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Particulate Hot Gas Stream Cleanup Technical Issues

Quarterly Report
April 1 - June 30, 1998

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For
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Office of Fossil Energy
Federal Energy Technology Center
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PARTICULATE HOT GAS STREAM CLEANUP TECHNICAL ISSUES

QUARTERLY REPORT

April 1998 - June 1998

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Contract No. DE-AC21-94MC31160
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EXECUTIVE SUMMARY

This is the fifteenth quarterly report describing the activities performed under Contract No. DE-AC21-94MC31160. The analyses of Hot Gas Stream Cleanup (HGCU) ashes and descriptions of filter performance studied under this contract are designed to address problems with filter operation that are apparently linked to characteristics of the collected ash. Task 1 is designed to generate a data bank of the key characteristics of ashes collected from operating advanced particle filters (APFs) and to relate these ash properties to the operation and performance of these filters and their components. APF operations have also been limited by the strength and durability of the ceramic materials that have served as barrier filters for the capture of entrained HGCU ashes. Task 2 concerns testing and failure analyses of ceramic filter elements currently used in operating APFs and the characterization and evaluation of new ceramic materials.

Task 1 research activities during the past quarter included characterizations of samples collected during a site visit on May 18 to the Department of Energy / Southern Company Services Power Systems Development Facility (PSDF) and a particulate sample collected in the Westinghouse filter at Sierra Pacific Power Company's Piñon Pine Power Project. Analysis of this Piñon Pine sample is ongoing: however, this report contains the results of analyses completed to date. Significant accomplishments were achieved on the HGCU data bank during this reporting quarter. The data bank was prepared for presentation at the Advanced Coal-Based Power and Environmental Systems '98 Conference scheduled for July, 1998.

Task 2 work during the past quarter consisted of testing two Dupont PRD-66C candle filters, one McDermott ceramic composite candle filter, one Blasch 4-270 candle filter, and one Specific Surface cordierite candle filter. Tensile and thermal expansion testing is complete and the rest of the testing is in progress. Also, some 20-inch long Dupont PRD-66C, McDermott ceramic composite, and Westinghouse Techniweave candle filters have been received for testing after their exposure to the gasification environment. One as-manufactured and one exposed element was received of each material and specimens are currently being machined from these candles.

INTRODUCTION

This is the fifteenth quarterly report describing the activities performed under Contract No. DE-AC21-94MC31160. Task 1 of this contract concerns analyses of HGCU ashes and descriptions of filter performance that are designed to address problems with filter operation linked to characteristics of the collected ash. Much of the work planned for Task 1 builds directly on work performed under a prior contract (No. DE-AC21-89MC26239) with the Department of Energy's Federal Energy Technology Center in Morgantown, WV (DOE/FETC-MGN). Task 2 of this contract includes characterization of new and used filter elements. Some of the problems observed at PFBC facilities include excessive filtering pressure drop, the formation of large, tenacious ash deposits within the filter vessel, and bent or broken candle filter elements. These problems have been attributed to ash characteristics, durability of the ceramic filter elements, and specific limitations of the filter design. In addition to the problems related to the characteristics of PFBC ashes, laboratory characterizations of gasifier and carbonizer particulates have shown that these ashes also have characteristics that might negatively affect filtration. Specifically, gasifier particulates may form filter cakes that accumulate in thickness quite rapidly and also may reentrain following cleaning pulses.

To identify which particulate characteristics can lead to problems with filtration, 348 particulate samples from fourteen facilities involved in FETC's HGCU program have been assembled. Three samples from gasification studies being carried out by Herman Research Pty. Ltd. (HRL) of Melbourne, Australia have also been included in the data bank. The most recent sample added to the data bank was collected in the Westinghouse filter at Sierra Pacific Power Company's Piñon Pine Power Project. Many of the samples in the data bank have been analyzed with a variety of laboratory tests. Physical attributes of the particles that have been examined include size distribution, specific surface area, particle morphology, and bulk ash cohesivity and permeability. A range of chemical analyses of these samples, as well as characterizations of agglomerates of particles removed from filter vessels at Tidd, Karhula and Foster Wheeler's pilot-scale combustion facility located in Livingston, New Jersey have also been performed. The data obtained in these studies are being assembled into an interactive data bank which will help the manufacturers and operators of high-temperature barrier filters tailor their designs and operations to the specific characteristics of the particulate materials they are collecting.

Two Dupont PRD-66C candle filters, one McDermott ceramic composite candle filter, one Blasch 4-270 candle filter, and one Specific Surface cordierite candle filter were received at SRI for testing. The test matrix for these candles along with the current status of the testing is presented in the discussion of Task 2 activites contained in this report. So far, the tensile and thermal expansion measurements have been completed and were summarized in a poster session at the Advanced Coal-Based Power and Environmental Systems '98 Conference. The other tests are in progress. The test matrix for the 20-inch long Dupont PRD-66C, McDermott ceramic composite, and Westinghouse Techniweave candle filters, as-manufactured and after exposure to the gasification environment, is presented in this report. Machining of these specimens is in progress.

OBJECTIVES

Task 1 of this project is explicitly designed to address aspects of filter operation that are linked to the characteristics of the collected particles. This task has two primary objectives. The first is the generation of an interactive computerized data bank of the key characteristics of HGCU ashes collected from operating high-temperature, high-pressure, particle filters. The data bank is structured to identify, when possible, relationships between HGCU particulate properties and the operation and performance of these filters. Construction of the data bank is intended to help manufacturers and operators of high-temperature barrier filters tailor process design and operation to the specific characteristics of the particulate materials they are collecting. The second objective is to relate these measured properties and the contents of the data bank to the operation and performance of the advanced particle filters and filter components. The first objective includes formatting the data bank and collecting, analyzing, and maintaining particulate samples from operating HGCU facilities. The second objective of this task involves the collection of operating histories from advanced particle filters, correlating these histories with sample characteristics, interpreting these correlations, and communicating results in the various venues prescribed by DOE/FETC-MGN.

The objectives of the Task 2 test program at Southern Research are as follows:

- Provide material characterization to develop an understanding of the physical, mechanical, and thermal behavior of hot gas filter materials.

- Develop a material property data base from which the behavior of materials in the hot gas cleanup environment may be predicted.

- Perform testing and analysis of filter elements after exposure to actual operating conditions to determine the effects of the thermal and chemical environments in hot gas filtration on material properties.

- Explore the glass-like nature of the matrix material.

TASK 1 ASSESSMENT OF ASH CHARACTERISTICS

Task 1 research activities during the past quarter included characterizations of samples collected during a site visit on May 18 to the PSDF and a particulate sample collected in the Westinghouse filter at Piñon Pine. Analysis of this Piñon Pine sample is ongoing: however, this report contains the results of analyses completed to date. Significant accomplishments were achieved on the HGCU data bank during this reporting quarter. The data bank was prepared for presentation at the Advanced Coal-Based Power and Environmental Systems ’98 Conference scheduled for July, 1998. Further additions and improvements to the data bank are planned for the next quarter.

SITE VISIT TO THE PSDF

A site visit was made on May 18 to the PSDF to characterize the condition of the Westinghouse FL0301 filter and to collect ash samples for analysis. Thirteen ash samples were collected during the visit. These samples are described briefly in Table 1. A videotape record was made of representative filter components. PSDF personnel employed a dirty shutdown procedure for this filter inspection. Following the last filtration cycle (approximately 38 minutes long) the coal feed was stopped and the neither of the two plenum assemblies in the filter was back pulsed. This caused the filter cakes to include residual and transient filter cake ash. This procedure was followed to allow differences in these two types of ash to be assessed. These measurements have been performed under Contract No. DE-FC21-90MC25140 and are not reported here.

Table 1
PSDF Filter Cake Ash Samples Obtained May 18, 1998

ID #	location	filter element type	amount, g	description
4303	B15	Pall 442T	425	whole candle
4304	B1	3-M oxide	1.8646	core sample
4305	B35	IF&P Reecer	2.2258	core sample
4306	B8	Schumacher T10-20	1.6886	core sample
4307	B20	McDermott oxide	2.3144	core sample
4308	B6	Pall aluminide	1.8599	core sample
4309	B6	Pall aluminide	1.9600	core sample
4310	B15	Pall 442T	2.0868	core sample
4311	B32	Pall 326	2.1658	core sample
4312	B18	3-M oxide	1.0811	core sample
4313	B14	DuPont PR66	2.2349	core sample
4314	B17	3-M type 203	2.0010	core sample
4315	T5	Schumacher TF20	2.2886	core sample

Because the thickness, porosity, and appearance of the filter cakes may depend on the type of candle substrate on which the cake formed, core samples and filter cake thickness measurements were made for cakes on all of the filter element types in the filter vessel. Core samples (for areal density determinations) were obtained from 10 candles in the bottom plenum and 1 candle in the top plenum. For each of these candles, measurements were about midway down the vertical length of the candle. The core sampler used had a cross-sectional area of 7.32 cm^2. Filter cake thicknesses were measured with the traversing transverse laser gauge at points just above or below the locations where the core samples were obtained. In general, the filter cakes covering the candles ranged in thickness from 3.7 to 6.8 mm. Data from the areal density and filter cake thickness measurements are summarized in Table 2.

Table 2
PSDF Filter Cake Areal Density and Thickness Measurements (May 18, 1998)

location	core sample weight, g	thickness, inches	areal density, lb/ft^2	porosity, %	comments
B1	1.8646	0.145	0.52	72.9	cake easily released
B35	2.2258	0.150	0.62	68.7	smooth cake
B8	1.6886	0.175	0.47	79.6	
B20	2.3144	0.237	0.65	79.4	tenacious residual cake
B6	1.8599	0.226	0.52	82.6	
B15	2.0868	0.266	0.58	83.4	tenacious residual cake
B32	2.1658	0.210	0.61	78.2	tenacious residual cake
B18	1.0811	0.206	0.30	88.9	cake easily released
B14	2.2349	0.219	0.63	78.5	cake easily released
B17	2.0010	0.16 to 0.31	0.56	--	lumpy, irregular thickness, residual cake embedded in weave
T5	2.2886	0.246	0.64	80.4	smooth cake easily released
avg.	1.9829	0.208	0.55	79.3	

Based on the data presented in this table, the average porosity of the PSDF filter cakes observed on May 18 was near 79%. A few of the measured porosity values (for candles B1, B35, and B18) deviated significantly from this average value. These deviations were probably caused by the degree of irregularity of the candle surface which would affect the measurements of filter cake thickness and/or the completeness with which ash was collected by the core sampler. The average areal density of the residual plus transient filter cakes measured on May 18 was 0.55 lb/ft^2. Sample ID # 4303 was selected for detailed measurements, which are discussed later in this report.

The general appearance of the filter cakes that were observed on May 18 suggest that some of the characteristics of the different filtering substrates may influence cake buildup. Figure 1 shows the appearance of the entire filter assembly during its removal from the filter vessel. In Figure 2 an apparent leakage path can be observed at the mounting location of one of the 3-M candles. An inadequate seal is believed to have caused this leakage path. Later design modifications to the conical mating surface on these 3-M candles eliminated this problem. The typical appearance of the filter cakes on the bottom plenum is shown in Figure 3. The ash deposits that formed around the mounting locations on the top filter plenum (Figure 4) were much like those observed on prior site visits. PSDF and Southern Research Institute personnel are currently designing the sampling protocol that will be used during the filter inspection that will occur in August. Attempts to correlate the characteristics of the filter cake with the type of filter element will continue during this upcoming inspection. These correlations should help establish the degree to which filter element design determines the characteristics of the residual and cleanable filter cakes.

Figure 1. Appearance of the entire filter assembly on May 18,1998 during removal from the filter vessel.

Figure 2. Apparent leakage path observed on May 18, 1998 at the mounting location of one of the 3-M candles. An inadequate seal is believed to have caused this leakage path. Later design modifications to the conical mating surface on these 3-M candles eliminated this problem.

Figure 3. Typical smooth filter cakes observed on the bottom filter plenum on May 18, 1998.

Figure 4. This photograph shows the typical ash deposits formed around the mounting locations on the top filter plenum (May 18, 1998).

LABORATORY ANALYSES OF PARTICULATE SAMPLES

Analyses of sample # 4303 from the PSDF, identified in Table 1, and sample # 4316, which was collected in the Westinghouse filter at Piñon Pine and provided by Satyan Katta of M.W. Kellogg, are discussed in the following sections.

PSDF Ash

The physical analyses performed on the PSDF and Piñon Pine samples are summarized in Table 3. The characteristics of the PSDF filter cake ash indicate that it should not cause unusually high filtering pressure losses.

