer. The process then allows the particulate free gas to be further processed in sulfur polishing beds for final sulfur removal. A second filter module serves as a guard device located downstream of the sulfur polishing beds to remove fine particulates generated by bed attrition. A third but smaller filter module is provided in order to remove debris released from the beds during regeneration cycles. During the conduct of the Texaco/Westinghouse DOE/METC test program reported herein, the pilot scale hot gas filter (utilizing cross flow and later, candle filter elements) system that was operated at the Texaco Montebello facility utilized the first of these particulate cleanup modules.

Ceramic barrier filters have been identified as a viable particulate control option for use in these coal-based power systems. The ceramic filter elements are near absolute filters, removing >99.9% of the entrained fines, have high throughput capability, are relatively inert to gas phase contaminants, and maintain stability and material strength at high temperatures. These characteristics protect the gas turbine from particle erosion and deposition and clean the fuel gas to meet particulate emission standards without additional expensive stack gas cleanup devices. The cross flow filter concept has been identified as one of the most cost effective technologies for advanced particle filtration.⁽¹⁾ Candle filters are also barrier devices of different geometry that are also being developed for hot gas cleaning. Both cross flow and candles were utilized in the test program described.

Figure 1.1 - Schematic of Hot Gas Cleaning Process in IGCC Power Plant

1.1 CROSS FLOW FILTER CONCEPT

The ceramic cross flow filter is illustrated in Figure 1.2. The filter element is comprised of thin porous ceramic plates that contain channels formed by ribbed sections. The plates are stacked and fired to form a monolithic porous structure. The two filter faces of the short side channels are exposed to the dirty gas. The gas and particulate flow into the short side channels, through the porous plates that form the "roof" and "floor" of the channels and into the longer channels that form the clean gas side. One end of the clean side channels is sealed to force the filtered gas to flow to a central collection plenum to which the filter is mounted.

The Westinghouse cross flow filter system design is schematically shown in Figures 1.3 and 1.4. The system consists of a refractory lined, coded pressure vessel that contains arrays of the cross flow filter element assemblies, Figure 1.3. The arrays are formed by attaching individual cross flow elements (Item 1, Figure 1.4) to a common plenum (Item 2, Figure 1.4) and discharge pipe. The arrays are cleaned from a single pulse nozzle source.

For efficient packaging, several of the individual plenum assemblies are arranged vertically from a common support structure, forming a filter cluster (Item 3, Figure 1.4). The filter cluster represents the basic module needed for constructing a large filter system. The individual clusters are supported from a common, high alloy tubesheet and expansion assembly that spans the pressure vessel and divides it into the "clean" and "dirty" gas sides. Hot, particulate laden gas enters the pressure vessel and passes through the filter element collecting solids as a cake on the surface of the filter. The filtered gas flows into the plenum pipes and exits to the clean side of the main tubesheet structure. The ash collected on the short side channels of the cross flow filter elements is removed by reverse pulse jet cleaning and falls into the ash collection system attached to the bottom of the pressure vessel housing.

Figure 1.2 - Schematic Representation of Cross Flow Filter

Figure 1.3 - Westinghouse Cross Flow Filter System Concept

Figure 1.4 - Westinghouse Concept for Constructing Filter System from Single Cross Flow Filter Elements

The cluster concept provides a modular approach to scaleup and permits maintenance and replacement of individual filter elements. A very similar design for the candle system has also been developed, Figure 1.5. Candle and cross flow clusters are interchangeable in the Westinghouse scheme.

The major attributes of the cross flow filter concept are its absolute filtration characteristics on ash material and capability to be operated at relatively high flow capacity (high face velocity) with low pressure drop. Since each of the filter plates represent a filter surface, the cross flow configuration provides very high filter surface area to volume characteristic and the potential to be compact and economic. Candle filter technology provides similar performance but somewhat lower surface area to volume packaging characteristics.

1.2 CROSS FLOW FILTER DEVELOPMENT

Westinghouse has focused on cross flow filters that have been fabricated from an alumina/mullite ($\text{Al}_2\text{O}_3/3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$)-based material. Development efforts have included scale-up of the filter elements from a 15.24 x 15.24 x 5.08 cm (6 x 6 x 2 inch) configuration, with rib-to-plate bonds, to a 30.48 x 30.48 x 10.16 cm (12 x 12 x 4 inch) body that incorporates a mid-ribbed bond (MRB) configuration. The MRB provides a symmetric plate design that has improved manufacturing characteristics, and eliminates high stress sharp channel corners by moving the bond to a low stress region.⁽²⁾

Modifications have also been made in the fabrication and manufacturing of the cross flow filter elements to improve retention of the base material strength and porosity properties while maintaining a crack-free, dimensionally stable, plate assembly with improved bond strength.⁽³⁾ An additional feature which has been incorporated into the cross flow filter design is the inclusion of a radiused flange section which eliminates stress risers, and provides a more delamination-resistant filter body.

Figure 1.5 - Hot Gas Cleaning Systems - Westinghouse Candle Filter System

The development of the cross flow filter has evolved through the stages of initial exploratory studies to proof-of-concept test at various bench-scale gasification and combustion facilities. Initial exploratory studies were focused on subscale filter element size (15.2 x 15.2 x 5.1 cm - 6 x 6 x 2 inch) tested in a bench-scale PFBC simulator and small fluid bed PFBC and gasifier facility.^(4,5) This work focused on evaluating the basic filtration properties of the cross flow geometry and methods to seal and mount the filter in high temperature gas streams. These studies demonstrated the technical and economic potential of the unique cross flow geometry. Bench-scale test results showed that 1) the conditioned filter resistance was low compared to other types of filter and inertial devices, 2) simple pulse-jet methods could be used to clean the filters, and 3) essentially absolute filtration on coal ash and char materials could be achieved. Delamination of the filter at the bonded joints was identified as a manufacturing development issue.

Initial scaleup of the filter element to commercial size (30.5 x 30.5 x 10.2 cm - 12 x 12 x 4 inch) and its testing was also accomplished. This testing included a very successful, 160 hour operation of an eight (8) element, four (4) module system under simulated PFBC conditions of the mid-rib bond cross flow filter design. The filters were flange mounted and compressively braced, an approach implemented to mitigate filter delamination. Post test inspection revealed that six (6) of the commercial scale filter elements had no structural damage but two (2) of the elements had suffered hairline delaminations that had apparently initiated from the mounting flange. Even with the delaminations, excellent filter system performance was achieved with outlet dust loadings ranging between 2 to 6 ppm.⁽⁶⁾

Following the subscale and initial full scale element testing summarized above, program emphasis was focused on integrated testing on pilot scale PFBC and gasification facilities. At the New York University PFBC facility located at the Antonio Ferri Laboratory in Westbury, New York, a Westinghouse cross flow filter system was

integrated into the test facility and operated in two separate 50 hour test programs.⁽⁶⁾ The filter unit consisted of five filter modules, each containing three filter elements, fifteen total elements (30.5 x 30.5 x 10 cm - 12 x 12 x 4 inch).

During the initial 50 hour test segment, operating at temperatures between 1300 and 1500°F (705 and 815°C), system pressure of 120 psia (8.3 bar), and filter face velocity of 5.2 ft/min (2.6 cm/sec) stable baseline operating pressure drop of 35 in wg (8.68 kPa) was achieved with simple pulse jet cleaning. Inlet PFBC dust loadings of 250 to 1056 ppm were reduced to outlet dust loadings of 2.9 to 8.9 ppm. Outlet cascade impactor dust sampling was also obtained that showed both loading and size distribution fall within published gas turbine tolerance requirements, Figure 1.6.

In the second 50 hour test run, the filter was operated at a 10 ft/min (5.1 cm/s), higher outlet dust loadings (up to 103 ppm) were encountered due to dust seal leaks that occurred after three of the five pulse valves malfunctioned and other facility operating problems were encountered. Inspection of the test unit showed that five of the fifteen filters had experienced hairline delamination cracks although none appeared to present a significant dust leak path. This testing also demonstrated that the 3M INTERAM[®] brand mat material used for gasketing was not sufficiently tolerant to temperature transients and susceptible to eventual eroding from between the filter and its mount.

Although cross flow filter field test programs provide opportunity for integrated operation in gas environments typical of large scale or commercial systems, they generally do not afford long operating periods. Also, filter test time is often compromised because of operational issues associated with the gasifier, combustor or some

Figure 1.6 - Data Comparing Outlet Particle Size Distribution with Turbine Tolerance Goals

other ancillary equipment or because of other test priorities. The Long Term Durability Testing of Ceramic Cross Flow Filter program (DE-AC21-87MC24022) was designed to provide dedicated filter test operations for test periods significantly longer than current pilot plant test programs.⁽⁷⁾

In this program, two dedicated HTHP filter test facilities (Figures 1.7) were constructed and operated. These test facilities are intended to provide simulated HTHP gas environments for evaluating the filter using ash materials from PFBC and coal gasification facilities. The PFBC simulator facility is designed for a gas flow up to 680 kg/hr (1500 lb/hr), combusting methane to provide the thermal input. A gravimetric dust feeder and a pneumatic transport line are used to re-entrain the ash. The second test system is a closed loop that is electrically heated and designed to provide a HTHP reducing or inert gas environment, permitting the feeding of char/ash material. In this facility, up to 680 kg/hr (1500 lb/hr) of gas flow is recirculated using a specially designed HTHP eductor. Approximately 10 percent of the gas is used as the motive flow for the eductor.

Both test loops have on-line ash collection and removal capability that permit round-the-clock operation over extended test periods (i.e., 100 hours or more). These facilities are operated over a wide range of flow, pressure and temperature conditions. Both test loops are instrumented to provide filter operating and system performance data, including a computer-based data acquisition system.

The program provided for 3000 hours of testing under PFBC conditions and 2000 hours under simulated gasification conditions. The goal was to achieve this testing utilizing a single set of cross flow filter elements, respectively. For the simulated gasifier testing utilizing a char feed, this goal was achieved. In the simulated PFBC testing a total of 3080 test hours was accomplished but events precluded the use of a single filter set. Two filters achieved over 1300 hours,

HTHP-PFBC SIMULATOR

Figure 1.7a - Schematic of Westinghouse PFBC Simulator Test Loop

RECIRCULATING GAS TEST LOOP

Figure 1.7b - Schematic of the Westinghouse Gasifier Simulator Test Loop

three other filters 1000 hours and one filter that was also utilized in the gasifier simulator testing had an accumulated exposure of over 2500 hours. Table 1.1 provides a summary of results from these extended testing periods.

Operating characteristics of the cross flow filter were investigated in the long term test runs. In the 1300 hour PFBC testing, the filters were subjected to over 2060 pulse cleaning cycles. The cross flow filters exposed to simulated PFBC conditions for 1100 hours were also exposed to simulated turbine trip and accelerated pulse cleaning cycles. In both the PFBC and simulated gasifier test loops, effective, on-line filter cleaning was demonstrated. Baseline filter system pressure drops were well below program criteria (<100 in wg, 25 kPa).

An important focus of the extended testing of the current program was the evaluation of filter system component durability. Test experience has demonstrated that the cross flow filter is basically an absolute filter on ash type material provided component integrity is maintained. In the PFBC simulator testing both filter element and gasket failures occurred that compromised filter performance. Although no gasket or filter failures were experienced in the gasifier simulator testing, ongoing cross flow filter testing in gasifier pilot plant systems had experienced such failures.⁽⁸⁾ In the early phases of the PFBC simulator testing an improved design of the ceramic mat gasket was developed and backfitted to both the PFBC simulator testing and ongoing gasifier pilot plant filter tests. Also, this improved gasket design was implemented into the testing in the gasifier simulator tests. In all subsequent testing, gasket failures have been eliminated utilizing this modified gasket design.

Cross flow filter element failures under service condition can be characterized as one or more of the following types: debonding of plate seams, delaminations (hairline cracks that follow plate seams), by cracks that propagate across the plate seams and cracks that occur along the mounting flange. Improvements in cross flow filter manufacturing have substantially improved filter element integrity as demonstrated by the durability of the cross flow filters used in the extended simulator test periods.

Table 1.1 - Summary of Cross Flow Filter Performance in
Long Term Durability Simulator Testing

	PFBC Ash Test Loop		Gasifier Char Test Loop
	Test Module	Test Module	Test Module
	#1	#2	#1
No. of Filters	2	4	2
Operating Conditions			
Temperature, °F	1550	1550	350-1200
Pressure, psia	85	85	85
Inlet Dust Loading, ppm	1000	1000	1000-1500
Face Velocity, ft/min	6 to 10	3 to 5	2-5
Cumulative Hrs.	1300	1100 2400	2000
Performance			
Avg. Outlet Loading, ppm	<1	<1	<1
Baseline Δp , in wg	8-20	4-10	1-4
Comments	Flange Failure	New Mount	No Failures

Uncontrolled plant thermal transients represent the major concern regarding delamination and filter plate cracking. Simulator testing has demonstrated that the cross flow filter can endure controlled plant transients typical of PFBC plant startup and turbine trip. A deficiency in the filter mount design that was not apparent from earlier short term tests caused flange cracking terminating the 1300 hour test run in the PFBC simulator testing that was not apparent from earlier short term tests. A redesign of the filter mount was made to eliminate the root cause of the observed failure; (nonuniform loading of the flange and the buildup of dust fines in crevices between the mount and filter flange). This design was implemented in subsequent PFBC simulator and Texaco gasifier pilot plant testing. Although testing has been limited (1000 to 2000 hours), no further failures in the filter flange were experienced in the Long Term Durability program.

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2. DESCRIPTION OF TEST FACILITIES

2.1 TEXACO PROCESS - ENTRAINED GASIFIER PILOT PLANT FACILITY

The Westinghouse Science and Technology Center (STC) with Texaco conducted a test program on a hot gas filter system which was integrated with the Texaco entrained-bed, slagging gasifier located at Montebello Research Laboratories (MRL) in California. Figure 2.1 shows the schematic arrangement of the test facility. The filter system and fines collection hopper are situated between the radiant and convective syngas coolers. As shown in the process schematic, a coal slurry and oxidant (air or oxygen) flow cocurrently downward through the gasifier. The partial oxidation reactions and ash melting that occur in the gasifier are carried out at temperatures of 1205-1540°C (2200 to 2800°F), and at 350 psig. The bulk of the molten ash is quenched in a slag bath located directly below the gasifier and withdrawn as a slurry. The hot syngas with a small amount of entrained ash/char exits the gasifier, is cooled in the radiant syngas cooler to a nominal 540 to 815°C (1000 to 1500°F) and introduced into the filter system. For some testing, a precleaning cyclone was used to reduce the filter inlet loading caused by soot blowing operations in the radiant cooler. The filtered gas proceeds to the convective cooler (which also houses the sorbent beds used for external desulfurization testing) and is then flared at the exhaust stack. The filter protects the sorbent beds from ash plugging. The Texaco test program also included the use of in situ sorbents. As shown, these sorbents were injected either into the gasifier, via the coal slurry, or into the radiant upflow cooler as a separate slurry. The particulate matter carried into the filter system would vary depending upon the in situ desulfurization method and sorbent utilized.

