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Long-Term Durability Testing of Ceramic Cross-Flow Filter

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ABSTRACT

Long term durability testing of the cross flow filter is described. Two high temperature, high pressure test facilities were built and operated. The facilities were designed to simulate dirty gas environments typical of Pressurized Fluidized Bed Combustion (PFBC) and coal gasification. Details of the design and operation of the test facilities and filter testing results are described.

EXECUTIVE SUMMARY

INTRODUCTION

The Department of Energy, Morgantown Energy Technology Center (DOE/METC) and Westinghouse are developing and evaluating a cross flow hot gas particulate filter for application in coal based, advanced power generation systems.

The cross flow filter concept and system design are described herein. Filter and system development have evolved through the stages of initial exploratory studies to proof-of-concept bench-scale tests, and, more recently, to pilot scale tests on the New York University (NYU) Pressurized Fluid Bed Combustor (PFBC) and on the Texaco gasifier at Montebell , California.[1,2,3]

The objective of the current program entitled "Long Term Durability Testing of Ceramic Cross Flow Filters" is to evaluate the materials and mechanical design aspects of the filter system and the operational requirements for integration with a prototypical gasifier or combustor. This work was accomplished through extended testing using flow facilities that could simulate the high temperature filtration process typical in advanced fossil process conditions such as PFBC and Integrated Gasification Combined Cycle (IGCC). Such long term filter testing could not be economically accomplished using existing pilot plant PFBC or gasifier facilities.

PROJECT DESCRIPTION

Two dedicated high temperature, high pressure (HTHP) filter test facilities were constructed and operated. These test facilities provide HTHP gas environments for evaluating the filter using ash materials from

PFBC and coal gasification facilities. Both facilities have HTHP flow capabilities to test up to four commercial scale (12 x 12 x 4 inch/ 30.5 x 30.5 x 10.2 cm) cross flow filter elements.

The PFBC simulator facility is designed for a maximum gas flow of 1500 lb/hr (650 kg/hr) and pressures of 150 psig (11 bar). Natural gas is combusted to provide the thermal input to raise the filter temperature as high as 1600°F (870°C). A gravimetric dust feeder with a pneumatic transport line is used to reentrain ash into the hot combustion gas. The facility is capable of simulating various plant operations including steady state and transient conditions (e.g., startup/shutdown, turbine trip and pulse cleaning). This is important when evaluating the effects of mechanical and thermal stresses on the filter module.

The gasification simulator system is a closed flow loop that is electrically heated and designed to provide a HTHP reducing gas environment, while permitting the feeding of gasifier char/ash material. In this facility, a maximum of 1500 lb/hr (650 kg/hr) of gas flow is recirculated using a specially designed high temperature, high pressure eductor. Approximately 10 percent of the gas is used as the motive flow, and system pressures of 150 psig (11 bar), and temperatures of 1200°F (650°C) are possible. A gravimetric dust feeder with a pneumatic transport line are used to feed the chosen char/ash.

Both test loops have the following characteristics:

1. Isokinetic sampling on the outlet of the filter to determine the particulate removal efficiency,
2. An adjustable high pressure gas supply for reverse pulse cleaning of the filters,
3. On-line ash collection and removal capability that permit round-the-clock operation over extended test periods (e.g., 100 hours or more), and
4. Instrumented to provide filter operating and system performance data, including a computer based data acquisition system.

PROJECT RESULTS

The program provides 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 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.

Table S-1 provides a summary of results from the filter testing programs. Average outlet dust loadings were below 1 ppmw, demonstrating particle collection efficiencies significantly better than the 99% program criteria.

Figure S-1 compares the outlet dust measurement data from this testing with the emission and turbine tolerance requirements projected for advanced, coal based systems. Data is also included from earlier cross flow filter testing on an actual PFBC pilot plant.(1) These results demonstrate the high performance potential of the cross flow filter in meeting both turbine tolerance and environmental emission requirements.

Results from the current simulator testing of the cross flow filter have been compared to filter testing in pilot plant facilities. This comparison for the PFBC case shows filters operated in HTHP simulator facilities behave very similar to filters tested in coal fired pilot plants. In both cases stable filter permeance is achieved in relatively few (<500) cleaning cycles. These results confirm that filter system operating characteristics (pressure drop, cleaning cycle, etc.) for PFBC application can be reasonably predicted based on HTHP simulator testing.

Table S-1 - Summary of Cross Flow Filter Performance in Long Term Durability Simulator Testing

	PFBC Ash Test Loop		Gasifier Char Test Loop
	Test Module #1	Test Module #2	Test Module #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

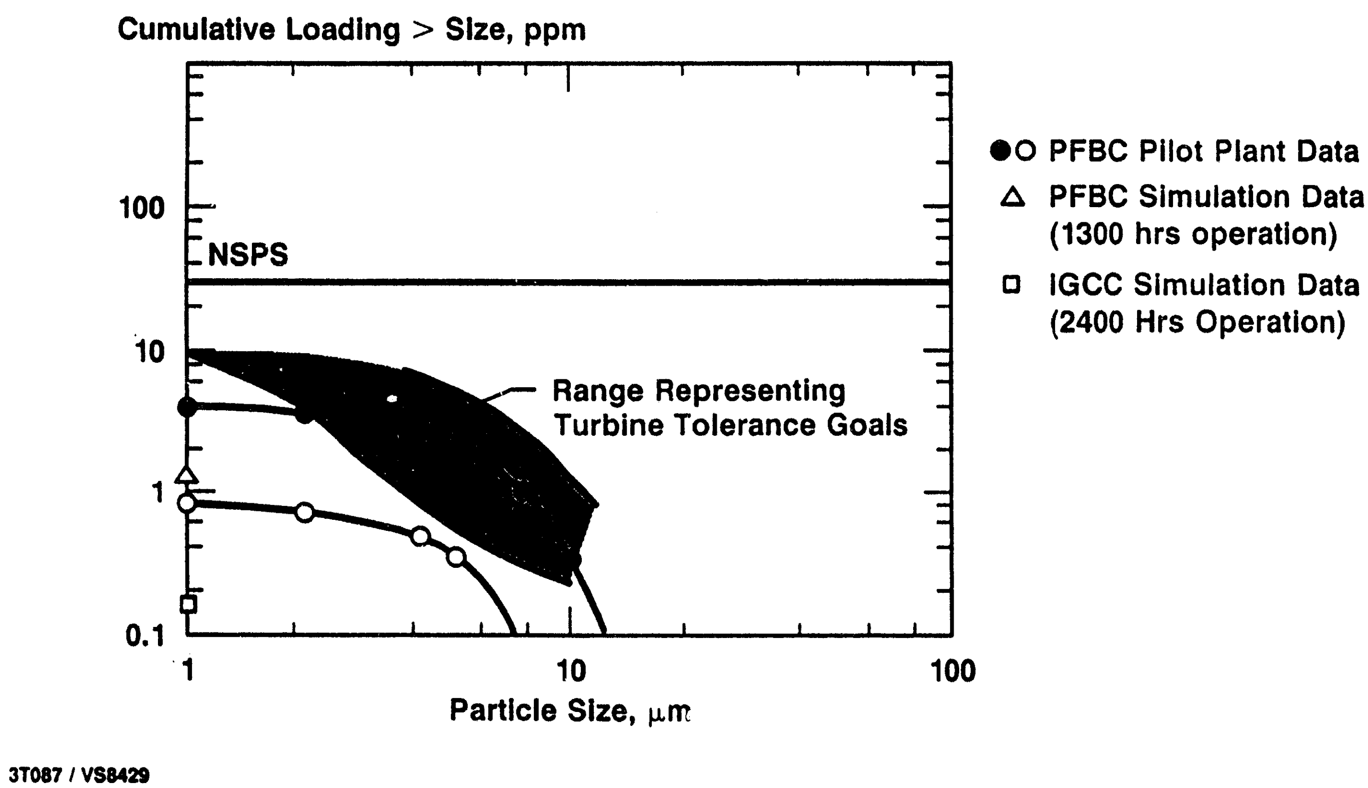

Figure S-1 - Comparison of Measured Cross Flow Filter Performance with Gas Turbine Tolerance

The cross flow filter testing in the gasifier simulator facility also shows stable filter permeance after a short initial conditioning period. The simulator testing however did not directly reproduce pilot plant results since filter permeance appears to be different for different gasifier types. This difference is attributed to the significantly different design and process conditions of gasifiers and the physical properties of the generated ash/char fines. The low particle density of gasifier fines suggests high reentrainment potential that may lead to apparent low filter permeance.

An important focus of the extended testing of the current program has been the evaluation of filter system component durability. 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 have experienced such failures.[3] In the early phases of the PFBC simulator testing an improved design of the ceramic mat gasket was developed by Westinghouse and backfitted to both the PFBC simulator testing and ongoing gasifier pilot plant filter tests. This improved gasket design was also implemented into the gasifier simulator testing. In all subsequent testing, gasket failures have been eliminated utilizing this modified gasket design. The improved gasket utilized NEXTEL(R) fibers wrapped in a NEXTEL(R) ceramic cloth. The cloth encapsulates the fiber and prevents bulk material loss during process operation.

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.

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 run in the PFBC simulator testing. 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 pilot plant testing. Although testing has been limited (1000 to 2000 hours), no further failures in the filter flange were experienced.

An important consideration in the long term durability of the cross flow filter is the stability of the ceramic matrix. This aspect of the filter development is being addressed in detail in a separate program, "Thermal/Chemical Stability of Ceramic Cross Flow Filter Materials," DE-AC21-88MC25034. This program is investigating for a variety of materials the combined and separate effects on long term material properties of the base matrix structure in the presence of alkali and possible generation of microcracking due to effects of pulse cleaning thermal fatigue. This work has demonstrated the relative inertness of the cross flow filter alumina/mullite matrix in both high temperature oxidizing and reducing gas environments of PFBC and gasifier systems, respectively. The cross flow filters exposed in the simulator testing reporting herein have confirmed the potential benefits of the alumina/mullite matrix.

PROJECT CONCLUSIONS

- Improvements in the long term durability of the cross flow filter has been achieved through improved filter manufacture and design of the filter mounting and gasket system. Further improvements in manufacturing quality assurance and development of nondestructive testing techniques are needed to ensure filter manufacturing specifications are met.

- Extended testing (>1000 hrs) has confirmed the high performance potential of the cross flow filter that was previously demonstrated in short term tests.

- The alumina/mullite matrix currently used for the cross flow filter appears as a preferred material choice for the wide range of process gas conditions represented by the different Advance Fossil Power Generation Systems that would use hot gas cleaning. Further improvements in material thermal fatigue toughness are needed to protect the filter system from unplanned plant process upsets.

- High temperature, high pressure PFBC simulator facilities are effective in reproducing filtration conditions representative of actual plant operations.

- Gasifier simulation testing using hot inert gas and char produced only similar plant trends regarding filter operating characteristics. Both simulator facilities should reproduce thermal and mechanical stressing typical of plant operations.

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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) and each of these systems rely on a gas turbine to generate all or a portion of the electrical power. 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 provide for a filter system that protects the gas turbine from particle erosion and deposition and cleans the gas to meet environmental 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]

1.1 CROSS FLOW FILTER CONCEPT

The ceramic cross flow filter is illustrated in Figure 1.1. 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 flows 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

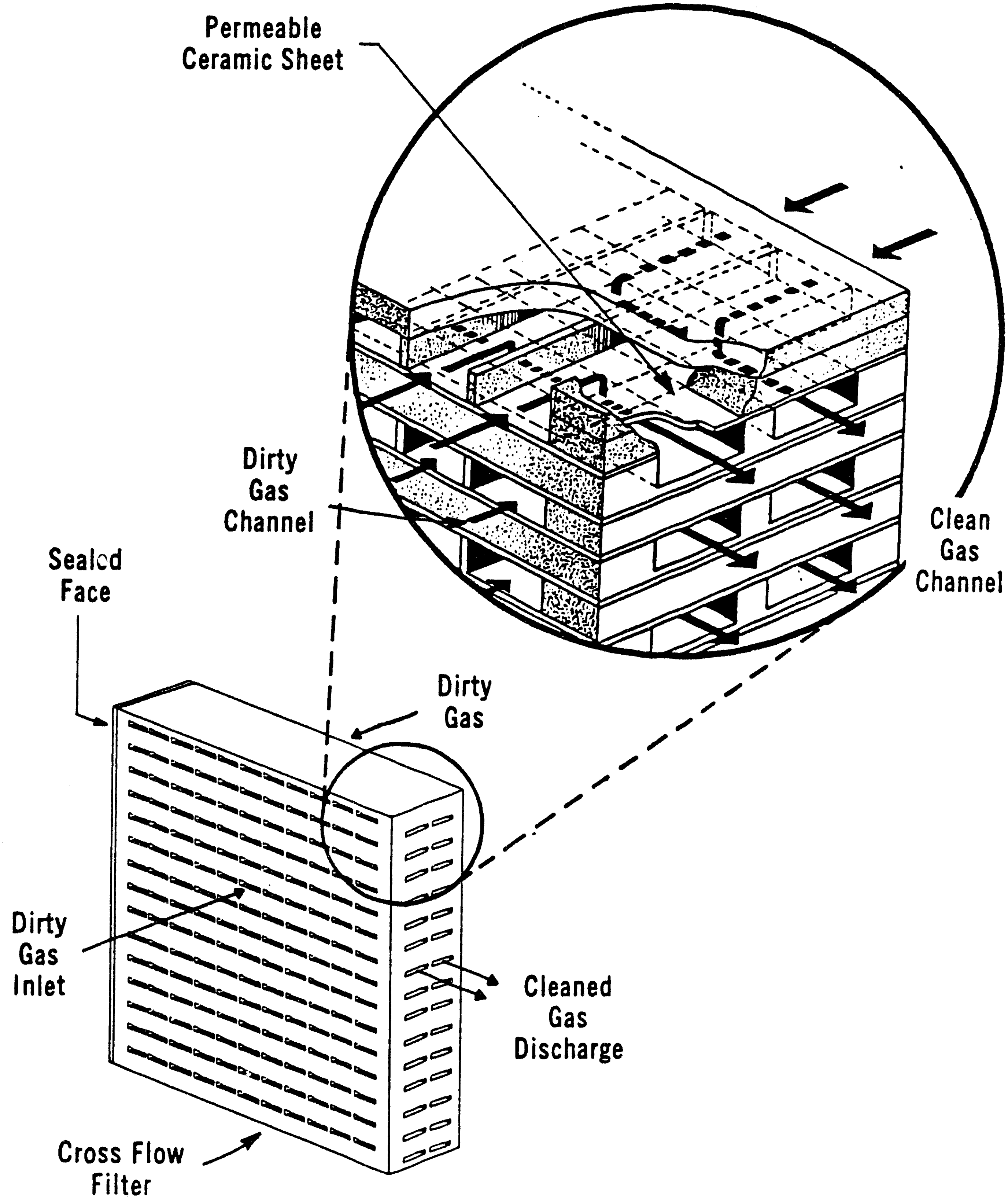

Figure 1.1 - Schematic Representation of Cross Flow Filter

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 1.2 and 1.3. The system consists of a refractory lined, coded pressure vessel that contains arrays of the cross flow filter element assemblies, Figure 1.2. The arrays are formed by attaching individual cross flow elements (Item 1, Figure 1.3) to a common plenum (Item 2, Figure 1.3) 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 1.3). 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. The cluster concept provides a modular approach to scaleup and permits maintenance and replacement of individual filter elements.

Hot, dirty gas enters the filter housing, and passes through the filter elements into the central plenum pipes, collected on the clean side of the tubesheet and passes through the vessel outlet nozzle. The ash collected on the short side channels of the 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.

The major attributes of this 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.

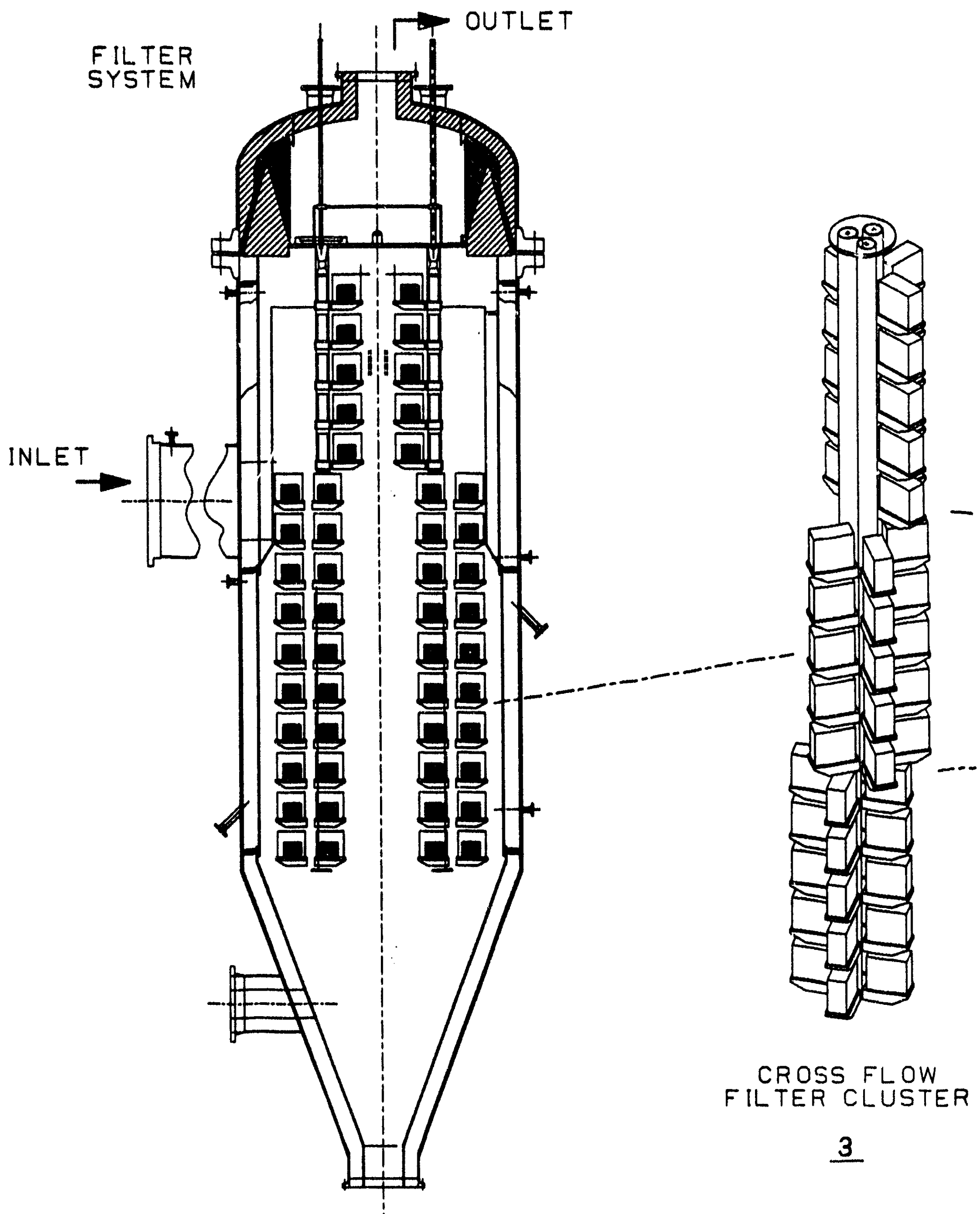

Figure 1.2 - Westinghouse Cross Flow Filter System Concept

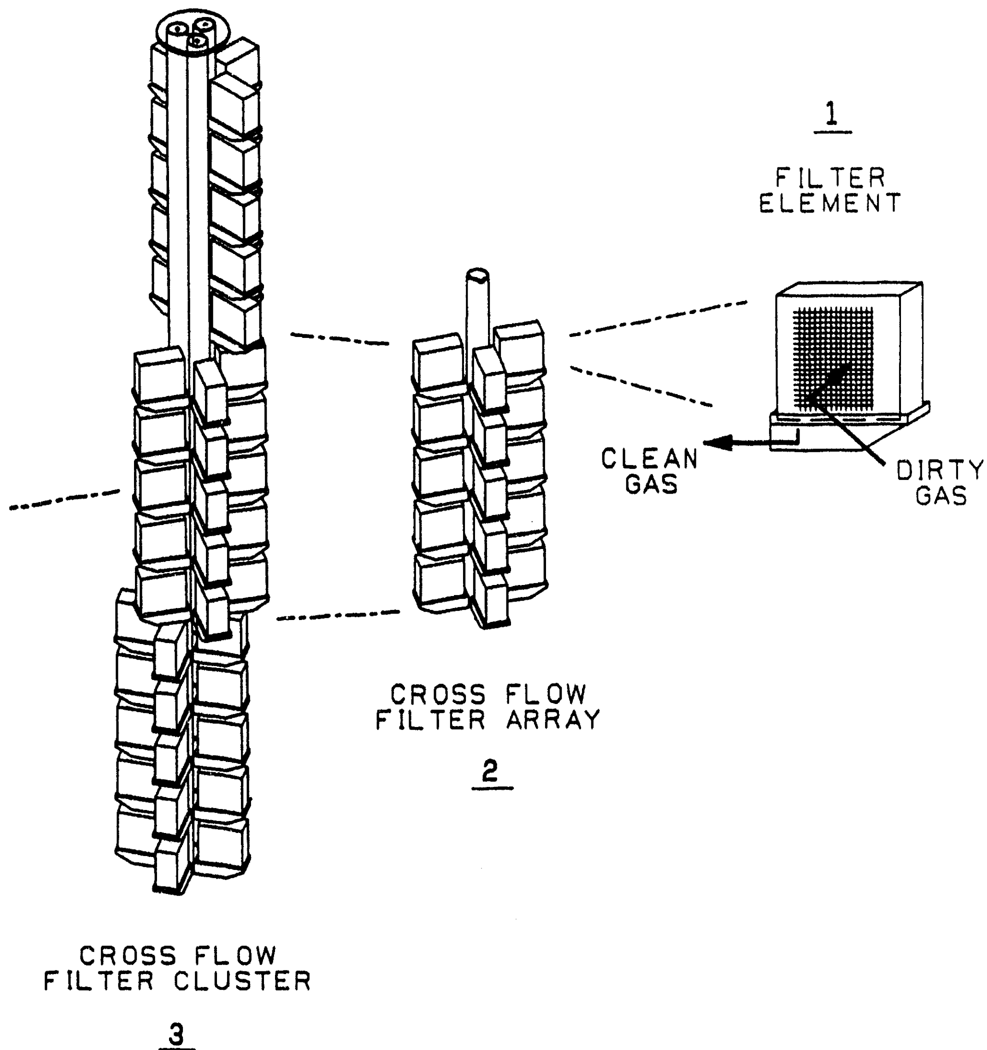

Figure 1.3 - Westinghouse Concept for Contstructing Filter System from Single Cross Flow Filter Elements

1.2 CROSS FLOW FILTER DEVELOPMENT

Westinghouse has focused on cross flow filters that have been fabricated from an alumina/mullite ($Al_2O_3/3Al_2O_3 \cdot 2SiO_2$)-based material. 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 elements (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.[2,3] These studies 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 also demonstrated the technical and economic potential of the unique cross flow geometry.