Table 3
Measured Physical Characteristics of PSDF and Piñon Pine Particulate Samples

quantity	ID # 4303 (PSDF)	ID # 4316 (Piñon Pine)
specific surface area, m^2/g	--	107
Stokes' MMD, µm	--	19
uncompacted bulk porosity, %	78	80.2
filter cake porosity	79	--
drag-equivalent diameter, µm	3.59	1.96
specific gas flow resistance, in H_2O·min·ft/lb*	2.9	7.7
specific gas flow resistance, in H_2O·min·ft/lb**	2.5	--
tensile strength, N/m^2	--	2.3
true particle density, g/cm^3	2.55	2.38

* calculated for an assumed filter cake porosity equal to the uncompacted bulk porosity

** calculated for a filter cake porosity equal to the value determined with the core sampler and thickness measurements (79 %)

Piñon Pine Filter Fines

Sample # 4316 was collected in early June from the system of hoppers attached to the Westinghouse filter vessel at Piñon Pine, and not from the surface of the filter elements. Therefore the sample may be more coarse than material collected on the filter elements. With only the currently available sample, it is not possible to determine what fraction, if any, of the size distribution presented in Figure 5 represents particles that settled in the hopper without ever reaching the filter cake. Determination of the degree of passive settling that may have occurred in the filter vessel would require analyses of particulate material collected directly from the surfaces of the candle filter elements. Consequently the behavior and characteristics of this sample may not accurately indicate the characteristics and behavior of the filter cake.

The measured physical characteristics of the Piñon Pine sample are summarized in Table 3. Although this sample has a relatively high specific surface area, the drag-equivalent diameter and uncompacted bulk porosity are high enough to keep the specific gas-flow resistance from being excessively high. If the particulate material that collects on the filters is finer than this sample, the filter cake porosity would probably be higher than 80 %, and the material's drag-equivalent diameter would probably be lower than 1.96 µm. This decrease would tend to offset the effect on specific gas-flow resistance of the increased filter cake porosity . The tensile strength of this sample is relatively low. Figures 6 and 7 present scanning electron micrographs of sample # 4316. Mineral analyses of this sample # 4316 are presented in Table 4. Because of the high calcium-to-sulfur ratio in this material, further tests are planned to determine the relative amounts of these two constituents as a function of particle size. These results will be included in the next quarterly report.

Table 4
Measured Chemical Characteristics of Piñon Pine Filter Fines (ID # 4316), % wt.

constituent	% wt.
Li_2O	0.01
Na_2O	2.1
K_2O	0.27
MgO	1.2
CaO	50.4
Fe_2O_3	4.2
Al_2O_3	9.2
SiO_2	19.9
TiO_2	1.8
P_2O_5	0.43
SO_3	8.0
LOI	53.0
soluble $SO_4^{=}$	3.2
Equilibrium pH*	11.53

* dimensionless

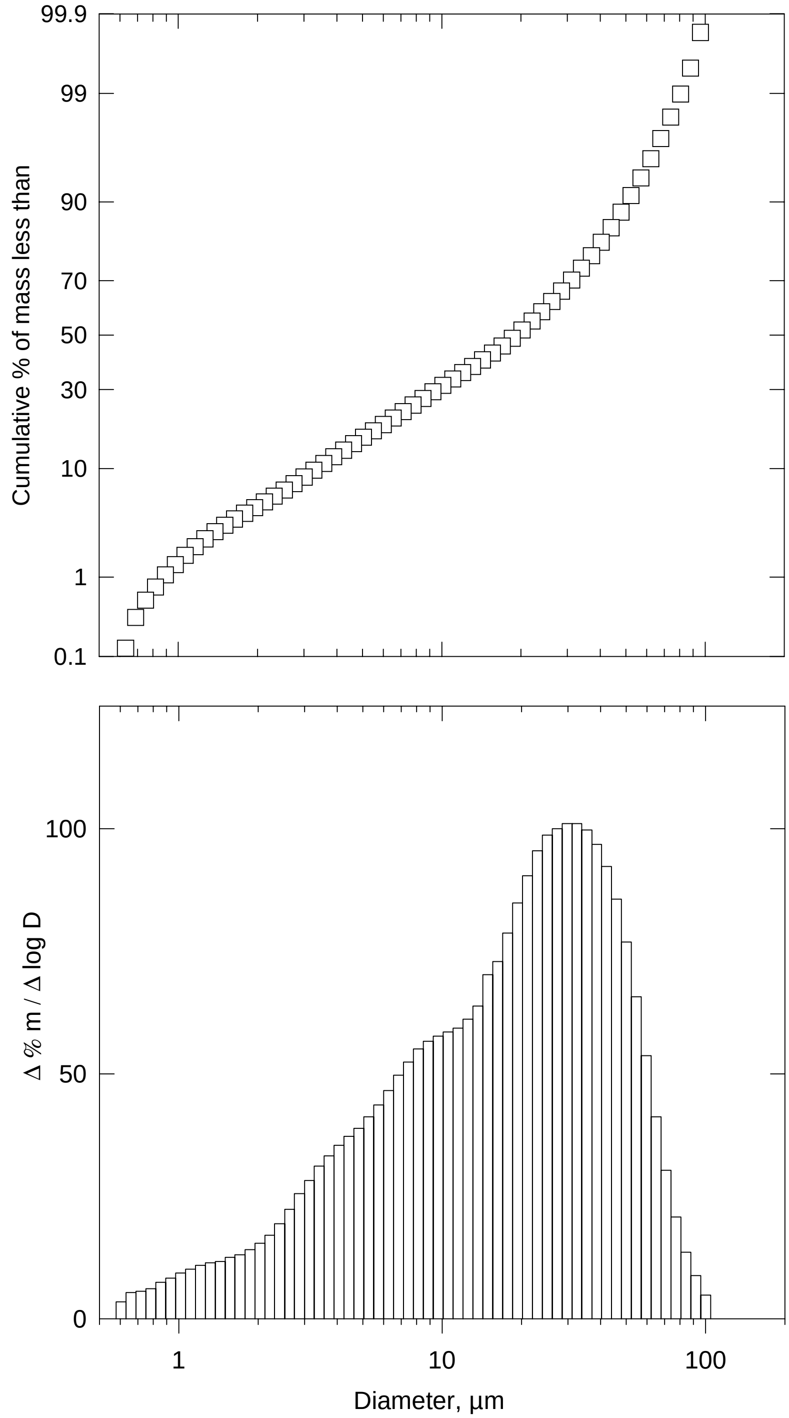

Figure 5. Differential and cumulative size distribution data measured for Piñon pine filter fines (ID # 4316) with a Leeds and Northrup Microtrac Particle Size Analyzer. The Stokes' MMD of this distribution is 19 µm.

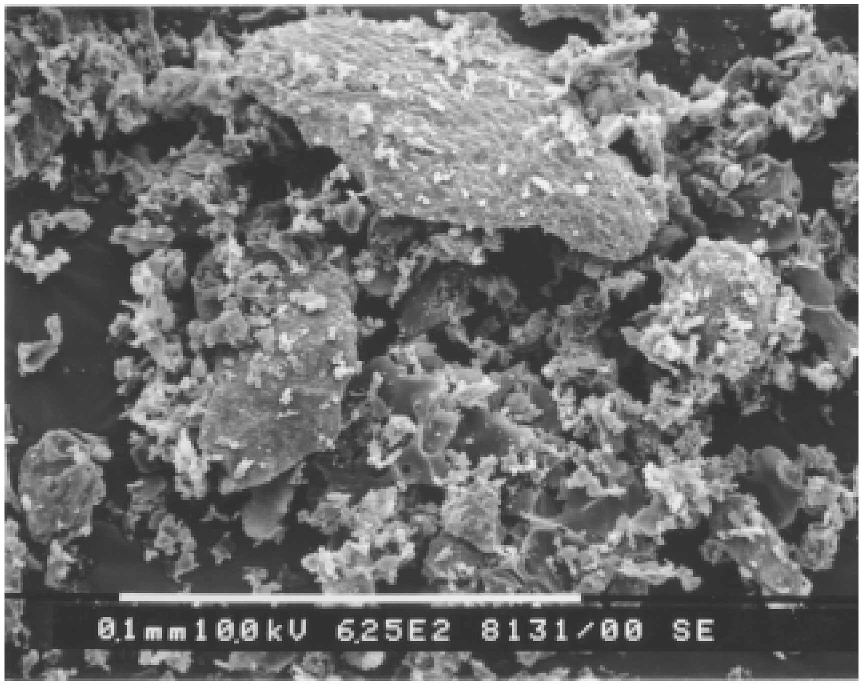

Figure 6. Scanning electron micrograph of Piñon Pine IGCC Power Project filter fines particulate sample (ID # 4316). The white bar at the bottom of the micrograph represents a length of 100 μm.

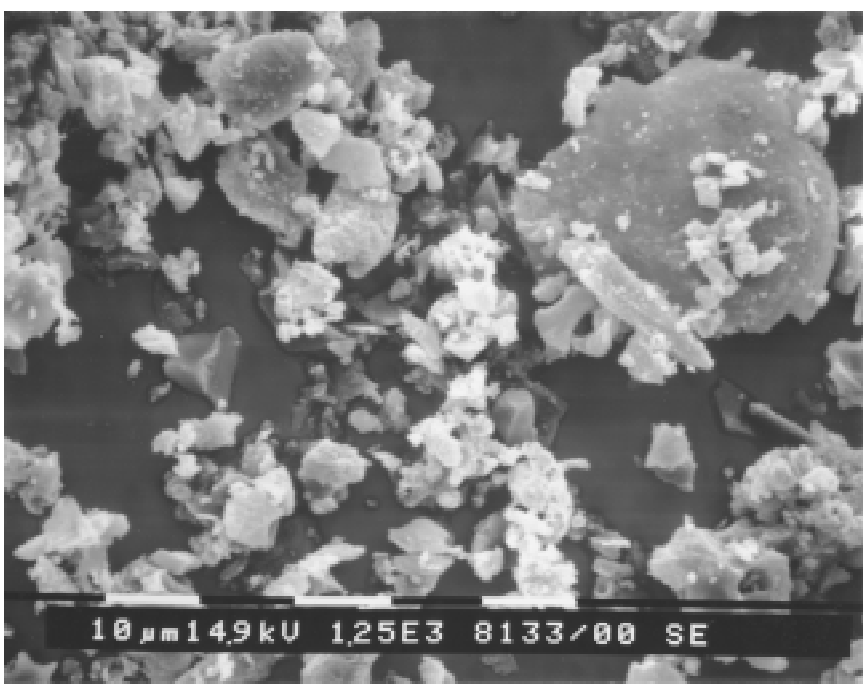

Figure 7. Scanning electron micrograph of Piñon Pine IGCC Power Project filter fines particulate sample (ID # 4316). The white bars at the bottom of the micrographs represent lengths of 10 μm.

ASH DATA BANK DEVELOPMENT

Much of the work during this past quarter has focused on the development of the Ash Data Bank. A paper describing this data bank was prepared by T.R. Snyder, L.G. Felix, and D.H. Pontius and submitted for inclusion in the Advanced Coal-Based Power and Environmental Systems '98 Conference scheduled for July, 1998.

To date, Southern Research Institute has analyzed about 151 of the 351 particulate samples that have been collected from fifteen advanced generation facilities:

- FETC Fluid Bed Gasifier with the Modular Gas Cleanup Rig (MGCR)
- Transport Reactor Development Unit located at the University of North Dakota's Energy and Environmental Research Center
- Foster Wheeler Development Corporation Integrated Carbonizer/CPFBC Pilot Plant at Livingston, New Jersey
- M.W. Kellogg Advanced Transport Reactor at the Department of Energy / Southern Company Services Power Systems Development Facility (PSDF
- Foster Wheeler's 10 MWt Pressurized Circulating Fluid Bed Facility in Karhula, Finland
- Sierra Pacific Power Company's Piñon Pine Power Project
- American Electric Power Service Company's 70 MWe Tidd Pressurized Fluidized-Bed Combustor
- Grimethorpe PFBC
- Westinghouse cross-flow filter at the Texaco Montebello Research Laboratory Gasifier
- M.W. Kellogg Transport Reactor Test Unit located in Houston, Texas
- New York University's Bubbling Bed PFBC
- Iowa State University's Atmospheric, Circulating Fluidized-Bed Combustor
- General Motors' Allison Coal-Fueled Turbine
- KRW Process Development Unit
- Herman Research Pty Ltd. Mulgrave Gasification Research Facility located in Australia.