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Figure 2.1 - Schematic of Texaco Entrained Gasifier Facility with Westinghouse Hot Gas Filter

A bypass line was also provided around the filter unit to permit operation of the gasifier in the event of filter failure and to help mitigate operational variances, should they occur.

At the initiation of a test run, the main gasifier head flange is removed and an atmospheric preheat burner is bolted on the flange. The burner is ignited and a steam eductor is used to aspirate the exhaust gases from the burner through the entire process train, including the filter system. Upon achieving a predetermined temperature inside the gasifier, the atmospheric burner is removed and substituted with a special proprietary process burner in preparation for light off. After achieving coal ignition at atmospheric pressure, the system is ramped to process conditions by throttling the pressure control valve. Thereafter, the flow control valves are opened to direct hot fuel gases into the syngas coolers and the filter system.

Typically Pittsburgh No. 8 coal was used as the feed coal throughout the entire test program at the Texaco gasifier. Table 2.1 provides a composition of the syngas which was typically produced. Since testing of the Westinghouse cross flow filter system was carried out in conjunction with Texaco's desulfurization program with DOE, the concentration of hydrogen sulfide (H_2S) in the syngas most likely varied. When no sulfur sorbents were added to the feed slurry, the H_2S syngas concentration was estimated to be 0.5% (dry) during oxygen-blown gasification of Pittsburgh No. 8 coal. When sulfur sorbents were added to the coal feed slurry, the concentration of H_2S in the syngas was estimated to be as low as 0.06%.

The concentration of particulates released into the syngas stream varied with throughput and the condition of the slag knockout pot which was located between the gasifier and the radiant syngas cooler. During testing there was no means to vary or regulate the concentration of fines carryover. Less than 10% of the gasifier coal feed ash was expected to have been carried over as particulates in the syngas at the exit of the radiant cooler. This is roughly equivalent to 4,000 ppmw entering the filter vessel.

Table 2.1 - Summary of Texaco Entrained Gasifier Operating Conditions

General:

Pressure:	350 psig
Temperature:	1200-1550°F
Gas Flow Rate:	
Nominal	2500 lb/hr (100 acfm)
Maximum	4000 lb/hr (160 acfm)
Dust Loading:	< 400 ppmw
Moisture Content:	~ 12% (air blown)
	24% (oxygen blown)

Gas Composition (dry):

	<u>O₂ Gasification</u> <u>(Vol%)</u>	<u>Air Gasification</u> <u>(Vol% Estimated)</u>
H ₂	35.6 to 37.4	12.0 to 16.0
CO	45.5 to 49.4	16.1 to 20.1
CO ₂	12.2 to 16.3	3.4 to 7.5
CH ₄	0.0 to 0.1	0.0 to 0.1
H ₂ S	0.0 to 0.6	0.0 to 0.3
N ₂	0.4 to 0.5	60.0 to 64.0

Typically ash within the coal feed is melted in the gasifier and is quite fluid at high temperature. If entrained syngas particulates have inadequate time to cool during transport from the gasifier through the radiant cooler, the potential exists for carryover of "sticky" particulates which contact and adhere to the filter surface. Filter pore plugging and subsequent gas flow restriction could also result from contact with "sticky" ash particulates.

The temperature of the syngas at the inlet to the ceramic cross flow filter system is governed by the gasifier exit temperature, the syngas production rate, and the amount of cold recycled gas to the radiant syngas cooler. The highest temperature, which is obtained at the highest throughput with no recycle syngas, and with external sorbents is approximately 845°C (1550°F). Lower temperatures are obtained by reducing the throughput or by recycling cold syngas to the radiant cooler. Adding recycled syngas also reduces the moisture content and particulate concentration, while increasing the total syngas feed to the ceramic filter.

2.2 DESCRIPTION OF WESTINGHOUSE HOT GAS FILTER SYSTEM

Throughout the entire course of testing, the Westinghouse filter system was located between the radiant and convective syngas coolers in the Texaco pilot plant gasifier system. A full port bypass valve was provided across the filter system to divert the bulk of the gasifier exhaust gas directly to the convective cooler. A description of the Westinghouse filter unit, pulse cleaning, ash collection, instrumentation, and gas sampling systems are provided in the following sections.

2.2.1 Filter Unit

A schematic of the Westinghouse hot gas filtration unit is shown in Figure 2.2. The mechanical drawings and Process and Instrumentation Diagrams (P&ID's) are provided in Appendix A. The nominally 3.0-m (10-ft) high, 1.05-m (41.8-in) OD pressure vessel was constructed and

CROSSFLOW FILTER VESSEL (Original Configuration)

1M902.BW

Figure 2.2 - Schematic of Westinghouse Hot Gas Filter Test Unit Using Ceramic Cross Flow Filters

rated at 450 psig at a 345°C (650°F) shell temperature as specified by ASME Section VIII requirements. The filter vessel was lined with 11.4-cm (4.5-in) of Harbison Walker Lightweight Castable 26 refractory. The vessel had 30.5-cm (12-in) 300 pound class flanged gas inlet and outlet nozzles with 10-cm (4-in) thick cast refractory lining. The gas inlet nozzle was placed below the level of the hanging filter modules to avoid direct impingement of incoming gas on the filter elements. The top gas outlet had a lined pipe tee, and was blind flanged at the top for additional access. The filter cake discharge at the bottom of the vessel had a 46-cm (18-in) 300 pound class flanged nozzle which joined the ash collection vessel that was provided by Texaco.

The filtration cavity in the vessel was enclosed within a 76.2-cm (30-in) diameter 316 stainless steel sheet liner. Incoloy-sheathed resistance heaters were provided for preheating the filter vessel during start-up, as well as for heating to keep the 316SS liner, and the dust that was in contact with the liner above the dew point.

Both the cross flow and candle filters were housed inside the 1.05-m (41.6-in) OD refractory and stainless steel sheet liner. During cross flow filter testing, either four or eight filter elements were mounted on two stainless steel plenums that were attached to a metal tubesheet. Alternately, nineteen candle filters were individually mounted from a single plenum which was directly attached to a metal tubesheet. Typically the cross flow and candle filter tubesheets were constructed out of 310 stainless steel with conical sections that served to minimize thermal and mechanical stress, and distortion during high temperature filter operation. The tubesheet was clamped between the full diameter vessel flanges and was pressure sealed using Flexitallic gaskets.

Pulse cleaning tubes were directed through the tubesheet and oriented concentrically with either the cross flow or candle filter plenum. Each plenum is also equipped with a recessed venturi that facilitated eduction of hot fuel gas from the clean side of the vessel, thereby augmenting the intensity of the reverse pulse and minimizing the thermal shock to the filters. High pressure nitrogen gas was used

during sequentially pulse cleaning events. The majority of the instrumentation leads also entered the pressure vessel through radial channels drilled through the tubesheet ring flange. Resistance heaters were strapped to the inside stainless steel liner of the filter vessel in order to provide filter preheat capabilities prior to gasifier operation. Following initial operation, these heaters failed and preheating of the filter unit was accomplished using the Texaco gasifier preheat system.

2.2.2 Pulse Cleaning System

The filter element pulse cleaning system P&ID is given in Appendix A (P&ID No. 6) and consisted of an external accumulator tank which was constructed from a 48 inch long piece of 10 inch pipe, with end caps, rated at 2200 psig at 100°F. Pulse cleaning gas was directed into a 2 inch nipple at the tank exit, and then into a 1 inch schedule 80 pipe. The pulse cleaning gas then entered a tee which acted as an elbow, and passed through four ball valves, and one solenoid valve. Following the valving, the gas contracted into a 1 x 3/4 inch NPT pipe reducer, and entered through a 0.875 inch diameter flange ring in the tubesheet. After passing through another 3/4 x 1 inch connector on the inside of the vessel, the gas was expanded into a 1 inch schedule 160 SS pipe inside the filter vessel. The thick walled pipe was needed to prevent blowback tube deflection, as a result of the high temperatures and occasional high pressures inside the pipe. Three elbows were used to form an expansion loop which terminated in a pipe nozzle over the clean-side plenum of each filter module.

During conduct of this program, the ceramic filter elements were pulse-cleaned using a high pressure (1500 to 2000 psig) nitrogen gas pulse. The typical length of a pulse during pulse cleaning was on the order of 0.25 seconds. Between blowback pulses the pressure drop increases across the filter as the dust cake builds. During filter operation the filters were cleaned on either a set trigger pressure drop, or time basis. The blowback sequence consisted of pulsing each

filter plenum once. When two plenums were utilized, pulsing was sequential with several seconds separating delivery of the pulse gas to each filter plenum.

2.2.3 Ash Collection

A simple ash collection system was utilized that consisted of a catch pot that filled and was emptied following each test run, see Appendix A, P&ID No. 7. A nitrogen purge line was provided to prevent syngas condensation and assist ash removal, if required.

2.2.4 Instrumentation

System instrumentation included capability for the following control and measurement functions:

1. Filter System Pressure Drop (P&ID No. 2, Appendix A)
2. Heater Control System (P&ID No. 3, Appendix A)
3. Blowback Pulse Pressure System (P&ID No. 4, Appendix A)
4. Filter Plenum Flow Systems (P&ID No. 5, Appendix A)
5. Filter Blowback System (P&ID No. 6, Appendix A)
6. Ash Collection Pot (P&ID No. 7, Appendix A)

All piping and instrumentation connections to the filter vessel, other than the heater connections, were made through the tubesheet flange ring, which rests between the lower vessel and the vessel head (P&ID No. 1, Appendix A).

The ceramic cross flow filter elements were pulse cleaned by high pressure nitrogen pulses. A differential pressure transmitter senses the pressure difference across the ceramic filters. Both sides of the transmitter were protected from the blowback pulse pressure rise by normally open solenoid valves which close during pulsing. The output signal was sent to the recorder, a digital panel meter, and a controller

which indicated the blowback pulses. A manual control override was also provided. A nitrogen gas purge line was connected to the high side line and allows for periodic flushing of this line to remove ash that may have entered the line. In parallel with the differential pressure transmitter was a differential switch which was used as a protective device preset to the maximum allowable Δp (i.e., 5 psid). If the Δp reached this pressure, the switch alarm alerted the operators to energise a by-pass valve so that the main gas flow was redirected around the filter vessel.

Thermocouples were used to measure the temperature of the center section and expansion cone section of the tubesheet. These were provided for informational purposes only.

An internal electric heating system was used to maintain temperature in the filter vessel (P&ID No. 3). The heater control system consisted of a temperature controller and a thermocouple that sensed the temperature of the heating element. Thermocouples monitored the temperature of the vessel liner which was displayed on a panel readout.

The blowback pulse intensity measurement system provided the capability of measuring the dynamics of pressure rise in a filter plenum during a pulse (P&ID No. 4). The low side of the differential pressure transmitter was connected to the filter plenum via the tubesheet and the high side was connected to the dirty side of the filter vessel. The output from the low side of the differential pressure transmitter was sent to a high speed recorder. A nitrogen purge line was connected to the high side line in order to blow out any ash that may accumulate.

The filter plenum flow system allowed for the measurement of the filtered gas flow through each of the two filter plenums, so as to verify proper flow distribution (P&ID No. 5). This was accomplished by measuring the differential pressure across the venturi section. The pressure differential transmitter sensed this Δp , sending a signal to a multipoint recorder. The low side of this transmitter was connected to

the venturi throat and the high side just upstream of the venturi contraction. The gas temperature was recorded at the outlet of the plenum which was then used to calculate the gas flow rates through both plenums. Normally the two open solenoid valves closed during the blowback pulse so as to protect the pressure differential transmitter.

In the filter blowback system, high pressure nitrogen gas from the plant supply line passed through the check valve and high pressure regulator, and pressurized the blowback pulse accumulator vessel (P&ID No. 6). The pressure vessel was fitted with a pressure safety valve, a valved vent, and a pressure gauge. A one inch supply line was instrumented with a local gauge and a pressure transmitter which sent an output signal to a panel mounted pressure indicator. This line fed two identical branches, one for each plenum. Each branch had a solenoid blowback valve. Each valve was positioned between a double block and bleed system consisting of one inch full-ported ball valves. The ball valves possessed electrical operators which opened just prior to blowback, and closed during normal operation. The solenoid valves were 110 V AC powered and were controlled automatically by a pressure controller, or operated in a manual mode. The blowback line terminated inside the filter vessel with the end of each pipe directing the pulse gas into the corresponding plenum venturi.

The ash vessel nitrogen purge system has been supplied in order to reduce the possibility of combustible gas accumulating in the ash collection pot (P&ID No. 7). The vessel was fitted at the bottom with a six inch ball valve, and a blind flange to allow for the periodic removal of ash. Nitrogen gas entered at a tapped flange at the connection of the ball valve and the vessel bottom, and flowed upward into the filter vessel to sweep out air and/or process gas.

2.2.5 Particle Sampling

Figure 2.3 shows a schematic of the particle sampling train used on both the inlet and outlet of the filter unit. A simple nitrogen-purged tubing probe was inserted into the flow path. The probe

Figure 2.3 - Schematic of Particulate Sampling Train Used to Measure Inlet/Outlet Dust Loadings

was fitted with provisions for rotation into and out of the flow stream. Sampling flow was set with a valve that would allow the isokinetic sample to enter a filter holder that contained a ceramic fiber paper filter upon which a sample was collected. The exhaust gas was then dried in a knock-out pot and drierite bed, and finally the gas flowed through a rotometer and flow totalizer.

The entire assembly from the probe flange to the sample filter holder consisted of a straight line configuration, in order to minimize loss of dust at curves or bends. The entire length was wrapped with heating tape to prevent condensation before the sample filter holder.

Sampling was conducted in order to adequately monitor the performance of the cross flow filters, and to detect at least 1 ppmw dust in the outlet gas stream. Because of isokinetic flow, and the small nozzle size, the total amount of gas sampled was very small.

The inlet sampling system was virtually the same as the outlet gas stream supply system. Due to a much higher inlet dust load (i.e., nominally 4,000 ppmw), the sample duration was on the order of about five minutes, with samples taken periodically. If the process gas flow rate changed during sampling, the sampling line flow rate was reset so as to maintain isokinetic flow.

3. TEST PROGRAM AND RESULTS

The Westinghouse high temperature, high pressure (HTHP) filter system was operated on the Texaco gasification subpilot-scale plant in Montebello, CA. The filter unit was designed to operate at 350 psig pressure, with an internal temperature of about 1500°F, a volumetric flow range of 70-120 acfm, and a nominal mass loading of 4,000 ppmw. Eleven test runs, beginning in April of 1989 and concluding in August 1992, were made that included seven tests using cross flow filters and four tests using ceramic candles. The candle filters were tested to provide data on an alternative geometry, providing a basis to better assess the performance and operating characteristics that may be unique to the cross flow geometry. Tables 3.1 and 3.2 provide overall operating summaries of the filter test runs. All testing utilized a Pittsburgh No. 8 coal with the gasifier being either oxygen or air blown. As indicated, various desulfurization schemes were used. Section 2 provided nominal syngas compositions for the various gasifier operating conditions. This section describes each of the HTHP filtration tests that were performed by Westinghouse, using either a cross flow or candle filter configuration.

