Advanced Hot Gas Filter Performance and Characterization

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Abstract

Commercialization of the hot gas filtration technology is focused on identifying the functional performance of specific filter system designs, integration with pilot and demonstration-scale first and second generation pressurized fluidized-bed combustion and integrated gasification combined cycle process systems, and developing a viable filtration media for extended service life. Significant accomplishments have been made during the past five years to not only manufacture advanced monolithic and fiber reinforced ceramic composite filter elements, but also to demonstrate their performance and potential useful service life in qualification and field test programs. The response, performance, and characterization of the advanced porous ceramic candle filters during operation in Westinghouse's Advanced Particulate Filtration system at the Foster Wheeler pressurized circulating fluidized-bed combustion test facility in Karhula, Finland, is discussed in this paper.[†] In addition, our efforts to establish extended functional life of the porous ceramic filter elements under simulated combustion conditions, and future efforts directed to service operation of the elements in demonstration-scale gasification systems are reviewed.

Introduction

Since the late 1970's, development of porous ceramic filter elements has expanded from the manufacture of monolithic oxide-based and clay bonded silicon carbide candles to the production of filament wound, continuous fiber reinforced ceramic composite, and sintered metal candle filters. Similarly transitioning of the candle filter technology to the production of monolithic cross flow filters, as well as alternate filter geometries has occurred.

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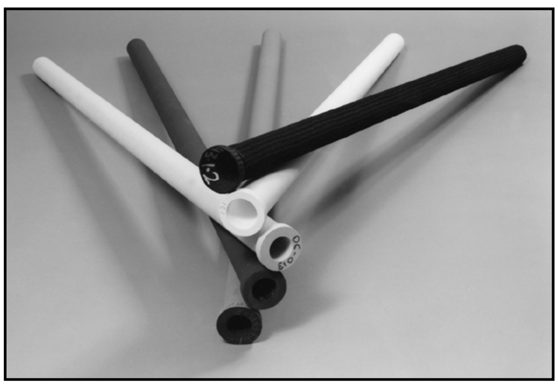
Emphasis at Westinghouse since 1990 has been focused on the design and operation of Advanced Particulate Filtration (APF) systems. At the American Electric Power (AEP) Tidd Demonstration Plant in Brilliant, Ohio, Westinghouse's APF housed 384 commercially available, 1.5 m porous ceramic candle filters which were subjected to pressurized fluidized-bed combustion (PFBC) conditions. Similarly, 128 commercially available, 1.5 m candles were installed and operated in Westinghouse's APF at the Foster Wheeler pressurized circulating fluidized-bed combustion (PCFBC) pilot-scale test facility in Karhula, Finland. The total operating service life of surveillance filters which were installed at these facilities is shown in Figure 1. In 1997, the opportunity to continue testing commercially available monolithic elements, and introduce the utilization of alternate monolithic and advanced continuous fiber reinforced ceramic composite candles occurred at Karhula. Similar testing is currently on-going in the Westinghouse Particle Collection Device (PCD) at the Southern Company Services (SCS) test facility in Wilsonville, Alabama.



Filter Supplier Matrix	Maximum Operating Hours	
	PFBC	PCFBC
Schumacher F40	5855	227[1]
Schumacher FT20	1705	2201[2]
Pall Vitropore 442T	1705	1341[1]
Pall 326		2201[2]
Coors P-100A-1 Alumina/Mullite	2815	716[1] 2201[2] 3311[3]
3M CVI-SiC	1705	627[4]
DuPont PRD-66	1705	581[5]
3M Oxide CFCC		
McDermott Oxide CFCC		581[5]
Techniweave Oxide CFCC		
Blasch Mullite/Alumina		581[5]
Other		342-581[6]

(1) 1992-1994 Test Campaign
(2) 1995-1997 Test Campaign
(3) 2201 hrs of Operation under PCFBC Conditions at Karhula and 1110 hrs of Operation under PFBC Conditions at Tidd
(4) 1995-1996 Test Campaign
(5) 1997 Test Campaign
(6) 1997 Test Campaign - Ceramic/Non Ceramic Filter Elements

Figure 1 — Westinghouse Advanced Particulate Filtration (APF) system field test experience.

Achieving three years of operational filter element life is the primary goal of the Westinghouse hot gas filter material development and component qualification programs. Efforts to demonstrate viable operation of the plant and warranted filter life are currently the focus of the Westinghouse APF system at the Sierra Pacific Power Company (SPPC), Piñon Pine, Tracey No. 4 Station in Reno, Nevada, which houses 748 candle filters. Commissioning of the SPPC integrated gasification combined cycle (IGCC) Demonstration Plant was initiated in 1997. In addition, Westinghouse is currently involved in the Clean Coal Program being undertaken at the McIntosh Unit 4 Demonstration Plant in Lakeland, Florida, where ~1500-2500 candle filters are targeted to be operated in PFBC and carbonizer process gas environments.

Objectives

The objectives of Westinghouse's Filter Component Assessment program with DOE/ FETC are to:

- Provide a more "ruggedized" filter system that utilizes porous ceramic filters which have improved resistance to damage resulting from crack propagation, thermal fatigue and/or thermal excursions during plant or process transient conditions, and/or mechanical ash bridging events within the candle filter array (Task 1).
- Assess the effects of long-term (i.e., 1000-1500 hours) pilot-scale exposure under actual pressurized circulating fluidized-bed combustion (PCFBC) conditions on advanced candle filter failure modes and degradation mechanisms (Task 2).
- Assess the stability of select advanced filter materials when subjected to long-term exposure in actual integrated gasification combined cycle (IGCC) gas streams (Task 3).
- Assess the potential long-term viability of field-exposed porous ceramic filter elements (Task 5).

Project Description

Efforts in the Filter Component Assessment program were initially focused on evaluating the filtration characteristics, mechanical integrity, and corrosion resistance of the 3M CVI-SiC composite, DuPont PRD-66 filament wound, DuPont SiC-SiC composite, and IF&P Fibrosic™ second generation candle filters, qualifying each filter element type for possible use in advanced coal-fired applications (Task 1). Efforts were then directed to similarly evaluate the performance of the 3M, McDermott, and Techniweave oxide-based continuous fiber ceramic composite (CFCC) candle filters, as well as the monolithic mullite-bonded alumina Blasch 4-270, and cordierite-based Specific Surface Taperflow™ filter elements. Qualification testing which was conducted in Westinghouse's PFBC test facility in Pittsburgh, Pennsylvania, typically was used to demonstrate retrofit capabilities of each element into existing system hardware, and high temperature filtration characteristics, mechanical integrity, and general operating performance of the various advanced candle filters.

In order to assess the effects of long-term pilot-scale exposure on candle filter failure modes and degradation mechanisms in Task 2, the high temperature creep resistant Schumacher Dia Schumalith FT20 and Pall 326 elements, Coors P-100A-1 alumina/mullite, and 3M CVI-SiC composite candles were installed in Westinghouse's APF system at Foster Wheeler's PCFBC test facility in Karhula, Finland. Three test campaigns were completed between November 1995 and October 1996 in which 112-128 candles were operated for a period of 1166 hours at temperatures of ~850ºC. Illinois No. 6 coal was used as the feed material, and either Linwood or Iowa Industrial limestone were utilized as sulfur sorbents (Table 1).

Table 1. Westinghouse APF testing at Foster Wheeler during 1995-1996.

Test Segment	1 11/95 - 12/95	2 2/96-4/96	3 8/96-10/96
Coal	Illinois No. 6	Illinois No. 6	Illinois No. 6
Sorbent	Linwood Limestone	Linwood Limestone	Linwood Limestone Iowa Limestone Resized Linwood Limestone
Number of Candles	112	112	128
Coors P-100A-1	24(5)-42(5)[(a)]	33(5)[(a)]	32(4)[(a)]
Schumacher FT20	32-35	35	46
Pall 326	32-35	35	45
3M CVI-SiC	24-0	9	5
Operating Hours (Coal)	153	387	626
Operating Temperature, °C	826-853	818-860	838-860
Operating Pressure, bar	10.7-11.1	10.6-11.3	10.5-10.7
Nominal Face Velocity, cm/s	3.5-4.1	3.1-4.2	3.0-3.4
Inlet Dust Loading, ppmw	12000-13500	12000-15500	11000-12500
d_{50} µm (Malvern)	NA	NA	23(20-26)

NA: Not Available.
(a) Numbers in Parenthesis Indicate Number of PFBC-Exposed Elements (AEP TS5).

Table 2. Westinghouse APF testing at Foster Wheeler during 1997.

