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A Simple Candle Filter Safeguard Device

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Introduction

In order to reach the highest possible efficiencies in a coal-fired turbine-based power system, the turbine should be directly fired with the products of coal utilization. Two main designs employ these turbines: those based on pressurized fluidized-bed combustors (PFBCs) and those based on integrated gasification combined cycles (IGCCs). In both designs, the suspended particulates, or dust, must be cleaned from the gas before it enters the turbine to prevent fouling and erosion of the blades. To produce the cleanest gas, barrier filters are being developed and are in commercial use. Barrier filters are composed of porous, high-temperature materials that allow the hot gas to pass but collect the dust on the surface. The three main configurations are candle, cross-flow, and tube. Both candle and tube filters have been tested extensively. They are primarily composed of coarsely porous ceramic that serves as a structural support, overlain with a thin, microporous ceramic layer on the dirty gas side that serves as the primary filter surface. They are highly efficient at removing particulate matter from the gas stream and, because of their ceramic construction, are resistant to gas and ash corrosion. However, ceramics are brittle, and individual elements can fail, allowing the particulates to pass through the hole left by the filter element and erode the turbine.

Because of the possibility of occasional filter breakage, safeguard devices (SGDs) must be employed to prevent the dust streaming through broken filters from reaching the turbine. The SGD must allow for the free passage of gas when it is not activated, but upon breaking of a filter, the SGD must either mechanically close or otherwise plug to prevent dust from reaching the turbine. The SGD must use existing filter system seals, gaskets, fixtures, and assemblies as much as possible. It must also activate quickly when a candle filter has failed, preferably preventing dust concentrations downstream of the SGD from exceeding 1 ppmw (Lippert and others 1995).

In addition, the SGD must be able to operate in an inactive mode with minimal pressure drop, and its operation cannot be affected by repeated backpulse cleaning events of up to 3 psia (155 mmHg) and ½ second in duration.

Production of a rapidly closing autonomous mechanical device that is dependable at high temperatures in a dusty gas stream is difficult because of problems with materials corrosion, dust leakage, and detection of candle failure. Therefore, the Energy & Environmental Research Center (EERC) is using its knowledge of the factors that make filter dust sticky at gas filtration temperatures to make an inexpensive SGD that rapidly and permanently plugs with dust upon filter failure. The SGD employs a sticky yet thermodynamically stable coating on a highly porous ceramic substrate. It would be placed at the outlet of a candle filter, as shown in Figure 1. The adhesive surface of the device will rapidly and permanently trap dust particles, causing the device to close the gas flow upon failure of a filter.

Just as different filter materials are used for combustion versus gasification conditions, different coatings will be used on an inert ceramic substrate to cover the typical range of conditions in PFBC (oxidizing) or IGCC (reducing) operating mode. For gasification, conditions in the Siemens-Westinghouse filter vessel at the Sierra Pacific Piñon Pine plant are being simulated in the testing. For combustion systems, the approximate conditions in the Siemens-Westinghouse particle filter used in conjunction with the Southern Company Services transport reactor being tested at the Power Systems Development Facility (PSDF) are employed. In both cases, however, the EERC SGD is composed of three main parts: the ceramic substrate, the adhesive coating, and the SGD housing. This report describes the development and laboratory testing of each of those parts as well as the bench-scale performance of both types of complete SGDs.

Porous ceramic substrates

The specifications for the porous ceramic substrates are that the pressure drop across the substrates must meet the requirements set forth by Siemens-Westinghouse and the diameter should be the same as the top flange of a candle filter (3 in. [7.62cm]). The Siemens-Westinghouse standards for its filter vessel are for an SGD not to increase pressure drop across the filter vessel by more than 1 psi (52 mmHg) during normal operation with a flow rate of 30 acfm (850 alpm). At room temperature and pressure, that converts into approximately 30 scfm (850 slpm) and 12 in. (22.4 mmHg) of water pressure drop.

During the course of the program, we evaluated four different types of ceramic substrates. They included disks made from bonded coarse ceramic particles, ceramic foam made by gas foaming in a gel, radial-flow cylinders made from woven ceramic fiber, and disks made by coating a polymer sponge with a slurry made from fine ceramic particles. The material chosen for making the SGD was the ceramic sponge, made by Porvair-Selee, because it combined a very low pressure drop, flexibility of compositions, and low cost. Six different ceramic sponge materials were investigated. They included 30-, 60-, and 80-pore per inch (ppi) zirconia-toughened alumina (ZTA) for the combustion SGD and 30- and 60-ppi silica-bonded silicon carbide (SiC) and 60-ppi fused silica disks for the gasification SGD. The disks were typically 2½ to 3 in. (6.35–7.62 cm) in diameter and 1 in. (2.54 cm) thick. Disks with densities of 18%–20% and with 60 ppi were ultimately chosen because they combined the necessary strength with a suitably low pressure drop.

