PARTICULATE HOT GAS STREAM CLEANUP TECHNICAL ISSUES

Task 1 ASSESSMENT OF ASH CHARACTERISTICS

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Abstract

This is the fourth annual report describing the activities performed under Task 1 of Contract No. DE-AC21-94MC31160. The analyses of hot gas stream cleanup (HGCU) ashes and descriptions of filter performance studied under this contract are designed to address problems with filter operation that are apparently linked to characteristics of the collected ash. This work is designed to generate a data base of the key characteristics of ashes collected from operating advanced particle filters and to relate these ash properties to the operation and performance of these filters and their components. This report summarizes characterizations of ash and char samples from pressurized fluidized-bed combustion and gasification facilities. Efforts are under way to develop a method for preserving fragile filter cakes formed on ceramic filter elements. The HGCU data base was formatted for Microsoft Access 97®. Plans for the remainder of the project include characterization of additional samples collected during site visits to the Department of Energy / Southern Company Services Power Systems Development Facility and completion and delivery of the HGCU data base.

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EXECUTIVE SUMMARY

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

Task 1 research activities during the past year included characterizations of ash and char samples from pressurized fluidized-bed combustion (PFBC) and gasification facilities to the HGCU data base. Research activities under Contract No. DE-AC21-94MC31160 will continue through September 1999. Plans for the remainder of the project include characterization of additional samples collected during site visits to the Department of Energy / Southern Company Services Power Systems Development Facility (PSDF) and completion and delivery of the HGCU data base. Additional plans are discussed in the body of this report.

INTRODUCTION

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

To identify which particulate characteristics can lead to problems with filtration, 355 particulate samples from fourteen facilities involved in FETC's HGCU program have been assembled. Three samples from gasification studies being carried out by Herman Research Pty. Ltd. (HRL) of Melbourne, Australia have also been included in the data base. Many of the samples in the data base have been analyzed with a variety of laboratory tests. Physical attributes of the particles that have been examined include size distribution, specific surface area, particle morphology, and bulk ash cohesivity and permeability. A range of chemical analyses of these samples, as well as characterizations of agglomerates of particles removed from filter vessels at Tidd, Karhula and Foster Wheeler's pilot-scale combustion facility located in Livingston, New Jersey have also been performed. The data obtained in these studies are being assembled into an interactive format which will help the manufacturers and operators of high-temperature barrier filters tailor their designs and operations to the specific characteristics of the particulate materials they are collecting.

OBJECTIVES

Task 1 has two primary objectives. The first is to generate a readily accessible data base of the key characteristics of particulate samples collected from operating advanced particle filters. The second objective is to relate these measured properties and the contents of the data base to the operation and performance of the advanced particle filters and filter components. The first objective includes formatting the data base and collecting, analyzing, and maintaining particulate samples from operating HGCU facilities. The second objective of this task involves the collection of operating histories from advanced particle filters, correlating these histories with sample characteristics, interpreting these correlations, and communicating results in the various venues prescribed by DOE/FETC-MGN.

POWER SYSTEMS DEVELOPMENT FACILITY

The Power Systems Development Facility is an engineering scale demonstration of two advanced coal-fired power systems including hot gas cleanup.[1, 2] The project is sponsored by Southern Company Services, Inc., and by the U.S. Department of Energy's Federal Energy Technology Center, under contract DE-FC21- 90MC25140. The first system placed on line was the M.W. Kellogg Transport reactor, which is an advanced circulating fluidized bed reactor designed to operate as either a combustor or a gasifier. The Transport reactor uses one of two possible hot gas clean-up filter technologies (particulate control devices or PCDs) at a component size readily scaleable to commercial systems. The second system to be demonstrated, Foster Wheeler's topped pressurized fluidized bed combustor (PFBC), incorporates a bubbling-bed carbonizer and a circulating PFBC and will also employ high-temperature PCDs.

The objectives of the PSDF are to develop advanced coal-fired power generation technologies through testing and evaluation of hot gas cleanup systems and other major components at the pilot scale and to assess and demonstrate the performance of the components in an integrated mode of operation. The facility is sized to test the components at capacities that are readily scaleable to commercial systems. The primary focus of the PSDF project is to demonstrate and evaluate high temperature PCDs that are the single most important component required for successful development of advanced power generation systems. High temperature PCDs are a common component of advanced gasification and APFBC technologies, both of which will be evaluated at the facility.

The M.W. Kellogg Transport reactor technology, under development at the PSDF at a scale of about 2 tons/hour of coal feed, can operate either as a gasifier or combustor. Tests can be conducted in both configurations. In the gasifier mode, coal is introduced and fired substoichiometrically. The coal devolatilizes, the volatiles pyrolize and the residual char is steam gasified. This staging of the gasification reaction forces oxygen to react with char rather than volatiles, as is characteristic in fluid bed gasifiers. As a result, the size of the gasifier (and the capital cost) is reduced because the amount of char to be gasified by reaction with steam (which is slow at the expected operating temperature) is reduced substantially. Operation in the combustion mode is similar, but the reactor is fired with excess air and a fluidized bed heat exchanger is included in the reactor loop to remove the heat released from the system.

The Transport reactor train is sized to process sufficient coal generating 1,000 acfm of gas to test the PCDs. Indirect cooling of the gas from the Transport reactor will allow testing of the PCDs with inlet temperatures between 650 F and 1,500 F and at pressures in the range 100 psia to 280 psia. The PCD in this train will receive exhaust gas from the Transport reactor operating in either gasification or combustion mode. The gas exiting the PCDs will be thermally oxidized in the gasification mode, cooled and filtered in the baghouse before discharge from the stack. The ash/char mixture produced in the gasification mode will be oxidized in the Sulfator prior to disposal. A Westinghouse-supplied filter system was used during commissioning of the Transport train. The dirty gas enters the PCD below the tubesheet and flows through the candle filters, and the ash collects on the outside of the filters. The clean gas passes from the plenum/candle assembly through the plenum pipe to

the outlet pipe. As the ash collects on the outside surface of the candle filters, there is a gradual increase in the pressure drop across the filter system. The filter cake is periodically dislodged by injecting high pressure gas pulse to the clean side of the candles. The cake then falls to the discharge hopper. When the Transport reactor is operated in combustion mode, the pulse gas is high pressure air. The pulse gas is routed individually to the two plenum/candle assemblies via injection tubes mounted on the top head of the PCD vessel. The pulse duration is typically 100-500 milliseconds. All operation to date has been with the Westinghouse FL0301 filter vessel. This vessel has a tangential inlet, and holds up to 91 filter elements in two plenums. The top and bottom plenum are pulse-cleaned separately.

SITE VISITS

Several planned and unscheduled shutdowns of the PSDF Transport reactor took place during fiscal year 1997. Three of these shutdowns afforded opportunities for direct observation of ash deposits in the Westinghouse FL0301 filter vessel when it was taken off line, and opened for inspection and refitting. In general, the site visits conducted at these times included video and still photography to document the condition of the vessel, followed by measurements of the thickness and areal density of the filter cakes at various locations in the assembly. On each site visit, sufficient ash was removed from at least one candle filter element for detailed analyses. In the following discussions, the general condition of the vessel, and the data and samples obtained while on-site are described. The detailed laboratory analyses of selected ash samples are discussed under the section entitled ANALYSES OF PSDF ASHES.

November 5, 1997

A site visit was made on November 5, 1997 to the PSDF to characterize the condition of the filter and collect ash samples for analysis. The unscheduled shutdown of the Transport reactor was conducted because of indications of candle filter element breakage. The filter elements were pulse-cleaned repeatedly following the last filtration cycle prior to shutdown. Although a few candle filter elements in the vessel were broken, the majority of the elements were intact and were covered with thin, uneven cakes. The candle breakages observed on this visit are not believed to have resulted from the characteristics of the collected ash, and are not discussed in this report. The reasons for these breakages have been investigated under DOE Contract No. DE-FC21-90MC25140 and are not reported here.

The samples collected during this site visit are identified in Table 1. Videotape and still pictures were made of all major subjects. Core samples (for areal density determinations) were obtained from 3 candles in the top plenum and 2 candles in the bottom plenum. For each of these candles, measurements were made about 10 inches below the tubesheet and 10 inches above the bottom of the candle. The areal density measurements are summarized in Table 2.

Table 1
PSDF Ash Samples Obtained November 5, 1997

ID #	location	~ amount, g	description / comments
4261	TP FC	30	
4262	BP FC	70	selected for detailed measurements
4263	BP TS	0.05	yellowish color deposit
4264	TP TS	15	
4265	BP TS	10	
4266	flat roof over top plenum	60	with nodules
4267	flat roof over top plenum	40	with nodules
4268	flat roof over top plenum	15	with nodules
4269	BP AS	70	
4270	TP CSC	20	
4271	outer wall of TP TS	15	
4272	outer wall of BP TS	20	
4273	6 each core samples TP FC	0.1 each	washed out with isopropyl & dried
4274	4 each core samples BP FC	0.1 each	washed out with isopropyl & dried

TP = Top Plenum
BP = Bottom Plenum
CSC = Center Support Column
AS = Ash Shed
TS = Underside of Tubesheet
FC = Filter Cake Ash from Candle Surface

Table 2
PSDF Filter Cake Areal Density Measurements (November 5, 1997)

location	areal density, lb/ft^2
top plenum	0.049
bottom plenum	0.047
near top of candles	0.039
near bottom of candles	0.057
overall average	0.047

The thickest cake nodule observed on candles in the top plenum was about 2 mm thick. On the bottom plenum a filter cake nodule was found that was about 2.5 mm thick. Filter cake thickness was measured at several points with a traversing transverse laser gauge. The data from these measurements are summarized in Table 3 but are probably not too meaningful because the cakes were very thin and had very irregular thickness.

Table 3
PSDF Filter Cake Thickness Measurements (November 5, 1997)

location	thickness, mm
top plenum (~10 inches below the top of the candle)	0.84
top plenum (~10 inches below the top of the candle)	1.40
top plenum (~10 inches above the bottom of the candle)	0.51
top plenum (~10 inches above the bottom of the candle)	0.64

January 20, 1998

A site visit was made on January 20, 1998 to the PSDF to characterize the condition of the filter and to collect ash samples. This visit followed the scheduled shutdown of the Transport reactor on December 9, 1997. The filter vessel was left closed and off-line until it was opened for inspection in mid-January 1998. All the filter elements were intact and in general, the filter cakes covering the candles ranged in thickness from 1 to 7 mm. Videotape and still pictures were made of all major subjects. Nineteen ash samples were collected while on site. These samples are briefly described in Table 4.

Table 4
PSDF Ash Samples Obtained January 20, 1998

ID #	location	~ amount, g	description / comments
4283	top plenum near top	1.5233	core sample
4284	top plenum near bottom	1.6702	core sample
4285	top plenum near top	1.8306	core sample
4286	top plenum near bottom	1.7111	core sample
4287	top plenum near top	1.5126	core sample
4288	top plenum near bottom	1.5542	core sample
4289	bottom plenum near top	1.9073	core sample
4290	bottom plenum near bottom	1.7668	core sample
4291	bottom plenum near top	2.2918	core sample
4292	bottom plenum near bottom	1.1176	core sample
4293	top plenum filter cake sample	100 g	whole candle length sample
4294	bottom plenum filter cake sample	100 g	whole candle length sample
4295	filter vessel hopper ash (PSDF ID: AB02476)	60 g	12/8/97 provided by PSDF personnel
4296	top plenum candle attachment	20 g	fluffy nodular growths
4297	bottom plenum candle attachment	10 g	fluffy nodular growths
4298	bottom plenum ash shed	10 g	conical surface
4299	top plenum flat roof	50 g	
4300	bottom plenum outer vertical surface of tubesheet	10 g	
4301	top plenum flat roof	10 g	with nodules

Core samples (for areal density determinations) were obtained from 3 candles in the top plenum and 2 candles in the bottom plenum. For each of these candles, measurements were made about 10 inches below the tubesheet and 10 inches above the bottom of the candle. The core sampler used had a cross-sectional area of 7.32 cm^2. Filter cake thicknesses were measured with the traversing transverse laser gauge at several points corresponding to the locations where the core samples were obtained. Data from the areal density and filter cake thickness measurements are summarized in Table 5. Based on the data presented in this

table, the average porosity of the PSDF filter cakes observed on January 20 was 76%. Two of the samples described in Table 4 (ID # 4294 and ID # 4295) were selected for detailed measurements, which are discussed later in this report.

Table 5
PSDF Filter Cake Thickness and Areal Density Measurements (January 20, 1998)

ID #	plenum location / averages	core sample weight, g	average thickness, mm	areal density, lb/ft^2
4283	top plenum (near top of candle)	1.5233	3.45	0.43
4284	top plenum (near bottom of candle)	1.6702	4.72	0.47
4285	top plenum (near top of candle)	1.8306	4.37	0.51
4286	top plenum (near bottom of candle)	1.7111	3.63	0.48
4287	top plenum (near top of candle)	1.5126	3.48	0.42
4288	top plenum (near bottom of candle)	1.5542	3.78	0.44
4289	bottom plenum (near top of candle)	1.9073	4.11	0.53
4290	bottom plenum (near bottom of candle)	1.7668	3.23	0.49
4291	bottom plenum (near top of candle)	2.2918	5.08	0.64
4292	bottom plenum (near bottom of candle)	1.1176	2.67	0.31
--	average top plenum	--	3.91	0.46
--	average bottom plenum	--	3.76	0.50
--	average (near top of candles)	--	4.09	0.51
--	average (near bottom of candles)	--	3.61	0.44
--	overall average	1.6878	3.86	0.47

The filter cakes that were observed on January 20 experienced extensive back pulsing prior to the opening of the filter vessel. Therefore, they are not necessarily representative of the appearance of the cakes at the beginning of filtration cycles during normal operation. However, the general appearance of the cakes and the various cake structures that were observed suggest that some of the characteristics of the ash and the different filtering substrates may influence cake buildup and the effectiveness of pulse cleaning.

Some simple procedures could be used during shutdown of the Westinghouse FL0301 filter vessel to determine the general effectiveness of pulse cleaning and possibly its effectiveness for various types of filter elements. During the filter shutdown prior to the January 20, 1998 site visit, and also in previous shutdowns, the filter has been extensively back-pulsed prior to cool down of the vessel. The FL0301 filter at the PSDF is configured so that the top plenum and bottom plenum are cleaned by separate, individually-controlled, back pulses. Therefore, during a scheduled shutdown of the filter, procedures could be modified so that the flow of particulate-laden flue gas through the filter vessel is discontinued at the end of a filtering cycle. To examine the effects of pulse cleaning on the filter cakes, only one of the two plenums could be pulse-cleaned in the normal manner following this last filtration cycle. The other plenum would not be cleaned. This “dirty shutdown” of one of the two plenums should provide valuable information on how back pulses clean the filter elements. To minimize the

interference of the pulse cleaning of one of the plenums on the uncleaned plenum, it would probably be more desirable to leave the top plenum uncleaned. Limiting the execution of back pulses during the shutdown procedure to only one pulse of just the lower plenum would allow examination of both the thickness and characteristics of the cleanable cakes (on the upper plenum), and the effectiveness of pulse cleaning and the characteristics of the residual cakes (on the lower plenum).

The appearance of the filter cake may have depended on the type of candle substrate on which it formed. A variety of filter elements were used in the PSDF in the operating period just prior to January, 1998. Although most of the candle filter elements were covered with filter cakes similar to the one shown in Figure 1, some of the cakes observed on the 3M filter elements were lumpier, and others were smoother, than the typical cakes shown in Figure 1. Figure 2 shows an example of one of the lumpier cakes present on one of the 3M candle filter elements. The degree of lumpiness of the filter cake was apparently not caused by the location of the elements in the filter array, because many of the filter elements adjacent to the one shown in Figure 2 were covered with significantly smoother cakes.

Figure 3 shows a filter cake that is somewhat smoother than the majority of cakes, and Figure 4 shows one of the smoothest cakes observed. In Figure 4, small pinholes are distributed over the surface of the cake. It is likely that these pinholes were formed by reverse flow during back pulsing; however, it is not known whether these pinholes were caused by the repeated pulses applied during shutdown, or whether they can be formed by a single back pulse. Figure 5 contrasts the appearance of the filter cakes shown in Figures 1 through 4 with a passive ash deposit formed on a set of stacked samples of various filter element materials located within the array of candle filter elements. This passive ash deposit has a very rough surface in comparison with the various filter cakes.

The types of filter cakes (thickness, lumpiness, and porosity) should be correlated with the type of filter element, if possible. These correlations should help establish the degree to which filter element design determines the characteristics of the residual and cleanable filter cakes. Depending on the particular locations of the various types of filter elements used during the run, the selective cleaning procedures described above that could be used during shutdown might also be used to compare the before- and after-cleaning appearances of various types of filter elements.

Figure 1. A representative photograph of the appearance of the majority of the filter cakes observed in the Westinghouse FL0301 filter at the PSDF on January 20, 1998.

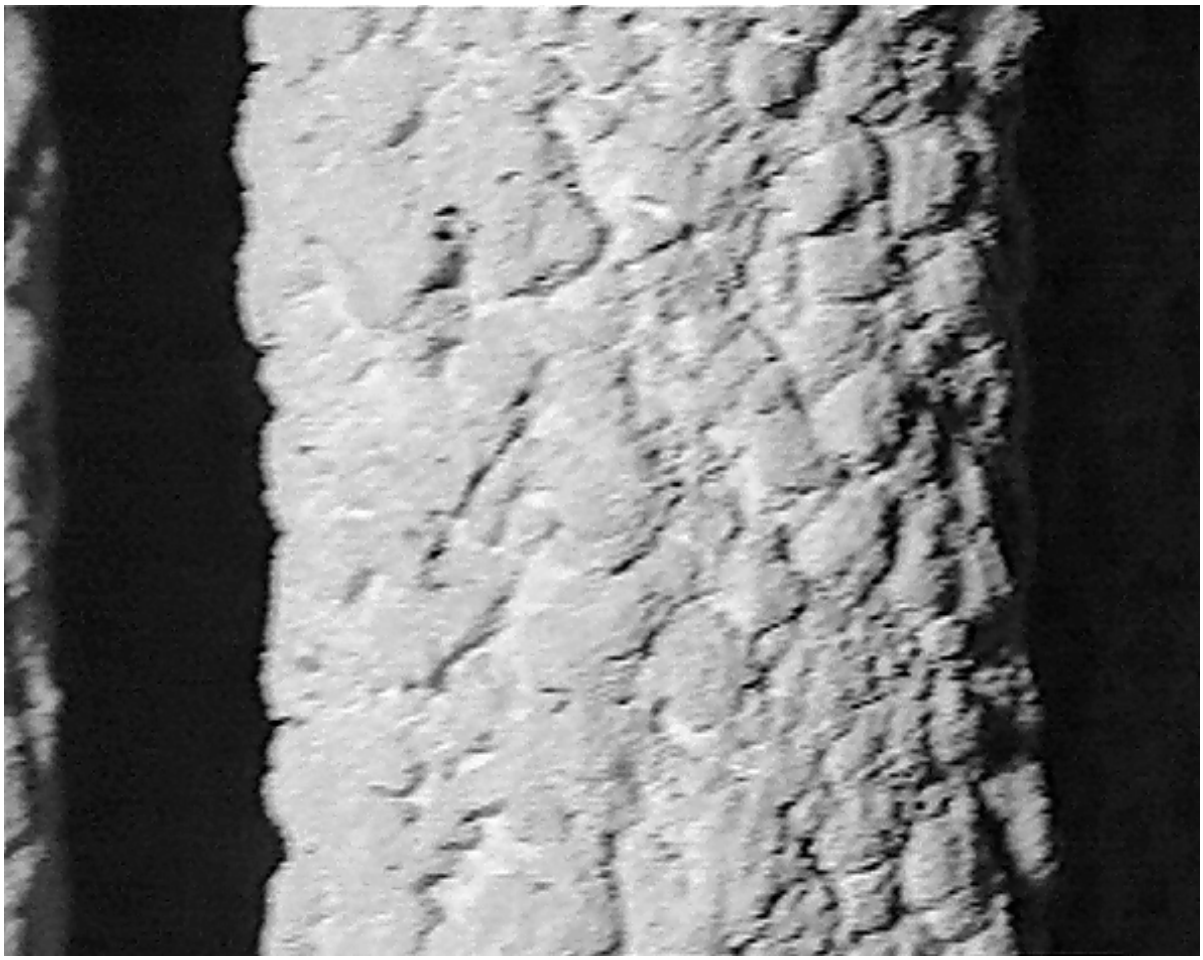


Figure 2. A representative photograph of the appearance of one of the lumpier filter cakes observed on a 3M filter element in the Westinghouse FL0301 filter at the PSDF on January 20, 1998.

Figure 3. A representative photograph of the appearance of a relatively smooth filter cake observed in the Westinghouse FL0301 filter at the PSDF on January 20, 1998.

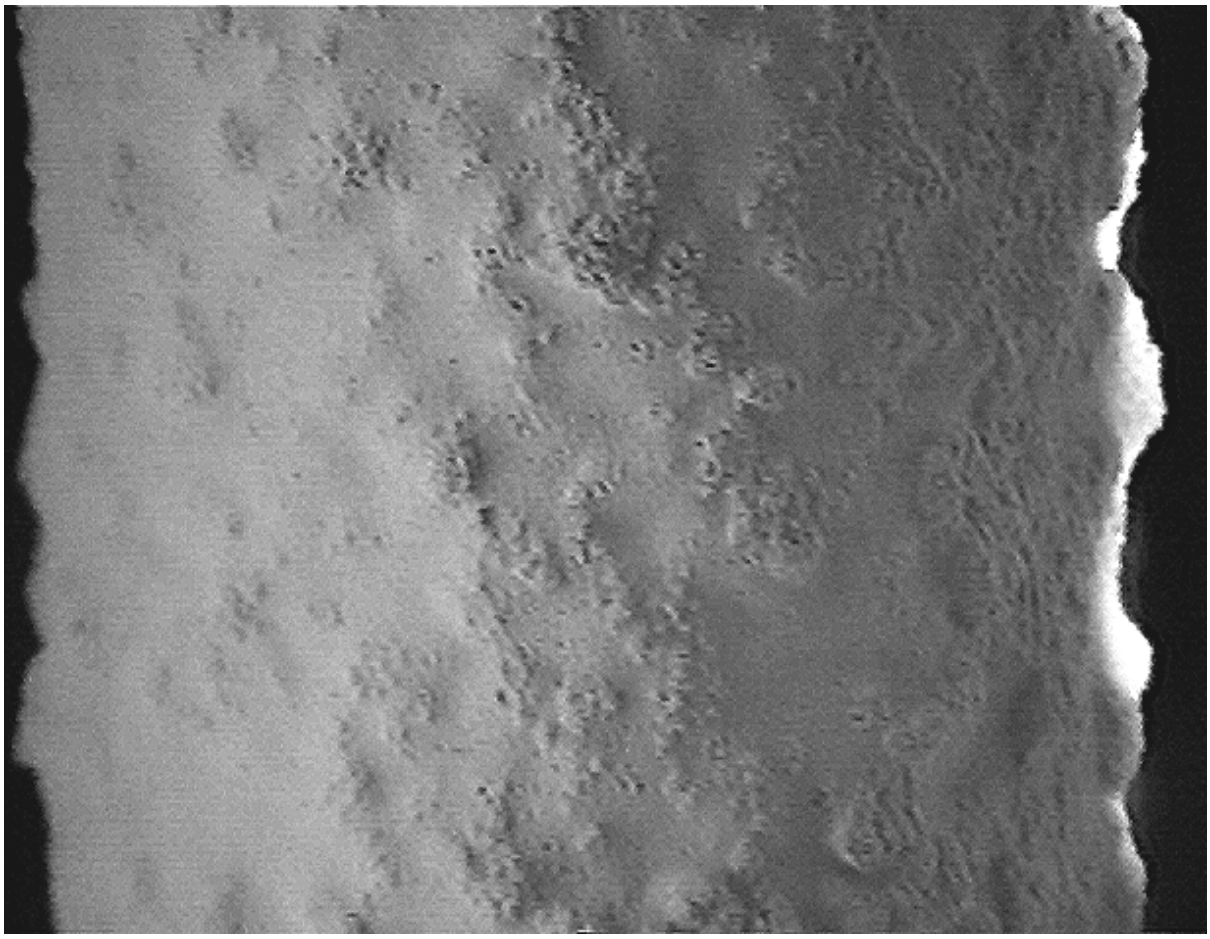


Figure 4. A representative photograph of the appearance of the smoothest filter cakes observed in the Westinghouse FL0301 filter at the PSDF on January 20, 1998. Small pinholes are distributed over the surface of the cake.