Test Segment	1 4/97 - 6/97	2 9/97-11/97
Coal	Eastern Kentucky	Eastern Kentucky
Sorbent	Florida Limestone	Florida Limestone
Number of Candles	128	90-112
Coors P-100A-1	72	28-33
Schumacher FT20	28	16-28
Pall 326	28	16-22
3M Oxide CFCC	–	7-0*
McDermott Oxide CFCC	–	6-7
Techniweave Oxide CFCC	–	2-0*
Blasch	–	4-6
DuPont PRD-66	–	7
Other	–	10
Operating Hours (Coal)	454	581
Operating Temperature, °C	820-850	700-750
Operating Pressure, bar	10-11	9.5-11
Nominal Face Velocity, cm/s	2.4-3.5	2.8-4.0
Inlet Dust Loading, ppmw	6600-10800	5700-9000
d_{50} µm (Malvern)		

* Failure of Elements after 40 Hrs of PCFBC Operation.

Post-test characterization of PCFBC-exposed surveillance candles included determining the resulting gas flow resistance of the filter elements, residual process temperature bulk strength, high temperature creep and thermal expansion properties, microstructure and phase composition of the ceramic matrices. In addition, characterization of ash samples that were removed from various locations within the three filter arrays was also conducted. These analyses included determining the bulk density, moisture content, bulk strength, thermal expansion, and identification of the morphology and composition of the ash materials.[1]

PCFBC testing was reinitiated in Karhula, Finland, in April 1997, and continued through November 1997, during which time coal and sorbent materials that are planned for the Lakeland PCFBC Clean Coal Demonstration Plant were utilized (Eastern Kentucky Beech Fork coal and Gregg Mine Florida limestone). Approximately 454 hours of operation of the Westinghouse APF were completed during TS1-97 (Table 2). The 128 candle filter cluster was operated at temperatures of ~850°C, consisting of a mixture of newly manufactured, as well as previously PCFBC or PFBC/PCFBC-exposed Schumacher Dia Schumalith FT20, Pall 326, and Coors P-100A-1 alumina/mullite candle filters. In September 1997 (TS2-97), advanced oxide-based monolithic and composite candles filters were installed and operated at temperatures of ~750°C for a period of 581 hours in conjunction with previously PCFBC-exposed commercially available candle filters.

Post-test characterization of select TS2-97 PCFBC-exposed candle filters is currently being conducted (Task 5), and recent results of this effort are presented in this paper. Extended life testing of select PCFBC-exposed candles is also being performed at the Westinghouse PFBC simulator test facility in Pittsburgh, Pennsylvania. Both monolithic and advanced second generation elements are being subjected to steady state testing, to a maximum of 20,000 accelerated pulse cleaning cycles (i.e., equivalent to ~10,000 hours of process operation), and to a maximum of 30 thermal transients simulating actual plant startup and/or shutdown cycles. Extended life testing is planned to be completed during the fall of 1998.

Additional effort has been focused in Task 3, to assess the stability of select advanced filter materials during long-term exposure in actual IGCC gas streams. To date design of a pressurized mini-vessel slip stream system has been completed, its position within the Sierra Pacific Power Company, Piñon Pine, IGCC Demonstration Plant in Reno, Nevada, has been identified, mini-candle filter elements have been procured, and metal structural coupons for exposure in the mini-vessel have been acquired. Construction and supply of the unit will be initiated after approval of the Westinghouse design specification packages for the pressure vessel and pulse gas skid has been received from Sierra and M. W. Kellogg, and interface engineering has been completed by M. W. Kellogg for retrofit of the unit into the existing plant.

Results and Accomplishments

The results and accomplishments that have been made by Westinghouse during conduct of the Filter Component Assessment program throughout the past year are presented in the following sections. A brief summary of the PCFBC test program conducted in Karhula, Finland, is initially presented to provide an overview of the strategy used for qualifying filter elements for selection and use in the Lakeland Clean Coal program, and to advance testing of second generation filter elements.[(2)]

Assessment of PCFBC Field-Exposed Advanced Candle Filters

Pilot-scale testing was conducted in the Westinghouse APF system at the Foster Wheeler test facility in Karhula, Finland, between April and June 1997 (TS1-97), utilizing previously PCFBC-exposed, commercially available Coors P-100A-1, Schumacher Dia Schumalith FT20, and Pall 326 filter elements. The 128 candle filter cluster was subjected to ~454 hours of operation at temperatures of ~850°C. Eastern Kentucky Beech Fork coal and Gregg Mine Florida limestone were used as feed materials. Testing was terminated in TS1-97 due to failure of three Coors P-100A-1 filter elements which had previously experienced 1110 hours of operation at AEP.

After dismantling and cleaning the entire cluster, 90 candles were installed, and testing resumed in September 1997 (TS2-97). In addition to the Coors P-100A-1, Schumacher Dia Schumalith FT20, and Pall 326 filter elements, seven oxide-based CFCC 3M and McDermott filter elements, as well as seven DuPont PRD-66 filament wound candles, six Blasch mullite-bonded alumina filters, and two Techniweave Nextel™ 720 oxide-based CFCC elements were installed in the bottom filter array. The unit was initially operated for a period of 40 hours at temperatures of 700-720°C prior to detecting dust in the outlet stream. Testing was subsequently terminated and the vessel was cooled. Post-test inspection of the filter cluster indicated that the two Techniweave and seven 3M oxide-based CFCC elements had experienced damage during the 40 hours of PCFBC operation. Close inspection of the Techniweave filter elements indicated that sections of the outer membrane through-thickness fibers were removed, and debonding of the outer seam and unwrapping of the 2-D fabric wrap or layered architecture resulted. Pinholes as a result of through-thickness fiber removal permitted ash fines to pass from the o.d. to i.d. surfaces of the PCFBC-exposed filter elements.

Similarly the 3M oxide-based CFCC elements experienced removal of sections from both the outer confinement and filtration mat layers, again permitting fines to pass from the o.d. to i.d. surfaces of the PCFBC-exposed filter elements. Sections of material beneath the confinement layer were also seen to be removed along the end caps of the 3M oxide-based CFCC filter elements. Although the Techniweave and 3M elements suffered damage during the 40 hours of PCFBC operation, all elements remained attached to the metal filter holder mounts. All of the damaged Techniweave and 3M PCFBC-exposed filters, and one as-manufactured element of each filter type were returned to Westinghouse for examination.

Since ash fines had been detected in the outlet gas stream after 40 hours of PCFBC operation, all elements in the bottom array were removed, and cleaned prior to reinstallation. During removal, one of the DuPont PRD-66 filter elements was broken at the base of the flange. This resulted due to the tight fit when ash became wedged in between the flange and filter holder mount. The broken element was replaced with an alternate, newly manufactured DuPont PRD-66 filter. Post-test inspection of the McDermott elements indicated that localized areas of the Saffil and alumina-enriched sol-gel matrix were removed adjacent to and below the outer

Nextel™ 610 filament surface. During cleaning of the McDermott elements, the relatively soft matrix lead to ‘pull-out’ of material and/or removal of broken Nextel™ 610 filaments. No apparent damage was experienced by the Blasch candles during either PCFBC testing or cleaning of the elements.

Once the bottom filter array and candles were cleaned (i.e., vacuum brushing; water washing), the elements were reinstalled in the array. Coors P-100A-1 alumina/mullite, Schumacher Dia Schumalith FT20, and Pall 326 elements were installed as replacements for the damaged Techniweave and 3M candles. PCFBC testing was then reinitiated and continued for an additional 199 hours of operation at 700-750°C using the Lakeland feed materials.

After 239 hours of service operation in TS2-97, testing was terminated and the unit was slow cooled, prior to inspection of the three filter arrays. During this planned outage, additional candles were installed to fill the bottom array. Testing was reinitiated and continued for an additional 342 hours of operation at temperatures of 700-750°C, again utilizing the Lakeland feed materials.

After completion of the PCFBC test campaign in 1997, the vessel was slow cooled, opened, and the filters were subsequently inspected. Post-test inspection of the filter arrays clearly indicated that ash bridging had not occurred (Figure 2). The thickness of the dust cake layer along the surface of the top array filter elements was ~2-3 mm, while an ~2-5 mm thick dust cake layer remained along the outer surface of the middle array elements, and an ~2-3 mm dust cake layer remained along the outer surface of the bottom array elements. The morphology of the ash fines that were present in the dust cake is shown in the scanning electron micrograph presented in Figure 3. Based on energy dispersive x-ray analysis (EDAX), the larger amorphous particles were considered to principally consist of ash fines (i.e., 69.06% O, 10.32% Si, 7.05% Al, 6.00% Ca, 3.88% S, 2.16% Fe, 1.10% K, 0.28% Ti, and 0.15% Mg; atomic percent basis), while the smaller agglomerated fines were considered to be primarily sorbent particles (i.e., 73.62% O, 10.68% Ca, 9.71% S, 3.12% Si, 1.96% Al, 0.50% Fe, 0.24% K, and 0.16% Mg).