COATING MATERIALS FOR COMBUSTION CONDITIONS

Compositions of the Sticky Coatings

During the program, several different chemical systems were investigated: $\text{Fe}_2(\text{SO}_4)_3$, FeSO_4 , Na_2SO_4 , K_2SO_4 , and MgSO_4 for combustion systems and various alkali silicates for the gasification system. The alkali sulfates were chosen for combustion systems because they naturally occur in filter dust. They are thermodynamically stable, and the gas stream should be saturated with them so they are not prone to evaporation. In addition, they all can be blended to make compounds with eutectic temperatures in the right range for the PSDF hot-gas filter vessel. The compounds were dried at 302°F (150°C) before weighing and were ground and mixed in a ball mill before reacting. The mixtures were heated in 10-mL sintered alumina crucibles placed in a larger alumina tray. To determine the degree of sintering of the compounds and measure their thermodynamic stability as determined by weight change, they were heated in a tube furnace in a simulated combustion gas at a flow rate of 1 scfm (approximately 1 furnace-tube volume change every minute). The gas composition was 4% O_2 , 14% CO_2 , and 1000 ppm SO_2 , with a balance of N_2 . No water vapor was included in these initial tests.

In general, the iron sulfates were less stable than the alkali sulfates, so they were dropped from further testing. A mixture of K_2SO_4 and Na_2SO_4 named Compound A was effective at sintering Tidd filter dust at 1472°F (800°C). The eutectic temperature for the K_2SO_4 – Na_2SO_4 chemical system is 1529.6°F (832°C), low enough to ensure that the material would sinter well at 800°C, but not completely fuse and, possibly, run off of the ceramic substrate (molten sulfates have very low viscosities). The tests were performed with a eutectic mixture of K_2SO_4 and Na_2SO_4 prepared and fused at 1562°F (850°C). After fusing, the compound was ball-milled and sieved to $\sim 30 \mu\text{m}$. The sieved material was added to the Tidd dust in quantities of 20% and 50% by weight and shaken in a ball mill without a ball to ensure good mixing. It was then heated in simulated flue gas without water vapor at 77°F/min (25°C/min) to 1472°F (800°C) and held for 15 minutes before cooling.

After cooling, the pure compound sintered well, but did not fuse. With as little as 20% of the Compound A mixed with the Tidd dust, a sintered mass formed that could easily be handled, although it was relatively easily crushed. With 50% of the compound, a hard pellet was formed that was much more difficult to break by hand. Its strength was similar to that of an aspirin tablet of a like size. Tidd dust with no compound did hold its shape somewhat, but the pieces were so weak that they could not be picked up by hand. No weight loss was measured in the Compound A material to the nearest 0.1 wt% upon fusing at 1562°F (850°C) for 15 minutes or on holding at that temperature for 25.5 hours.

Although the tests of Compound A were successful at 1472°F (800°C), the Wilsonville facility often operates at around 1382°F (750°C). Compound A was not effective at sintering the Tidd filter dust at that temperature. Therefore, a different material called Compound B was developed for use in the lower temperature range. Compound B is formed from 90% K_2SO_4 and 10% MgSO_4 . As shown in Figure 2, one of the two eutectic temperatures for this system is 1374.8°F (746°C) (American Ceramic Society 1969). Compounds were prepared at several ratios of K_2SO_4 and MgSO_4 bracketing the ratio of the eutectic composition. They were made by

mixing dried reagent-grade compounds, ball-milling, and fusing at 1976°F (1080°C) which is just above the melting temperature of the K_2SO_4 . They were then ball-milled and sieved to $-30\ \mu\text{m}$ and mixed with the Tidd dust in ratios of 20% and 50% of the compounds. As was done with Compound A, the compound–dust mixtures were shaken in a ball mill to mix them, then tapped into a crucible and heated to 1382°F (750°C) for 15 minutes in simulated flue gas. Figure 3 shows the sintered Compound B–dust mixtures after removal from the crucible.

In contrast to the Compound A–dust mixtures, the Compound B–dust mixtures were much more sintered at 1382°F (750°C). They had approximately the same strength as the Compound A–dust mixtures sintered at 1472°F (800°C). The relatively high fragmentation of the 20% B pellet was caused by the difficulty in removing it from the crucible. A total of six different ratios of K_2SO_4 and $MgSO_4$ were tested. All sintered the dust well at 1382°F (750°C), but only Compound B did not produce enough liquid to spontaneously separate from the unmelted material.

To determine the influence of different flue gas constituents on the stability of Compound B, thermogravimetric analysis (TGA) was performed in a variety of atmospheres. The baseline gas composition simulated the CO_2 , O_2 , and N_2 concentrations in a PFBC system. For different tests, SO_2 and H_2O were introduced, along with vaporization products from Tidd filter dust (by passing the baseline gas through a hot packed bed of the dust). The tests were done by heating at 5°C/min to 1382°F (750°C), then holding for 2 hours. The Compound B weight remained stable (within 0.1%) during the isotherm in each type of atmosphere (100% N_2 or $CO_2/N_2/O_2$ or $SO_2/N_2/O_2/CO_2$), indicating that it does not slowly decompose or change form. These tests indicate that for the Siemens-Westinghouse filter vessel operating near 1382°F (750°C), Compound B is the preferred sticky material, whereas for systems operating in the range of 1472°F (800°C), Compound A would be more preferable.