The data bank comprises samples and information from a broad selection of advanced combustion processes and facilities developed and operated by a wide range of power systems developers, power producers, and researchers. The facilities included in the data bank range from bench-scale units to full-scale power plants. Because many of the processes being tested were under development and optimization when samples and operating data were obtained, the data presented in the data bank may not always be representative of normal, or optimized, process operation. In fact, a significant proportion of data and samples obtained for analysis are included precisely because they are representative of unusual, or troublesome, system behavior. In addition, the physical characteristics of particulate samples are especially sensitive to the locations in the processes from which the samples were obtained. Consequently, users of the data bank are discouraged from making extensive comparisons between different processes or samples. The data bank is intended to provide the user with information describing the characteristics and behavior of specific samples and test facilities. When sufficient operating data, samples, and sample analyses are available to draw conclusions about system or process behavior, the data bank includes discussions of these conclusions. In addition, references and key personnel are listed for the processes and facilities represented in the data bank. Instead of including lengthy descriptions of these facilities, the user of the data bank is directed to these sources for more detailed information.

The data bank is structured about Microsoft Access 97®. Current plans call for a run-time version of Microsoft Access to be included with the data bank. The arrangement of information in the data bank allows the user to review a variety of information including photographs, scanned images, plots, figures, text, and numerical values. To facilitate presentation of this wide variety of data formats, the data bank utilizes Adobe Acrobat® PDF (portable document format) files at various points in its construction. Therefore, software to install Adobe Acrobat Reader® is included with the data bank. Minimum system requirements for running the data bank are an IBM-compatible PC with a Pentium processor or higher, Microsoft Windows 95® or Windows 98® operating system, 16 megabytes of RAM, a 4X or faster CD-ROM drive, and a video card configured for a 1024 by 768 display with a minimum of 256 colors.

Upon activating the data bank, the user initially views a title page and a page containing cautionary notes and instructions for proper use and interpretation of the information in the data bank. In exiting this screen, the user is allowed either to select from six in-depth discussions of ash behavior and/or analyses procedures or to examine information and particulate sample analyses measured for each of the fifteen facilities. The first of these in-depth discussions presents one of the principal findings of this task - a coherent mechanism describing how and why consolidated ash deposits form in PFBC filter vessels. This description is based on site observations made at the Tidd PFBC, field and laboratory analyses of ashes and nodules collected from Grimethorpe, Tidd and Karhula, and a review of literature describing eutectic formation, sintering, and consolidation of boiler tube deposits. The next three in-depth discussions review the factors in a PFBC that contribute to filter system failure, inertial particle collection in barrier filter vessels, and the potential for rapid increases in the thickness of transient IGCC filter cakes. The fifth and sixth discussions accessible for review from this screen detail the procedures and sampling protocol used during site visits, and the techniques used in the laboratory to characterize particulate samples. All six of these in-depth discussions employ the Adobe Acrobat file format described above. Further discussions may be added to this list as project activities clarify other aspects of the effects of particulate characteristics on hot gas filter operation.

If the user has chosen to examine data and samples for specific facilities, a screen is displayed which permits the user to select one of the fifteen HGCU facilities to examine in detail. Once a facility has been selected, the data bank lists the primary participating organizations and principal contact personnel for the facility. The user can then select and review one of the six categories listed: brief description of the facility; process schematics; plant photographs; technical references; on-site inspections; or particulate sample analyses. Under the first category, brief descriptions, up to two pages of text, are provided for each of the facilities in the data bank from which the various particulate samples were obtained. Series of process schematics and plant photographs can be scrolled through by selecting the second or third category. Examples of the screens that are used to display process schematics and plant photographs are shown in Figures 8 and 9. The fourth category provides the user with references to more detailed information about the facility. The category for on-site inspections contains information gathered during filter inspection and sampling trips made by Southern Research Institute personnel. Information in this category covers four site visits to the Tidd PFBC, one visit to the MGCR at Morgantown, and five inspection and sampling trips to the PSDF. After the user selects a particular site visit to review, the data bank provides a brief summary of the condition of the filter, the sampling procedures and the particulate samples obtained, and some of the key data obtained during the visit. A series of photographs of the filter cakes and ash deposits observed during the visit can also be reviewed.

When the user wishes to review the analyses of samples obtained from a particular facility, a scroll-down list of the samples is displayed. Included with this listing are brief descriptions of the samples, and where and when they were obtained. Because not all of the samples archived in the data bank have been analyzed, this list will indicate which of the samples in the data bank have been tested. This screen is shown in Figure 10. After a sample is selected to examine in detail, a screen is displayed that summarizes the physical and chemical analyses that have been performed on that sample. Figure 11 presents this screen display for one of the Tidd samples. Physical attributes that have been measured and are included in this display include median particle size, specific surface area, particle morphology, bulk ash cohesivity, permeability, and tensile strength. This screen also provides access to scanning electron micrographs of many of the samples in the data bank. In general, these micrographs were obtained and can be viewed at four different magnifications. Chemical analyses of the selected sample are also summarized on this screen. Some of the samples collected which have unusual histories or unique characteristics have been analyzed with special techniques. When special analyses have been performed on the selected sample, the results of these analyses can also be accessed from this screen. This screen also provides a direct link to descriptions and explanations of the various analyses used to characterize the samples.

Each screen shown during operation of the data bank offers the user the option of exiting the program. When this option is selected, a final screen is displayed which credits the various organizations and individuals that made significant contributions to the data bank. Acquisition of particulate samples and analyses of their physical and chemical characteristics is an ongoing process. Therefore information will be added to the data bank throughout the duration of this project. Current project plans call for the data bank to be issued to FETC on CD-ROM at the end of FY98.

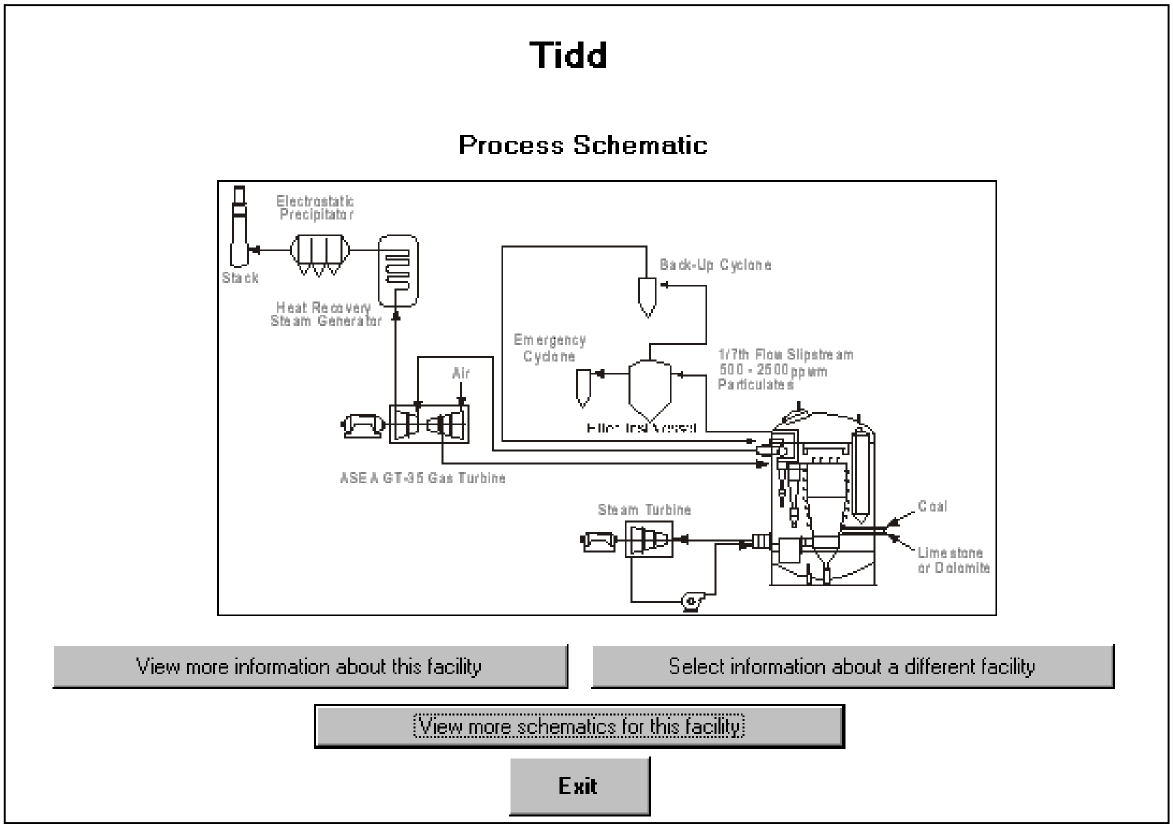

Figure 8. Example of the screen used to display process schematics.

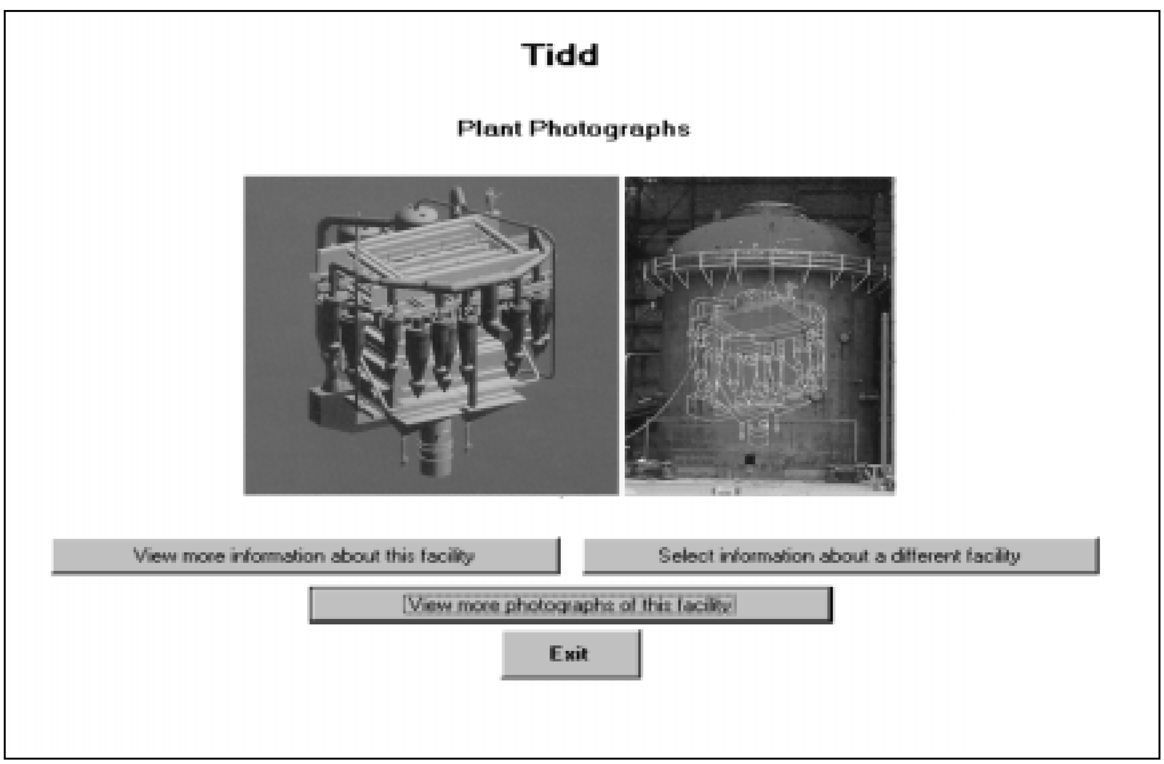

Figure 9. Example of the screen used to display plant photographs.