With the exception of crack formations around the densified plug inserted into the end cap of a Pall 326 filter element, and scratches along the membrane of the clay bonded silicon carbide filter elements, all elements were intact at the conclusion of PCFBC testing in 1997. Although divot formations were not observed along the outer surface of the DuPont PRD-66 filter elements, cleaning and handling frequently lead to the formation of minor abrasions along the outer surface of the DuPont, as well as McDermott elements.

Once again, localized removal of the matrix and fibers along the outer surface of the McDermott candles was identified at the conclusion of PCFBC testing in 1997. In addition, fibers along the i.d. wall of the McDermott elements were infrequently seen to be torn, dangling into the i.d. bore of the elements, most likely as a result of insufficient bonding and adherence during pulse cleaning. Thinning along the center of the PCFBC-exposed Blasch end caps resulted in the vicinity of the plug inserts used to cap and seal the filter elements during manufacturing.

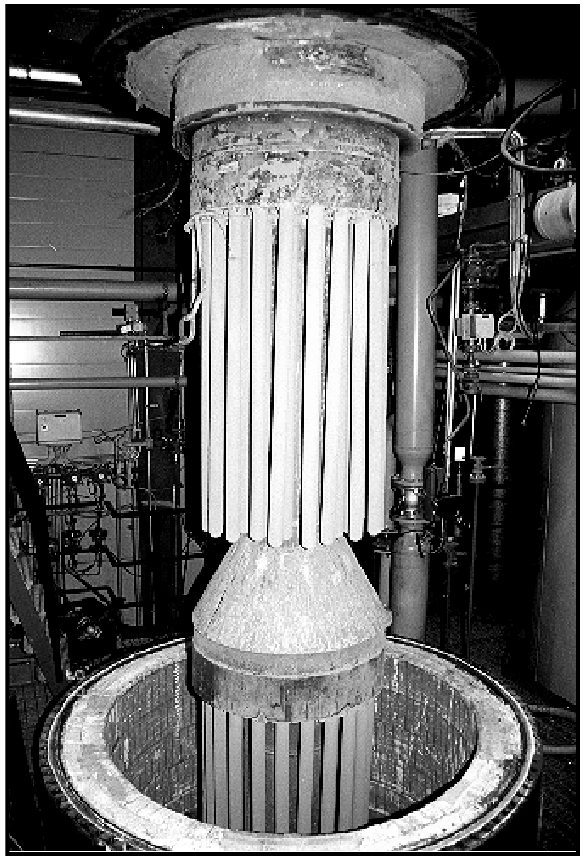


Figure 2 — Westinghouse APF at the completion of TS2-97.

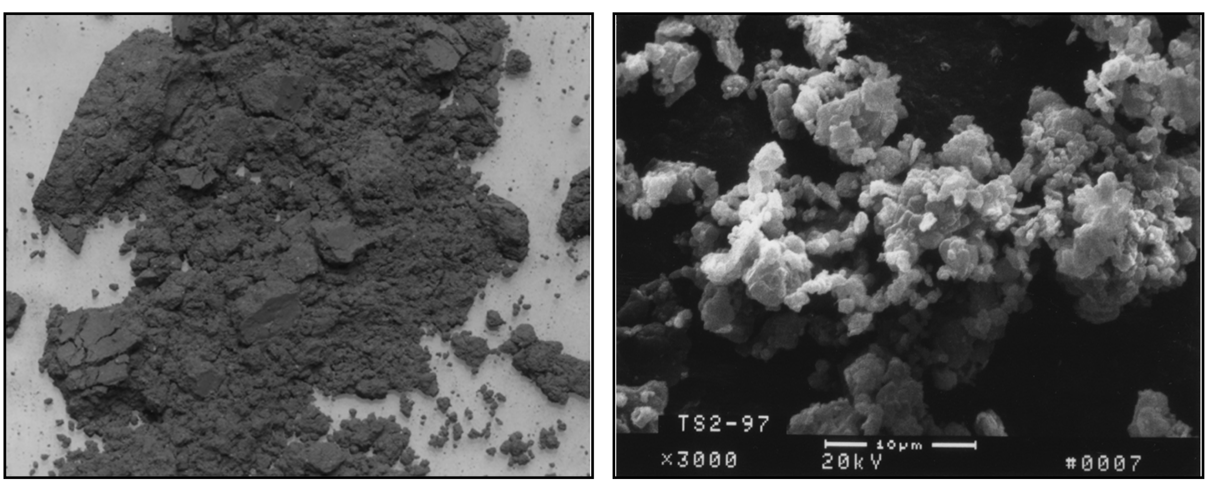


Figure 3 — PCFBC ash generated during utilization of Lakeland feed materials.

Throughout this effort, as in many past programs, Westinghouse has discussed with each filter element supplier, the need, as well as potential manufacturing approaches required to improve the quality, integrity, and performance of the various elements in order to achieve extended operating material and component life in advanced coal-fired applications. Many of the manufacturing modifications have been either initiated or implemented by the various filter element suppliers.

As part of Westinghouse's filter material surveillance program, select, commercially available, as-manufactured and PCFBC-exposed Coors P-100A-1, Pall 326, and Schumacher FT20 monolithic filter elements, and advanced McDermott composite, DuPont PRD-66 filament wound, and advanced monolithic Blasch filter elements have recently been subjected to residual strength characterization, creep strain, and gravimetric analyses. Microstructural analyses are currently continuing. The results of these efforts follow.

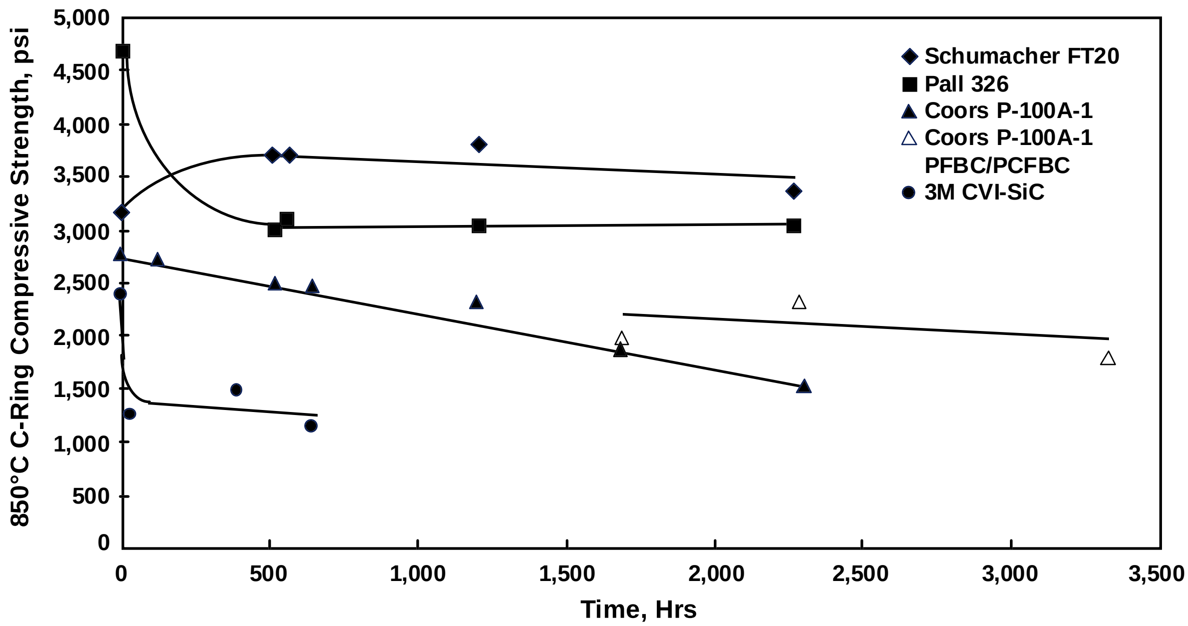
Compressive and Tensile Strength

The residual process temperature strength of the PCFBC-exposed monolithic and advanced second generation candle filters is shown in Figures 4 and 5. Both the Schumacher Dia Schumalith FT20 and Pall 326 elements appear to have achieved a conditioned strength along their o.d and i.d. surfaces (compressive and tensile strengths, respectively). In contrast, a gradual reduction in strength appears to continue to occur for the Coors P-100A-1 alumina/mullite filter matrix.