Method for Coating the Ceramic Substrate

The high solubility of the Compound B constituents in water indicated that dip-coating the porous ceramic substrates may be the easiest method to prepare the SGD. To prevent separation of the constituents during drying, gelatin was added to the salt solution, and the gel was vacuum-dried. The gelatin was burned out at 1292°F (700°C) in air. Figure 4 is a scanning electron micrograph (SEM) showing the remaining salt material in a pore of the sponge. SEM analyses indicate that on a micrometer-sized scale, the potassium and magnesium salts did not separate from each other during drying. However, the dried gelatin material mixture was not effective at sintering Tidd ash at 1382°F (750°C) as was the fused compound B, indicating that simply drying the gel is not sufficient to activate the precipitated salts. In addition, pressure drop measurements indicated that the dried gel-filled pores exhibited an excessively high pressure drop. Therefore, the coated ceramic sponge material was fired at 1976°F (1080°C) both to activate the Compound B and fuse it to the walls of the substrate.

SGD mechanical design

Both the combustion and gasification SGDs consist essentially of disks of coated porous ceramic sponge 3 in. (7.62 cm) in diameter and 1 in. (2.54 cm) thick. The disks are seal-welded in a metal cylinder to the hold-down plate used to seal the candle filters in the tube sheet. They are supported with coarse backup metal plates so that they can withstand high pressure drop periods such as a backpulse or candle filter failure at the full filter system pressure drop. This design is

shown in Figure 5. It consists of the coated ceramic sponge disk inserted into a metal cylinder manufactured from 3-in. (7.62 cm) Schedule 40 pipe and is sealed around the outside of the disk with either Interam intumescent mat material or with a compressed layer of glass fiber Kaowool. The disk is also held in place with gaskets of Interam gasket material on the top of the upper coarse metal support disks. The Interam gasket material expands upon heating to ensure that the disk will remain sealed in the metal cylinder even with the differences in the expansion coefficients between the metal cylinder and the ceramic.

Combustion Testing

The bench-scale tests of the combustion SGDs were performed in the pressurized fluidized-bed reactor (PFBR) which has been constructed to simulate the bed chemistry, ash interactions, and emissions from a PFB under closely controlled conditions. This reactor has been used for sorbent characterization, gaseous emissions including trace elements, agglomeration, and hot-gas cleanup testing in a cost-effective manner over a wide range of operational conditions. The conditions used during the SGD tests were similar to those in the Siemens-Westinghouse particle filter being tested at the Southern Company Services PSDF while operating as a combustor. The typical range of operating conditions for the system is listed in Table 1.

A bench-scale filter vessel was used in conjunction with the PFBR to obtain high-temperature, high-pressure operational data on the SGDs. This vessel handles all of the gas flow from the PFBR at its nominal design conditions. It is shown in a schematic with the PFBR in Figure 6. The vessel has a 10-in. (25.4-cm) i.d. and is 60 in. (152 cm) long (including cone, vessel, and cap) and can handle a gas flow up to 30 scfm (850 slpm) at 1550°F (843°C) and 150 psig (11 atm). The tube sheet is interchangeable to handle different-sized filters or SGDs. The filters are currently sealed in an uncooled tube sheet with a bolted metal plate and Nextel fiber gaskets which counteract the upward force imparted across the candle filter by the filter's differential pressure.

The uncooled tube sheet used in the filter vessel was 2 in. (5.1 cm) thick, with three hemispherical openings for the candle filters, along with hold-down plates to seal the candle filters in place. Holes were drilled through the side of the tube sheet to allow pressure tap measurements between the candle filter and the SGD. Two additional differential pressure transmitters were added to the data acquisition and control system to permit measurements of pressure drops across both the candle filter and the SGD. The vessel is sized for three candle filters up to 18 in. (46 cm) long with a 2.375-in. (6.0325-cm) o.d. This provides candle space of 3.85-in. (9.78-cm) center line to center line and enables filter face velocities as low as 3 ft/min (1.5 cm/sec) to be tested in the PFBR. Higher face velocities can be achieved by using shorter or fewer candles or moderately higher gas flow rates, although plans are to use three candle filters. For the SGD testing, up to three 15-in. (38-cm) candle filters and SGDs were placed in the filter vessel. The nitrogen backpulse system is designed to supply a minimum of three candle volumes per pulse. Room temperature backpulse nitrogen was used in this program. Continuous emission sampling of the flue gas measures the levels of O₂, SO₂, NO_x, N₂O, CO, CO₂, and hydrocarbon. Solid samples collected included bottom ash, fly ash, and particulate samples from the stack to determine the particulate loading leaving the filter vessel.

Three different parameters of SGD performance were measured over each 2-day test. The first parameter was unactivated pressure drop, which was determined by measuring the pressure drops across each candle filter and the SGD on top of each filter at ambient temperatures and face velocities of 4, 7, and 10 ft/min (2.0, 3.6, and 5.1 cm/sec). This test was repeated at 900°F (482°C). The pressure drop data for these tests are shown in Table 2.

The second measurement was used to demonstrate under actual coal combustion conditions the SGD operability under the inactive mode of operation. During this phase of the test, the system was to nominally run continuously for 24 hours. Operation was nominally conducted with the following backpulse conditions:

- One pulse of room temperature nitrogen per candle, nominally a 500-ms duration.
- Pulse pressures in the cavities of up to 3 psi (155 mmHg) above inlet (dirty gas) pressure.
- Initiation of backpulse when the candle filter reaches the preselected level of a 30-minute time interval, although shorter periods would be selected if the filter differential pressure increased more than 3 psi.

