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Assessment of Metal Media Filters for Advanced Coal-Based Power Generation Applications

Keywords: Particulate removal, PFBC, PCFBC, Gas phase sulfur and alkali species, Metal media, Advanced alloys, Intermetallics

Introduction

Advanced coal and biomass-based gas turbine power generation technologies (IGCC, PFBC, PCFBC, and Hipps) are currently under development and demonstration. Efforts at the Siemens Westinghouse Power Corporation (SWPC) have been focused on the development and demonstration of hot gas filter systems as an enabling technology for power generation. As part of the demonstration effort, SWPC has been actively involved in the development of advanced filter materials and component configuration, has participated in numerous surveillance programs characterizing the material properties and microstructure of field-tested filter elements, and has undertaken extended, accelerated filter life testing programs. This paper reviews SWPC's material and component assessment efforts, identifying the performance, stability, and life of porous metal, advanced alloy, and intermetallic filters under simulated, pressurized fluidized-bed combustion (PFBC) conditions.[†]

Objective

The objectives of this program are to evaluate the potential use of porous metal media for hot gas filter applications in PFBC systems. Siemens Westinghouse[1] has worked with key industry metal media suppliers to develop suitable, corrosion-resistant materials representing both the metal powder, fiber, and wire laminate technologies. The application of metal media to PFBC requires materials capable of withstanding operating temperatures of 650°C to 900°C (1200°F to 1650°F) in coal combustion process streams that potentially contain gas phase sulfur and alkali.

Approach

In 1998, SWPC initiated a program with DOE/NETL to develop and evaluate the use of porous, high temperature, metal media candle filters for PFBC and pressurized circulating fluidized bed combustion (PCFBC) applications. In conjunction with U.S. Filter/Fluid Dynamics (USF)[2], Pall Advanced Separation Systems, Mott Corporation, Fairey Microfiltrex,[3] Technetics, and Ultramet, SWPC produced

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[†] Effort sponsored by DOE/NETL under Contract No. DE-AC2-98FT40002 under the direction of Mr. Theodore McMahon.

[1] Formerly the Westinghouse Electric Corporation.

[2] Currently Pall Corporation.

[3] Currently Microfiltrex, a member of the Porvair Filtration Group.

composite metal media filter elements for exposure to simulated PFBC conditions in SWPC STC's test facilities in Pittsburgh, PA.

Advanced alloys selected for evaluation in this program included Haynes 230, Haynes 214, Haynes 188, Haynes 556, iron aluminide (FeAl), and FeCrAl(Y) porous metal media. Elements constructed from 310S, Inconel 600, and Hastelloy X were included as commercially available materials for comparison in this program. Approximately 25 μm diameter metal media fibers were sinter bonded at high temperature, forming a ≤1 mm thick filtration mat layer that was subsequently structurally supported via internal or external, perforated, densified metal tubes and/or wire mesh screens. Similarly sized metal particles were sinter bonded into thicker walled (i.e., ~2-4 mm), porous, metal media filter sections.

Project Description

Five test campaigns were conducted at SWPC STC for periods up to ~1,000 hours in duration, exposing six, 1.5 m, composite metal media candle filters to temperatures 650°C (1200°F), 760°C (1400°F), and 840°C (1550°F), and system pressures of 1,013kPa (147 psia), under simulated PFBC process gas conditions containing 200 ppmv SO_2/SO_3 (Figure 1). Gas phase alkali was included in the 840°C (1550°F), simulated PFBC, process gas environment in Test Campaign No. 5, at concentrations of 1 ppmv. Pre- and post-test characterization of the component, metal media, and welds included visual inspection, room temperature gas flow resistance measurements, microstructural analyses, and high temperature tensile strength testing.

Results

Component Architecture and Performance under Simulated PFBC Operating Conditions

The filtration media of the USF filter element sections consisted of multiple layers of ~25 μm diameter metal media fibers that were sinter bonded together forming a porous mat-like structure that was embedded along a metal wire mesh support layer (Table 1). Subsequently the filtration mat was wrapped around a thick-walled, perforated, cylindrical, 310S internal structural core, and longitudinally seam welded. Similarly, the architecture of the Fairey Microfiltrex filter element sections consisted of a longitudinally seam welded, porous, fibrous, filtration mat and an external wire mesh support layer that were welded to an underlying perforated cylindrical metal structural support. In contrast, the Technetics filter element sections consisted of an internally porous, fibrous, metal filtration layer and only an external wire mesh support layer. Joiner end rings of 310S were welded to the cylindrical USF filter sections for assembly of multiple units into an ~1.5 m composite candle filter. Joiner end rings of 310S were also welded to the Fairey Microfiltrex and Technetics filter element sections.

Sinter bonded metal particles (i.e., powder) were used in the manufacture of the porous Pall and Mott filter element sections. Only the Pall Hastelloy X filter section contained a longitudinal seam weld. Joiner end rings of 310S were added to the cylindrical Pall and Mott filter sections, prior to assembly with the Fairey Microfiltrex and Technetics filter sections, forming an ~1.5 m composite candle. Fail-safe/regenerator-contained flanges and end caps were welded to the body of each composite candle filter.

As shown in Figure 2, the as-manufactured, room temperature, gas flow resistance through the sinter bonded fibrous, USF, Fairey Microfiltrex, and Technetics metal media filter element sections was ≤2 in-wg at 10 ft/min. In contrast, the as-manufactured, room temperature, gas flow resistance through the sinter bonded metal powder, Pall and Mott filter media ranged from 4 to 10 in-wg at 10 ft/min. In

terms of component architecture and relative gas flow resistance, the porous sinter bonded metal powder media is analogous to the thicker walled, oxide or nonoxide-based, monolithic, ceramic filter materials (i.e., Coors P-100A-1 alumina/mullite; Schumacher FT20; Pall 326; Blasch and Ensto mullite bonded alumina; etc.), while the porous sinter bonded fibrous metal media is analogous to the thinner walled, continuous fiber ceramic composites (CFCC; 3M oxide/nonoxide, McDermott, and Techniweave CFCCs), and filament wound porous ceramic filter matrix (DuPont[4] PRD-66).

After completion of 500 hours of 650°C (1200°F) simulated PFBC testing, all filter element sections remained intact (Table 2). As temperature was increased to 760°C (1400°F), circumferential failure of the Pall 310S filter element sections resulted along the metal joiner ring welds. When retrieved from the ash hopper, brittle failure of the powder metal media was observed. At temperatures >650°C (>1200°F), debonding and removal of sections of the USF Haynes 556 media resulted, reducing the expected particulate collection efficiency of the porous filtration media. Similar failure of the Pall 310S and USF Haynes 556 media occurred at temperatures of 815-840°C (1500-1550°F). In the presence of gas phase sulfur and alkali at 840°C (1550°F), densification of the outer surface of the USF FeCrAl, Haynes 230, 310S, and Inconel 600 filtration media resulted. In addition, failure of the Pall FeAl and 310S matrices, the USF Haynes 214, Haynes 188, Haynes 556, and Hastelloy X matrices, and Fairey Microfiltrex FeCrAl matrix occurred. Circumferential cracks near the metal joiner ring of the Mott Inconel 600 filter section were observed, and the integrity of the Technetics' longitudinal seam weld was questioned.

Microstructural Characterization

Pall FeAl (74.77% Fe, 22.85% Al, 2.38% Cr). The open porosity throughout the ~1.6 mm, cross-sectioned, sinter bonded FeAl wall was retained during exposure of the Pall filter element sections to 650-840°C (1200-1550°F) simulated PFBC operating conditions (Test Campaign No.1 — No. 5; Figure 3). An ~0.2 μm thick alumina-enriched surface oxide formed along the outer periphery of the sinter bonded FeAl particles after 500 hours of exposure at 650°C (1200°F). The thickness of the alumina-enriched surface increased to ~0.5 μm after 986 hours of operation at 840°C (1550°F). Negligible intragranular oxidation was observed, while limited oxidation was detected between adjacent sinter bonded FeAl particles.

Impact of Gas Phase Alkali. After 225 hours of exposure in the 840°C (1550°F), sulfur and alkali-containing,[5] simulated PFBC environment, failure of the Pall FeAl filter media occurred. Volume expansion of the FeAl filter matrix resulting in longitudinal, as well as circumferential distortion, and generation of raised bubble-like formations with matrix cracking were evident (Figure 4). The diameter of the bubble-like formations was nominally 25 mm, ranging between 10 and 40 mm. An iron-sulfur-oxide-enriched phase formed along the outer surface of the filter media. Sodium was also detected to be present. An ~0.2-0.3 mm "orange" band formed, defining the outer periphery of the raised bubble-like formations. The "orange" band consisted of iron oxide and sodium sulfate. Along the raised section of the bubble-like formations, ~20-30 μm sodium-sulfur-enriched crystals (i.e., sodium sulfate complex) were formed. Low concentrations of sulfur were present within the underlying iron oxide-enriched outer surface of the raised bubble-like formations.

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[4] Currently GE Power Systems.

[5] A solution of sodium chloride was injected into the combustor gas passage, which subsequently was converted to sodium sulfate as a result of reaction with gas phase sulfur in the simulated PFBC process gas stream.

When the Pall FeAl filter media was cross-sectioned, a continuous melt-like iron oxide phase was seen to have formed along the o.d. and i.d. surfaces of the filter wall, closing porosity, limiting direct passage of the process gas through the filter media (Figure 5). Similarly, the open porosity through the filter wall was reduced as a result of oxidation of the sinter bonded FeAl particles. An iron oxide (FeO)-enriched phase formed along the outer surface of the contained particles. Subsequently $FeAl_2O_x$ and $FeAlO_x$ were formed, surrounding the underlying particle core. Sulfur was detected to be present within both iron aluminate-enriched layers. The central core of the residual FeAl particles was either a densified structure consisting principally of the base metal iron, or an internally oxidized mottled structure consisting principally of iron oxide.