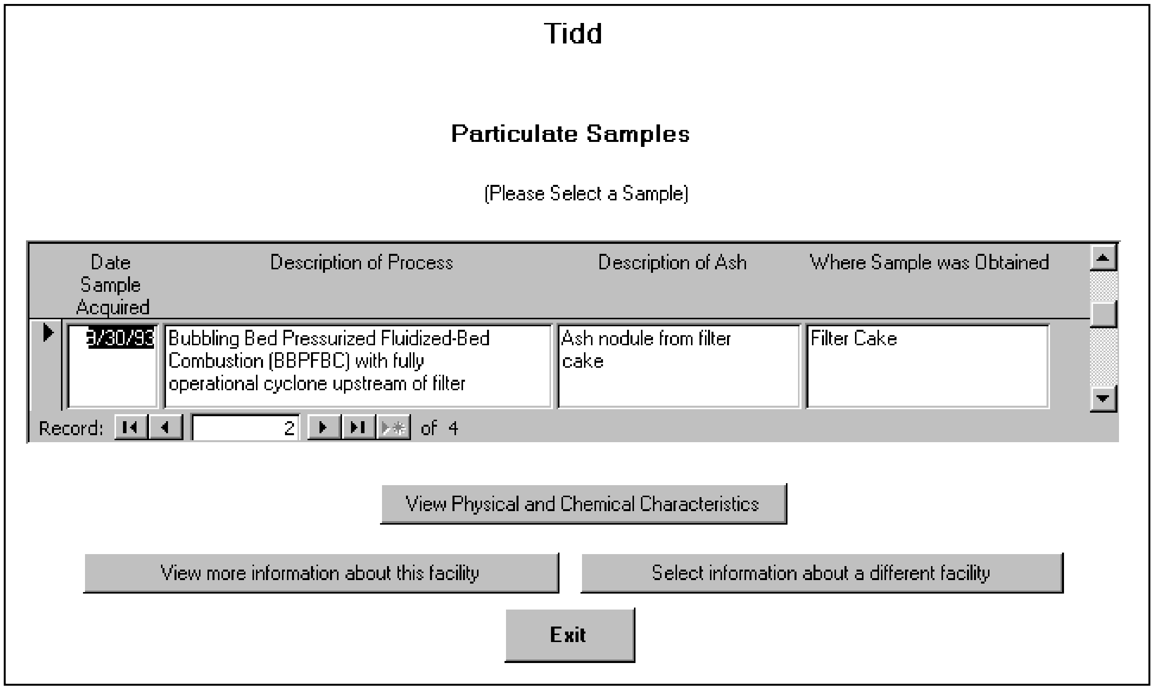

Figure 10. Samples are selected for subsequent examination of their characteristics using this screen. This screen is being modified to list more samples.

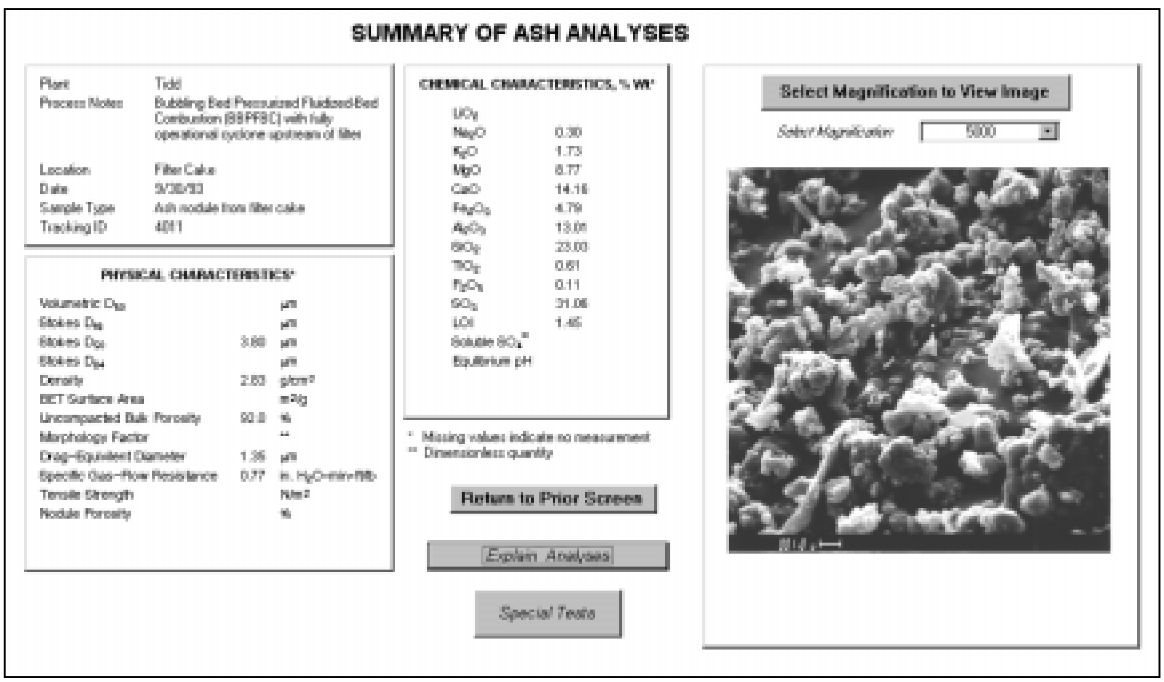

Figure 11. Measured sample characteristics are displayed on this screen.

TASK 2 FILTER MATERIAL CHARACTERIZATION

Tensile and thermal expansion testing of two Dupont PRD-66C candle filters, one McDermott ceramic composite candle filter, one Blasch 4-270 candle filter, and one Specific Surface cordierite candle filter were completed during the past quarter. The test matrix for these candles along with the current status of the testing is presented in Table 5. So far, the tensile and thermal expansion measurements have been completed and were summarized in a poster session at the Advanced Coal-Based Power and Environmental Systems ’98 Conference. All results obtained to date were written up in the paper “Preliminary Evaluation of Candidate Filter Materials” which was submitted for inclusion in the proceedings of the conference. A copy of that paper is provided as an appendix to this quarterly report. The other tests are in progress. The test matrix for the 20-inch long Dupont PRD-66C, McDermott ceramic composite, and Westinghouse Techniweave candle filters, as-manufactured and after exposure to the gasification environment, is presented Table 6. Machining of these specimens is in progress.

Table 5
Test Matrix for Dupont PRD-66C, McDermott Ceramic Composite, Blasch 4-270, and Specific Surface Cordierite Candle Filter Materials

Material	Test	Replications at Temp. (°F) RT	1800	Status
Dupont PRD-66C	Tn-hoop	18		complete
	Tn-axial	6		complete
	TE-axial	2----------------→		complete
	TE-hoop	2----------------→		complete
	K-radial	2----------------→		in progress
	Tn-creep-ax	3 (temperatures TBD)		more mat'l req'd
	microscopy	X		in progress
McDermott	Tn-hoop	9		complete
	Tn-axial	3		complete
	TE-axial	2-----------------→		complete
	TE-hoop	2-----------------→		complete
	K-radial	2-----------------→		in progress
	Tn-creep-ax	3 (temperatures TBD)		more mat'l req'd
	microscopy	X		in progress
Blasch	Tn-hoop	9		complete
	Tn-axial	4		complete
	TE-axial	2-----------------→		complete
	K-radial	2------------------→		in progress
	Tn-creep-ax	3 (temperatures TBD)		in progress
	Microscopy	X		in progress
Specific Surface	Tn-hoop	4		complete
	Tn-axial	5		in progress
	TE-axial	2-----------------→		complete
	TE – hoop	2-----------------→		complete
	K – radial	2-----------------→		in progress
	Tn-creep-ax	3 (temperatures TBD)		in progress
	Microscopy	X		in progress

Legend: Tn - tensile, TE - thermal expansion, K – thermal conductivity

Table 6

Test Matrix for Dupont PRD-66C, B&W, and Westinghouse Techniweave Candle Filter Materials, As-Manufactured and After Gasification Exposure

Material	As-manufactured/ Exposed	Test	Replications at Temp. (°F) RT	1800
Dupont PRD-66C	As-manufactured	Tn-hoop	6	
		TE-hoop	1----------------→	
		microscopy	X	
Dupont PRD-66C	Exposed	Tn-hoop	6	
		TE-hoop	2----------------→	
		microscopy	X	
Techniweave	As-manufactured	Tn-hoop	6	
		TE-hoop	2-----------------→	
		microscopy	X	
Techniweave	Exposed	Tn-hoop	6	
		TE-hoop	2-----------------→	
		microscopy	X	
B&W	As-manufactured	Tn-hoop	3	
		TE-hoop	1-----------------→	
		microscopy	X	
B&W	Exposed	Tn-hoop	3	
		TE-hoop	2-----------------→	
		microscopy	X	

FUTURE WORK

Efforts under Task 1 during the next quarter will include presentation of project results at the Advanced Coal-Based Power and Environmental Systems '98 Conference scheduled for July, and further analyses of the Piñon Pine particulate sample. A site visit to the PSDF for filter inspection and sampling is planned for August. Improvements and modifications to the HGCU data bank will continue during the next quarter. In the upcoming quarter, the testing shown in the test matrices of Tables 5 and 6 will be completed. Note that more Dupont PRD-66C and McDermott ceramic composite material will be required.

Preliminary Evaluation of Candidate Candle Filter Materials

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Introduction

Coal-fired Pressurized Fluidized Bed Combustion (PFBC) and Integrated Gasification Combined Cycle (IGCC) systems require ceramic candle filter elements that can withstand the mechanical, thermal, and chemical environment of hot gas cleanup applications. These systems require filter elements to sustain the thermal stresses of normal operations (pulse cleaning), of start-up and shut-down conditions, and of thermal transients generated during process upsets. They must have sufficient strength to withstand the mechanical loads associated with handling and assembly. For long-term operation, they must withstand the chemical environment of the PFBC system at temperatures up to 1600°F without chemical degradation, creep, or static fatigue failure.

Previous characterization of candidate candle filter materials has focused on Schumacher and Pall clay-bonded SiC and Coors P-100A-1 alumina mullite filters. Results obtained for the SiC materials indicate that up to 1400°F, these materials potentially have a long life (thousands of hours) in the absence of major process upsets and temperature excursions. Above 1400°F, creep, static fatigue, and property degradation will limit the use of clay-bonded SiC materials. Coors alumina mullite is not susceptible creep or property degradation; however, static fatigue and susceptibility to thermal stress failure, especially in the event of temperature excursions, will limit the use of this material.

Dupont/Lanxide PRD-66C, McDermott continuous fiber ceramic composite, Blasch Precision Ceramics 4-270 monolithic oxide ceramic, and Specific Surface cordierite have been manufactured in an effort to provide candle filters which can survive long term operation at temperatures up to 1600°F in the hot gas filtration environment of PFBC systems. Dupont/Lanxide PRD-66C is an all-oxide candle filter manufactured using a consumable textile grade glass yarn in an Al_2O_3 binder. Two PRD-66C candle filters with dimensions of ~2.35” O.D. x ~1.74” I.D. x ~60” long were supplied for testing. McDermott continuous fiber ceramic composite is manufactured of continuous Nextel 610 fiber and chopped saffil fiber in an Al_2O_3 binder. One McDermott candle filter with dimensions of ~2.36” O.D. x ~1.94” I.D. x ~60” long was supplied for testing. Blasch Precision Ceramics 4-270 is a mullite-bonded aluminum oxide monolithic ceramic. One Blasch candle filter with dimensions of ~2.36” O.D. x ~1.50” I.D. x ~60” long was supplied for testing. Specific Surface cordierite candles consist of two concentric filter walls, shaped like a sock with the toe end tucked back inside, connected by “stiffeners”. The outer filter wall is ~2.40” O.D. x ~1.98” I.D. and the overall candle length is ~12.75”. All testing was conducted on specimens taken from the outer wall of one candle filter. Preliminary evaluations have been conducted on the materials listed above in order to obtain an initial indication of the materials ability to operate in the hot gas filtration environment. Properties measured include room temperature hoop tensile strength, room temperature axial tensile stress-strain response, thermal expansion from room temperature to ~1600°F, and thermal conductivity from room temperature to ~1600°F. Results obtained to date are presented in this paper.

Objectives

Objectives of the test program at Southern Research are as follows:

1. Provide material characterization to develop an understanding of the physical, mechanical, thermal behavior of hot gas filter materials.

2. Develop a material property data base from which the behavior of materials in the hot gas cleanup environment may be predicted.

3. Perform testing and analysis of filter elements after exposure to actual operating conditions to determine the effects of the thermal and chemical environments in hot gas filtration on material properties.

Approach

Based on the anticipated operating conditions in the hot gas cleanup environment and on the in-service performance of candle filters tested to date, several critical issues have been identified for candle filter materials. A summary of the critical material issues for candle filters is given in Table 1. As shown, material issues are summarized in four categories, installation and handling, pulse cleaning, process upsets, and life, which place different requirements on the candles. The candles must have sufficient strength to withstand the mechanical loads and "toughness" to withstand bumps, nicks, scrapes, etc. associated with handling and installation. During pulse cleaning, the backpulse imparts a temperature difference on the inside surface of the candle rapidly enough that the temperature distribution through the candle wall is nearly a step function. That is, the surface achieves the temperature of the backpulse gas while the rest of the material is still at the nominal operation temperature. Therefore, the thermal stress level during pulse cleaning is set by the candle operating temperature, backpulse gas temperature, Young's modulus of the candle, and the thermal expansion of the candle while thermal diffusivity has little influence. During process upsets, the temperature changes over a period seconds or minutes so that the material through the wall thickness will react and heat up or cool down so that a more moderate gradient is obtained. The temperature gradients generated during process upsets will depend on the thermal diffusivity of the candle. Therefore, since the thermal stress level depends on the temperature gradient, the thermal stresses generated during process upsets will be set by the temperature rise/drop rate of the upset, Young's modulus, thermal expansion, and thermal diffusivity of the candle. Long-term operation will require candle filters that can survive the thermal and chemical environment without creep or static fatigue failure or excessive property degradation due to chemical attack. Testing was conducted according to the test matrix shown in Table 2. This test matrix was designed to address the critical issues discussed above. For example, mechanical strength is addressed by tensile strength measurements while thermal stress susceptibility is addressed by measuring tensile stress-strain, thermal expansion, and thermal conductivity measurements. There are several critical material issues not discussed above such as permeability, ability to manufacture to desired dimensions, cost, etc. These issues are not being addressed under the current test plan for these materials at Southern.