For each test run, the pressure drop characteristics of the filter unit was monitored and recorded. Appendix C provides data from two test runs (Run 6 and Run 10) that show the filter pressure drop characteristics typifying the filter operation in the subpilot scale entrained gasifier facility. Run 6 corresponds to the cross flow filter testing, while Run 10 shows candle filter data. Varying process gas conditions, uncertainty in actual filter inlet loading, and the relatively short cleaning cycles have complicated the utilization of these pressure drop traces as a reliable tool to interpret filter performance or identify abnormal operation. For example, damage to or

Table 3.1 - Westinghouse Filter Operating Summary

Test	Filter	Date	Hours	Startups	Oxidant	Additive	Pre-Cyclone
1	Cross Flow	4/89	48	1	O ₂	None	No
2	Cross Flow	7/89	35	1	Air	None	No
3	Cross Flow	7/89	29	2	Air	None	No
4	Cross Flow	8/89	103	1	Air	FeO _x Internal	No
5	Cross Flow	11/89	65	3	Air	CaCO ₃ External	yes
6	Cross Flow	1/91	42	3	O ₂	None	Yes
7	Cross Flow	5/91	60	3	O ₂	FeO _x -CaCO ₃ Internal	No
8	Candle	9/91	62	2	O ₂	None	No
9	Candle	11/91	34	2	O ₂	None	No
10	Candle	12/91	89	5	O ₂	None	No
11	Candle	7-8/92	101	8	O ₂	None	No

Table 3.2 - Westinghouse Filter Process Data Summary

Test	Filter	Date	Temp (°F)	Inlet Loading (ppmw)	Gas Flow (SCFM)	Notes
1	Cross Flow	4/89	1000	2000- 10000	400-940	310 pounds of solids collected from catch-pot.
2	Cross Flow	7/89	1250	250- 1220	290-730	34 pounds of solids collected from catch-pot.
3	Cross Flow	7/89	1300	270- 22500	180-640	
4	Cross Flow	8/89	1300	280- 2900	210-640	64 pounds of solids collected from catch-pot. Leak developed; one element was blown off seat and some filter element holding rods were missing. While filter was operating; outlet alkali concentration 10-50 wppb; inlet alkali 1-100 wppm.
5	Cross Flow	11/89	1400	650- 12350	140-600	Cycle time dropped below 1 minute without dolomite injection. During dolomite injection cycle time was 15-20 minutes.
6	Cross Flow	1/91	1200	1170- 1934	450-680	100 gallons of water taken from filter catch-pot after shutdown. 150 pounds of solids collected from the catch-pot.
7	Cross Flow	5/91	1400	1640	270-600	Rapid depressurization upstream of filters at shutdown; all elements were broken.
8	Candle	9/91	1300	1076- 1873	380-630	84 pounds of solids collected from catch-pot.
9	Candle	11/91	1300	768- 2525	380-660	52 pounds of solids collected from catch-pot.
10	Candle	12/91	1300	NA	340-580	
11	Candle	7-8/92	1500	NA		112 pounds of solids collected from catch-pot.

failure of the filter elements could not, in general, be identified or correlated to any change in the characteristic features of the system pressure drop.

3.1 FILTER SYSTEM COMMISSIONING TEST - CROSS FLOW

A commissioning test (Test No. 1) was conducted on the Westinghouse cross flow filter system over a four day period in April 1989. Two hot gas filter plenums were utilized in the commissioning effort. Each plenum contained two 12 x 12 x 4 inch alumina/mullite cross flow filter elements. During the commissioning test, the Texaco gasifier was operated in an oxygen-blown mode using a feed source slurry of Pittsburgh No. 8 coal and external sorbent beds for sulfur removal. Precleaning cyclones were not utilized during this phase of testing.

The four cross flow filters were operated over a temperature range of 790° to 1020°F, with a volumetric gas flow rate of 47 to 110 acfm. Four steady state test periods were identified for filter performance characterization and solids sampling system shakedown. The hot gas filter system was successfully operated for the planned 48 hours. The operational performance of the filter system, the pulse cleaning subsystem, and the inlet and outlet isokinetic sampling loops were assessed during this phase of testing. Table 3.3 summarizes the filter performance data for various steady state test periods.

During the commissioning test, the cross flow filter elements were periodically reverse pulse cleaned for a total of 270 pulses. During the initial 21 hours of filter operation, the system was pulse cleaned at a trigger pressure drop of 50 inches of water using tank pressures in the range of 850 to 940 psig. The time between filter pulse cleaning events ranged between 10 to 15 minutes during this test period, Figure 3.1, Set Point 3. For the balance of the commissioning test, the pulse tank pressure was increased to 1100 psig. At the higher syngas flows (95-110 acfm), higher trigger and baseline pressure drops were experienced. Pulse cleaning frequency also increased, ranging between 3 to 6 minute intervals, Figure 3.1, Set Point 6. Although

Table 3.3 - Nominal Filter Performance Data, April 1989 Texaco Test

Set Point	Hours at Set Point	Temp. °F	Gas Flow		Pressure Drop in wg		Dust Loadings	
			SCFH	ACFM	Trigger	Baseline	Inlet ppm	Outlet ppm
1	3.5	1016	30770	66	50	8	9109**	
2	3.5	876	16120	31	38-50	5		
3	13	790-845	40240*	76	50-70	13-20	2118	2.2 6.2
4	2.5	926	47570*	95	80-90	26		2.2
5	7	990	52700*	110	90	32-35	2646	
6	14.5	934-975	48300*	98	95	30-33	6752*** 1931 2490	3.9 2.1 4.0

* Includes 8000 SCFH cold recycle gas leak from soot blower.
 ** Gasifier operation not stabilized, possibly low carbon conversion
 *** During soot blowing operation

Test Run 1 (Commissioning) - Cross Flow
Filter Pressure Drop - Set Point 3 (76 ACFM)

Time (1 Div = 1.8 min)

Test Run 1 (Commissioning) - Cross Flow
Filter Pressure Drop - Set Point 6 (98 ACFM)

Time (1 Div = 1.8 min)

Figure 3.1 - Typical Cross Flow Filter Pressure Drop Characteristics During
Steady State Operation (Commissioning Test Run)

stable baseline pressure drops were achieved in this testing, the pressure drop levels were higher and cleaning cycles more frequent than initially predicted. These aspects of the filter operation are reviewed and discussed in Section 4.

The inlet and outlet isokinetic sampling systems operated successfully during the commissioning test, and a total of six sets of samples were obtained. The overall operational performance of the sampling system was judged to be satisfactory, gas flow rates were closely controlled, and the samples were uniformly dry. The inlet mass loading varied between 1,930 and 9,110 ppm, while the outlet mass loading varied between 2.1 and 6.2 ppm, Table 3.3. These loadings are significantly below the NSPS limits for gasifier combined cycle power plants, and well below the gas cleanliness requirements for sorbent bed operation.

Inspection of the dust hopper after completion of the commissioning test indicated that approximately 310 lbs of fines had been collected, which was consistent with the nominal mass balance during gasifier and filter system operation. A small sample of collected ash was sent to Southern Research Institute for characterization. Results of this laboratory analysis are given in Appendix B and discussed in Section 4. A borescope inspection of the clean-side internal surface of each filter plenum showed no evidence of cross flow filter delamination or dust seal leakage. Based on this inspection, it was concluded that the filter unit did not need to be disassembled and that plans for the next test period could proceed.

3.2 HTHP FILTRATION UNDER AIR-BLOWN GASIFICATION WITH EXTERNAL SULFUR REMOVAL BEDS - CROSS FLOW

Two subsequent hot gas filtration tests were conducted during July 1989 using the original four cross flow filter elements. Tests No. 2 and 3, Tables 3.1 and 3.2. The integrated gasification system was

operated in an air-blown mode, using external sorbent beds for sulfur removal. As in the commissioning test, precleaning cyclones were not used during this phase of testing.

Twenty-nine hours of filter operation were initially completed at a nominal temperature of 1250°F and with gas flow rates of 42-102 acfm at a pressure of 350 psig. Although the internal filter vessel heaters malfunctioned during this period of testing, a gradual temperature ramping of the filters occurred as a result of exposure to the hot syngas flow. The four cross flow filters experienced an inlet dust loading of 250 to 1,220 ppm, and achieved an outlet dust loading of 23 to 33 ppm. Testing was temporarily terminated as a result of a loss of slurry feed to the gasifier.

Six additional hours were logged by the cross flow filter system under similar air-blown gasification conditions after restart. During the six hour test period, the filter process heaters remained inactive, and the four cross flow filters experienced a nominal temperature of 1300°F, and gas flow rates of 24-91 acfm at 350 psig. Although high filter inlet dust loadings of 22,525 ppm were measured, satisfactory particulate collection efficiencies were demonstrated by the filter system as indicated by the 80-114 ppm outlet dust loadings. Excessive pulse cleaning frequencies were necessary to clean the four cross flow filters due to the abnormally high inlet dust loadings. Testing was ultimately terminated as a result of a leak in the gasifier air supply line.

After cooldown, the filter unit was disassembled and an inspection of the filter was performed. One of the four filter elements had developed a hairline crack on a dirty gas channel plate-to-plate interface. This filter element was replaced with another as-manufactured cross flow filter element. In addition to the filter hairline crack, three of the four cross flow filter gaskets had partially eroded and evidence of dust leakage was observed. These gaskets were replaced and testing resumed.

Testing resumed during July 1989 under air-blown gasification conditions with external sulfur removal. As in the previous test campaigns, precleaning cyclones were not utilized. Similarly, the filter process heaters remained inactive. The original four cross flow filter elements were exposed at a nominal temperature of 1300°F, and gas flow rates of 30-89 acfm for an additional 29 hours to inlet dust loadings of 270-2900 ppm. Outlet dust loadings ranged from 5-65 ppm. Testing was terminated due to a leak in the filter bypass valve, and temperature control problems in the gasifier slag knockout pot. After cooldown, a borescope inspection of the filter clean side showed no visible filter or gasket issues. The unit, therefore, was not disassembled.

3.3 HTHP FILTRATION UNDER AIR-BLOWN GASIFICATION WITH IRON OXIDE DESULFURIZATION - CROSS FLOW

During August 1989, the Texaco gasifier was operated under an air-blown gasification mode, with iron oxide added to the coal feed as a desulfurization sorbent (Test No. 4). As in previous test campaigns, the precleaning cyclones were not utilized. The Westinghouse cross flow filter system operated for 63 hours at nominal temperatures of 1030-1430°F, and gas flow rates of 22-86 acfm at 350 psig. During this phase of testing, inlet dust loadings ranged from 280 to 2866 ppm, with outlet dust loadings of 59-115 ppm.

Once again the filter system heat-up was controlled by gradual ramping of the syngas flow. During the first 12 hours of filter operation, the pressure drop signal was lost as a result of a rupture in an internal pressure tap connection. The four cross flow filters were pulse cleaned on an equal time interval basis until a sparger tube was substituted for the failed pressure tap. Thereafter the filters were pulse cleaned on a very frequent basis (i.e., cycle time ranged between 15 seconds and 3 minutes). Pluggage of the cross flow filter dirty gas channels may have occurred when the sensor malfunctioned and proper cleaning periods could not be established.

After approximately 25 hours of filter operation, the pressure drop decreased abruptly from the baseline of 52 to 8 inches of water, following a pulse cleaning sequence. This suggested that at least one of the four cross flow filter elements had developed a serious breach. After an additional 38 hours, outlet dust loadings of 91 ppm were measured. Testing was ultimately terminated after completion of the Texaco sorbent test program.

Post-test inspection of the four cross flow filter elements indicated that three of the four filters were intact, showing no signs of delamination or cracking. These filters had acquired a total of 166 hours of hot testing during the first four test campaigns. The fourth filter element had been sheared off at the flange-to-filter body surface, and also appeared to have been unseated by the reverse pressure generated during pulse cleaning. This filter element initially had a thinner flange section in comparison to the other cross flow filter elements, and an abnormally sharp edge on the flange-to-body contoured surface. The filter body showed no evidence of cracks or delaminations.

Post-test inspection also indicated that three of the four dust seals were partially eroded. This suggested that the gasket material needed to be encapsulated and/or reinforced to minimize erosion and increase their durability during pulse cleaning. An aggressive testing campaign was conducted to identify alternate gasket seal materials. Materials were procured and subjected to prototypical seating stresses, thermal stresses, and transient hydrodynamic stresses that were expected to occur during delivery of a cleaning pulse. Based on maintaining seal integrity at high temperature, a Nextel fiber-MM² Mat composite gasket was designed and utilized in subsequent test efforts.

Post-test inspection of the filter vessel internal heaters indicated that the cold pin junctions had completely corroded, and were shorted due to moisture contamination of the electrical insulation. A cap was welded to the heater body, filled with a refractory potting compound, and coated with a high temperature moisture sealer. The heating elements were then mounted on the internal metal liner that was installed inside the filter vessel.

During this phase of the program, both Westinghouse and the Coors Ceramics Company considered various approaches for further extending the life of the cross flow filter element. This resulted from concerns that arose during simultaneous conduct of alternate Westinghouse-DOE/METC programs. From prior experience, delamination sporadically occurred along the mid-rib bond or gas channel seams during hot gas filtration testing. In order to minimize delamination, cross flow filter elements were manufactured using a single firing step to maximize the sintering reactivity of the mid-rib bonds or gas channel seams. In addition, the configuration of the dirty and clean gas channels was modified to enhance the cleaning effectiveness of the back pulse action. While the overall filtering area was maintained at 8 square feet, the number of dirty gas cross flow filter channels was increased from 158 to 198, and the number of clean gas channels was reduced from 4 to 3. This modification essentially reduced the size of the dirty gas channels such that a higher pulse gas flow velocity could be achieved through the clean-to-dirty gas channel wall, thus effectively increasing the dust cake removal efficiency.

3.4 HTHP FILTRATION UNDER AIR-BLOWN GASIFICATION CONDITIONS WITH EXTERNAL CALCIUM CARBONATE SPRAY DESULFURIZATION - CROSS FLOW

In November 1989, a 65 hour high temperature cross flow filter test was completed (Test No. 5). The Texaco system was configured to utilize a calcium-based sorbent slurry injection stream which was installed at the bottom of the upflow radiant cooler. In addition, cyclones were installed upstream of the filter vessel, with the hot by-pass line placed between the entrance to the cyclone and the outlet of the filter vessel.