USF FeCrAl (Hoskins 875 fibers: Fe, 22.5% Cr, 5.5% Al, 0.5% Si, 0.1% C). During the initial 242 hours of operation in the 650°C (1200°F), simulated PFBC, process gas environment, an ~0.1 μm thick alumina-enriched phase formed along the outer surface of the sinter bonded FeCrAl fibers in the USF filtration media. After 1,016 hours of operation in the 760°C (1400°F) simulated PFBC environment, the thickness of the alumina-enriched layer increased to ~0.2-0.5 μm. After 476 hours of operation in the 840°C (1550°F) simulated PFBC process gas environment, a discontinuous ~1-2 μm thick, alumina-iron oxide-chromia layer formed along the outer surface of the FeCrAl fibers (Figure 6). Although surface oxidation of the FeCrAl fibers occurred, the open porosity of the USF filtration media was retained. During simulated PFBC testing, internal oxidation of the FeCrAl fibers was not observed. Negligible oxidation resulted along the fibrous sinter bond interface.

Impact of Gas Phase Alkali. In contrast, the open porosity of the USF FeCrAl filter media was limitedly retained after 225 hours of operation in the 840°C (1550°F), simulated PFBC, process gas environment which contained both gas phase sulfur and alkali (Figure 7). Alumina-enriched, ~2-3 μm, needle-like whisker formations resulted along the outer surface of the FeCrAl fibers and FeCrAl structural support mesh. Internal oxidation was not observed throughout the sinter bonded USF FeCrAl fibers.

After 496 hours of operation in the 840°C (1550°F), simulated PFBC, process gas environment, the microstructure of the USF FeCrAl fibrous filtration mat was no longer retained due to oxidation and coalescence of the originally porous, fibrous, metal media. Gas flow permeability through the oxidized filtration mat was severely restricted. Surface and subsurface void formations frequently resulted along the periphery of the USF FeCrAl structural support mesh after 496 hours of operation in the gas phase sulfur and alkali-containing, simulated PFBC, process gas environment. Limited sulfation was seen to have resulted within chromia-enriched phases that were embedded within the coalesced USF FeCrAl fibrous media.

USF Haynes 230 (57% Ni, 22% Cr, 14% W, 5% Co, 3% Fe, 0.1% C, 0.4% Si, 0.5% Mn, 0.02% La, 0.015% B, 2% Mo. 0.3% Al). The open porosity of the USF Haynes 230 was retained after 500 hours of operation in the 650°C (1200°F), simulated PFBC, process gas environment (Figure 8). An ~2.5-3.0 μm thick oxygen-chromium-nickel-enriched layer formed along the surface of the sinter bonded Haynes 230 fibers. Internal oxidation of the fibers was initiated.

Oxidation similarly resulted along the outer surface of the sinter bonded Haynes 230 fibers in the USF filtration media after 258 hours of operation in the 760°C (1400°F), simulated PFBC, process gas environment. The open porosity of the filtration media appeared to have been retained during the initial 258 hours of exposure, but may have been limited after 524.5 and 1,016 hours of operation. With time,

an ~3-5.5 μm thick oxide scale formed along the outer surface of the Haynes 230 fibers in the USF filtration media.

At 760°C (1400°F), an external nickel oxide layer initially formed along the outer surface of the Haynes 230 fibers. Subsurface layers were enriched with chromia and minor concentrations of nickel, and a nickel chromate spinel. After 524.5 hours, iron was seen to be present within a thin band that formed between the external nickel oxide and chromia-enriched layers. Along the i.d. or pulse cycled surface of the USF Haynes 230 filter element, a thicker (i.e., ~2 μm) oxygen-nickel-iron-enriched layer formed along the outer surface of the USF Haynes 230 fibers. As the simulated PFBC exposure time was extended to 1,016 hours, nickel oxide was identified as the primary phase along the outer surface of the Haynes 230 fibers, with minor concentrations of nickel present within an underlying chromia-enriched subsurface layer.

After 259 hours of operation in the 815°C (1500°F), simulated PFBC, process gas environment, oxidation similarly resulted within the USF Haynes 230 filtration media. The open porosity of the filtration media appeared to have been retained during the initial 259 hours of operation, but may have been limited after 986 hours of exposure in the 815-840°C (1500-1550°F) simulated PFBC environment. With time, an ~1.5-6 μm thick oxide scale formed along the outer surface of the 815-840°C (1500-1550°F), simulated PFBC-exposed, Haynes 230 fibers in the USF filtration media. A continuous, ~10-30 μm thick, iron-nickel oxide spinel or nickel oxide layer formed along the o.d. surface of the Haynes 230 filtration media.

Microstructural characterization of the Haynes 230 fibers within the USF filtration media indicated that the fibers were encapsulated with an external chromia-enriched layer, and a subsurface chrome-nickel oxide layer after 259 hours of exposure in the 815°C (1500°F) simulated PFBC environment. After 476 hours of exposure at 815-840°C (1500-1550°F), a nickel oxide or nickel-iron oxide layer, and a subsurface chromia layer formed along the outer surface of the Haynes 230 fibers. After 986 hours of exposure, the outer surface of the oxide was enriched with either a chromium-iron-nickel spinel or a nickel-chromate complex. Chromia was present as the primary subsurface oxide phase.

Void formations were evident along the oxide/base metal interface of the USF Haynes 230 fibers. With continued exposure time at 760°C (1400°F) and 815-840°C (1500-1550°F), this became more pronounced. Intragranular oxidation within Haynes 230 fibers, oxidation between sinter bonded Haynes 230 fibers, as well as oxidation at the Haynes 230 fiber/Hastelloy X structural support mesh interface resulted during exposure of the USF filtration media in the 760°C (1400°F) and 815-840°C (1500-1550°F), simulated PFBC, process gas environment.

A Hastelloy X structural support mesh was used in the manufacture of the USF Haynes 230 filtration media. An ~3-6 μm thick oxide scale formed along the outer surface of the 760°C (1400°F), simulated PFBC-exposed, Hastelloy X structural support mesh. Between 258 and 524.5 hours of simulated PFBC exposure, the outer surface of the oxide layer was enriched with oxygen-nickel-iron. Subsurface layers consisted primarily of oxygen-chromium-nickel, and subsequently chromia. After 1,016 hours of simulated PFBC operation, the composition of the oxide layer was seen to be enriched with nickel oxide along the outer surface of the scale, followed by an oxygen-nickel-iron-enriched layer, and subsequently a chromia-enriched layer.

In the 815-840°C (1500-1550°F), simulated PFBC-exposed, USF Haynes 230 filter media, an ~1-10 μm thick oxide layer formed along the outer surface of the Hastelloy X, structural support mesh. Within the initial 259 hours of operation, the oxide layer consisted of chrome-nickel spinel. After 476 and 986 hours of exposure, the external chrome-nickel spinel became enriched with iron, while a chromia-enriched subsurface oxide formed.

Impact of Gas Phase Alkali. In the presence of gas phase alkali, oxidation resulted along the outer surface of the Haynes 230 fibers after 225 hours of operation in the 840°C (1550°F), simulated PFBC, process gas environment, limiting the open porosity of the filtration media (Figure 9). Internal oxidation and numerous voids were observed along the cross-sectioned surface of the Haynes 230 fibers. With continued exposure (i.e., 496 hours of operation), extensive oxidation was seen to have resulted along the o.d. surface of the filter element sections, as well as within the filtration mat, severely limiting the open porosity of the USF Haynes 230 filter media.

The thickness of the oxide layer that formed along the outside surface of the Haynes 230 fibers tended to increase with continued operation in the 840°C (1550°F) simulated PFBC environment (i.e., ~1-25 μm after 225 hours; ~25-50 μm after 496 hours). The outer surface layer of the oxide after both 225 and 496 hours of operation was enriched with nickel and oxygen. Subsurface oxides consisted of oxygen-chromium-nickel-iron phases.

The thickness of the oxide layer that formed along the outer surface of the Hastelloy X structural support mesh in the USF Haynes 230 filter media tended to remain constant after 225 and 496 hours of exposure in the 840°C (1550°F), alkali-laden, simulated PFBC, process gas environment (i.e., ~4.25 μm and ~5 μm, respectively). The composition of the outer surface of the oxide was enriched with oxygen-nickel-chromium. Within the 496 hour-exposed, Hastelloy X structural support mesh, a subsurface chromia layer was identified.

Alternate Commercial and Advanced Alloys. Microstructural analyses for the USF Haynes 214, Haynes 556, Haynes 188, 310S, Inconel 600, and Hastelloy X media, as well as the Pall Hastelloy X and 310S, the Mott Inconel 600, and the Fairey Microfiltrex and Technetics FeCrAl media will be presented in future publications. Information generated to date indicates that typically an ~0.5-3 μm thick oxide-enriched layer formed along the external surface of the USF Haynes 214, Hastelloy X, Haynes 188, and Haynes 230 sinter bonded filtration mat fibers during operation in the 650°C (1200°F) simulated PFBC environment. Extensive oxidation (i.e., 8-10 μm) and pore closure resulted along the surface of the USF Inconel 600, 310S, and Haynes 556 fibers under comparable operating conditions, restricting gas flow through the filter media.

Mechanical Properties — Process Temperature Tensile Strength

Figures 10-13 identify the impact of simulated PFBC exposure on the residual tensile strength of the porous sinter bonded filter materials. As-manufactured and residual process temperature strength are shown to be dependent on the architecture of the filtration media (i.e., sinter bonded fibers vs powders; monolithic filter wall vs inclusion of mesh support layers), as well as the composition of the metal alloys or intermetallic substrates used to construct the porous filter element sections.

In general, the porous, fibrous, nickel-based, USF filter media tended to initially experience an increase and subsequently a reduction in tensile strength during operation in the 650°C (1200°F) simulated PFBC environment. With the exception of the USF FeCrAl media, an increase in tensile strength for

the USF iron-based alloys was observed at 650°C (1200°F). The 650°C (1200°F) tensile strength for the USF cobalt-based media remained relatively constant with time. As simulated PFBC operating temperatures were increased to 760-840°C (1400-1550°F), the tensile strength of the USF filter media decreased. Although dependent on the alloy or intermetallic composition, process temperature tensile strength generally stabilized with continued simulated PFBC exposure time. Typically the presence of gas phase sulfur in the 840°C (1550°F) PFBC process gas promoted a slight further reduction in metal media tensile strength in comparison to the strength of the various USF filter materials during exposure in a sulfur-free process gas environment. In contrast, significant reduction in metal media tensile strength resulted at 840°C (1550°F) when gas phase alkali and sulfur were present in the simulated PFBC process gas stream. Similar trends were observed for the Pall, Mott, Fairey Microfiltrex, and Technetics porous filter media.