Bench-scale test results showed that the conditioned filter resistance was low compared to other types of filter and inertial devices; that simple pulse-jet methods could be used to clean the filters; and that essentially absolute filtration on coal ash and char materials could be achieved. Delamination of the filter at the rib to plate bonded joints was identified as a manufacturing development issue.

Modifications were 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.[4] Additional features which were incorporated into the cross flow filter design included: 1) a radiused flange section which eliminates stress risers, and provides a more delamination-resistant filter body and 2) incorporation of 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.[5]

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.[3]

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,or 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 350 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 1.4. 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.

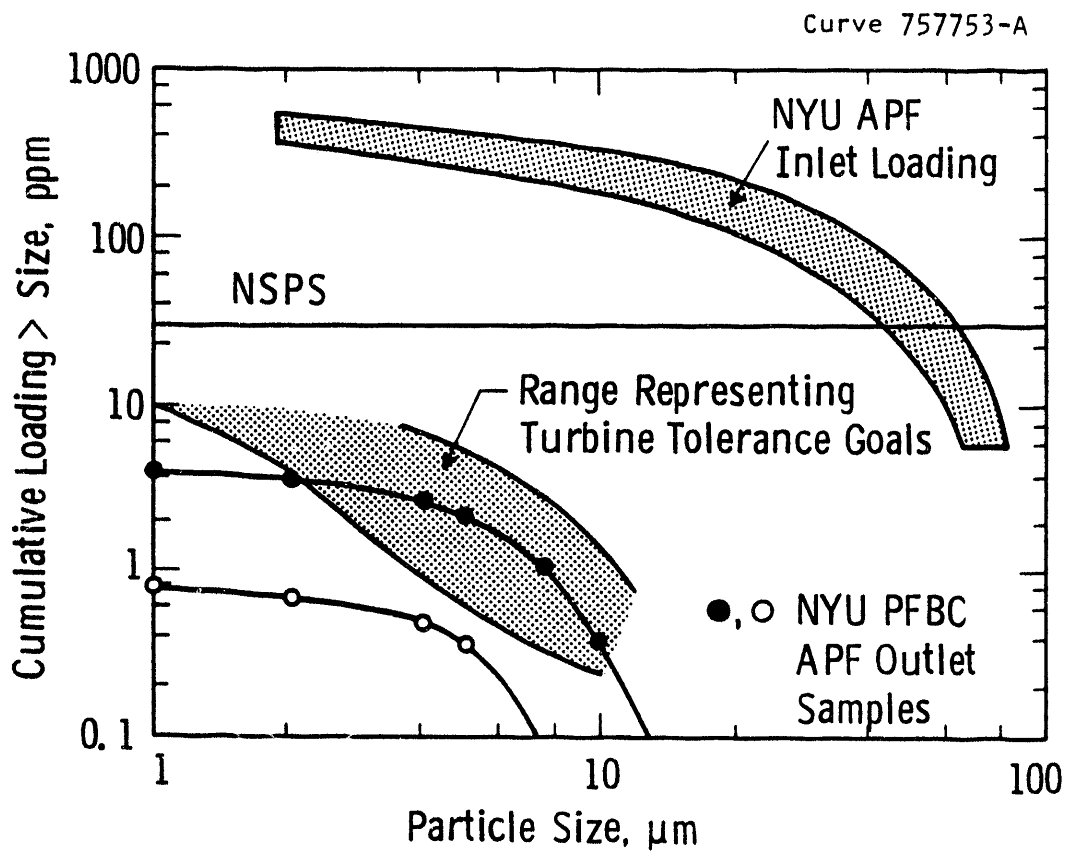

Figure 1.4 - Data Comparing Outlet Particle Size Distribution with Turbine Tolerance Goals

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 was susceptible to eventual eroding from between the filter and its mount.

Concurrently with the PFBC testing, Westinghouse, under DOE/METC sponsorship (DE-AC21-88MC24021), initiated a program to test the ceramic cross flow filter on the Texaco entrained gasifier pilot unit located in Montebello, California.[7] In this test program, a four (4) element (and later eight (8) element) cross flow filter system was integrated with a 15 tpd Texaco entrained gasifier, wherein a number of hot gas desulfurization technologies were investigated. Except for the initial 48 hour long commissioning test, the filter unit operated in support of the Texaco base gasification/desulfurization program. Approximately 400 total hours of operation were attained that cover seven (7) different test runs and a range of flow conditions. Because of the high resistance to flow of gasifier ash and its low bulk density (high reentrainment potential), operating filter face velocity was maintained relatively low, 1 to 3 ft/min resulting in acceptable and generally stable baseline pressure drop.

Isokinetic sampling in the Texaco tests showed outlet dust loadings as low as 2 to 6 ppm, demonstrating the high collection efficiency potential of the filter in gasification applications. Filter flange and gasket failures were also encountered, but were corrected with the design and implementation of an improved high temperature filter mount and reinforced alumina fiber gasket. This same mount and gasket design were also implemented into the Long Term Durability test program described herein.

1.3 LONG TERM DURABILITY TESTING

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 other ancillary equipment or because of other test priorities.

The Long Term Durability Testing of Ceramic Cross Flow Filter program reported herein was designed to provide dedicated filter test operations for test periods significantly longer than current pilot plant test programs. The program utilizes facilities that simulate coal based combustion and gasification process operating conditions to expose the filter to the mechanical and thermal stressing imposed in actual applications. By reentraining actual ashes obtained from operating plants, the basic filtration properties, such as collection efficiency, cleaning and filter permeance are evaluated.

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2. EXPERIMENTAL TEST PLAN

This section describes the overall test plan used in the long term durability testing program. The plan includes overall test objectives, a description of the test facilities, a description of test procedures and criteria utilized in evaluating filter performance. At the beginning of the contract period, a formal experimental test plan document was developed and submitted to DOE. During the course of the program, this initial plan was modified as required to accommodate actual test events and learning experience. However, the program in general proceeded as originally planned. The test plan provides for efficient and cost effective long term testing of cross flow filters under simulated pressurized fluidized bed combustion (PFBC) and integrated gasification combined cycle (IGCC) filter process conditions.

2.1 OBJECTIVE

The objective of this work is to evaluate the long term mechanical and material stability of components used in the design and construction of ceramic cross flow filter systems, and to evaluate the stability of their filtration properties over time while operating at high temperature, high pressure (HTHP) conditions. The testing is accomplished using HTHP flow facilities that are capable of feeding combustor and gasifier ashes under simulated process conditions. The program provides for 3000 hours of testing under PFBC conditions and 2000 hours under IGCC conditions. The goal was to achieve this testing utilizing a single set of filter elements. For the IGCC conditions, this goal was achieved. In the 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, three other filters 1000 hours and one filter that was also utilized in the IGCC simulator testing had an accumulated exposure of over 2500 hours.

2.2 DESCRIPTION OF TEST FACILITIES

In this program, two high temperature, high pressure (HTHP) test loops were designed, constructed and operated. A photograph of the two test loops is shown as Figure 2.1. One test loop is a natural gas fired combustion facility that utilizes reentrained fly ash to simulate Pressurized Fluidized Bed Combustion (PFBC) process conditions. The second test loop uses recirculated gas that is electrically heated, and reentrained gasifier char and ash to simulate gasifier process conditions. A detailed description of these test loops is provided below. Both loops are installed in the same laboratory (building), sharing common service facilities and control room and could be operated in parallel. The laboratory has approximately 2042 ft^2 of floor area, 20 ft overhead height with a 5 ton X-Y hoist that provides full coverage for assembly and disassembly of the test systems.

2.2.1 PFBC Simulator Test Loop

The PFBC simulator test loop, shown schematically in Figure 2.2, is designed for a gas flow up to 1500 lb/hr and pressures up to 150 psig. This unit is an upgraded and larger version of an existing Westinghouse facility and utilizes many of the features of this earlier design.[1] In the upgraded design, the filter test unit is housed in a 3 ft (0.91 m) diameter, 10 ft (3.05 m) high refractory lined pressure vessel that is designed to contain hot gas up to 1650°F (900°C).

Thermal input is provided by the combustion of natural gas. A gravimetric dust feeder and pneumatic transport line are used to reentrain fly ash and produce a hot dirty gas at the filter test unit. The cleaned gas is exhausted through a water cooled exhaust line and through a water cooled back pressure control valve. Collected ash is

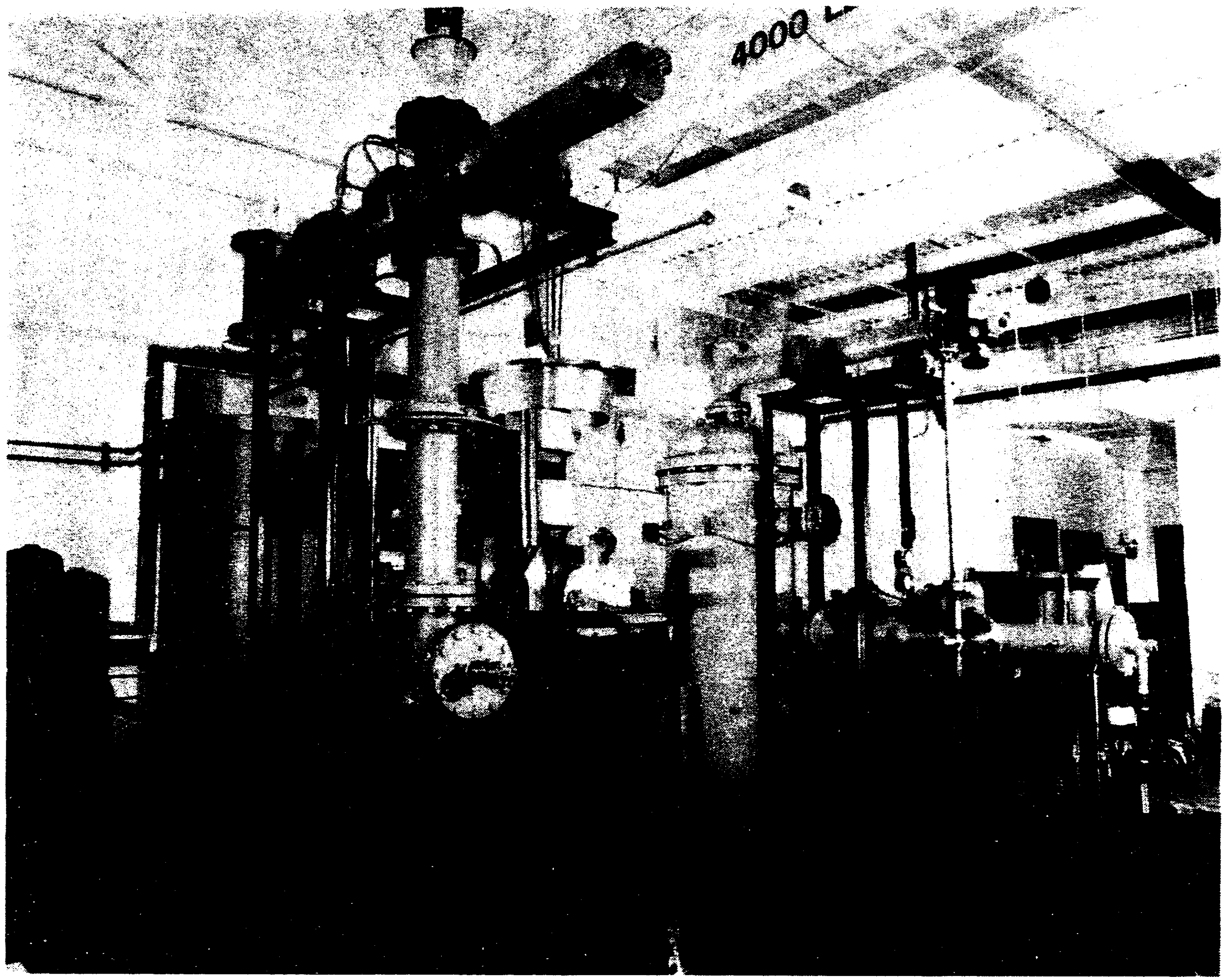

Figure 2.1 - Photograph of Westinghouse High Temperature, High Pressure IGCC and PFBC Simulator Test Loops

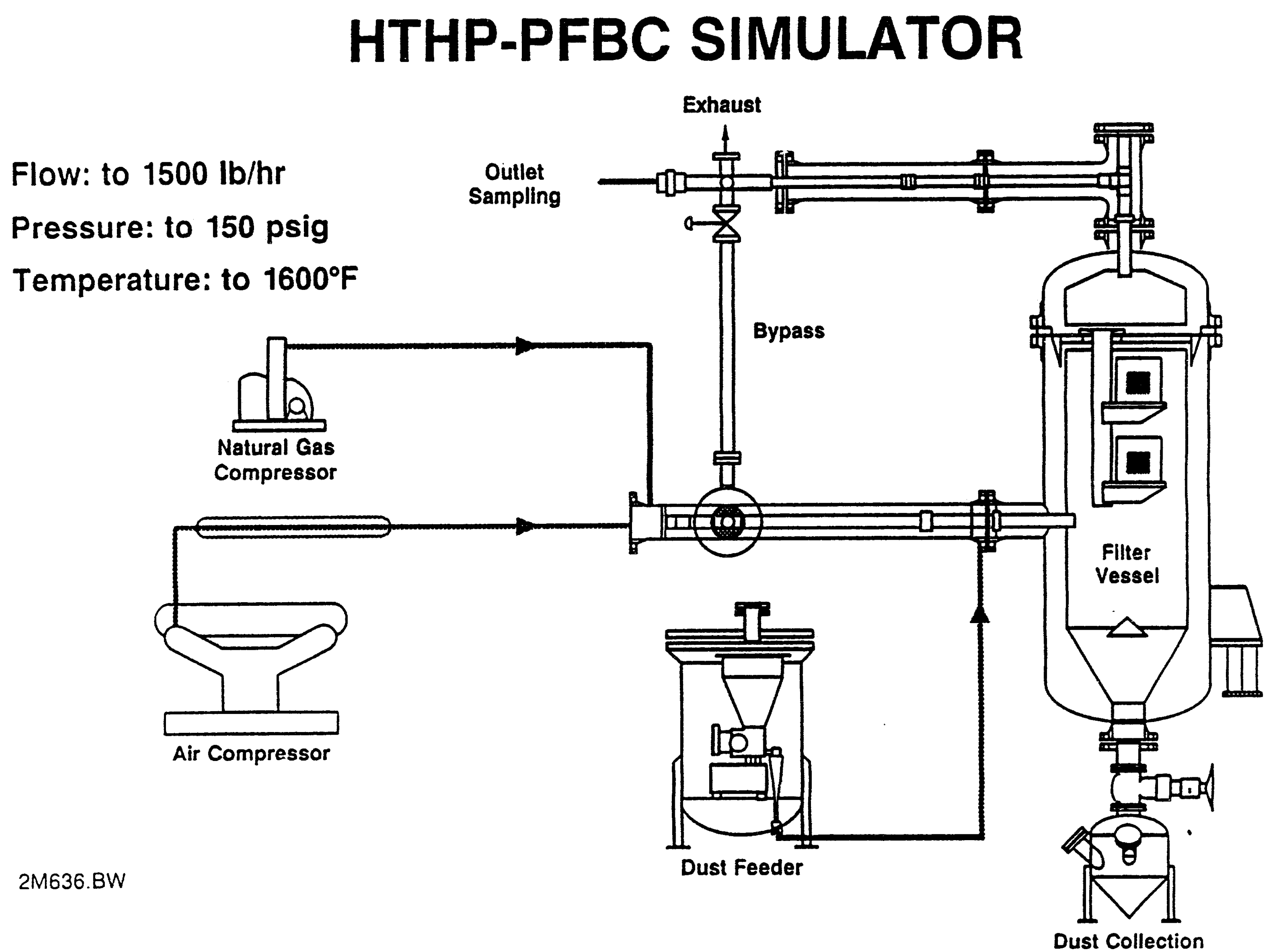

Figure 2.2 - Schematic of Westinghouse PFBC Simulator Test Loop

discharged from the filter by pulse-jet cleaning provided by a separate high pressure nitrogen source and controlled with fast acting solenoid valves. The discharged ash is collected in a hopper below the main filter vessel. This hopper is designed to be pressure cycled in order to remove the collected ash while filter operation is continued (or only minimally disrupted).

The test loop is fully instrumented and automatically controlled to set point conditions. A computer based control and data acquisition system is provided. The detailed Process and Instrumentation Diagram (P&ID's) and mechanical drawings of the major piping and vessel components are provided in Appendix A. A brief description of the subsystems comprising the PFBC simulator loop is provided below.

Gas Supply

The high-pressure air supply is a 75 hp two-stage reciprocating compressor that is capable of continuously providing up to 285 scfm (8.1 m^3/min) of air to 200 psig (14.8 bar). A second, 250 psig (18.2 bar), 130 scfm (3.7 m^3/min) unit is currently connected in parallel to the air supply and can be operated to extend the range of flow conditions to those required for this test passage, i.e., 100 actual cubic feet per minute, at a nominal pressure up to 150 psig (11.4 bar).

A natural gas fired combustor system is used to raise the temperature of the supplied air to a temperature between 1550°F (844°C) and 1700°F (927°C) at the filter and to give a gas composition that is representative of the combustion products from a PFBC facility. The approximate gas composition is:

Nitrogen	73%
Water Vapor	14%
Carbon Dioxide	7%
Oxygen	6%

assuming that the natural gas is all methane and that it all oxidizes to carbon dioxide. These are reasonable assumptions for the combustion conditions used for this test passage.

The combustor is fired on natural gas from a new, larger, oil-free compressor, that is used to boost house-supplied natural gas from 15 to 200 psig (2 to 14.8 bar) for use in the passage. The high-pressure natural gas is piped through the flow control valve directly to the combustor section of the passage. In this refractory-lined spool piece, a small aerodynamically shaped flame holder stabilizes the flame as the bulk of the passage flow is mixed and heated. It has been our experience that direct fired systems such as this prove to be very reliable systems operating at high temperatures.

Dust Feed/Metering System

The ash feed system consists of a K-Tron loss in weight powder feeder with a twin screw feed barrel, Model LWF20 with a capacity of 22.0 lb/hr (100 kg/hr). The feeder is enclosed in a pressure vessel sized to house both the feeder and storage hopper. A small quantity of pressurized air is used to entrain the metered ash and carry the ash into the main gas flow. PFBC fly ash obtained from various operating facilities is used.

Process Instrumentation and Control Devices

The passage flow, temperature, and pressure control system ensures accurate and constant passage test conditions. The flow control systems consist of conventional orifice plates with pressure, differential pressure, and temperature transmitters reporting to a standard utility type of recording mass flow controller. Temperature control is effected by sensing passage temperature and subsequent automatic adjustment of the fuel (natural gas) flow control valve. Passage pressure is maintained by a system back pressure control valve and controller. All passage operating parameters are controlled, displayed digitally, and strip chart recorded at the main passage control panel, and transmitted to a computer for later data reduction and graphing.

The Piping and Vessel Design

The piping and device pressure housings are refractory lined, carbon steel pipe sections so that the pressure boundaries run at relatively low temperature. The inlet 8 inch diameter pipe section is provided in a length that minimizes heat loss while enabling a proper particulate/gas sample to be taken from the gas entering the filter housing proper. The system is configured for cross flow filter PFBC testing at high temperature and pressure.

2.2.2 Gasifier Char, HTHP Recirculating Gas Test Loop

The gasifier simulator test loop is shown schematically in Figure 2.3. The filter unit is housed on a 3 ft diameter (0.91 m), 10 ft (3.05 m) high refractory lined pressure vessel that is designed to contain the recirculating hot gases. This facility is a closed loop system that is electrically heated and designed to provide a HTHP reducing or inert gas environment, and permitting the feeding of gasifier char/ash materials. The system is first charged with a mixed (or inert) gas, pressurized and the gas circulated at a rate up to 1500 lb/hr (680 kg/hr) using a specially designed high temperature, high pressure eductor unit. Approximately 10 percent of the gas is extracted, cooled, recompressed, heated and then reintroduced as the motive gas flow to drive the eductor. The gas is capable of being heated to about 1200°F (650°C).

A gravimetric dust feeder and pneumatic transport line are used to reentrain the char ash and produce a hot dirty gas at the filter unit simulating gasifier filter operation. Collected char ash is discharged

RECIRCULATING GAS TEST LOOP

Flow: to 1500 lb/hr

Pressure: to 150 psig

Temperature: to 1200°F

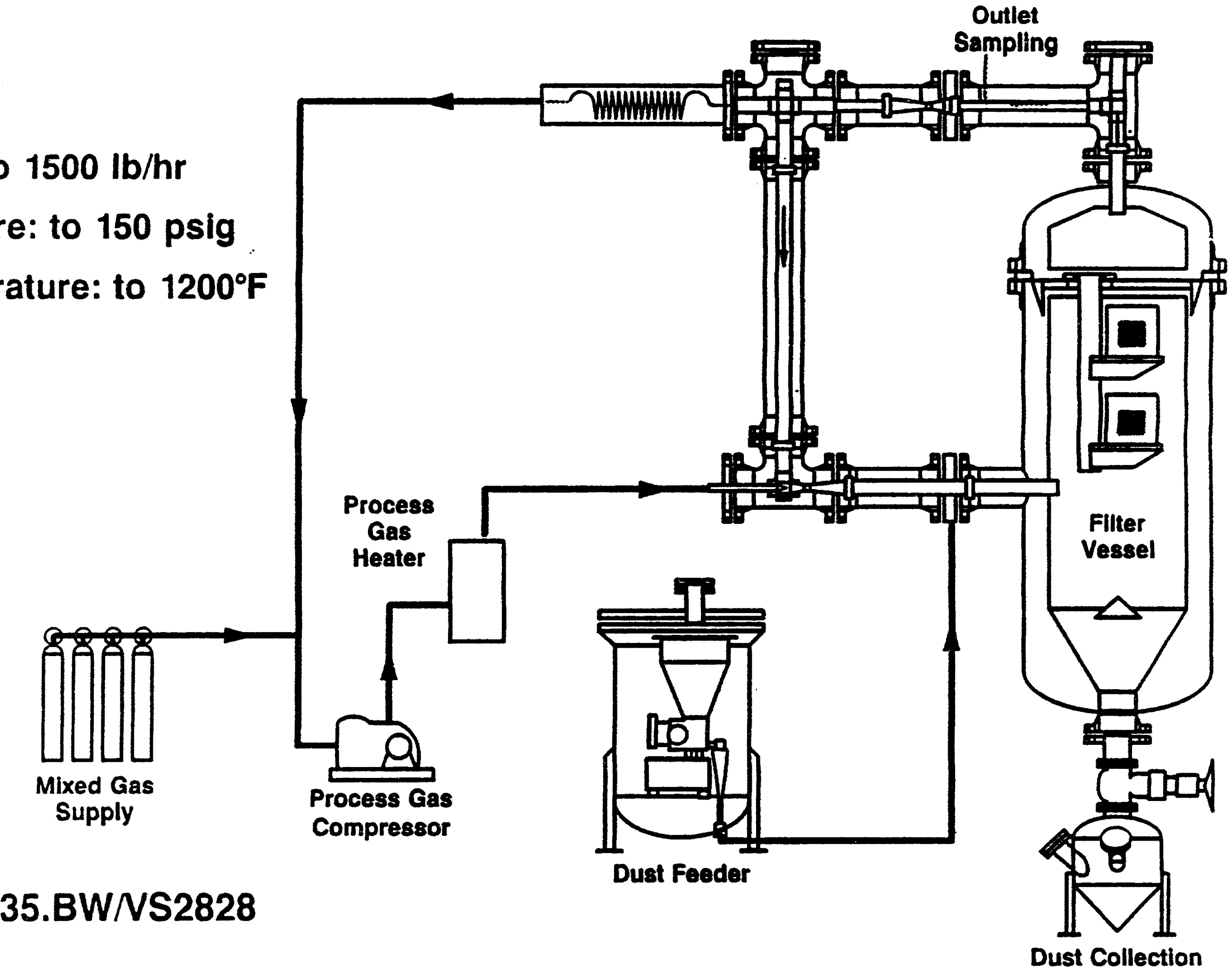

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Figure 2.3 - Schematic of the Westinghouse Gasifier Simulator Test Loop

from the filter by pulse jet cleaning provided by the high pressure mixed gas (inert gas) source and controlled with fast acting solenoid valves. The discharged char ash is collected in a hopper below the main pressure vessel. This hopper is designed to be pressure cycled in order to remove the collected ash while filter operation is continued (or only minimally disrupted).