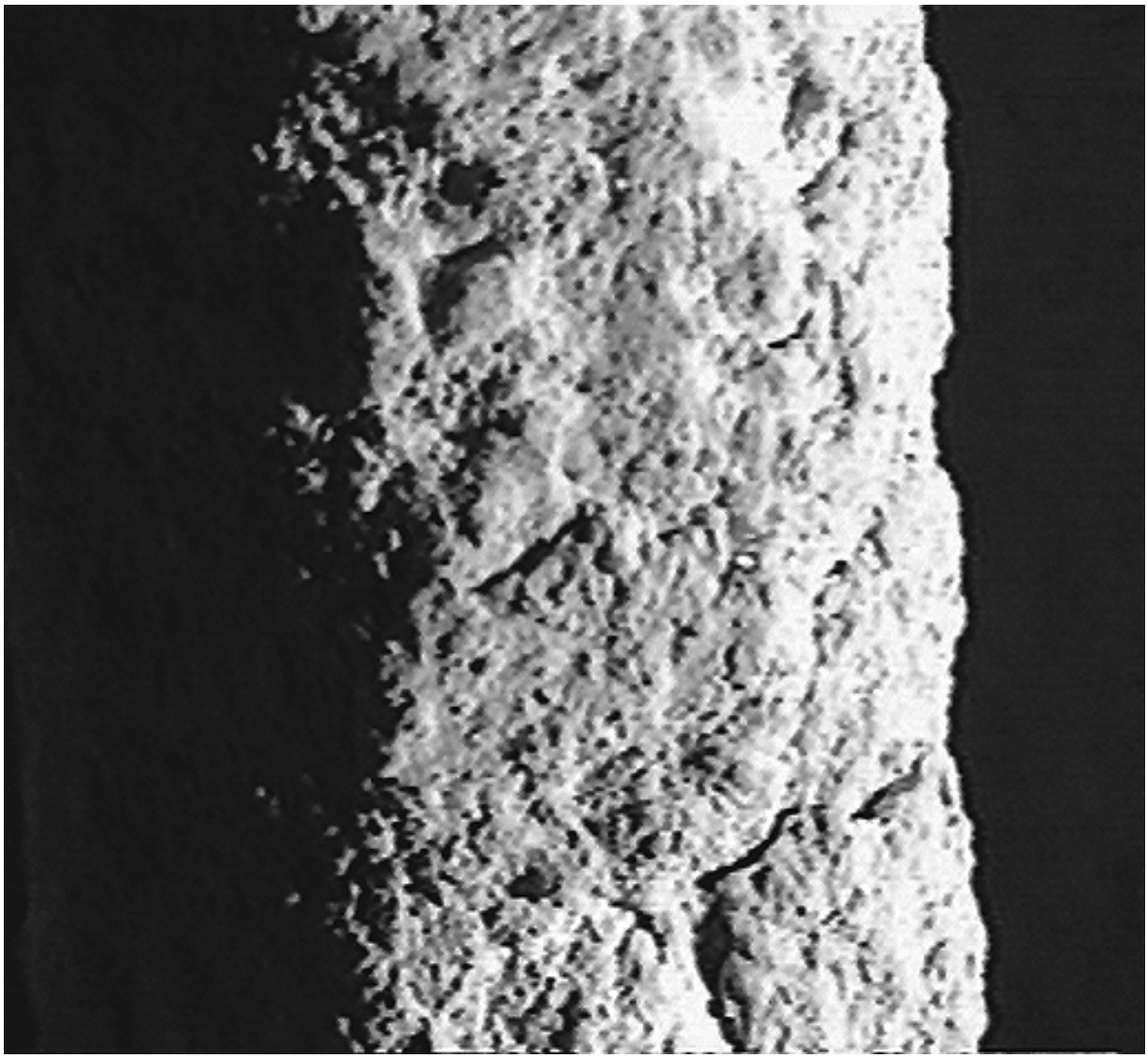


Figure 5. A representative photograph of the appearance of a passive ash deposit formed on a set of stacked samples of various filter element materials located within the array of candle filter elements. This deposit was observed in the Westinghouse FL0301 filter at the PSDF on January 20, 1998.

May 18, 1998

A site visit was made on May 18, 1998 to the PSDF to characterize the condition of the Westinghouse FL0301 filter and to collect ash samples for analysis. PSDF personnel employed a dirty shutdown procedure for this filter inspection. Following the last filtration cycle (approximately 38 minutes long) the coal feed was stopped and the neither of the two plenum assemblies in the filter was back pulsed. (Both plenums were left uncleaned because it was thought that the force of the pulse in the filter vessel during the cleaning of one of the plenums would disturb and possibly compress the filter cakes on the uncleaned plenum.)

Thirteen ash samples were collected during this site visit. These samples are described briefly in Table 6. A videotape record was made of representative filter components. All the filter elements were intact and most were covered relatively smooth filter cakes. The filter cakes present on some of the filter elements seemed to comprise a smooth, soft outer layer over a somewhat lumpier, inner layer. Most of these somewhat lumpier filter cakes were located on the top plenum assembly. These lumpier filter cakes ranged in thickness from 3.7 to 6.8 mm. The dirty shutdown procedure supposedly caused the filter cakes on both plenums to include residual and transient filter cake ash. The appearance of the lumpier cakes suggested that the deposition of the transient filter cakes during the last filtration cycle tended to reduce the irregularities in the underlying residual cake structures. Although no direct measurements were made to quantify this supposed effect, this type of smoothing over of filter cakes following cleaning cycles has been verified and studied for low-temperature fabric filtration of conventional pulverized-coal ashes at utility boilers.[3]

Table 6
PSDF Filter Cake Ash Samples Obtained May 18, 1998

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

The dirty shutdown procedure was followed to allow differences in residual and transient to be assessed. These measurements have been performed under Contract No. DE-FC21-90MC25140 and are not reported here.

Because the thickness, porosity, and appearance of the filter cakes may depend on the type of candle substrate on which the cake formed, core samples and filter cake thickness measurements were made for cakes on all of the filter element types in the filter vessel. Core samples (for areal density determinations) were obtained from 10 candles in the bottom plenum and 1 candle in the top plenum. For each of these candles, measurements were about midway down the vertical length of the candle. The core sampler used had a cross-sectional area of 7.32 cm^2. Filter cake thicknesses were measured with the traversing transverse laser gauge just above or below the locations where the core samples were obtained. Data from the areal density and filter cake thickness measurements are summarized in Table 7.

Table 7
PSDF Filter Cake Areal Density and Thickness Measurements (May 18, 1998)

location	core sample weight, g	thickness, mm	areal density, lb/ft^2	porosity, %	comments
B1	1.8646	3.7	0.52	72.9	cake easily released
B35	2.2258	3.8	0.62	68.7	smooth cake
B8	1.6886	4.4	0.47	79.6	
B20	2.3144	6.0	0.65	79.4	tenacious residual cake
B6	1.8599	5.7	0.52	82.6	
B15	2.0868	6.8	0.58	83.4	tenacious residual cake
B32	2.1658	5.3	0.61	78.2	tenacious residual cake
B18	1.0811	5.2	0.30	88.9	cake easily released
B14	2.2349	5.6	0.63	78.5	cake easily released
B17	2.0010	4.1 to 7.9	0.56	--	lumpy, irregular thickness, residual cake embedded in weave
T5	2.2886	6.2	0.64	80.4	smooth cake easily released
avg.	1.9829	5.3	0.55	79.3	

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

The general appearance of the filter cakes that were observed on May 18 suggest that some of the characteristics of the different filtering substrates may influence cake buildup. Figure 6 shows the appearance of the entire filter assembly during its removal from the filter vessel. The typical appearance of the filter cakes on the bottom plenum is shown in Figure 7. The ash deposits that formed around the mounting locations on the top filter plenum (Figure 8) were much like those observed on prior site visits.

Figure 6. Appearance of the entire filter assembly on May 18, 1998 during removal from the filter vessel.

Figure 7. Typical smooth filter cakes observed on the bottom filter plenum on May 18, 1998.

Figure 8. This photograph shows the typical ash deposits formed around the mounting locations on the top filter plenum (May 18, 1998).

ANALYSES OF PSDF ASHES

The majority of the physical analyses performed on the samples listed in Tables 1, 4, and 6 are summarized in Table 8. Chemical analyses performed on these samples are presented in Table 9. Additional measurements performed on these samples are discussed in the following sections.

Table 8
Physical Characteristics of PSDF Samples

location / date / quantity / ID #	filter cake 11-5-97 4262	filter cake 1-20-98 4294	filter hopper 12-8-97 4295	filter cake 5-18-98 4303
specific surface area, m^2/g	5.3	--	--	--
Stokes' D_{16}, μm	1.2	--	--	--
Stokes' D_{50}, μm	3.8	8.6	18	--
Stokes' D_{84}, μm	13	--	--	--
GSD of size distribution	3.2	--	--	--
uncompacted bulk porosity, %	87	84	77	78
filter cake porosity, %	--	76	--	79
drag-equivalent diameter, μm	1.49	2.31	3.47	3.59
specific gas-flow resistance, in H_2O·min·ft/lb*	2.9	2.6	3.7	2.9
specific gas-flow resistance, in H_2O·min·ft/lb**	11	--	--	--
specific gas-flow resistance, in H_2O·min·ft/lb***	--	9.7	--	--
specific gas-flow resistance, in H_2O·min·ft/lb****	--	--	--	2.5
tensile strength, N/m^2	> 16	--	--	--
true particle density, g/cm^3	2.78	2.50	--	2.55

* calculated for an assumed filter cake porosity equal to the uncompacted bulk porosity
** calculated for the porosity of a nodule removed on November 5, 1997 (80.5 %)
*** calculated for the filter cake porosity measured on January 20, 1998 (76 %)
**** calculated for the filter cake porosity determined with the core sampler and thickness measurements on May 18, 1998 (79 %)

Table 9
Chemical Composition of PSDF Ashes, % wt.*

ID # location date	4262 filter cake 11-5-97	4294 filter cake 1-20-98	4295 filter hopper 12-8-97
Li_2O	--	0.054	0.036
Na_2O	0.06	0.110	0.088
K_2O	1.76	0.695	0.844
MgO	8.00	4.49	8.08
CaO	9.98	5.91	9.05
Fe_2O_3	4.78	3.47	2.69
Al_2O_3	21.93	11.1	6.82
SiO_2	43.37	39.6	38.5
TiO_2	1.13	1.07	0.944
P_2O_5	0.51	0.303	0.307
SO_3	6.34	11.9	9.86
SrO	0.19	--	--
BaO	0.09	--	--
LOI	1.94	5.82	0.812
soluble $SO_4^=$	11.6	11.3	9.8
Equilibrium pH	7.3	--	--

* Equilibrium pH is dimensionless

The measured size distribution of PSDF filter cake ash (ID # 4262) is presented in Figure 9. SEM photomicrographs of the November 1997 filter cake ash sample (ID # 4262) are shown in Figure 10. During examination of the filter cakes on November 5, One nodule (from sample # 4268) was large enough and strong enough for a porosity determination to be performed by ethanol impregnation. The value of porosity measured for this nodule taken from the flat roof over the top plenum (80.5%) was used in one of the two calculations of specific gas-flow resistance presented in Table 8. The strong effect that filter cake porosity has on specific gas-flow resistance is evident in the two values calculated for ID # 4262 (2.9 and 11 in $H_2O \cdot min \cdot ft/lb$). The actual porosity of the filter cakes formed in the PSDF should be more precisely determined if thicker filter cakes are present when the filter vessel is opened for inspection and sampling. Additionally, as PSDF operation continues, the range of filter cake characteristics induced by differences in various process parameters may become better defined as more samples from distinct periods of operation become available.

Because the PSDF samples that were obtained on January 20, 1998 included filter cake ashes and a corresponding hopper ash, analyses were performed to determine specific physical and chemical differences between samples obtained from these two locations. Measurements of size distribution, uncompacted bulk porosity, and specific gas-flow resistance (with associated drag-equivalent diameter) all indicate that these two ashes have significantly different physical characteristics (Table 8). The characteristics of the PSDF filter cake ash indicate that it should not cause unusually high filtering pressure losses.

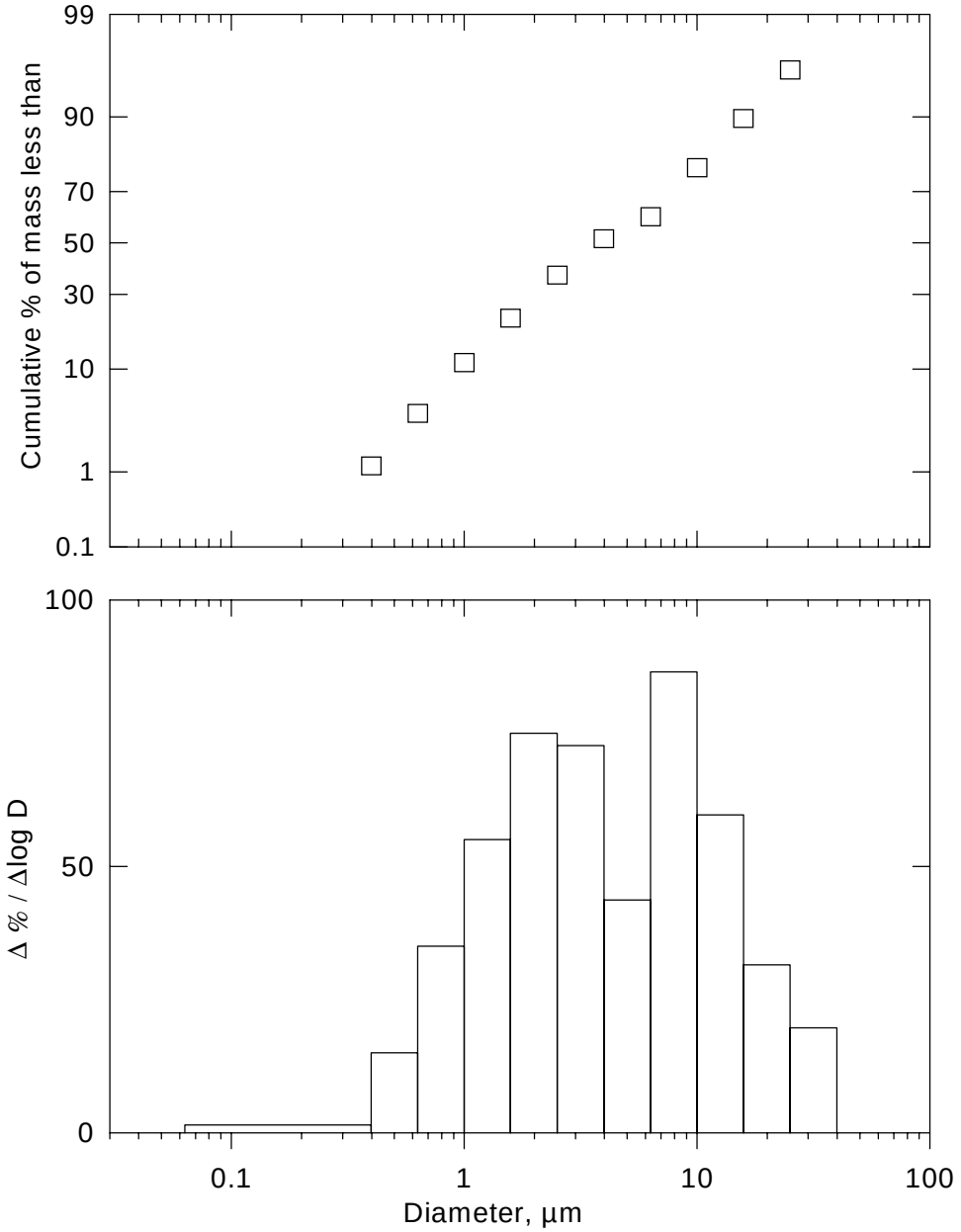


Figure 9. Cumulative and differential size distribution data measured for PSDF filter cake ash (ID # 4262) measured with a Shimadzu SA-CP4 Centrifugal Particle Size Analyzer. The Stokes' D_{16} of this distribution is 1.2 µm, its D_{50} is 3.8 µm, its D_{84} is 13 µm, and its geometric standard deviation is 3.8. (These size distribution data include the assumption that the sample contains no particles smaller than 0.063 µm.)

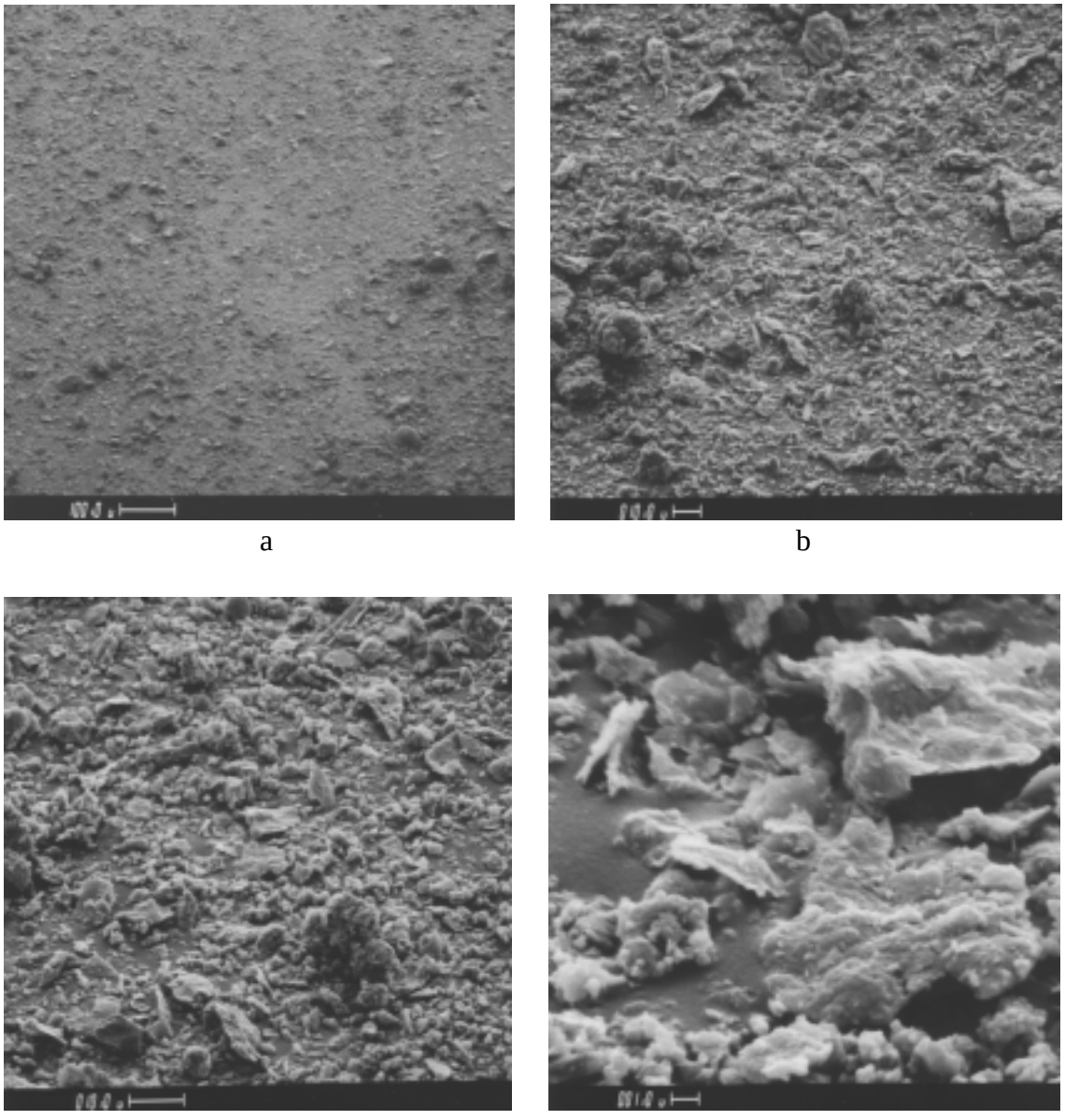


Figure 10. Representative scanning electron micrographs of PSDF filter cake ash (ID # 4262) taken at a) 100X, b) 500X, c) 1000X, and d) 5000X.

The chemical analyses of these samples (Table 9) indicate enrichment of calcium and magnesium in the coarser hopper ash particles, and enrichment of alumina and iron compounds in the finer filter cake ash particles. The higher calcium and magnesium concentrations in the hopper ash reflect the coarseness of the sorbent in comparison to the fly ash particles exiting the transport reactor. There also is some enrichment of sulfur in the filter cake ash sample, probably because of additional scrubbing of SO_2 from the flue gas by unreacted sorbent material in the filter cake. The increased LOI values measured for the filter cake ashes (ID #'s 4262 and 4294) over the hopper ash (ID # 4295) are probably the result of water adsorption by the filter cake ashes during the periods of time between shutdown of the transport reactor and the opening of the filter vessel for sample collection. The shutdown in November, 1997 was precipitated by a "thermal event" in the filter vessel which occurred on November 2. Following shutdown procedures, sample # 4262 was obtained on November 5. The time between shutdown and the collection of samples in January, 1998 was much longer. The system was shut down on December 9, 1997, but the filter vessel was not opened for inspection and sampling until January 20, 1998. Thus sample # 4294 had a much longer period of time of exposure to relatively cool, moist air prior to its collection from the surface of filter elements in the bottom plenum. In contrast, the hopper ash sample analyzed (ID # 4295) was collected from the ash discharge system during system operation on December 8, 1997, and was immediately placed in a sealed container. As with all samples after their collection, this hopper ash sample was kept in sealed containers until it was analyzed.