Summary Conclusions

Based on simulated PFBC testing in SWPC STC's test facility, the lower tensile strength FeCrAl(Y) and FeAl matrices, as well as higher tensile strength Haynes 214, Hastelloy X, Haynes 188, and Haynes 230 media are currently recommended for consideration and possible extended use in 650°C (1200°F), coal-fired systems, provided acceptable filter particulate collection efficiencies and reverse pulse cleaning characteristics are achieved.

Both the porous Pall FeAl and USF FeCrAl filter media are considered as potentially viable materials for extended use in 760°C (1400°F) PFBC operations. Extended exposure at 840°C (1550°F) beyond 1,000 hours of simulated PFBC testing will be required to demonstrate oxidative stability of these materials. The functional use of the nickel-based USF Haynes 230 filter media is expected to be limited with extended operating time in 760°C (1400°F) PFBC applications, and is not recommended for extended use at 840°C (1550°F).

In the presence of gas phase alkali, the functional integrity and performance of all porous metal, advanced alloy, and intermetallic filter media are severely impacted in 840°C (1550°F) PFBC systems.

Future Activities

To date, the current SWPC program has been focused on identifying the high temperature oxidative stability of the various porous metal, advanced alloy, and intermetallic filter media during extended exposure to simulated PFBC operating conditions. Verification of the particulate collection efficiency for the various filter component architectures needs to be demonstrated prior to SWPC's final recommendations for support and use of select porous sintered metal media in advanced coal-fired combustion systems.

Acknowledgments

We wish to acknowledge Ted McMahon at DOE/NETL for his guidance and technical support during conduct of this program. In addition, the efforts of Tom Lippert, Eugene Smeltzer, George Schneider, John Meyer, Tom Mullen, and Bob Walko at SWPC STC are acknowledged. The efforts of Nat Quick and Alex Sobelevsky at USF, John Sawyer and Nelson Sobel at Pall, Sunil Jha at Mott, Tony McDowell and Ian Boxall at Fairey Microfiltrex, Doug Chappel at Technetics, and Ed Stankiewicz at Ultramet are also acknowledged.

Test Campaign	System Temp	Cumulative Operating Duration, Hrs		
		Segment No. 1	Segment No. 2	Segment No. 3
1	**650°C (1200°F)**	242	500	—
2	**760°C (1400°F)**	258	524.5	1,016
3	**840°C (1550°F)**	259*	476	986
4	**840°C (1550°F)[(a)]**	253	546.5	1,014
5	**840°C (1550°F)[(b)]**	225	496	—

* 815°C (1500°F).
(a) Absence of SO_2/SO_3.
(b) Inclusion of SO_2/SO_3 and gas phase alkali.

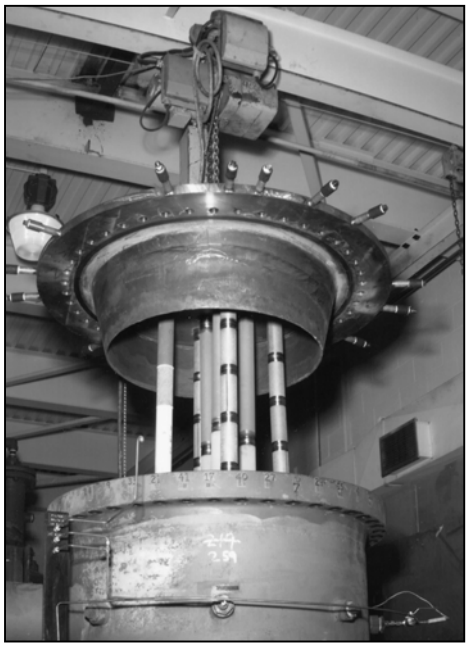


Figure 1 — Composite Metal Filter Array Used in SWPC STC PFBC Simulator Testing.

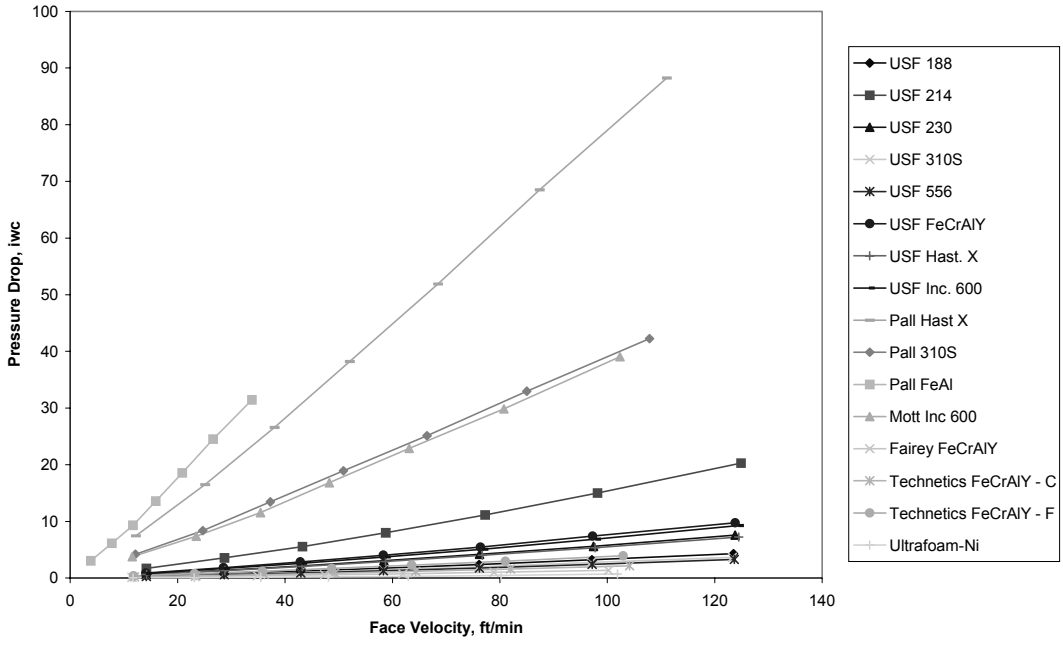
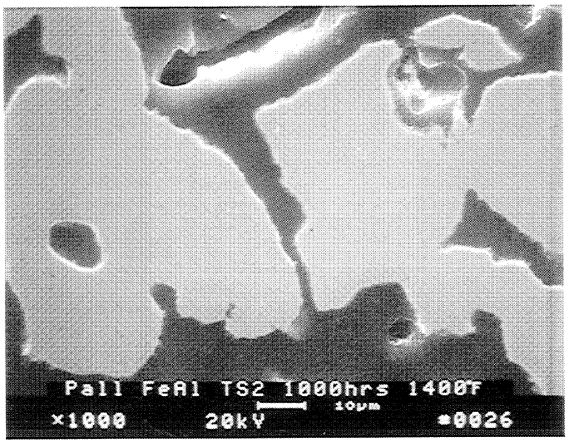
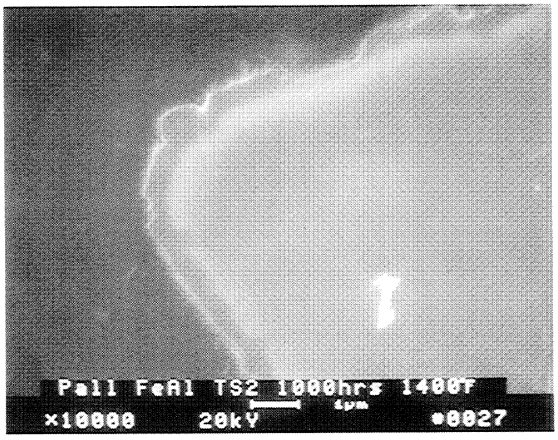
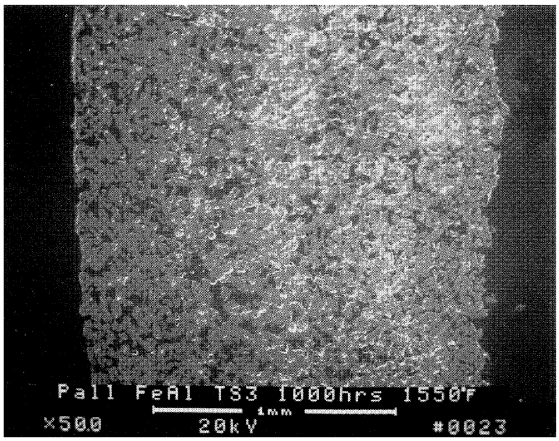
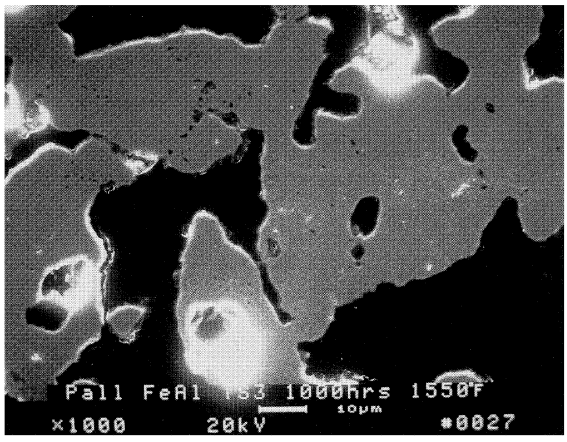


Figure 2 — Room Temperature Gas Flow Resistance through the As-Manufactured Porous Metal Filter Media.