The test loop is fully instrumented and automatically controlled to set point conditions. A computer based control and data acquisition system is provided. The detailed process and instrumentation diagrams (P&ID's) and mechanical drawings of the major piping and vessel components are provided and described in Appendix B. A brief description of the subsystems is provided below.

Gas Supply

The gas supply for this system is provided by pre-mixing the desired gases. The gas flow rate is maintained at a minimum of 50 acfm (1.4 m^3/min). The temperature is controlled to between 900° and 1200°F (482 and 650°C) with a nominal value of 1000°F (538°C) during steady-state operation. Heating of the gas is achieved with electrical heaters. An electrical process gas heater is used to heat the high pressure motive gas mixture as it enters the closed system. A unit with a capacity of approximately 24 KW is used for this duty. Armstrong Engineering Associates, Inc. supplied a radiant furnace with an Incoloy 800 H helically wound coil to contain the gas for this service.

Throughout the rest of the gas flow path, electrical heaters are imbedded in the refractory lining to offset the heat loss from the system. Since this duty was estimated to be 0.2 KW/ft of piping, low heat flux, rugged service, heaters were utilized for this application.

The pressure can be maintained between 160 and 290 psia (11 to 20 bar) with a nominal value of 160 psia (11 bar) by pressure regulation of the mixed gas reservoir. This high pressure gas supply is maintained with a small gas compressor that recompresses approximately 10% of the system flow that is used as the motive gas for the jet eductor, the dust feed system and the blow-back system. Since the system is of a closed loop, recycle design, once the simulated gas is introduced into the system and the test conditions are established, the gas composition remains constant.

Jet Eductor System

The jet eductor serves to recirculate the hot pressurized gas that must overcome filter and piping flow losses. The analysis, design and qualification of this key component is provided in Appendix C. The jet eductor pump operates by accelerating the heated motive gas flow through a convergent nozzle that is positioned at the inlet of a converging/diverging venturi. The venturi section connects the gas piping in the recirculation loop.

Dust Feed/Metering System

Dust feed to the system consists of redispersed and sized char, metered into the system by the powder feed system described for the PFBC loop. In this case a small amount of the pressurized motive gas is used to entrain the metered char into the test loop. The particle dust loading is between 1000 and 4000 parts per million by weight. Two sources of char were utilized: the filter catch from the KRW fluidized bed gasifier and a filter catch from the Texaco entrained bed gasifier.

Pulse Jet Cleaning System

Pulse jet cleaning of the cross-flow filters is accomplished using high pressure system gas from the motive gas compressor. System gas is used in order to maintain the gas composition. The gas is held in a pressure regulated reservoir at 300 to 500 psig (22 to 35.5 bar).

Fast acting, 1/2 inch pipe size solenoid valves are actuated with an electronic timer, with a typical "ON" time of 0.1 second. The solenoid valves have a block valve on either side so they can be changed during operation in case of a failure. The gas is released through a 3/4 inch tube nozzle into the filter plenum. This reverse flow of gas removes the collected dust from the filter. The blowback sequence can be initiated manually or automatically based on time or pressure drop.

Process Instrumentation and Control Devices

The passage flow, temperature, and pressure control systems ensure accurate and constant passage test conditions. A jet eductor pump is used to recirculate the hot, pressurized gas. Flow is increased or decreased by controlling the quantity of motive gas used to drive the eductor (see Appendix C). Temperature control is accomplished by sensing passage temperature and adjusting the process gas and the electrical heaters to compensate for heat losses. Passage pressure is maintained by a pressure relief control valve and controller. All passage operating parameters are controlled, displayed digitally, and recorded on a strip chart at the main passage control panel. The data is also stored on a computer for data reduction and graphing.

Piping and Vessel Design

The piping and device pressure housing are refractory lined carbon steel pipe sections so that the pressure boundaries remain at relatively low temperature. A 2 inch (5.1 cm) diameter stainless steel liner is used to separate the process gas stream from the refractory material (e.g., Fiberfrax or castable ceramic). The inlet pipe section is provided in a length that minimizes heat loss while enabling a proper particulate/gas sample to be taken from the gas entering the filter housing proper, if required. The pressure boundary is 8 inch (20.3 cm) diameter carbon steel pipe and the filter vessel is a 40 inch (1.02 m) diameter coded pressure vessel with a 30 inch (0.76 m) diameter liner.

The filter vessel has an internal straight section, from the tube sheet used to support the filters to the start of a discharge cone section, of approximately 6 feet (1.8 m). This provides adequate volume for positioning the filters to be tested and enough flexibility to test a wide variety of configurations. Electrical heaters in the pipe and vessel maintain the desired operating temperature by compensating for the system heat losses.

2.3 OPERATING PROCEDURES AND TEST CRITERIA

This section describes the overall operation of the test facilities and summarizes the criteria used to evaluate filter system operation.

Facility Operation

In general, both test loops were operated in parallel, which provided scheduling, manning and cost benefits. Two different test approaches were utilized. One approach was to operate the facility over a 12-hour test day period (7:30 am to 7:30 pm) followed by a shutdown and restart the following morning, continuing Monday through Friday. The overnight shutdown resulted in only a partial cooldown of the facility, thus allowing a hot restart of the test unit. The second approach was to operate the facility 24-hours per day over a 5 day period followed by a weekend shutdown. In both scenarios, the weekend shutdown would result in a cold restart the following Monday. It was concluded that both hot and cold restarts were important operating modes and would be included in the test program. Specific PFBC plant transients corresponding to plant startup and turbine trip were also identified and repeatedly simulated in one segment of the test program. A second segment in the PFBC simulator testing included accelerated pulse cleaning. Table 2.1 outlines the range of operating parameters incorporated in the test program. System pressures were below maximum values to maintain a high volumetric flow and keep filter face velocity as high as possible when utilizing more than one filter element.

Table 2.1
Summary of Test Facility Operating Parameters
Utilized in the Test Program

Test Parameters	PFBC Simulator	Gasifier Char/Ash Recirculating Gas Loop
Operating Pressure, psig	85 to 165	85
Operating Temperature, °F	1500 - 1600	350 - 1200
Dust Loading, ppm	1000 - 2000	1000 - 2000
Ash Type	PFBC	Gasifier Char
Filter Face Velocity, ft/min	3 - 10	2 - 5
No. of Filters Tested at One Time	2 - 4	2

In the gasifier char/ash recirculating gas loop, system temperature and pressure were varied to increase gas density. This provided test flexibility to reproduce potential reentrainment effects of low particle to gas density ratios representative of actual entrained gasifier environments.

Test Criteria

Filter evaluations were based on the following performance criteria:

- Outlet dust loading
- Collection efficiency (>99%)
- Baseline pressure drop (<100 in H_2O)
- Stability of baseline pressure drop, i.e., constant filter permeance
- Materials characterization

1. <u>Outlet Dust Loading</u>

In advanced coal based power generation application, the purpose of the hot gas filter is to remove sufficient particulate to meet regulatory stack gas emission requirements and protect downstream components (such as the gas turbine and heat exchange components) from particle erosion and deposition. Requirements for the latter depend on manufacturing specification and overall process integration of this equipment into the plant. It is generally accepted that both particle loading and particle size distribution are important in the erosion and deposition mechanism. Thus, criteria for turbine protection is likely to include both loading and particle size distribution.

In the long term durability test program, outlet dust loading is determined from simple isokinetic extractive grab samples that are suitable for gravimetric analysis and subsequent particle size analysis if desired. The particle size distribution is determined using coulter-counter or x-ray sedimentation methods. It is noted, however, that under normal filter operating conditions, the quantity of dust collected on the outlet sample is small (even with relatively long sampling times) and not generally amenable to size distribution analysis. When sufficient dust quantity is collected, it is generally indicative of a dirty side breach or failure in the filter. In these cases, the outlet size distribution is expected to be the same as the inlet. In the test program, outlet sampling was conducted nearly continuously. This is accomplished because the outlet sampling system is designed with an isolation valve that permit removal and quick replacement of the collected sample. Thus, a continuous outlet loading history of the testing is obtained. This is extremely beneficial since the sampling can also be used to pinpoint dust leaks indicative of filter or system failures and correlate these events in time with various operating events.

2. Collection Efficiency

Filter collection efficiency (1- outlet loading/inlet loading) x 100 is a parameter measuring the fraction of the inlet dust removed and is of general value in comparing the relative performance of different filter devices. It depends on knowledge of both inlet and outlet loading. In the long term durability testing, the inlet loading is not sampled but calculated from the dust feed rate based on the loss-in-weight gravimetric dust feeder and material gas flow. Experience has shown that inlet dust loadings based on these measurements is as reliable and accurate as extractive sampling techniques.

3. Baseline Pressure Drop

Equation 2-1 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.

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

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 in this test program is defined as the gas pressure drop through the filter immediately following the cleaning event and is represented by the first term of Equation 2.1, i.e.,

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

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 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.

In the long term durability testing, baseline pressure drop is directly measured by differential pressure measurements made across the filter unit. This data is recorded and displayed on strip charts.

4. Stability of Baseline Pressure Drop (Constant Filter Permeance)

Following an initial filter conditioning period, it is required that the filter display "stable" baseline pressure drop characteristics to maintain operability. Thus, effective cleaning of the filter (dust cake removal) must occur. Effective cleaning depends on a variety of physical and operating parameters such as ash cake properties, and the design and operation of the pulse gas system. Detailed analytical models have been developed to help guide the design and operation of the filter cleaning system. The reverse cleaning pulse intensity generated on the filter clean side represents one of the most significant parameters in the cake removal process.

In the long term durability testing, periodic measurements were made of pulse gas intensity. This was accomplished by placing a small diameter pressure tube on the clean side of the filter plenum and connecting the tube to a fast response differential pressure transducer. The transducer output was recorded on a high-speed oscillographic recorder.

Ash cake properties such as cohesivity, adhesivity and flow resistance are also important in establishing pulse gas cleaning requirements. These parameters may vary widely with ash type and as yet have not been well defined or characterized for hot gas systems.

5. Material Characterization

A wide range of analytical and microscopic methods are available for examining and evaluating both dust and filter materials. The porous ceramic material used in manufacturing barrier filters generally contain an amorphous (glass) phase and possibly clay binders that can react to gas phase alkali and/or steam. Crystallization of the amorphous phase can occur at process temperatures which may cause a mismatch in the thermal/physical properties of the ceramic matrix. Subsequent thermal cycling may result in microcracking and loss of material strength, or perhaps failure. In the long term durability program various analytical techniques were applied to evaluate material response of the filter exposed to testing.

2.4 REFERENCES

1. Ciliberti, D. F., "Hot Gas Cleanup Using Ceramic Cross Flow Membrane Filters," Final Report, DOE Contract No. DE-AC21-79ET15491, DOE/ET/15491-1565, December 1983.

3. SUMMARY OF TEST RESULTS

This section describes the sequence of testing, events that occurred during testing, and summarizes results from both the PFBC and gasifier simulator testing. Section 4 provides an evaluation of these test results, compares this simulator data to actual plant filter data and, generally assesses cross flow filter development.

3.1 OVERVIEW

PFBC Simulator Testing

Approximately 3080 hours of cross flow filter testing was accomplished in the PFBC simulator facility, but events precluded the use of a single set of filter elements. In this testing, fifteen (15) different cross flow filters were utilized in sets of either two (2) or four (4) and exposed to steady state and/or thermal transient testing. Six (6) of the fifteen (15) filters failed as a result of inadvertent exposure to severe thermal transients.

Four (4) cross flow filters were exposed to programmed thermal transients simulating repeated PFBC plant startup, turbine trip and accelerated pulse cleaning. Two of these filters experienced partial delamination cracks but no significant dust penetration was experienced. Delaminations are hairline cracks that occur along the plate seams that are formed during the current cross flow filter manufacturing process. Flawed, or incomplete, bonding can occur along the seams during filter manufacturing that provides active sites for initiating delamination.

Two (2) filters achieved over 1300 hours of testing but then experienced cracks in their mounting flange. This resulted in measurable outlet dust exceeding New Source Performance Standards (NSPS) and the testing of these elements was therefore terminated. A redesign of the filter mounting system was made and implemented. In subsequent testing, no further flange failures were experienced.

Three (3) filters experienced over 1000 hours of testing and a fourth filter, that was initially utilized in the gasifier testing rig, had an accumulated exposure of over 2500 hours.

In the early portions of the PFBC filter durability testing, failure in the filter mount gasketing system was experienced. This earlier gasket design utilized the 3M INTERAM® gasket media originally developed for automobile catalytic support insulation. This material performs well in short term tests but will vitrify under PFBC temperature conditions and eventually erode. A modified gasket was developed by Westinghouse that uses a contained ceramic fiber mat. This gasket has performed without failure or leakage in all subsequent filter testing.

In the PFBC simulator testing, filter performance in general was excellent, with low outlet dust loadings (<1 ppm on average) and stable and acceptable baseline pressure drop.

Gasifier Simulator Testing

Over 1900 hours of cross flow filter testing was accomplished in the gasifier char, gas recirculating test loop utilizing a single set of filter elements. No filter failures were experienced in this testing.

The filter used in this testing was from the same manufacturing lot as the filters in the PFBC testing. Stable pressure drop characteristics and excellent particle collection efficiencies were achieved. Outlet particle loadings were in general less than 1 ppm on average. Testing utilized chars obtained from both the KRW fluid bed and Texaco entrained bed gasifiers.

Most testing in this loop was conducted at relatively low temperature <500°F (<260°C) in an attempt to reproduce entrained gasifier gas density conditions. The low bulk density of gasifier char/ash and relatively high fuel gas density (high gasifier pressure), provides high potential for fines reentrainment due to drag effects. The operating pressure of the Westinghouse gasifier simulator facility was limited to less than 100 psia (6.9 bar). Therefore, to reproduce the reentrainment potential of actual gasifiers, required operating in the simulator at reduced gas temperatures.

3.2 PFBC SIMULATOR FILTER TESTING

Table 3.1 shows a summary of test filters and cumulative operating experience. A summary of test experience of each filter set is given below.

Filters WRTX-11 and WRTX-1

These filters were separately tested in the existing, smaller PFBC simulator rig to achieve initial filter conditioning and qualify other filters from this same manufacturing lot for use in a DOE field test program (DE-AC21-88MC24021). The intent was to then mount these filters into the new long term durability test loop whose construction was in the process of being completed. This initial testing showed acceptable filter permeance and qualified the balance of the filters for field test implementation.

PFBC simulator testing on these filters was conducted on a 2 shift, 24 hour/day basis. After 127 hours of testing on filter WRTX-11, a facility operational problem caused combustor flame-out that

Table 3.1 -- Summary of Cross Flow Filter Testing
in PFBC Simulator Facility

Test Filter	Cumulative Test Hrs	No. of Pulse Cleaning Cycles	No. of Startup/ Shutdowns Standby	Cold
WRTX-11	127	123	15	6
WRTX-1	366	508	20	7
WRTX-9	1304	2068	43	6
WRTX-10	1304	2068	43	6
WRTX-48	335	472	12	12
WRTX-53	335	472	12	12
WRTX-66	38	3	2	4
WRTX-70	38	3	2	4
WRTX-76	1096	390	48	20
WRTX-77	1096	390	48	20
WRTX-78	1096	390	48	20
WRTX-81	320	141	5	5
WRTX-80	191	31	0	2
WRTX-84	104	32	8	2
WRTX-21*	2400	747	35	(73) 11

* Approximately 1900 hours accumulated in gasifier rig testing (see Table 3.6).

went undetected. This allowed full compressor flow of cold air to impinge on the hot filter subjecting it to severe thermal shock. Severe cracking occurred across the filter plates, but the filter remained intact on the mount with no evidence of delamination along plate seams.

Filter WRTX-1 was also conditioned in the existing and smaller PFBC simulator rig. Testing on this filter was initially interrupted after 278 hours when outlet loadings suggested some dust leakage. Subsequent examination showed the filter to be intact but a corner of the INTERAM® gasket had blown out. The gasket was replaced and testing continued.

After approximately 366 hours of exposure, a similar (to WRTX-11) thermal transient and subsequent filter cracking pattern was experienced. Testing was terminated and a modification made to the facility to incorporate an audible alarm to detect combustion flame-out and alert the operator to take appropriate actions to initiate opening of the filter bypass leg. Although combustor flame-out has occurred in subsequent testing, appropriate actions were taken and there has been no evidence of filter failures caused by inadvertent thermal transients in this test rig.

At this time, Westinghouse also undertook the development of a contained gasket seal that utilizes a silica-boria-alumina fiber mat and Nextel fabric. This gasket design was implemented in subsequent testing.

Figures 3.1 and 3.2 show the measured performance of cross flow filter WRTX-1. Filter permeance and measured outlet dust concentration are shown. Fitler permeance is defined and discussed in Section 4. The data points given in Figure 3.1 represent the filter system pressure drop (normallized for flow conditions) following each cleaning cycle. Figure 3.2 gives the filter outlet dust loading measured at regular intervals using isokinetic sampling techniques.

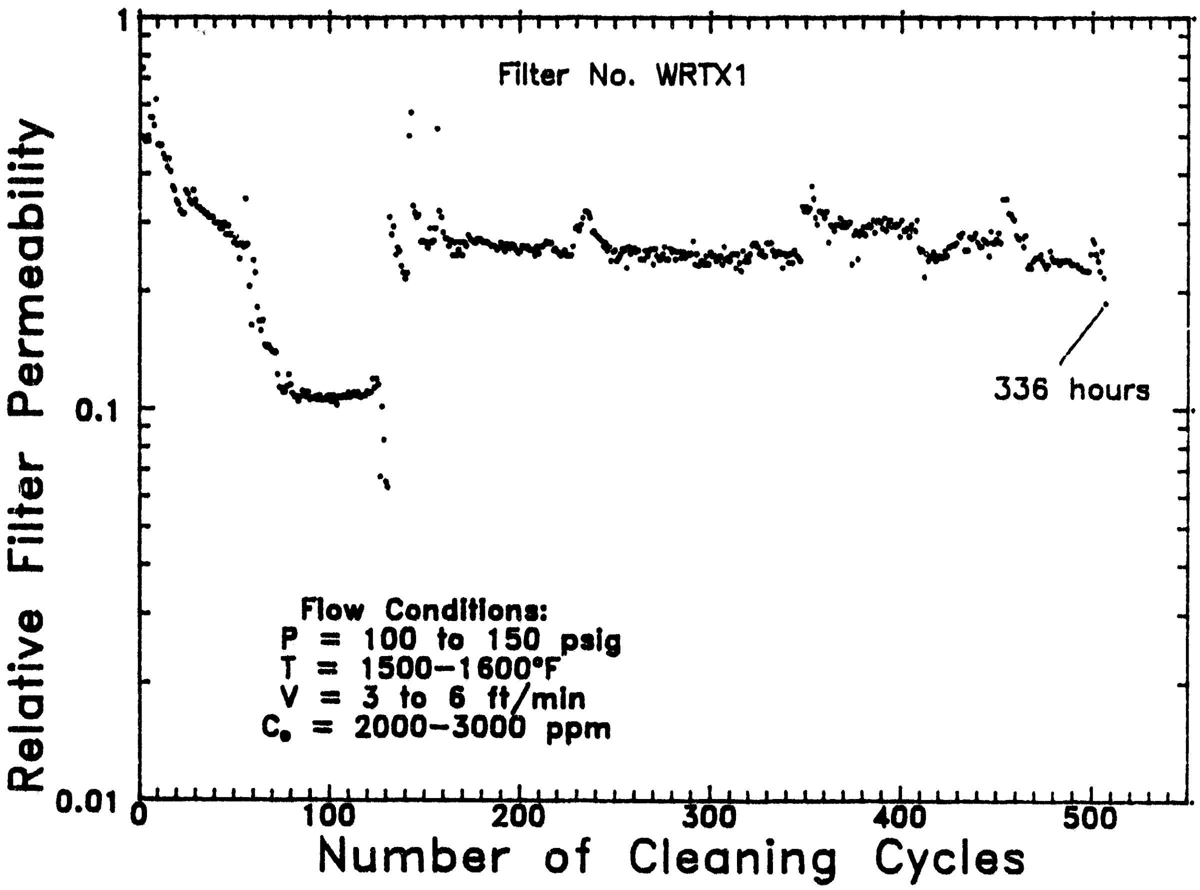


Figure 3.1 - Cross Flow Filter Permeance Trend in Long Term Durability Tests

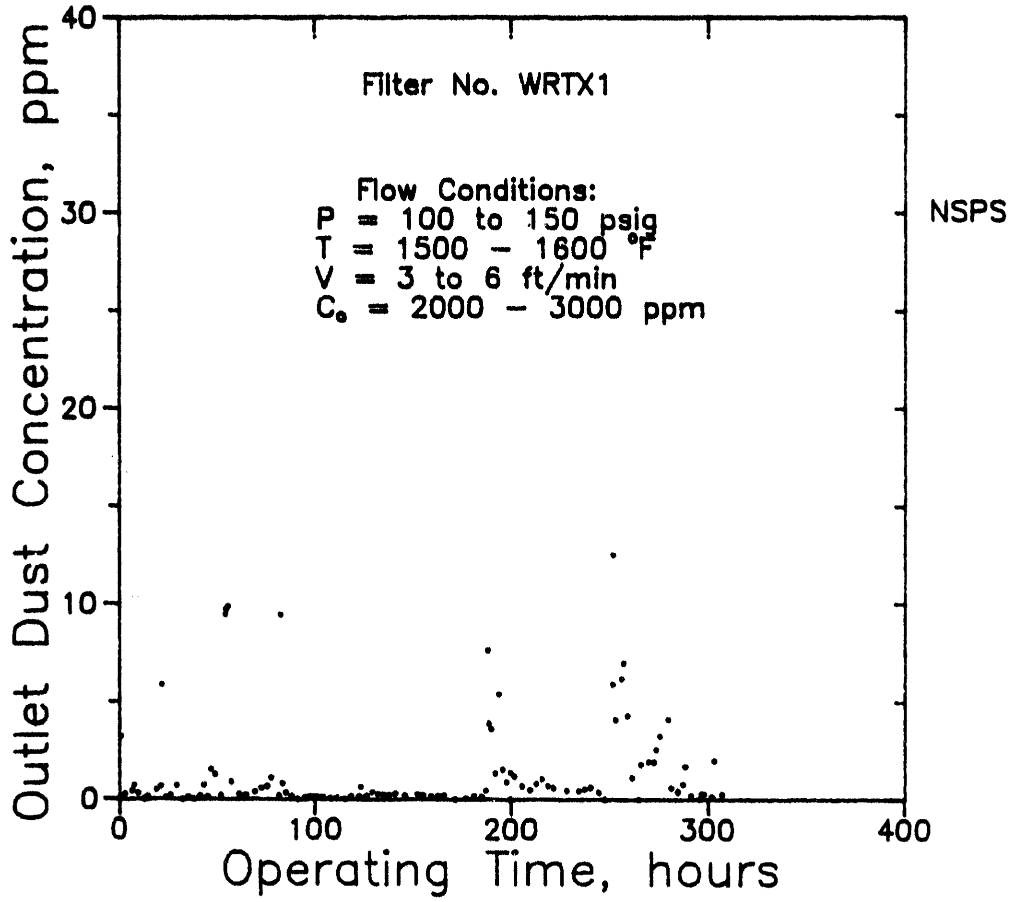


Figure 3.2 - Cross Flow Filter Outlet Dust Loading in Long Term Durability Tests

Steady state filter permeance ranged around 0.25 to 0.30, Figure 3.1, with the conditioned baseline pressure drop between about 7 to 10 in wg (2 to 2.5 kPa). In the early part of testing, filter permeance decreased to 0.10 but subsequent inspection showed the pulse nozzle to be misaligned. Figure 3.2 shows outlet dust loading measured over the course of testing. In general, excellent performance is indicated.