Figures 4 and 5 indicate that a lower initial and residual strength results for the advanced second generation porous ceramic matrices in comparison to the commercially available monolithic filter materials. A gradual increase in both compressive and tensile strength of the DuPont PRD-66 filament wound matrix occurred during the initial 581 hours of operation in the PCFBC environment. This has previously been demonstrated by Westinghouse,[3,4,5] and is considered to result from either penetration of ash fines into the filament wound filter matrix, or crystallization of amorphous phases originally contained in the as-manufactured filter matrix. A gradual loss of matrix strength along the o.d. surface, while a nearly constant retention of strength along the i.d. surface of the McDermott candle occurred during the initial 581 hours of operation in the PCFBC environment. For the Blasch matrix, a slight increase in residual strength along both o.d. and i.d. surfaces occurred.

Many discussions have been focused on the techniques utilized to establish both initial, as well as residual strength of process-exposed porous ceramic filter matrices. Westinghouse typically utilizes 15 mm sections cut from candle filters, and tests each section as a c-ring in compression and tension, at room temperature and at process operating temperature. These results are used to monitor the trend or changes in material strength which occur during continued life of the elements in various field service applications.

Table 3 and Figure 6 identify the calculated strengths of various porous ceramic filter matrices when 15 or 25.4 mm sections are tested as o-rings, or when 254 mm sections are subjected to burst strength testing. As shown in Table 3, negligible differences in the resulting



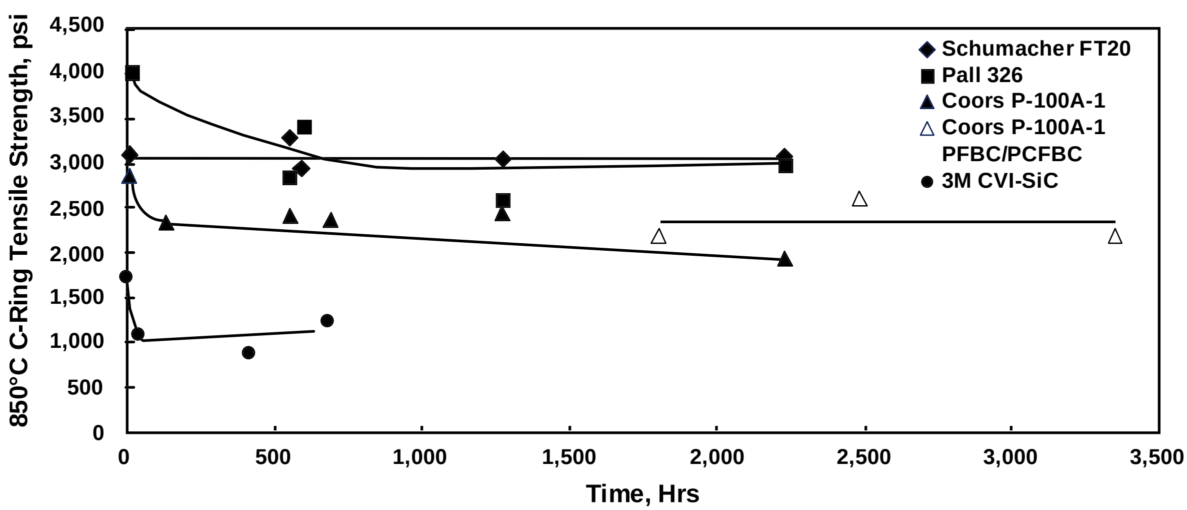
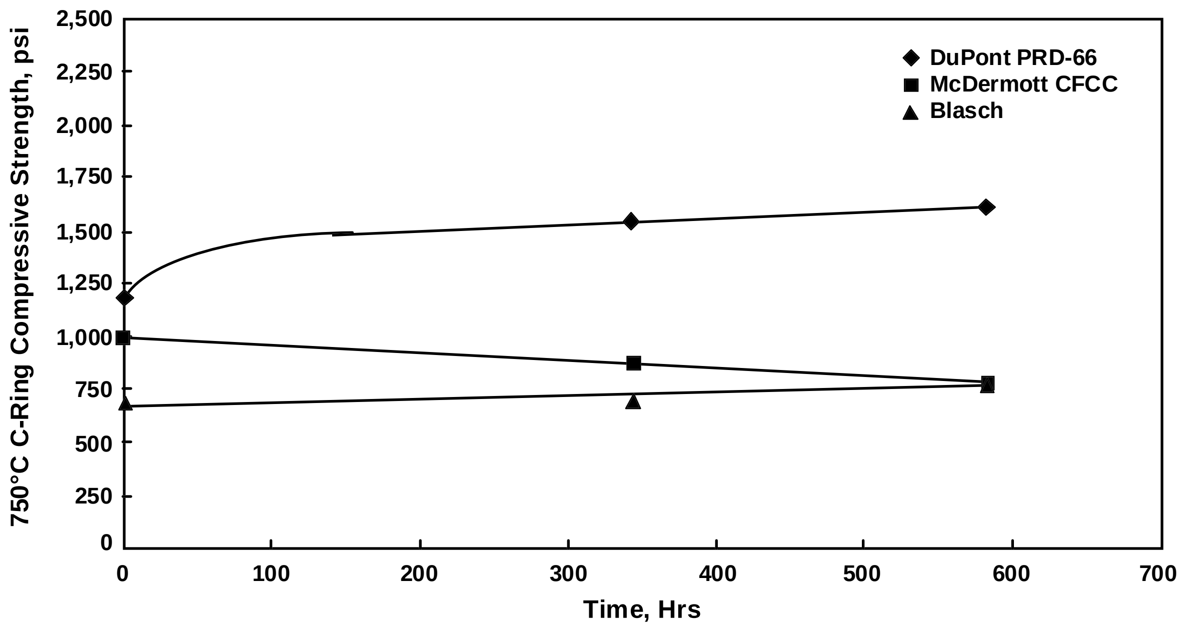


Figure 4 — Residual strength of the PCFBC-exposed commercially available monolithic filter materials and 3M CVI-SiC composite filter matrix.

calculated strengths are identified when testing was conducted with either 15 mm c-ring sections, or 15 or 25.4 mm o-ring sections. What is, however, evident is that a lower hoop strength resulted for the DuPont PRD-66 filament wound filter matrix, but a higher hoop strength for the McDermott element resulted in comparison to either the c-ring or o-ring calculated strengths.



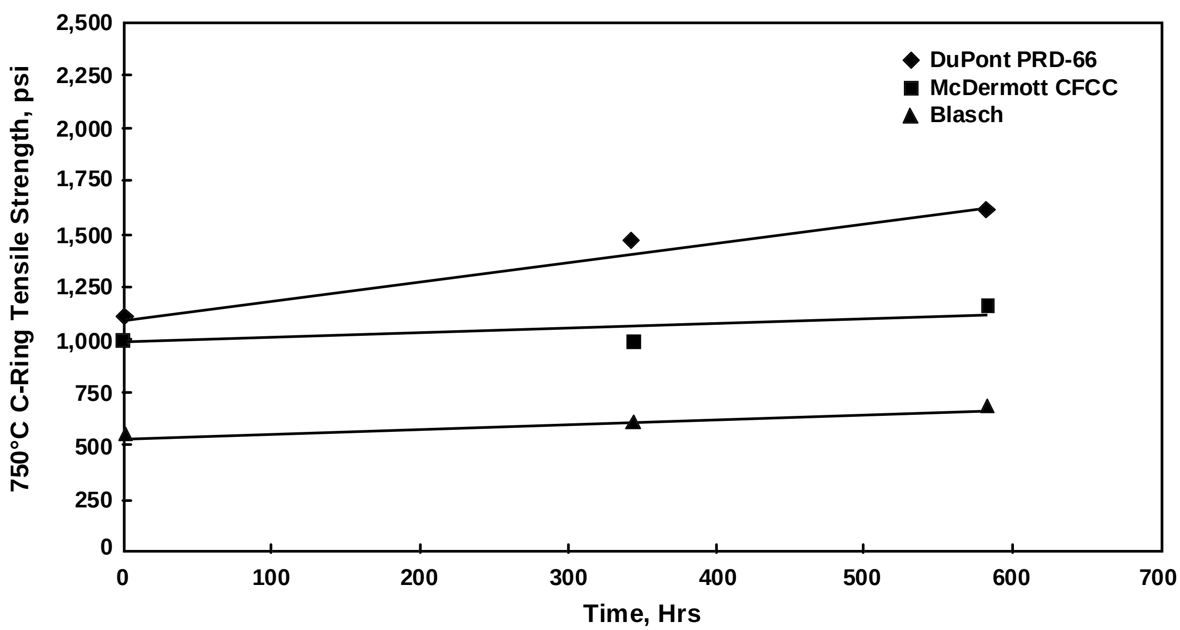


Figure 5 — Residual strength of the PCFBC-exposed filament wound, continuous fiber ceramic composite and advanced second generation monolithic filter matrices.