Results

Dupont/Lanxide PRD-66

Room temperature axial tensile stress-strain responses were measured on six specimens. Three specimens were machined from two different filter elements and the specimens were taken from various axial locations (that is, bottom, middle, and top). Each specimen consisted of a 7-inch long, full diameter section of the element. Two inches on each end of the specimens were used for gripping, leaving a three-inch long gage section. Strain was measured over a two-inch long region at the middle of the gage section. The responses were digitized and are shown in Figure 1 and the properties obtained are summarized in Table 3. Note that four of the specimens failed at the glue line at the end of the grips. Failure at the glue line appeared to have little affect on the ultimate strength or strain-to-failure; however, the values were not included in the calculation of averages. The average properties obtained were: ultimate tensile strength – 290 psi, Young's modulus – 0.35 msi, and strain-to-failure – 1.65 mils/inch.

Room temperature hoop tensile properties were measured on eighteen specimens. Nine specimens were machined from various axial locations of two different candles. Strain gages were mounted to the inside and outside surfaces of four specimens both to try and obtain a measure of Young's modulus in the hoop direction and to investigate the anisotropic behavior of the material. Note that some difficulty in using strain gages with this material is acknowledged. First, the surfaces are rough which leads to difficulty attaching the gages. Second, strain gage epoxy impregnates the pores and can affect the measured values. However, even with these difficulties the strain gages were used because it is necessary to understand the anisotropic nature of the material. For an isotropic material, hoop stresses are given by the classical elasticity equation for a thick-walled ring:

$$\sigma_\theta = \frac{a^2 P}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right)$$

where: σ_θ = loop tensile stress
P = uniform internal gage pressure
a = inside radius
b = outside radius

If the stresses are evaluated at the ID and OD, then a ratio of $\frac{\sigma_{\theta/ID}}{\sigma_{\theta/OD}} = \frac{1}{2}\left(1 + \frac{b^2}{a^2}\right)$

is obtained. Further, if the stress-strain response is linear, then $\frac{\varepsilon_{\theta/ID}}{\varepsilon_{\theta/OD}} = \frac{1}{2}\left(1 + \frac{b^2}{a^2}\right)$

For the PRD-66C rings tested, the ratio of $\frac{\varepsilon_{\theta/ID}}{\varepsilon_{\theta/OD}}$ was calculated to be 1.2 for the isotropic stress distribution. However, results obtained from the strain gages showed that $\frac{\varepsilon_{\theta/ID}}{\varepsilon_{\theta/OD}}$ ~3.5. These results indicate that the PRD-66C material is anisotropic. The equation for maximum stress in an anisotropic thick-walled ring is given by (see Lekhnitskii, Reference 1):

$$\sigma_\theta = \frac{P_i k\left(\frac{a}{b}\right)^{k+1}}{1 - \left(\frac{a}{b}\right)^{2k}}\left[\left(\frac{a}{b}\right)^{k-1} + \left(\frac{b}{a}\right)^{k+1}\right]$$

where σ_θ,Pi, a, and b are as defined above and k = $\sqrt{\frac{E_\theta}{E_r}}$

The hoop tensile properties are summarized in Table 4. Strength values are shown as calculated by the isotropic solution and the anisotropic solution while Young's modulus values shown were all calculated by the anisotropic analysis. Since only four strain gaged specimens have been tested, the anisotropic values should be considered preliminary until more strain gage data are obtained. Average properties were: ultimate tensile strength – 840 psi by isotropic solution and 1400 psi by anisotropic solution, Young's modulus – 3.0 msi, and hydrostatic pressure at failure – 240 psig.

Axial and diametral thermal expansions are plotted in Figure 2. A secant coefficient of thermal expansion (CTE) between 500 °F and 1500 °F was calculated for the axial direction and a value of 2.2 x 10^{-6}/°F was obtained. The CTE was calculated over this temperature range because it is likely that pulse cleaning and most thermal transients would occur within this range. The diametral expansion plotted in Figure 2 represents the change in diameter divided by the initial diameter. For anisotropic materials, thermal stresses are generated by temperature changes and these stresses restrain the specimen from its free expansion. Therefore, the expansion shown represents a structural value, not a material property. That is, the values would be different if the dimensions (ID and OD) were different.

McDermott Ceramic Composite

Room temperature and tensile stress-strain responses were measured on three specimens taken from various axial locations of one filter element. Specimen and loading configurations were like those used for PRD-66C. The responses were digitized and are shown in Figure 3 and the properties obtained are summarized in Table 5. Note that one specimen failed in the grip section. This was the first specimen tested and it was determined that failure occurred in the grip due to insufficient epoxy impregnation. For the two subsequent tests, better epoxy impregnation was obtained and failure occurred in the gage. The values shown in Table 5 for ultimate tensile strength and strain-to-failure correspond to the endpoints shown in Figure 3 and represent the point where maximum load was measured. The specimen did continue to carry some load and strain beyond this point; however, it is likely that damage had occurred which would render the material ineffective as a filter. To determine the damage level this material could withstand and still operate effectively would require additional work. Based on the endpoints as shown in Figure 3, properties obtained were: ultimate tensile strength – 610 psi, Young's modulus – 0.45 msi, strain-to-failure – 2.1 mils/inch.

Hoop tensile tests were conducted on one-inch high rings but the ultimate strength was not obtained because fiber pullout rather than tensile failure occurred. Additional longer specimens were not tested because all material had been consumed for other test specimens. Longer specimens will be tested when more material becomes available.

Axial and diametral thermal expansions are plotted in Figure 4. The secant CTE between 500°F and 1500°F was 4.6 x 10^{-6} in./in./°F. As with PRD-66C, the diametral expansion shown in Figure 4 includes the effect of thermal stresses generated due to differences in radial and hoop thermal expansion.

Blasch Precision Ceramics 4-270

Room temperature and tensile stress-strain responses were measured on four specimens taken at one axial location of one candle filter. Two additional specimens failed during machining. Unlike PRD-66C and McDermott, these specimens were taken from the wall of the candle filter and machined to a cylindrical, dogboned shape. Overall specimen length was 4.1 inches with the gage dimensions were 0.25" dia. x 1.20" long. The stress-strain responses obtained were digitized and are shown in Figure 5 and the properties obtained are summarized in Table 6. As shown, considerable variability was seen. Average properties were: ultimate tensile strength – 250 psi, Young's modulus – 0.80 msi, strain-to-failure – 0.30 mils/inch.

Room temperature tensile hoop strength was measured on nine specimens machined from various axial locations of one filter element. Values obtained were calculated from the elasticity solution for isotropic, thick-walled rings. Although it was not verified that this material is isotropic, there were no reasons to suspect anisotropy. The wall of each specimen had relatively thick and thin sections and all calculations were based on an average thickness. Hoop tensile results are summarized in Table 7. Average values were: ultimate tensile strength - 440 psi and hydrostatic pressure at failure – 180 psig. These average values do not include results obtained from specimens Tn-Hoop-1, 2, and 3. These specimens all came from the same region near the closed end of the filter. One of these specimens broke in handling and the other two failed at stress levels well below the other six specimens.

Axial thermal expansion is plotted in Figure 6. The secant CTE between 500°F and 1500°F was 4.1 x 10^{-6} in./in./°F.

Specific Surface Cordierite

Room temperature hoop tensile strength was measured on four specimens, two taken from near the flanged end of the candle and two taken from near the opposite end. The results are summarized in Table 8. Two ultimate strength values, 370 psi and 270 psi, were obtained and the corresponding values of hydrostatic pressure at failure were 70 psig and 53 psig. The other two specimens failed at very low stress levels. However, these specimens were taken from the region of the candle where "stiffeners" connect the inner and outer filter walls. The connection of the stiffeners to the candle wall likely served to reduce the strength of these two specimens so that these values do not represent the strength of the material. During service, the stiffeners may cause stress or strain intensification.

Axial thermal expansion is plotted in Figure 7. The secant CTE between 500°F and 1500°F was 1.0×10^{-6} in./in./°F.

Material Comparisons

Probable value axial, room temperature stress-strain curves for Dupont/Lanxide PRD-66C, McDermott ceramic composite, and Blasch 4-270 are plotted in Figure 8 along with previously reported curves for Pall 326, Schumacher TF20, and Coors P-100A-1. All the new materials had lower strengths than Pall, Schumacher, or Coors. However, PRD-66C and McDermott ceramic composite had much greater strain-to-failure which may lead to a tougher material more likely to survive thermal stresses generated during process transients. Room temperature tensile strengths in both the axial and hoop directions (where available) are compared for several materials in as-manufactured condition in Figure 9. This figure illustrates the lower as-manufactured strengths of the new materials. Several additional issues including material variability and property degradation during service should be addressed by future testing. Axial thermal expansion is plotted for the same seven materials in Figure 10. This figure shows McDermott ceramic composite and Blasch 4-270 have thermal expansion approaching the literature values for alumina with CTE values of 4.6×10^{-6} in./in./°F and 4.1×10^{-6} in./in./°F, respectively. Pall 326, Schumacher TF20, Coors P-100A-1, and Dupont PRD-66C and similar thermal expansions with CTE values ranging from 2.2×10^{-6} in./in./°F for Pall 326 and Coors P-100A-1. Specific surface cordierite has the lowest expansion with a CTE of 1.0×10^{-6} in./in./°F. Some key properties of several candle filter materials are compared in Table 9.

Conclusions

Dupont/Lanxide PRD-66C and McDermott ceramic composite have lower tensile strength than previously tested Pall 326 or Coors P-100A-1. The McDermott material has a strength comparable to Schumacher TF20 while PRD-66C is weaker. However, both materials had a strain-to-failure of approximately 3 times Coors P-100A-1 and an order of magnitude greater the clay-bonded SiC materials. The combination of tensile strain-to-failure and thermal expansion indicates that both PRD-66C and the McDermott material may withstand more sever temperature gradients than the previously tested materials. Thermal conductivity measurements are needed to evaluate the ability of these materials to survive during process upsets. Also, additional testing is needed to address life issues including creep and property loss during service for PRD-66C and McDermott ceramic composite.

Blasch 4-270 had a lower tensile strength than the previously tested materials and a strain-to-failure similar to Pall 326 and Schumacher TF20. Thermal expansion was higher than the clay-bonded SiC or Coors alumina mullite materials. The all-oxide composition may lead to better chemical compatibility in the PFBC environment than clay-bonded SiC; however, the combination of low strength and strain-to-failure with high thermal expansion may lead to problems surviving process upsets.

Specific Surface cordierite was manufactured and tested under this program both to evaluate a manufacturing technique and to investigate the use of cordierite as a candle filter material. The limited testing completed so far on this material indicates a reasonable tensile strength, although lower that for most other candle materials tested, and the lowest thermal expansion of any candle tested so far were obtained.

Future Plans

Future plans at Southern include:

- complete testing shown in the test matrix for PRD-66C, McDermott ceramic composite, Blasch 4-270, and Specific Surface cordierite (more PRD-66C and McDermott material are required).
- measure residual properties after service in PFBC to address long-term survivability.
- perform testing on additional materials as they become available.