Inertial Effects in the Westinghouse FL0301 Filter Vessel

In most filter applications, ash particles entering the filter vessel are apparently segregated based on their physical characteristics. The mechanism that is most likely responsible for this segregation is the selective continued entrainment of ash particles as determined by their individual settling velocities. As the gas entering the vessel slows to the filtering face velocity, previously entrained ash particles with higher settling velocities tend to divert from the flow paths of the flue gas. Their trajectories instead become governed by the force of gravity, and they settle into the hopper before they ever reach the filter cake. Finer ash particles with low enough settling velocities continue to be entrained in the gas up until they impact on the surface of the filter cake. The same mechanism of selective continued entrainment would also apply to ash particles ejected from the filter cake during cleaning pulses. Individual ash particles, or agglomerates of ash particles with small enough settling velocities will reentrain in the flue gas and be recollected on the filter cake. Particles and agglomerates of particles with sufficiently high settling velocities will permanently leave the filter cake and settle into the hopper.

The degree to which the PSDF hopper ash contains large particles not found in the PSDF filter cake ash can be observed in the size distribution data obtained with a Microtrac Size Analyzer for hopper and filter cake ashes (Figures 11 and 12). During the preparation of ash samples for the measurement of size distribution with this device, a small portion of the sample is suspended in a clear fluid (usually isopropyl alcohol), and submitted to ultrasonic agitation for several minutes. This procedure is intended to break up any agglomerates of ash particles that may have formed either during the collection process (on surfaces in the filter vessel), or during the storage of the samples prior to their analysis. Provided this agitation successfully breaks up all the agglomerates the ash samples, the measured size distributions

of the filter cake samples should represent the entrained ash as it was when it reached the surface of the filter cake, and the measured size distribution of the hopper ash should be representative of the size distribution of the entrained ash entering the filter vessel. (For the purposes of the calculations in this section, the hopper ash sample (ID # 4295) is assumed to be well-mixed and representative of ash collected in the hopper over several filtration cycles. In a single filtration cycle ash is collected in the hopper by passive dropout while the flue gas is being filtered, and by the capture of ash ejected from the filter cakes immediately following cleaning pulses. These distinct mechanisms may cause samples taken from the ash disposal system to have different characteristics depending only on the time within the filter cycle that the samples were deposited in the hopper.)

The differential size distribution data measured for the filter cake ash have been scaled down by a factor of 0.59 to match the magnitude of the corresponding differential size distribution data measured for the hopper ash for the finer particles (Figure 11). The two distributions coincide up to a particle size of about 8 µm. (These data are presented on a basis of the fraction of the mass in the specified size range normalized by the change in the log of the particle diameters between the limits of the size range. No scales are presented for the ordinate axis in either size distribution plot because of the scaling applied to the filter cake ash data.) The factor of 0.59 applied to the filter cake ash size distribution implies that about 41% of the mass of the entrained particles entering the filter vessel settle out prior to reaching the filter cake surface.

Because the PSDF has the capability of assessing the concentration of suspended particles at the inlet to the filter vessel with Southern Research Institute's on-line sampling system, the degree to which initially entrained particles settle out could be very useful for determining the concentration of suspended ash reaching the filter cake while the vessel is on line.

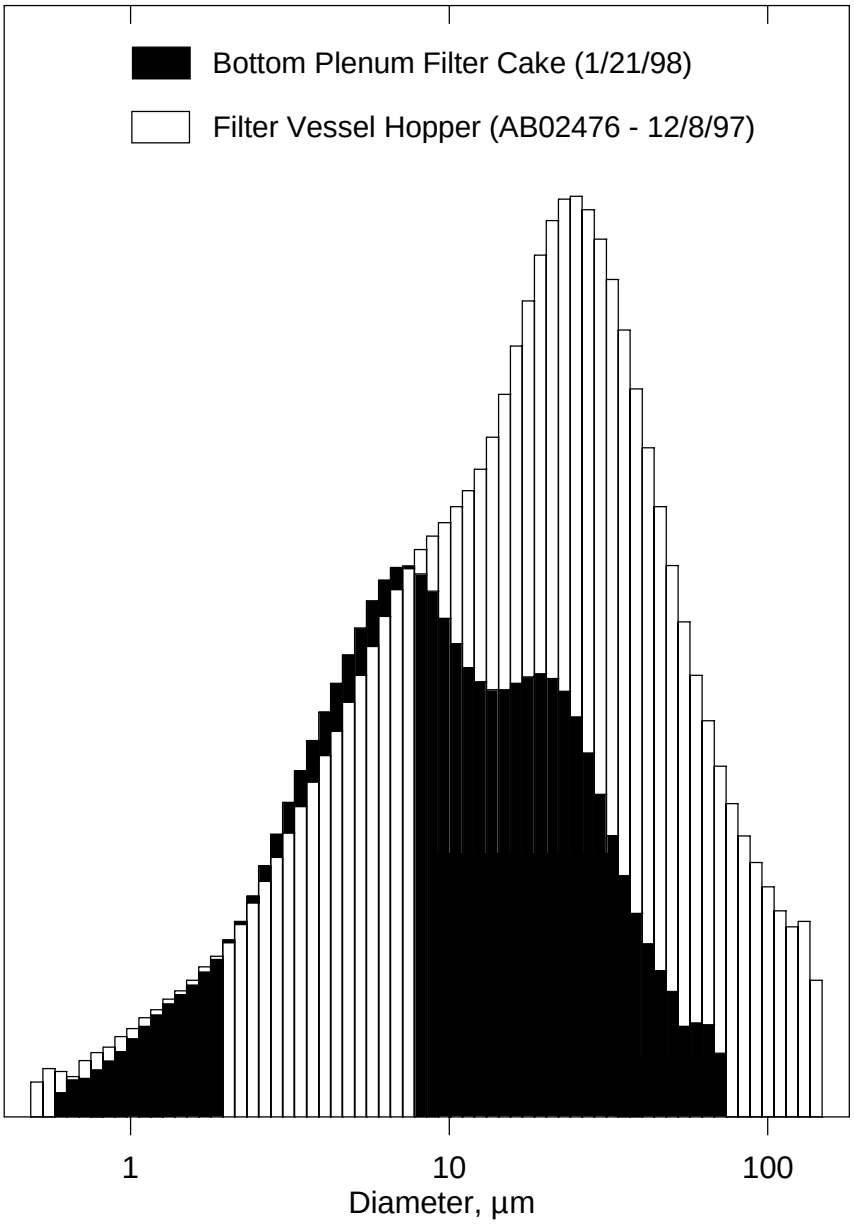


Figure 11. Differential size distribution data measured for PSDF filter cake ash (ID # 4294) and hopper ash (ID # 4295) measured with a Leeds and Northrop Microtrac Analyzer. The size distribution of the filter cake ash has been linearly scaled down by a factor of 0.59 to cause the shape of the finer portions of these two distributions to coincide as much as possible.

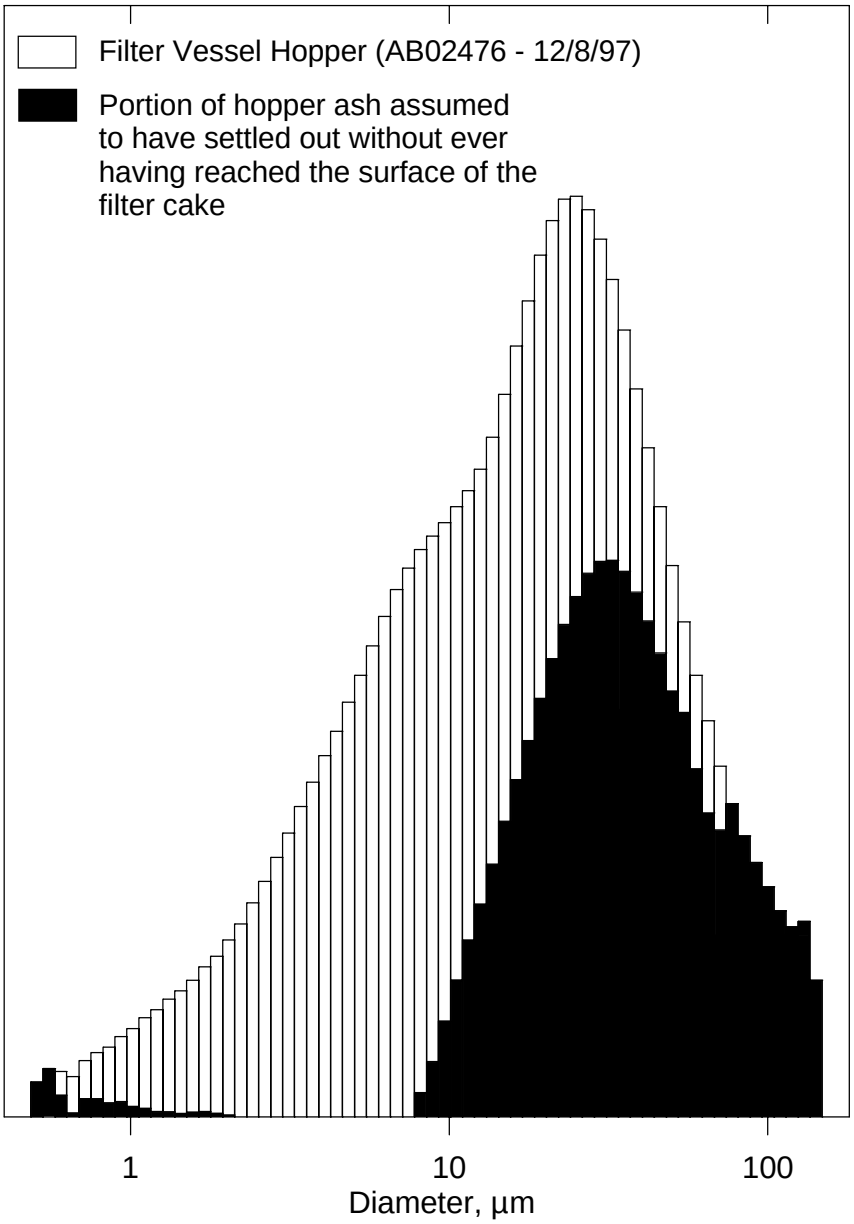


Figure 12. Differential size distribution data measured for PSDF hopper ash (ID # 4295) measured with a Leeds and Northrop Microtrac Analyzer. The difference of the size distribution of the filter cake ash (ID # 4294) presented in Figure 11 has been subtracted from the size distribution of the hopper ash to display the size distribution of the particles assumed to have settled out in the hopper without having ever reached the filter cake surface.

It should be noted that gravitational settling of coarser entrained particles prior to collection on the filter cake is not the only possible explanation for physical differences in hopper and filter cake ashes. Preferential cleaning and/or reentrainment of different-sized particles may also contribute to these differences. Some simple procedures could be used to help verify the degree to which the described settling process affects the amount of ash that reaches the filter cake (contributing to pressure loss through the vessel). If the design of the hopper evacuation system allows, the hopper could be evacuated at various points in a representative filtration cycle and its contents weighed and/or analyzed for size distribution. Key data could be obtained if this process were performed just prior to, and just following, a cleaning pulse. In addition, useful information could be obtained at filter vessel shutdown if the candles in at least one of the plenums were not pulsed following the last filtration cycle, and if the hopper was evacuated following the last filtration cycle, but before cool down. This should allow direct correlation between measured filter cake weight and filtering pressure loss. It would also be beneficial if, when possible, these procedures could be performed at other HGCU facilities.

Comparison of Specific Gas-Flow Resistance and K2

The recent acquisition of ash samples and corresponding operating data from the PSDF has allowed an evaluation of the accuracy of laboratory permeability measurements in comparison with filtration data obtained directly from filter operation. The pressure losses incurred across the filter experienced during HGCU operation depend on various operating parameters, such as flue gas flow rate, filter temperature, mass loading of suspended particulate entering the filter, and gas composition. Once these operating parameters are established, various parameters related to ash characteristics determine the rate at which pressure drop accumulates during a filtering cycle. These include the rate of deposition of mass on the filter cake, the permeance of the filter cake, and the effectiveness and distribution of filter cake removal by periodic pulse cleaning. (Pulse cleaning effectiveness also depends strongly on various design and operating features of the pulse system.) The previous section discussed the various data and assumptions regarding the rate of deposition of mass on the filter cake during recent operation of the PSDF.

The effectiveness of pulse cleaning will be discussed here only in terms of the brief portion of each filtration cycle that is required to reestablish an accumulation of pressure drop that increases proportionally with time. Because each cleaning pulse decreases the uniformity of the filter cake by the removal of various portions of the cake more effectively than other portions, the flow resistance through the through different areas of the cake also becomes less uniform following a pulse cleaning. As the flue gas tends to flow more rapidly through portions of the cake with lower resistance (usually regions with thinner cakes), entrained particles are more rapidly deposited in regions with lower flow resistance. During this period of the filtration cycle, pressure drop increases more rapidly with time than during the period just before cleaning. This process tends to cause the flow distribution through the surface of the cake to become more uniform.

Once the flow distribution over the surface of the cake has become more or less uniform, the pressure drop across the filter cake will rise proportionately with time (provided the other various parameters discussed above remain constant). During this period of constantly rising

pressure drop, the specific resistance, or K2, associated with the filter cake can be determined. For periods of stable filter operation, K2 is calculated by normalizing the rise in filter cake drag over a given period of time by the increase in areal loading experienced by the filter cake during that same period of time.

Given certain assumptions, the operating data available from the PSDF can be combined with the various ash analyses described in preceding sections to derive K2 for the period of PSDF filter operation just prior to the January site visit. Operators at the PSDF provided a summary of operating parameters during a on-site review meeting conducted on January 21, 1998. A selection of these parameters is summarized in Table 10.

Table 10
Selected PSDF Operating Parameters (provided by PSDF personnel)

plenum temperature	1375 °F
absolute filter system pressure	14.5 bar
actual filter face velocity	4.1 ft/min
inlet loading	11,300 ppmw
pulse frequency (duration of filtration cycle)	40 minutes
ΔP rise during filtration cycle	30 inches H_2O
CO_2 in flue gas	8.6 % by volume
N_2 in flue gas	81.5 % by volume
O_2 in flue gas	5.5 % by volume
H_2O in flue gas	5.0 % by volume

A representative pressure drop trace from December 8, 1997 is shown in Figure 13. Examination of several representative filter vessel pressure drop traces indicated that a constant rate of increase of filtering was reestablished about 2 to 3 minutes after each cleaning pulse. Therefore, for simplicity, each entire filtering cycle lasting 40 minutes was assumed to represent stable filter operation. Consequently, the rate of increase of filter cake pressure drop is about 0.75 inches H_2O/min.

The next step required to calculate K2 is to normalize by the rate of increase in areal loading. The inlet loading to the filter vessel is 11,300 ppmw. However, based on the discussion presented in the preceding section, only 59 % of this mass should be assumed to reach the surface of the filter cake. Therefore the concentration of particles in the flue gas as it reaches the cake is 6667 ppmw. Assuming the density of the combustion gas is 0.0822 lb/ft^3 at STP, this value converts to about 13.9 grains/acf. Because each ft^2 of filter cake filters 4.1 ft/min x 40 min = 164 acf of flue gas during each filter cycle, each ft^2 of filter area increases its areal loading by 2280 grains (or 0.326 lb) during the 40 minutes between pulse cleaning cycles. Therefore the addition of 0.326 lb of ash to each ft^2 of filter cake area increases the pressure drop by 30 inches of H_2O (at a face velocity of 4.1 ft/min). Pressure drop is linearly proportional to face velocity, so at a face velocity of 1 ft/min, that same 0.326 lb of additional filter cake would generate 7.3 inches of H_2O. Therefore, K2 of the filter cake formed during stable operation just prior to the January site visit is calculated to be 22.4 in H_2O·min·ft/lb.

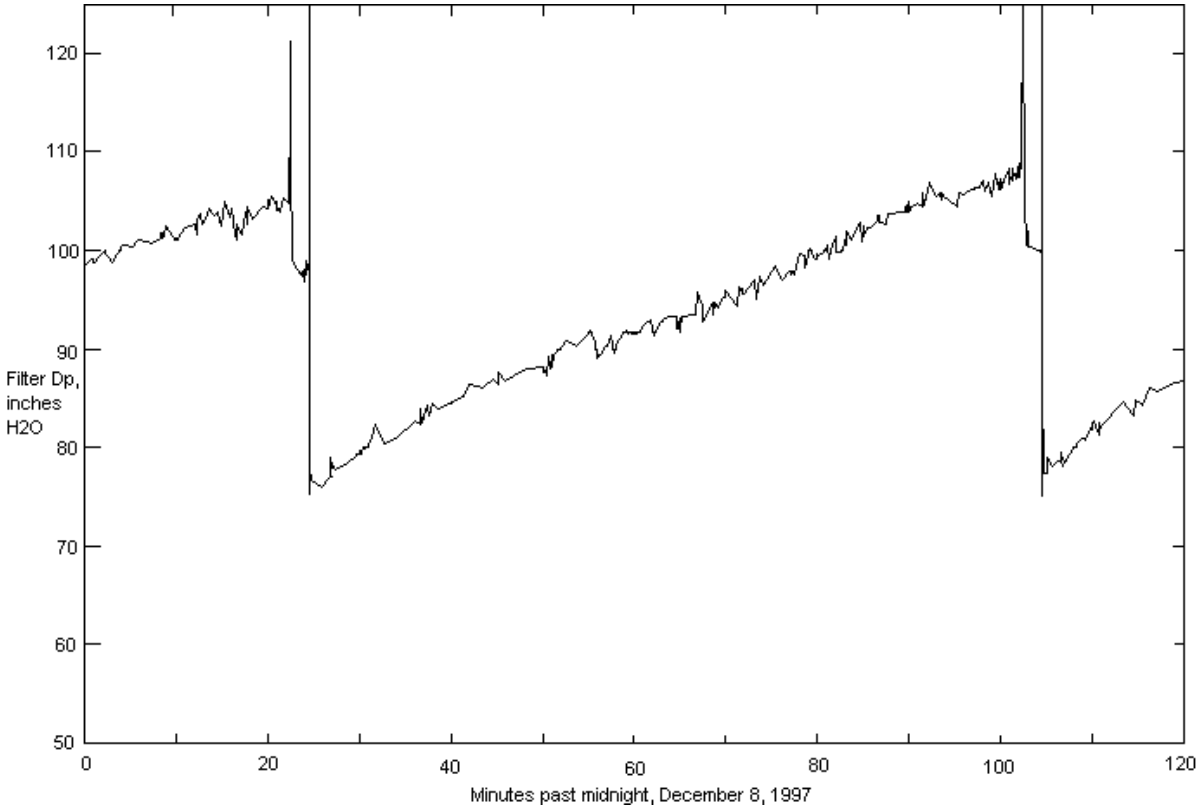


Figure 13. Pressure drop data from FL0301 operation early on December 8, 1997.

To convert the laboratory measurement of specific gas-flow resistance to PSDF filter conditions, it is necessary to correct the laboratory value of 9.7 in H_2O·min·ft/lb for differences in gas viscosity only. (Changes in temperature and pressure are already accounted for in the calculations of field K2 and laboratory specific gas-flow resistance by the considerations of the actual gas volumes filtered in each case.) The viscosity of the air used in the laboratory measurement at 75 °F is 184 μpoise. No direct measurements of flue gas viscosity have been made at the PSDF; however, several algorithms exist for the calculation of gas viscosity based on its composition and temperature. The gas composition and temperature data in Table 8 were input into a model used to calculate the viscosity of flue gases for the reduction of data from impactor sampling trains. The viscosity of the flue gas at 1375 °F was calculated to be 406 μpoise. Therefore the laboratory value of specific gas-flow resistance must be corrected by a factor of 406/184, or 2.21. Increasing the value of specific gas-flow resistance measured in the lab (9.7 in H_2O·min·ft/lb) by a factor of 2.21 yields a value of 21.4 in H_2O·min·ft/lb, which agrees well with the calculated K2 (22.4 in H_2O·min·ft/lb).

KARHULA PRESSURIZED CIRCULATING FLUID BED FACILITY

The Foster Wheeler Pressurized-Circulating Fluid Bed (PCFB) test facility Karhula, Finland was constructed and originally operated by Ahlstrom Boilers.[4] The 10 MWt (34.1 MMBtu/hr) facility has a fuel feeding capacity of 15,900 lb/hr, an operating temperature of 1615 °F, and an operating pressure of 16 bar. The barrier filter, which was designed by Westinghouse, operates without an upstream cyclone.[2] The filter vessel is closely coupled to the reactor vessel with the flue gas entering the filter vessel normal to the vessel wall (in contrast with the tangential inlet of the FL0301 filter vessel at the PSDF). This arrangement causes the flue gas to impinge directly on the shroud installed around the filter assembly. The filter consists of a single, three array cluster that holds up to 128 cylindrical filter elements. Filter operation has been reliable, with only isolated episodes of ash bridging. Inlet dust loadings have been as high as 13,000 ppm. A number of coal and sorbent combinations have been evaluated. Some of the tests performed at Karhula have been to evaluate the coal and sorbent planned for the Lakeland PFBC.

ANALYSES OF KARHULA ASHES

Mr. Reijo Kuivalainen of Foster Wheeler Energia OY provided seven samples from the Westinghouse filter assembly following a test conducted with Lakeland coal and sorbent during the last quarter of 1997 of the Foster Wheeler CPFBC Facility at Karhula. Of these ash samples (described in Table 11), samples # 4276 and # 4277 were selected for detailed analyses. The results of most of these analyses are presented in Tables 12 and 13. Cumulative and differential size distribution data measured for Karhula hopper ash (ID # 4276) and filter cake ash (ID # 4277) as measured with a Leeds and Northrop Microtrac Analyzer are presented in Figures 14 and 15. SEM photomicrographs of sample # 4277 are presented in Figure 16.