Figure 6 clearly shows the relationship between c-ring and o-ring calculated strengths for PCFBC-exposed commercially available and second generation filter elements. The manner in which the wall thickness of the sample is measured (i.e., Ave: Average of four locations, 90° to each other, prior to testing; Min: Minimum wall dimension at the fracture site after testing), has a

Table 3. As-manufactured candle filter strength.

As-Manufactured Material	O-Ring Diametral Strength, psi 750°C		C-Ring Compressive Strength, psi 750°C (25°C)	C-Ring Tensile Strength, psi 750°C (25°C)	Hoop Strength, psi 25°C
	15 mm	25.4 mm	15 mm	15 mm	254 mm
DuPont PRD-66	1388 ± 42	1284 ± 296	1223 ± 103 (976 ± 107)	1159 ± 202 (1041 ± 170)	731
McDermott CFCC	1068 ± 73	1111 ± 61	956 ± 346 (898 ± 166)	1008 ± 228 (1207 ± 202)	1256

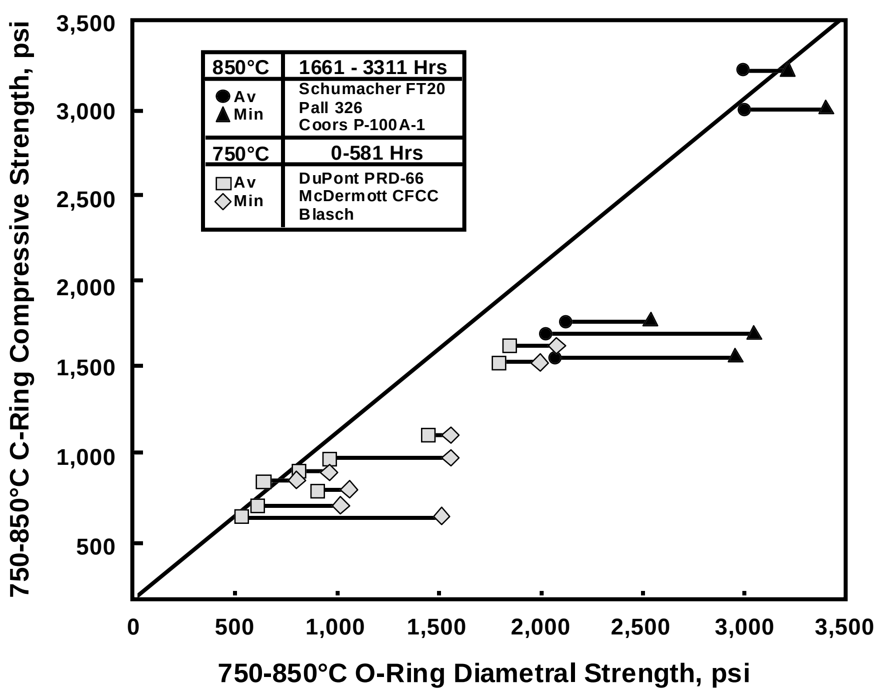


Figure 6 — Process temperature strength correlation.

significant impact on the magnitude of the calculated diametral o-ring strength. Utilizing an averaged o-ring wall thickness, a nearly direct correlation between compressive c-ring and o-ring diametral strength results. Utilizing the minimum wall thickness at the fracture location identifies the apparent lack of concentricity throughout the wall which results during manufacture of the filter elements.

Hoop Stress, Elastic Modulus and Poisson's Ratio

A 254 mm section of material was removed from each of the TS2-97 PCFBC-exposed commercially available monolithic and advanced second generation candle filters. Two 90° strain gage rosettes were installed along both inside and outside surfaces of the filter sections, at approximately the center of each test sample. A water filled bladder was inserted into the i.d. bore of each filter section, and was subsequently pressurized to determine the ultimate hoop strength of the filter material.

The pressure required to fail each filter section, the ultimate hoop stress, elastic modulus, and Poisson's ratio established for the PCFBC-exposed filter sections are presented in Table 4. When compared to the porous ceramic filter materials in their as-manufactured state, the general trends identified via c-ring strength determination are identified via the burst strength data for the PCFBC-exposed filter matrices.

Table 4. Material properties of the PCFBC-exposed porous ceramic candle filters.

Candle Identification Number	Operating Time, Hrs	Burst Pressure, psi	Ultimate Hoop Stress, psi	Modulus, psi x 10^6	Poisson's Ratio
Schumacher Dia Schumalith FT20					
As-Manufactured	—	665	1703	7.3	0.17
S350F/108 (T12)	540	555	1496	7.44	0.21
S350F/42 (B15)	505	590	1584	7.39	0.15
S350F/30 (T26)	1166	720	1942	5.77	0.11
S350F/7 (T18)	2201	585	1025	2.82	0.13
Pall 326					
As-Manufactured	—	NE	NE	NE	NE
R5-655 (M21)	540	525	1369	5.00	0.16
R5-654 (B21)	505	520	1344	5.15	0.16
R6-674 (M26)	1166	650	1641	4.83	0.13
R2-669 (M18)	2201	690	1764	4.83	0.11
Coors P-100A-1 Alumina/Mullite					
As-Manufactured	—	860	2317	5.7	0.23
FC-070 (B22)	505	540	1503	4.84	0.21
DC-051 (B1)	1650 (a)	505	1373	5.18	0.20
FC-035 (B16)	626 (TS3)	520	1425	3.90	0.18
FC-007 (B29)	1166	565	1402	3.44	0.25
EC-014 (B28)	2276 (a)	505	1380	4.37	0.24
FC-040 (M6)	1661	588	1599	4.36	0.12
FC-018 (M16)	2201	545	1473	5.79	0.18
AB-13 (M15)	3311 (a)	520	1441	3.99	0.15

NE: Not Evaluated.
(a) PFBC/PCFBC-Exposed Candle Filter.

Table 4 (Cont'd). Material properties of the PCFBC-exposed porous ceramic candle filters.

Candle Identification Number	Operating Time, Hrs	Burst Pressure, psi	Ultimate Hoop Stress, psi	Modulus, psi x 10^6	Poisson's Ratio
3M CVI-SiC Composite					
As-Manufactured	—	NE	1.01 ksi	2.96-3.38	0.14-0.27
M-51103 (B36)	387	133	1179	3.35	0.22
M-51153 (B31)	626	105	946	5.59	0.34
McDermott CFCC					
As-Manufactured BW-7-6-3	—	220	1256	1.61	0.99
BW-7-5-15 (B14)	342	140	845	1.80	1.04
BW-7-5-30 (B33)	581	185	1077	1.61	1.13
DuPont PRD-66					
As-Manufactured D-583	—	195	731	7.85	1.09
D-580 (B51)	342	190	735	8.19	0.71
D-587 (B50)	581	210	792	6.57	0.71
Techniweave					
As-Manufactured	—	284	3512	12.4	—
T1	40	202	2092	15.7	0.24
3M Oxide-Based CFCC					
As-Manufactured (Type A) (b)	—	64	572	6.0	0.27
710 (Type A)	40	54	443	1.8	0.61
As-Manufactured (Type B) (c)	—	118	1460	6.3	0.32

NE: Not Evaluated.
(b) Type A: Outer Confinement Layer: Coarse Nextel™ 550; Filtration Mat: α-Al_2O_3; Triaxial Support Braid: Nextel™ 610.
(c) Type B: Outer Confinement Layer: Fine Nextel™ 610; Filtration Mat: α-Al_2O_3; Triaxial Support Braid: Nextel™ 610.

High Temperature Creep

High temperature creep testing was conducted on 115 mm x 8.5 mm x 12 mm bars that were removed from the 2201 hour, PCFBC-exposed, Schumacher Dia Schumalith FT20 and Pall 326 candle filters. The Schumacher Dia Schumalith FT20 and Pall 326 filter materials unlike the Schumacher Dia Schumalith F40 and Pall Vitropore 442T filter materials, exhibited negligible high temperature creep when a 500 psi, 4-point bend, flexural load was applied to the surface of the bend bars for a period of 500 hours at temperatures of 750°C and 850°C (Table 5 and Figure 7). The enhanced high temperature creep resistance of the Schumacher Dia Schumalith FT20 and Pall 326 filter matrices resulted from manufacturing changes that had been made to the binder phase during production of both filter elements.