During the initial 42 hours of HTHP filter testing, the gasifier was operated without sorbent injection. This period was marked by excessively short pulse cleaning cycles, ranging between 0.5 and 3 minutes. Because of the shortened intervals, the bypass valve was opened to provide operational flexibility for off-line cleaning. As a

result of utilizing the upstream cyclone, the particle size of the filtered solids had apparently been reduced, thereby increasing the impedance of the filter dust cake and rate of pressure drop buildup.

During the final 20 hours of EHTP filter testing the gasifier was operated with a coarse dolomite slurry injection. In sharp contrast to the previous 42 hours of testing, the filter cleaning cycles ranged between 10 and 30 minutes. During both phases of testing, gas flow rates of 50 to 94 acfm at 350 psig were maintained through the filters. Inlet dust loadings to the cross flow filters ranged from 650 to 12,350 ppm, while outlet dust loadings ranged between 18.9 and 176 ppm. Testing was ultimately terminated when a plug formed in the Texaco sorbent injection system.

Post-test inspection of the filter system indicated that one out the four cross flow filter elements delaminated along a dirty gas channel seam, and that the body had been severed from the flange at a 45° shear angle. The failure mode of the cross flow filter was considered to have resulted from the frequent backpulsing required to dislodge the fine dust cake. The remaining three filter elements were found to be intact. However, during the disassembly process, one of these filters also delaminated.

The dust seal gaskets on the two remaining intact cross flow filters were found to be intact. The gasket on the delaminated filter, however, was eroded by the bypassing flow of the backpulse gas across the breached surface. One of the gaskets had been misaligned during filter assembly, and consequently was partially eroded.

Inspection of the internal surface of the filter vessel liner clearly showed indications of a gas rebound path across the inlet baffle plate. This observation suggested that the gas was deflected by the baffle plate, which then formed eddies on the back surface of the filter vessel close to the bottom element on the second plenum. Throughout

this test program, three cross flow filter elements which had been mounted at the bottom position of plenum No. 2 experienced failure during high temperature, high pressure testing.

In an attempt to eliminate direct impingement of high velocity gases and solids on any filter element, efforts were directed to designing a retrofit of the filter unit internals. Prior to subsequent testing at Texaco, the filter unit system redesign was evaluated at Westinghouse in our cold flow model test facility. This work is summarised in Section 4.

3.5 HTHP FILTRATION UNDER OXYGEN-BLOWN GASIFICATION CONDITIONS WITH EXTERNAL SULFUR REMOVAL - CROSS FLOW - TEST NO. 6

Based on the information generated from the cold model and vibration tests, the design of the filter unit was modified, (Figure 3.2). The modified design included a coaxial shroud around the filter plenum to promote uniform gas distribution and downflow. In addition the filter plenums were redesigned to hold four filters each instead of two, and the filter mount was redesigned to include a rugged swivel bar clamp to more evenly distribute the load along the filter flange. Composite gaskets consisting of Nextel fabric and 3M's MM Mat were substituted for the previous Interam gasket seals.

Operation of the Texaco gasifier resumed in August 1990, after replacement of the dolomite sorbent with a calcined limestone sorbent. During initial system pressurization following gasifier light-off, a hot spot was observed in the quench pot, and a system shutdown was necessary.

Following system repair and other facility maintenance delays, the high temperature, high pressure filter testing was resumed in January 1991 (Test No. 6). During this phase of testing, the gasifier was operated in an oxygen-blown mode without in-situ sulfur sorbents. The hot gas filtration unit consisted of two plenums, each containing

CROSSFLOW FILTER VESSEL

(Modified
Configuration)

24041.200

Figure 3.2 - Schematic of Modified Cross Flow Filter Unit

four cross flow filter elements. A precleaning cyclone which was previously installed to separate spent limestone particles injected downstream of the gasifier continued to operate during this test. A cascade impactor particle sampling train, designed and built by SRI, was also implemented for the inlet filter leg.

In Test No. 6 the filter system was preheated by ramping the gasifier slipstream flow through the radiant cooler. In this manner a nominal filter temperature of 1200°F was achieved in five hours. The filter system was operated at a nominal flow rate of 60 acfm with an effective face velocity of 1 fpm. Inlet dust loadings ranged between 1,170 and 1,934 ppm, with a mass mean particle size diameter of $\sim 4 \mu\text{m}$ (established from the cascade sampling train). Approximately 20 percent of the inlet dust loading was comprised of particles that were less than $1 \mu\text{m}$.

During filter operation, hot gas cleaning was performed with a blowback tank pressure of 900 psig which typically reduced the pressure drop across the filter from 95 to 50 inch wg. Pulse cleaning frequencies varied between 4 and 6 minutes during steady state operation. After 33 hours of operation, outlet dust loadings ranged between 183 and 788 ppm, and the filter system was taken off-line. A total of 42 hours of operation was achieved. Filter unit pressure drop characteristics for this test run are provided in Appendix C.

Post-test inspection of the filter system indicated that the two bottom filters on each plenum were wet and had delaminated. The bottom filter on one plenum also appeared to have sustained a V-shaped fracture across the top closed section of the filter. One filter, located at the second position from the bottom, also appeared to have experienced delamination along a dirty gas channel seam. Dust, however, was contained along the dirty gas channel surfaces in the vicinity of the delamination. Although the remaining five cross flow filters were intact, their channels were filled with dust which had apparently been reentrained and deposited during pulse cleaning.

After removing the three damaged cross flow filters, a pool of water was seen inside the metal fixtures that supported the cross flow filter elements. Approximately 150 pounds of solids and 100 gallons of water were drained from the bottom of the ash hopper. The source of the water leak was not conclusively established. All four bottom cross flow filter (three damaged and one intact filter element) were replaced with new filter elements prior to subsequent testing.

Of the four bottom filters that were removed, the one which remained intact was subjected to permeability characterization. Testing indicated that the filter retained only 5 percent of its original permeability after exposure to the Texaco gasifier dust. This is viewed as a substantial loss in permeability in comparison with the 20 to 30 percent retention by filters which operated under pressurized fluidized-bed combustion conditions. The low residual permeability, however, does not account for the relatively high baseline Δp experienced during testing. The projected baseline Δp , based on the actual face velocity, should have remained below 6 inch wg, in comparison to the >30 inch wg that was actually experienced. This suggests that the plugged filters resulted from either poor cleaning, or from earlier testing where the filters were permitted to operate for long periods without cleaning.

In view of the anomaly in the baseline pressure drop described above, and the possibility of ineffective cleaning, an evaluation of the pulse cleaning system was made. This analysis showed that the pulse jet issuing from the pulse nozzle may not have been attaching to the throat of the eductor, limiting the effectiveness of the filter cleaning. A modified venturi design with a long τ throat section, was implemented.

3.6 HTHP FILTRATION UNDER OXYGEN-BLOWN GASIFICATION CONDITIONS WITH EXTERNAL SULFUR REMOVAL - CROSS FLOW - TEST NO. 7

During May 1991, the Texaco gasification system was operated in an oxygen-blown gasification mode (Test Campaign No. 7) using external sulfur sorbents. Precleaning cyclones were not used during this phase

of testing. A significant filter temperature transient was experienced during initial pressurization (i.e., after gasifier lightoff) which exceeded the recommended cross flow filter system ramp rates. Significant fluctuations in the Texaco gasifier operation (flow and temperature) were experienced making it difficult to maintain steady state conditions during the 60 hour filter test period. During testing the inlet sample lines were frequently plugged, possibly indicative of high particulate loadings. During the last 24 hours of testing, the filter Δp measurement failed. Texaco experienced an overheating and rupture of one of its pressure vessels which necessitated rapid shutdown of the system. This event may have imposed a high Δp across the tubesheet and filter unit, contributing to the damage incurred within the filter vessel. The tubesheet plate had completely separated from the expansion cone, and all eight cross flow filters were damaged. Inspection of the ash in the collection hopper revealed the presence of broken pieces from at least one cross flow filter.

Since the repair and replacement schedule for the damaged tubesheet and filters would delay the planned Texaco testing program, alternative filter choices were explored. An existing candle filter tubesheet and plenum assembly was available that could be easily adapted to the Texaco pressure vessel. Benefits of testing a candle filter array at Texaco included:

1. Direct comparisons between candle and cross flow filter systems, to determine if the previously observed characteristics are indicative of the process gas, type of ash, or geometry of the filter.
2. Supporting the design and operation of larger scale DOE funded candle filter installations by demonstrating the feasibility of pulse cleaning a large candle array (19 candles) from a single nozzle source.
3. Demonstrating the durability and adequacy of the candle mount and seals used in the larger scale program.

3.7 OXYGEN-BLOWN GASIFICATION TESTING OF A CANDLE FILTER CLUSTER WITH EXTERNAL DESULFURIZATION AND REGENERATION - CANDLE

In this test, Test No. 8, a 19-candle filter array was implemented, replacing the cross flow filter test section. Seventeen 1.5 m silicon-carbide Schumacher F40 Dia Schumalith candles, and two 1 m alumina/mullite Coors Ceramics candles were housed in individual filter mounts and connected to a common plenum section, Figure 3.3.

During Test No. 8, Texaco operated the gasifier in an oxygen-blown mode with an external sulfur bed that incorporated off-line regeneration. At operating conditions, a maximum temperature of 1400°F was experienced by the candle filter array. Table 3.4 provides a summary of the filter operating data. During the sulfidation phases of the external sorbent bed (Phase I, II, III, and V in Table 3.4), the candle filters experienced gas flows of 70 to 90 acfm. During sorbent regeneration (Phase IV), the flow of gas through the filters was reduced to approximately 60 acfm.

During the initial twelve hours of operation with coal (Phase I), the candle filter operating baseline pressure drop ranged from 4 to 10 inch wg. Following this initial period, the gasifier flow was increased from approximately 70 to 90 acfm. The baseline filter pressure drop increased significantly, ranging from 50 to 70 inch wg, but remained reasonably stable once steady state flow conditions were established (Phase II, III, and V). At low flow conditions (i.e., 60 to 70 acfm, Phase IV), baseline pressure drop remained constant at ~30 to 40 inch wg.

The resulting pressure drop through the candle filter system indicated that the overall operating characteristics did not appear to differ significantly from those of the cross flow filter system. This suggested that the relatively high operating Δp experienced in the gasification system was probably process dependent and not associated with the type of filter element.

Figure 3.3 - HTHP Candle Array Arrangement

Table 3.4 - Nominal Filter Performance Data Test No. 8, August 1991

Test Period	Elapsed Time Hrs	Flow SCFH	Filter Temp °F	Face Velocity Ft/Min	Nominal Cycle Times Min	Operating Pressure Drop, in wg	
						Baseline Range	Trigger Range
Gasifier Startup	2	0 to 19,000	280 - 770	0.6		-	-
Phase I	9	23,000 29,000	770 to 1385	0.7 to 1.3	60 - 30	4 - 10	40 - 50
Phase II	2.5	36,800 38,000	1400	1.6 1.7	2 - 10	10 - 70	50 - 100
Phase III	5.0	34,500	1400	1.5	4 - 10	50 - 70	100 - 115
Phase IV	8.0	28,000	1240	1.2	5 - 7	30 - 40	60 - 90
Phase V	5.0	32,000	1325	1.4	1 - 4	50 - 90	90 - 115
Phase VI	4.5	27,000 20,000	1300 1000	1.2 0.7	7 and up	40	100 - 75
Phase VII	1.0	2000 6400	1000 450	0.7 0.2	>60	40 - 5	75 - 20
Shutdown							

Two outlet and inlet samples were taken during candle filter operation. Inlet dust loadings ranging from 1,000 to 2,000 ppm were identified, typical of previous cross flow filter tests. Outlet loadings appeared to be dust free, but contaminated with debris. After ~25 hours operation, testing was terminated when a high filter system pressure drop resulted (i.e., ΔP exceeded gauge readouts), and the filter bypass leg suffered an apparent blockage. Subsequent inspection of the gasifier unit indicated that the gasifier slag removal system had malfunctioned, causing excessive ash carryover.

A borescope inspection of the filter unit was conducted and indicated that the filters had not experienced any obvious problems. A flow test using ~10,000 acfm nitrogen gas was also conducted to determine if the filters suffered significant blinding. The flow test results indicated nominally expected pressure drop characteristics.

3.8 OXYGEN-BLOWN GASIFICATION TESTING OF A CANDLE FILTER CLUSTER WITH EXTERNAL DESULFURIZATION AND REGENERATION - TEST NO. 9 - CANDLE

A second test run was conducted utilizing the 19-candle array previously operated during Test No. 8. Test No. 9 was a repeat of the earlier test plan, i.e., external desulfurization and regeneration. Approximately 34 hours of operation was achieved (including time to change process conditions).

The gasifier was operated in the oxygen blown mode with an external sulfur bed that was regenerated off-line. Table 3.5 summarizes the test results. Filter test operations are divided into five (5) test segments:

- Gasifier Startup
- Phase I - Bed Heatup
- Phase II - System Restart
- Phase III - Sulfidation
- Phase IV - Regeneration

Table 3.5 - Summary of Texaco Gasifier, Hot Gas Filter (19-Candle Array) Test - Test No. 9

Test Segment	System Pressure psig	Filter Temperature °F	Flow acfm	Filter Pressure Drop, in wg		No. of Cleaning Cycles	Time at Conditions Hrs
				Baseline Range	Trigger Range		
Startup	0-385	400-875	0-38	-	40	1	4.0
Phase I	363	875-1100	38-60	9-12	40-50	3	2.0
Phase II	387-347	900-1330	50-80	11-29	50-60	12	4.0
Phase III	350-360	1300-1425	90	44-200	>250	~275	10.0
Phase IV	350-360	860-1000	40-30	40-80	60-160	~180	7.0

NOTE: Time at conditions excludes time between test phases.

The Westinghouse filter was first preheated to about 400°F utilizing the same aspirated hot gas flow that preheats the gasifier system prior to gasifier lightoff. At lightoff, the system is pressurized to about 350 psig and flow slowly increased to operating value.

During Phase I, the Texaco external sulfur beds are brought to the desired operating temperature using an external heating source, while operating the filter to remove particulate from the generated fuel gas. Relatively low filter pressure drops were experienced during this period. Just prior to the initiation of the desulfurization test, overheating of the upstream transfer line (unrelated to the filter) occurred, forcing a temporary shutdown for repair.

With correction of the overheated transfer line problem, operation was resumed with continued preheating of the sulfur bed and filtering of the fuel gas, Phase II. During this phase, flow was increased to about 80 acfm. Stable and acceptable operation of the filter was experienced through both Phase I and Phase II.

Following the preheat of the sulfur beds, part of the filtered fuel gas flow was diverted through the sulfur beds to begin the sulfidation portion of the test program, Phase III. Pressure drop increased dramatically with the inability to sustain a stable baseline condition within the pressure transmitter range. Various actions were taken to determine if the observed response was real or instrument related. Cleaning of the filter was set on a timer mode (about 3 minutes) and the system allowed to operate while Texaco completed their sulfidation run. The increased pressure drop experienced during Phase III results from an increase in the syngas flow when the sorbent beds are being operated.