Table 11
Karhula Ash Samples Received from Foster Wheeler Energia OY

ID #	location	description
4276	hopper	ash from silo after test run
4277	filter cake	top array
4278	filter cake	middle array
4279	filter cake	bottom array
4280	bottom plate	
4281	conical ash shed	over middle plenum
4282	conical ash shed	over bottom plenum

Table 12
Physical Characteristics of Karhula Samples

quantity ID #	4276	4277
specific surface area, m^2/g	1.6	2.2
Stokes' D_{50}, μm (Microtrac Particle Size Analyzer)	31	12
Stokes' D_{50}, μm (Bahco Classifier)	15	7.8
uncompacted bulk porosity, %	75	82
drag-equivalent diameter, μm	5.01	2.72
specific gas-flow resistance, in H_2O·min·ft/lb*	2.2	2.4
tensile strength, N/m^2	7.8	19
true particle density, g/cm^3	2.73	2.76

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

Table 13
Chemical Composition of Karhula Ashes, % wt.*

ID #	4276	4276	4276	4277	4277
location	hopper	hopper	hopper	filter cake	filter cake
particle size range	< 45 μm	> 45 μm	all	all	< 45 μm
Li_2O	0.02	0.02	0.02	0.02	0.02
Na_2O	0.70	0.52	0.64	0.61	0.78
K_2O	1.4	1.5	1.4	1.6	1.6
MgO	0.87	0.87	0.87	0.88	0.87
CaO	23.9	24.3	24.0	21.3	21.0
Fe_2O_3	8.1	6.2	7.5	8.1	8.4
Al_2O_3	16.8	16.0	16.5	16.9	17.1
SiO_2	32.0	35.4	33.1	31.5	31.7
TiO_2	1.3	0.83	1.1	1.2	1.2
P_2O_5	0.18	0.15	0.17	0.18	0.19
SO_3	13.1	14.2	13.5	15.7	15.9
LOI	0.74	0.70	0.73	0.62	0.62
soluble $SO_4^=$	16.7	16.0	16.5	19.6	19.4
Equilibrium pH	--	--	--	10.18	--

* Equilibrium pH is dimensionless

Because the Karhula samples that were provided included filter cake ashes and a corresponding hopper ash, analyses were performed to determine specific physical and chemical differences between samples obtained from these two locations. Measurements of size distribution, specific surface area, uncompacted bulk porosity, specific gas-flow resistance (with associated drag-equivalent diameter), and tensile strength (see Table 12) all indicate that these two ashes have significantly different physical characteristics. Two different techniques were used to measure the size distributions of these two ashes. The median diameters obtained with the Bahco Aerodynamic Classifier are significantly lower than the values measured with the Leeds and Northrup Microtrac Particle Size Analyzer.

These differences were caused by the sieving out of the coarser particles from the samples prior to classification with the Bahco device. (The Bahco device cannot accurately size particles larger than around 25 µm.) Although the Bahco data reflect the relative coarseness of these two samples, the data obtained with the Microtrac Analyzer (Figures 14 and 15) most accurately represent the size distribution of these samples because the Microtrac analyses were based on the entire spectrum of particle sizes in the samples.

As discussed under the analyses of PSDF ashes, measurements of particle size distribution can be used to estimate the extent to which the entrained ash particles entering the filter vessel at Karhula may have settled in to the hopper prior to ever reaching the filter cake surface. The degree to which the Karhula hopper ash contains large particles not found in the Karhula filter cake ash can be observed in the data presented in Figures 14 and 15. These data indicate that around 64 % of the material entering the filter vessel at Karhula settled into the hopper without reaching the surface of the filter cake.

The hopper ash (ID # 4276) and the filter cake ash (ID # 4277) exhibited similar values of specific gas-flow resistance, despite their other physical differences. The reason for this similarity is the offsetting effect that filter cake porosity and specific surface area have on each other. Coarser particles, like those in the Karhula hopper sample, exhibit lower bulk cohesivity and would form filter cakes with lower porosities. In general, however, coarser particles also exhibit lower specific surface areas (as can be seen in Table 12). Pressure loss across a filter cake is incurred as the flue gas follows a tortuous path through the cake and past the surfaces of the particles. Because Karhula filter cake ash has more specific surface area than the corresponding hopper ash, the beneficial effect of the greater porosity of the filter cake is offset by the higher specific surface area of the filter cake ash particles.

Analyses were also performed to determine the extent to which the physical segregation of particles discussed above affected the chemical composition of the hopper and filter cake ashes (Table 13). In general, the chemical composition of the hopper and filter cake ashes are basically independent of particle size. The chemical species in the hopper ash that most deviate from this trend are Na_2O, Fe_2O_3, TiO_2, and P_2O_5, which are enriched in the finer ash particles, and SiO_2, which is enriched in the coarser ash particles. For the filter cake ash, the only chemical species found to be size dependent was Na_2O, which, like the hopper ash, was enriched in the finer particles. In a comparison of the chemistry of the hopper and filter cake ashes, the main difference was in their sulfur contents. As has been previously reported under this project and by other researchers, sulfur was enriched in the filter cake ash relative to the hopper ash, most likely by the additional scrubbing of SO_2 from the flue gas by unreacted sorbent in the filter cake.

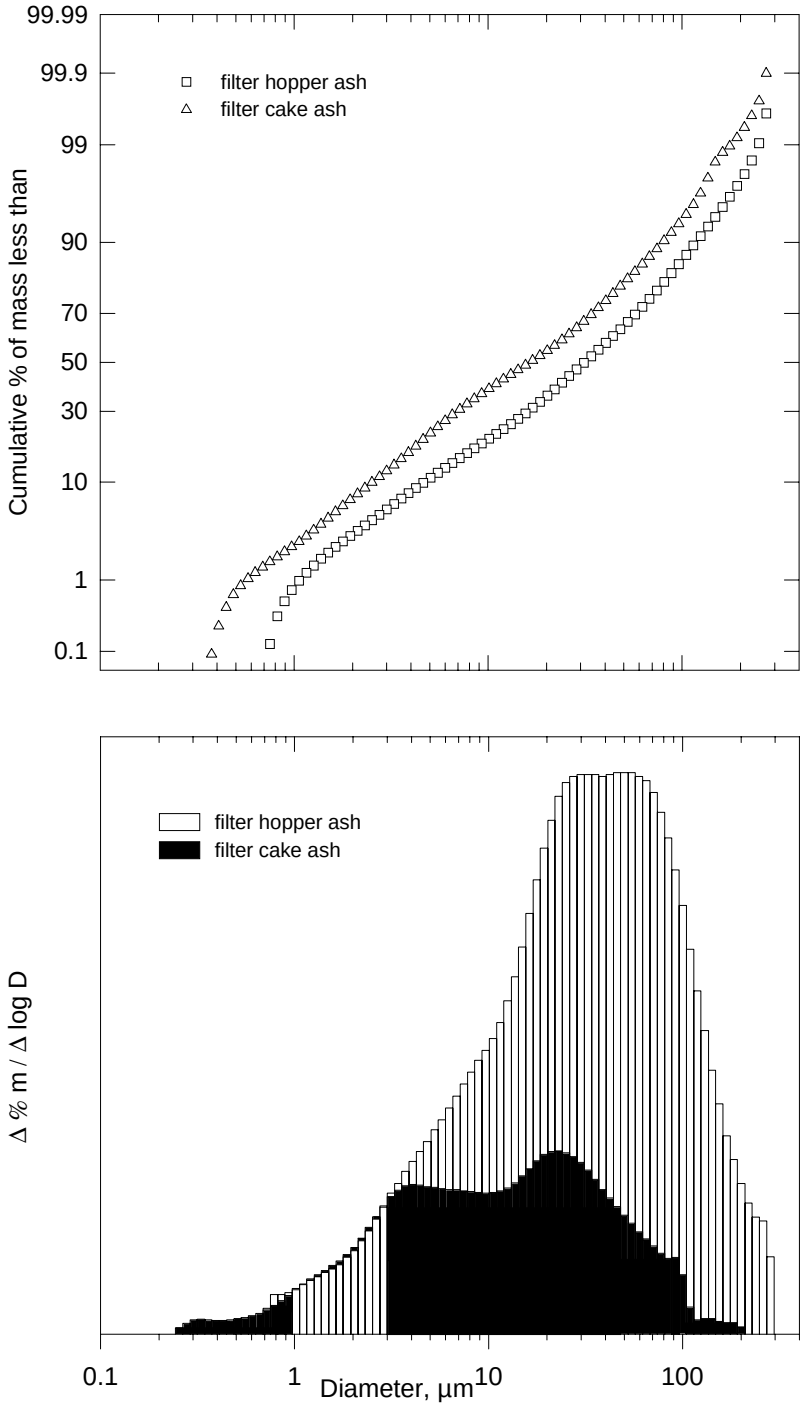


Figure 14. Cumulative and differential size distribution data measured for Karhula hopper ash (ID # 4276) and filter cake ash (ID # 4277) measured with a Leeds and Northrup Microtrac Particle Size Analyzer. The size distribution of the filter cake ash has been linearly scaled down by a factor of 0.36 to cause the shape of the finer portions of these two distributions to coincide as much as possible.

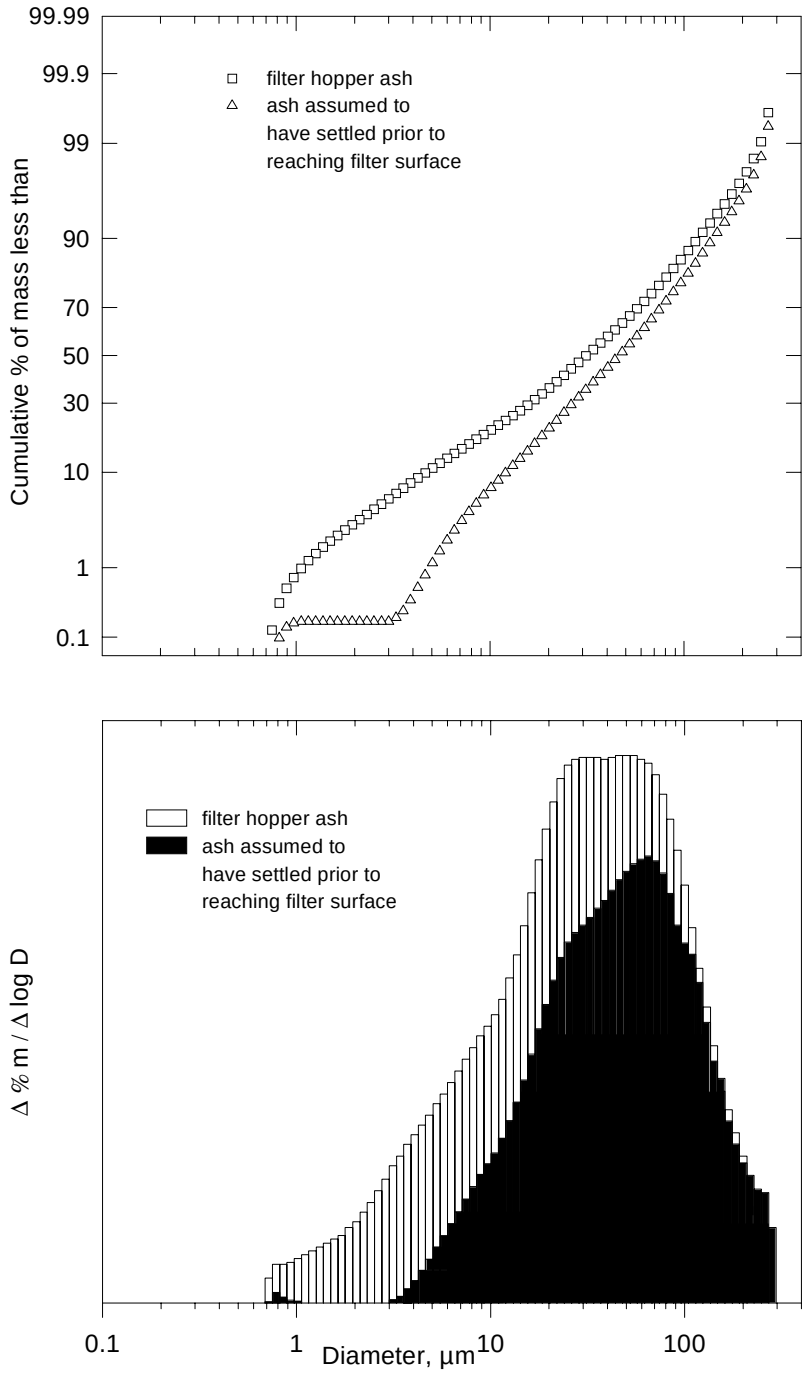


Figure 15. Cumulative and differential size distribution data measured for Karhula hopper ash (ID # 4276) measured with a Leeds and Northrop Microtrac Analyzer. The difference of the size distribution of the filter cake ash (ID # 4277) presented in Figure 14 has been subtracted from the size distribution of the hopper ash to display the size distribution of the particles assumed to have settled out in the hopper without having ever reached the filter cake surface.

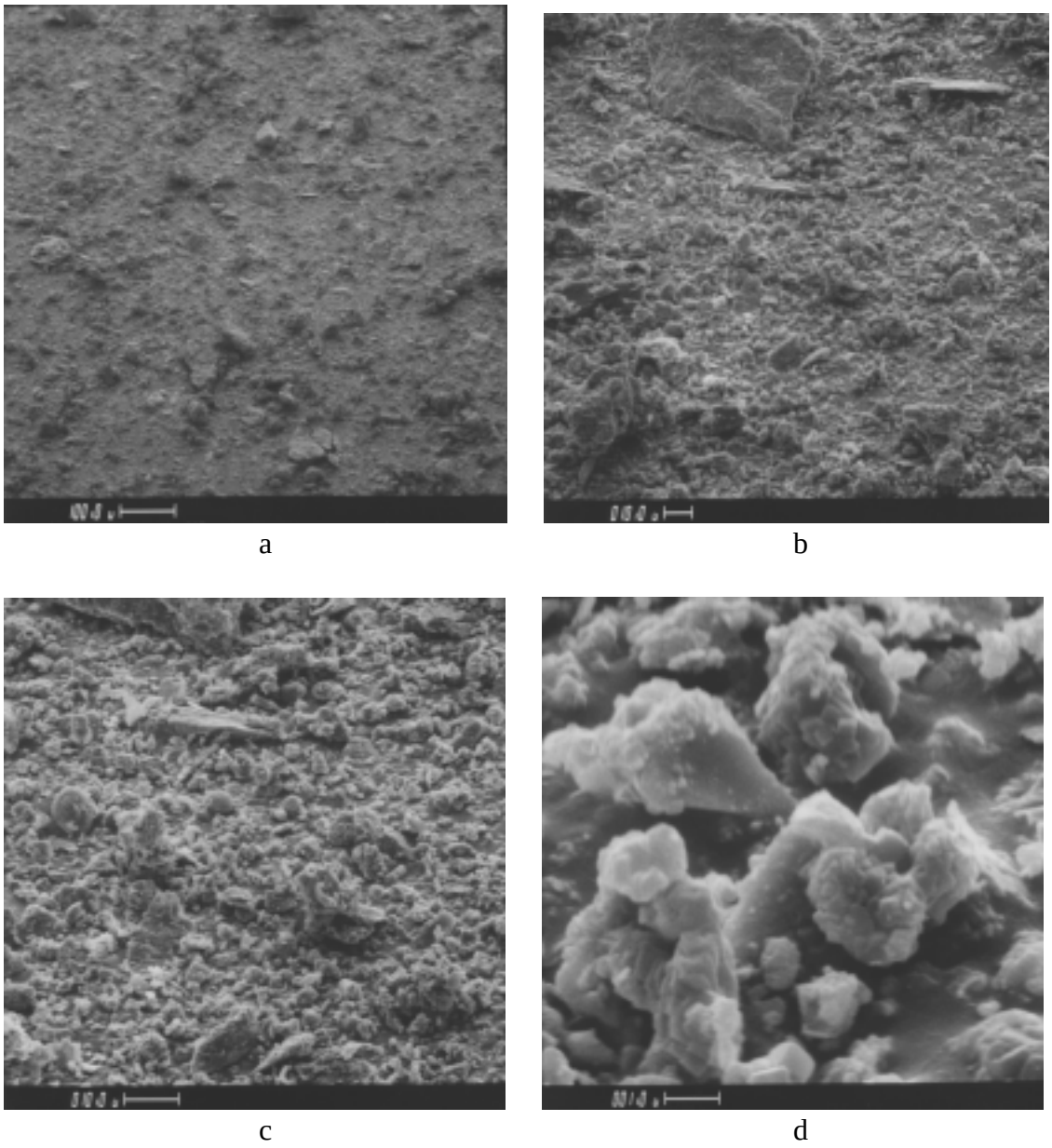


Figure 16. Representative scanning electron micrographs of Karhula filter cake ash (ID # 4277) taken at a) 100X, b) 500X, c) 1000X, and d) 10,000X.

PIÑON PINE POWER PROJECT

In the Piñon Pine IGCC Power Project, the Sierra Pacific Power Company is operating a KRW fluidized bed gasifier on low sulfur coal from southern Utah.[5] The net power output of the plant is 99.7 MWe. Hot gas cleanup is provided by a Westinghouse barrier filtration system.[2] The filtration vessel is 10 ft. in diameter, and contains 748 candle filter elements on sixteen plenum assemblies. The filter design departs from earlier, smaller-scale Westinghouse designs in that all maintenance on the filter elements (initial installation, inspection, and element replacement) will be performed inside the filter vessel by specially trained personnel. The Piñon Pine gasifier is started up on coke breeze before switching to coal.

ANALYSES OF PIÑON PINE FILTER FINES

The Piñon Pine gasifier was operated for about seven hours on June 2, 1998 at a pressure of 100 psig and over a temperature range of 1600 to 1800 °F. Problems not directly related to filter operation caused the gasifier to be shut down after this short run. Sample # 4316 was collected following this brief period of operation from the system of hoppers attached to the Westinghouse filter vessel. Because of the brevity of this run, it is not known to what extent this sample represents steady-state gasifier operation. As further samples become available from more extended periods of Piñon Pine operation, the characteristics of the particulate material generated by this gasifier should become better defined.

The measured physical characteristics of the Piñon Pine sample # 4316 are summarized in Table 14. Because this sample was not taken from the surface of the filter elements, it may be more coarse than material collected on the filter elements. With only the currently available sample, it is not possible to determine what fraction, if any, of the size distribution presented in Figure 17 represents particles that settled in the hopper without ever reaching the filter cake. Determination of the degree of passive settling that may have occurred in the filter vessel would require analyses of particulate material collected directly from the surfaces of the candle filter elements. Consequently the behavior and characteristics of this sample may not accurately indicate the characteristics and behavior of the filter cake. If the particulate material that collects on the filters is finer than this sample, the filter cake porosity would probably be higher than 80 %, and the material's drag-equivalent diameter would probably be lower than 1.96 µm. This decrease would tend to offset the effect on specific gas-flow resistance of the increased filter cake porosity . The tensile strength of this sample is relatively low. Low tensile strength may increase the likelihood of particle reentrainment following cleaning pulses.

Even though sample # 4316 has a relatively high specific surface area, the drag-equivalent diameter and uncompacted bulk porosity are high enough to keep the specific gas-flow resistance from being excessively high. Specific surface area and drag-equivalent diameter of particulate samples are both indications of the morphology of the particles in the sample. In general, the drag-equivalent diameter value is significantly smaller for samples with very high specific surface areas. However, because adsorption of nitrogen molecules provides the basis for the BET method for determination of specific surface area, the value returned includes the surface area found in ultrafine pores on the surfaces of the particles, and also the

surface area within "dead-end" pores that may exist in the particles. The permeability measurements that provide the basis for the calculation of the drag-equivalent diameter depend on the drag that is induced as gas passes over the surfaces of the particles. Surface features of the particles smaller than the mean free path of the gas molecules flowing by them do not significantly influence drag. Also, because the gas flowing by the particles does not significantly flow into any "dead-end" pores, the surface area in these pores does not affect drag. Therefore, the degree of correlation between the drag-equivalent diameter and specific area of a sample depends on the particular morphologies of the particles in the sample. This effect is one of the primary reasons permeability measurements are more reliable than specific surface area measurements for assessing the affects of particle morphology on the inherent drag characteristics associated with particulate samples.

Table 14
Measured Physical Characteristics of Piñon Pine Filter Fines (ID # 4316)

quantity	value
specific surface area, m^2/g	107
Stokes' MMD, µm (Microtrac Analyzer)	19
Stokes' MMD, µm (Bahco Classifier)	12
uncompacted bulk porosity, %	80.2
drag-equivalent diameter, µm	1.96
specific gas flow resistance, in H_2O·min·ft/lb*	7.7
tensile strength, N/m^2	2.3
true particle density, g/cm^3	2.38

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

Figures 18 and 19 present scanning electron micrographs of sample # 4316. Mineral analyses of this sample # 4316 are presented in Table 15. Because of the high calcium-to-sulfur ratio in this material, further tests were conducted to determine the relative amounts of these two constituents as a function of particle size.

Table 15
Measured Chemical Characteristics of Piñon Pine Filter Fines (ID # 4316), % wt.

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

* dimensionless

The size distribution of sample # 4316 was also measured with a Bahco Aerodynamic Classifier. This yielded the size distribution data shown in Figure 20 and Table 16, as well as size-fractionated particulate samples for chemical analysis. Six of the size fractions produced in the classification of the sample were submitted for determination of loss-on-ignition (LOI), and calcium and sulfur contents. The results of these chemical analyses are presented in Table 17, along with corresponding values for the source material. All nine size fractions and the source sample were also submitted for C-H-N analyses, which are summarized in Table 18 and Figure 21.

Both types of chemical analyses indicate that in general, the sorbent material is concentrated in the larger particles that are collected in the filter hopper, while the finer particles presumably contain a higher proportion of char. The coarsest size fraction (diameter > 26.7 µm) deviated from this trend, suggesting a bimodal distribution of the char particles.

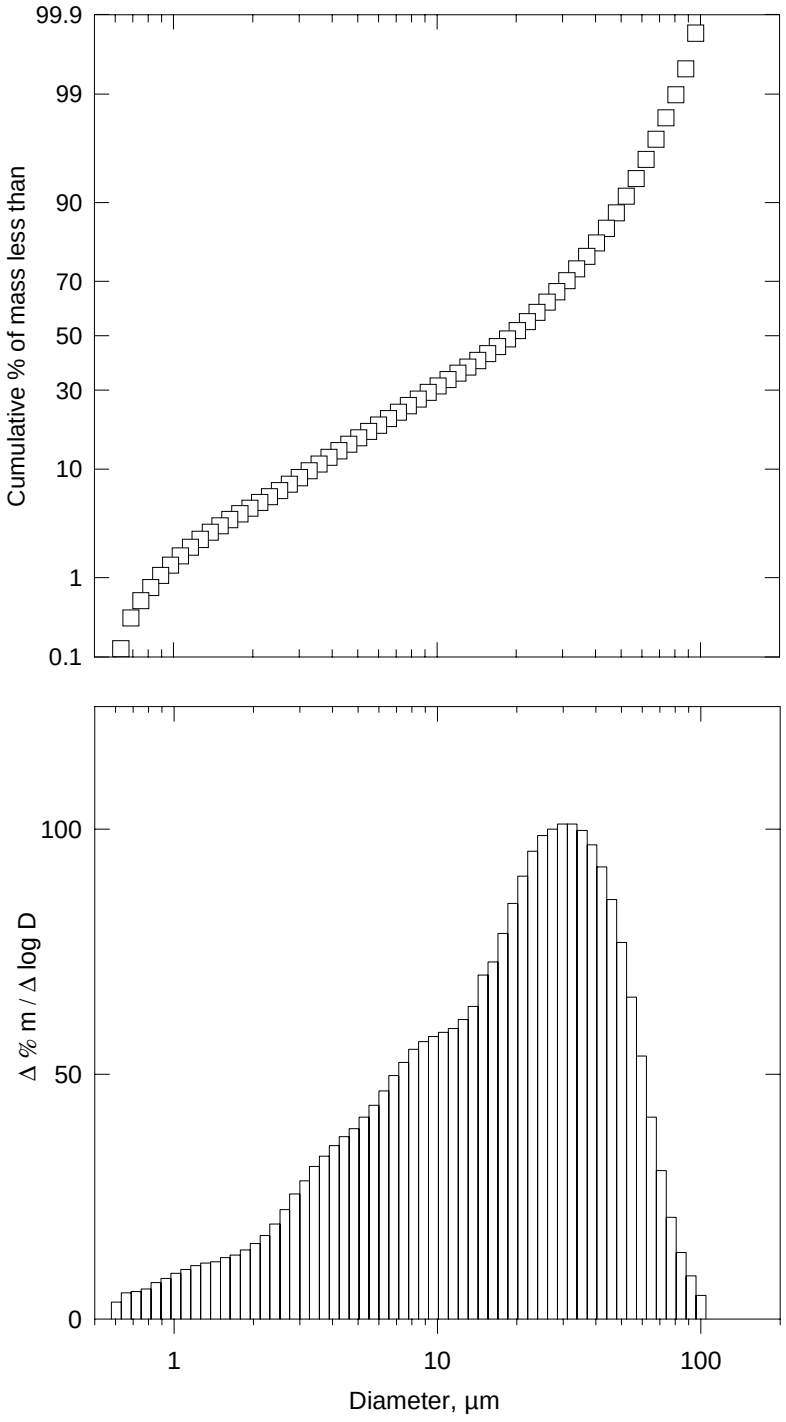


Figure 17. Differential and cumulative size distribution data measured for Piñon Pine filter fines (ID # 4316) with a Leeds and Northrup Microtrac Particle Size Analyzer. The Stokes' MMD of this distribution is 19 µm.