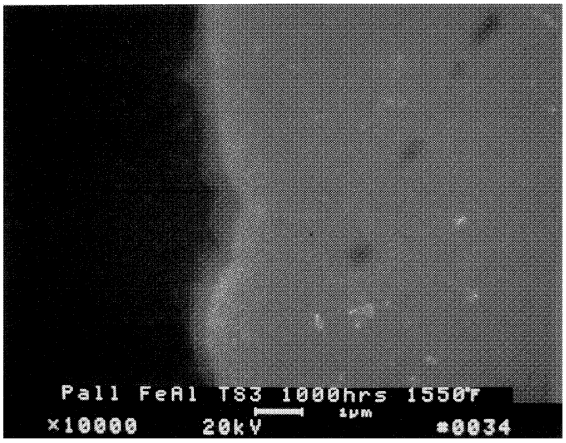
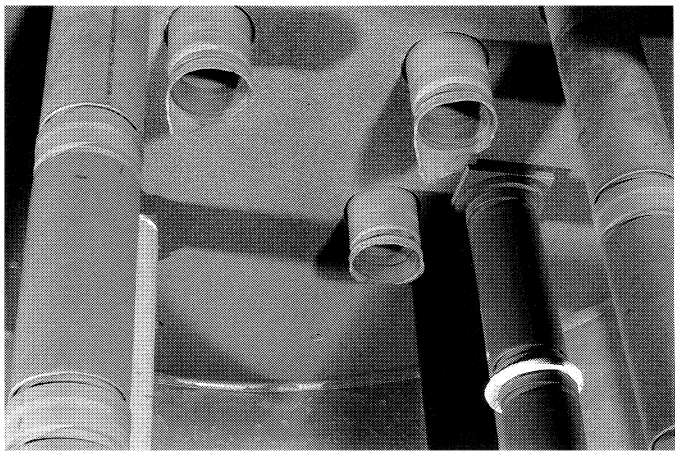
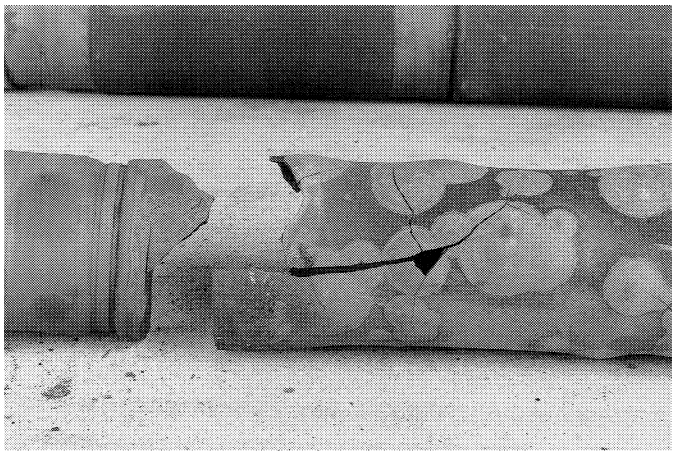
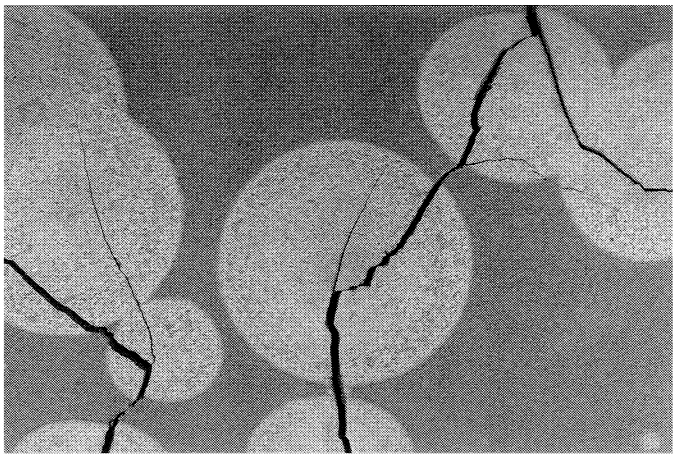
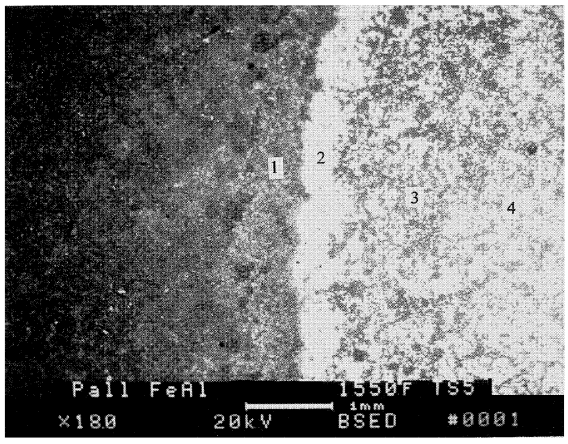


Figure 3 — Morphology of the Pall FeAl Porous Filter Media after ~1,000 Hours of Exposure under 760-840°C (1400-1550°F) Simulated PFBC Operating Conditions.





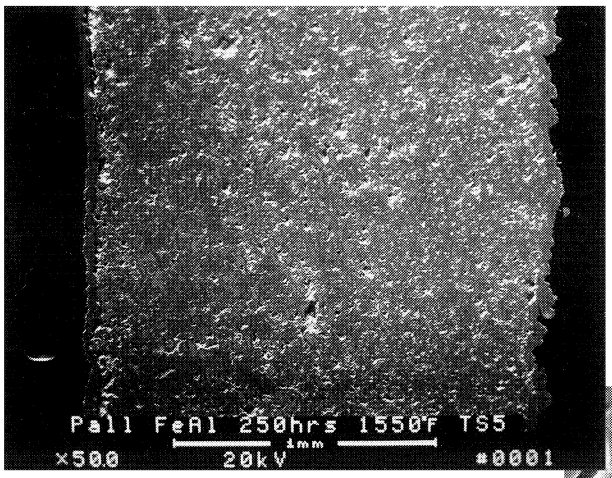


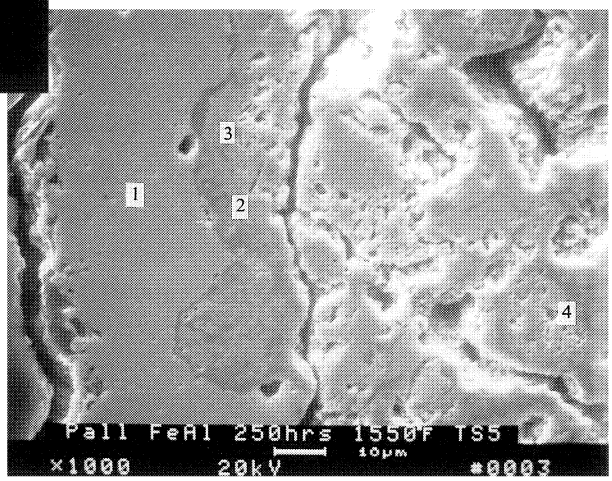


EDAX Analysis, Atomic%

1. 63.34% O, 22.63% Fe, 7.13% Al, 3.39% Na, 2.07% S, 0.88% Cr, 0.57% Ni
2. 54.52% O, 33.45% Fe, 4.68% Na, 3.94% Ni, 1.74% S, 0.81% Mn, 0.48% Ca, 0.38% Cr
3. 63.08% O, 21.66% S, 14.11% Na, 1.15% Fe (Sodium Sulfate Particle)
   52.71% O, 39.18% Fe, 4.31% Ni, 1.33% Mn, 0.88% S, 0.81% Cr, 0.78% Na (Substrate Surface)
4. 62.50% O, 21.85% S, 14.20% Na, 1.44% Fe (Sodium Sulfate Particle)
   49.60% O, 46.66% Fe, 0.95% Ni, 0.86% Na, 0.80% Cr, 0.57% Mn, 0.55% S (Substrate Surface)

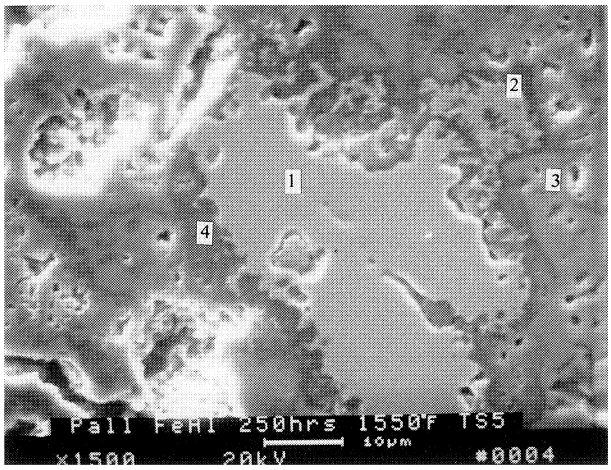
Figure 4 — Failure of the Pall FeAl Filter Element Sections after 225 Hours of Exposure in the 840°C (1550°F) Simulated PFBC Process Gas Environment Containing Gas Phase Sulfur and Alkali.





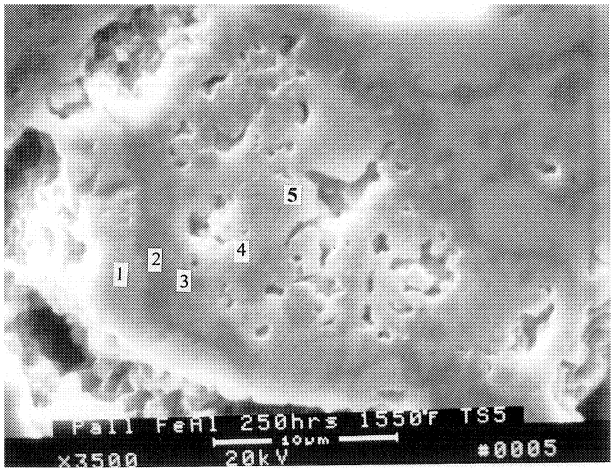
EDAX Analysis, Atomic%

1. 54.44% O, 45.56% Fe
2. 61.44% O, 28.68% Al, 8.11% Fe, 1.77% Cr
3. 55.10% O, 37.88% Fe, 5.43% Al, 1.59% Cr



EDAX Analysis, Atomic%

1. 90.92% Fe, 6.61% O, 1.89% Al, 0.59% Cr (Core)
2. 90.18% Fe, 7.19% O, 1.81% Al, 0.82% Cr
3. 52.02% O, 46.96% Fe, 0.70% Al, 0.34% Cr
4. 60.29% O, 33.10% Al, 5.05% Fe, 0.83% Cr, 0.73% S



EDAX Analysis, Atomic%

1. 54.58% O, 40.88% Fe, 4.13% Al, 0.40% Cr
2. 61.00% O, 25.37% Al, 11.81% Fe, 1.43% Cr, 0.40% S
3. 55.96% O, 21.33% Fe, 19.89% Al, 2.40% Cr, 0.42% S
4. 54.65% O, 37.22% Fe, 6.06% Al, 2.08% Cr
5. 54.83% O, 32.32% Fe, 9.78% Al, 3.06% Cr (Core)

Figure 5 — Accelerated Oxidation of the Pall FeAl Filter Media after 225 Hours of Exposure in the 840°C (1550°F) Simulated PFBC Process Gas Environment Containing Gas Phase Sulfur and Alkali.