Reference

1. Lekhnitskii, S.G., Anisotropic Plates, Gordon and Breach Science Publishers, 1968.

Acknowledgments

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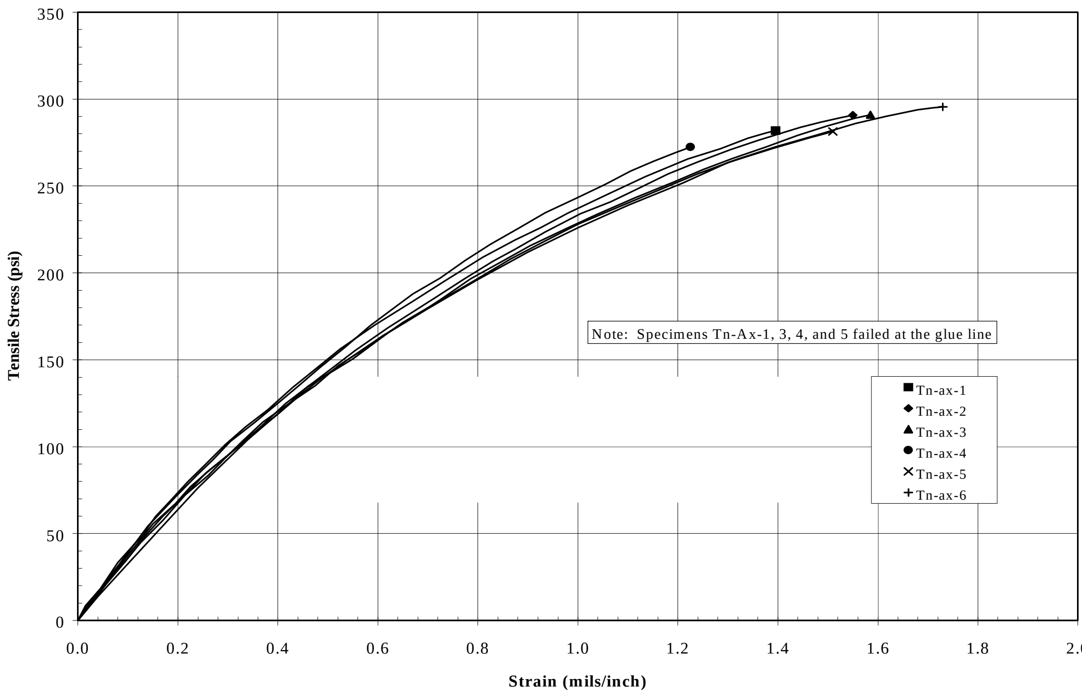

Figure 1. Axial Tensile Stress-Strain Responses for Dupont/Lanxide PRD-66C

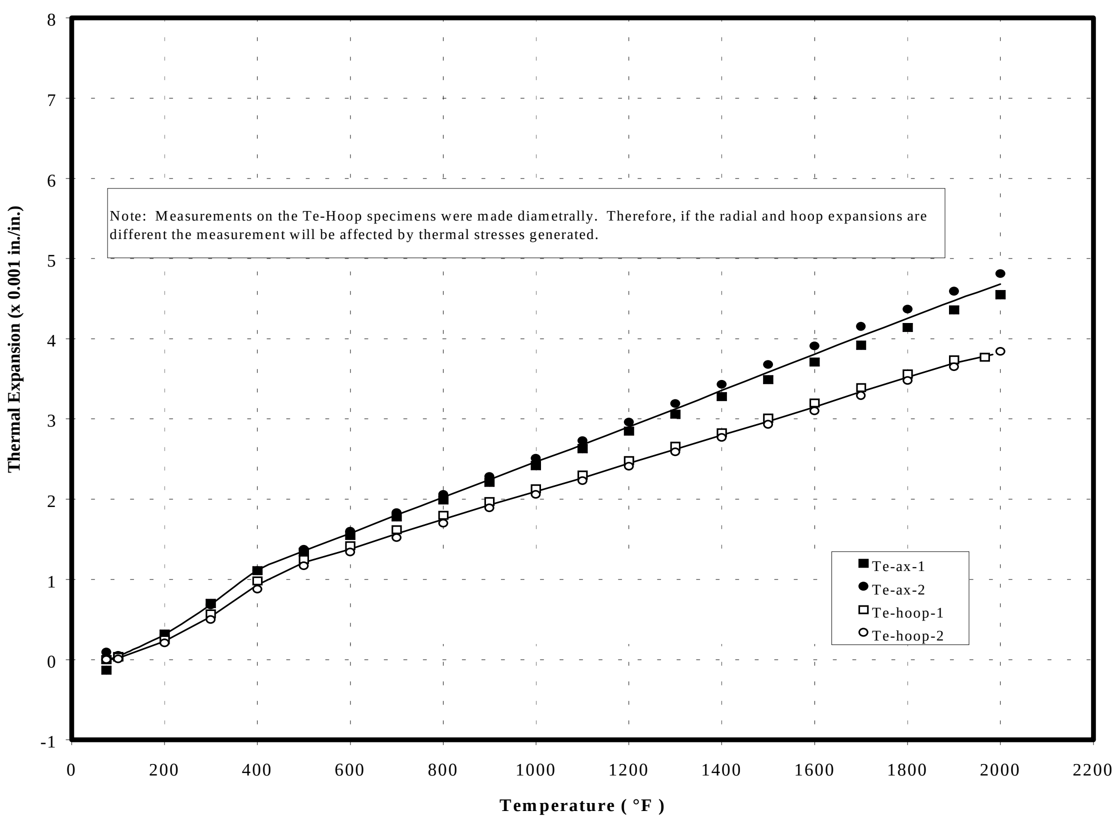

Figure 2. Thermal Expansion of Dupont/Lanxide PRD-66C

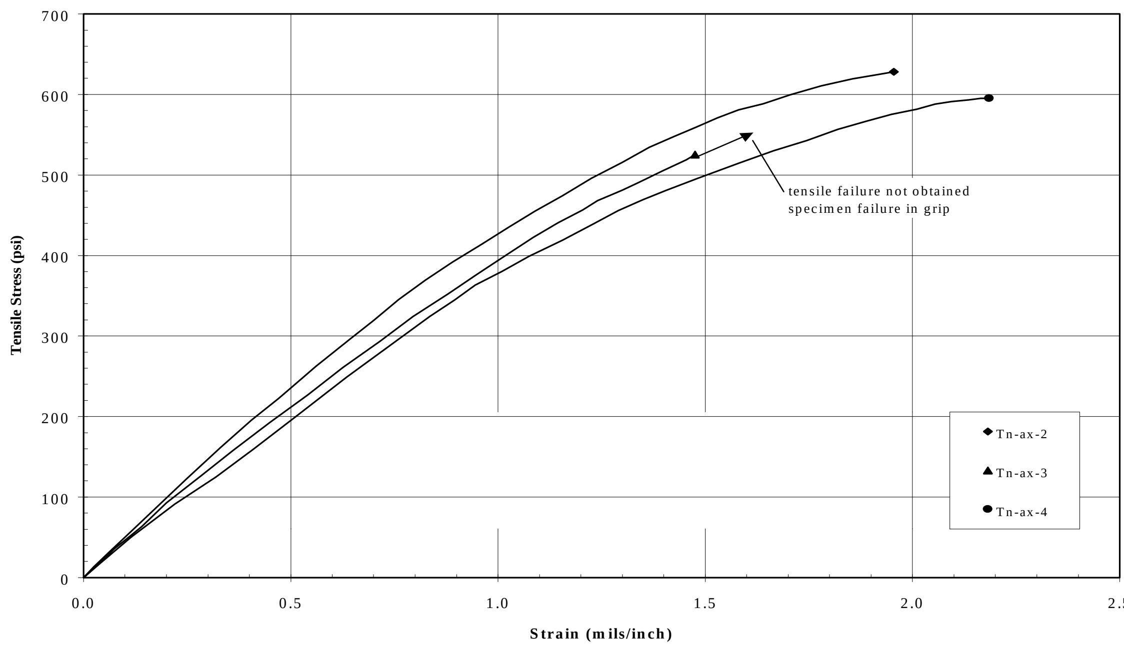

Figure 3. Axial Tensile Stress-Strain Responses of McDermott Ceramic Composite

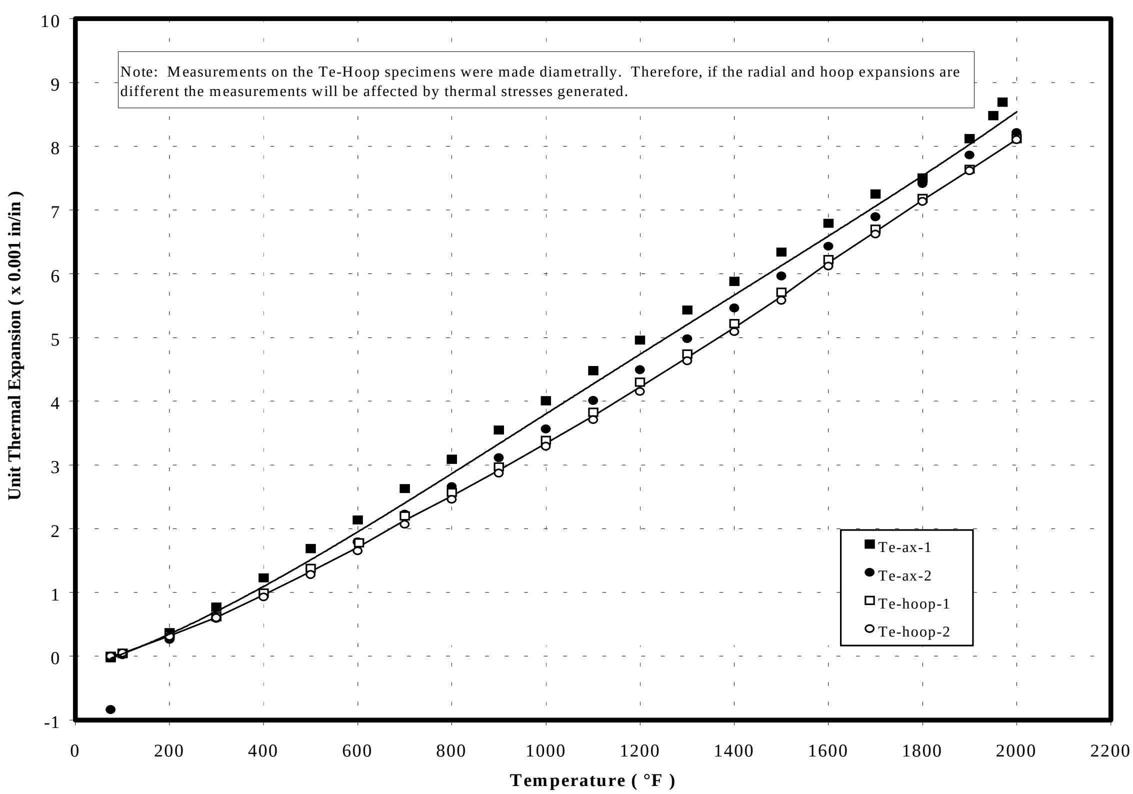

Figure 4. Thermal Expansion of McDermott Ceramic Composite

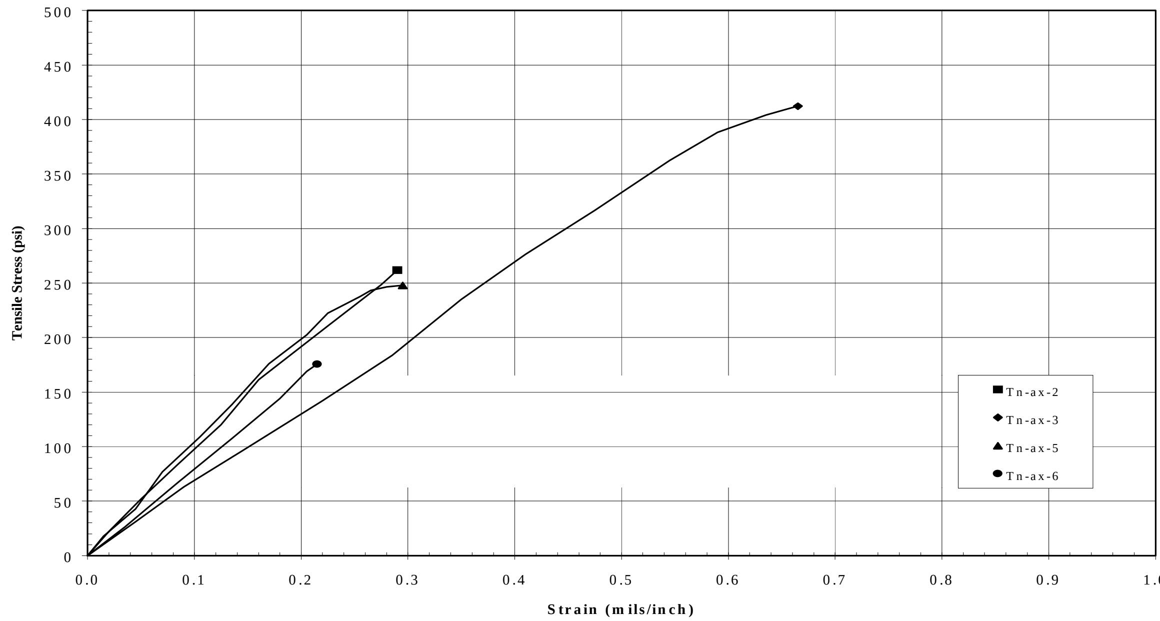

Figure 5. Axial Tensile Stress-Strain Responses of Blasch Precision Ceramics 4-270