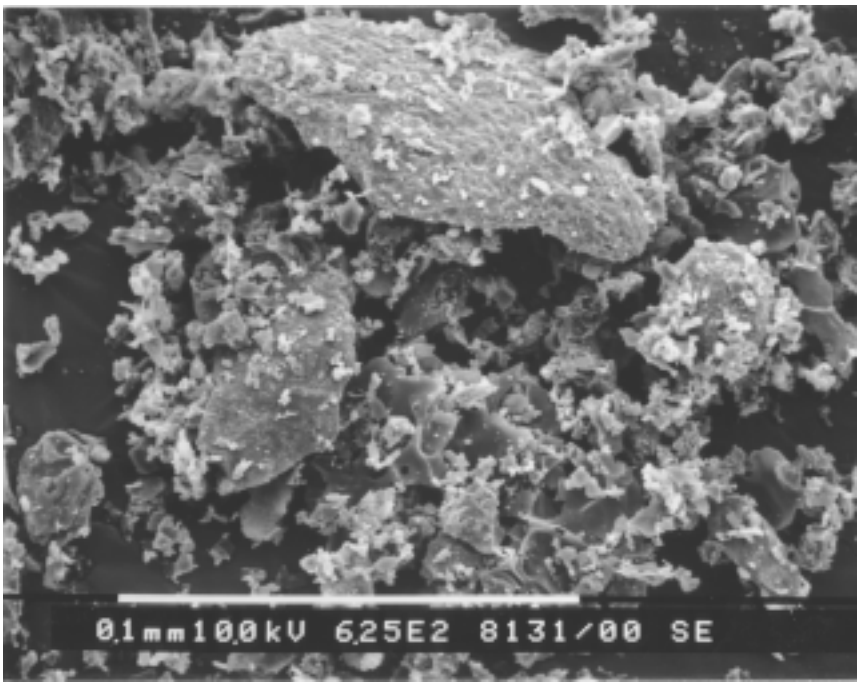


Figure 18. Scanning electron micrograph of Piñon Pine IGCC Power Project filter fines particulate sample (ID # 4316). The white bar at the bottom of the micrograph represents a length of 100 μm.

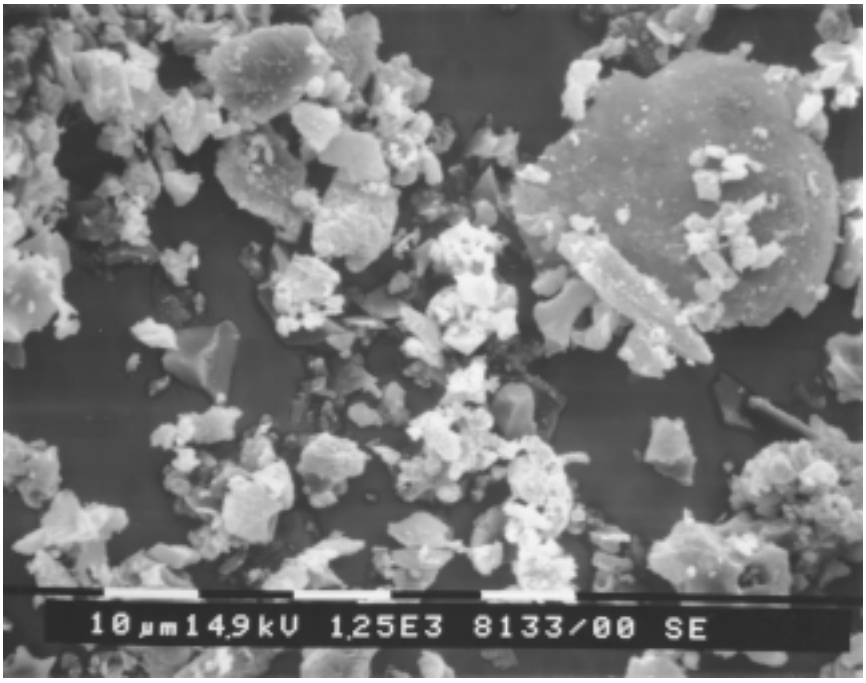


Figure 19. Scanning electron micrograph of Piñon Pine IGCC Power Project filter fines particulate sample (ID # 4316). The white bars at the bottom of the micrograph represent lengths of 10 μm.

Table 16
Size Distribution Data Measured for Piñon Pine Filter Fines (ID # 4316)
with a Bahco Aerodynamic Classifier

particle size range	% of mass in size range	cumulative % of mass smaller than upper size limit
diameter < 1.6 µm	6.9	6.9
1.6 µm < diameter < 2.5 µm	5.9	12.8
2.5 µm < diameter < 4.7 µm	13.8	26.7
4.7 µm < diameter < 8.2 µm	10.7	37.4
8.2 µm < diameter < 11.5 µm	9.6	47.0
11.5 µm < diameter < 18.9 µm	16.7	63.7
18.9 µm < diameter < 23.9 µm	5.9	69.6
23.9 µm < diameter < 26.7 µm	2.5	72.1
diameter > 26.7 µm	27.9	100.0

Table 17
Selected Chemical Constituents Measured for Piñon Pine Filter Fines (ID # 4316)
and Six Selected Size Fractions

particle size range	LOI, % wt.	CaO, % wt.	SO_3, % wt.
source sample (all diameters)	53.0	50.4	8.0
diameter < 1.6 µm	69.5	41.9	8.5
1.6 µm < diameter < 2.5 µm	68.3	45.2	7.9
2.5 µm < diameter < 4.7 µm	65.3	47.9	7.0
4.7 µm < diameter < 8.2 µm	60.2	49.3	7.2
11.5 µm < diameter < 18.9 µm	43.2	54.8	7.8
diameter > 26.7 µm	44.4	55.2	6.8

Table 18
C-H-N Analyses of Six Selected Size Fractions of Piñon Pine Filter Fines (ID # 4316)

particle size range	carbon, % wt.	hydrogen, % wt.	nitrogen, % wt.
source sample (all diameters)	46.59	0.74	1.04
diameter < 1.6 µm	62.90	1.22	1.00
1.6 µm < diameter < 2.5 µm	62.26	1.16	0.67
2.5 µm < diameter < 4.7 µm	59.03	1.09	0.44
4.7 µm < diameter < 8.2 µm	54.20	0.99	0.39
8.2 µm < diameter < 11.5 µm	48.24	0.80	0.61
11.5 µm < diameter < 18.9 µm	36.65	0.62	0.49
18.9 µm < diameter < 23.9 µm	35.26	0.58	0.88
23.9 µm < diameter < 26.7 µm	36.11	0.64	0.94
diameter > 26.7 µm	50.72	0.74	0.62

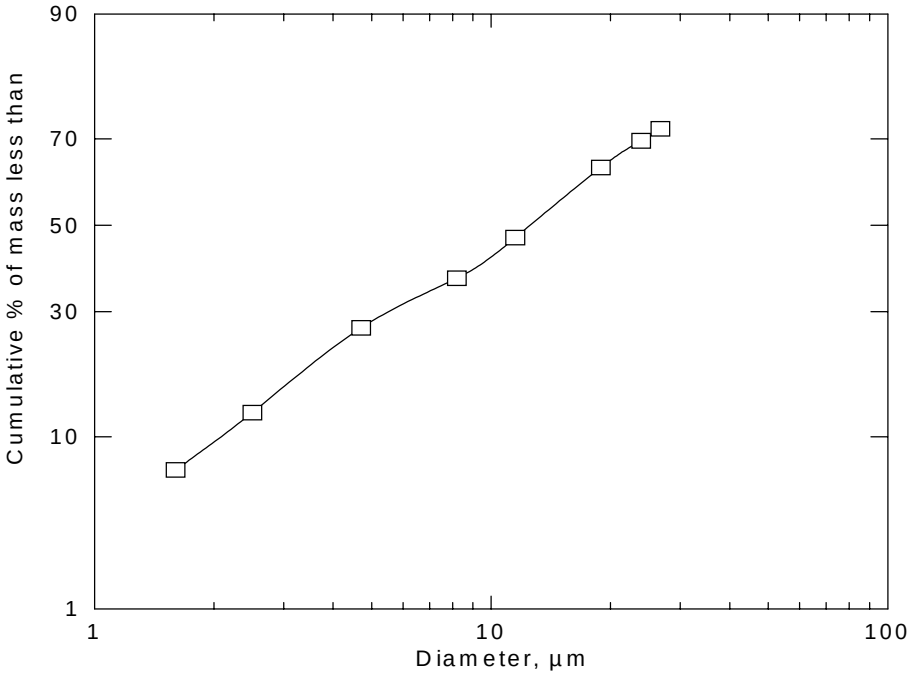


Figure 20. Cumulative particle size of the Piñon Pine filter fines (ID # 4316) measured with a Bahco Aerodynamic Classifier.

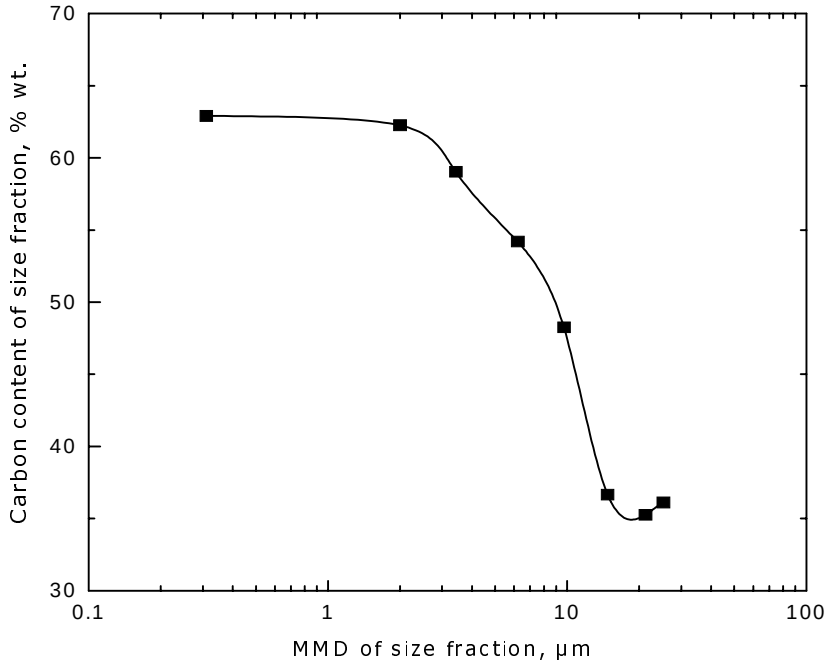


Figure 21. Carbon contents of the various size fractions of Piñon Pine filter fines (ID # 4316). The carbon content (50.7 %) of the size fraction of particles larger than 26.7 µm is not represented on this plot.

TRANSPORT REACTOR DEVELOPMENT UNIT

The Transport Reactor Development Unit (TRDU) is located at the University of North Dakota's Energy & Environmental Research Center (EERC) and was built under Southern Company Services, Inc. Contract No. C-92-000276.[6] The M.W. Kellogg Company designed and procured the reactor and provided valuable on-site personnel for start-up and during operation. The Electric Power Research Institute (EPRI) was involved in establishing the program and operating objectives with the EERC project team. The 200-lb/hr coal-limestone feed TRDU was built to augment studies performed with the Transport Reactor Test Unit in Houston and to provide support for the 3400-lb/hr feed rate Wilsonville Transport Reactor at the PSDF. Research at the TRDU also indirectly supports the Foster Wheeler advanced pressurized fluid-bed combustor, also located at the PSDF, and the Clean Coal IV Piñon Pine IGCC Power Project. Research at the TRDU is sponsored by the U.S. Department of Energy (DOE) Federal Energy Technology Center (FETC), under Contract DE-FC21-93MC30097. The TRDU has an exit gas temperature of up to 980 °C (1800 °F), a gas flow rate of 300 scfm, and an operating pressure of 120-150 psig.

The hot gas filter vessel (HGFV) is designed to handle all of the TRDU gas flow at its nominal operating conditions. This vessel has a 1.22-m inner diameter and is 4.7 m long with a refractory inside diameter of 71 cm (28 in.) and a shroud diameter of 61 cm (24 in.). Filter vessel design capabilities include operation at elevated temperatures (to 950 C) and pressures (up to 11.4 bar), with the initial test program operating in the 540 – 650 C range. The HGFV can operate with filter face velocities in the range of 1.25 to 5.1 cm/s. Nineteen 1-meter candles were used in the initial tests, but 1.5-meter candles can be installed.

ANALYSES OF TRDU PARTICULATE SAMPLES

Michael Swanson of the University of North Dakota's Energy and Environmental Research Center provided seven samples from operation of the TRDU. Some of these samples were analyzed completely, while only limited analyses were performed on others. The samples are identified in Table 19. The physical and chemical analyses performed on these samples are summarized in Tables 20 and 21. Measured size distributions of these samples are presented in Figures 22 through 28. Representative scanning electron micrographs of these samples are shown in Figures 29 through 33.

Table 19
Identification of TRDU Samples

ID #	run mode	run type sample	dates and sampling times
4324	gasification	P051 filter hopper char	2/25/97 @ 12:00 to 2/27/97 @ 00:15
4325	gasification	P051 filter cake char	2/28/97 @ EOT (end of test)
4326	gasification	P056 filter hopper char	2/22/98 @ 08:00 to 16:15
4327	gasification	P056 filter hopper char	2/25/98 @ 06:40 to 10:00
4328	gasification	P057 filter hopper char	4/4/98 @ 14:00 to 18:00
4329	gasification	P057 filter hopper char	4/7/98 @ 08:50 to 12:00
4330	combustion	P058 filter hopper ash	5/5/98 @ 17:00 to 5/8/98 @ 09:50

Table 20
Physical Characteristics of TRDU Samples

quantity ID #	4324	4325	4326	4327	4328	4329	4330
uncompacted bulk porosity, %	90.7	88.8	88.1	83.0	88.5	87.4	38.4
Stokes' MMD, µm	4.23	3.63	--	22.6	--	18.6	162
specific surface area, m^2/g	99.8	48.6	--	18.2	--	32.5	3.8
true density, g/cm^3	2.32	2.38	--	2.36	--	2.21	2.69
drag-equivalent diameter, µm	0.556	0.708	--	--	--	--	--
specific gas flow resistance, in H_2O·min·ft/lb*	9.1	9.5	--	--	--	--	--

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

Table 21
Chemical Composition of TRDU Samples, % wt.

constituent ID #	4324	4325	4327	4329	4330
Li_2O	0.01	0.01	0.01	0.02	<0.01
Na_2O	1.0	0.95	0.60	2.3	0.15
K_2O	0.12	0.18	0.89	0.62	0.09
MgO	13.4	12.5	16.4	8.1	4.4
CaO	40.4	42.2	26.3	18.5	7.2
Fe_2O_3	7.0	8.0	9.5	4.2	0.67
Al_2O_3	14.9	14.4	7.2	10.4	0.80
SiO_2	11.0	12.2	19.3	51.1	79.6
TiO_2	3.0	2.7	0.66	0.98	0.08
P_2O_5	0.76	0.96	0.13	0.27	0.04
SO_3	9.1	4.5	17.3	4.3	3.5
LOI	46.0	48.7	38.0	51.4	1.9

Several trends are evident in these data. As would be expected, the combustion sample (ID # 4330) differs in every respect from the gasification samples. Its physical properties show that it is coarser, much less cohesive, and has much less specific surface area than the char samples. Its chemistry also is quite different than those of the char samples.

Some distinctions and comparisons can also be made among the char samples. The least cohesive char is ID # 4327 (based on its uncompacted bulk porosity), which is also the coarsest of the chars that were characterized. Also in agreement with sample # 4327 being the coarsest of these chars, its specific surface area is lower than the other char samples analyzed.

The char samples generated in run P051 (ID #'s 4324 and 4325) are significantly finer than the chars generated in run P056 or run P057. These differences correlate with the uncompacted bulk porosities and specific surface areas of the chars from run P051, which are higher than the values measured for run P056 and run P057. Background information

describing these runs and the samples submitted for analysis was provided by Michael Swanson. The sample information data sheets provided by Mr. Swanson are presented in Appendix A. There were two primary differences between runs P051 and P056: There was no recirculation of dipleg solids during run P051, while dipleg solids were recirculated during all of run P056. This recirculation could have resulted in more carryover of coarse particles to the filter vessel. The second difference between these two runs was the fuels used. Wyodak coal was used throughout run P051 and for the first part of run P056. The second part of run P056 was fueled with Illinois #6 coal. (Bituminous coal from the SUFCo mine was used in run P057.) The differences in the fuels may be responsible for the measured differences in the size distributions and other characteristics of the chars produced in these runs. The size distribution of sample # 4326 has not yet been measured. This analysis should help isolate the cause of these observed differences, and will be performed in the near future. Also, the quantity of Plum Run dolomite used for sulfur control may have affected the size distributions of these particulate samples.[7]

It is also interesting to compare the characteristics of the char collected from the hopper during run P051 (ID # 4324) with the char collected from the filter cake on the candles after the run (ID # 4325). As has been observed in other filter vessels, the hopper material is coarser than the filter cake material; however, there is relatively little difference between the MMD's of these two samples. Although the relative fineness of these two samples would suggest that the filter cake char (ID # 4325) would exhibit a higher specific surface area and a smaller drag-equivalent diameter, this is not the case. The larger specific surface area of the char from the hopper compared with the value measured for the filter cake material agrees with the difference in the values of drag-equivalent diameter of these two samples. These data suggest that the coarsest particles in the hopper char sample are more irregularly shaped (rougher and less spherical) than the particles in the filter cake sample. This type of behavior has been observed before (with some AFBC ash particles). This trend suggests that the mechanisms producing the finer particles differ from those forming the coarser particles, and that the mechanism producing the finest particles creates smoother, more spherical particles than the mechanism responsible for the formation of the coarser particles.

As was done for ashes from the PSDF and Karhula, the size distributions of the two char samples from run P051 were compared to estimate the degree of settling in the filter vessel prior to formation of the filter cake. (This type of comparison should be valid if TRDU operation during the period when the hopper sample was obtained is comparable to the period of operation when the filter cake sample was formed. Because these two samples were reported to have been generated during steady state operation, this should be the case.)

The mechanism of selective continued entrainment described under the analyses of PSDF ashes would also apply to particles ejected from the filter cake during cleaning pulses. Individual char particles, or agglomerates of char particles with small enough settling velocities will reentrain in the flue gas and be recollected on the filter cake. Particles and agglomerates of particles with sufficiently high settling velocities will permanently leave the filter cake and settle into the hopper. This type of preferential settling of agglomerates may also affect the type of comparison and estimates described below. Other parameters that would affect the proportion of material settling out prior to filtration include inlet particle size distribution, face velocity, and candle geometry.

The measured size distributions of char samples collected during run P051 have permitted an estimate of the degree to which larger particles settle out in the TRDU filter vessel. Particles found in the TRDU hopper but not found in the filter cake char can be observed in the size distribution data obtained with a Microtrac Size Analyzer for these two samples (shown in Figures 22 through 24).

The differential size distribution data measured for the filter cake char have been scaled down by a factor of 0.673 to match the magnitude of the corresponding differential size distribution data measured for the hopper char. The two distributions coincide well up to a particle size just over 1 µm. (These data are presented on a basis of the fraction of the mass in the specified size range normalized by the change in the log of the particle diameters between the limits of the size range. No scales are presented for the ordinate axes in the differential size distribution plots shown in Figures 24 and 25 because of the scaling applied to the filter cake char data.) The factor of 0.673 applied to the filter cake char size distribution implies that during run P051 about 33 % of the mass of the entrained particles entering the filter vessel settled out prior to reaching the filter cake surface.