The third portion of each 2-day baseline test was to demonstrate the effectiveness of the SGD when a candle filter fails. Following the completion of the unactivated test, a drill bit welded on a stainless steel shaft was inserted through a thermocouple port, specifically modified to accommodate it, to break or drill a hole in one of the candle filters during operation. This allowed the SGD above the candle to be activated while in operation with the other filter(s) handling the increased load once the SGD plugged. The pressure drop across the filter as a function of time and the time required to plug the filter were measured. The system was run through several pulse cycles over an 8-hour period to demonstrate the ability of the SGD to retain a permanent dust seal. In addition to the pressure drop data, several EPA Method 5 particulate tests were conducted to characterize the particle-size loading and distributions at the outlet of the filter/SGD as a function of time. The results from each test included a fractional collection efficiency curve, pressure drop across the SGD as a function of time, and mass of dust that passes through the filter/SGD.

Figure 7 shows a closeup of the SGDs in place on the tube sheet of the hot-gas filter vessel. Coal feed was initiated at the completion of the baseline tests. While the overall filter vessel differential pressure increased steadily, differential pressure did not increase across any of the SGDs. Backpulsing the candle filters had no apparent effect on the performance of the SGDs. Difficulties with both the data acquisition system and the filter vessel backpulse system forced a shutdown after 4.1 hours of operation. The system was depressurized and cooled while repairs were made to the data acquisition system.

During the first 20 hours of testing, the SGDs performed as expected, maintaining a consistent differential pressure of about 1.4 in. H₂O (2.6 mmHg), even as the filter vessel differential pressure rose from 5 to 15 in. H₂O (9.3 to 28.0 mmHg) while a permanent dust cake developed

on the filters. The filter vessel inlet temperature was 1500°F (816°C), and the temperature near the candles was about 1420°F (771°C).

On the third day of testing a candle filter, associated with SGD G, was broken on-line. The flow rate and pressure data are shown in Figure 8. In order to break the filter, a drill bit was installed in a flange in the side of the filter vessel at the time the candles were installed. Initially, a drill was used to rotate the bit in an attempt to make a hole in the candle filter. However, the filter proved too hard to drill into, so the bit was hammered into the filter until it broke. The differential pressure across the filter vessel dropped immediately as the candle was broken, but climbed back to the original level within 5 minutes and continued climbing as the SGD was rapidly plugging with filter dust. The differential pressure across SGD G was about 1.2 in. H₂O (2.2 mmHg) before the candle was broken, but in 5 minutes it had risen to 10 in. H₂O (18.7 mmHg). The SGD differential pressure continued to measure about 3 in. H₂O (5.6 mmHg) higher than the filter vessel differential pressure for the remainder of the test period (about 4 hours). About 40 minutes after the candle was broken, the filter vessel differential pressure had reached 15 in. H₂O (381 mmHg), reflecting the increase in face velocity from about 3.3 ft/min (1.7 cm/s) to about 5 ft/min (2.5 cm/s). At this point, the first backpulse was initiated. The filter vessel differential pressure displayed a “sawtooth” pattern every 30 minutes, varying 3 in. H₂O (5.6 mmHg) with each backpulse sequence. Gradually, the baseline differential pressure (measured after backpulsing) across the filter vessel reached 15 in. H₂O (28.0 mmHg), indicating that the SGD was permanently blocked. Over the course of the day, the pressure transmitter was switched to SGDs F and H to verify that they were handling the increase in flow. After the first candle was broken, the differential pressure across SGDs F and H increased slightly, from about 1.2 in. H₂O (2.2 mmHg) to about 1.7 in. H₂O (3.2 mmHg), as the gas flow through them increased because of the plugging of SGDG.

During the bench-scale test, a series of dust-loading measurements were performed to determine the ability of the SGD to prevent passage of particulate matter after a candle filter breaks. A modified EPA Method 5d (EPA 2002) sample train was used. Modifications to the Method 5 train included the use of a 2.5-in. (6.35-cm) stainless steel pressurized filter holder operated at 150 psi (11.2 atm) and 400°F (204°C). Since the system was at pressure, the sample pump was eliminated and a needle valve substituted on the outlet side of the filter to control flow rates. A series of impingers was used to collect moisture, and a dry gas meter was used to measure the total gas volume sampled.

Overall, the results of the bench-scale tests of the 60-ppi combustion SGD showed plugging of the SGD within a few minutes of the breakage of a candle filter. In addition, the activated SGDs were not damaged by backpulse cleaning; different SGDs had reproducible behaviors; and they irreversibly plugged. Also, particulate concentrations in the gas downstream of the SGDs generally did not increase because of breakage of a candle filter, implying that the SGDs were very efficient at capturing the particles passing through the broken candle. However, overall particulate loadings were higher than is desirable, even before breaking the candle filter. The relatively high loadings implied a possible leak of particulates around the candle filters and SGDs. Therefore, the particulate filters were analyzed by SEM. The analyses showed that almost all of the weight gain on the particulate-sampling filters was due to condensation of acid gases

and iron sulfate that were in the vapor phase at the temperatures of the candles and SGDs. No ash particulates were seen on the surfaces of the sampling filters.