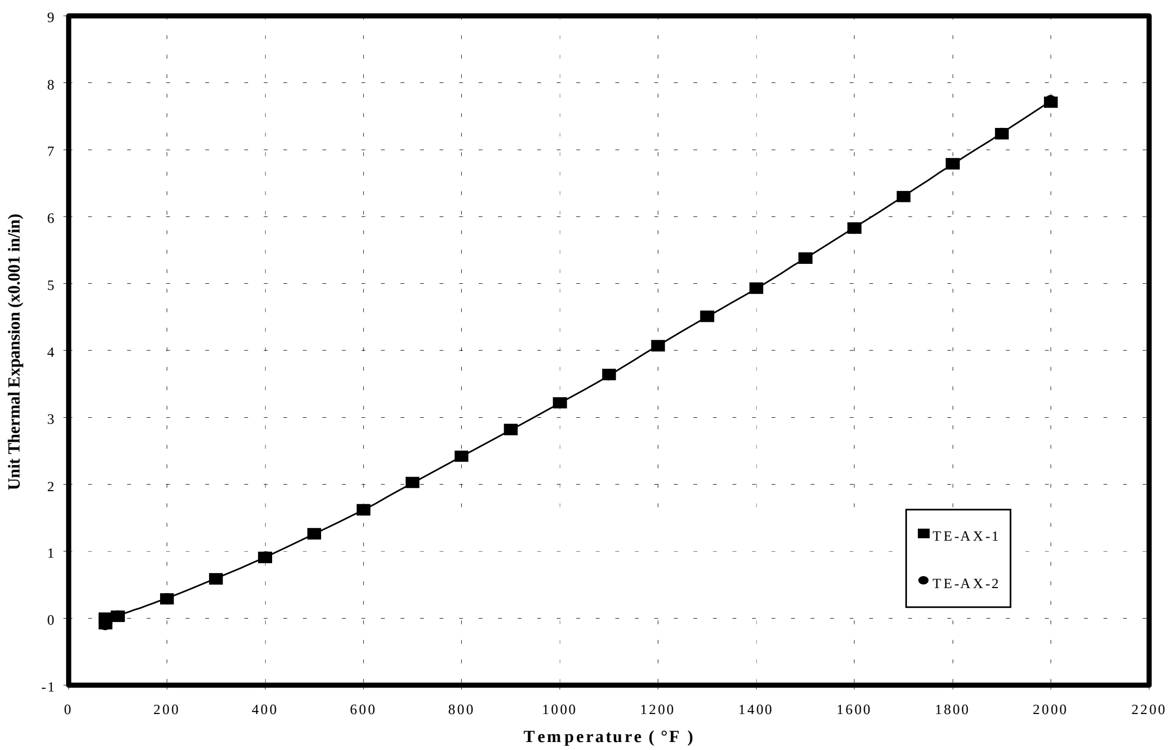

Figure 6. Axial Thermal Expansion of Blasch Precision Ceramics 4-270

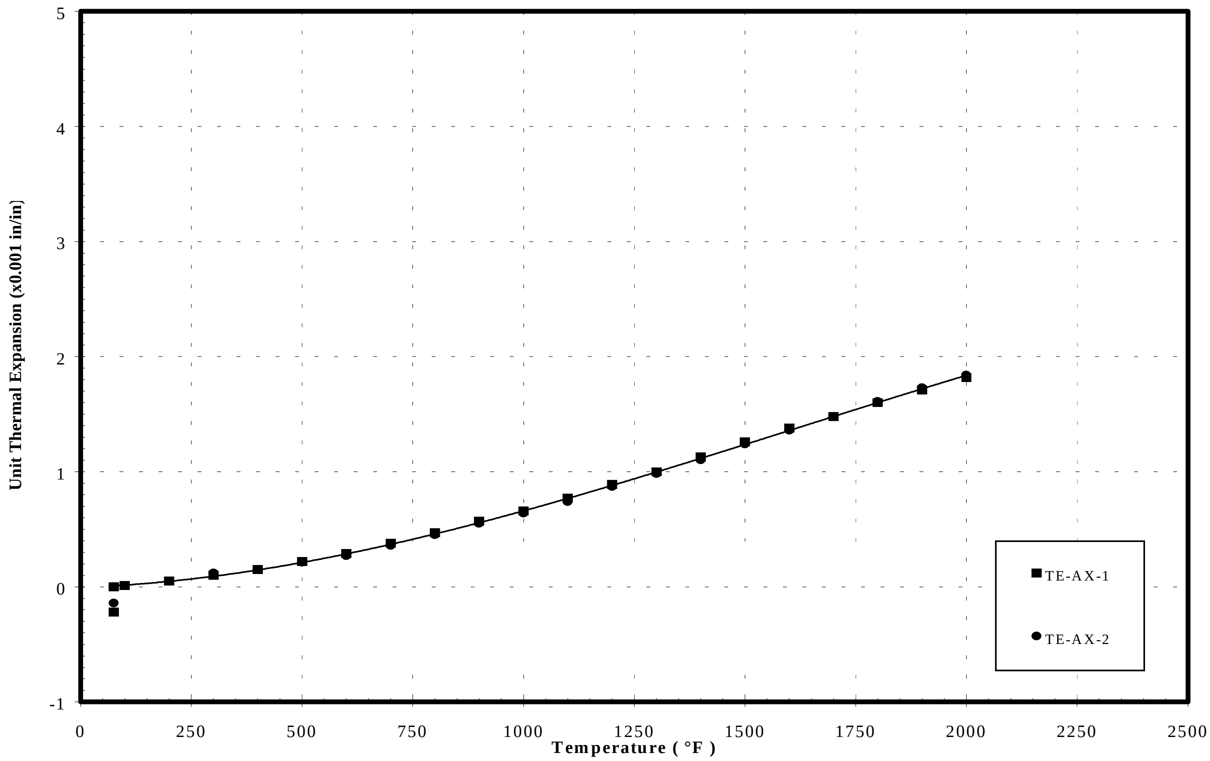

Figure 7. Axial Thermal Expansion of Specific Surface Cordierite

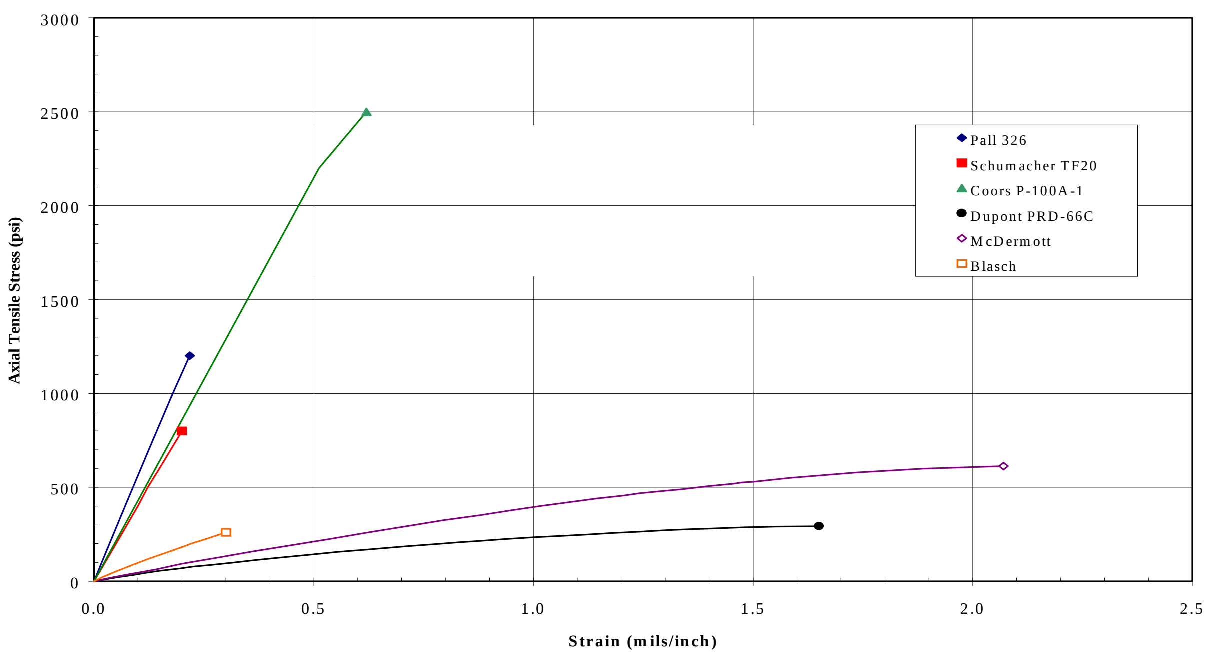

Figure 8. Probable Value Axial Tensile Stress-Strain Responses at Temperature

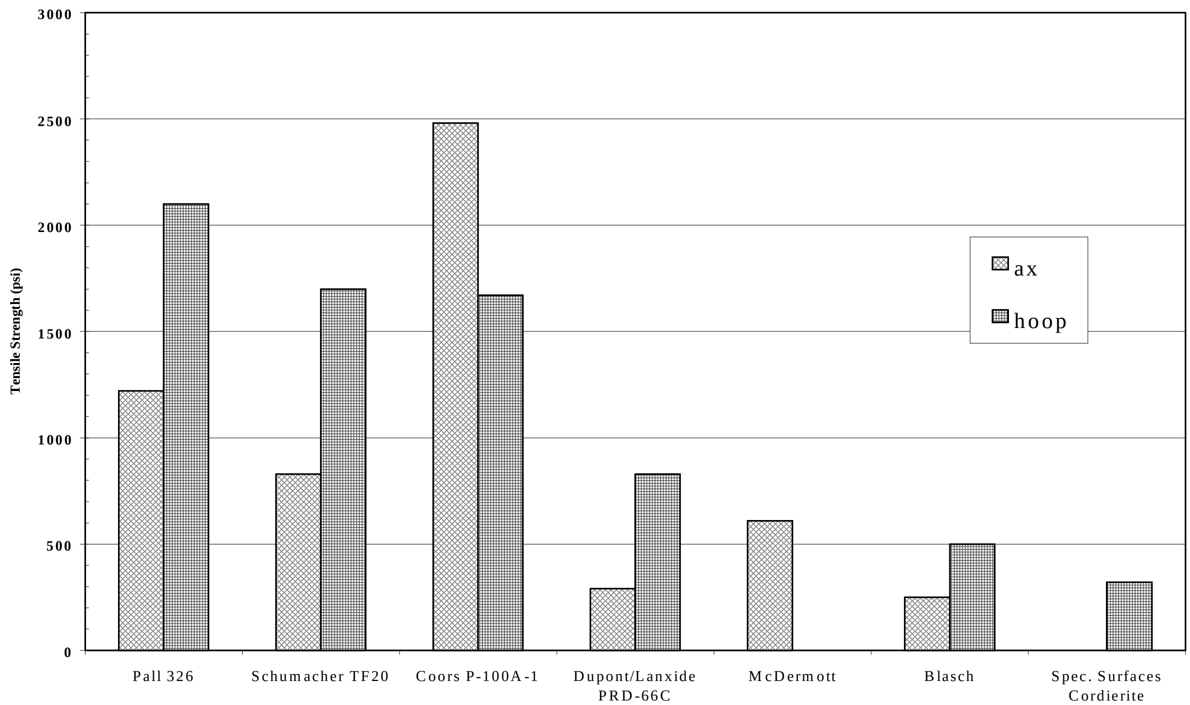

Figure 9. Room Temperature Tensile Strength of Several Candle Filter Materials

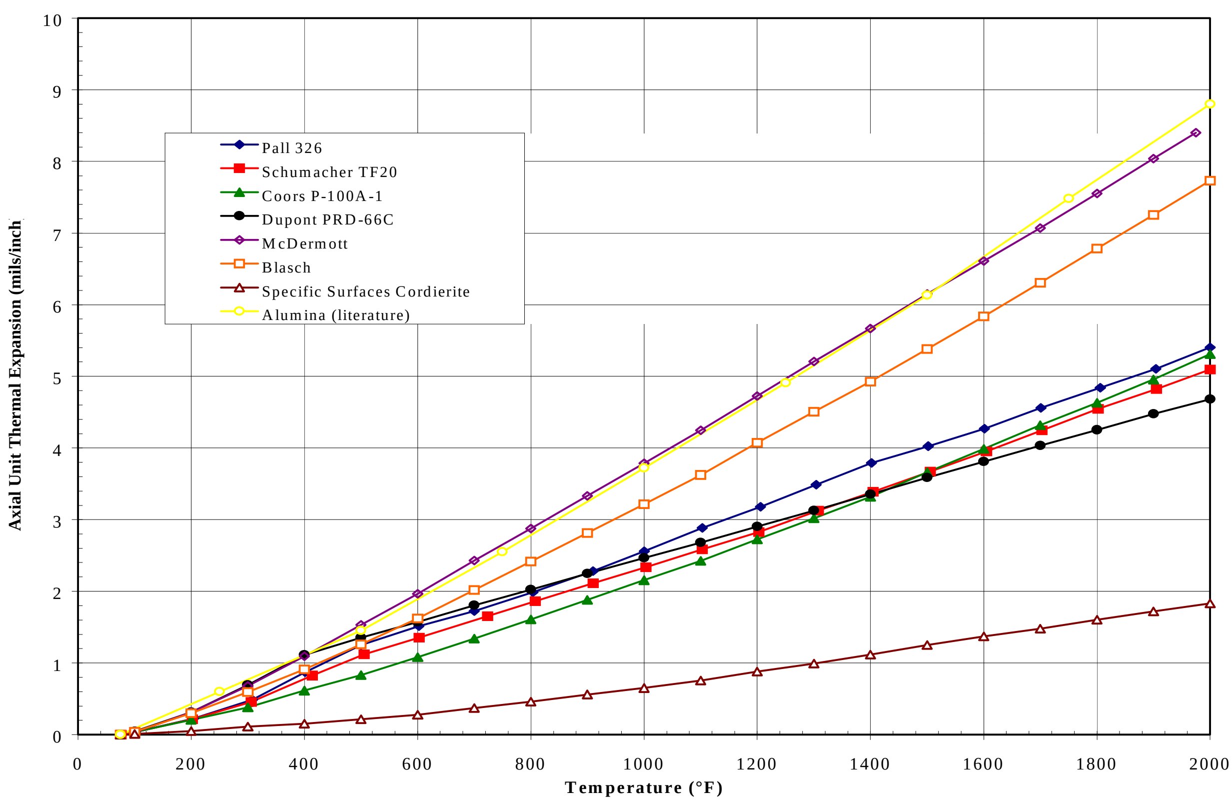

Figure 10. Axial Thermal Expansion of Several Candle Filter Materials

Table 1
Critical Material Issues for Candle Filters

Installation and Handling	**Process Upsets (thermal stress and other loads)**	**Life (creep, static fatigue, degradation)**	**Pulse Cleaning (thermal stress)**
Tensile strength "Toughness"	Thermal expansion Tensile strain-to-failure Thermal conductivity Tensile Strength "Toughness"	Creep Static fatigue/crack propagation Degradation	Thermal Expansion Tensile strain-to-failure "Toughness"

Table 2
Test Matrix for PRD-66C, McDermott Ceramic Composite, Specific Surfaces Cordierite, and Blasch Precision Ceramics Candle Filters

Material	**Test**	**Replications at Temp. (°F)** **RT** **1800**
Dupont PRD-66C	Tn-hoop	18
	Tn-axial	6
	TE-axial	2-----------------------------→
	TE-hoop	2-----------------------------→
	K-radial	2--------------------→
	Tn creep – ax	3 (temperatures TBD)
	Microscopy	X
McDermott	Tn-hoop	9
	Tn-axial	3
	TE-axial	2-----------------------------→
	TE-hoop	2-----------------------------→
	K-radial	2--------------------→
	Tn creep – ax	3 (temperatures TBD)
	Microscopy	X
Specific Surface	Tn-hoop	4
	Tn-axial	5
	TE-axial	2-----------------------------→
	TE-hoop	2-----------------------------→
	K-radial	2--------------------→
	Tn creep – ax	3 (temperatures TBD)
	Microscopy	X
Blasch	Tn-hoop	9
	Tn-axial	4
	TE-axial	2----------------------------→
	K-radial	2--------------------→
	Tn creep – ax	3 (temperatures TBD)
	Microscopy	X

Legend: Tn - tensile, TE - thermal expansion, K – thermal conductivity

Table 3

Summary of Axial Tensile Results for Dupont/Lanxide PRD-66 Candle Filter Material

Filter Identification	Specimen Number	Test Temperature (°F)	Specimen I.D. (in.)	Specimen O.D. (in.)	Ultimate Tensile Strength (psig)	Young's Modulus (msi)	Strain-to Failure (mils/in.)	Notes
C631	Tn-Ax-1	RT	1.75	2.35	280	0.38	1.40	Failed at end of grips
C631	Tn-Ax-2	RT	1.74	2.35	290	0.35	1.56	
C631	Tn-Ax-3	RT	1.74	2.35	290	0.36	1.59	Failed at end of grips
C638	Tn-Ax-4	RT	1.74	2.33	270	0.35	1.22	Failed at end of grips
C638	Tn-Ax-5	RT	1.73	2.34	280	0.30	1.57	Failed at end of grips
C638	Tn-Ax-6	RT	1.73	2.34	~~290~~	~~0.34~~	~~1.74~~	
					283	0.35	1.51	

Table 4

Summary of Hoop Tensile Results for Dupont/Lanxide PRD-66 Candle Filter Material

Filter Identification	Specimen Number	Test Temperature (°F)	Specimen I.D. (in.)	Specimen O.D. (in.)	Maximum Hydrostatic Pressure (psig)	Isotropic Ultimate Tensile Strength[1] (psi)	Anisotropic Ultimate Tensile Strength[2] (psi)	Anisotropic Young's Modulus[2] at I.D. (msi)		Strain-to-Failure (mils/in.)	
								0°	90°	0°	90°
C631	Tn-Hoop-1	RT	1.75	2.35	193	680	1130				
C631	Tn-Hoop-2	RT	1.74	2.35	191	660	1080	3.2	3.2	>0.18	>0.30
C631	Tn-Hoop-3	RT	1.75	2.36	249	860	1440				
C631	Tn-Hoop-4	RT	1.75	2.35	249	870	1440				
C631	Tn-Hoop-5	RT	1.74	2.36	220	750	1280				
C631	Tn-Hoop-6	RT	1.74	2.35	239	830	1390				
C631	Tn-Hoop-7	RT	1.75	2.35	250	870	1450				
C631	Tn-Hoop-8	RT	1.75	2.35	195	670	1140	3.1	3.1	>0.39	>0.24
C631	Tn-Hoop-9	RT	1.74	2.35	238	820	1380				
C638	Tn-Hoop-10	RT	1.73	2.34	258	870	1490				
C638	Tn-Hoop-11	RT	1.75	2.35	221	770	1280	3.7	1.2	>0.25	1.02
C638	Tn-Hoop-12	RT	1.74	2.34	278	950	1610				
C638	Tn-Hoop-13	RT	1.74	2.34	253	880	1460				
C638	Tn-Hoop-14	RT	1.74	2.34	253	890	1470				
C638	Tn-Hoop-15	RT	1.74	2.33	270	950	1570				
C638	Tn-Hoop-16	RT	1.73	2.34	271	920	1570				
C638	Tn-Hoop-17	RT	1.73	2.36	237	790	1370	3.1	2.8	0.47	0.48