Filter WRTX-9 and WRTX-10

Filters WRTX-9 and -10 were installed in the new PFBC simulator rig. Each filter was mounted on its own plenum and cleaned with separate pulse nozzles. The Westinghouse upgraded, contained fiber mat gasket was utilized with the standard, horizontal flange mount. Approximately 1304 hours of operation were achieved with 2068 cleaning cycles, 6 cold starts and 43 startups from hot (~800°F, 430°C) standby. Table 3.2 provides additional operating history of this filter set. The filter was operated at face velocities of 6 and 10 ft/min utilizing two different PFBC ash materials. The specific pressure drop characteristics for this test run are provided by the computer developed traces given in Appendix D. Typically, the baseline pressure drop ranged around 12-14 inches wg at 6 ft/min (3 to 3.5 kPa at 3 cm/sec) and increased correspondingly at the 10 ft/min (5 cm/sec) condition.

Filter permeance (expressed as a ratio of actual to initial) for this testing is shown in Figure 3.3. Initial filter conditioning was achieved within the first 50 to 100 cleaning cycles with stable baseline operation achieved over the test period. Conditioned filter permeance appeared to range around 20 to 25%, completely acceptable for cross flow filters as evidenced by the low actual pressure drop characteristics (see Appendix D). Excellent filter performance was also achieved over the testing period as indicated by the outlet dust sampling, Figure 3.4.

At the 1304 hour mark, a sharp peak (100 ppm) in outlet dust loading was evidenced suggesting some breach between dirty and clean gas

Table 3.2 - Testing Summary - PFBC Simulator Filter Elements WRTX-9 and WRTX-10

	Operating Period, Hours			
	0-672	672-1188	1189-1258	1259-1304
Test Conditions:				
Gas Temperature, °F	1500-1600	1550-1600	1550-1600	1550-1600
System Pressure, psig	70	70	70	70
Inlet Loading, ppm	1000	1000	1000	1000
Ash Type	PFBC Exxon-Ground	PFBC Exxon-Ground	PFBC Grimethorpe	PFBC Grimethorpe
d_{50}, μ	6.1	6.1	5	5
Face Velocity, ft/min	6	10	10	6
Baseline ΔP, in. w.g.	8-13	15-19	16-20	12-14

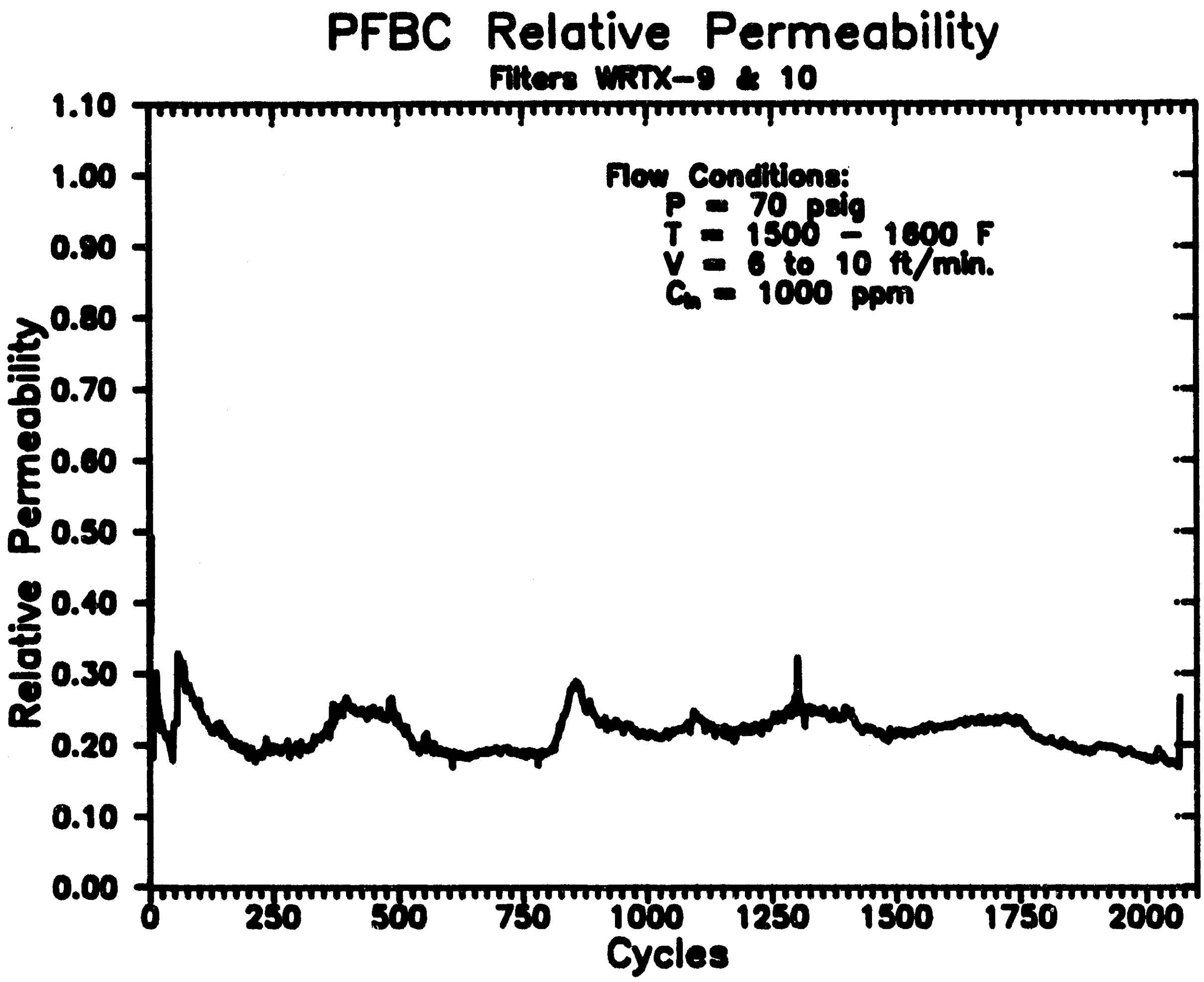


Figure 3.3 - Filter Permeance Trend in 1300 Hour PFBC Simulator Testing (WRTX-9 and WRTX-10)

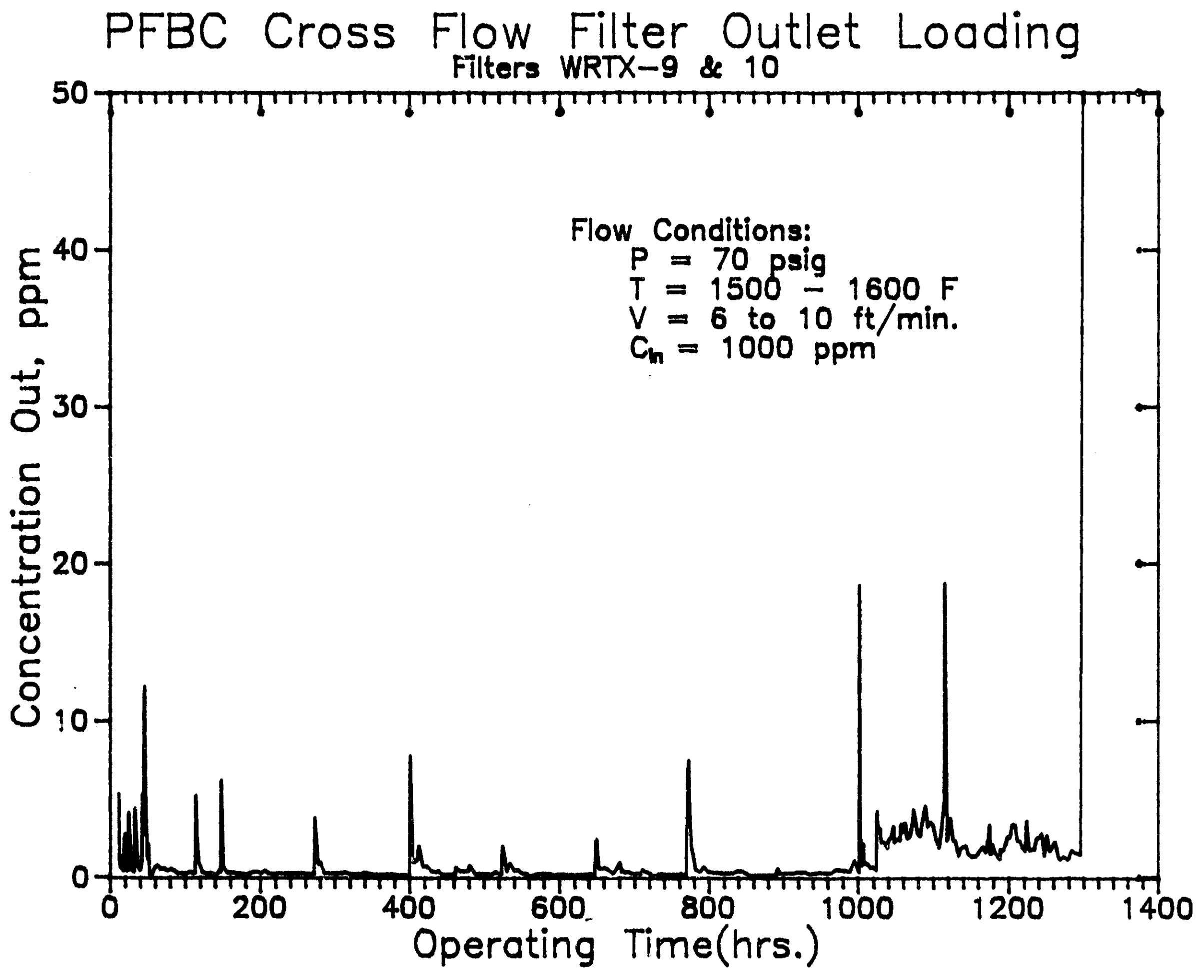


Figure 3.4 - Cross Flow Filter Outlet Dust Loadings Measured in 1300 Hour PFBC Simulator Testing (WRTX-9 and WRTX-10)

side had occurred. Testing was terminated and the filter unit inspected. A substantial crack along the flange of WRTX-10 had occurred which accounted for dust penetration, Figure 3.5. Filter WRTX-9 also exhibited a similar flange crack, but further inspection indicated there was no significant leakage of dust. Based on this test run it was concluded that the design of the filter mount was not optimum and led to the cracking of the filter flanges under the applied thermal and mechanical stresses. A comprehensive analysis of the failure and mount deficiencies was undertaken, and a revised mount design developed. This effort is described in detail in Appendix E. It is also noted that similar flange failures were being experienced in the field test program (DE-AC21-88MC24021). The revised mount design was implemented in subsequent in-house long term durability and field tests. No further flange failures were experienced in the PFBC simulator testing utilizing the revised mount design.

Filters WRTX-48 and WRTX-53

Following the testing of WRTX-9 and 10 described above, filters WRTX-48 and 53 were installed utilizing the revised mount design. Tables 3.1 and 3.3 summarize the initial 297 hours of operation of these filters under steady state conditions. In this time period, both filters experienced 469 cleaning cycles coupled with 8 cold facility starts and 10 hot restarts. At the 6 ft/min (3 cm/sec) face velocity, pressure drop was similar to the WRTX-9 and WRTX-10 testing. Outlet dust loadings were again low, averaging below 2 ppm.

Following this initial 297 hours, testing was halted and the filters were visually inspected and found to be in excellent condition. It was also decided at this point to implement thermal transient testing that would simulate PFBC startup and plant turbine trip conditions. Accelerated pulse cleaning transients were included. This work was in conjunction with Proof-of-Concept testing that was part of the DOE/AEP (American Electric Power) hot gas filter program (DE-FC21-89MC26042).

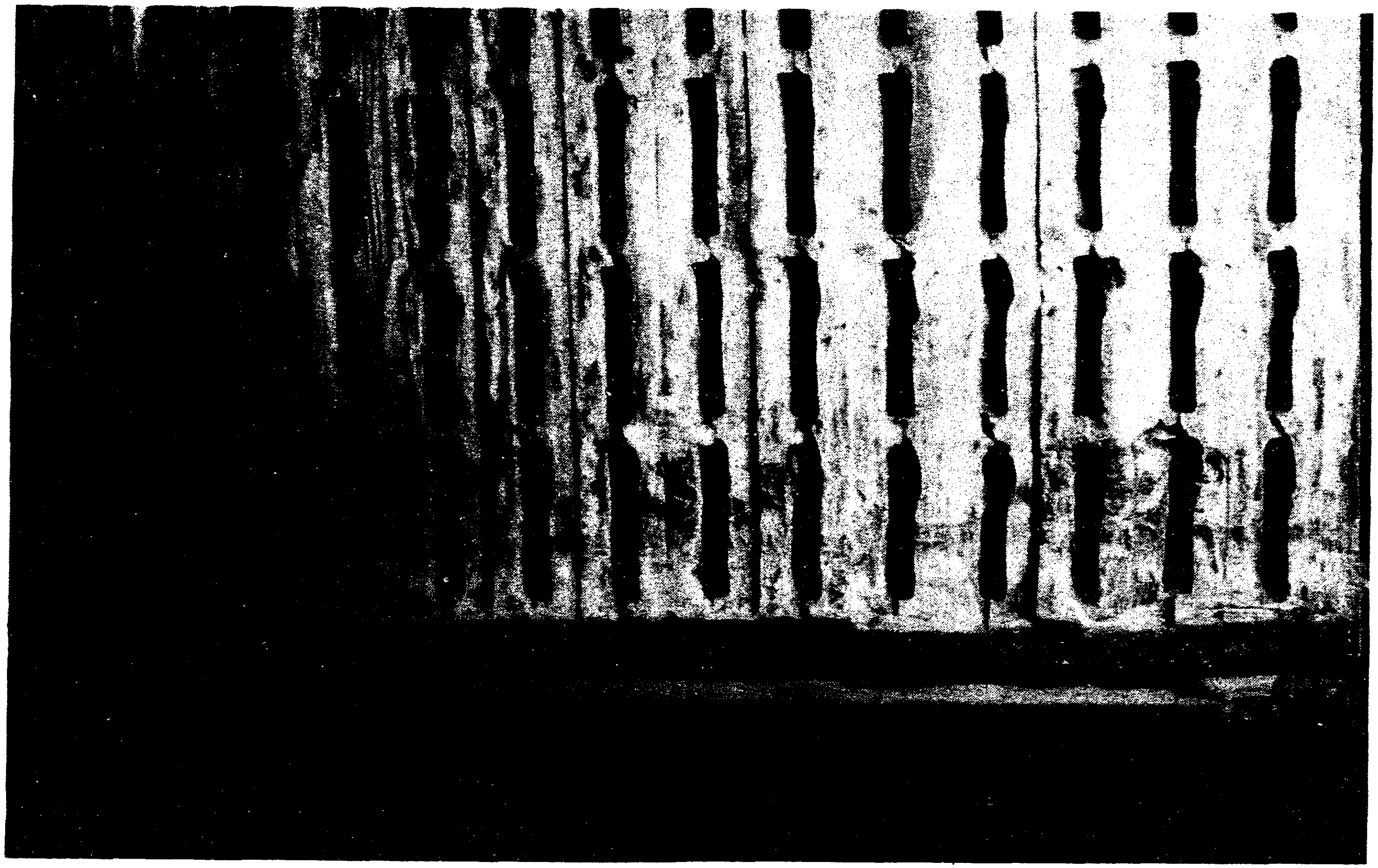


Figure 3.5 - Photograph Showing Flange Failure Experience in Cross Flow Filter WRTX-10

Table 3.3 -- Summary of Steady State PFBC Simulator Testing, Cross Flow Filter WRTX-48 and WRTX-53

	Operating Period, Hours
	0 - 297
Test Conditions:	
Gas Temperature, °F	1500 - 1600
System Pressure, psig	70
Inlet Loading, ppm	1000
Ash Type	PFBC Grimethorpe
d_{50}, μ	5
Face Velocity, ft/min	6
Baseline ΔP, in. wg.	2.5 - 10

For this purpose, two additional cross flow filters were added, filter WRTX-66 and WRTX-70.

Filter WRTX-48, WRTX-53, WRTX-66 and WRTX-70 (Thermal Transient Testing)

For this testing the filter system configuration was modified by placing two filters each on two separate plenum pipes. One pulse nozzle cleaned two filters, Figure 3.6. Initial transient testing was to simulate PFBC turbine trip conditions.

The simulated turbine trip transient, shown in Figure 3.7, produces a cooling of the gas passing through the filters. The transient is produced by shutting-off fuel flow an quickly increasing air flow and decreasing system pressure. The imposed thermal transient simulates the steepest gradient predicted to occur in an actual PFBC turbine trip scenario. In pursuit of simulating the turbine trip thermal transient, a significantly more severe transient (estimated to be about twice the thermal gradient) resulted and all four filters experienced partial or full delamination cracking. Testing was halted, and a more complete analysis undertaken to understand the projected thermal transients and how to better control them in the simulation testing.

Filter WRTX-76, WRTX-77, WRTX-78 and WRTX-81 (and WRTX-80 and WRTX-84) (Thermal Transient Testing)

Four new filters were installed, and thermal transient testing restarted. However, facility conditions were modified to better simulate actual PFBC transients (shown in Figure 3.7) and avoid the severe transients incurred in earlier testing. Table 3.4 provides a summary of the nominal test conditions corresponding to steady state conditions. Pressure drop and gas temperature during the transient testing are given in Appendix F. A total of 615 hours of testing was accumulated in this test period.

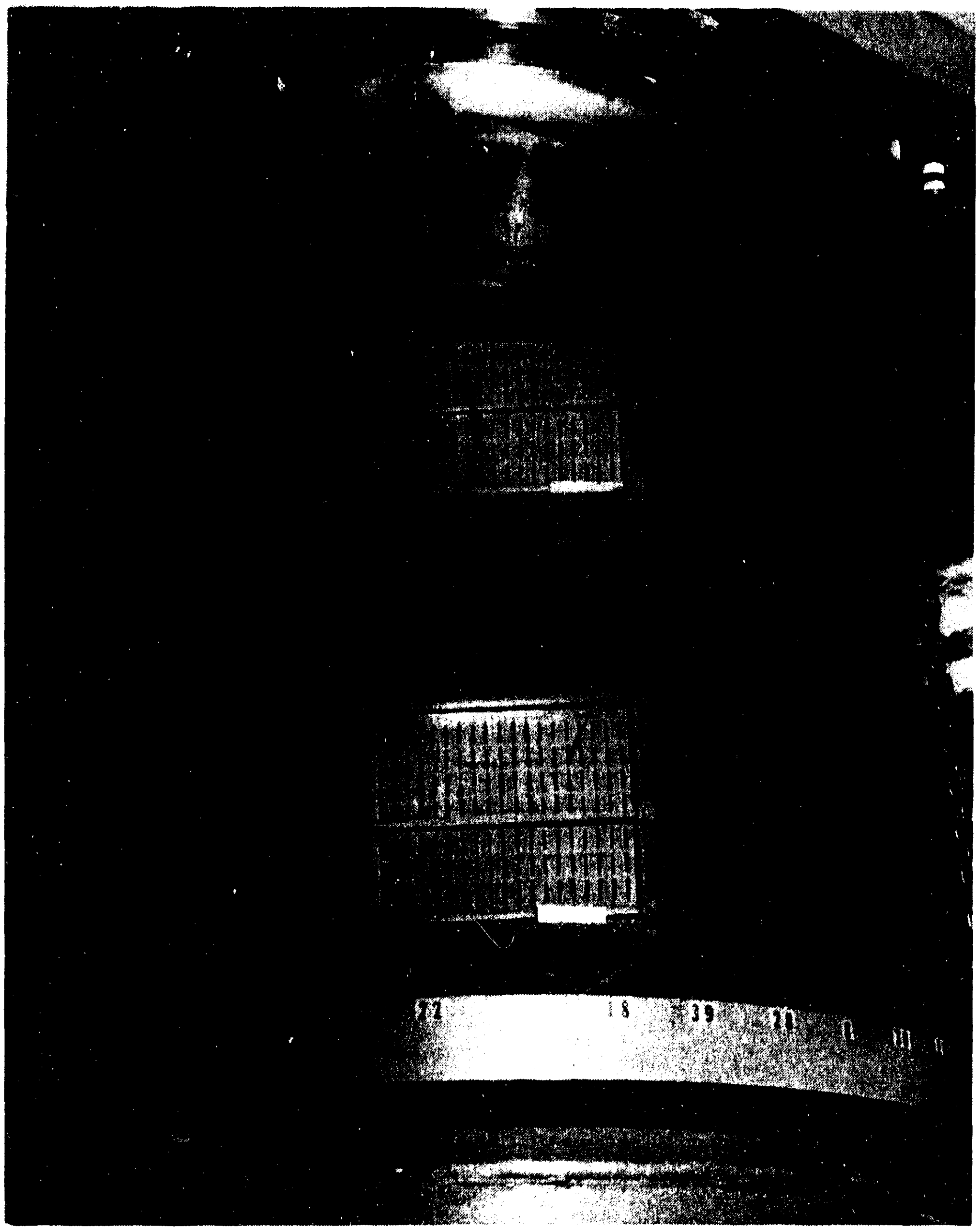


Figure 3.6 - Photograph showing two cross flow filter elements arranged on a single plenum pipe and cleaned with a single pulse nozzle. A second plenum pipe (not visible) is also present with two additional filter elements.