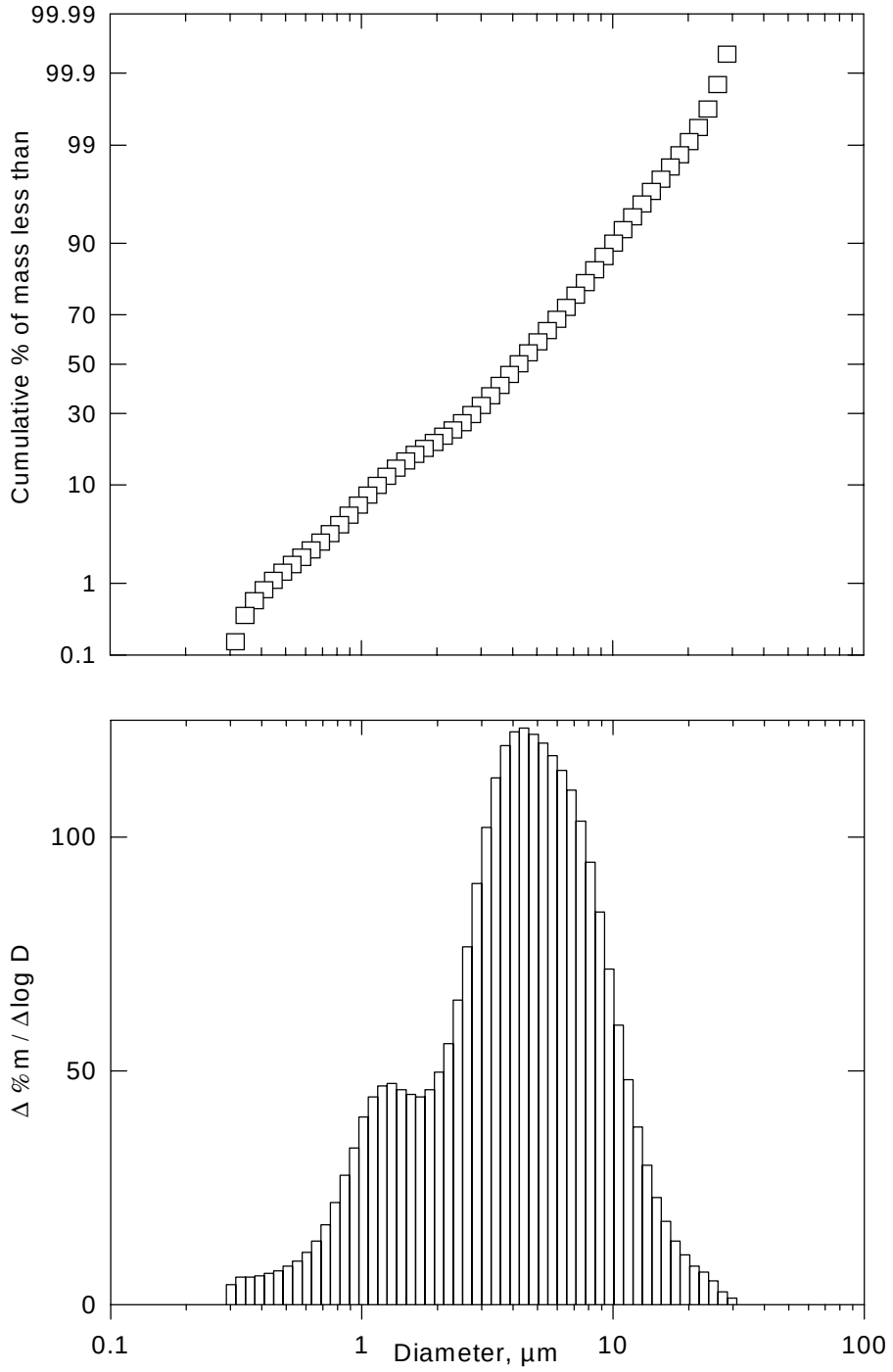


Figure 22. Cumulative and differential size distribution data for P051 filter hopper char (ID # 4324) measured with a Leeds and Northrup Microtrac Particle Size Analyzer.

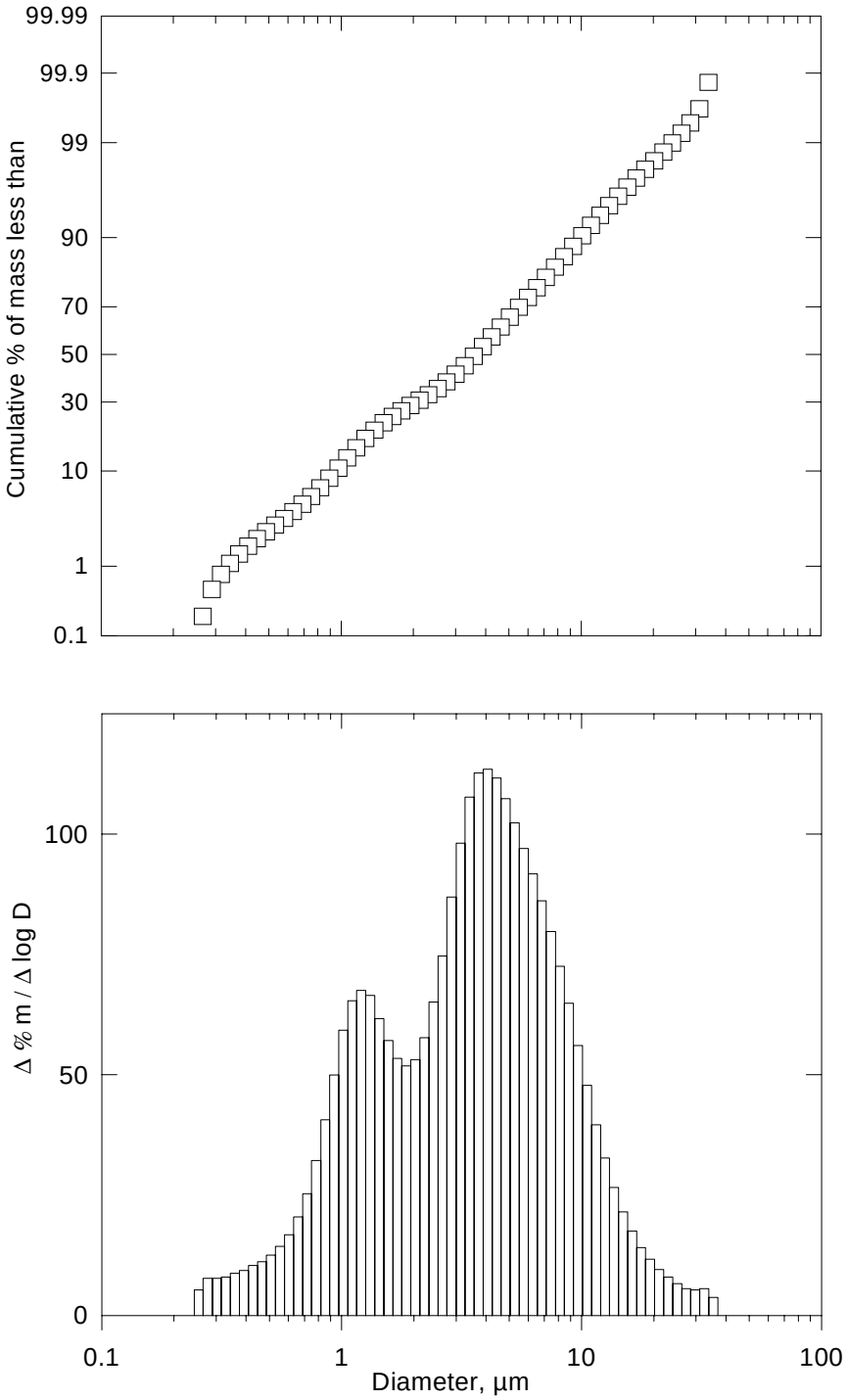


Figure 23. Cumulative and differential size distribution data for P051 filter cake char (ID # 4325) measured with a Leeds and Northrup Microtrac Particle Size Analyzer.

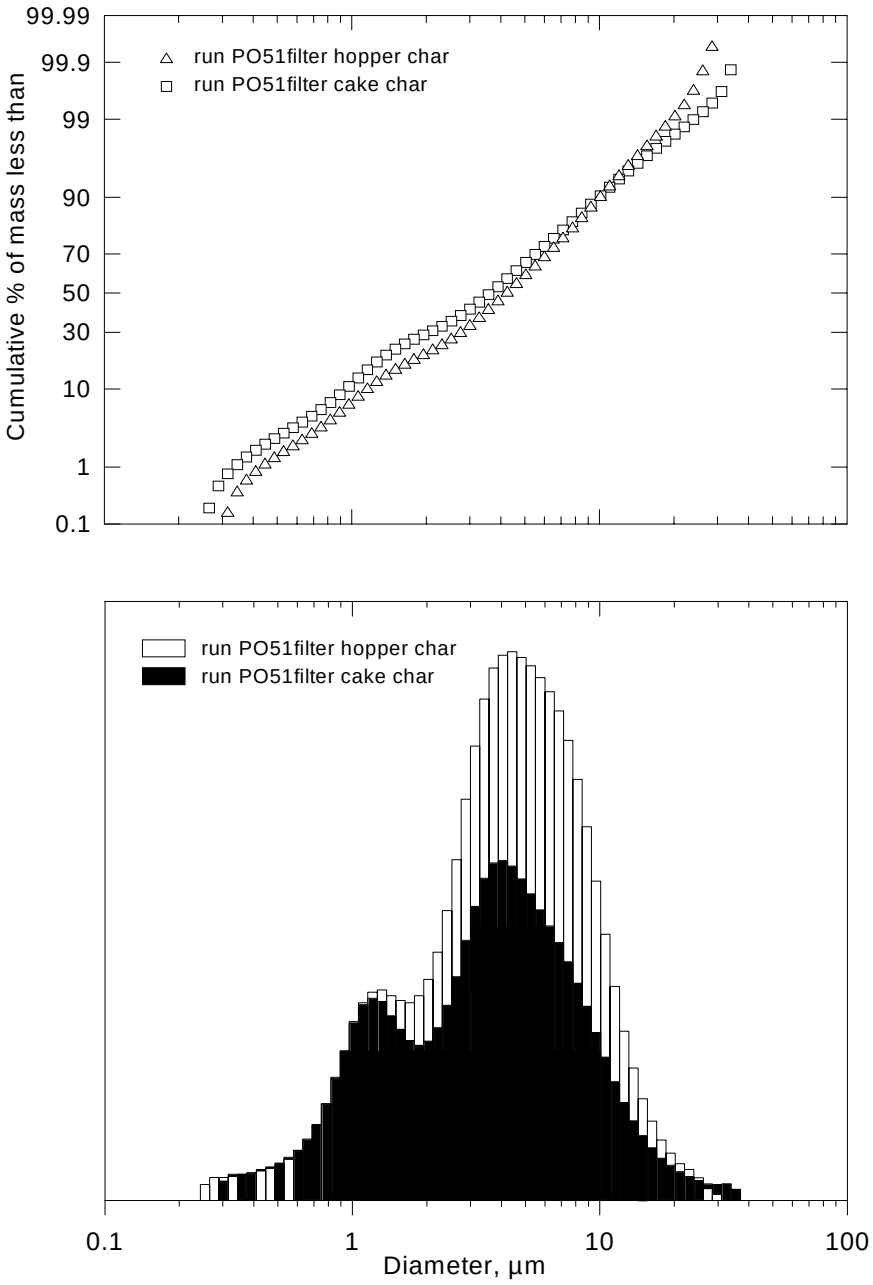


Figure 24. Cumulative and differential size distribution data for P051 filter cake char (ID # 4325) and filter hopper char (ID # 4324) measured with a Leeds and Northrup Microtrac Particle Size Analyzer. The differential data for the filter cake char in the lower graph have been scaled down by a factor of 0.673 to align the finest portion of its size distribution with that of the filter hopper char.

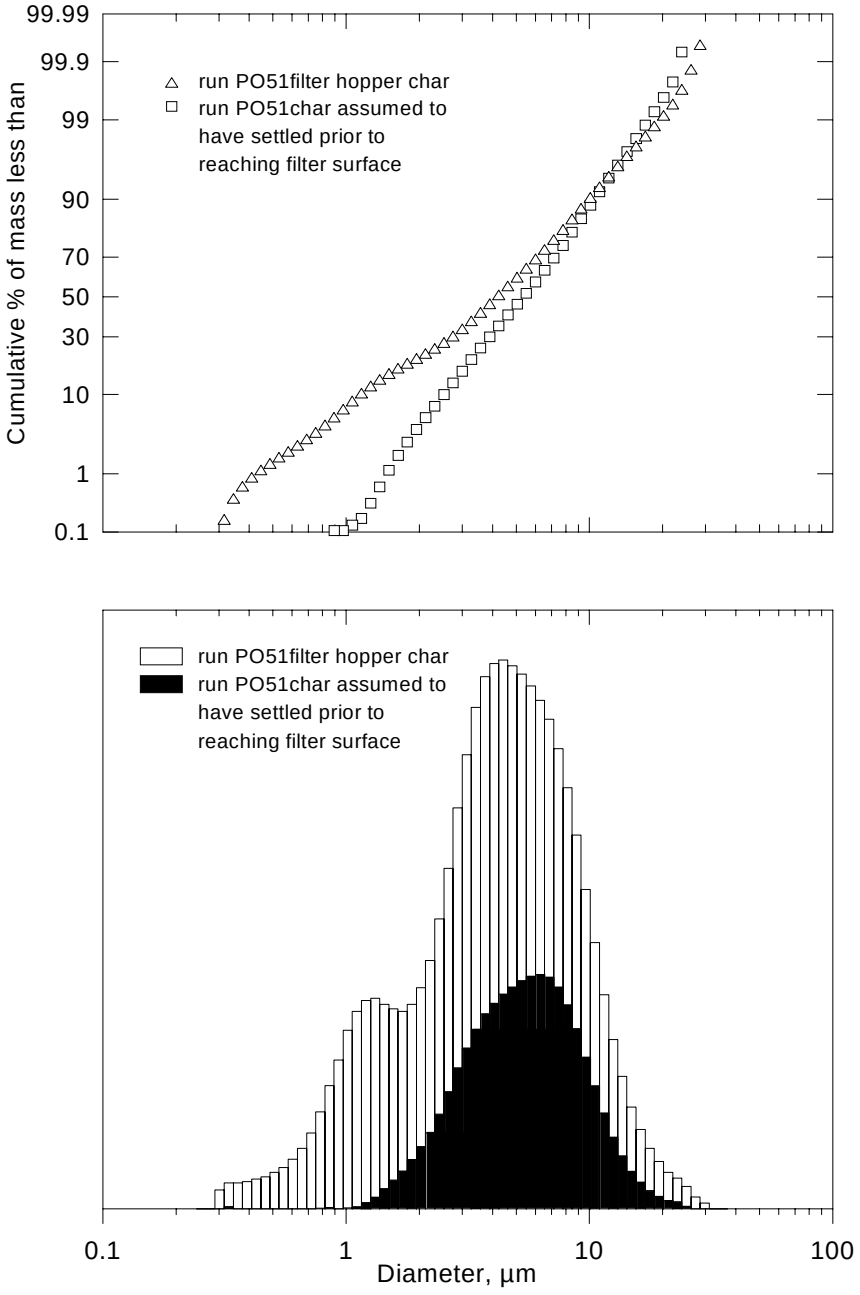


Figure 25. Cumulative and differential size distribution data for P051 filter hopper char (ID # 4324) and the portion of the char entering the filter vessel that is assumed to have settled out prior to reaching the surface of the candle filters. The calculation for assumed settling was derived from the comparison and scaling shown in Figure 24.

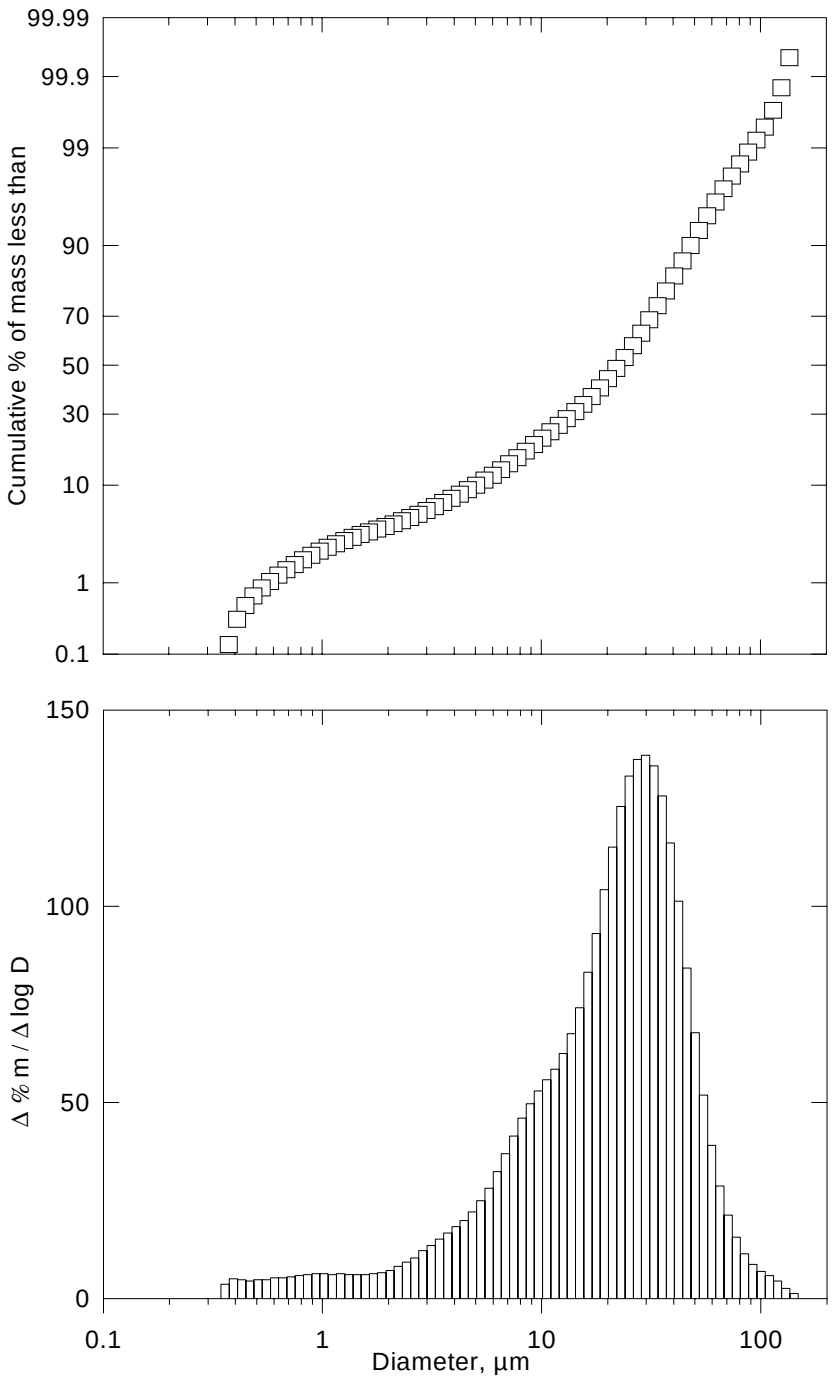


Figure 26. Cumulative and differential size distribution data for P056 filter hopper char (ID # 4327) measured with a Leeds and Northrup Microtrac Particle Size Analyzer.

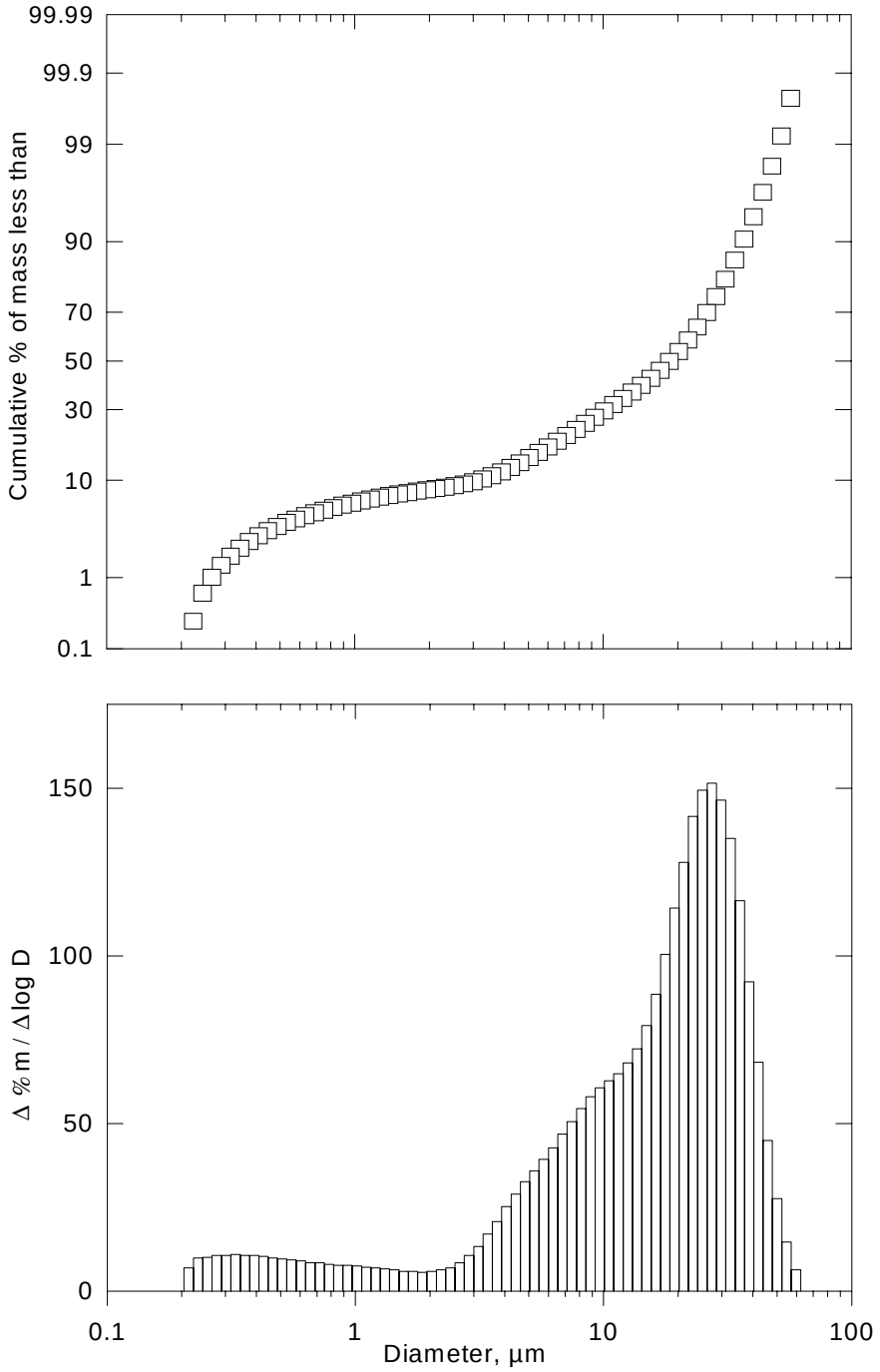


Figure 27. Cumulative and differential size distribution data for P057 filter hopper char (ID # 4329) measured with a Leeds and Northrup Microtrac Particle Size Analyzer.