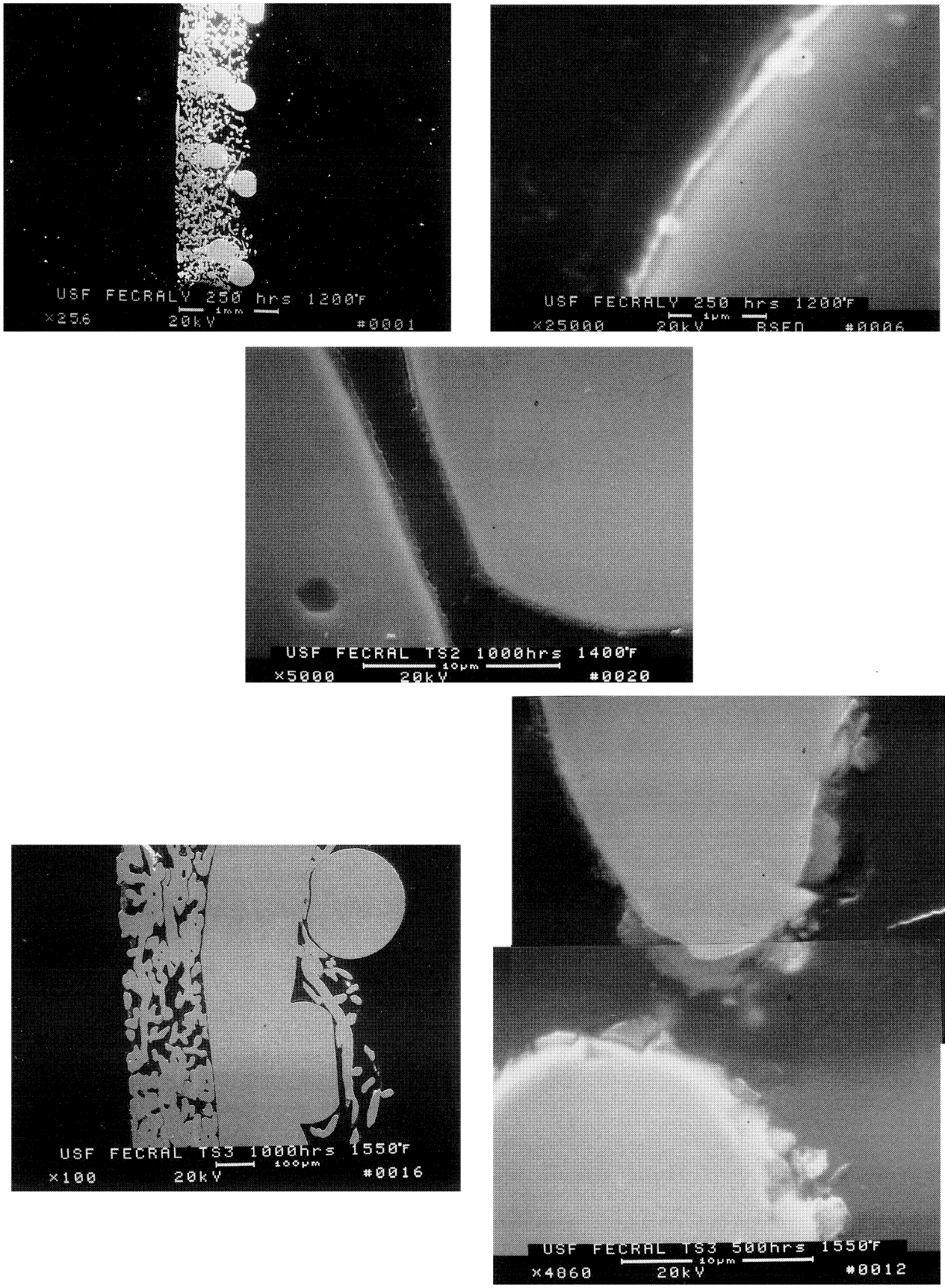
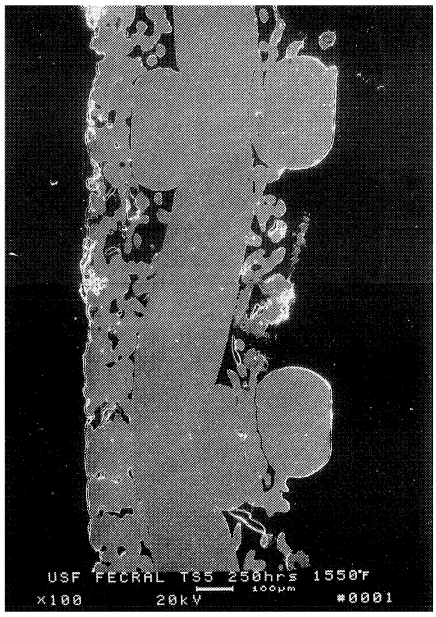
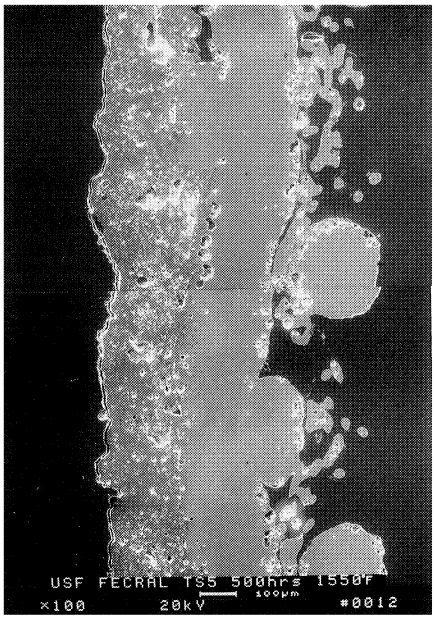
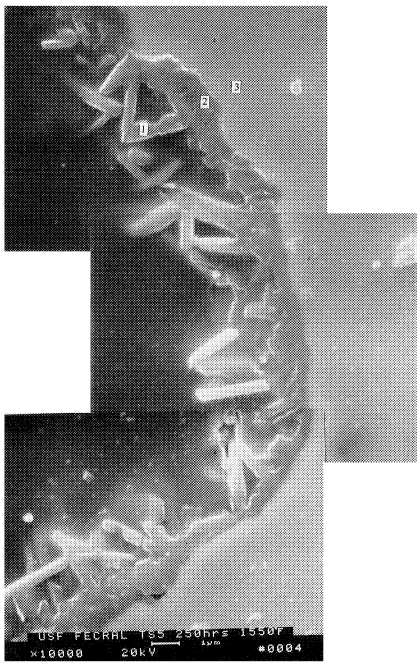
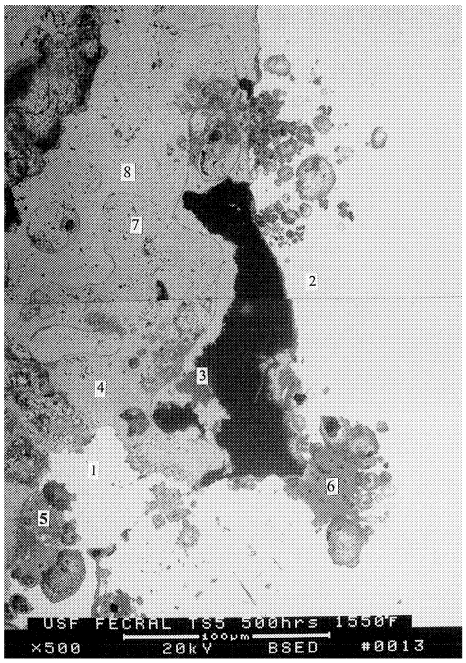


Figure 6 — Morphology of the USF FeCrAl Filter Media after Exposure to 650-840°C (1200-1550°F) Simulated PFBC Operating Conditions.









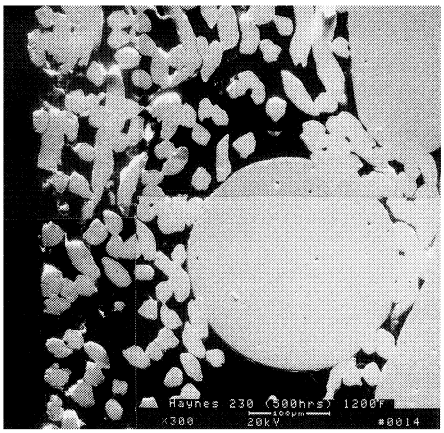
EDAX Analysis, Atomic%

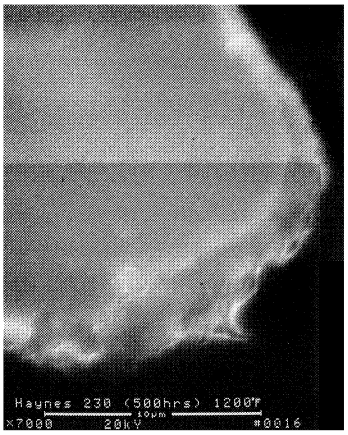
1. 62.30% O, 30.57% Al, 2.72% Fe, 2.62% Cr, 1.80% Si
2. 51.12% O, 30.09% Al, 10.60% Fe, 7.21% Cr, 0.97% S
3. 73.22% Fe, 23.11% Cr, 2.56% Al, 1.12% Si

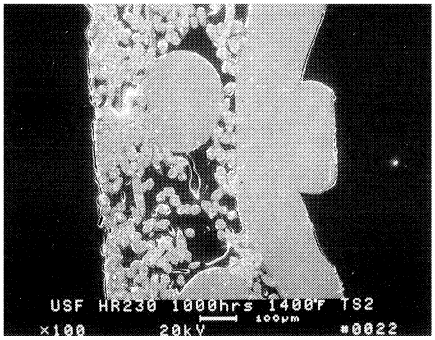
EDAX Analysis, Atomic%

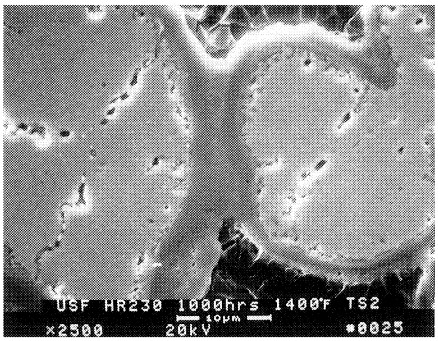
1. 90.61% Fe, 8.29% Cr, 1.11% Si (FeCrAl Fiber; Depleted Base Metal)
2. 76.83% Fe, 22.07% Cr, 1.10% Si (FeCrAl Structural Support Mesh; Depleted Base Metal
3. 61.86% O, 36.42% Al, 1.04% Fe, 0.67% Cr
4. 52.33% O, 35.36% Cr, 6.51% Fe, 3.24% S, 1.50% Si, 1.07% Al
5. 57.70% O, 26.84% Cr, 14.04% Al, 1.10% Fe, 0.32% S
6. 62.30% O, 35.31% Al, 2.03% Cr, 0.36% Fe
7. 54.55% O, 32.98% Fe, 10.88% Cr, 1.09% Si, 0.51% Al
8. 53.39% O, 33.50% Fe, 11.48% Cr, 1.63% Al

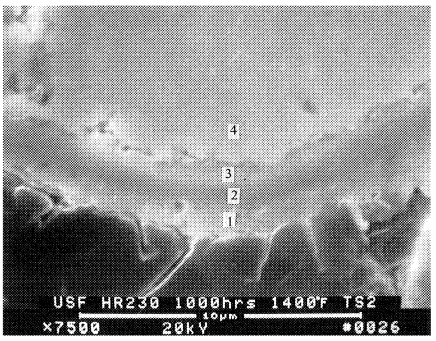
Figure 7 — Morphology of the USF FeCrAl Filtration Media after Exposure to 840°C (1550°F) Simulated PFBC Operating Conditions Containing Gas Phase Sulfur and Alkali.