Table 5. Percent creep strain and silica concentrations in PCFBC-exposed clay bonded silicon carbide filter matrices.

Filter	PCFBC Operating Time, Hrs	% Silica	% Creep Strain*
Schumacher FT20	–	11.72	0.085
	540	17.23	0
	1166	15.51	0.038
	2201	10.68	0.06(a)
			0.11(b)
Pall 326	–	6.86	0.085
	540	13.75	0
	1166	9.77	0
	2201	9.70	0.03(a)
			0.00(b)

* 500 psi, 843°C, 300-500 Hrs.
(a) 750°C, 500psi.
(b) 850°C, 500psi.

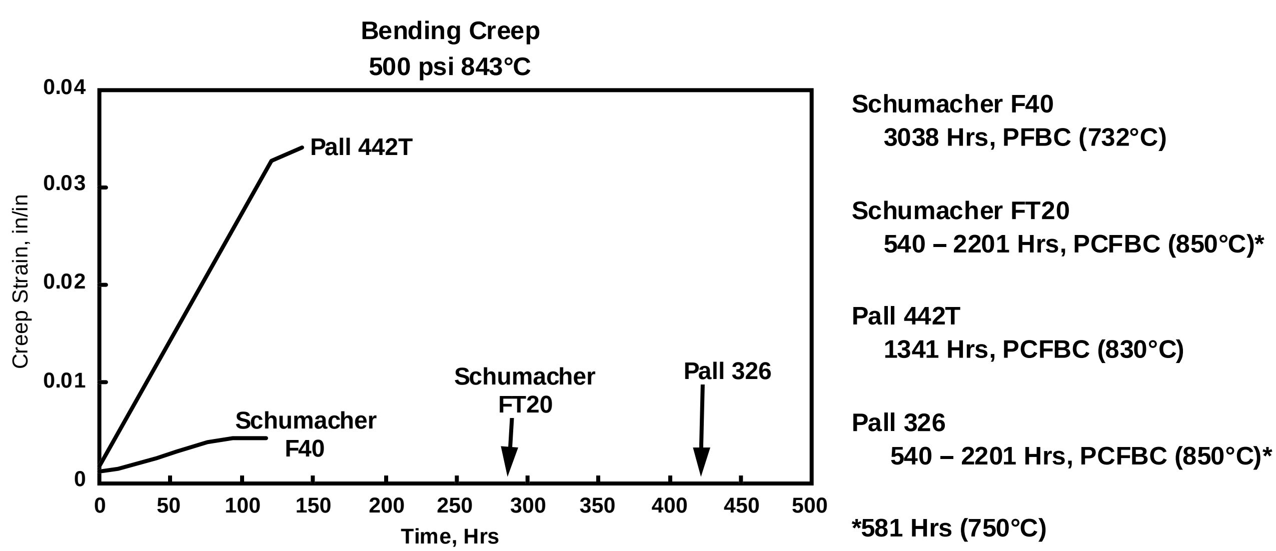


Figure 7 — Creep strain of PCFBC-exposed nonoxide-based candle filters.

During post-test inspection of the 2201 hour, PCFBC-exposed, filter elements, the candles were visually inspected, and the overall lengths of the filter elements were measured. Cracks were not observed along the outer surface of the filter body (i.e., below the flange of the clay bonded silicon carbide candles). An elongation of between 9-11 mm (0.6-0.7%) was observed for the Schumacher Dia Schumalith FT20 candles, and between 8-9.5 mm (0.5-0.6%) for the Pall 326 filter elements (Table 6 and Figure 8). The apparent decrease in the elongation rate was considered to have resulted from reduction in the PCFBC operating temperature from 850°C to 750°C during testing in TS2-97. Since high temperature creep testing of the Schumacher FT20 and Pall 326 filter materials did not identify significant binder phase creep, the observed candle elongation was attributed to continued oxidation of the silicon carbide grains in the PCFBC environment.

Gravimetric Analysis

In an attempt to demonstrate that oxidation of silicon carbide continues to occur with extended operation in the high temperature PCFBC environment, sections of the TS2-97 2201 hour PCFBC-exposed Schumacher FT20 and Pall 326 matrices were removed from the filter elements, and subjected to gravimetric analysis. Two competitive reactions are projected within the clay bonded silicon carbide matrices during operation in combustion gas environments. These include:

- Oxidation of silicon carbide to form silica (SiO_2) which decreases in rate with time
- Crystallization of SiO_2 as tridymite, cristobalite or mullite (via reaction of SiO_2 with Al_2O_3).

As shown in Table 5, the free (i.e., amorphous) silica concentrations were lower after 2201 hours of PCFBC operation in comparison to the amorphous silica concentrations identified for shorter periods of operation. Crystallization of the Schumacher FT20 oxide-containing phase was expected to have continued to occur, thus decreasing the solubility of the matrix in hydrofluoric acid (HF), resulting in a lower reported free silica content. In contrast, the concentration of free silica only slightly decreased in the Pall 326 filter matrix after 2201 hours of PCFBC operation.

Microstructural Analysis

Efforts at Westinghouse have been initiated to discern the resulting morphology and changes that may have occurred within the commercially available monolithic, as well as advanced second generation porous ceramic filter materials after extended operation in the PCFBC process gas environment. To date, only the 2201 hour, PCFBC-exposed, Pall 326 matrix has been characterized.

As shown in Figure 9, extensive crystallization of the binder and/or oxide coating that encapsulated the outer surface of the silicon carbide grains continued to occur. At higher magnification (Figure 10), the coalesced binder or outer oxide coating appeared to consist of two

Table 6. Elongation of clay bonded silicon carbide candle filters.

Filter Element	Tidd PFBC		Karhula PCFBC	
	Operating Time, Hrs	Elongation, mm	Operating Time, Hrs	Elongation, mm
Schumacher Dia Schumalith F40	5855	5-7	227	ND
Schumacher Dia Schumalith FT20	1705	ND	1166	6-8
	–	–	1620	8-10
	–	–	2201	9-11
Pall Vitropore 442T	1110	0-4	1341	1-26
Pall 326	–	–	1166	5-8
	–	–	1620	7-9
	–	–	2201	8-9.5

ND: Not Determined.

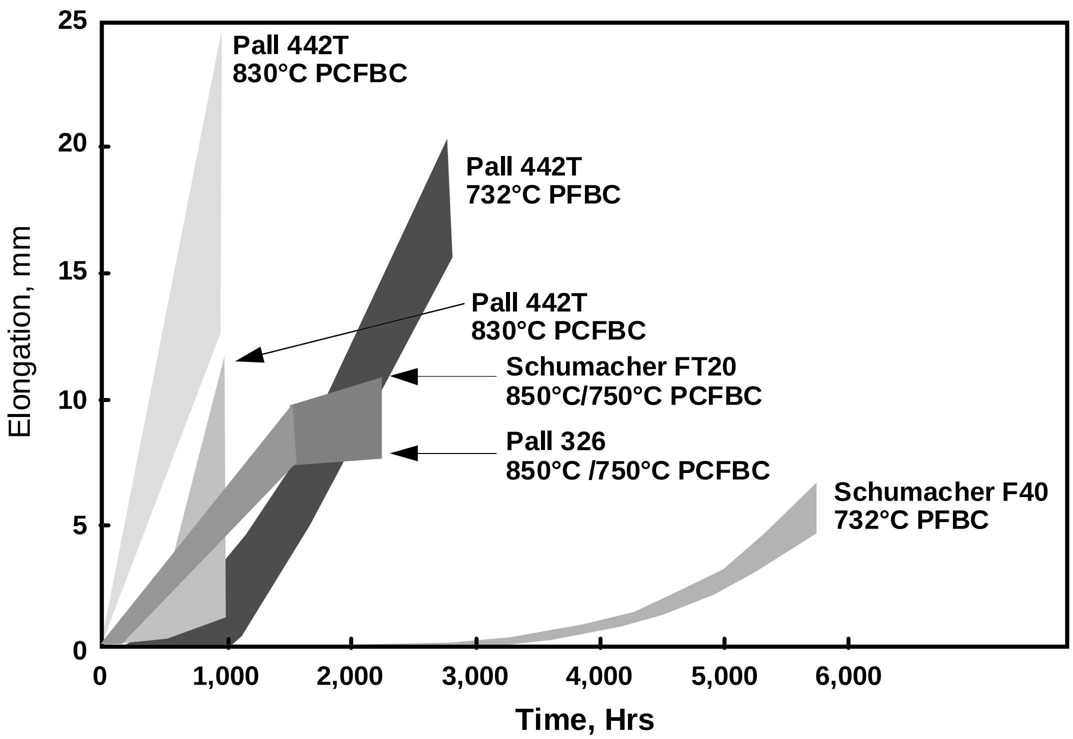


Figure 8 — Impact of process operating conditions on clay bonded silicon carbide candle filter elongation.