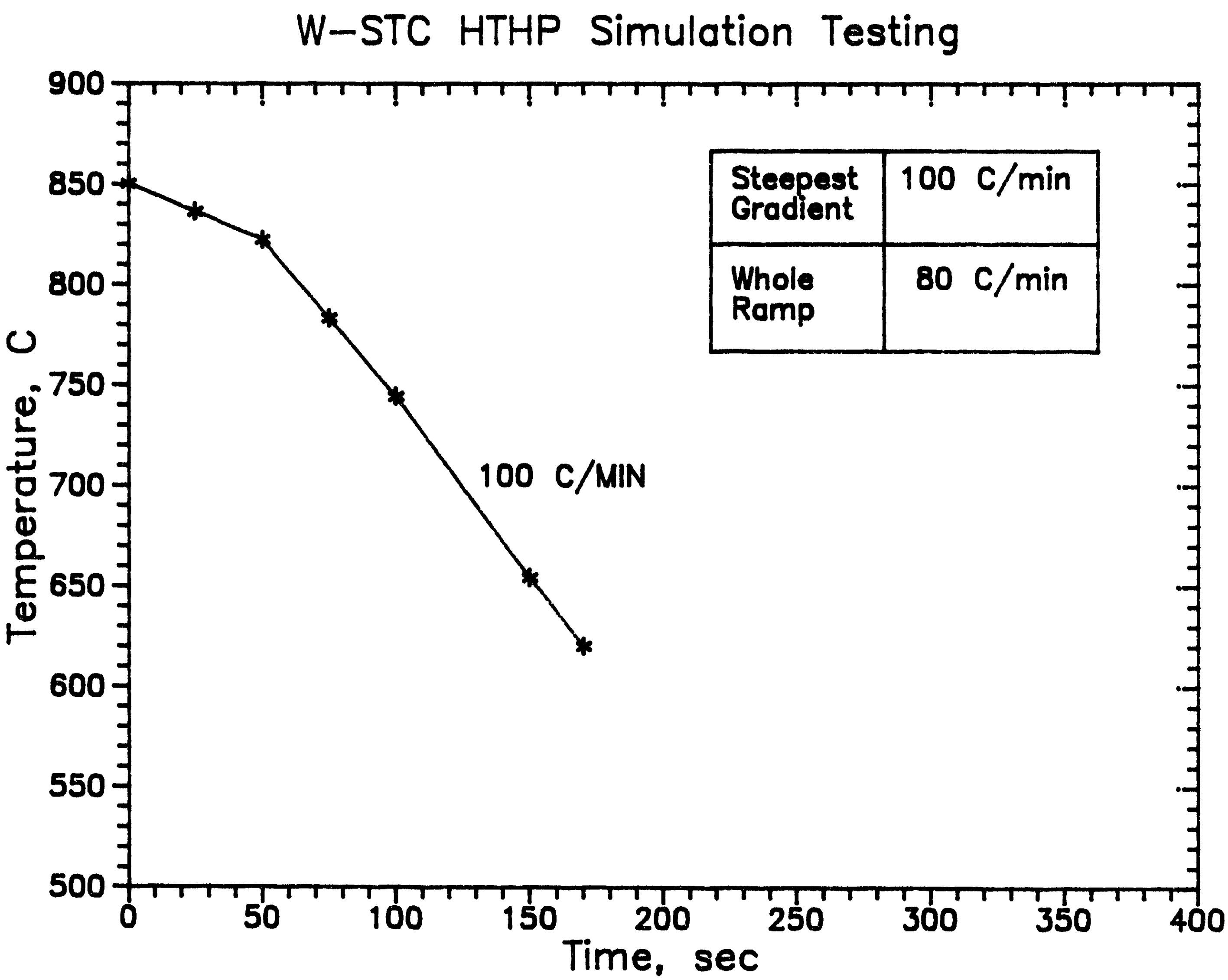


Figure 3.7 - Rapid Cooling Transient Testing PFBC Turbine Trip

Table 3.4 -- Summary of PFBC Simulator Testing Conditions (Nominal) Cross Flow Filter Elements WRTX-76, 77, 78 and (81, 80 and 84) (Including 10 Turbine Trip Transients, 90 Startup Transients, and 1000 Pulses)

	Operating Period, Hours
	0 - 615 (320, 101, and 104)
Test Conditions:	
Gas Temperature, °F	1500 - 1600
System Pressure, psig	75
Inlet Loading, ppm	1000
Ash Type	PFBC Grimethorpe
d_{50}, μ	5
Face Velocity, ft/min	4
Baseline ΔP, in. wg.	1 - 10

The first 300 hours were conducted at steady state to condition the filters and establish baseline performance. Following the steady operation, ten (10) turbine trip transients were conducted followed by a brief period of steady state operation. During this period (at about 320 hours) a small, but discernible, dust leak (about 10 ppm) was observed from outlet dust sampling. Inspection showed that filter WRTX-81 had experienced a small delamination, this filter was replaced with WRTX-80, and testing continued.

Again, about 70 hours (390 hours cumulative) of steady state testing was completed prior to initiating the second set of thermal transient tests. These tests simulated PFBC plant startup. Ninety (90) startup thermal cycles were conducted in groups of ten (10) followed by a period of dust feeding and outlet sampling. The outlet sampling was used as a means of detecting if any failure in the filters occurred during the particular thermal cycle sequence. The startup thermal transient testing covered about 124 hours (524 hours cumulative).

Following the last thermal transient tests a brief steady state test period was conducted. A small dust leak (~14 ppm) was again observed and the testing stopped and filter system inspected. Filter WRTX-80 (which had replaced WRTX-81) showed a delamination and was replaced with WRTX-84.

Thermal transient testing was continued. Accelerated pulse cleaning cycles were conducted under HTHP conditions. One thousand (1000) cycles were completed over a 50 hour period (574 cumulative hours) followed by a short 41 hour steady state test period (615 cumulative hours). Outlet dust loadings were very low suggesting no failed filters.

Testing was halted, however, and the system inspected. All filters appeared in excellent condition. Filter WRTX-84 was replaced with WRTX-21, taken from the gasifier char, recirculating test loop (where it had achieved over 1900 hours of exposure). Testing in the gasifier char loop had been completed.

Filter WRTX-76, WRTX-77, WRTX-78, WRTX-21 (Steady State)

Following thermal transient testing and filter system inspection as described above, the system was reassembled and filter testing continued. Table 3.5 summarizes the normal operating conditions for this test period. A total of 480 additional test hours were achieved operating with a single shift, 12 hour per day schedule. Filter system pressure drop characteristics for this period are given in Appendix G. Typically, the baseline pressure drop ranged around 4 to 5 inch of wg indicative of the low face velocities. Maintaining the 4-element test configuration was chosen over higher face velocity (fewer filters) since all 4 filter elements had significant test history. Filter permeability and outlet dust concentration for this final test segment is shown in Figures 3.8 and 3.9, respectively.

Prior to system shutdown, it was decided to pulse clean only the filters on plenum pipe number 1. This would provide a visible contrast between a "dirty" and "pulse cleaned" cross flow filter after long term exposure to dust, Figures 3.10 and 3.11, respectively. These photographs suggest that during filtration bridging across channels will occur with considerable dust buildup over the filter face. Closure of some channels occurred. The cleaned filter shows substantial removal of the ash and appearance of opened channels. Following disassembly, the filters were inspected and found in excellent conditions.

3.3 GASIFIER CHAR, RECIRCULATING GAS TESTING

In this testing, two (2) cross flow filters (WRTX-20 and WRTX-21) were exposed to 1919 hours of testing that used two different types of reentrained gasifier char in a hot, pressurized inert gas flow. Over the test period, Table 3.1, the filters were pulse cleaned 561

Table 3.5 -- Summary of PFBC Simulator Test Conditions, Cross Flow Filter Elements WRTX-76, 77, 78 and 21

	Operating Period, Hours
	616 - 1096 (1919 - 2400)
Test Conditions:	
Gas Temperature, °F	1500 - 1600
System Pressure, psig	80 - 100
Inlet Loading, ppm	1000
Ash Type	PFBC Grimethorpe
d_{50}, μ	5
Face Velocity, ft/min	2.5 - 2.9
Baseline ΔP, in. wg.	4 - 6

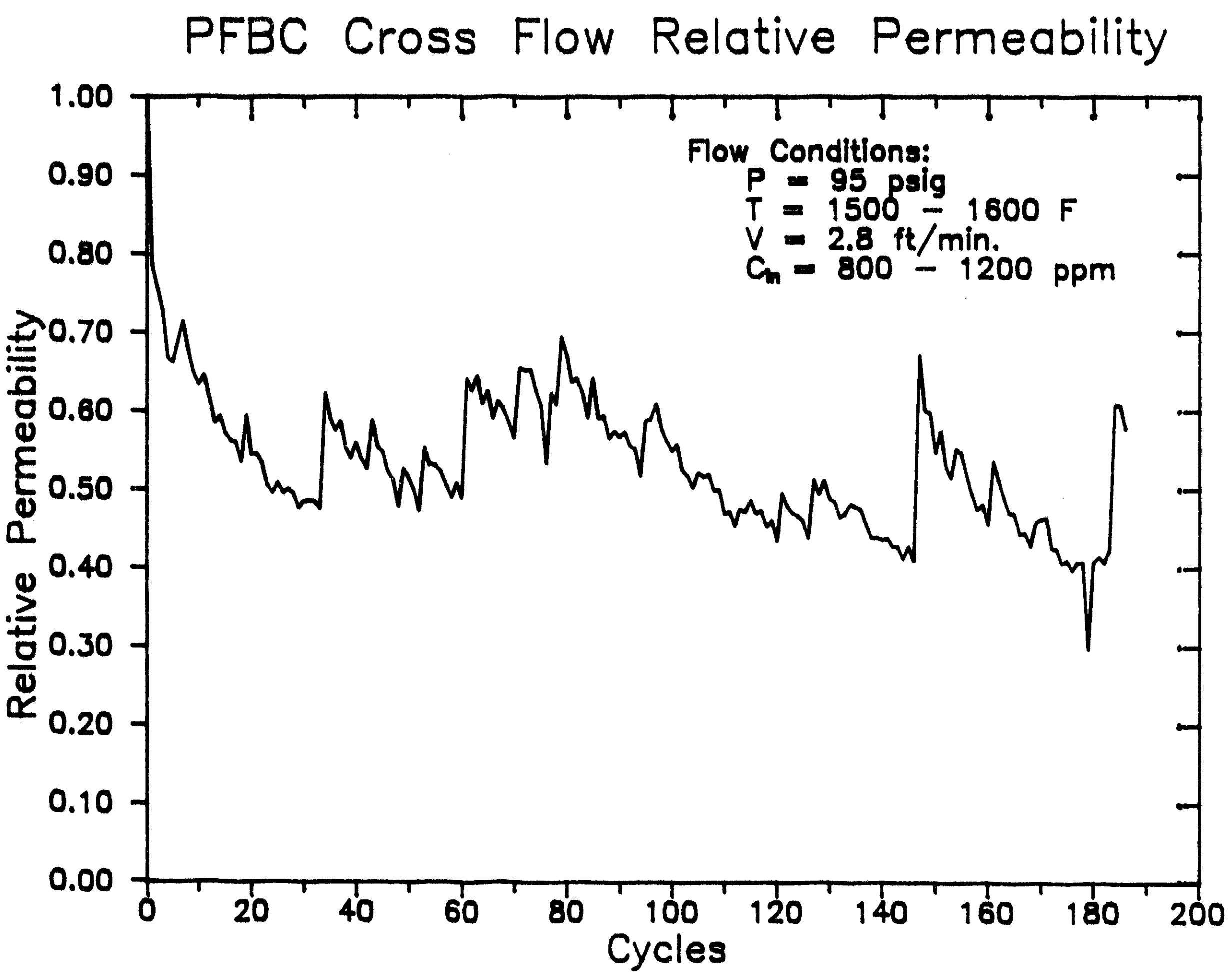


Figure 3.8 - Filter Permeance Trend During Final Steady State Test Segment, WRTX-76, WRTX-77, WRTX-78 and WRTX-21

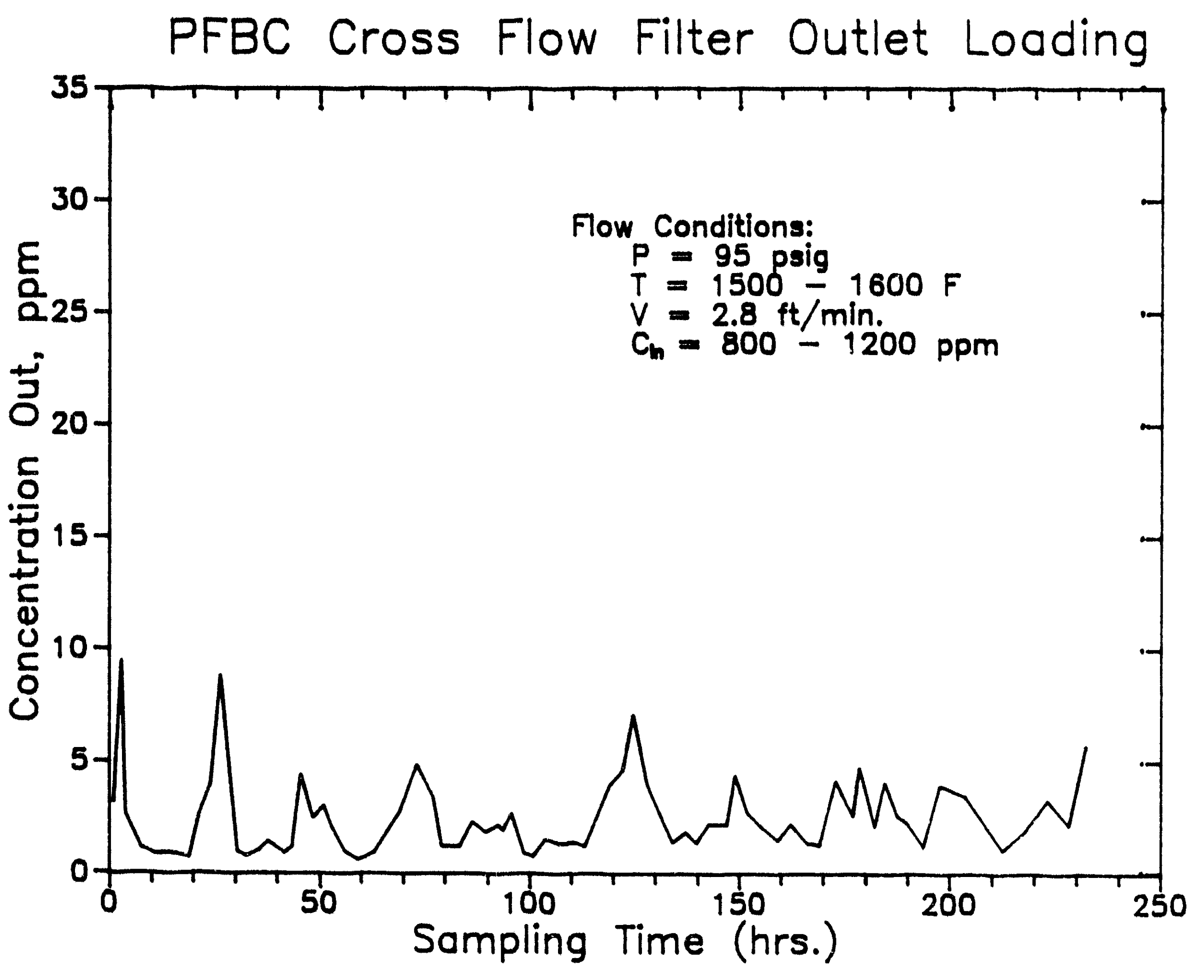


Figure 3.9 - Filter Permeance Trend During Final Steady State Test Segment, WRTX-76, WRTX-77, WRTX-78 and WRTX-21

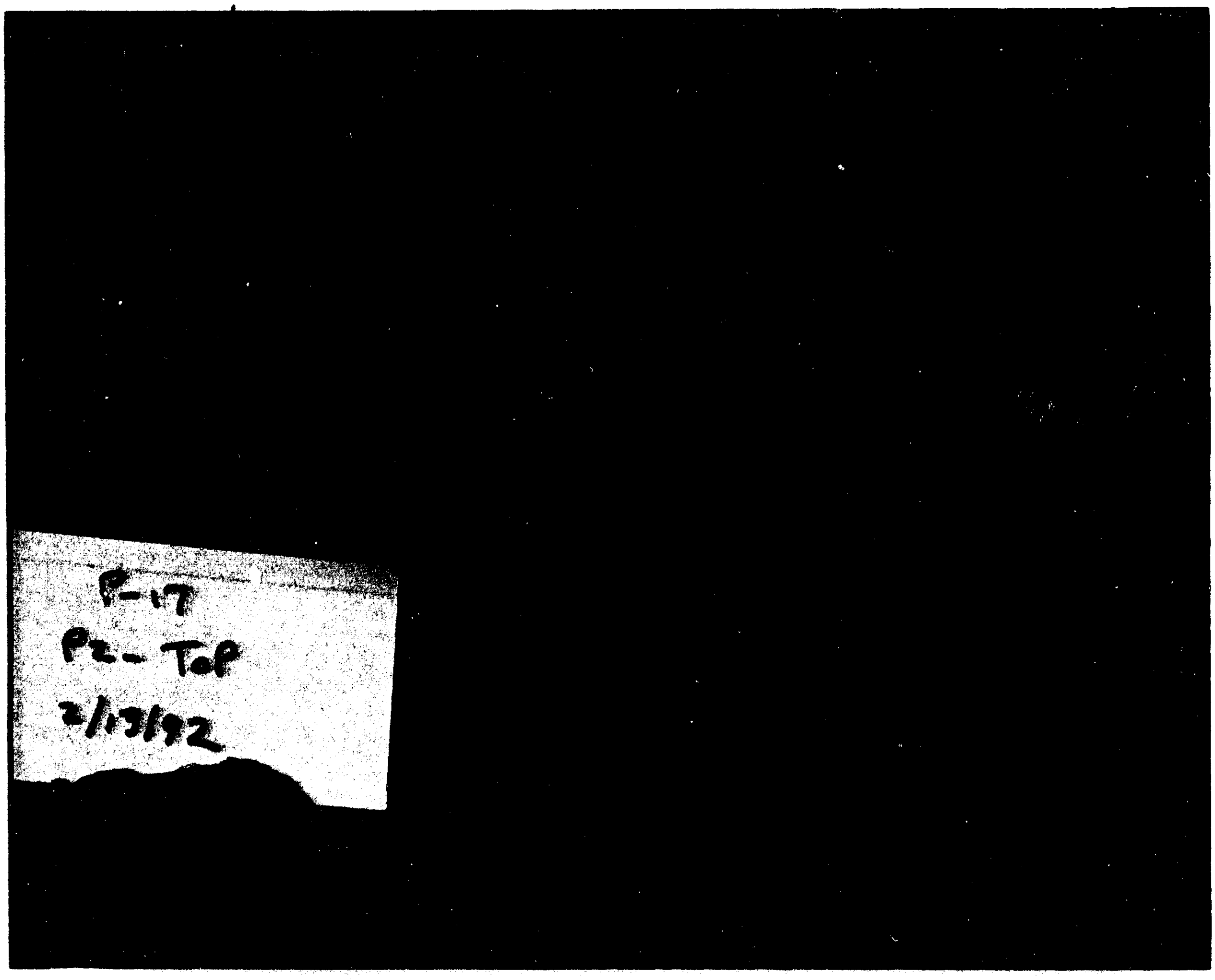


Figure 3.10 - Photograph Showing Condition of Cross Flow Filter Prior to Pulse Cleaning