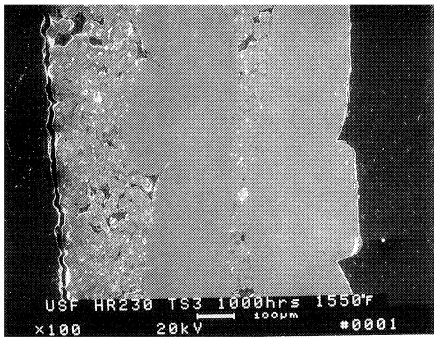


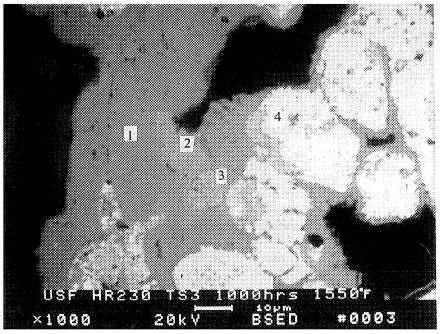


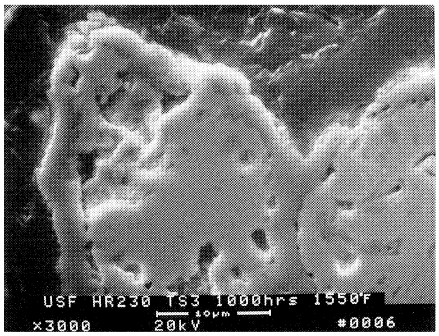


EDAX Analysis, Atomic%

1. 52.09% O, 36.17% Ni, 5.47% Cr, 4.19% Fe, 1.87% Mn, 0.20% W
2. 50.39% O, 36.63% Cr, 8.08% Ni, 2.53% Fe, 1.53% Mn, 0.54% W, 0.30% Mn
3. 56.16% O, 32.44% Cr, 6.15% Ni, 2.39% W, 1.18% Fe, 0.99% Mo, 0.69% Mn
4. 69.79% Ni, 16.31% Cr, 9.87% 3.15% W, 0.71% Mo, 0.16% Mn (Base Metal)



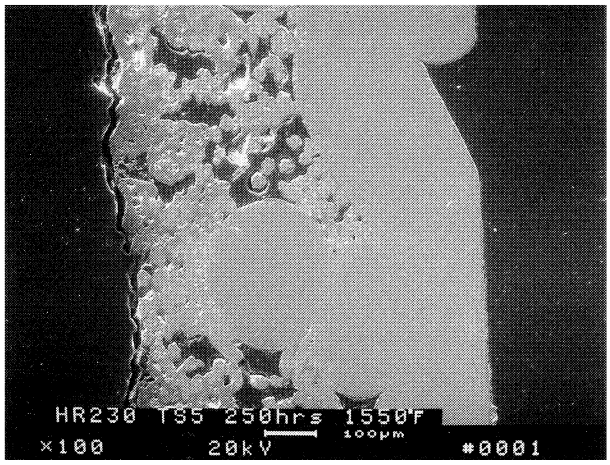


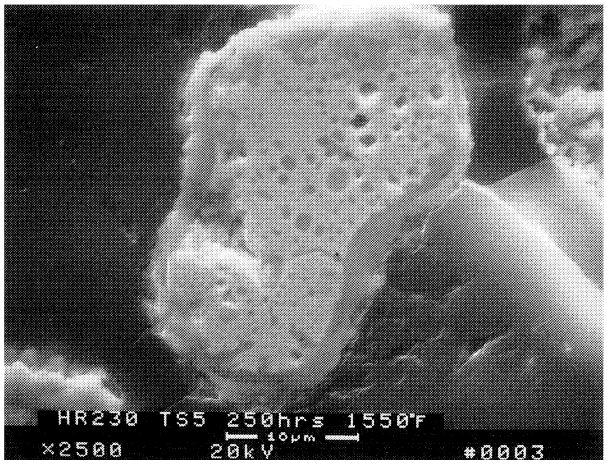


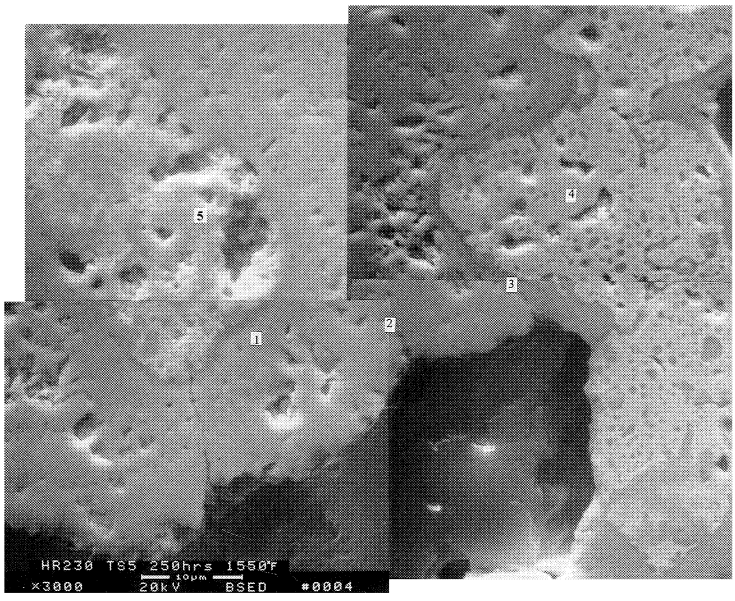
EDAX Analysis, Atomic%

1. 48.73% O, 18.01% Fe, 16.02% Ni, 15.16% Cr, 1.73% Co, 0.35% Mn
2. 50.62% Ni, 36.60% O, 5.49% Cr, 3.03% Fe, 2.02% Co, 1.27% Si, 0.97% Mn
3. 43.54% O, 31.72% Ni, 15.68% Cr, 3.84% Fe, 2.81% Co, 1.55% Mn, 0.86% W

Figure 8 — Morphology of the USF Haynes 230 Filter Media after Exposure to 650-840°C (1200-1550°F) Simulated PFBC Operating Conditions.







EDAX Analysis, Atomic%

1. 50.79% O, 18.61% Cr, 18.15% Ni, 10.87% Fe, 1.26% Mn, 0.31% W
2. 61.97% Ni, 36.03% O, 0.90% Fe, 0.88% Cr, 0.22% Mn
3. 52.50% O, 32.07% Cr, 12.42% Ni, 1.65% Fe, 0.85% Mn, 0.51% W
4. 85.51% Ni, 5.85% Fe, 4.52% W, 2.15% Cr, 1.70% Mo, 0.27% Mn
5. 53.76% O, 24.65% Cr, 15.63% Ni, 3.90% Fe, 1.19% Mn, 1.14% W

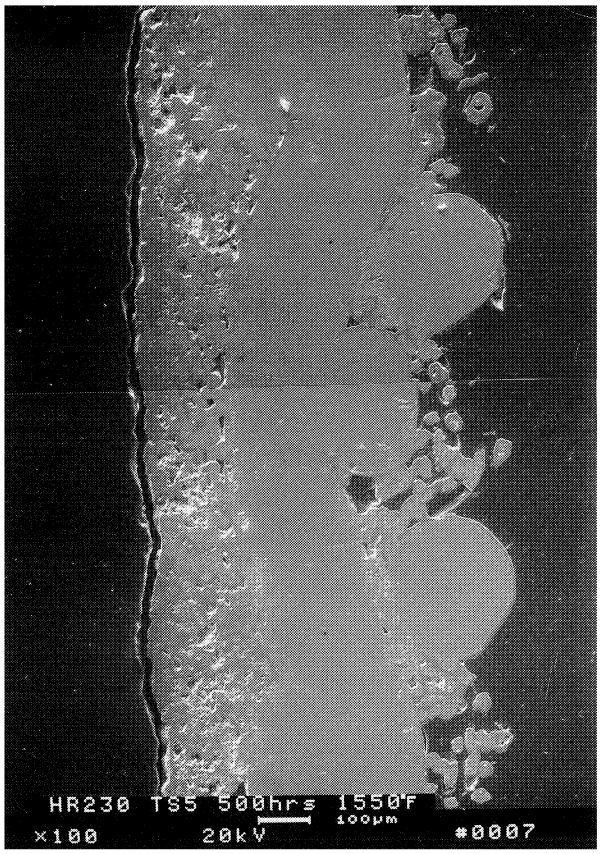


Figure 9 — Morphology of the USF Haynes 230 Filtration Media after Exposure to 840°C (1550°F) Simulated PFBC Operating Conditions Containing Gas Phase Sulfur and Alkali.