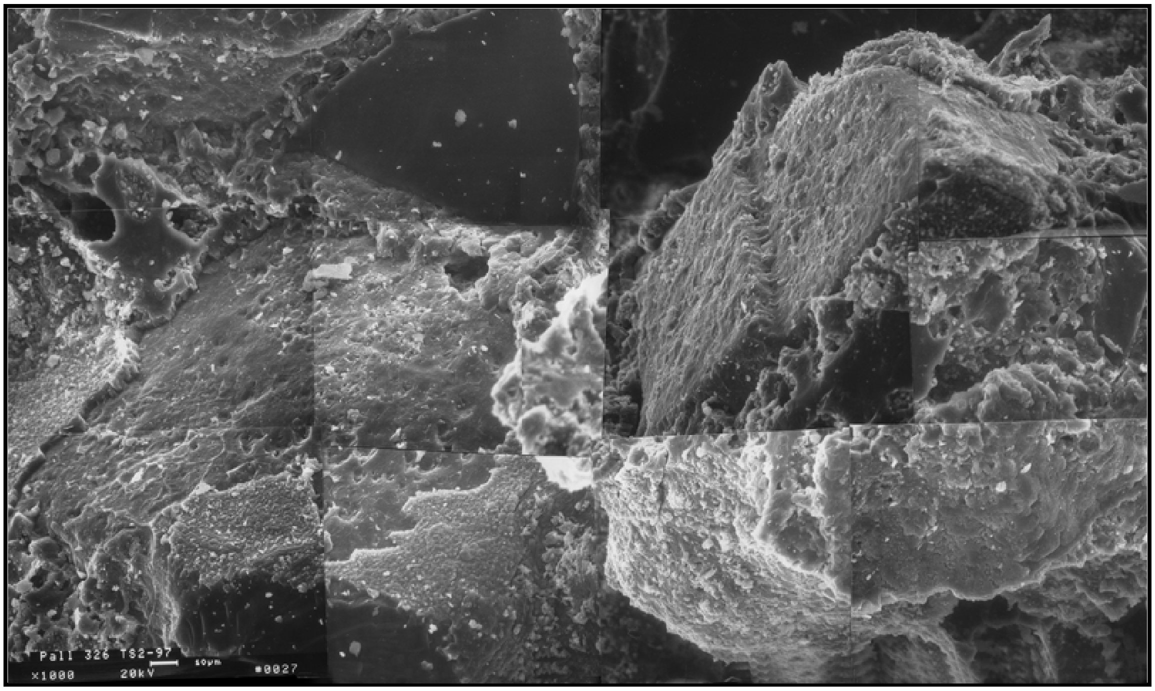


Figure 9 — Morphology of the 2201 hour, PCFBC-exposed, Pall 326 clay bonded silicon carbide filter matrix.

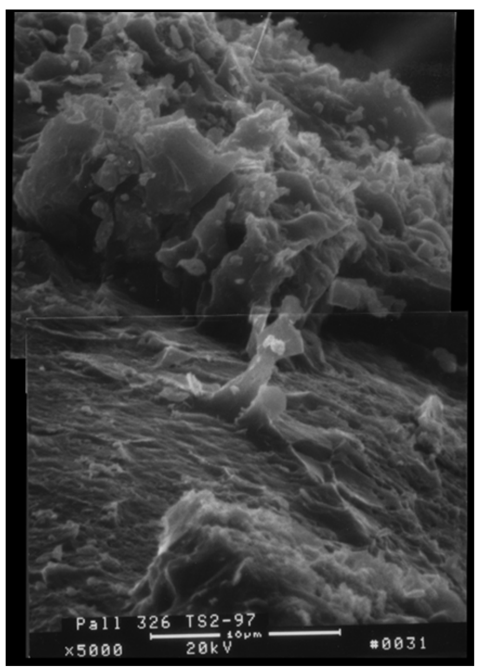


Figure 10 — Grain growth of the silica-enriched binder and outer surface coating that encapsulated the silicon carbide structural support grains in the 2201 hour, PCFBC-exposed, Pall 326 filter matrix.

structures: an outer surface that contained amorphous and/or melt-like features, and an interior region that clearly identified grain growth. The mottled surface features of the underlying silicon carbide grain which once had a smooth, non-textured surface, appeared to be the site for growth of the silica-enriched grains in the outer encapsulating shell. Identification of the formation of silica in silicon carbide and/or nitride-based materials during use in PCFBC applications confirms previous Westinghouse thermodynamic equilibrium calculations.[(6)]

By monitoring the microstructural changes that occur within the porous ceramic filter matrices during extended operation in advanced coal-fired applications, potential life-limiting material degradation mechanisms are continually assessed.

Filter Flange Strength Measurements

Filter elements are purchased to a specified flange, total length, and o.d. surface dimensional tolerance for use in the Westinghouse APF systems. However, as shown in Figure 11, the contour of the flange, and the wall thickness of the various monolithic and advanced composite candle filters vary, depending on the manufacturing process utilized to construct each filter element.

During installation, the candle flange is gasketed and fitted into a metal holder, and subsequently bolted to secure and position each element in the filter array. The applied loads are intended to be sufficient to seal and capture the candle flange within the metal holder mount.

For the McDermott composite candle during field operation, depressions and/or splitting of the insert from the remainder of the flange were seen to have occurred. Alternately the thin walled 3M CVI-SiC composite filter flange tended to crack, if the spacer distance between the bolts was reduced to prevent movement of the candle within the holder mount. Similarly fine hairline cracks were observed along the outer surface of the DuPont PRD-66 filament wound flange after 581 hours of PCFBC operation. In contrast during field operation, crack formations along the monolithic flanges were not observed using the same mounting arrangement.

In an attempt to assess the ultimate radial load that can be applied to the flange of the monolithic and advanced composite filter elements, flange sections (i.e., 40 mm sections from the top of the flange) were cut from the various filter elements. Each section was subjected to diametral testing at either 750°C or 850°C.[1] Diametral testing reflected a load imparted by the presence of ash between the gasketed flange and the inner surface of the metal holder.

The compressive load to failure for the continuous fiber reinforced ceramic composite filter flanges ranged between 26.2 and 102.6 pounds, while the compressive load to failure for

[1] The process operating temperature which the specific candle had been subjected to during PCFBC testing in Karhula, Finland, during the 1995-1997 test campaigns was used in this effort. For example, Coors, Pall, Schumacher, and 3M candles were subjected primarily to 850°C process temperatures, while DuPont PRD-66, McDermott, and Blasch candles experienced operating temperatures of 750°C.

the monolithic flanges ranged between 76.5 and 610.5 pounds. The ultimate load to failure for the filament wound flange was 247.6 pounds.

Similar flange crush strength testing is recommended to be conducted utilizing Westinghouse's filter gasketing and mounting configuration.