C638	Tn-Hoop-18	RT	1.73	2.34	~~271~~	~~930~~	~~1570~~				
					241	831	1396				
					27	93	158				
					11%	11%	11%				

Notes: 1. Isotropic stress calculations by Lame's solution
2. Anisotropic stress calculations as given by Lekhnitskii

Table 5

Summary of Hoop Tensile Results for McDermott Candle Filter Material

Filter Identification	Specimen Number	Test Temperature (°F)	Specimen I.D. (in.)	Specimen O.D. (in.)	Maximum Hydrostatic Pressure[1] (psig)	Isotropic Maximum Tensile Stress[1,2] (psi)	Anisotropic Maximum Tensile Stress[1,3] (psi)	Anisotropic Young's Modulus[2] at I.D. (msi) 0°	Anisotropic Young's Modulus[2] at I.D. (msi) 90°	Strain-to-Failure (mils/in.) 0°	Strain-to-Failure (mils/in.) 90°
8-1-23	Tn-Hoop-1	RT	1.96	2.43	>90	>420	>540				
8-1-23	Tn-Hoop-2	RT	1.94	2.36	>105	>540	>670	0.7			
8-1-23	Tn-Hoop-3	RT	1.94	2.39	>107	>520	>650				
8-1-23	Tn-Hoop-4	RT	1.95	2.36	>110	>590	>710				
8-1-23	Tn-Hoop-5	RT	1.94	2.38	>99	>490	>620				
8-1-23	Tn-Hoop-6	RT	1.94	2.36	>97	>500	>610				
8-1-23	Tn-Hoop-7	RT	1.94	2.36	>108	>560	>690				
8-1-23	Tn-Hoop-8	RT	1.94	2.34	>121	>580	>760	1.0	1.1	0.75	0.81
8-1-23	Tn-Hoop-9	RT	1.96	2.43	~~≥124~~	~~≥580~~	~~≥750~~				
					>107	>530	>670				

Notes: 1. Tensile failure was not obtained because the yarns pulled out. The values shown were the maximum values measured before pullout occurred. A longer specimen is required to obtain tensile failure.
2. Isotropic stress calculations by Lame's solution
3. Anisotropic stress calculations as given by Lekhnitskii

Table 6

Summary of Axial Tensile Results for Blasch Precision Ceramics Candle Filter Material

Filter Identification	Specimen Number	Test Temperature (°F)	Ultimate Tensile Strength (psi)	Young's Modulus (msi)	Strain-to-Failure (mils/in.)	Notes
BPC-B14	Tn-ax-1					Broke during machining
BPC-B14	Tn-ax-2	RT	260	0.96	0.30	
BPC-B14	Tn-ax-3	RT	410	0.67	0.67	
BPC-B14	Tn-ax-4	RT				Broke during machining
BPC-B14	Tn-ax-5	RT	250	1.03	0.30	
BPC-B14	Tn-ax-6	RT	175	0.81	0.22	

Table 7

Summary of Hoop Tensile Results for Blasch Precision Ceramics Candle Filter Material

Filter Identification	Specimen Number	Test Temperature (°F)	Specimen I.D. (in.)	Specimen O.D. (in.)	Maximum Hydrostatic Pressure (psig)	Ultimate Tensile Strength (psi)	Notes
BPD-B14	Tn-Hoop-1	RT					Broke in handling
BPD-B14	Tn-Hoop-2	RT	1.44	2.37	99	220	
BPD-B14	Tn-Hoop-3	RT	1.45	2.36	138	300	
BPD-B14	Tn-Hoop-4	RT	1.51	2.35	210	510	
BPD-B14	Tn-Hoop-5	RT	1.52	2.36	210	520	
BPD-B14	Tn-Hoop-6	RT	1.51	2.37	175	420	
BPD-B14	Tn-Hoop-7	RT	1.56	2.37	186	470	
BPD-B14	Tn-Hoop-8	RT	1.56	2.37	191	490	
BPD-B14	Tn-Hoop-9	RT	1.56	2.36	~~218~~	~~560~~	
					178	436	
					41	118	
					23%	27%	

Table 8

Summary of Hoop Tensile Results for Specific Surfaces
Cordierite Candle Filter Material

Filter Identification	Specimen Number	Test Temperature (°F)	Specimen I.D. (in.)	Specimen O.D. (in.)	Maximum Hydrostatic Pressure (psig)	Ultimate Tensile Strength (psi)	Young's Modulus at I.D. (msi)		Strain-to-Failure (mils/in.)		Notes
							0°	90°	0°	90°	
3	Tn-Hoop-1	RT	1.98	2.40	70	370	1.25	1.25	0.3	0.29	
3	Tn-Hoop-2	RT	1.98	2.40	53	270					
3	Tn-Hoop-3	RT	1.98	2.39	10	50					specimen adjacent to "stiffener"
3	Tn-Hoop-4	RT	1.98	2.40	7	30					specimen adjacent to "stiffener"

Table 9
Properties of Candle Filter Materials

	Pall 326	Schumacher TF20	Coors P-100A-1	Dupont PRD-66C	McDermott Ceramic Composite	Blasch 4-270	Specific Surface Cordierite
RT Axial Tensile Strength, psi	1220	830	2480	290	610	250	
RT Axial Young's Modulus, msi	5.7	4.0	4.3	0.35	0.45	0.80	
RT Axial Strain-to-Failure, in/in	0.23	0.21	0.62	1.65	2.10	0.30	
RT Hoop Tensile Strength, psi	2100	1700	1800	830		500	320
RT Hoop Young's Modulus, msi				3.2	1.0		
Maximum Hydrostatic Pressure, psig	860	660	680	240		200	60
Average Axial CTE 500 – 1500 °F, in/in/°F	2.8	2.5	2.8	2.2	4.6	4.1	1.0
Thermal Conductivity at 1000 °F, BTU-in/hr-ft²-°F	38	52	11				

PARTICULATE HOT GAS STREAM CLEANUP TECHNICAL ISSUES

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