Following sulfidation, the fuel gas flow through the filter was reduced in an effort to reduce system pressure drop. Over the regeneration period, Phase IV, quasi-steady operation was indicated with

pressure drop responding to flow changes. At this point, it became evident that a plug had occurred in the bypass leg, thus preventing the ability to divert flow. Upon restart of the sulfidation cycle, pressure drop again increased and would have exceeded pressure transmitter limits if operation continued. A decision was made to shut down and identify the pluggage problem.

Subsequent inspection of the gasifier unit showed a problem had occurred in the gasifier slag removal system causing excessive ash carryover. Following testing, a borescope inspection of the filter unit was conducted that indicated the filter had not experienced any obvious problems. A flow test was also conducted to determine if the filters suffered significant blinding. About 10,000 acfm of nitrogen gas was passed through the filter and pressure drop measured. These tests indicated nominally expected pressure drop characteristics. On this basis, a decision was made not to open the system for any additional inspection or cleaning, but prepare for a late November or early December test.

3.9 OXYGEN-BLOWN GASIFICATION TESTING OF A CANDLE FILTER CLUSTER WITH EXTERNAL DESULFURIZATION AND REGENERATION - TEST NO. 10 - CANDLE

A third test run, Test No. 10, was conducted utilizing the 19-candle array previously operated during Test No. 9. The gasifier was operated in the oxygen blown mode with an external sulfur bed that was regenerated off-line. Table 3.6 provides a summary of the filter operating parameters during this test program. Filter unit pressure drop data for this test run are provided in Appendix C.

The gasifier and filter units were preheated by aspirating hot gas through the gasifier unit. With regard to the filter, the purpose is to preheat the unit above fuel gas dew point conditions. After approximately 36 hours of preheat operation, (with some minor stops and restarts) a filter temperature of about 330°F was achieved prior to

Table 3.6 - Nominal Filter Performance Data, Test No. 10, December 1991

Test Segment	Filter Temperature °F	Flow acfm	Filter Pressure Drop, in wg		No. of Cleaning Cycles	Time at Conditions Hrs
			Baseline Range	Trigger Range		
Preheat	0 - 330	--	--	--		36
Startup	330 - 1000	20 - 87	30 - 130	50 - 200	140	7
Phase I	1400	80 - 90	150 - 200	200 - 250	110	5
Phase II	1130	45	75	100	44	5
Phase III	1400	80 - 90	200	250	130	5.5
Phase IV	1150	50	130 - 150	170 - 200	130	8
Phase V	1400	80 - 90	200	250	50	3
Phase VI	1150	40	100	150	60	5

gasifier lightoff. During this period, the filter unit operated at about ambient pressure, and was pulse cleaned on a 5 to 10 minute cycle to prevent buildup of ash or other debris that may have collected in the lines from previous tests. The cleaning was done using a nominal 220 psi N₂ source.

During startup the gasifier is ignited, pressurized and flow initiated through the filter system. Filter temperature is slowly increased from the initial preheat value to about 1000°F. This required about 7 hours of operation.

Filter pressure drop increases due to both increasing temperature and flow conditions. Over this period, flow was increased from about 20 acfm to about 47 acfm. Following the initial couple of cleaning cycles, the filter was set on an automatic cleaning cycle initially corresponding to 5 minutes, but reduced to 3.5 minutes to keep the trigger pressure drop below about 150 in wg. Following initial preheat, the filter was taken off-line by opening the bypass valve in an effort to increase the rate of preheat to the external sorbent beds. During this approximately 4 hour period, the filter continued to operate, but at low pressure drop because of the significantly reduced flow. Following this action, the filter was brought back on-line and the flow increased to continue the sorbent bed heatup operation. Again, filter pressure drop increased due to increased flow and temperature. Flow ranged from about 50 acfm to 87 acfm (1.7 ft/min) while the average temperature across the filter increased from about 750 to 1390°F.

Following satisfactory preheat of the external sulfur beds, Texaco initiated their sulfidation cycle, Phase I, which lasted approximately 5 hours. During this period, flow adjustments were made through the filter in an effort to keep the trigger pressure drop below 250 in wg which represents the upper limit of the measuring gauges (transmitter). Again, cleaning of the filter was on an automatic timing

cycle corresponding to 2-1/2 to 3 minutes. Flow through the filter is estimated at about 80 to 90 acfm (1.7 ft/min). Average filter temperature remained about constant (1400°F).

Following sulfidation, the sorbent bed was taken off-line for regeneration, Phase II. During this 5 hour period, flow to the filter system was reduced and pulse cleaning intervals were increased to between 5 to 10 minute cycles. The filter baseline pressure drop decreased from 180 in wg to about 170 in wg. Flow at this condition was approximately 45 acfm while filter operating temperature decreased to 1130°F.

Following regeneration, syngas flow was again diverted through the sorbent bed, Phase III. During this 5-1/2 hour period, flow through the filter was initially increased, with a corresponding increase in baseline pressure drop followed by quasi-steady operation. Again, pulse cleaning varied from 5 to 2 minutes.

Following completion of the second sulfidation cycle, the sorbent bed was again taken off-line for regeneration, Phase IV. During this nominal 8 hour period, filter flow was reduced, but maintained at approximately 50 acfm. Filter pressure drop remained reasonably stable with the filter being cleaned on 3 to 5 minute cycles.

Following the second regeneration cycle, syngas was again diverted through the sorbent bed to begin a third sulfidation cycle, Phase V. During this nominal 3 hour period, the flow rate through the filter was increased (nominally 80 to 90 acfm) and maintained to keep the maximum filter pressure drop below 250 in wg.

Following the sulfidation cycle, a third regeneration cycle was initiated, Phase VI. During this nominal 5 hour period, flow through the filter was decreased (nominally 40 acfm) and cleaning cycle time

increased. Following this regeneration cycle, operation of the gasifier was terminated completing the test program.

3.10 OXYGEN-BLOWN GASIFICATION TESTING OF A CANDLE FILTER CLUSTER WITH EXTERNAL DESULFURIZATION AND REGENERATION - TEST NO. 11 - CANDLE

A fourth test run, Test No. 11, was conducted utilizing the 19-candle array previously operated during Test No. 10. The gasifier was operated in the oxygen blown mode with an external sulfur bed that was regenerated off-line. Table 3.7 provides a summary of the filter operating parameters during this test program.

Normal preheating of the filter was accomplished by aspirating hot air from the gasifier unit that was being preheated using a propane torch. Some difficulties were encountered with this approach and an alternate N_2 preheat was utilized.

At gasifier lightoff, the system is pressurized to about 350 psig and syngas flow and temperature are slowly increased to operating value. Filter system pressure drop first increased to expected value (based on previous test). Following initial startup, the filter inlet temperature increased above 1000°F and the pressure drop increased significantly. Although pressure drop was high, filter operation appeared stable.

Following the preheat of the sulfur sorbent beds, part of the filtered syngas was diverted through the sorbent beds to begin the sulfidation portion of the test program, Phase I. Shortly into this testing, the syngas flow was reduced to control sorbent bed temperature with the filter pressure responding accordingly. Flow control of the system could not be maintained due to non-filter related problems, and the gasifier operation was shut down.

Table 3.7 - Nominal Filter Performance Data, Test No. 11, July/August 1992

Test Segment	Dates	System Pressure psig	Filter Inlet Temperature °F	Flow acfm	AP		No. of Cleaning Cycle	Time at Conditions Hrs
					Baseline in wg	Trigger in wg		
Preheat	7/8/92 7/13/92	0	70 - 270	-	10 - 30		>250	~96
Gasifier Startup	7/13/92	0 - 365	270 - 982 982 - 1640	0 - 52 54 - 57	16 - 34 150 - 170	50.57 198 - 240	4 ~170	4 8.5
Phase I (Desulfurization)	7/13/92	351	1680 1430 - 830	63.4 63 - 13	198 198 - 30	240 240 - 46	20 ~110	1 5.5
			Shutdown - Non Filter Related Operating Problem					
Preheat Restart (Reverse N ₂ Flow)	7/21/92	0	70 - 335	-	-			24
Gasifier Restartup and Bed Preheat	7/22/92 7/24/92	0 - 350 350 350	335 - 500 1090 1680	40 88	14 - 26 160	35 - 39 181	14 60	2 8.5
Phase IA	7/24/92	350	1800-1260	88 - 56	180 - 240	off scale	25	3
Phase IB	8/11/92	350	1693	93	63	130	9	1.5
Phase IIB	8/12/92	350	1400	97	52	110	35	4.6
Phase IIIB	8/12/92	350	1700-1300	97 - 38	126 - 114	130	19	2.5
Phase IVB	8/12/92	350	1440	87	168	141	36	6
Phase VB Shutdown	8/12/92	350	1508	73	234	218	15	2.4

Following the initial shutdown and system maintenance, the gasifier test program was restarted. Several stops and starts were incurred during this period. A filter operating temperature of over 1800°F at the inlet (1300°F outlet) was measured. Filter pressure drop again appeared to increase with both flow and syngas temperature consistent with the initial startup but not in the expected proportion to temperature and flow effects.

Following preheat of the sulfur sorbent beds, part of the filtered syngas was diverted through the sorbent beds to begin the sulfidation portion of the test program, Phase 1A. A filter inlet gas temperature over 1800°F was measured. Since the baseline filter pressure drop was near the upper limit of Δp transmitter range, an 8 minute cleaning cycle was implemented. Stable operation of the filter appeared to be achieved over the 3 hour test period. Testing was terminated when a hot spot occurred on the transfer pipe between the gasifier and radiant cooler.

Following repair of the transfer pipe, testing was reinitiated, Phase 1B. Following preheat, gasifier lightoff and sorbent bed preheating, part of the filtered syngas was diverted through the sorbent beds to begin the sulfidation portion of the test program. Filter pressure drop was lower than anticipated based on the earlier testing.

Following sulfidation, the sorbent beds are regenerated off-line while the filter continues operation on the syngas flow, Phase IIB.

Following regeneration, syngas flow was diverted back through the sorbent beds, Phase IIIB. During this period syngas flow was reduced to compensate for a higher flow resistance encountered in the sorbent beds. This suggests the possibility of significant dust penetration through the filter system consistent with the somewhat lower filter pressure drop.

Again, following sulfidation, the sorbent beds are regenerated off-line, while the filter continues operation on the full syngas flow, Phase IVB.

Following regeneration, syngas flow was diverted back through the sorbent beds, Phase VB. It appeared that during this test phase, filter pressure drop returned to the earlier higher levels. Following this phase, the test program was completed and the gasifier was shut down.

No filter particle sample was accomplished during operations due to an inoperable sampling system. Inspection of the filter revealed three broken candles. Based on the sorbent bed pressure drop, this event likely occurred during Phase IIIB as noted above.

4. DISCUSSION OF RESULTS

The Texaco hot gas filter test program has provided baseline operating and performance data for both a cross flow and candle filter unit when integrated with an entrained gasifier. The test program has been summarized in Section 3. This section provides an evaluation of the test program findings. Filter performance, filter operating characteristics and materials durability issues are discussed.

4.1 FILTER PERFORMANCE

For oxygen blown IGCC systems the hot gas filter performance requirement is set by environmental emissions and the need to protect downstream equipment such as sorbent beds and gas turbine components. Stack emission limits and gas turbine tolerance to particle erosion may require an outlet dust loading at the filter of about 150 ppm or less than 10 μm particles (including the dilution effect of the combustion air). In the test program, the filter inlet and outlet dust loadings were measured periodically using isokinetic, total mass sampling. These results are given in Table 4.1. Cascade impactor sampling of both the inlet and outlet was also conducted by Southern Research Institute in two test runs, Tests 6 and 7. These results have been reported elsewhere.⁽¹⁾

As shown by the results reported in Table 4.1, the inlet dust loadings to the filter varied over a wide range. In one test, (Test 2) an inlet loading of over 22,500 ppm is reported. This condition may have corresponded to soot blowing operations occurring in the radiant cooler upstream of the filter. The otherwise wide variation in inlet dust loading is attributed to relatively small variations in gasifier operating conditions.

Table 4.1 - Summary of Filter Performance in Entrained Gasifier Tests

Test	Filter Type/ No. Used	Hours Operation	Inlet Loading ppm	Outlet Loading ppm	Remarks
1	Cross Flow/4	58	2490 to 9109	2.2 to 6.2	- Borescope inspection showed no filter issues.
2	Cross Flow/4	35	250 to 1220 up to 22525	23 to 33 80 to 114	- Gasket seal leaks experienced on 3 filters - one filter had a delamination crack.
3	Cross Flow/4	29	270 to 2900	5 to 65	- Borescope inspection showed no filter issues.
4	Cross Flow/4	103	280 to 2866	59 to 115	- Gasket leaks on all four filters, one filter had a sheared flange.
5	Cross Flow/4	65	650 to 12,350	19 to 176	- Sheared filter flange and delamination.
6	Cross Flow/8	42	1170 to 1934	183 to 788	- Bottom filters were water soaked and damaged.
7	Cross Flow/8	60	1640	No Data	- Plugged inlet sample line. Outlet sample line was inoperable.
8	Candle/19	62	1076 to 1873	160 to 600	- Borescope inspection showed no filter issues.
9	Candle/19	34	768 to 2525	116 to 617	- Inspection showed no filter issues or dust leak path.
10	Candle/19	89	NA	NA	- Borescope inspection showed no filter issues.
11	Candle/19	101	NA	NA	- 3 Filters broken during operation.

The outlet dust loadings also varied over a relatively wide range. Test results from the initial filter operation (using cross flow filter elements) show outlet dust loadings as low as 2 to 6 ppm. These results demonstrate the performance potential of a ceramic barrier filter device to meet particulate cleanup requirements in entrained gasification applications.

In some tests, physical damage to the filter and/or dust seals were evident that would cause a breach between the dirty to clean gas side of the filter and cause increased outlet dust loading. In the later test runs it became apparent that significant contamination to the outlet gas piping had occurred that adversely influenced sampling results. Outlet loadings of several hundred parts per million were being measured (Tests 8 and 9, for example) however, inspection of the filter unit showed no evidence of any dirty to clean side breach after testing.

In addition to achieving acceptable outlet loadings, the hot gas filter must maintain a stable operating pressure drop. High system pressure drop at a nominally low face velocity and short cleaning cycles were experienced in the entrained gasification filter testing. These results suggest difficult filtration conditions indicative of high ash flow resistance, low filter permeability, and dust reentrainment.