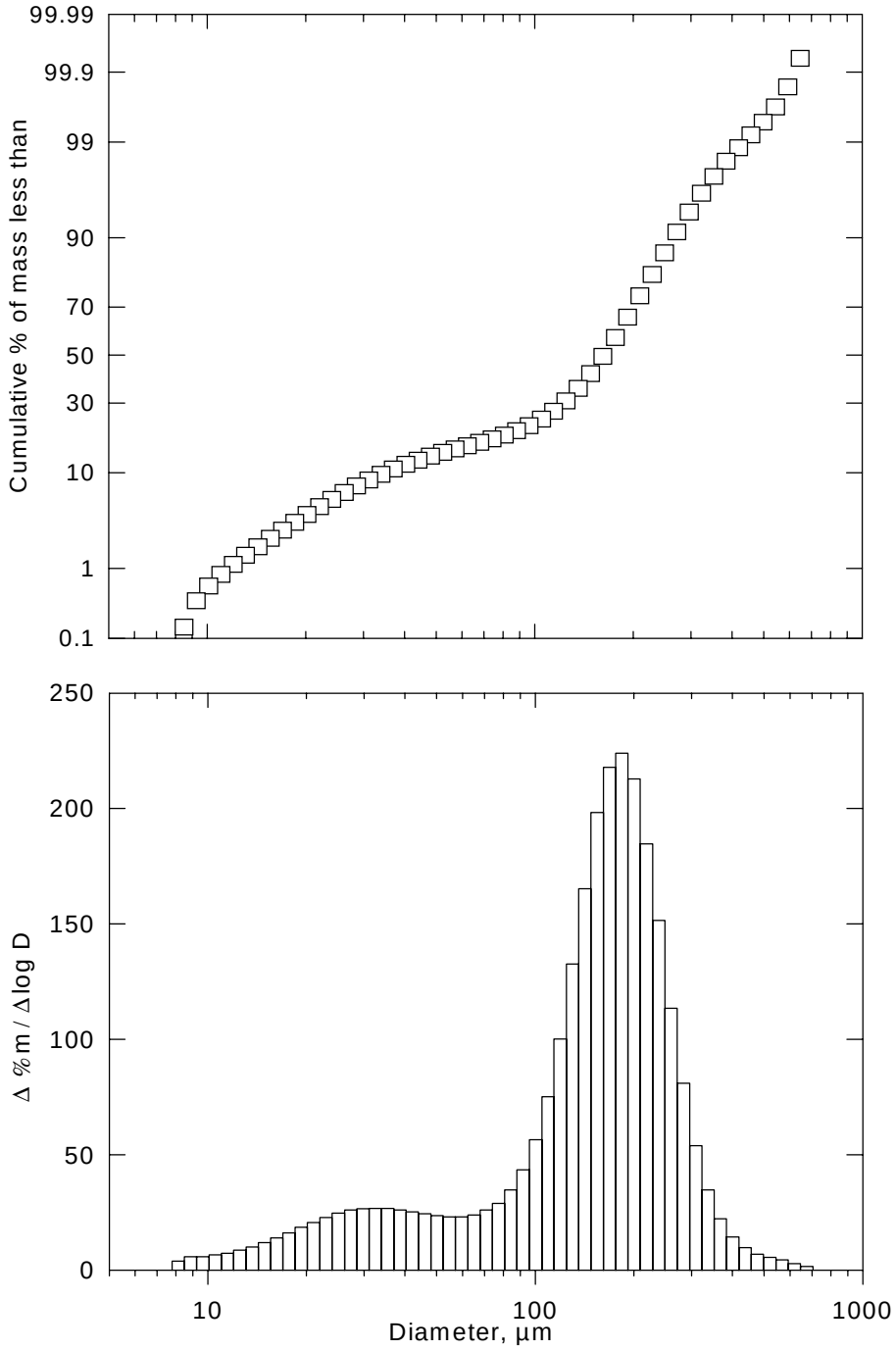
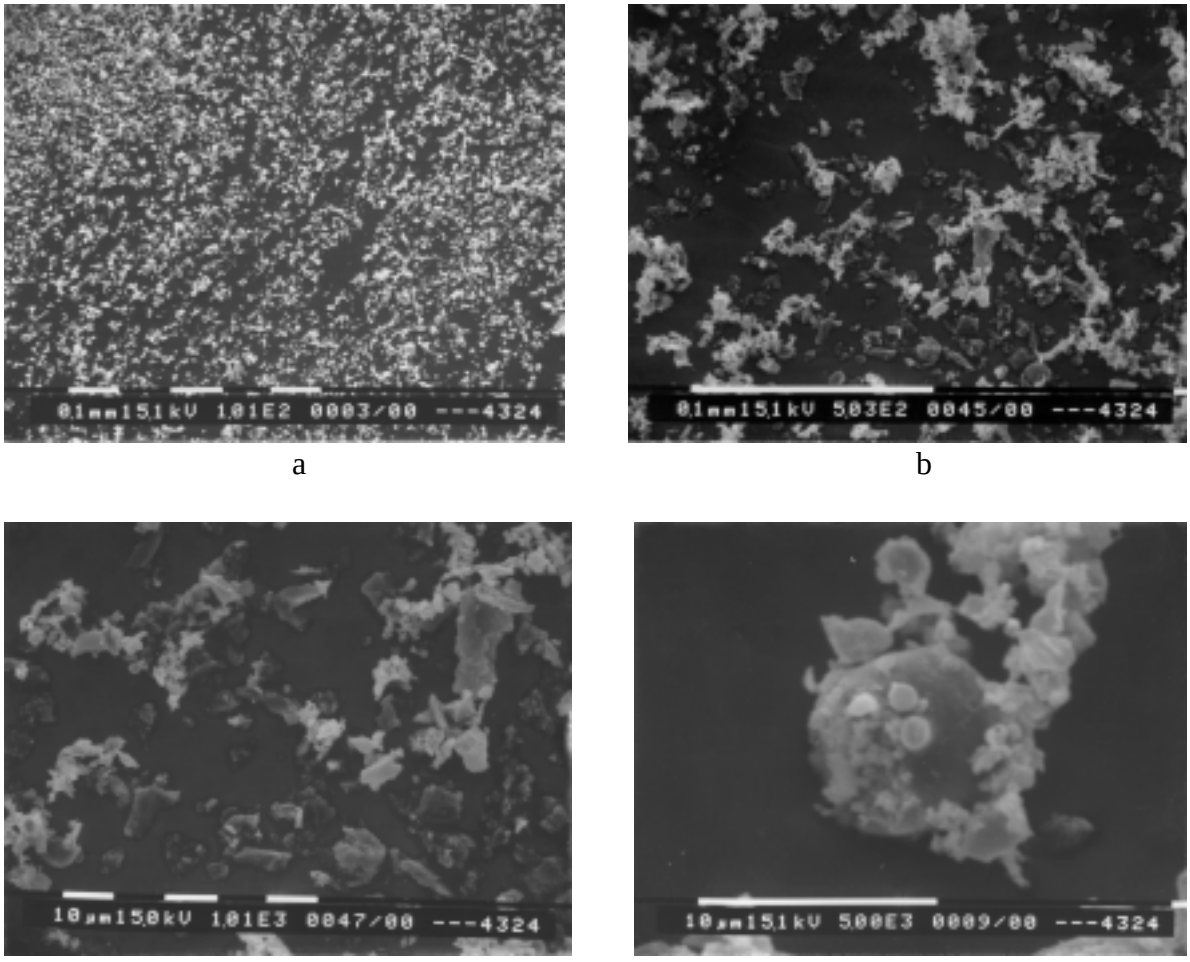


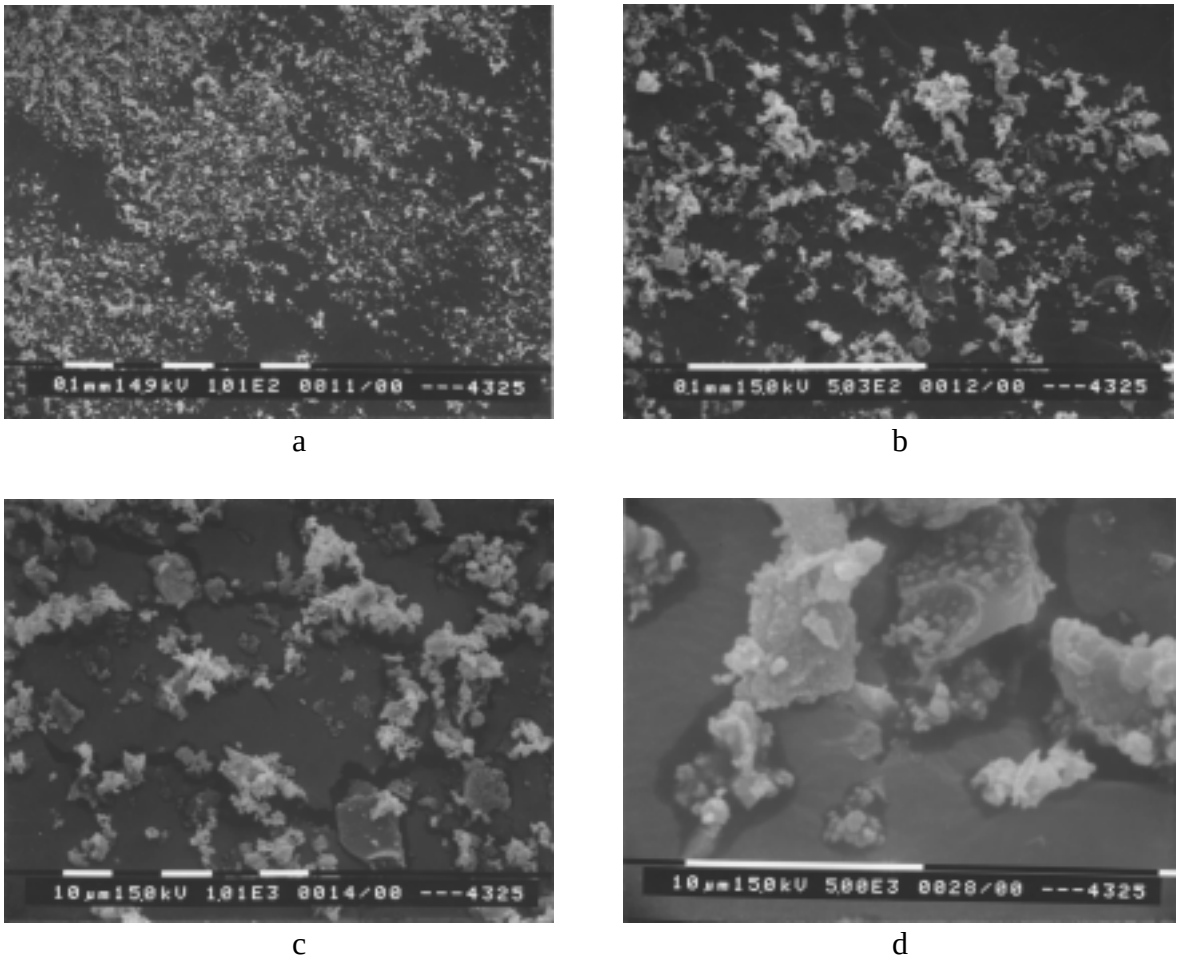
Figure 28. Cumulative and differential size distribution data for P058 filter hopper char (ID # 4330) measured with a Leeds and Northrup Microtrac Particle Size Analyzer.



a b

c d

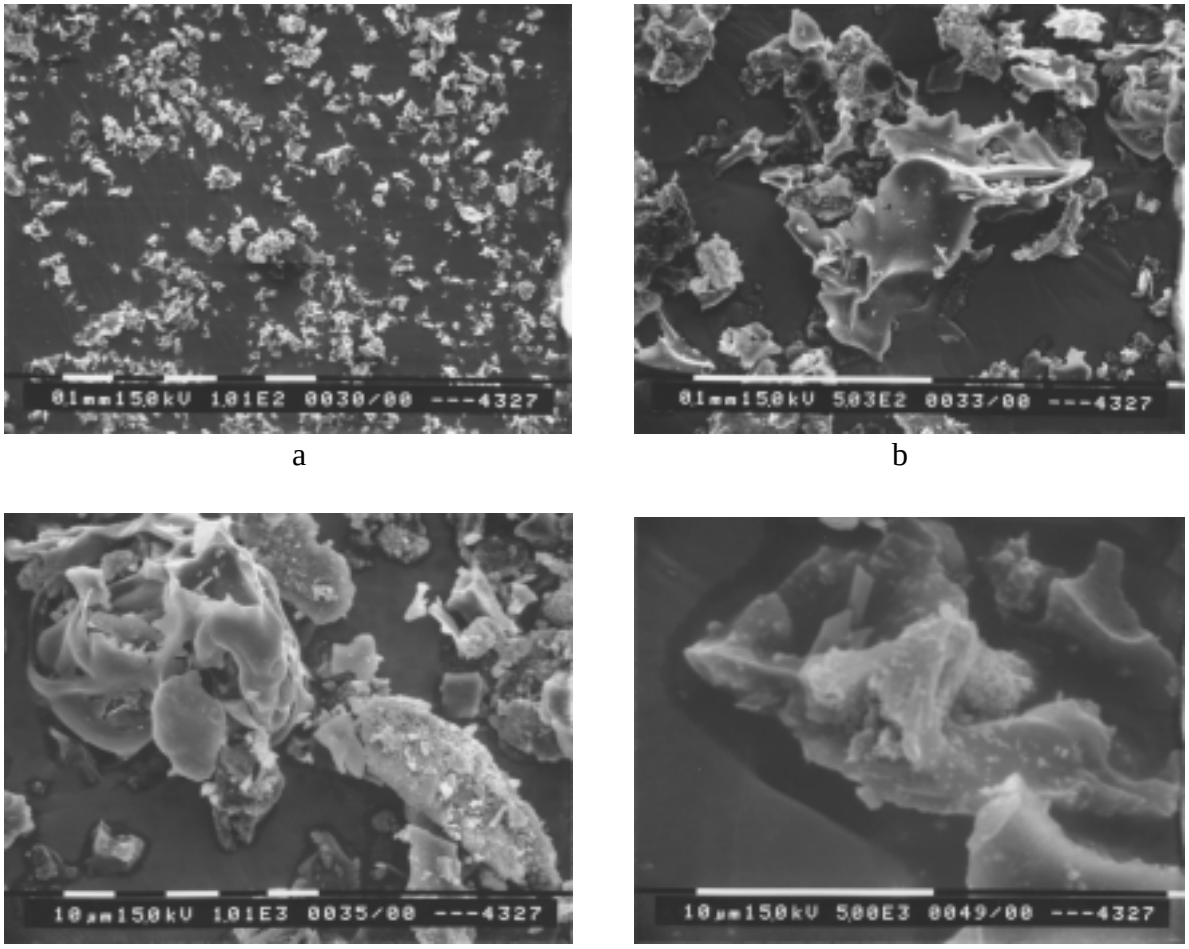
Figure 29. Representative Scanning Electron Micrographs of P051 filter hopper char (ID # 4324) taken at magnifications of a) 100x, b) 500x, c) 1000x, and d) 5000x.



a b

c d

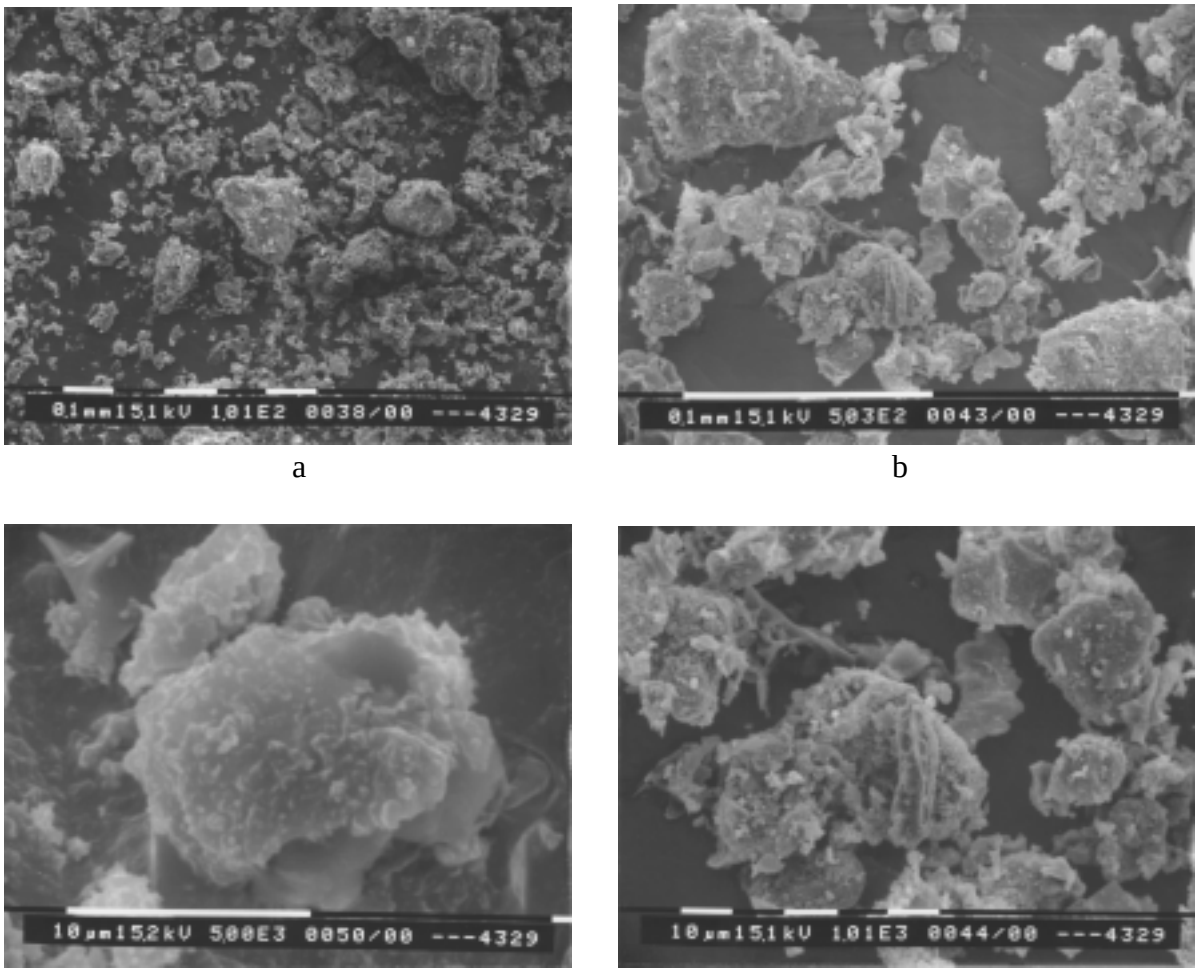
Figure 30. Representative Scanning Electron Micrographs of P051 filter cake char (ID # 4325) taken at magnifications of a) 100x, b) 500x, c) 1000x, and d) 5000x.



a b

c d

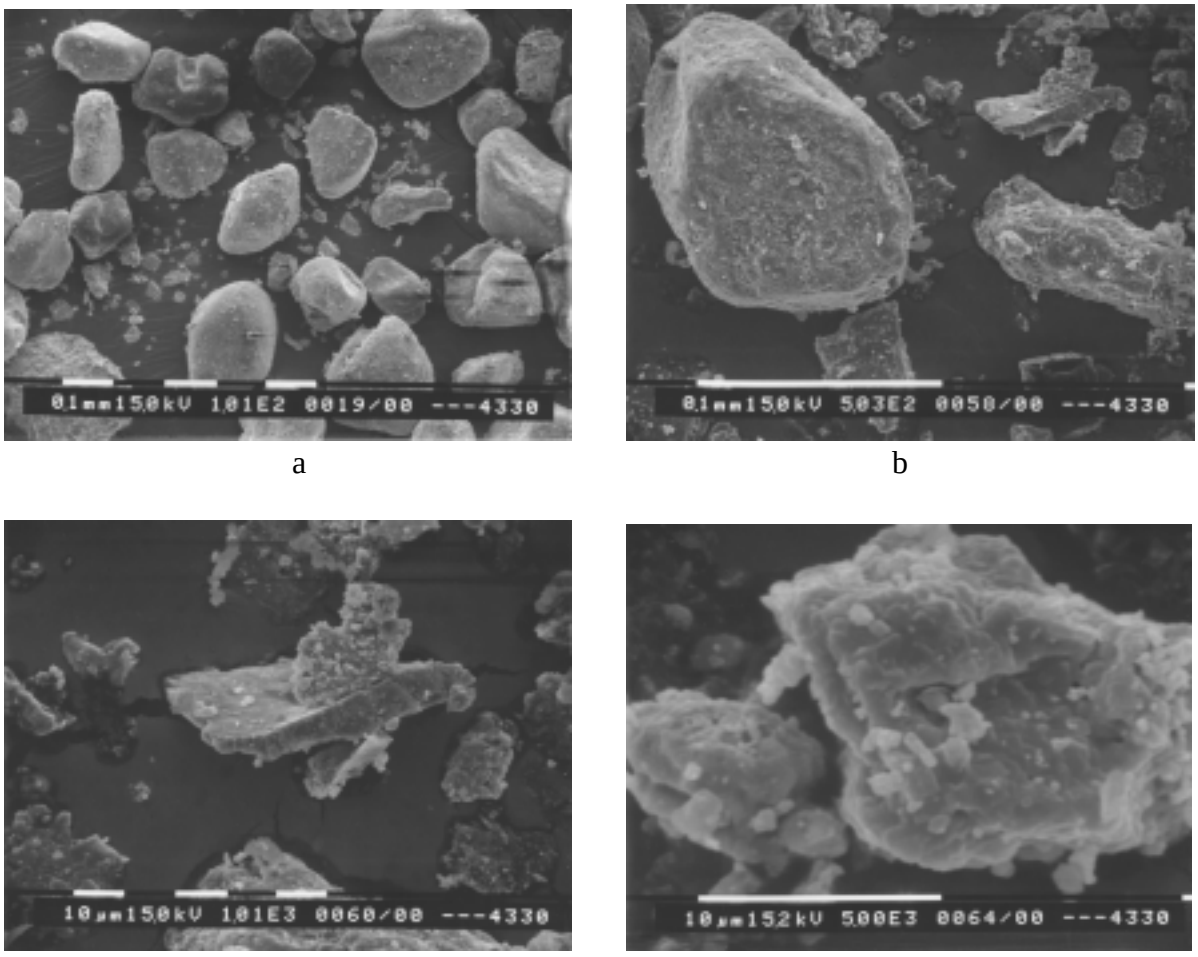
Figure 31. Representative Scanning Electron Micrographs of P056 filter hopper char (ID # 4327) taken at magnifications of a) 100x, b) 500x, c) 1000x, and d) 5000x.



a b

c d

Figure 32. Representative Scanning Electron Micrographs of P057 filter hopper char (ID # 4329) taken at magnifications of a) 100x, b) 500x, c) 1000x, and d) 5000x.



a b

c d

Figure 33. Representative Scanning Electron Micrographs of P058 filter hopper ash (ID # 4330) taken at magnifications of a) 100x, b) 500x, c) 1000x, and d) 5000x.

LABORATORY TECHNIQUES

REPRODUCIBILITY OF MEASUREMENTS

Several procedures were carried out to evaluate the techniques and applicability of the measurements of specific gas-flow resistance and uncompacted bulk porosity that have been made on many of the samples in the HGCU data base. Specific issues that have been addressed include reproducibility of measured values, the effect of non-uniform porosity of the sample in the permeability cell, and the applicability of permeability data measured at ambient pressure to filter cake behavior in the filter (at pressures of 10 to 15 bar). Measurements planned for the next quarter will determine the applicability of permeability data measured at ambient temperatures to the high-temperature conditions in the filter (1300 to 1650 °F). The review of the laboratory technique for measurement of uncompacted bulk porosity included reproducibility of measured values and the influence of screen mesh size.