In order to determine the depth of penetration into and characteristics of the dust plugging of the SGDs, one of the activated SGDs was infiltrated with cyanoacrylate vapor (Super Glue) to lightly fix the trapped ash within the SGD. The structure was then slowly infiltrated with liquid epoxy. After polymerization, the SGD was cross-sectioned and polished. Figure 9 is a photograph of a polished cross section of the SGD. Gas flow would have been from the top in this picture. It shows that the red ash had penetrated densely approximately one-third of the way into the porous ceramic before the SGD was plugged. There were light bands of ash that penetrated somewhat further, but the light pink material below the dense red layer contains very little ash that was most likely carried into the SGD by the epoxy. This depth of penetration indicates that a 1-in. (2.5-cm)-thick ceramic substrate is the appropriate thickness.

Figure 10 shows an SEM photograph of a pore containing ash in the densely filled section of the exposed SGD. The SGD ceramic is ZTA. Within the porous ceramic structure, the zirconia appears as 1- to 5- μm -diameter blobs in the darker gray alumina matrix. The black area is the epoxy-filled pore. The larger, light gray blobs near the bottoms of the insides of the pores are primarily the Compound B sticky coating material which has either floated off into the epoxy or is present as blobs of material supported in a light gauze made of the compound, which is not obvious. The much smaller particles suspended in the epoxy in the main body of the pore are ash particles composed primarily of aluminosilicates derived from clay particles in the coal. They are typically only a few micrometers in diameter.

Our original assumption in the design of the SGD and the adhesive coating was that a few larger dolomite sorbent particles would be carried into the SGD as the candle was broken, and they would be stuck within the pores by the adhesive. In fact, very few sorbent particles were observed within the substrate, and none of them was even close to being large enough to block the passages between the pores. The lack of larger sorbent particles seen in cross section most likely occurs because the larger particles tend to settle out in the filter vessel and so do not reach the SGD. Because they are so few, the probability of cross-sectioning one during sample preparation is very low. However, it also indicates that plugging did not occur by a few large particles. Instead, it appears that the low-viscosity adhesive coating material lightly coats the particles entering the pores and causes them to agglomerate. The agglomeration force is very low, but it is apparently sufficient to hold the particles together against a high-pressure backpulse of nitrogen. Also, the amount of adhesive coating on an individual particle is so low that it cannot be clearly analyzed by SEM. Other bench-scale tests with higher-viscosity silicate-based adhesive coatings designed for stability in a gasification atmosphere were not successful, indicating that the coating must have a low viscosity in order to work properly.

Summary and Conclusions

The initial hypothesis of the work was that upon breakage of a filter, the adhesive coating would trap larger dust particles within the interpore openings of the ceramic substrate to block further dust flow through the SGD. To prevent the particles from being blown out of the device upon backpulsing, it was believed that the coatings should be either viscous or reactive with the dust to form a solid bond. To ensure the long life of the coatings, it is necessary that they either have

very low vapor pressures and reactivities with the gas stream or that the gas stream be already saturated with the components of the coating. Therefore, two coatings were developed. The one for gasification conditions is a viscous silicate with a low vapor pressure. For combustion conditions, a low-viscosity potassium–magnesium sulfate material was developed that would react with larger limestone sorbent particles to form a solid to lock the particles in place. The combustion adhesive coating was based on materials that are known to be sticky and commonly exist in filter dust from coal-fired systems. The natural occurrence of the adhesive components in filter dust ensures that they are saturated within the gas stream and so will not evaporate or change chemical form. The SGDs were tested in a bench-scale hot-gas filter system connected to both PFBC and gasification systems.

Tests in the bench-scale reactors showed that the combustion SGDs covered with the low-viscosity adhesive coating worked very well, plugging within minutes of a filter break. Only the bottom third of the SGD was filled with ash before plugging, indicating that little if any dust would pass to the turbine in a power system. The adhesive was most effective when it had a low viscosity and wet the dust particles. SEM analyses indicated that the pore openings were not plugged with small numbers of large particles. Instead, large numbers of small particles derived from coal minerals filled the pore and were likely coated with the low-viscosity adhesive. The coating caused them to agglomerate within the pore so that they were not removed on reverse-pulse cleaning and also prevented other particles from passing through the SGD. For the gasification SGD, a low-viscosity coating that is thermodynamically stable in the gas stream must be developed.

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References

1. Lippert, T.E.; Bruck, G.J.; Sanjana, Z.N.; Newby, R.A. Westinghouse Advanced Particle Filter System. In *Proceedings of the Advanced Coal-Fired Power Systems '95 Review Meeting Vol. I*; DOE/METC-95/1018, Vol. 1 (DE95009732), June 1995; pp 123–139.
2. Levin, E.M., Robbins, C.R., McMurdie, H.F., Eds. *Phase Diagrams for Ceramists Volume 2*; American Ceramic Society, 1969; 253 p.
3. U.S. Environmental Protection Agency Method 5D. www.epa.gov/TTN/EMC/PROGAT.html (accessed Feb 2002).