Equation 4.1 relates the gas pressure drop through the filter media and ash cake to the filter and cake physical properties and process parameters of the operating system.

$$\Delta p = \frac{\mu V}{K_f} + \frac{\mu C V^2 \theta}{\rho_c K_c} \quad (4-1)$$

where

- μ = gas viscosity
- V = filter face velocity (actual gas volumetric flow/filter area)
- C = dust concentration
- θ = time
- ρ_c = bulk density of the dust cake
- K_f = filter permeance
- K_c = cake permeance

Baseline pressure drop is defined as the gas pressure drop through the filter, immediately following the cleaning event, and is represented by the first term of Equation 4.1, i.e.,

$$\Delta p_{bl} = \frac{\mu V}{K_f} \quad (4-2)$$

The filter permeance, K_f , establishes the baseline pressure drop and may be considered a property of the conditioned filter media. It is generally accepted that in barrier filter devices, that some quantity of ash will become trapped in the surface pore structure of the filter media and become a permanent layer that contributes significantly to filter permeance. Low filter permeance leads to high baseline pressure drop with corresponding parasitic loss in cycle energy efficiency. Also, high baseline pressure drop can adversely impact the design and integrity of the dust seals and metal structures used to support the filter system. Increasing filter surface area to reduce face velocity, and therefore, pressure drop can adversely impact system economics.

The baseline filter pressure drops in the Texaco test program were directly measured by differential pressure measurements made across the filter unit. This data was summarized in Section 3 for the different filter tests. Figure 4.1 compares the filter permeance trend from the Texaco entrained gasifier filter testing with similar data from other test programs. The data is normalized by plotting the "Relative Permeance" (i.e, K_f/K_{f0}) as a function of filter cleaning cycle. Plant

Figure 4.1 - Comparison of Filter Permeance Trends in Different Plant Applications

data is shown for typical pressurized fluidized bed combustor (PFBC) application as well as the KRW fluid bed gasification PDU. Test data include operation with cross flow and candle filters. The entrained gasifier test experience that utilized both cross flow and candle filter test units show significantly lower permeance than either the PFBC or fluid bed gasifier experiences. Low filter permeance can be the result of several factors, i.e., poor cleaning, reentrainment of fines and/or high ash flow resistance.

Both the PFBC and KRW ashes were generated in a sulfur sorbent containing fluid bed that operates at relatively low temperatures (1600°F, 870°C). Thus, the combustion and fuel gas contain both char, ash and attrited sorbent particles. The entrained gasification process occurs at over 2500°F (1370°C), generally above the ash softening point. Sulfur sorbents were not utilized upstream of the filter. Thus, in this case, the fuel gas contains primarily char and ash particles. The characterization of the entrained gasifier ash and its comparison with both the PFBC and KRW ashes are discussed in Section 4.2

Visual inspection of the test unit following some of the test runs suggest effective cleaning was occurring with the candle filters. A thin and uniform crusty layer was apparent over the candle with small, random patches of filter cake, Figure 4.2. The inspection of the cross flow filters showed mixed results. Clogging of nearly all dirty side channels was clearly evident on those filter elements that had experienced gasket or flange failures. The undamaged filters appeared cleaner with generally opened but constricted channels. The bulk of the residual ash could be easily brushed except for a thinner crusty layer that appeared to cover the filter dirty side surface.

The cross flow filter assembly used in Tests 1 through 5 contained 4-filter elements (approximately 28 ft² of filter surface). In Tests 6 and 7 the unit was modified to hold 8-cross flow elements (56 ft² of filter surface). Assuming completely "clogged" channels, the

Figure 4.2 - Photograph Showing Nature of Residual Dust Observed on the
Candle Filters After Test No. 9

cross flow filter surface area is probably reduced to less than 8 and 16 ft² for the 4 and 8 element assemblies, respectively. The candle unit contained 19 elements representing approximately 51 ft² of filter surface area. In view of the post test visual inspection, it could be expected that significantly higher pressure drops would have occurred during the operation of the cross flow unit. Comparison of the operating characteristics given in Section 3 shows that the cross flow exhibited similar or lower pressure drops. This suggests that the cross flow had at least equivalent active surface area as the candle unit. Therefore, it is unlikely that the clogged cross flow channels represent the condition during normal operations.

The filter permeance discussed above and shown in Figure 4.1 were based on the baseline pressure drop trend measured during test operations. Selected filter elements (both cross flow and candle) were recovered and tested in a laboratory apparatus to measure their flow permeability. The test consists of flowing a known quantity of air through the filter (with any residual dust layer) and measuring the resulting pressure drop. These results are then compared with the as fabricated filter permeability, Figure 4.3. These results show, as expected, a decrease in flow permeability (increase in flow resistance) of the used cross flow and candle filter elements. The decrease measured, however, does not account for the low filter permeance determined from the operating data. These results suggest:

1. The flow resistance of the entrained gasifier ash under ambient conditions is significantly lower than under process gas environment and temperature,
2. Significant reentrainment or poor cleaning are occurring under process conditions that effectively mask the actual baseline pressure drop.

Figure 4.3 - Comparison of Flow Permeability of Used (Texaco) and Unused Filter Elements

The poor cleaning scenario is not, however, consistent with the candle filter inspection observations. Low ash flow permeability and its potential for reentrainment would appear to be the primary factors in establishing filter operating pressure drop characteristics in this test program.

4.2 CHARACTERIZATION OF ENTRAINED GASIFIER ASH

A range of test and measurement methods were used to characterize samples of the collected filter ash catch from the entrained gasifier testing. The testing has included cascade impactor sampling⁽¹⁾ and laboratory ash analysis (Appendix B) conducted by Southern Research Institute (SRI) and off-line filter testing conducted by Westinghouse. A brief summary of the ash characterization studies is presented.

Sedigraphic analysis, Figure 4.4, based on samples from Test Run 1, show a substantial weight fraction (about 8%) of particles in the particle size range of less than 1.5 μm . Over 14% of the mass in this sample is below 2.3 μm . The large fraction of particles in the 10 to 30 μm range that is also present is not surprising in this sample since in Test No. 1 there was no precleaning cyclone ahead of the filter unit. The high entrainable fines fraction may be an important factor in the high baseline pressure drop observed. With repeated cleaning cycles, the very small fines reentrain and deposit back on the filter. These fines form a thin, highly resistive and adhesive layer of concentrated fines that is not easily dislodged during subsequent pulse cleaning.

Other laboratory data were developed that generally reflect on the pressure drop characteristics of the filter cake. Two of these parameters are the Drag-Equivalent Diameter and Cake Resistance. The Drag Equivalent Diameter is not a measurement of physical size, but rather a fitted parameter ranking the characteristic gas flow resistance

Figure 4.4 - Mass Population for Texaco Ash Sample (Test No. 1)

of ashes at equal porosities. Increasing values indicate a lower cake resistance. The drag equivalent diameter for the Texaco ash sample was $0.621 \mu\text{m}$. SRI reports that this value is quite low (high cake resistance) when compared to PFBC or conventional pulverized coal boiler (PC) ashes. SRI provides a more general comparison of gasifier, PFB and PC ash characteristics.⁽²⁾ These results in general support the high pressure drop characteristics observed in the entrained gasifier filter testing.

A direct measurement of cake resistance was also developed by feeding reentrained ash material at process conditions (T, P) and collecting the ash on the actual filter media. This approach reproduces flow conditions, but does not reproduce gas-phase compositions. Table 4.2 provides a summary of the Texaco ash characterization and compares this with similar data for fluid bed gasification and PFBC ashes. These results show that filter cake flow resistance increases with decreased particle size and is significantly higher for the tested gasification ashes, consistent with the SRI laboratory analysis.

The possibility of pore pluggage by the gasifier fines through the wall of the filter causing high pressure drop was also investigated. SEM and microprobe analysis of used filters were conducted. These results showed an accumulation of the gasifier ash fines along the dirty gas channels but typically limited to within only the first 100-200 μm (2 or 3 pore layers) of the filter matrix. A much smaller quantity of ash was also found deeper into the filter wall. These fines appeared attached to the amorphous (glass) phase of the cross flow mullite structure, but did not appear to cause any significant pore blockage. Based on these results, it is concluded that in-depth filter wall pluggage by fines was not a contributing factor in the high pressure drops encountered in the filter tests on the Texaco entrained gasifier. In general however, this test program was too short in duration to establish any long term effects of fines accumulating in the filter pores.

Table 4.2 - Comparison of Ash Characteristics for Gasification and PFBC

<u>Parameter</u>	<u>Texaco Ash Sample</u>	<u>KRW Ash Sample</u>	<u>PFBC Ash Samples</u>		
			<u>Course</u>	<u>Nominal</u>	<u>Fine</u>
Mean Dia., μm	4.5 ⁽¹⁾	3.5	9.7 ⁽¹⁾	3.6 ⁽¹⁾	2.4 ⁽¹⁾
Bulk Density (lb/ft ³)	8 - 15				
Drag-Equivalent ⁽¹⁾ Diameter, μm	0.62	0.46	1.25	.87	0.35
Flow Resistance (1/ft ⁻²)x10 ¹⁰	110	130	7	18	26

(1) From SRI Sample Analysis

The issue of dust cake reentrainment has been extensively investigated for conventional pulse jet baghouses.⁽³⁾ The potential for reentrainment in the filter in gasifier application is seen by comparing the relevant process and cake properties as shown in Table 4.3. The low bulk density and large fraction of fines present appear to provide favorable conditions for reentrainment. Test experience suggests that PFBC ashes are cohesive and when pulse-cleaned from the filter maintain relatively large agglomerates with low entrainment potential. Under ambient conditions, the entrained gasifier ashes visually appear noncohesive although some property parameters (uncompacted bulk porosity) suggest otherwise (see Reference 2). If the entrained gasifier ash is truly noncohesive, the large agglomerates when pulse cleaned from the filter may be redispersed to form reentrainable fines.

The possibility of reentrainment with high ash resistance in the entrained gasifier application was recognized early in the Texaco test program, and design modifications were implemented in an effort to circumvent these potential issues. Two basic changes were made to the filter unit following Test No. 5. The first modification was to reduce filter face velocity by doubling filter surface area. The number of cross flow filter elements were increased from 4 to 8. This was equivalent to a four-fold increase in the time between cleaning cycles, which was ranging from 0.5 to 2 minutes. The second modification involved the implementation of a cylindrical coaxial shroud. The purpose of the shroud was three-fold; to distribute the incoming solids and gas stream in an axisymmetric manner; to decelerate the gas in the annulus region between the shroud and liner; and to allow the gas to enter the filtration zone in a top-down flow orientation. The predominantly downward flowing gas would promote the settling of the dislodged dust cake fragments thus reducing the extent of redeposition. The above described modifications were utilized in the cross flow Tests No. 6 and 7. Unfortunately, both test runs experienced other operating

Table 4.3 - Comparison of Filter Duties

	<u>Cold End Baghouse</u>	<u>PFBC</u>	<u>IGCC</u>
Pressure, psia	15	215	365
Temp, °F	300	1600	1200
ρ_{gas} , lbs/ft ³	0.05	0.2	0.4
ρ_{solids} , lbs/ft ³	60	60	10
$\rho_{\text{solids}}/\rho_{\text{gas}}$	1200	300	25
Reentrainment Potential	Low	Moderate	High

problems that prevented quantitatively evaluating the modifications. It did appear in Test No. 6 that somewhat longer filtration cycles were achievable. In this test, pulse cleaning frequencies ranged between 4 to 6 minutes compared to the sometimes less than 2 minutes experienced in the earlier test runs.

Although the actual entrained gasifier test runs could not conclusively confirm the expected advantages of the coaxial shroud, the rationale for its implementation was evaluated in a full scale, Plexiglas model. The model contained two plenum sections each with five cross flow elements, very similar to the actual Texaco filter installation. A summary of this work is given in Section 4.3 below.

4.3 COLD FLOW MODELING OF CROSS FLOW FILTER

In support of the filter design modification implemented in the Texaco cross flow filter unit, cold flow testing was conducted to simulate the modified configuration at full scale. The cold flow model, shown in Figure 4.5, consists of an air blower, two cross flow filter plenum modules, a transparent Plexiglas vessel that houses the filter assembly, a dust injection system, a filter pulse-back system, and instrumentation and data acquisition. The cold model facility was built and operated in support of another DOE contract. A complete description of its design and operational capabilities is provided in Table 3.2.⁽⁴⁾ The cold model is used for:

- System flow and pressure drop measurements
- Flow visualization using smoke and/or dust
- Flow field velocity profile and pattern using anemometers
- Comparison of alternative gas shrouding and/or inlet configuration
- Distribution of the pressure pulse during cleaning
- Visualization of the filter pulse cleaning event showing cake removal
- Measurement of flow and pulse cleaning induced vibration using accelerometers.

Figure 4.5 - Photograph Showing Full Scale Cross Flow Filter Cold Flow Model with Coaxial Shroud

The mathematical basis for the valid simulation of the flow and vibration characteristics under cold flow conditions is provided in Reference 4.

Utilizing the radial gas inlet port with a coaxial shroud simulating the modified Texaco filter configuration, flow visualization studies using smoke injection and the measurement of the flow velocities were conducted. Figure 4.6 shows a schematic representation of the observed flow field pattern. In general, the gas was observed to distribute uniformly across the top of the shroud and maintain a downward orientation over the length of the shroud. Below the shroud, a gentle downward flow was observed at near the vessel wall with a clockwise swirl that had a velocity component that ranged from 0.5 to 4 ft/s depending on the inlet gas flow rate (100 to 400 acfm). The downward component of the flow formed an annular region that was approximately 10 inches wide extending inward from the vessel wall. The annular region represented about 75 percent of the superficial area of the vessel internals. Starting beneath the shroud region, there also was a gas upflow between the two filter plenums that had a velocity component that ranged below 1 ft/sec. Below the filter plenums and in the ash hopper the gas appeared to be stagnant.

Flow vibrational measurements were also conducted using the cold flow test facility. Vibrational measurements were conducted by attaching two accelerometers to the outside surface at the bottom (lowest) of one plenum. This arrangement allowed measurement of vibration in two horizontal directions, one perpendicular and one parallel to the surface of the filter flow channels. Three different vibrational tests were performed:

- Normal gas flow alone
- During pulse cleaning - no flow
- Gas flow with pulse cleaning.

FLOW FIELDS OBSERVED IN FILTER SYSTEM MODEL

2M642.BW

Figure 4.6 - Flow Fields Observed in Filter System Model

During the normal gas flow period, the accelerometer data showed little or no low frequency pendulum-type vibration. An acceleration peak of only 0.04 g's was measured.

For the pulse cleaning vibrational test, pulse tank pressures were varied from 40 to 200 psi with the pulse duration varying from 0.1 to 0.2 seconds. Vibrational inner action effects between the two plenums was also investigated including the case of coupled and uncoupled plenums (bottom braced). Plenum accelerations induced by the back-pulse event ranged in the order of 10 to 20 g's in the direction perpendicular to the filter surface and varied with pulse tank pressure. No appreciable difference in vibration intensity was observed when the two plenum modules were coupled. Stresses imposed on the filter due to the observed accelerations and frequencies were estimated to be no more than about 50 psi if uniformly distributed over the filter flange surface. Vibration induced by pulse cleaning is therefore not expected to cause filter element failure unless coupled with other stresses. Vibration could however promote the rapid transmission of a small crack once formed by other mechanisms.