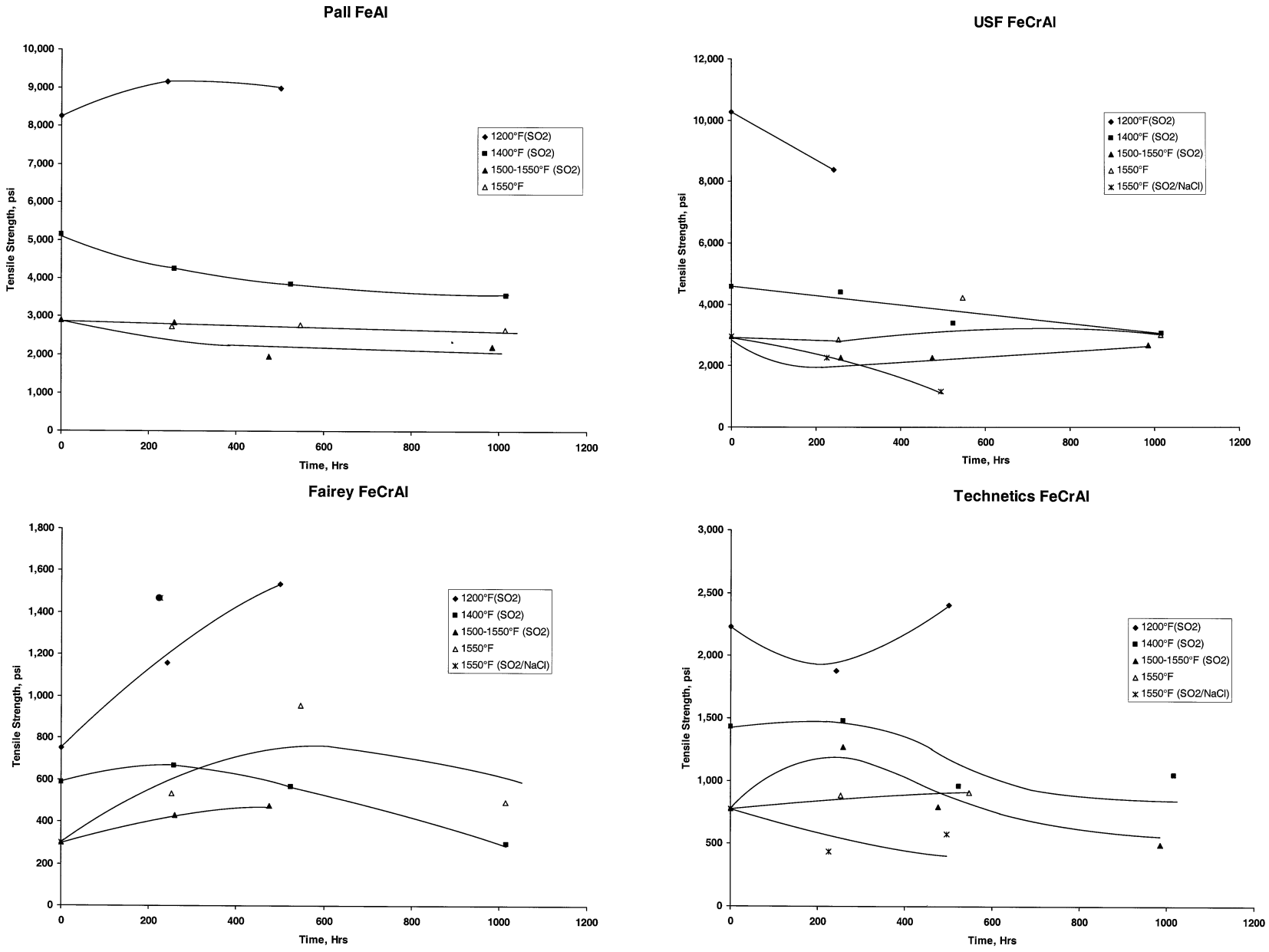


Figure 10 — Process Temperature Tensile Strength of the Iron-Based, Intermetallic, Porous Filter Media after Exposure to Simulated PFBC Operating Conditions.

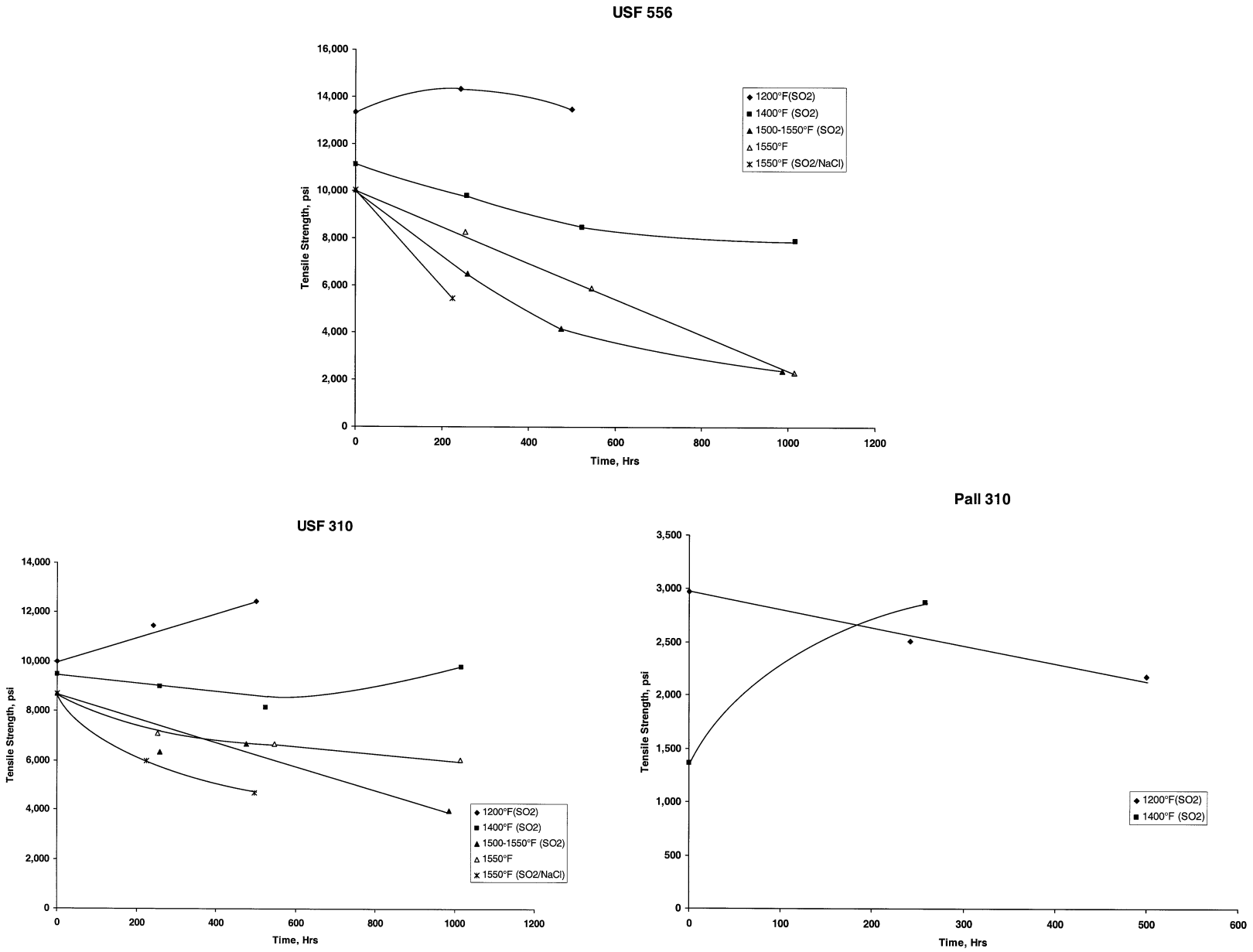


Figure 11 — Process Temperature Tensile Strength of the Iron-Based, Advanced and Commercial Alloy, Porous Filter Media after Exposure to Simulated PFBC Operating Conditions.

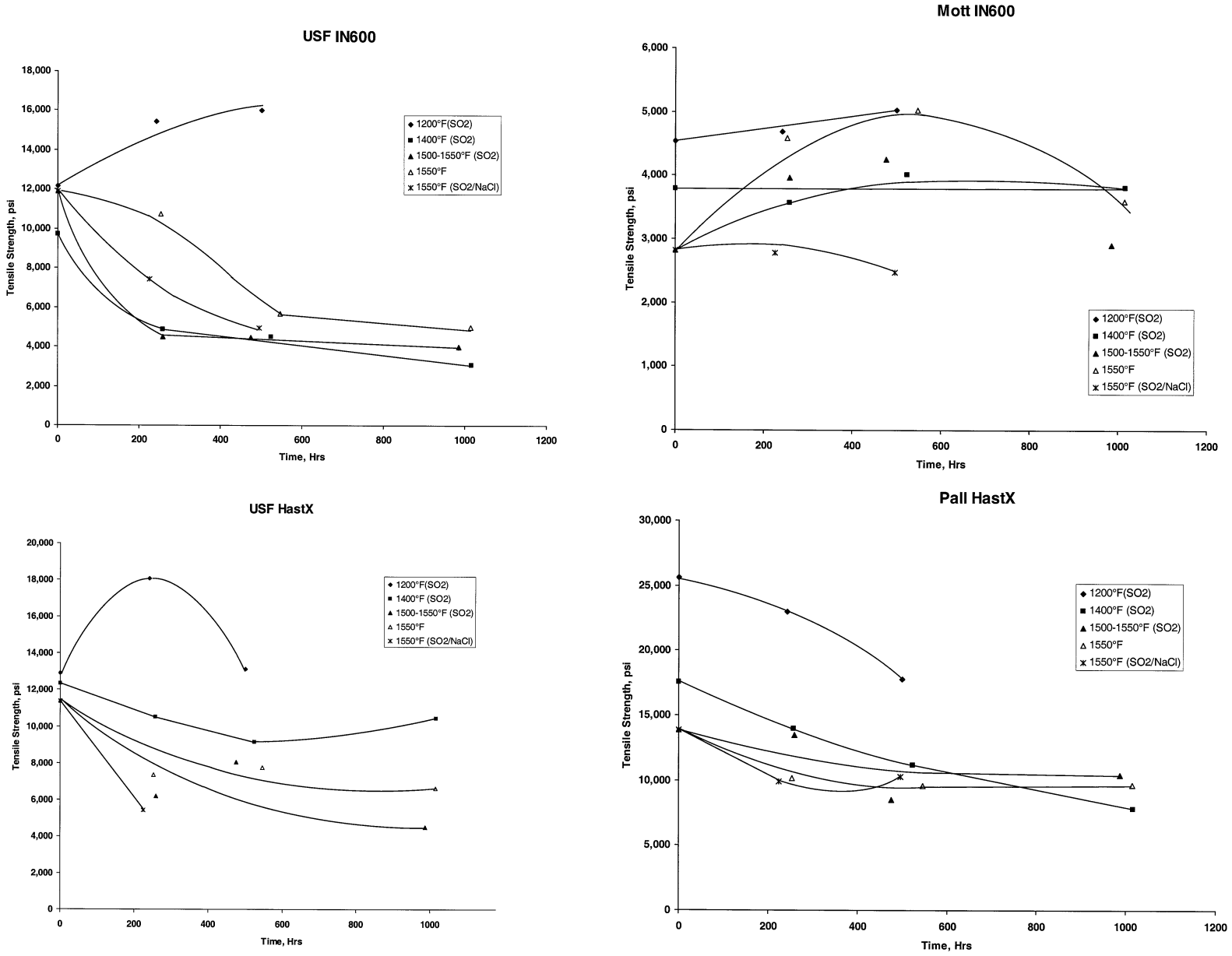


Figure 12 — Process Temperature Tensile Strength of the Nickel-Based, Commercial Alloy, Porous Filter Media after Exposure to Simulated PFBC Operating Conditions.