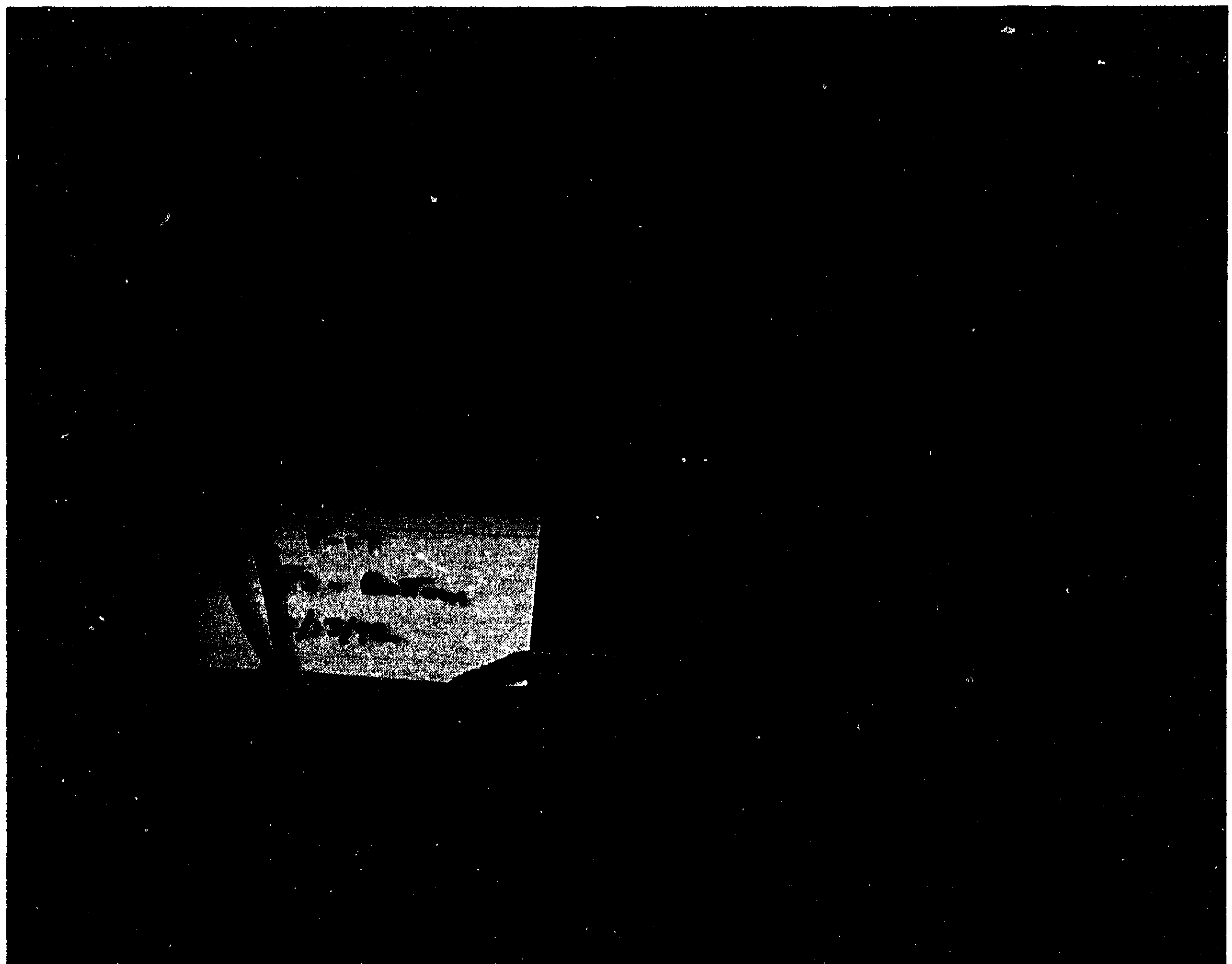
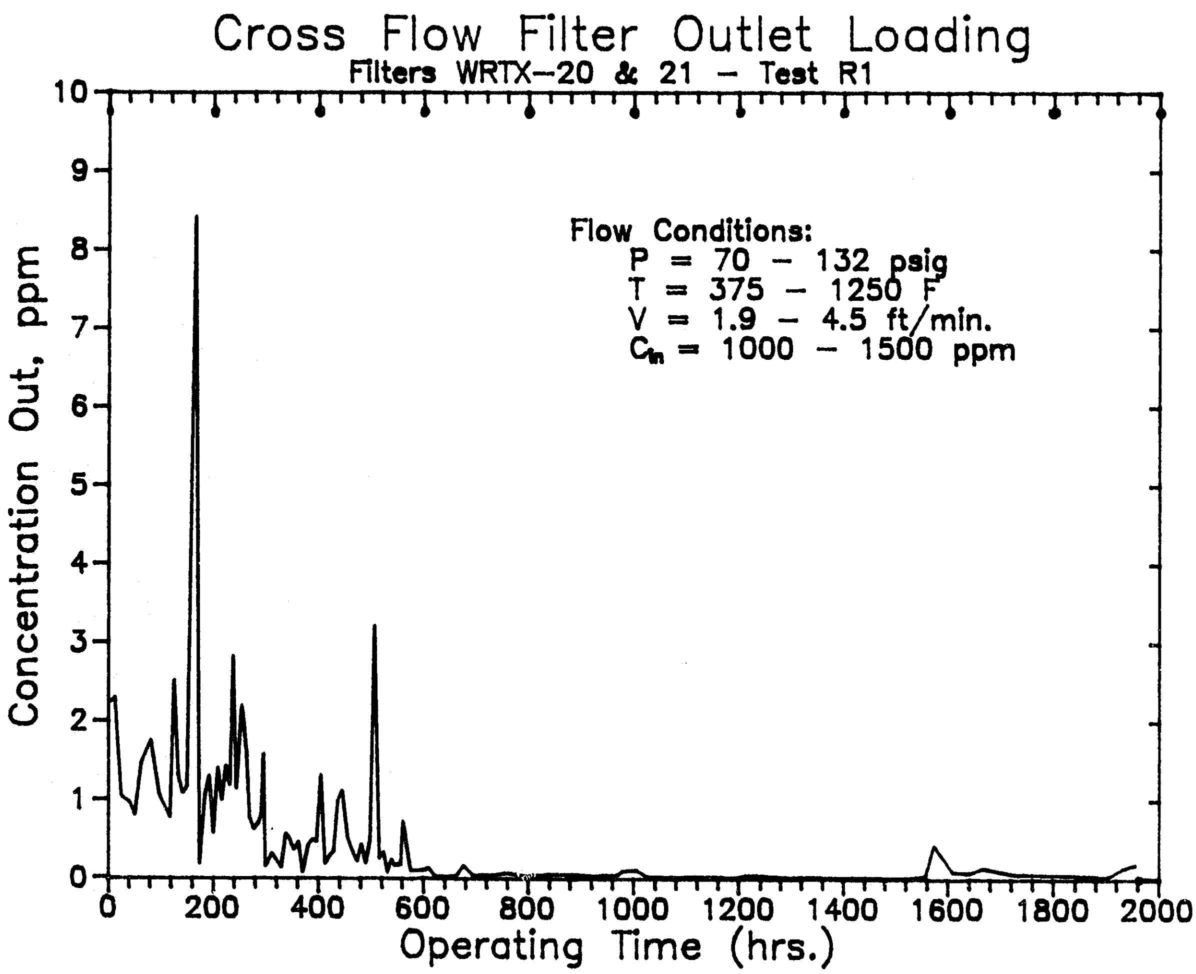


Figure 3.11 - Photograph Showing Cross Flow Filter After Pulse Cleaning



Operation Notes for Test R1
561 Cycles
1919 Hours Flow Exposure time

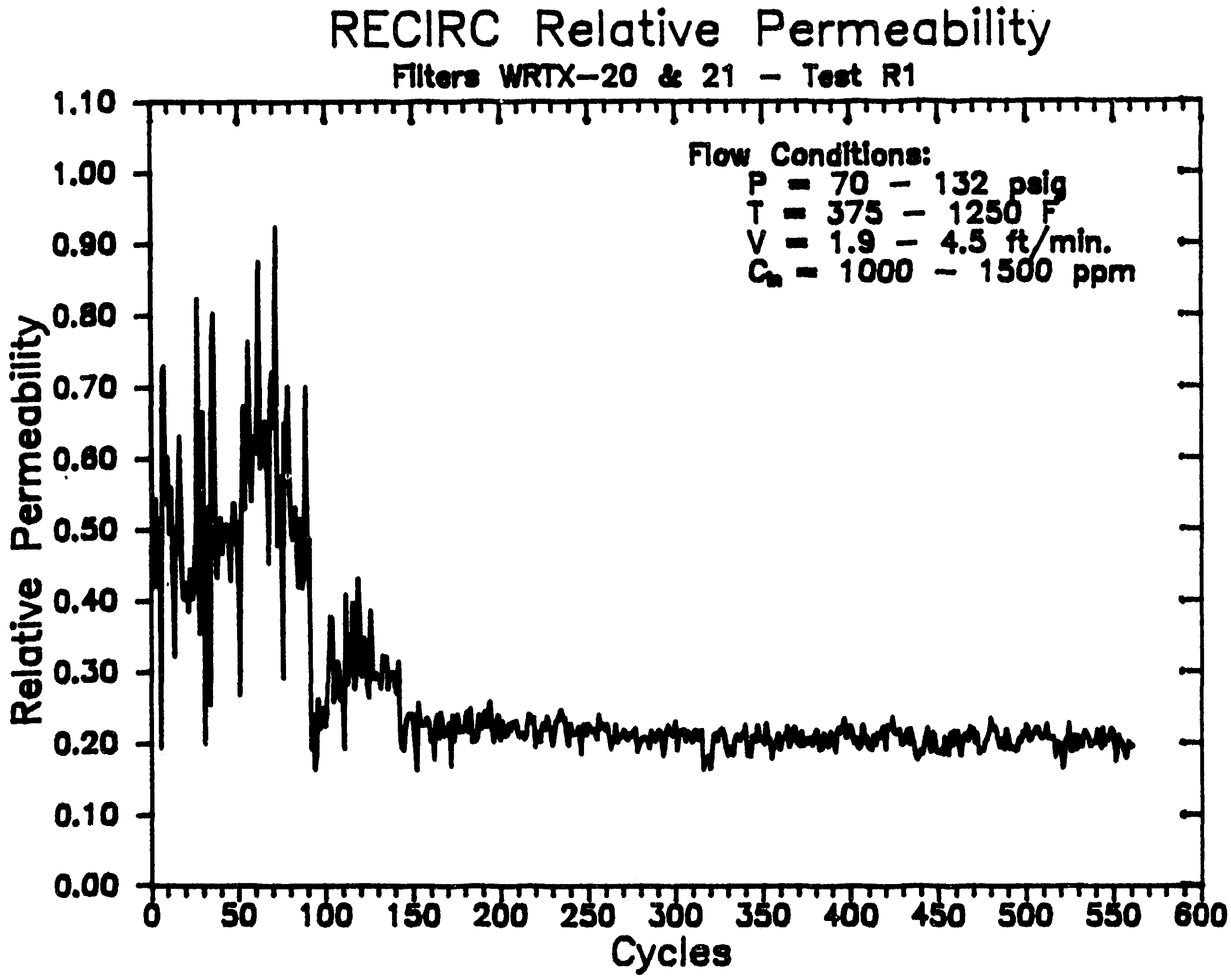
Figure 3.12 - Measured Outlet Dust Loadings During Cross Flow Filter Gasifier Simulator Testing - Filters WRTX-20 and WRTX-21

times, and experienced 73 startup/shutdown cycles. Testing was conducted over range of operating conditions (see Table 3.6). Filter face velocity was maintained at relatively low values corresponding to gasifier field test programs. Throughout the test program, filter performance was excellent with outlet dust loading averaging below 1 ppm. Figure 3.12 shows the measured outlet dust loading as recorded from isokinetic grab samples taken over the test period. In general, baseline filter pressure drop was low, ranging from 2 to 5 in wg, varying with face velocity and depending on operating temperature. Pressure drop traces from selected portions of the test program are given in Appendix H. Stable filter permeance appeared to be achieved after about 150 cleaning cycles, Figure 3.13.

Following test segment 6, the filter system was disassembled and inspected. Figure 3.14 shows a photograph of one pulse cleaned filter as it appeared on disassembly. Both filters were found to be in excellent condition. Filter WRTX-21 was placed into the PFBC simulator rig and was exposed to an additional 600 hours of testing under combustion conditions at 1550°F (nominal).

Table 3.6 - Summary of Cross Flow Filter Test Condition Exposed to Gasifier Char (WRTX-20 and WRTX-21)

	Operating Period, Hours				
Test Conditions:	(1) 0 - 458	(2) 459 - 766 and (3) 903 - 1311	(4) 767 - 902	(5) 1312 - 1493	(6) 1494 - 1919
Gas Temperature, °F	850 - 1200	334	334	334	334
System Pressure, psig	70	132	132	132	70
Inlet Loading, ppm	1000	1500	1500	1500	1500
Ash Type, Gasifier Char	Texaco	Texaco	KRW	Texaco	Texaco
d_{50}, μ	5.4	5.3	4	5.3	5.3
Face Velocity, ft/min	3	1.9	1.9	3.3	4.5
Baseline ΔP, in w.g.	1 - 2	1.1	1.1	2-3	3-4



Operation Notes for Test R1
561 Cycles
1919 Hours Flow Exposure time

Figure 3.13 - Measured Cross Flow Filter Permeance in Simulated Gasifier Testing - WRTX-20 and WRTX-21

Figure 3.14 - Photograph Showing General Appearance of Pulse Cleaned Cross Flow Filter After About 1900 Hours of Testing with Gasifier Char

4. DISCUSSION OF RESULTS

The purpose of this section is to report the evaluation of the cross flow filter long term durability simulator testing data, compare this filter data to actual plant filter data, and assess results on cross flow filter development.

4.1 COMPARISON OF PFBC SIMULATOR AND PLANT FILTER TESTING

Table 4.1 compares the pertinent operating parameters of PFBC (nominal) with the PFBC simulator facility used in this test program. Although the Westinghouse simulator facility is methane fired, the major gas phase constituents (CO_2, H_2O) are reasonably similar. Operating at the same system temperature and pressure in the simulator facility (with reentrained PFBC ash) reproduces the relevant filtration properties of gas to particle density ratio and gas viscosity.

Equation 4.1 shows that if the filter unit in the simulator facility is operated at the same face velocity, V, and solids loading, C, the filter pressure drop characteristics should be reproduced if filter and cake permeance, K_f, K_c are reproduced.

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

where

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

Table 4.1 - Comparison of PFBC and Simulator Operating Conditions

	Actual PFBC	Simulator
Pressure, psia	164	80-164
Temperature, °F	1550	1550
Gas Composition (Mole %)		
CO_2	13.5	17
H_2O	10.4	14
SO_2	233 ppm	-
O_2	3.7	6
N_2	72.3	73
Alkali	<2 ppm	(1)
Molecular Wt.	29.3	~29
Gas/Solid Properties		
Gas Viscosity (lbm/ft-sec)	3.1×10^{-5}	3.1×10^{-5}
Solids Bulk Density (lb/ft^3)	40-60	40-60
Solids/Gas Density Ratio	250	250
Mass Mean Particle Size	~2 μ	(2)

(1) Alkali condensed on ash particles may be released during reentrainment.

(2) Agglomerated fines may not be redispersed during reentrainment.

Filter permeance, K_f, establishes the filter baseline pressure drop after cleaning. Fine particulate entrained in the gas may reach the filter surface and become trapped in the pore structure of the filter resulting in a decrease in K_f with time.

Figure 4.1 compares the relative permeance (K_f/K_c) of both candle and cross flow barrier filters in PFBC simulator data with actual PFBC tested filters. By comparing the relative permeance of the filters over time (or number of cleaning cycles), the effect of initial filter permeability is normalized. Figure 4.1 shows that barrier filters operated in the PFBC simulator facility show permeance trends similar to actual PFBC tested filters. Thus, on this basis, the baseline pressure drop characteristics experienced in long term durability simulator testing of the cross flow filter should be representative of actual plant data.

Reproducing the particle size distribution using redispersed ash is highly problematic in simulator facilities. It is generally accepted that the fraction of very fine reentrained ash will not be dispersed in simulator facilities. This is qualitatively substantiated by comparing the cascade impactor sampling conducted during the PFBC plant tests at the New York University facility during cross flow filter testing[(1)] with coulter counter data of the PFBC ash feed used in the simulator testing, Table 4.2. Assuming the coulter counter data represents what can be achieved in dispersing ash in the simulator facility, this data suggests particles smaller than 1μ are not present as discreet fines in simulator testing. Some loss in the 2μ particle range may also occur.

Scanning electron micrographs (SEM) taken from filter samples operated in the PFBC simulator facilities, given in Appendix I, show particle morphology characteristics and provide evidence of particle penetration into the pore structure at the surface of the cross flow filter. Particle fines are found only in the first few pore layers of the filter. Penetration of fines into the interior of

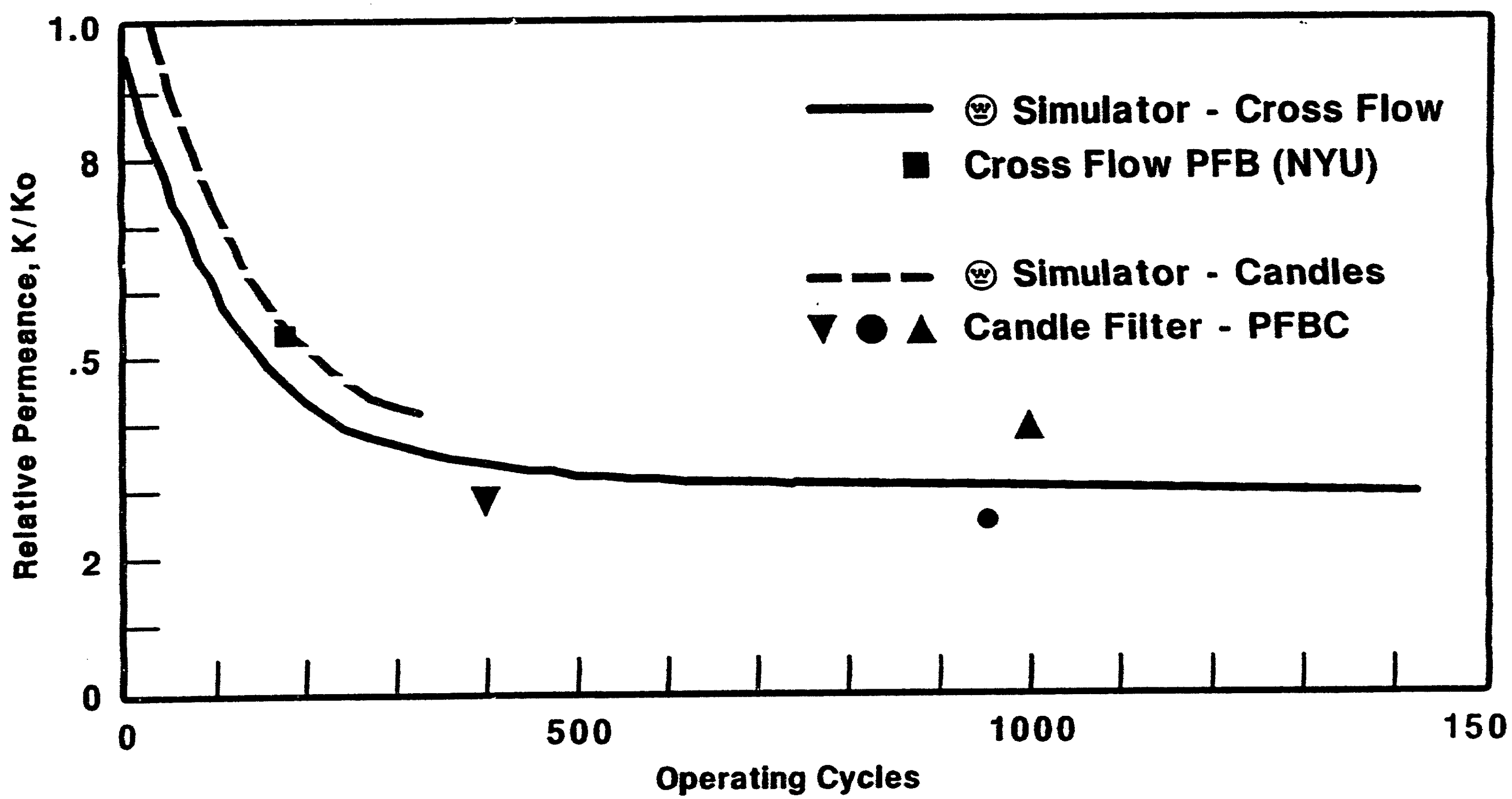


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Figure 4.1 - Comparison of Westinghouse Simulator PFBC and Plant Experience

Table 4.2 - Comparison of Coulter Counter and Cascade Impactor Data From Simulator and Plant Tests

Fraction Less Than	Coulter Counter Data - PFBC Ash Samples	Cascade Impactor Data (1) at Filter Inlet
1 μ	0	2%
2 μ	7 to 12%	7 to 20%

the filter matrix is negligible. Typically fines that are retained within the filter matrix are seen principally to adhere to the amorphous (glass) phase. Similar particle behavior has been experienced in field tested cross flow filters.

The cross flow filter is characterized by an average pore structure that may range from 40 to 60 microns. Thus, in the simulator testing the fine particle fraction ($<2\mu$) that are not redispersed are likely carried to the filter surface and into the surface pore structure on the surface of the larger 10 to 20 μ particles. This behavior is thought to reproduce the "surface blinding" that accounts for the very similar behavior in filter permeance experienced in actual plant and simulator testing. The presence of fines, as seen in the SEM's, do not present any substantial pore blockage, even in the filters exposed for 1300 hours of operation.

Ash cake permeance, K_c, establishes filter cake pressure drop properties and may be important in establishing requirements for filter cleaning. Factors that are thought to effect cake permeance include particle size distribution, porosity, compressibility, presence of alkali and particle chemistry. These parameters obviously depend on coal type, sorbent and actual process conditions. Differentiating Equation 4.1 with respect to time, θ, and solving for K_c gives the following expression that is dependent on known or experimentally measured parameters,

$$K_c = \frac{CV^2\mu}{\rho_c(\Delta p/\Delta\theta)} \quad (4\text{-}2)$$

where $\Delta p/\Delta\theta$ is the slope of the pressure drop (saw-tooth) curve generated during filter testing. Table 4.3 compares values of K_c determined from various filter testing, including the long term durability program. The data include simulation testing using reentrained ash from PFBC and data from pilot scale PFBC operations. These results appear to show a correlation with particle size, i.e.,

Table 4.3 - Comparison of Ash Cake Permeability for Different Ashes and Test Conditions

Test System	Dust Type	Average Particle Diameter d_{50}	Cake Permeability ft^2 (10^{-12})
W HTHP long term durability rig - cross flow filter	• Reentrained PFBC ash 2nd stage catch-ground	6.5 μ	2.1 to 4.0
	• Grimethorpe filter catch	5.0 μ	.7 to 1.9
W HTHP facility, candles (Ref. 1)	• Reentrained PFBC ash 2nd stage catch-ground	5.5 μ	4.8 to 10.7
W HTHP facility candles (Ref. 1)	• Reentrained PFBC Ash 2nd stage catch	25 μ	43
METC Atm fluid bed - candle (Ref. 2)	• Coal combustor, with cyclone	6.8	1.5
		11.4	6.7
		8.2	1.2
		4.2	0.33
New York University PFBC cross flow	• Coal combustor, with primary cyclone	3.5 to 5 μ	1.6

increased permeability with larger mass mean size. The actual plant data also compares well with the K_c values indicative of the reentrained (simulator) ash cases. The favorable comparison between the K_c values measured in actual and simulator testing may again be the result of the non-dispersed fines fraction remaining as agglomerates to larger particles, but depositing on the filter surface in a manner that is representative of the original cake structure.

The relationship of filter cleanability to cake permeance (flow resistance) has also been demonstrated in simulator testing. Table 4.4 compares qualitative results of cleaning tests using different PFBC ash materials. These ashes were obtained from different operating facilities that utilized different coal and sorbent types. With increasing cake flow resistance (decreasing permeance) cleaning pulse intensity had to be increased to achieve filter cleaning.