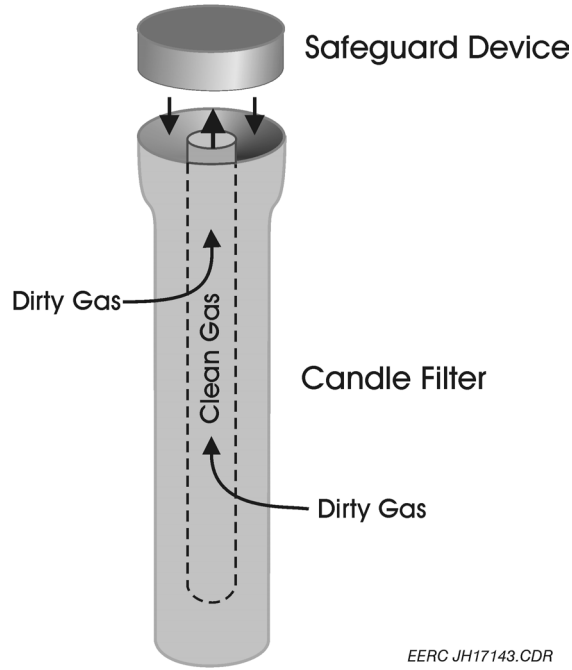


Figure 1. The placement of an SGD at the outlet of a candle filter.

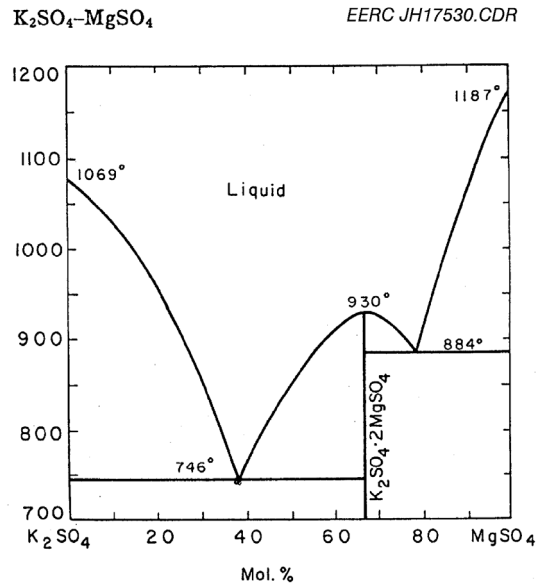


FIG. 2893.—System K_2SO_4 - $MgSO_4$.

S. M. Mikimov, N. I. Kri'lova, and A. G. Bergman, *Akad. Nauk Uzbeksk. SSR, Tashkent, Inst. Khim. Trudy*, 2, 100 (1949).

Figure 2. Phase diagram for the K_2SO_4 and $MgSO_4$ system (taken from Volume 2 of *Phase Diagrams for Ceramists*, published by the American Ceramic Society [2]).



Compound B
Powder

20% B, 80% Ash

50% B, 50% Ash

Figure 3. Photograph of pellets of mixtures of Compound B and Tidd dust, heated to 1382°F (750°C) in simulated flue gas for 15 minutes.

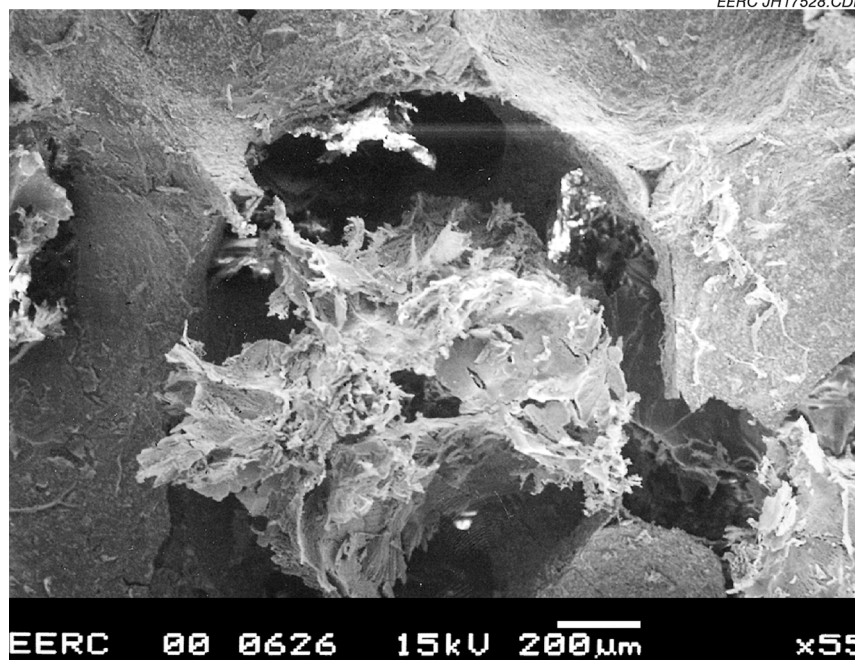


Figure 4. SEM photograph showing the remaining gel-derived Compound B precursor material in a pore of the ZTA substrate.