4.4 FILTER UNIT DURABILITY

Testing on the Texaco entrained pilot plant gasifier facility exposed the hot gas filter to a wide range of operating and upset conditions. Both cross flow and candle filter elements were damaged in one or more of the tests. In the early cross flow testing, the dust seals (gaskets) used in the filter mounting to the plenums failed resulting in dust leaks and perhaps contributing to filter failures.

Table 4.4 provides a listing of the cross flow filters used, exposure hours and failure mechanism observed (if any). The filters lost in Tests 6 and 7 are shown but should be discounted because of the facility upsets that occurred (see Section 3) that likely caused (or significantly contributed to) the failures. In Tests 1 through 5, a total of 9 cross flow filters were utilized.

Table 4.4 - Summary of Cross Flow Filter Usage

Filter Identification	Test	Type Failure	Operating Hours
2	1,2,3,4	None	215
WRTX 12	1,2,3,4	None	215
13	1,2,3,4	None	215
14	1,2	Delaminated	83
4	3,4	Failed Flange	132
15	5	None	65
16	15	Delaminated	65
17	5	Failed Flange	65
18	5	None	65
44	6	None	42
46	6	Delaminated	42
47	6,7	See Note 1	102
49	6,7	See Note 1	102
51	6	Delaminated	42
54	6,7	See Note 1	102
55	6,7	See Note 1	102
50	7	See Note 1	60
52	7	See Note 1	60
83	7	See Note 1	60
86	7	See Note 1	60

Note 1 - Operational Events

Test 6 - Water found in lower filter plenum
 - 100 gal water recovered from ash hopper.

Test 7 - Significant thermal transient on startup
 - Temperature and flow fluctuations experienced
 - Rapid depressurization
 - Broken tubesheet

Five of these filters were not physically damaged. Two of the four damaged filters suffered cracked flanges. The other two filters experienced delamination only. Inspection of the delaminated only filters showed evidence of only very little ash breaching through the delamination crack. Delaminations are believed to be the product of weak bonding of the filter plates during manufacturing and could be eliminated if a monolithic cross flow structure is developed.

Coincidentally with the occurrence of the cracked flange in the Texaco filter unit, two similar failures had also occurred in the Westinghouse test facilities after over 1300 hours of operation at 1550°F under simulated PFBC conditions. As part of this in-house program, Westinghouse undertook a redesign of the filter mount. The modified mount design was backfitted into the simulator testing at Westinghouse and the filter unit at Texaco. Analysis showed the original mount suffered from three principal deficiencies:

1. Nonuniform loading of the ceramic flanges imparting point or line stresses and large bending moments,
2. Relaxation of the filter clamping bolts causing excessive loosening of the mount, and possible levitation of the ceramic element during reverse pulse cleaning, and
3. Wedging of dust in the cavities outside the filter element seating area that caused high stresses due to differential contractions during shutdown periods.

A modified and improved clamping design was developed that corrected these identified deficiencies. The design is described in the Long Term Durability Final Report.⁽⁶⁾

In addition to the mount redesign, a redesign of the gasket used for the dust seal was also made. The original dust seal used in the Texaco filter unit utilized an 0.15 inch thick Interam[®] Brand Mat

made by the 3M Company. This material is made of alumina silicate fibers interspersed with an intumescent or heat expandable layer of vermiculite. This material shows low mechanical strength and has limited temperature capability before losing its intumescent property. In the Texaco entrained gasifier application, high pulse gas intensity (10 to 20 psi) is required because of the high resistance of the ash cake. With these high back pressures, these seals are prone to erode if the reverse pulse gas flows through the seal joint. To circumvent the use of this relatively weak and temperature limited seal, Westinghouse developed a Nextel-reinforced Interam MM Fiber Blanket seal that was also backfitted into the Texaco filter unit subsequent to Test 5. This seal design is significantly resistant to erosion or blowout.

In Tests No. 6 and 7 the retrofit mount and dust seal were implemented. As described earlier, severe plant upsets occurred and several filters were broken in Test 6 and all filters broken in Test 7. Of the eight filters in Test 6, three failed. None of the filters failure, however, involved either a flange crack of the earlier type or eroded dust seal. In Test 7, damage to the filter bodies was extensive including some flange breakage. However, no dust seals were lost.

One cross flow filter which had operated during Tests 1 and 2 has been subsequently characterized for material strength. Bend bar samples were cut from the thin wall gas channels. These results showed a slightly lower strength (<5%) over similar samples taken from a filter of the same fabrication lot. This difference may not be statistically significant. Comparison of bend bar samples taken from the flange region of the as fabricated and used filters showed no strength difference. Thus, short term exposure of the alumina/mullite cross flow filters to the entrained Texaco gasifier fuel gas did not result in any significant material strength degradation.

In Tests 8, 9, 10 and 11, a nineteen (19) element candle array was utilized. Seventeen (17) of the candles were the silicon carbide F40 Dia Schumalith, (1.5 meter long) and two candles were a first generation Coors alumina/mullite, (1 meter long). A borescope inspection after Test 8, a visual inspection (unit disassembly) following Test 9, and a borescope inspection after Test 10 revealed no failed filters. After Test 9, one candle was removed and the seal inspected. No dust leak was evident. Following Test 11, the filter unit was disassembled and then inspected. Three candles were broken (one of the SiC's and both of the developmental alumina/mullite elements). A second SiC candle broke when attempting to remove it from its mount. It was evident from the increased pressure drop through the Texaco sorbent beds that at least one candle had failed about midway through the test period.

4.5 CHARACTERIZATION OF FILTER MATERIALS

4.5.1 Cross Flow Filters

The alumina/mullite matrix used in the manufacture of cross flow (and candle) filters consists of 60 to 70% mullite ($3\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$) and 3-5% alumina (Al_2O_3) with varying concentrations of the amorphous and anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) phases. In general, when exposed to the entrained gasifier reducing gas process conditions, a crystallization of the amorphous phase will occur forming additional anorthite. Mullitization and/or recession of the amorphous phase of the alumina/mullite matrix also occurs that can alter the general appearance of the pore structure. The long term effects of these phase changes are yet unknown.

The characterization of the physical, mechanical and microstructural properties of one cross flow filter that had been exposed in the Texaco gasifier testing has been reported.⁽⁶⁾ Results of this work show that the room temperature flexural strength of the

filtering surface of the cross flow element decreased only very slightly (~5%) after 77 hours exposure to the entrained gasifier environment. However, a moderate decrease in the Weibull modulus (14 to 9) was measured for the exposed filter suggesting a possible change (increase) in its flaw population. Microstructural investigations, which included SEM and EDAX analysis, revealed no substantial physical changes to the filter as a result of the testing nor the presence of any chemical or phase changes not anticipated based on the process gas conditions.

4.5.2 Candle Filters

In the Westinghouse high temperature, high pressure (HTHP) particulate removal system which operated at the Texaco gasification facility in Montebello, California, two 1 m P-100A alumina/mullite and seventeen 1.5 m clay bonded silicon carbide F40 candles were subjected to ~400 hours of operation in the 700°C reducing gas environment. After testing was completed, both P-100A alumina/mullite filters had fractured near or within the flange holder, while only one clay bonded silicon carbide F40 candle failed also near the flange. During shipment to Westinghouse, the clay bonded silicon carbide F40 candles fractured into numerous segments. A reduction in material strength of the clay bonded silicon carbide matrix was evident not only in the fragility of the exposed candles during transport, but also in the retention of only ~65% of the full candle 4-point flexure strength after operation in the Texaco gasification environment.

Sections of the P-100A alumina/mullite and clay bonded silicon carbide F40 candles that were retrieved from the ash hopper were subjected to room temperature and process temperature strength characterization (i.e., O-ring compression and tension testing). As shown in Table 4.5, the as-fabricated room temperature strengths of the P-100A alumina/mullite and clay bonded silicon carbide F40 candles were nearly comparable. The initial hot strength of the P-100A alumina/mullite matrix appears to be marginally stronger in comparison to the clay bonded silicon carbide F40 matrix.

Table 4.5 - Bulk Material Strength

Candle ID	Temp., °C	Time, Hrs	Room Temperature C-Ring		Hot Strength C-Ring		
			Compression, psi	Tension, psi	Compression, psi	Tension, psi	
<hr/>							
Alumina/Mullite (P-100A)							
C-9	---	---	1938*179	1855*201	2203*215 (1)	2815*416 (1)	
C-19	700	400	703*377	558*303	676*352 (2)	839*454 (2)	
<hr/>							
Clay Bonded Silicon Carbide (F40)							
S/APF-153	---	---	1300*213	1907*111	1416*127 (3)	2328*228 (3)	
S/APF-135	700	400	1103*146	1063*218	1068*121 (4)	1653*249 (2)	
<hr/>							

- (1) Hot Strength Tested At 870°C.
- (2) Hot Strength Tested At 700°C.
- (3) Hot Strength Tested At 732°C.
- (4) Hot Strength Tested At 800°C.

After exposure in the 700°C reducing gas environment, the P-100A alumina/mullite matrix experienced a relatively uniform loss of room temperature bulk material strength. Only 30-36% of the initial P-100A alumina/mullite strength (i.e., ID and OD strength, respectively) was retained in the material. The low retained strength in the P-100A (alumina/mullite) candle filters appear in sharp contrast to the high (~95%) retained strength of the cross flow reported in Reference 7 (summarized above). A direct comparison, however, is cautioned due to difference in conditions of the actual test runs, filter configuration, and processing and material test methods (bend bar vs C-ring).

In contrast, the clay bonded silicon carbide F40 matrix retained ~85% of its as-manufactured bulk strength along the candle OD surface, while ~56% along the candle ID surface. The influence of pulse cleaning appears to have induced moderate thermal fatigue as evidenced by the lower ID strength in the clay bonded silicon carbide F40 matrix in the gasification environment. Note that since both of these materials were sections that had failed and fallen into the ash hopper, we suspect that the bulk material strengths shown in Table 4.5 reflect the catastrophic failure events that the candle matrix experienced.

As shown in Table 4.5, the hot strength at 700°C is comparable to the reported room temperature strengths for both the P-100A alumina/mullite and clay bonded silicon carbide F40 filters that were exposed to the reducing gas environment. As with room temperature strength, the P-100A alumina/mullite matrix underwent a significant loss of process temperature bulk material strength, in comparison to a somewhat greater retention of the initial bulk material strength in the clay bonded silicon carbide F40 matrix at comparable test conditions.

Note that with the exception of the Texaco-exposed P-100A alumina/mullite matrix, all tested samples have a 10-20% 1σ variation in bulk material strength. The significant variation (i.e., 50%) indicated for the P-100A alumina/mullite material implies a lack of homogeneity within the candle body after exposure to the Texaco gasification conditions.

In an attempt to identify changes that occurred within the microstructure of each material, sections of both the Texaco exposed P-100A alumina/mullite and clay bonded silicon carbide materials were subjected to scanning electron microscopy/energy dispersive x-ray analysis (SEM/EDAX). Characterization of the clay bonded silicon matrix after exposure in the Texaco gasification environment indicated that <5-10 μm nearly spherical droplet formations resulted along the binder coated grains that were directly beneath the fibrous candle OD membrane. The droplet formations were identified to be compositionally similar to the binder phase (i.e., silicon, aluminum, potassium, and sodium). Perhaps either carryover of liquid aerosol droplets from the gasifier or sorbent bed resulted along the surface of the clay bonded silicon carbide grains, or outgassing of the underlying substrate occurred.

Typically micron and submicron-sized ash fines were detected along the clay bonded silicon carbide surface. At these locations mullite-like rods and whiskers were evident, indicating that crystallization of the binder matrix had resulted during the high temperature exposure in the Texaco gasification environment.

Further crystallization of the binder phase was evident along the ID surface of the clay bonded silicon carbide filter matrix that was exposed to the Texaco gasification environment. The mottled surface appearance of the ID binder phase was uncharacteristic of the mullite whisker- or needle-like formations that were observed along the OD surface. Further effort is needed to identify the resulting phase and possible impact of pulse cleaning on the binder phase transitions.

Iron was frequently detected in localized areas along the binder/grain interface. Iron which is initially present in the as-manufactured clay bonded silicon carbide matrix, conceivably migrated to the grain interface during filter operation. The interaction of iron with the adjacent silicon carbide grain could potentially lead to the formation of an iron silicate complex (i.e., FeSiO_3 or Fe_2SiO_4). The

relatively low operating temperatures of the Texaco gasification system (i.e., 1300°F) are substantially below the the melt temperatures of either iron silicate complex (i.e., ~1140°C; ~1500°C, respectively).

Characterization of the Texaco exposed alumina/mullite filter matrix was conducted along the flange areas of the candles that were initially returned to Westinghouse. In comparison to the as-manufactured matrix, mullitization and/or recession of the amorphous phase in the alumina/mullite matrix was evident.

4.6 REFERENCES

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5. SUMMARY AND CONCLUSIONS

The performance and durability of a hot gas, cross flow filter system was evaluated while integrated with the operation of the Texaco 15 tpd, entrained-bed gasifier pilot plant facility that is located at their Montebello Research Facilities (MRL) in California. A candle filter unit was also tested for comparative purposes. The gasifier operates at a system pressure of 350 psig under either oxygen or air blown conditions, producing a maximum fuel gas flow to the filter system of 120 acfm. Except for the initial filter commissioning test, all the hot gas filtration tests were conducted in conjunction with Texaco's prime contract with DOE/METC which focused on exploring and demonstrating advanced hot gas desulfurization technology. This work included use of external sorbent beds downstream of the hot gas filter. In the Texaco test program, the hot gas filter unit was positioned between the gasifier and the sorbent bed, and used to filter the hot (1000 to 1500°F) particle laden fuel gas carried from the gasifier through the radiant cooler section. The filter therefore, protected the sorbent beds from plugging due to excessive ash carryover. In a commercial IGCC power plant, the hot gas filter would also protect the gas turbine component from particle erosion and provide sufficient particle removal to meet environmental emission requirements.

In the MRL facility, tests were conducted in both the oxygen and air blown mode and some tests included a precleaning cyclone upstream of the filter. Test flexibility was provided by including a bypass leg around the filter unit. These process and configuration alternatives provided a relatively wide variation in the filter inlet dust loading and gas temperature conditions. Eleven separate test runs were

conducted utilizing the Westinghouse hot gas filter system integrated with the Texaco gasifier operation. The test program was initiated in April 1989 and concluded in August 1992.

The first five test runs utilized a 4-element cross flow configuration accumulating approximately 280 hours of operation. This test series included operation with and without the precleaning cyclone and in two tests the sulfur sorbents were injected upstream of the filter unit. The filter operated over a range of gas flows corresponding to a filter face velocity ranging from about 2 to 4 ft/min. Nine different cross flow elements were utilized in this test series. The mounting flanges on two of the filters were damaged. Erosion of the dust seals and dust leakage through the seals was also evident.