The effect of cake permeance on cleaning can also be demonstrated by comparing filter pressure drop traces taken from the long term durability test program where different PFBC ashes were used, Figures 4.2 and 4.3. F [illegible] 4.2 shows a test sequence using a "high" permeance ash (ash samp [illegible] where very repeatable and stable filter pressure drop characteristics are experienced (good cleaning). Changing to the "low" permeance ash (ash sample 4) and initiating filter cleaning operation at the same pulse conditions gave dramatically unstable pressure conditions, Figure 4.3. The poor cleaning with the number 4 PFBC ash sample was also experienced at the Grimethorpe PFBC hot gas filter test facility.

4.2 COMPARISON BETWEEN SIMULATOR AND GASIFICATION PLANT EXPERIENCE

Figure 4.4 shows a comparison of the gasifier simulator filter testing with plant experience. The cross flow filter relative permeance (K_f/K_{f_0}) is shown as a function of filter cleaning cycles. The

Table 4.4 - Comparison of PFBC Ash Properties and Filter Cleaning

PFBC Ash Sample	Cake Bulk Density* gm/cc	Flow Resistance (Relative)	Mass Mean Particle Size* (μm)	Cleaning Pulse Intensity Required (Relative)
1	0.4	1	7.8	Lowest
2	0.6	1.8	5.3	Medium
3	0.3	2.7	3.5	High
4	0.2	6.8	4.0	Highest

*Cake Sample

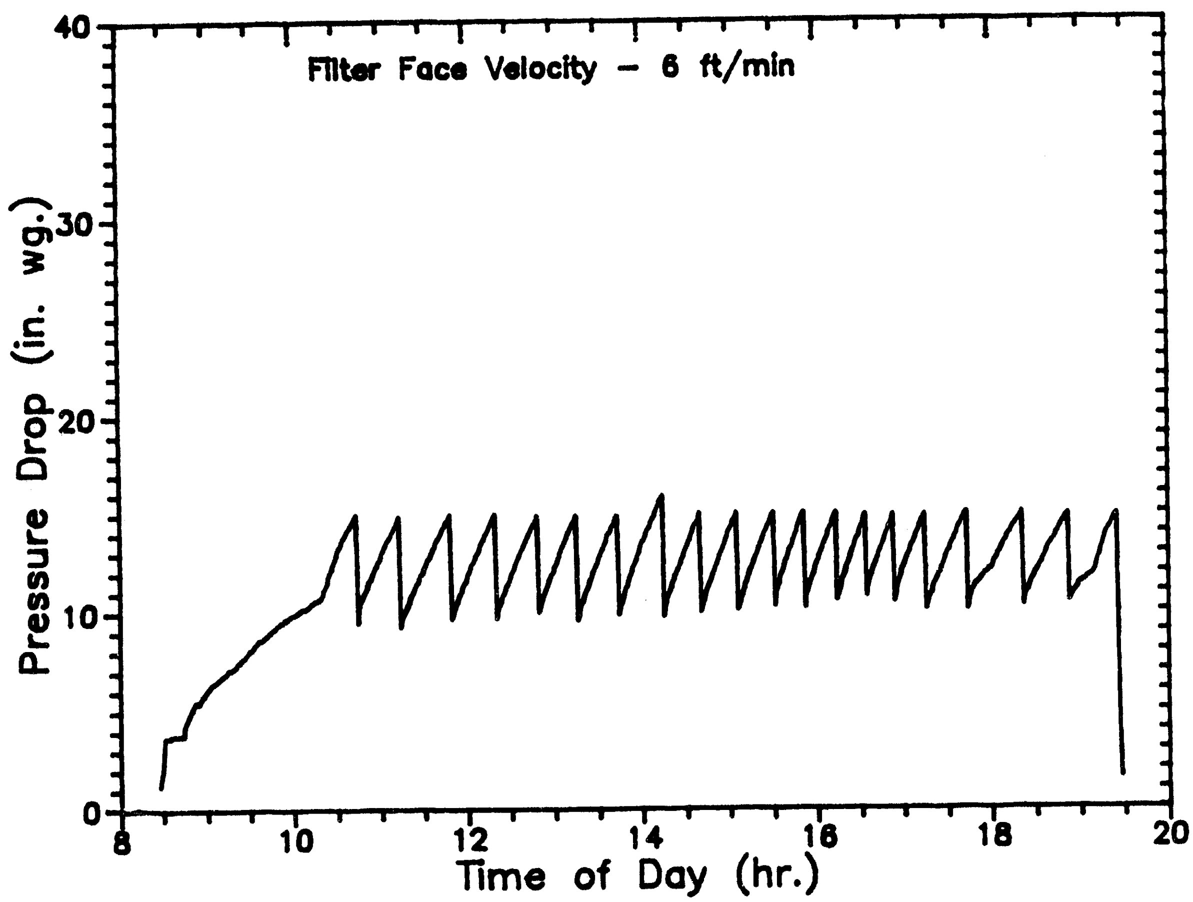

Figure 4.2 - Cross Flow Filter Pressure Drop Characteristics Using "High" Cake Permeance PFBC Ash

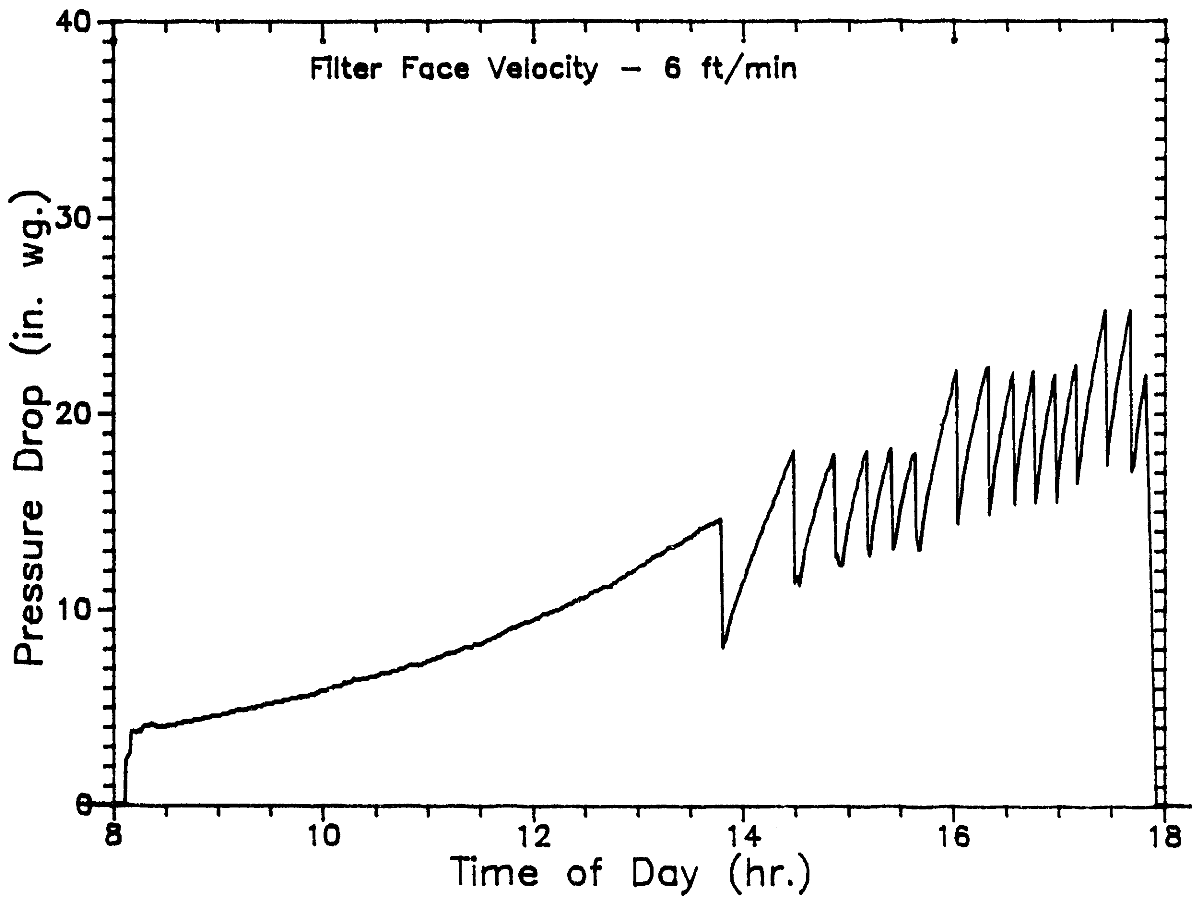

Figure 4.3 - Cross Flow Filter Pressure Drop Characteristics Using "Low" Cake Permeance PFBC Ash (Grimethorpe Red)

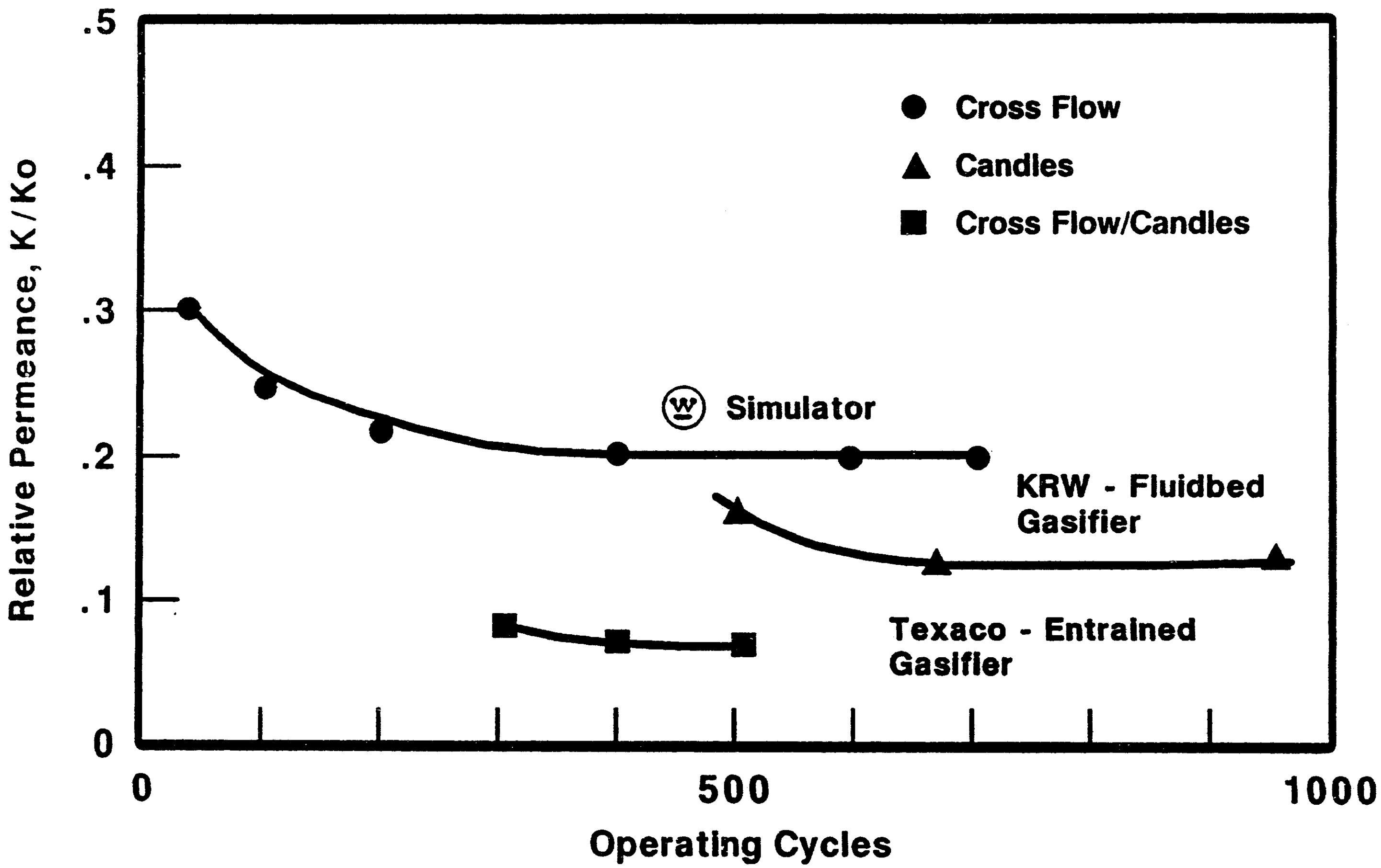

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Figure 4.4 - Comparison of W Gasifier Simulator and Plant Experience

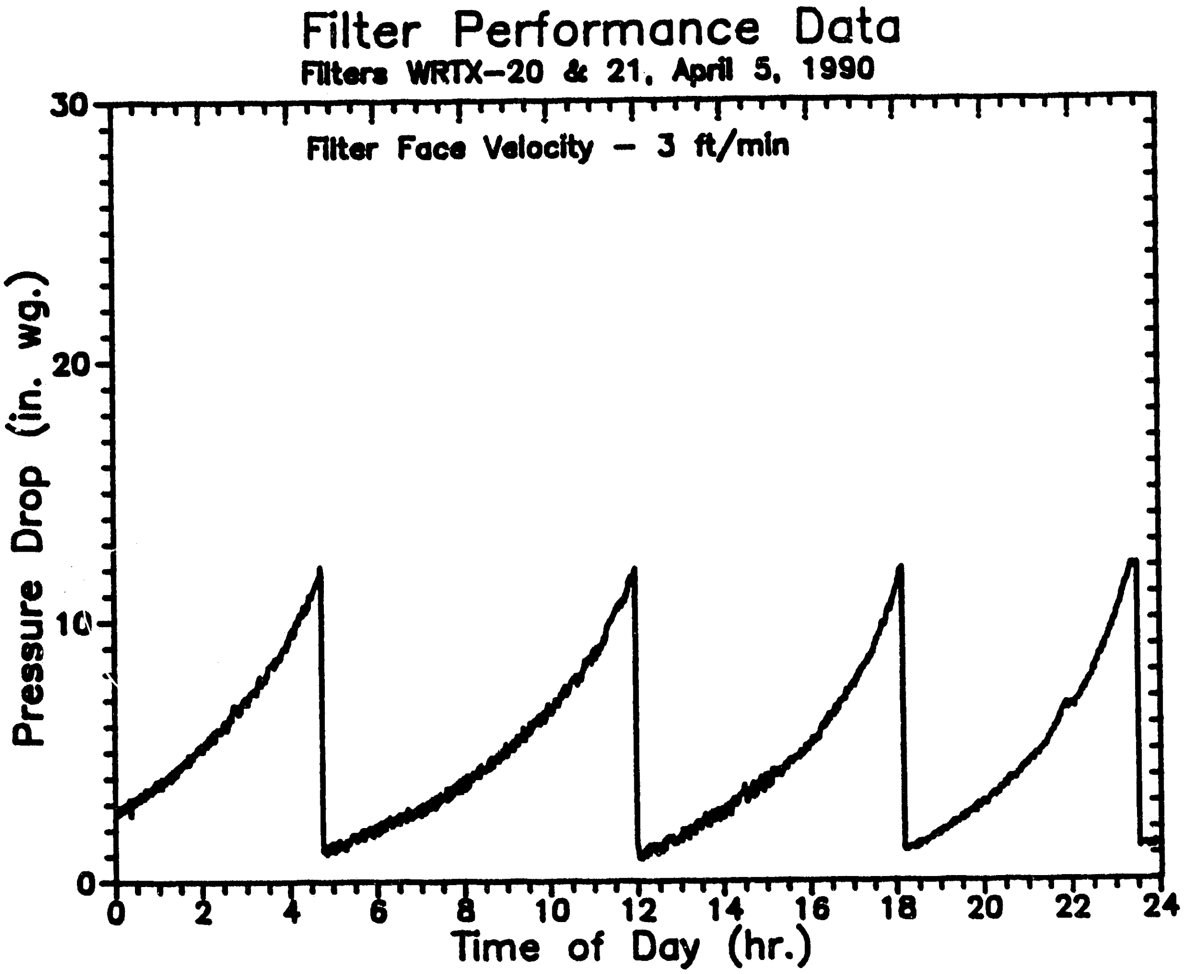
simulator data is compared with cross flow and candle filter data from previous gasifier pilot plant test programs. Plant data is shown for the KRW fluid bed gasification PDU that utilized the silicon carbide candle filters[2] and for the Texaco entrained gasifier pilot plant that has now utilized both cross flow and candles.[3]

As with the PFBC filter data, filter permeance decreases with operation. However, in the gasification case, the simulator and plant data show similar trends but do not correspond as well as the PFBC data. Significant differences in filter permeance is also evident between the two different gasifier types. This difference is likely indicative of the significant difference in the two gasification processes and resulting generation of ash and char.

The KRW char is generated in a sulfur sorbent containing fluid bed that operates at relatively low temperatures (1600°F, 870°C). Thus the fuel gas contains both char, ash and attrited sorbent particles.

The entrained gasification pilot plant 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, see Appendix I. Particle morphology, size distribution and fraction of fines present in the fuel gas are therefore significantly different in the two cases. These differences may substantially influence the filter surface conditions.

Additional factors in gasification systems may influence filter operating conditions. Both the fluid bed and entrained gasifier ashes are very noncohesive, contain a bimodal size distribution with a substantial weight fraction of particulate in the less than 2.3 μm range and exhibit very low cake bulk density.[3] These ash cake characteristics suggest high reentrainment potential in the pilot plant testing. Possible reentrainment effects in the gasifier simulator testing was



Operation Notes for April 5, 1990

2153 Changed Process Gas make-up to N_2

ΔP Trigger = 12" wc

Pulse Cleaning - 200 psig/0.1 sec

Figure 4.5 - Cross Flow Filter Pressure Drop Characteristics from Gasifier Simulator Test Series 1

investigated. Test Series 1 (Table 3.6) was operated at relatively high temperature and low pressure corresponding to relatively low gas density. Typical filter pressure drop characteristics from this test segment are shown in Figure 4.5.

In Test Series 2 (and subsequent gasifier simulator testing) it was decided to operate at low temperature and higher system pressure to increase gas density (comparable to entrained gasification), and therefore, provide a better simulation of potential particle reentrainment effects. In addition, operating conditions (inlet loading, face velocity and trigger Δp) in Test Series 2 were adjusted (see Table 3.6). The intent of changing the operating conditions was to approximate the cleaning frequency experienced in Test Series 1, assuming no significant char reentrainment effects, i.e.,

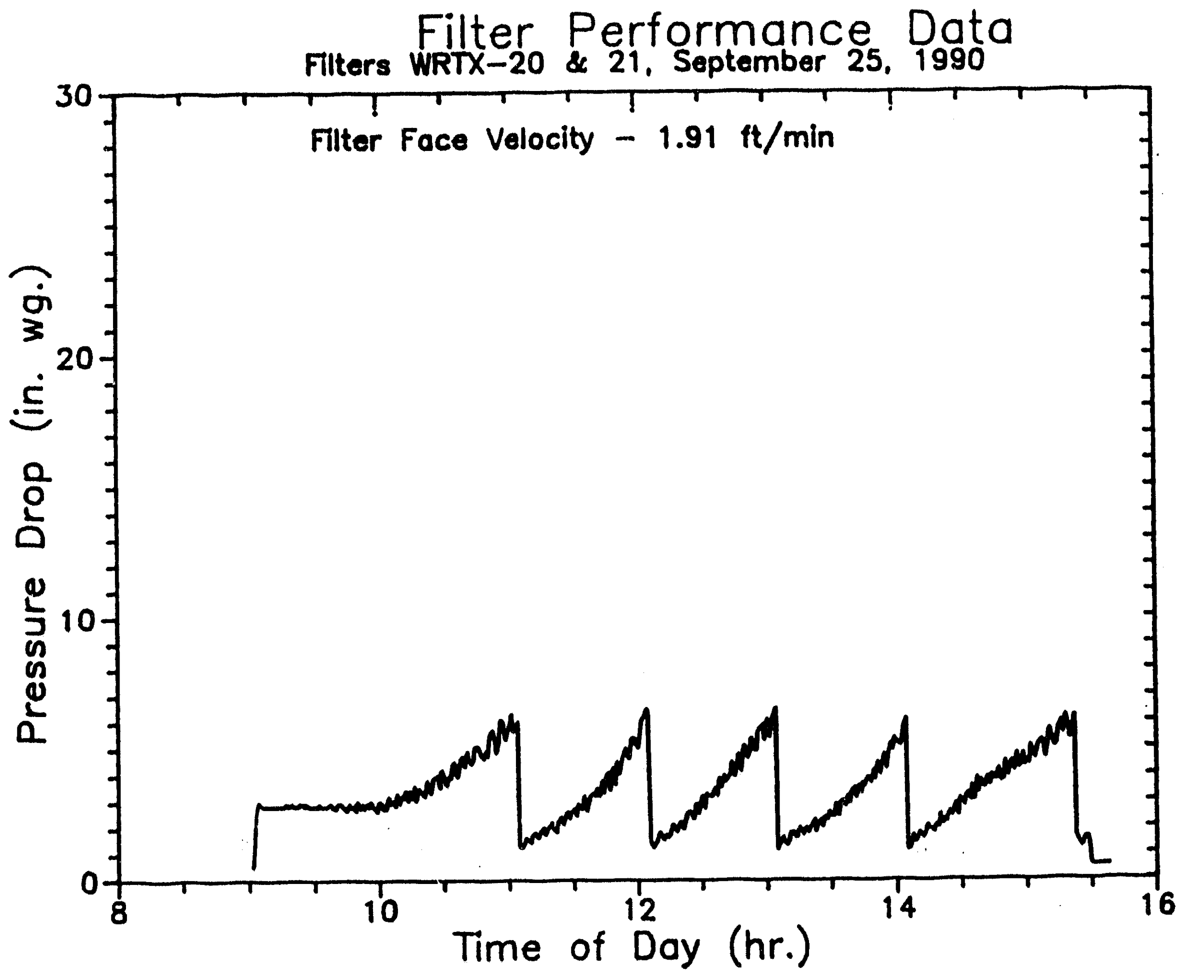
Cleaning frequency (2) = Cleaning frequency (1) if:

$$\frac{\Delta p_1}{\Delta p_2} = \frac{C_2}{C_1} \times \left(\frac{V_2}{V_1} \right)^2 = 1$$

Substituting actual test conditions, Table 3.6, would predict that the Test Series 2 cleaning should be approximately:

$$\theta_2 = \frac{6}{12} \times \frac{1000}{1500} \times \left(\frac{3}{1.9} \right)^2 \times 7 = 6.3 \text{ hours}$$

Figure 4.6 shows a segment of the pressure drop trace for the Test Series 2 sequence. As apparent, cleaning frequency ranged around 1 hour or approximately 6 times more frequent than would be anticipated based on the Series 1 testing. This comparison strongly suggests potential reentrainment effects have been promoted in the simulator facility by increasing gas density.



Operation Notes for September 24, 1990:

8 hour test

ΔP Trigger = 6" wc

Pulse Cleaning - 300 psig/0.1 sec

Figure 4.6 - Cross Flow Filter Pressure Drop Characteristics from Gasifier Simulator Test Series 2

Comparison of this simulator testing with field data suggests that the filter operating characteristics in the actual gasifier environment are significantly underestimated from the simulator testing.[3] Reentrainment effects in the simulator testing may be mitigated because the fine fraction may not be effectively redispersed, but remain attached to the larger particle fraction. PFBC ashes appear to be very cohesive with low reentrainment potential.