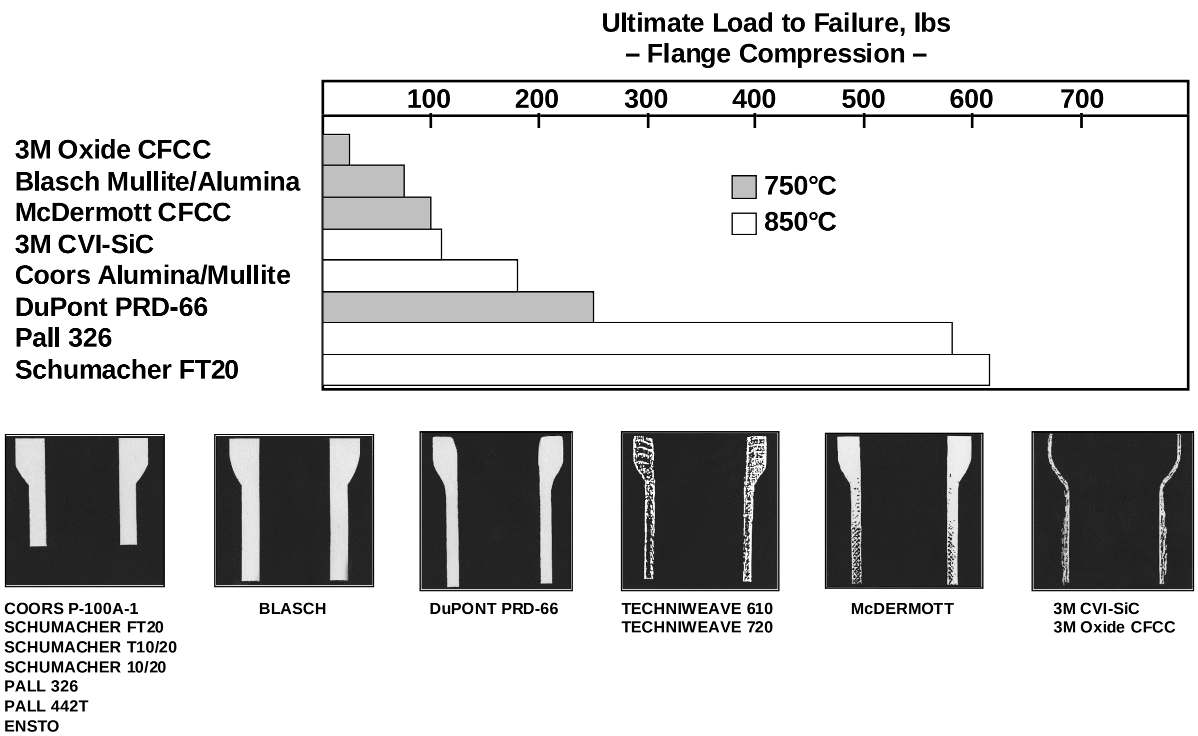


Figure 11 — Cross-sectioned wall thickness and strength of the commercially available monolithic and advanced second generation candle filter flanges.

Extended Filter Life Testing

In order to simulate the impact of long-term thermal fatigue or shock on the stability of the various commercially available monolithic and advanced second generation filter matrices, extended life testing of PCFBC-exposed candles is being conducted at Westinghouse in our PFBC simulator test facility in Pittsburgh, Pennsylvania. To date the array of elements shown in Figure 12 has been subjected to ~40 hours of steady state filtration at temperatures of 845°C, and is currently undergoing exposure to an accelerated pulse cycling campaign. Our objectives are to subject the filter array to 20,000 pulse cycles, simulating 10,000 hours (i.e., >1 year) of service life. The thermal intensity of the pulse used in this effort reflects field service conditions, with a single pulse cycle being delivered to the entire filter array every two minutes. Westinghouse has previously demonstrated that a two minute interval between pulse cycles is sufficient to return the temperature along the i.d. surface of the various filter elements to process operating temperatures.[4]

Once the accelerated pulse cycling campaign is completed, the filter array will be subjected to a maximum of thirty thermal transients that are representative of actual field startup and shutdown process conditions. In this manner, the thermal fatigue characteristics of the various monolithic and composite matrices will be identified, projecting extended filter life during commercial service operation. The results of this program will be presented in a future publication.

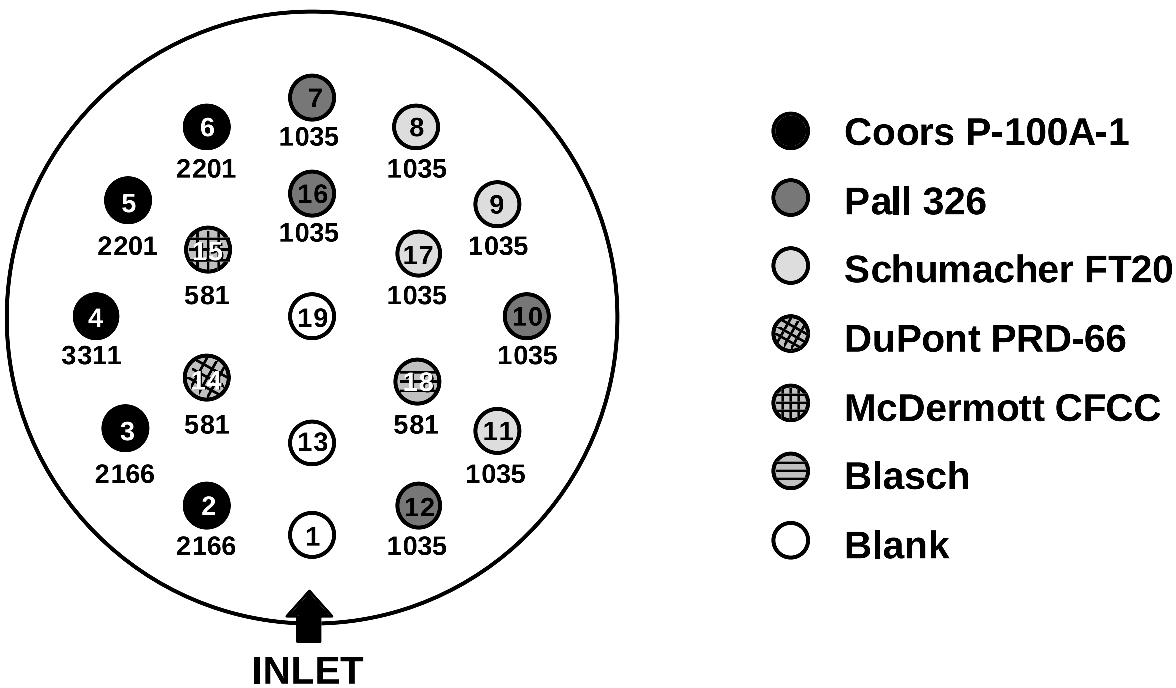


Figure 12 — Extended filter life testing of PCFBC-aged candle filters. Total number of PCFBC operating hours are shown below each filter location.

Candle Filter Exposure in IGCC Applications

In order to assess the stability of the advanced filter materials during long-term operation in IGCC applications, Westinghouse has designed a mini-filter slip stream system which is planned to be installed and operated at the Sierra Pacific Power Company (SPPC), Piñon Pine Demonstration Plant in Reno, Nevada. The mini-filter system will be located downstream of Westinghouse’s main APF system which currently houses 748, 1.5 m Pall Vitropore 442T filter elements.

In the mini-filter, porous ceramic and sintered metal mini-candles (i.e., 305 mm) will be exposed to cleaned, particulate-free, fuel gas for extended periods of time. In addition to the ceramic filter elements, alternate ceramic filter material and structural metal coupons will be housed in the mini-vessel and exposed to the fuel gas environment in a flow-over fashion. To date, Westinghouse has purchased and inspected the following mini-candles:

- Schumacher Dia Schumalith T10/20
- Schumacher Dia Schumalith FT20
- Pall 326
- Pall Vitropore 442T
- Coors P-100A-1 Alumina/Mullite
- DuPont PRD-66
- 3M CVI-SiC
- Pall Iron Aluminide.

Westinghouse has designed the mini-filter vessel and ancillary equipment, meeting design specifications identical to those required for design and construction of the main vessel. Currently Westinghouse is awaiting approval by M. W. Kellogg and Sierra Pacific for acceptance of the design packages, and M. W. Kellogg's interface effort for installation of the mini-filter system into existing plant process gas stream lines. Once the mini-filter vessel and ancillary equipment design packages are accepted by M. W. Kellogg and Sierra Pacific, Westinghouse will initiate the manufacture of the mini-filter vessel and ancillary equipment, prior to shipment and installation at site.

Application/Benefits

As a key component in advanced coal- or biomass-based power applications, hot gas filtration systems protect the downstream heat exchanger and gas turbine components from particle fouling and erosion, cleaning the process gas to meet emission requirements. When installed in either PFBC or IGCC plants, lower downstream component costs are projected, in addition to improved energy efficiency, lower maintenance, and elimination of additional and expensive fuel or flue gas treatment systems. As a critical component, long-term performance, durability, and life of the porous ceramic filter elements are essential to the successful operation of hot gas filtration systems in advanced combustion and gasification applications.

Future Activities

Efforts will be focused on:

- Completion of the microstructural analyses of select TS2-97 PCFBC-exposed candle filters.
- Completion of extended life testing of PCFBC-exposed filter elements and development of life assessment models.

- Issuance of Topical Reports for Task 1 — Assessment of Prototype Advanced Hot Gas Candle Filters, and Task 5 — Assessment of Advanced Filter Failure Modes.
- Construction, installation, and operation of the mini-filter slip stream system at the Sierra Pacific Power Company, Piñon Pine, IGCC test facility in Reno, Nevada.
- Characterization of the IGCC-exposed ceramic and sintered metal filters and structural metal coupons.

Acknowledgment

We wish to acknowledge Mr. Richard A. Dennis at DOE/FETC in Morgantown, WV, for his guidance and technical support during conduct of this program.

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