In test runs 6 and 7, accounting for approximately 102 hours of operation, the cross flow unit was upgraded to an 8-element configuration and included a modified dust seal and flange mounting arrangement. Operating face velocities were reduced to between 1 to 2 ft/min. The precleaning cyclone was used in Test 6. In Test 7 no cyclone was utilized, but both iron oxide and calcium based sorbents were injected upstream of the filter. In both tests, upsets in the operation of the facility produced conditions in the filter unit that lead to damaged filter elements.

Tests 8 through 11 used a 19-element candle filter array that was operated for approximately 286 hours. Seventeen of the candles were the 1.5 m clay bonded Schumacher Dia Schumalith elements, two candles were 1 m long, first generation Coors alumina/mullite elements. In this test series, only the external sorbent beds were utilized and there was no precleaning cyclone directly upstream of the filter. With the 19-element candle array, the filter unit operated at a nominal face velocity ranging from 1 to 2 ft/min. Three candle elements were apparently broken during Test Run no. 11.

Based on the test program conducted, the following overall results and conclusions are made:

- The performance potential of the cross flow filter was demonstrated during the initial test runs. Outlet particle loadings ranging between 2 to 6 ppm were measured which are significantly below any environmental or gas turbine requirement.
- Visual inspection of the filter gasket seals and tubesheet, in lieu of outlet sampling, proved to be a more reliable means of evaluating filter dust collection performance. The outlet sampling was unreliable because of ash contaminating the piping system once a filter failure had occurred.
- Candle filter performance potential was demonstrated in Test Runs 8 through 10. Following Test Run 10, the candles and respective dust seals were inspected and found to be in excellent condition with no obvious breach having occurred between the dirty and clean gas sides. A failure in the candle unit occurred in Test Run 11.
- Characterization of the entrained gasifier ash shows high flow resistance, low bulk density and high fines ($<2 \mu\text{m}$) fraction. These properties provide for high reentrainment potential for noncohesive ashes. Careful characterization of gasifier ashes is required to properly design and size a barrier filter unit for IGCC power plants.
- Both candle and cross flow filter units showed pressure drop characteristics that appear significantly different than fluid bed combustion experience. Thus, the high baseline pressure drop and high cleaning frequency experienced in the initial cross flow testing are not unique to the cross flow geometry, but indicative of the entrained gasifier application (i.e., high cake resistance and significant reentrainment).

- The precleaning cyclone had little effect on the filter system operating characteristics.
- Although filter pore pluggage by gasifier fines was not a significant factor in filter degradation in this testing, longer term operation will be required to confirm this conclusion.
- Both cross flow and candle filter elements were damaged in respective testing. The damaged cross flow elements included both delamination and cracking of the mounting flange. A redesigned filter mounting system and dust seal was implemented that appeared to correct the flange and seal erosion problems. The delamination cracks experienced in some of the cross flow filters in the Texaco testing did not appear to seriously compromise performance (based on appearance of the dust tracks) but remain to be corrected through improved manufacturing and inspection procedures. Candle filter breakage did not appear to be attributable to the mounting arrangement since the breakage occurred well below the candle holder assembly.

APPENDIX A

Westinghouse Hot Gas Filter Test Unit

Mechanical Drawings

and

Process and Instrumentation Diagrams

Westinghouse Cross Flow Filter - F-101

ITEM	DESCRIPTION	QTY	UNIT	REMARKS
1	STEEL SHEET PILING	100	LINEAL FEET	100' x 12" x 1/2"
2	STEEL SHEET PILING	100	LINEAL FEET	100' x 12" x 1/2"
3	STEEL SHEET PILING	100	LINEAL FEET	100' x 12" x 1/2"
4	STEEL SHEET PILING	100	LINEAL FEET	100' x 12" x 1/2"
5	STEEL SHEET PILING	100	LINEAL FEET	100' x 12" x 1/2"
6	STEEL SHEET PILING	100	LINEAL FEET	100' x 12" x 1/2"
7	STEEL SHEET PILING	100	LINEAL FEET	100' x 12" x 1/2"
8	STEEL SHEET PILING	100	LINEAL FEET	100' x 12" x 1/2"
9	STEEL SHEET PILING	100	LINEAL FEET	100' x 12" x 1/2"
10	STEEL SHEET PILING	100	LINEAL FEET	100' x 12" x 1/2"

NOTES:
 1. SEE SHEET PILING 115 FOR DETAIL TO
 2. SEE SHEET PILING 116 FOR DETAIL TO
 3. SEE SHEET PILING 117 FOR DETAIL TO
 4. SEE SHEET PILING 118 FOR DETAIL TO
 5. SEE SHEET PILING 119 FOR DETAIL TO
 6. SEE SHEET PILING 120 FOR DETAIL TO
 7. SEE SHEET PILING 121 FOR DETAIL TO
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 9. SEE SHEET PILING 123 FOR DETAIL TO
 10. SEE SHEET PILING 124 FOR DETAIL TO

NOTES:
 1. SEE SHEET PILING 115 FOR DETAIL TO
 2. SEE SHEET PILING 116 FOR DETAIL TO
 3. SEE SHEET PILING 117 FOR DETAIL TO
 4. SEE SHEET PILING 118 FOR DETAIL TO
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 10. SEE SHEET PILING 124 FOR DETAIL TO

NOTES:
 1. SEE SHEET PILING 115 FOR DETAIL TO
 2. SEE SHEET PILING 116 FOR DETAIL TO
 3. SEE SHEET PILING 117 FOR DETAIL TO
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 10. SEE SHEET PILING 124 FOR DETAIL TO

[illegible]

CHANCE ALLOWS
NO MANUAL
CROSSING

CHURCH DI

TITLE: F-101 LINDER ASST 2238D22		DATE: 2 1967	
PART NAME: LINDER ASST PART NUMBER: 2238D22		QUANTITY: 1	
MATERIAL: ALUMINUM FINISH: ANODIZED		TOLERANCES: DECIMALS DIMENSIONS: DECIMALS	
DRAWING: 2238D22 REVISION: 1		CHECKED: [Signature] DATE: 2/1/67	
DESIGNED: [Signature] DATE: 1/1/67		APPROVED: [Signature] DATE: 1/1/67	
CAUTION: NO MINOR CHANGES ALLOWED		W.D. 6-24-68 SHOWN FROM 18.31 17.5 SUPPLIES	

A-8

DESIGN SPECS:

1. DESIGN CONDITIONS 2200 PSIG - 100 f
2. CONSTRUCTION - FUSION WELDED - DYE PENETRANT TEST
3. CODE REQUIREMENTS - ASME SECT VIII
4. WELDERS QUALIFIED PER ASME CODE SECT IX
5. TESTING - 2200 PSIG HYDROSTATIC COMPLETE ASSY.
6. STAMPING - PER CODE

TANK E-02 ACCUMULATOR TANK

ITEM NO.	ITEM NAME	QTY	UNIT	REMARKS
1	COMP	1	EA	1000 WELB COMP
2	NOZZLE	2	EA	100 WELB NOZZLE
3	PIPE	1	EA	100 WELB PIPE
4	NOZZLE	2	EA	200 WELB NOZZLE

CLASUS DWG-NO MANUAL
CHANGES ALLOWED

REV	DATE	BY	CHKD	DESCRIPTION
1	10/10/01	J. J. J.	J. J. J.	ISSUED FOR FABRICATION

TANK E-02
 ACCUMULATOR TANK
 2238042
 01269
 12
 0.301

P&ID NO. 1

HEATER CONTROL SYSTEM

P&ID NO. 3

BLOW BACK PULSE PRESURE SYSTEM

P&ID NO. 4

FILTER PLENUM 1 FLOW SYSTEM

FILTER PLENUM 2 FLOW SYSTEM

P&ID NO.5

D.301.4134A93.R1

FILTER BLOWBACK SYSTEM

P&ID NO.6

ASH COLLECTION POT F-103

P&ID NO. 7

APPENDIX B

Results of Laboratory Analysis of Filter Catch - April 1989 Test

LABORATORY ANALYSIS OF PARTICULATE SOLIDS
(By Southern Research Institute)

The laboratory tests described in this report were performed on a bulk sample (1 qt) of material identified as sample number 89MRL047. This material was collected in the ash pot, which is attached directly to the bottom of the filter vessel, after the completion of the checkout run of the Westinghouse Ceramic Cross-Flow Filter in April 1989. The test methods and results are described in the following paragraphs, and brief explanations of the significance of the results are given where appropriate.

Bulk Porosity - This value expresses the resultant porosity of a column of material under a given compressive load (including zero for the uncompacted bulk porosity). Relatively large values of bulk porosity correspond to highly cohesive particles. The results for the sample provided were as follows:

Uncompacted bulk porosity - 91.6%

Compacted bulk porosity - 70.7%

The latter measurement is somewhat arbitrary, corresponding to a load near the asymptotic limit of compaction for our specific laboratory apparatus. Furthermore, in the case of very porous materials such as the given sample, the compaction cell will not hold enough material to compare with less porous samples. The values of porosity measured for the sample under test were very large compared with conventional fly ashes and similar materials. Gasifier chars taken downstream of recycle cyclones are even more porous, however.

Density - Determination of the true particle density is a standard measurement that is made with a helium pycnometer. The particle density is required for calculating dust cake and bulk porosities. It is also used in developing the relationship between the dust cake thickness and the areal density for a given material. The true particle density for the sample is 2.62 g/cm³.

Particle Size Distribution - Our usual laboratory procedure employs the Bahco classifier to determine the particle size distribution in terms of aerodynamic diameters. This sample did not behave well in the Bahco device; there was a strong tendency to clog the feed nozzle. Only the first two cut points could be determined with any reliability at all. These results showed 7.8% of the mass was less than 1.5 μm in diameter, and 14.6% was smaller than 2.3 μm .

Relative gas flow resistance - This test is performed by filtering air at a measured flow rate through a simulated dust cake of known porosity in a laboratory device, while measuring the pressure drop. The simulated dust cake is free of cracks and crevices, and its porosity is uniform and homogeneous. In this test the relative gas flow resistance was found to be 1.0 in $\text{H}_2\text{O} \cdot \text{min} \cdot \text{ft} / \text{lb}$ at an estimated porosity of 91.6%. This value is low compared with the relative gas flow resistances of most fly ashes from pulverized coal boilers and AFBC plants.

Drag-equivalent Diameter - This quantity is not a measurement of a physical dimension, but a fitted parameter ranking the characteristic gas flow resistances of particulate materials at equivalent dust cake porosities. Increasing values of drag-equivalent diameters indicate lower resistance to gas flow at a given porosity. Measurements of physical size generally correlate with this expression; however, the drag-equivalent diameter best expresses the fineness of an ash as it relates to its effect on relative gas flow resistance. Determining the value of this quantity is a way to take into account the implicit effects of such characteristics as morphology and cohesivity of the material. The drag-equivalent diameter for the test material was 0.621 μm which is quite small compared with the values of this quantity for PC, AFBC, and CFBC ashes. The relatively low gas flow resistance arises from the compensating effect of the high degree of porosity.

Scanning Electron Microscopy - A series of SEM photographs were taken and evaluated. At the lowest magnification, many particles have dimensions of 100 μm or more. That results is not surprising, given the nature of the process and the absence of any kind of collecting device upstream of the filter system. It is not necessarily true that the largest of these particles actually reached the dust cake; gravitational settling may have removed some of them as they entered the enclosure.

At higher magnification, the intermediately sized particles are nearly spherical in shape, with relatively smooth surfaces. Most of the particles, however, have a rough spongy-looking texture. The combination of fairly smooth, spherical particles and rough, irregularly shaped particles is an unusual combination.

The highest magnification showed the presence of many sub-micron particles. They show up especially well on the relatively smooth surfaces of the spherical particles. It would be difficult to see them at all on the rougher particles.

Clearly, a large fraction of the mass could be removed by the use of a mechanical collector upstream of the filter system, since there are substantial numbers of particles larger than 20-50 μm . The sub-micron particles might cause problems with pressure drop, but there will probably be enough particles of intermediate size to moderate any unfavorable effects.

APPENDIX C

Filter Pressure Drop Characteristics
During Operation on the Texaco Entrained Gasifier

Test Run 6 - Cross Flow Filter

Test Run 10 - Candle Filter

Test Run 6 - Cross Flow Filter
Pressure Drop Data

Texaco Filter Performance Data (S1)
January 16, 1991

Texaco Filter Performance Data (S2)

January 17, 1991

Data between 02:42 and 04:50 missing due to communications interruption
05:11 delta-P line clogged - blown out
07:48 delta-P line clogged - blown out

Texaco Filter Performance Data (S3)

January 17, 1991

Texaco Filter Performance Data (S4)

January 17, 1991

Texaco Filter Performance Data (S5)

January 17, 1991

Texaco Filter Performance Data (S6)

January 17, 1991

Figure 14

21:05 open By-Pass - 26 in.
21:30 Pulsing P1 only
21:44 Pulsing P2 only
22:30 delta-P lines purged
22:40 Pulsing both plenums
23:03 open By-pass - 33 in.
23:52 disable P2

**Test Run 10 - Candle Filter
Pressure Drop Data**

Figure 1

Texaco Filter Performance Data

Figure 2
Texaco Filter Performance Data

December 4, 1991
2252 Flow increase

Figure 3
Texaco Filter Performance Data

December 5, 1991
0115 Flow to filter stopped (Bypass valve opened)

Figure 4
Texaco Filter Performance Data

December 5, 1991
0548 Flow Restarted to filter

Figure 5
Texaco Filter Performance Data

1006 Flow started to sorbent bed

Figure 6
Texaco Filter Performance Data

1006 Flow started to sorbent bed

Figure 7

Texaco Filter Performance Data

1500 Flow to sorbent bed stopped

Figure 8

Texaco Filter Performance Data

1500 Flow to sorbent bed stopped

Figure 9
Texaco Filter Performance Data

2145 Flow started to sorbent bed

Figure 10
Texaco Filter Performance Data

December 5, 1991
2145 Flow started to sorbent bed

Figure 11
Texaco Filter Performance Data

0143 Flow to sorbent bed stopped

Figure 12
Texaco Filter Performance Data

0143 Flow to sorbent bed stopped

Figure 13
Texaco Filter Performance Data

Figure 14
Texaco Filter Performance Data

December 6, 1991
0955 Flow started to sorbent bed

Figure 15
Texaco Filter Performance Data

0955 Flow started to sorbent bed

Figure 16
Texaco Filter Performance Data

1311 Flow to sorbent bed stopped

Figure 17
Texaco Filter Performance Data

1311 Flow to sorbent bed stopped

Figure 18
Texaco Filter Performance Data

Figure 19
Texaco Filter Performance Data

Figure 20
Texaco Filter Performance Data

END

**DATE
FILMED**

3 / 30 / 94