A second major difference between gasifier and PFBC ash characteristics is filter cake permeability (or flow resistance). Data taken from plant tests suggest that the gasifier char may be 4 to 7 times more resistive than PFBC ash that exhibit similar mass mean particle diameter. Similar data has also been reported by others.[4] Simulator cake permeance data, Table 4.5 , also show higher flow resistances (lower cake permeability) for the gasifier char over PFBC cakes exhibiting similar mass mean particle size.

The above data and analysis suggest that the operating and performance characteristics of barrier filter devices for PFBC application can be reasonably predicted based on simulator testing. Gasifier simulator testing showed similar trends experienced in plant testing but did not effectively reproduce the reentrainment conditions that are thought to be significant in pilot plant facilities. Gasifier gas composition was not reproduced in the simulator facility which may also be a contributing factor. Both the PFBC and gasifier simulator facilities utilize full scale filter components and operate at temperature and pressure conditions that expose the filter to thermal, hydrothermal and mechanical stressing of actual plant conditions. Thus, the major materials durability factors are reproduced. Cross flow filters examined after simulator and plant testing have also shown very similar changes in materials morphology. These and other aspects of the cross flow filter long term durability testing are discussed below.

Table 4.5 - Comparison of Filter Cake Permeance in Gasifier and PFBC Simulator Testing

Test System	Dust Type	Average Particle Diameter	Cake Permeability ft^2 (10^{-12})
• Long Term Durability PFBC Simulator, Cross Flow Filter	PFBC - Exxon Ash	6.5 μ	2.1 to 4.0
• Long Term Durability Gasification Simulator, Cross Flow Filter	Char from Entrained Gasifier	5.3 μ	0.9 - 1.2

4.3 CROSS FLOW FILTER PERFORMANCE POTENTIAL

Table 4.6 shows a summary of cross flow filter performance from both PFBC and gasification simulator testing. Only the longest two segments of PFBC testing are included. The data show the range of filter face velocities and baseline pressure drop over which the filter test units were operated. As described in Section 3, nearly continuous isokinetic particle sampling was conducted on the outlet side of the filters in both the gasification and PFBC simulator testing. As given in Table 4.6, these data when averaged over the respective test periods show the average outlet particle loading to be less than 1 ppm, demonstrating the high performance potential of the cross flow filter. These results are also pictorially illustrated in Figure 4.7 which compares a photograph of one outlet sample (right) with a sample representing the filter inlet concentration (1000 ppm).

The high performance potential of the cross flow filter is significant because of the stringent requirement for gas cleanup in advanced fossil power generation cycles. In these applications, hot gas filter particle removal requirements include meeting emission limits (New Source Performance Standards, NSPS) and protecting the gas turbine from particle erosion and deposition. Figure 4.8 illustrates these requirements for PFBC and compares cross flow filter performance data from recent pilot plant and the current PFBC simulator testing.[1] The cross flow filter pilot plant data includes cascade impactor sampling that provides estimates of the outlet particle size distribution. The simulator data is total outlet mass and therefore is represented as a single data point.

NSPS, shown as a horizontal solid line in Figure 4.8, when expressed as a mass loading depends on coal type and PFBC cycle efficiency but in general will range between 20 to 30 ppm. Both the pilot plant and simulator data show outlet measurements that fall well below NSPS emission requirements. It should also be noted that even

Table 4.6 - Summary of Cross Flow Filter Performance in Long Term Durability Simulator Testing

	PFBC Ash Test Loop		Gasifier Char Test Loop
	Test Module #1	Test Module #2	Test Module #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

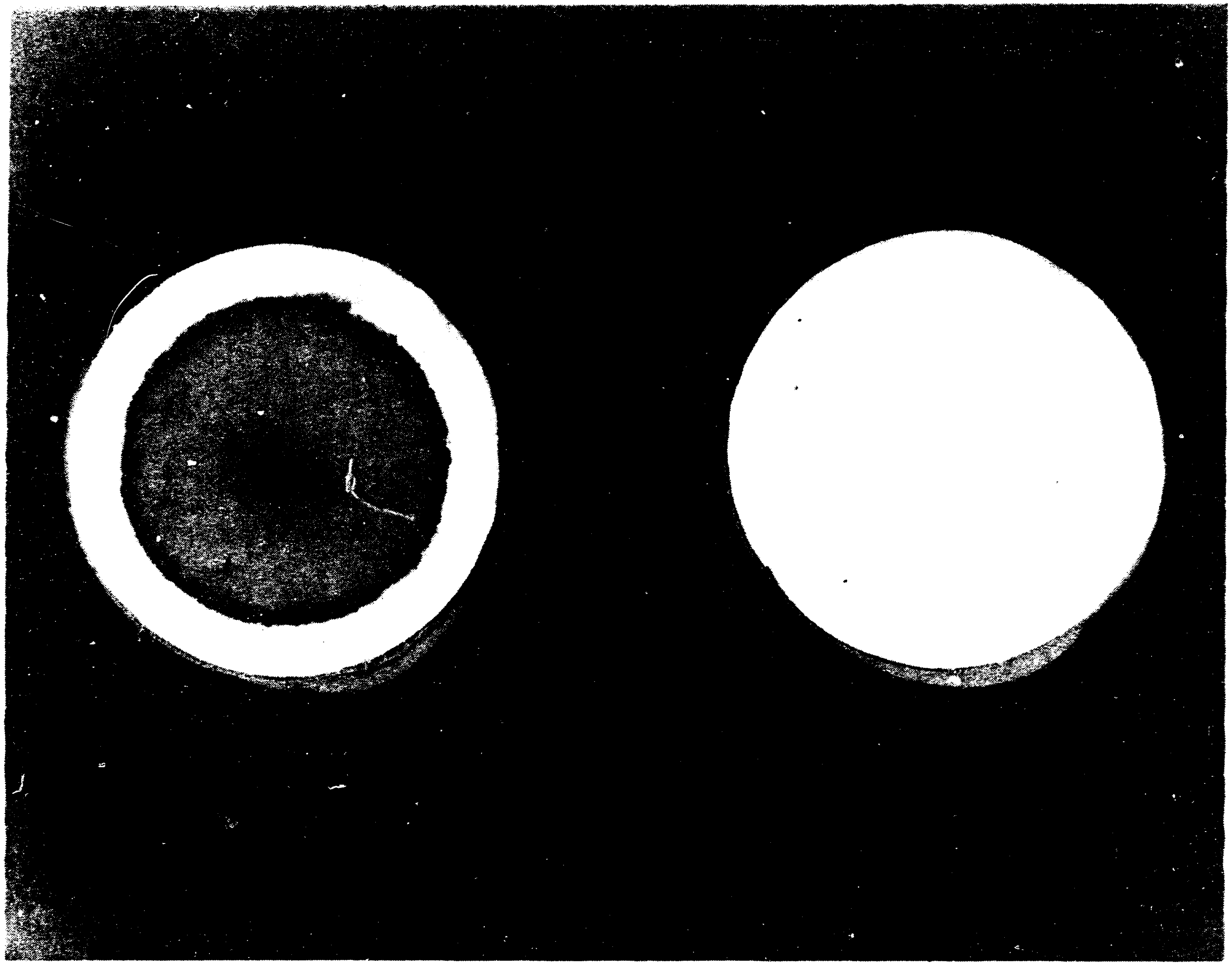


Figure 4.7 - Photograph Comparing Outlet Loading Sample Taken from PFBC Simulator Testing with 1000 ppm Inlet Loading

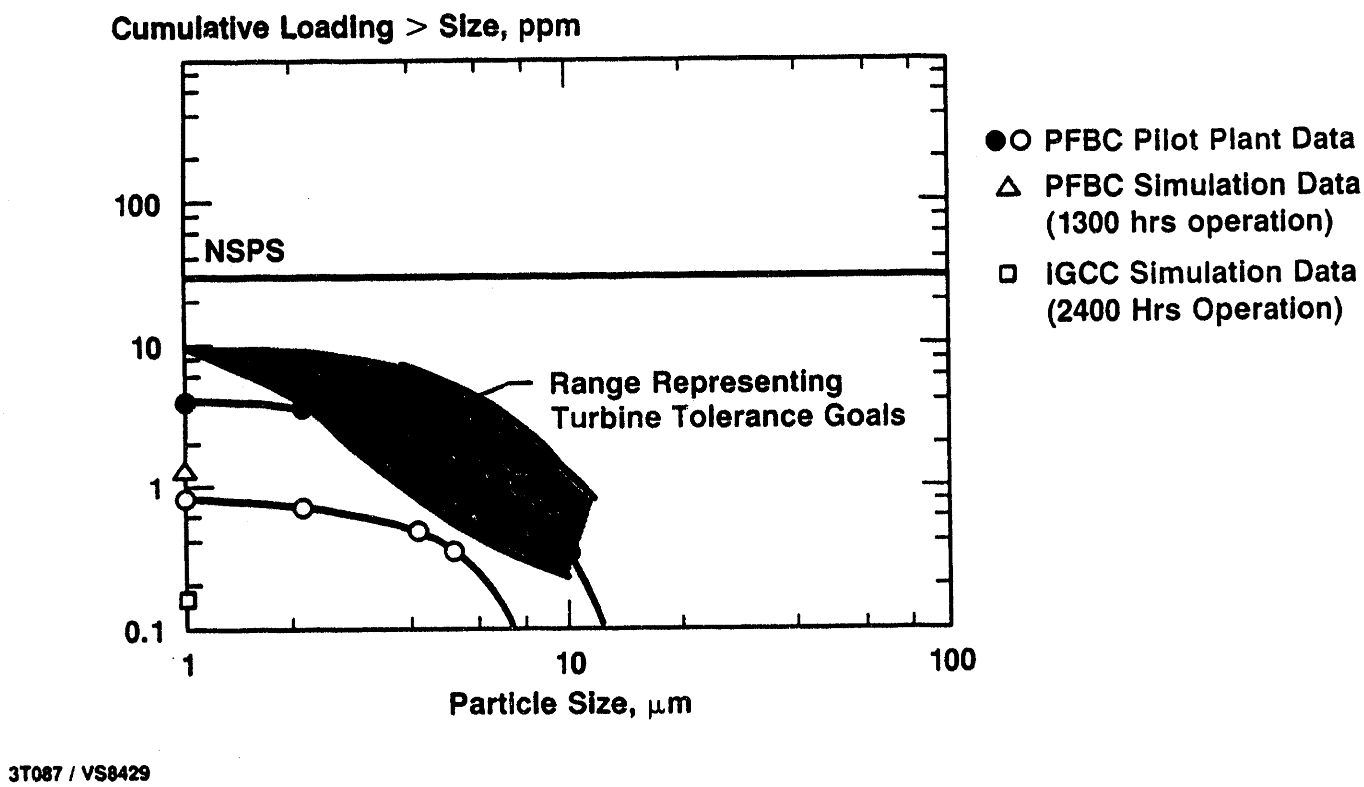


Figure 4.8 - Comparison of Cross Flow Filter Performance with Cleanup Requirements

larger performance margins exist with the gasifier systems since the fuel gas following hot gas filtration is subsequently diluted with combustion air. Thus, results from the long term durability testing confirm shorter term pilot plant test results and show the cross flow filter when operating over extended test periods can meet and significantly improve upon NSPS requirements.

Gas turbine tolerance to particulates, as nominally represented by the shaded region in Figure 4.8, will depend on the specifics of the turbine design. Turbine tolerance depends on both total loading and size distribution. Although actual size distributions were not measured in the simulator testing, the <1 ppm average total loading would clearly suggest a performance level consistent with the most stringent turbine tolerance requirement.

4.4 CROSS FLOW FILTER DURABILITY

As suggested above, the cross flow filter is basically an absolute filter when component integrity is maintained, i.e., no failed filter elements or gaskets. In the PFBC simulator testing, and in ongoing pilot plant gasification filter testing,[3] both filter element and gasket failures have occurred. In these instances, depending on the type of failure, the performance of the cross flow filter can be substantially compromised.

Filter Gasket Durability

In high temperature applications, some type of a ceramic dust seal (gasket) must be used between the filter element and its mount. In general, these seals have typically utilized some type of unconstrained ceramic fiber blanket or mat gasket. Failure of these seals can result in substantial compromise in the filter system performance, even though no damage has occurred with the filter element. Gasket failures result in a one (1) to two (2) order of magnitude increase in the outlet particle loading, i.e., 10 to 100 ppm. As discussed in Section 3, gasket failures were encountered when utilizing the unconstrained fiber blanket and mat type gasket. A modified gasket design described in Appendix E was developed that utilizes a reenforced ceramic fiber mat. This design has substantially eliminated gasket failure.

Filter Element Durability

Cross flow filter element failures under service conditions can be characterized as debonding, as delaminations (hairline cracks that follow plate seams), by cracks that propagate across the plate seams or as cracks that occur along the mounting flange. Although no filter failures of any type were experienced in the gasifier simulator testing, parallel testing in an actual entrained gasifier system did show filter flange cracking (prior to mount redesign), delamination, and cracking across filter plate seams. However, significant plant transients and upsets have been experienced in the gasifier plant tests, as opposed to the very controlled and nearly steady state conditions of the gasifier simulator testing. The PFBC simulator testing included both steady state and thermal transient testing. Under these conditions filter element failures were experienced.

Although debonding, delamination and filter plate cracking have all been identified in earlier filter development program testing, the occurrence of the filter flange cracks represent a relatively new and potentially serious deficiency in the filter system design. Cracking of the flange had occurred in earlier versions of the cross flow filter, but was apparently corrected by increasing flange thickness. In the current long term durability test program, however, the deficiency of the filter mounting system was identified. This aspect of the program is described and evaluated in detail in Appendix E. A modified mount design, illustrated in Figure 4.9, was developed and implemented into

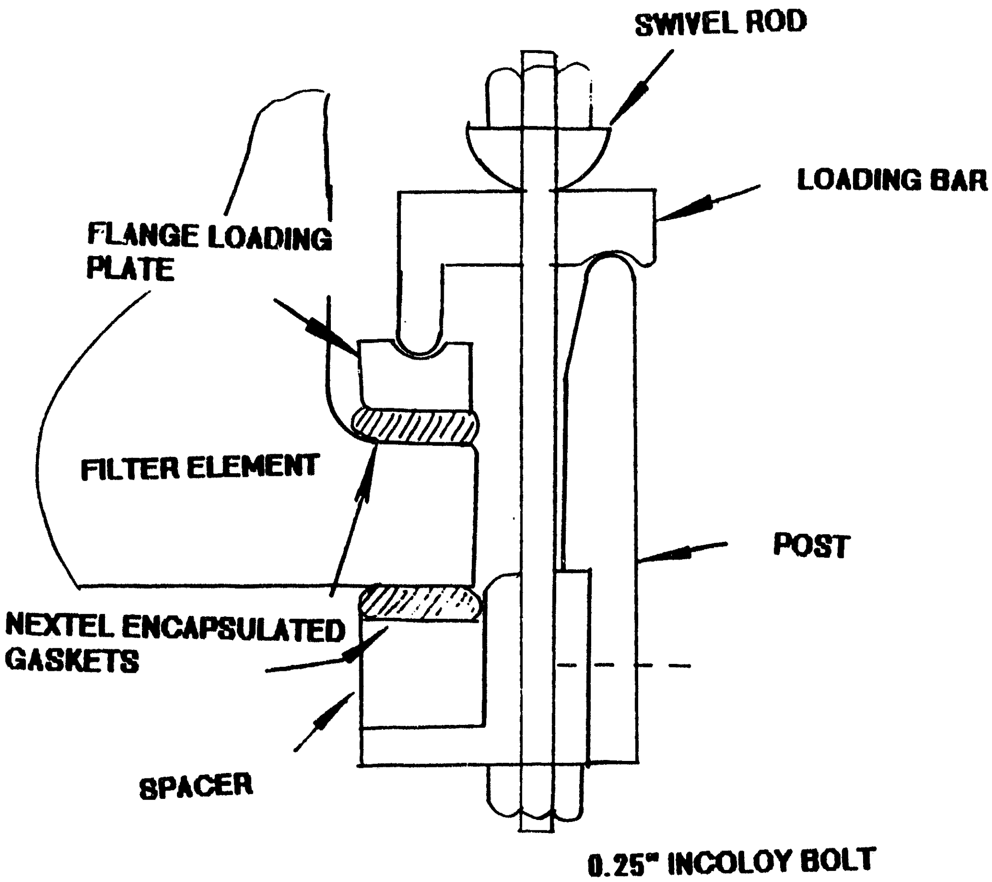


Figure 4.9 - End View of Modified Element Mount Fixture

the subsequent simulator testing as well as the ongoing entrained gasifier pilot plant filter testing. The salient features of the design include:

1. The Nextel reinforced gaskets are used on the upper and lower surfaces of the ceramic flange. Note that the upper gasket after compression now provides a compliant layer to smooth out the seating forces imposed by the flange loading plate and also ensures a resilient shock-absorbing layer to cushion the vibrational forces generated during pulse cleaning.

2. The single clamp plate is now substituted by a flange loading plate and a separate loading bar with a swivel action. This type of clamping arrangement ensures that, regardless of the ceramic flange geometric variations, the loading plate will remain parallel and horizontal whereas the loading bar can rotate as necessary without actually interfering with the edge of the ceramic flange.

3. A metal post is attached to the outside of the existing fixture such that the loading bar is simply supported on either side of the bolting axis. Thus the bolting forces are directly transferred into an equivalent seating force on the filter, without the use of shims.

4. The eight 316 stainless steel bolts are substituted by fourteen bolts made of creep resistant Incoloy 800 alloy. During the assembly procedure a weight is placed on the element to precompress the bottom gasket. The clamping device is now mounted and the 14 bolts are sequentially torqued up to 10 in-lbs. After removal of the weight, the two gaskets will be loaded in series to approximately 2700 lbs of seating force.

5. The filter seating area is elevated by the use of a spacer such that no dust can accumulate between the flange and the metal fixture. Notwithstanding the rugged gasket seating properties of the modified design, this feature ensures that no residual transverse stresses can act on the flange during shutdown conditions.

Although testing has been limited, with the implementation of this modified mount design in both simulator and pilot plant facilities, no further failures in the filter flange have been experienced.

In the PFBC simulator testing that included plant thermal transient testing as outlined in Section 3 and detailed in Appendix J, debonding, delamination and filter plate cracking were experienced. Photographs showing the different failure modes are provided in Appendix J. Nine different cross flow filter elements in groups of four were subjected to thermal transients testing. The first filter grouping of four elements all failed during a very severe thermal transient that occurred initially when trying to produce a much less severe, but PFBC indicative turbine trip transient. These filters were replaced. Although not considered as representative of controlled PFBC transient conditions, the data and discussion of these four filters are included in Appendix J for completeness. These filters failed by debonding (WRTX-53) partial delamination (WRTX-53, 48, 70) and horizontal plate cracking (WRTX-66). It is interesting to note that even with these different type "failures," there was substantial evidence that very little dust actually penetrated to the clean gas side of filters. Longer operation in the failed mode, however, may have produced a substantial compromise in filter performance; this testing was not conducted. It is also noteworthy that in the failed mode, no section or piece of the filter actually dropped off the mount, i.e., each filter appeared to be intact until it was physically removed from its mount (the photographs given in Appendix J are after mount disassembly).

Following the initial severe thermal transient testing, better control of the PFBC simulator facility was achieved. Five different filters were then tested under PFBC transient conditions. Three of these filters survived with no visible damage. Two of the filters suffered in-service failure; one filter showed a debonding while the second a partial delamination crack. Debonding failures (complete separation at a plate seam) is viewed as a manufacturing deficiency that as yet cannot be detected by current nondestructive inspection techniques. Again, evidence suggests that only a very small amount of dust penetration occurs as a result of a simple delamination crack. In general, cross flow filter performance appears significantly more tolerant to in-service cracking of the ceramic elements than candle or tube geometries. However, efforts continue to develop the cross flow filter manufacturing process to improve bulk material properties and uniformity.

Cross Flow Filter Materials Characterization

Cross flow filter material stability is being investigated in a companion DOE program (DE-AC21-88MC25034). This work has demonstrated the relative inertness of alumina/mullite in both high temperature oxidizing and reducing gas conditions representative of PFBC and gasifier systems, respectively. At high temperature (1300-1600°F, 700-870°C) alumina/mullite undergoes conversion of its amorphous or glass containing phase(s) to a crystalline anorthite structure which appear to impart high temperature strength to the filter matrix. Conversion or crystallization is enhanced by the presence of steam and gas phase sodium. Continued conversion of the anorthite to the long-term production of tridymite appears to level material strength gain. Testing in this program has also shown exposure of the alumina/mullite material to simulated pulse cleaning thermal transients reduces material bulk strength. Thus, initially, competing effects appear to occur; an increase in strength due to anorthite formation and formation of microcracks due to pulse cleaning thermal transient effects that decrease strength. Quantitative XRD analysis of the cross flow filter tested for 1300 hours in the long term durability program under simulated PFBC conditions has confirmed the conversion of the amorphous to anorthite, paralleling actual plant experience and the bench scale testing reported in the DE-AC21-88MC25034 contract work.[5]

Detailed material property characterizations have been conducted on the cross flow filters exposed to 1300 hours of PFBC simulator testing. These data include room temperature bulk material strength data and Weibull statistics determined from 4-point bend bar data and material property data (4-point bend) under process temperature conditions, Appendix K and Appendix L.

In summary, findings from these material strength studies suggest the following:

- The initial (unused filter) hot strength is lower than initial cold strength. Apparently, the higher amorphous content of the unused filter is reflected as a higher cold strength bulk prr erty.

- Although room temperature material strength decreases with operating time, actual hot strength increases (because of the above described phase conversion). Once conversion of the amorphous phase is complete, the hot and cold bulk strength should be comparable (this had not yet occurred in the 1300 hour test sequence reported herein).

- Cold strength data suggests after 1300 hours of long term durability testing, the web (filter core) and flange sections of the cross flow filter to exhibit lower strength than the top closed end of the filter element. This is not unexpected because of the thermal cycling duty experienced by both the web and flange sections compared to the filter top end.

Actual stressing conditions in cross flow filters have been predicted.[6] These models indicate the possibility of stressing conditions during pulse cleaning that would begin to approach the room temperature bulk strength measured in the filter. Although the model calculations are based on somewhat incomplete process and material property input data, they do suggest that the loss of material cold strength shown in the 1300 hour test could be sufficient to cause concern regarding possible failure (as had occurred). To date there is insufficient confidence in the models to draw firm conclusions regarding actual filter stressing. However, it appears prudent to evaluate means to increase filter strength even if lower flow permeability must be accepted.

4.5 REFERENCES

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