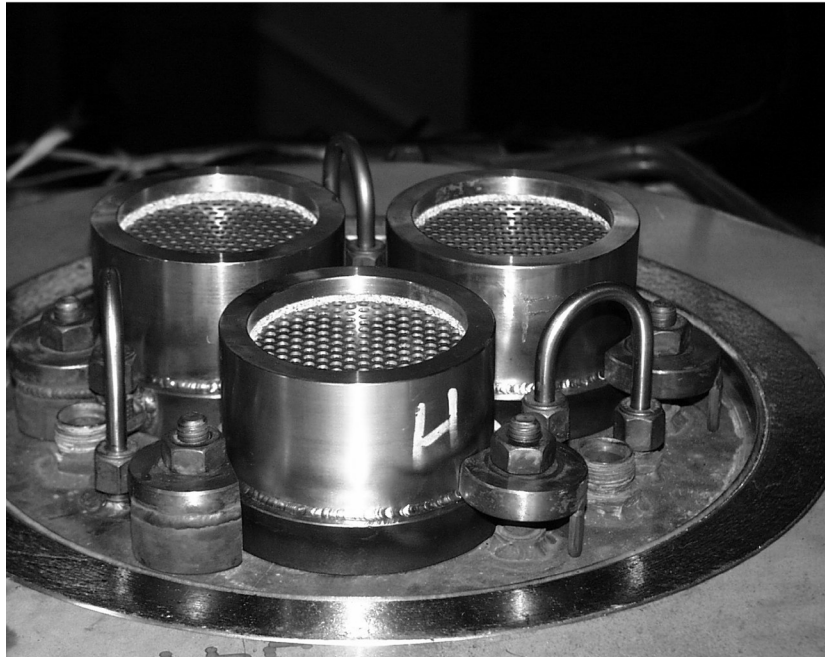


Figure 7. Close-up of the SGDs in place on the tube sheet of the hot-gas filter vessel.

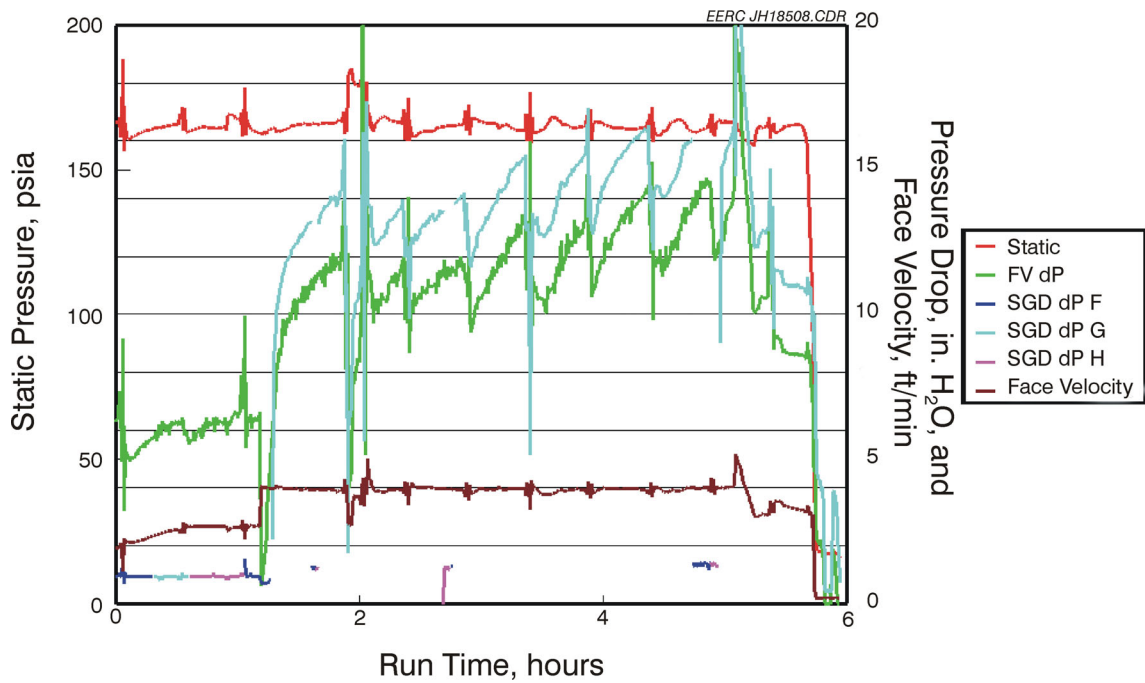


Figure 8. PFBR test data illustrating the changes caused by the breakage of a candle filter.