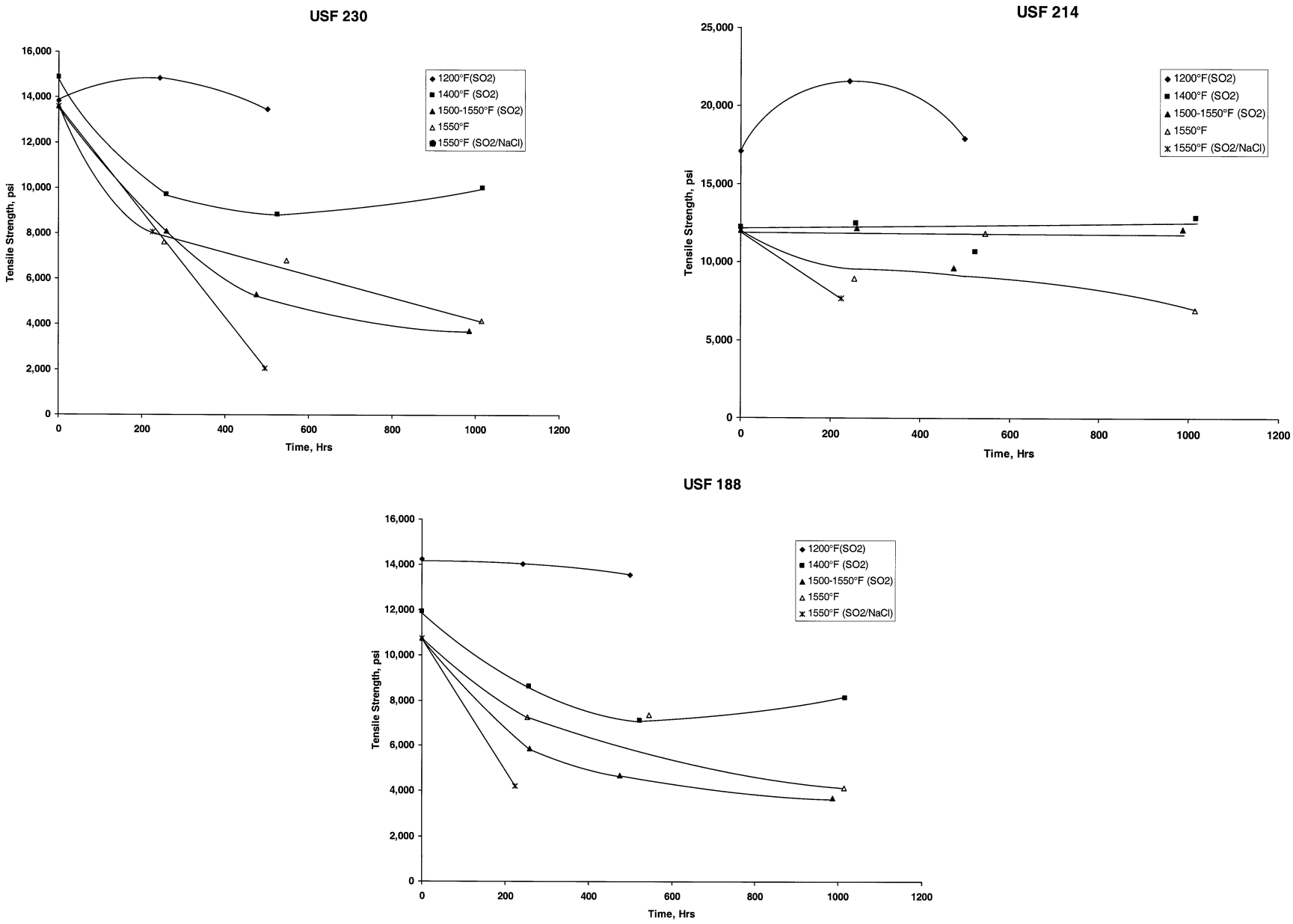


Figure 13 — Process Temperature Tensile Strength of the Nickel- and Cobalt-Based, Advanced Alloy, Porous Filter Media after Exposure to Simulated PFBC Operating Conditions.

TABLE 1 — DEVELOPMENTAL AND COMMERCIALLY AVAILABLE METAL FILTER MEDIA — COMPONENT ARCHITECTURE —

Supplier	Metal Media	Media Architecture	Outer Wire Mesh	Internal Structural Core	Longitudinal Weld	Weld Material	End Rings **
U.S. Filter	310	Fiber	Hast X/Hast X (a)	310	Included	556 Wire	310S/310S
	Inconel 600	Fiber	Hast X/Hast X (a)	310	Included	556 Wire	310S/310S
	Hastelloy X	Fiber	Hast X/Hast X (a)	310	Included	556 Wire	310S/310S
	Haynes 214	Fiber	FeCrAlY/ FeCrAlY or Hast X or Inconel (a)	310	Included	556 Wire or Inconel	310S/310S
	Haynes 556	Fiber	Hast X/Hast X (a)	310	Included	556 Wire	310S/310S
	FeAl (Mod)	Fiber	Hast X/Hast X (a)	310	Included	Kanthal	310S/310S
	FeCrAlY	Fiber	FeCrAlY/ FeCrAlY or Hast X (a)	310	Included	Kanthal or 556 Wire or Hastelloy	310S/310S
	Haynes 188	Fiber	Hast X/Hast X (a)	310	Included	556	310S/310S
	Haynes 230	Fiber	Hast X/Hast X (a)	310	Included	556	310S310S
Pall	310S	Powder	None	None	None	309/310	310S/310S
	Hastelloy X	Powder	None	None	Included	Hastelloy C276	310S/ Hastelloy C276
	Iron Aluminide	Powder	None	None	None	309/310	310S/310
Mott	Inconel 600	Powder	None	None	None	Inconel 82	310S
Fairey Microfiltrex	CCTF™	Fiber	Hastelloy C276	Hastelloy C276 316L Support Core	Included	Autogeneous ***	310S
Technetics	FeCrAlY*	Fiber			Included	Hastelloy X	310S
Ultramet	Ni	Reticulated Foam	None	None	None	None	None

(a) Mesh embedded within filtration mat/Mesh layered between filtration mat and structural support core.
* Fe (22.5% Cr, 5% Al, 0.5% Y)
** Transition rings added to join porous metal filter media sections.
*** Weld pool generated from parent metal.

TABLE 2 — METAL FILTER MEDIA AND COMPONENT PHYSICAL INTEGRITY

Filter Media	Simulated PFBC Operating Conditions				
	650°C (1200°F)	760°C (1400°F)	815-840°C (1500-1550°F)	840°C (1550°) — No SO_2 —	840°C (1550°F) — SO_2 & Na —
Pall FeAl	Intact	Intact	Intact	Intact	Failure at weld; Volume expansion; Raised Bubbles; Longitudinal and circumferential distortion within 225 hrs
USF FeCrAl	Transverse linear indications and through-cracks along longitudinal weld seam after 242 hr; Section removed and media was modified	Intact	Intact	Intact	Intact; Densified external surface (496 hrs)
USF Haynes 230	Intact	Intact	Intact	Intact	Intact; Densified external surface (496 hrs)
USF Haynes 214	Intact	Intact	Intact	Intact	Removal of the filtration media and outer mesh within 496 hrs
USF Haynes 188	Intact	Intact	Intact	Intact	Expansion and separation of filtration media radiating from the circumferentially welded metal joiner rings within 496 hrs (i.e., elephant foot formation); Longitudinal cracks within filter media
USF Haynes 556	Intact	Isolated removal of the outer filtration mat occurred within 1,016 hrs	Isolated removal of the outer filtration mat occurred within 259 hrs	Isolated removal of the outer filtration mat occurred within 253 hrs	Expansion and separation of filtration media radiating from the circumferentially welded metal joiner rings within 496 hrs (i.e., elephant foot formation); Longitudinal cracks within filter media
USF 310	Intact	Intact	Intact	Intact	Intact; Densified external surface (496 hrs)
USF Inconel 600	Intact	Intact	Intact	Intact	Intact; Densified external surface (496 hrs)
USF Hastelloy X	Intact	Intact	Intact	Intact	Expansion and separation of filtration media radiating from the circumferentially welded metal joiner rings within 496 hrs (i.e., elephant foot formation); Longitudinal cracks within filter media; Embrittlement and cracking of the filtration media.
Pall 310S	Intact	Circumferential failure at metal ring weld within 258 hrs	Circumferential failure at metal ring weld within 259 hrs	Circumferential failure at metal ring weld within 253 hrs	Circumferential failure at metal ring weld within 225 hrs
Pall Hastelloy X	Intact	Intact	Intact	Intact	Surface scaling (496 hrs)
Mott Inconel 600	Intact	Intact	Intact	Intact	Crack detected near circumferential weld to ring with 225 hrs
Fairey Microfiltrex FeCrAl	Intact	Intact	Intact	Intact	Failure of the external Hast C276 mesh; Localized removal of filtration mat within 225 hrs
Technetics FeCrAl	Intact	Intact	Intact	Intact	Continuity of the longitudinal weld in question (496 hrs)