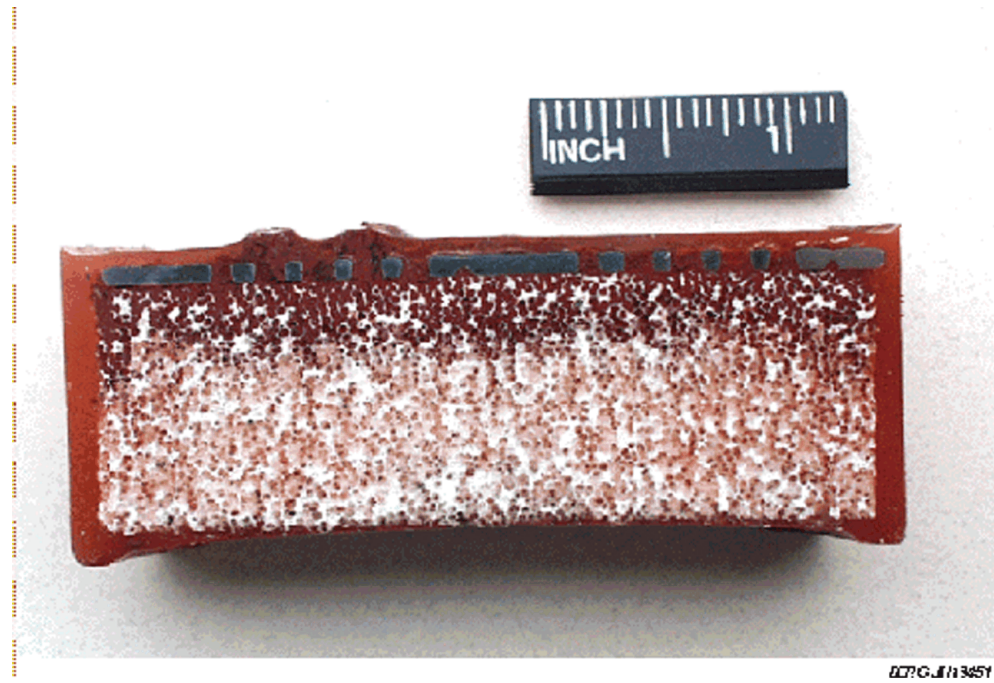


Figure 9. Cross section of one of the combustion SGDs after a bench-scale combustion test.

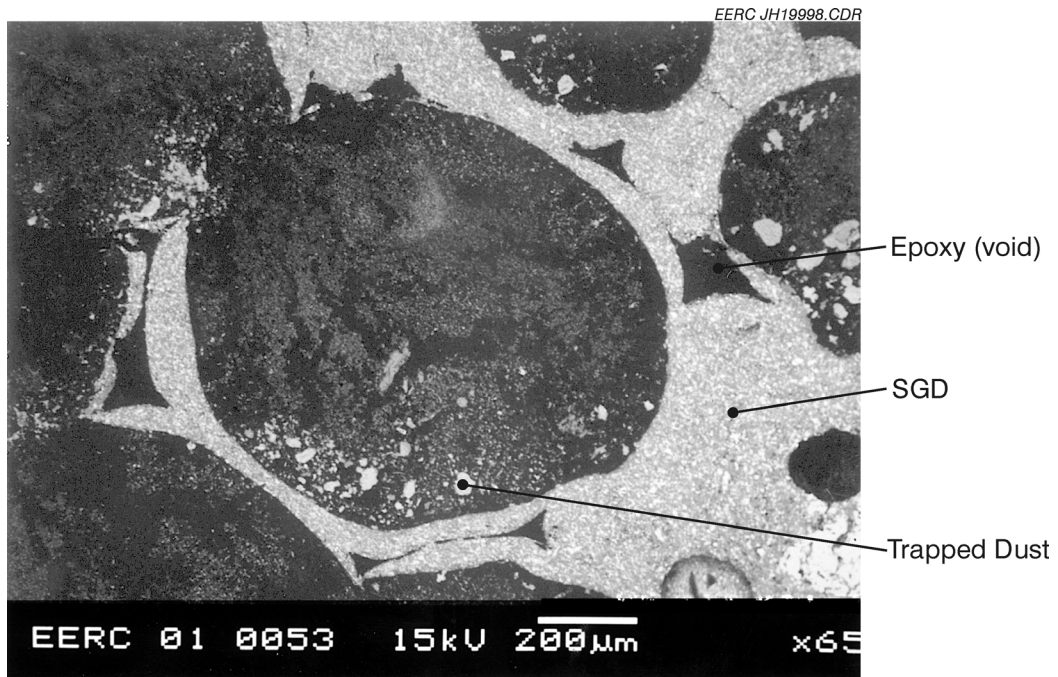


Figure 10. SEM photograph of a pore containing ash in the densely filled section of the exposed SGD.

Table 1. Typical PFBR Operating Conditions

Reactor Diameter	2.875-in. (7.303-cm) i.d.
Temperature	1400°–1700°F (760°–930°C)
Pressure	0–150 psig (1–11 atm)
Gas Flow Rate	1–30 scfm (28–850 slpm)
Coal Feed Rate	1–8 lb/hr (0.5–3.6 kg/hr)
Velocity	1–10 ft/sec (30–305 cm/sec)
Cyclone Exit Temperature	1600°F maximum (871°C)
Particulate Loading	200–9000 ppm

Table 2. Baseline PFBR Test Data for the 60-ppi SGD¹

Temperature, °F (°C)	Face Velocity, ft/min (cm/sec)	Static Pressure, psia (atm)	Filter Vessel dP, in. H ₂ O (mmHg)	SGD dP, in. H ₂ O (mmHg)
80 (27)	3.9 (2.0)	9 (1.6)	1.5 (2.8)	0.5 (1.0)
80 (27)	6.0 (3.5)	15 (2.0)	2.3 (4.3)	0.8 (1.4)
80 (27)	9.9 (5.0)	28 (2.9)	2.5 (4.7)	0.9 (1.7)
900 (482)	4.2 (2.1)	29 (3.0)	3.3 (6.2)	0.7 (1.4)
900 (482)	7.0 (3.6)	45 (4.1)	7.0 (13.1)	1.3 (2.4)
900 (482)	7.5 (3.8)	39 (3.7)	7.5 (14.0)	1.5 (2.8)

¹ “Clean” tests of safeguard devices, December 13, 2000.