To perform the laboratory measurement of the specific gas-flow resistance of a particulate sample, a known mass of the sample is loaded into the permeability cell and slightly agitated to induce a relatively uniform distribution of sample within the cell. The top of the sample is then smoothed with a flat disc. The sample is not compacted any further at this time. After noting the height of the sample, room air is drawn through the sample at three different flow rates (highest rate first). The pressure loss through the sample (and the sintered metal base of the cell) is recorded for each of these flows. Air flow is discontinued and the height of the sample is once again measured to detect any compaction of the sample by the pressure that resulted from the air flow. (This height is used for calculating the porosity of the sample at the time of the measurement of the pressure loss.) The sample is then slightly compacted with a flat disc and the process is repeated. In most cases, the permeability of a sample is measured at three different porosities.

After normalization of pressure drop by the face velocity of gas through the sample in the test cell and by the areal mass loading of the sample in the test cell (equation 1), calculations of drag-equivalent diameter values are accomplished by fitting the measured data to a permeability model of the form shown in equation 2.

$$R = \Delta p/(UW) \tag{1}$$

$$R = 10^8 \cdot (\mu/D^2) \cdot (1/\rho) \cdot [111-211\varepsilon+100\varepsilon^2]^2 \tag{2}$$

where:
- R = specific gas-flow resistance of the porous bed, μbar·sec·cm/g
- Δp = pressure drop across the porous bed, μbar
- U = face velocity of the gas through the sample in the test cell, cm/s
- W = areal mass loading of the sample in the test cell, g/cm^2
- μ = gas viscosity, poise
- D = drag-equivalent diameter of the sample, μm
- ρ = average true density of the sample particles, g/cm^3
- ε = porosity of the sample in the test cell, dimensionless ($0 < \varepsilon < 1$).

When this equation is converted to the English units commonly used in filtration, R is expressed in units of: in H_2O·min·ft/lb.

To determine the uncompacted bulk porosity of a sample, the sample is sifted through a 60-mesh screen (250 µm opening) into a wide, short, open-topped cylinder. The sample is sifted into the container until it is overflowing, and then the excess sample is scraped off, leaving the container completely full of sifted sample. The porosity of this sample is calculated from the weight of the sample, the volume of the container, and the true density of the sample particles.

Using the technique described above, replicate measurements were performed on one of the PSDF filter cake ashes obtained on January 20 (see Table 4 for more descriptions of this sample). The results of four repetitions of the measurement of specific gas-flow resistance are summarized in Table 22. The quantity $1/D^2$ is calculated and shown for each test because this is the value that enters directly into the equation 2 for the calculation of specific gas-flow resistance.

Table 22
Specific Gas-Flow Resistance Measurements of PSDF Filter Cake Ash (ID # 4294)

test point #	porosity, %	D, µm	$1/D^2$
1	77.4	2.155	--
1	70.9	2.348	--
1	67.6	2.376	--
point #1 average	--	2.293	0.1902
2	77.8	2.271	--
2	72.2	2.363	--
2	67.6	2.409	--
point #2 average	--	2.348	0.1814
3	76.4	2.237	--
3	69.9	2.353	--
3	67.9	2.338	--
point #3 average	--	2.309	0.1876
4	76.4	2.182	--
4	72.2	2.340	--
4	67.8	2.374	--
point #4 average	--	2.299	0.1892
overall average	--	2.312	0.1871

The data shown in Table 22 indicate that the laboratory technique used for the measurement of specific gas-flow resistance provides consistent values of drag-equivalent diameter.

Four replicate measurements of uncompacted bulk porosity were performed on sample ID # 4294. Two measurements of uncompacted bulk porosity were also performed on this same sample using a 325-mesh screen (45 µm opening). These measurements are summarized below.

Table 23
Uncompacted Bulk Porosity Measurements of PSDF filter cake ash (ID # 4294)

trial #	UBP, % (60-mesh screen)	UBP, % (325-mesh screen)
1	83.6	87.5
2	83.6	87.8
3	83.9	--
4	85.0	--
average	84.1	87.6

The data in Table 23 indicate, that as with the measurements of specific gas-flow resistance, the technique for determination of uncompacted bulk porosity yields reproducible values. (The influence of mesh size on uncompacted bulk porosity is discussed later in this report.)

EFFECT OF NON-UNIFORM DUST CAKE POROSITY ON GAS FLOW

In measuring the permeability of a sample of dust it is sometimes tacitly assumed that the sample is reasonably homogeneous. To examine the effects of an inhomogeneous spatial distribution of porosity in a test apparatus, some simple, but relatively extreme cases can be examined by calculation. In the following discussion gas flow resistance is compared in three cases (see Figure 34). Common among the three cases are the total mass of the sample, and its total volume. Also, the total cross-sectional area A and the total thickness H are held the same for all three cases. In the first example the sample is a single homogeneous disc, as might be used in a permeability cell. In each of the other two examples the dust is divided into three domains of different porosity. In one, the domains are arranged such that the gas flows through the three separately (in parallel), and in the other, the gas passes sequentially through three layers (in series).

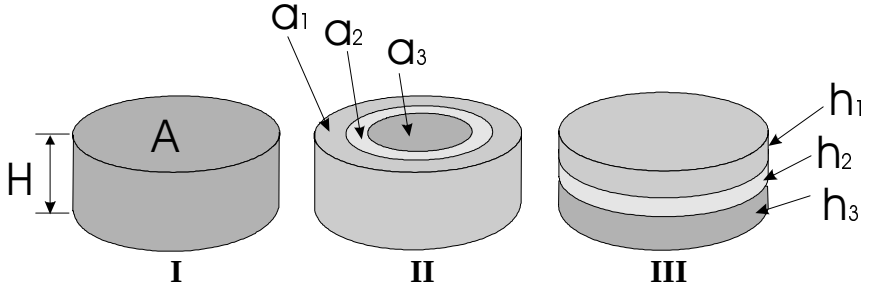


Figure 34. Configurations for dust samples.

The first sample is a straightforward application of gas flow through a uniform, homogeneous dust layer of thickness H. The cross-sectional area A is bounded at the cylindrical surface, so that the gas flow is all along a direction normal to the surface A. This condition is similar to that of a sample in a cylindrical permeability cell. The normalized gas flow resistance R is the ratio of the pressure drop p to the gas volume flow rate per unit area q/a for unit dust cake loading λ =m/A (mass per unit area of dust cake).

$$R = \left[\frac{p}{q/A}\right]\frac{1}{\lambda} \tag{3}$$

Given porosity ε and particle density ρ, the mass is simply m = ρAH(1-ε), and λ = ρH(1-ε), and

$$R = \frac{Ap}{q\rho H(1-\varepsilon)} \tag{4}$$

Defining r_h, the resistance of a specific homogeneous sample, as the ratio of pressure drop to total gas volume flow rate gives

$$r_h = \frac{p}{q} \tag{5}$$

$$= \frac{RH}{A}\rho(1-\varepsilon) \tag{6}$$

In the second sample, there are three parallel regions. The flow rate through each region is q_i (i =1,2,3) the gas flow resistance for each is r_i, and the cross-sectional area of each is a_i. Since the pressure drop P across the cell must be the same for all parts of the cell, then $P = q_i r_i$. The total gas flow Q must be the sum of the q_i, so

$$Q = \sum_i \frac{p_i}{r_i} \tag{7}$$

$$= \frac{P}{H\rho}\sum_i \frac{a_i}{R_i(1-\varepsilon_i)} \tag{8}$$

The gas flow resistance r_p for the sample is the ratio of P to Q, which results in

$$r_p = \left[\frac{1}{H\rho}\sum_i \frac{a_i}{R_i(1-\varepsilon_i)}\right]^{-1} \tag{9}$$

In the third sample, the flow rate through all three layers must be the same ($Q = q_i$), but the pressure drop p_i across each is defined by $p_i = Q r_i$. The total pressure drop is the sum of the p_i, so

$$P = Q\sum_i r_i \tag{10}$$

and r_s is simply

$$r_s = \frac{1}{A}\sum_i h_i r_i \rho(1-\varepsilon_i) \qquad (11)$$

Example:

In the following simple illustration, only three different regions are used for cases two and three. For consistency, the overall porosity and the overall dimensions are required to be the same for all three cases. A porosity ε = 85%, yields R = 4.43 for the homogeneous case, as noted above. The following values agree with this condition.

Table 24
Assumed Distributions of Volume, Mass, and Porosity
for Series and Parallel Examples (Configurations II and III in Figure 34)

i	v_i	ε_i, %	m_i	R_i	a_i	h_i
1	0.25V	82	0.30M	7.94	0.25A	0.25H
2	0.50V	85	0.50M	4.43	0.50A	0.50H
3	0.25V	88	0.20M	2.22	0.25A	0.25H

In this table, v_i is the volume of the i^{th} region in terms of the total volume V, and m_i is the mass of the i^{th} region in terms of the total mass M.

Based on these distributions of volume and mass (and consequently, porosity), the relative values of normalized flow resistance in these three cases can be calculated and expressed as:

$$r_h = 0.665\frac{H\rho}{A},$$

$$r_s = 0.756\frac{H\rho}{A}$$

and

$$r_p = 0.536\frac{H\rho}{A}.$$

The relative values of normalized flow resistance in these three cases can also be expressed as:

$$r_s = 1.14 r_h$$

and

$$r_p = 0.81 r_h.$$

Therefore, these calculations demonstrate that even in the two extremely non-uniform cases described above, the overall effect of non-uniformity of porosity in the permeability cell is not too severe. The series-type non-uniformities would tend to overestimate the flow resistance of a uniform sample, while the parallel path-type uniformities would tend to

underestimate the flow resistance of a uniform sample. In fact, because the types of non-uniformities that would most likely be encountered in a prepared sample in the cell would combine parallel and series path effects, these effects would tend to mitigate each other, and the overall value measured would probably quite closely approximate the flow resistance of a uniform sample. Additionally, because every effort is made to load the permeability cell uniformly in preparation for the laboratory measurement, the poor distribution of porosity assumed for the series and parallel-path cases probably represent worst-case boundaries for the technique.

EFFECT OF SCREEN MESH SIZE ON UNCOMPACTED BULK POROSITY

The uncompacted bulk porosity of a sample is one of the estimates that has been used for filter cake porosity when no direct measurements on existing filter cakes can be made. Although there is some evidence to suggest that uncompacted bulk porosity may slightly overestimate or underestimate filter cake porosity (see Table 8), it is also useful for ranking sample cohesivity, and still may be a component of any eventual model for estimating filter cake porosity from bulk sample characteristics measured in the laboratory. The technique that is currently used for measuring uncompacted bulk porosity has been described above, and uses a 60-mesh screen (250 µm opening) to break up large agglomerates and establish uniformity of the sample. However, it is reasonably certain that many relatively large agglomerates still exist in the sample after it has passed through the 60-mesh screen. Therefore two measurements of uncompacted bulk porosity were made using a 325-mesh screen with openings of 45 µm. Although these smaller openings still allow agglomerates of particles to pass through, the overall porosity of the sample deposited in the wide, short, open-topped cylinder was expected to depend on the size of the screen openings.

The data in Table 23 demonstrate that using the 325 mesh screen generated consistent results; however, the average value of uncompacted bulk porosity measured (87.6%) was significantly greater than the average value determined using the 60 mesh screen (84.1%). These data may be useful in designing a procedure for more accurately estimating filter cake porosity from bulk sample characteristics measured in the laboratory.

PERMEABILITY AS A FUNCTION OF GAS PRESSURE

The ultimate value of a laboratory determination of the specific gas-flow resistance of a sample is in estimation of, or comparison to, operating data from high-temperature, high-pressure HGCU filters. The gas laws governing the actual volume of a gas as a function of temperature and/or pressure are well established. However, most of the filtration theories describing the pressure losses generated as a known actual volume of gas passes through a porous bed are at least partly derived from empirical data, which is usually obtained from ambient pressure and ambient temperature measurements. Because the conditions in HGCU filters differ significantly from ambient conditions, two experiments were designed to verify the effects of absolute gas pressure and gas temperature on the permeability of a particulate sample.

To determine whether all changes in the specific gas-flow resistance of a particulate sample measured at two widely different absolute pressures could be entirely explained by

differences in actual gas volume, the device shown in Figure 35 was constructed. To perform the measurements of specific gas-flow resistance, the permeability cell located in the pressure vessel was loaded with PSDF filter cake ash (ID # 4294). The ash in the cell was thoroughly compacted to prevent cracks from developing in the ash sample. (Cracks can develop in the sample in the permeability cell if the sample is highly porous, and/or if the pressure drop across the sample is too great. If cracks form in the sample, the test must be aborted and the sample reloaded.) To induce flow through the sample, the pressure in the vessel was increased to 24.7 psia. At this vessel pressure, the pressure drops across the ash sample and across the orifice were measured. The vessel pressure was then increased to 164.7 psia. (This was the highest pressure that could be obtained with the gas regulator.) The flow through the sample was adjusted to provide the same pressure loss across the orifice that was observed at an absolute vessel pressure of 24.7 psia. The temperature monitors in the device verified that no corrections for gas volume resulting from temperature differences were necessary. Therefore it was possible to directly compare the ratio of the two absolute vessel pressures with the ratio of the two pressure losses across the ash sample at the two absolute vessel pressures. These two ratios agreed within 6 %. Other runs made with the device yielded similar results. Therefore, no significant correction to permeability measurements made at ambient pressures (other than correction for actual gas volume) need to be performed to apply these permeability data to filter cakes in high-pressure environments. If needs arise to investigate the effects on permeability of higher absolute pressures than were tested in these experiments, a gas regulator with a higher range can be purchased, and additional measurements can be made.

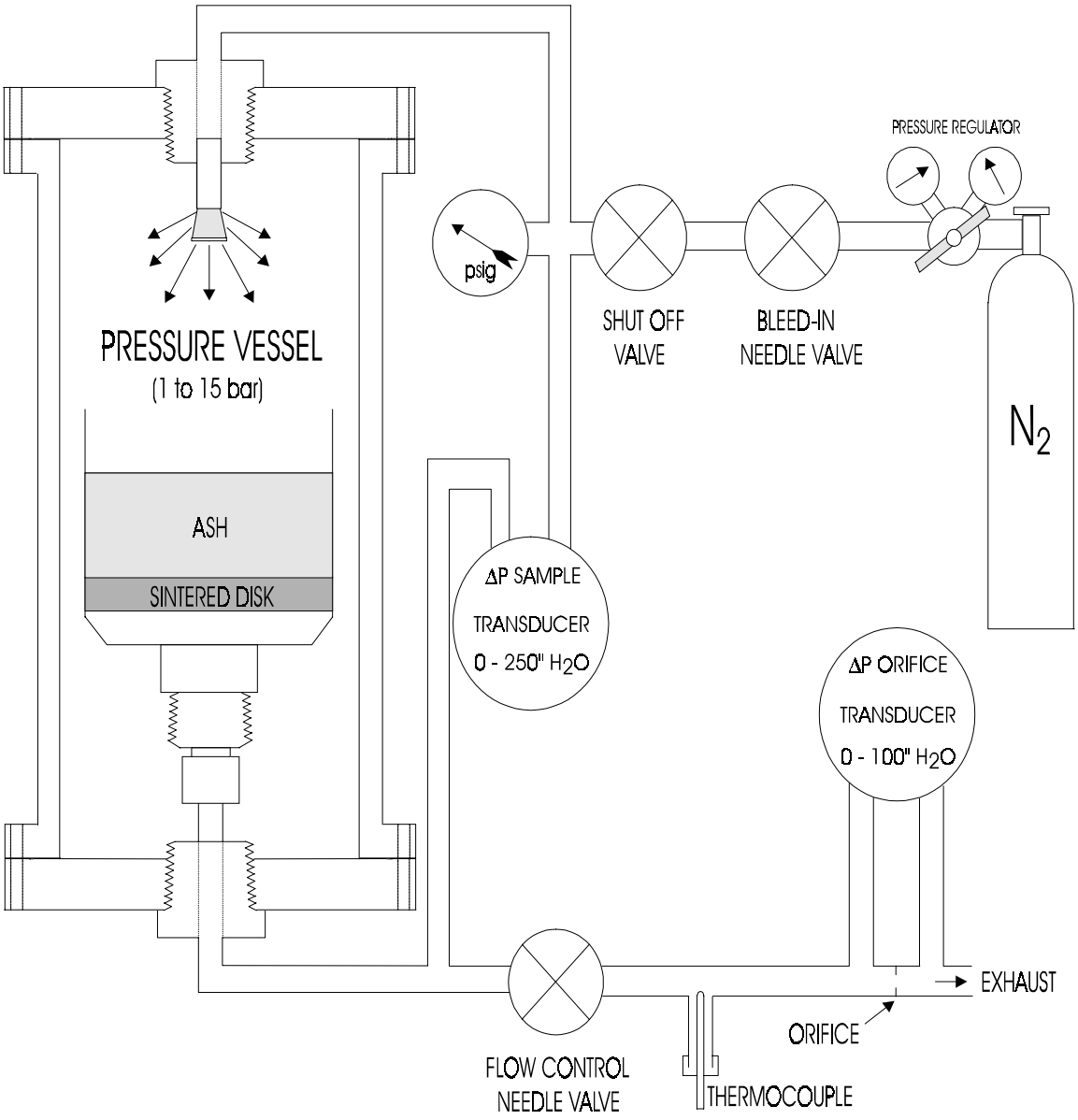


Figure 35. Schematic diagram of a setup for evaluating the effect of absolute gas pressure on the specific gas-flow resistance of a particulate sample.

DEVELOPMENT OF A TECHNIQUE FOR PRESERVATION OF FILTER CAKES

Filter cakes that have been observed on-site at the PSDF (and other facilities) are quite fragile. Although relatively strong nodular deposits obtained at the Tidd PFBC were successfully encapsulated and preserved for analysis by the infiltration of low-viscosity epoxy, efforts to apply this epoxy to more fragile cakes has resulted in their destruction. Therefore, laboratory experiments were undertaken to develop a method to strengthen these fragile cakes prior to the introduction of the low-viscosity epoxy. To develop this method, a loosely sifted sample of PFBC ash was placed on a paper filter substrate. This sample was placed in a bell jar and the jar was flushed with dry nitrogen. Then a tub of low-viscosity cynoacrylate glue ("super glue") that had been placed on a hot plate in the bell jar was heated to a range of 232 to 280 °F to induce production of super glue vapor. A vacuum pump was then used to draw this vapor thorough the loosely packed PFBC ash sample. After about 45 minutes the experiment was discontinued and the sample withdrawn for examination. The passage of vapor successfully hardened the sample although the sample was still quite porous. The passage of vapor through the sample did not appear to alter its structure. Although there are plans to verify the ability of this sample to absorb low-viscosity epoxy, it is expected that impregnation with epoxy should be successful.

In preparation for the hardening of a significant portion of a filter cake while still on its filter element substrate, a preliminary design of a laboratory apparatus has been prepared (Figure 36). When this device is fabricated, it should allow the bottom 8 to 14 inches (and possibly more) of a filter cake formed on a candle filter element to be preserved intact. After strengthening the cake, the entire lower portion of the filter element (candle and cake) will gradually be impregnated with epoxy. (This must be done in relatively thin layers, to allow proper curing of the epoxy.) Following encapsulation, sectioning, and polishing, fully encapsulated filter cake/filter element specimens should be available for distribution and analysis. If this technique is successful for PFBC filter cake preservation, there is every expectation that it will also be effective for preserving gasification filter cakes.

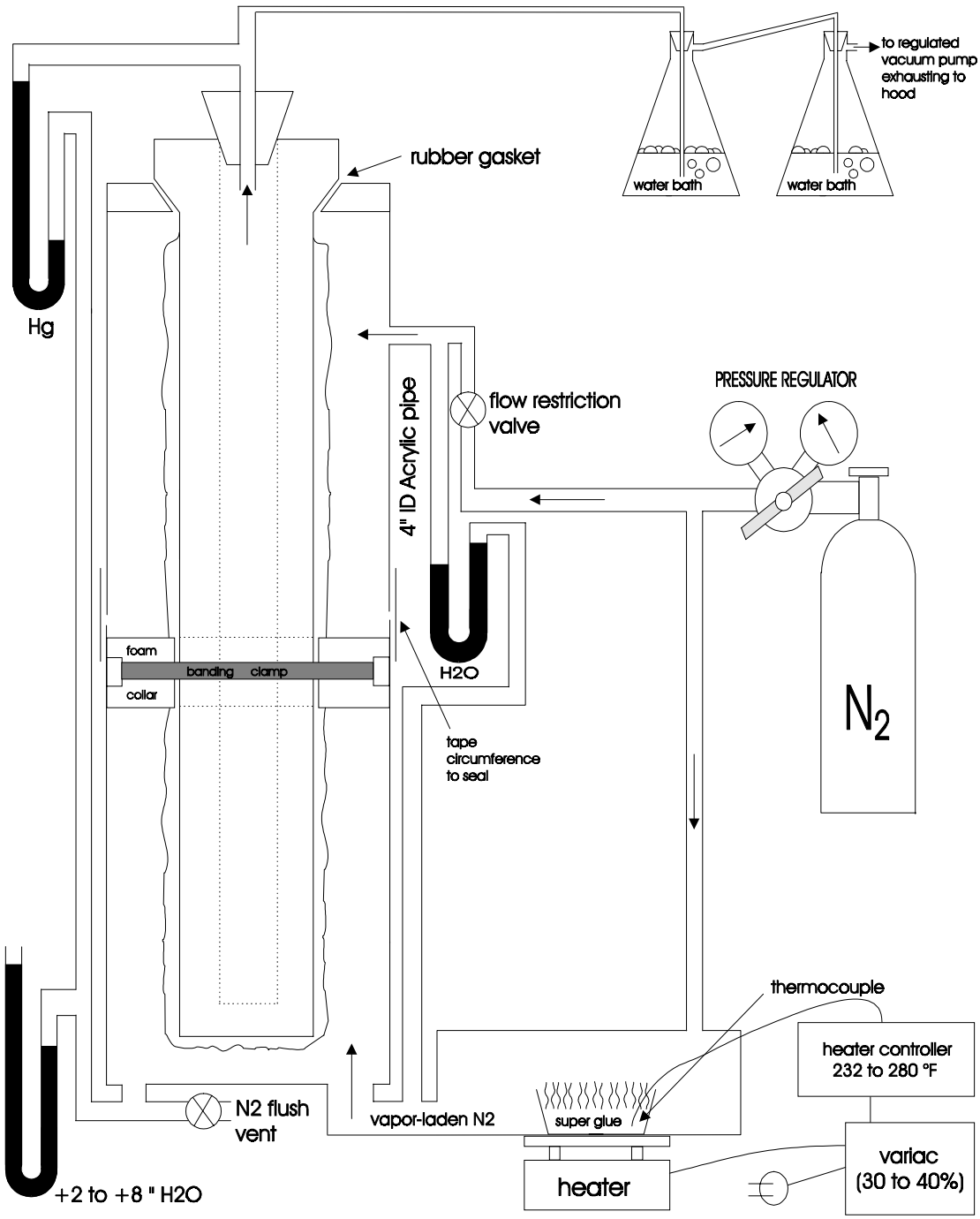


Figure 36. Schematic diagram of a device for using cynoacrylate glue to strengthen filter cakes formed on a candle filter element in preparation for subsequent impregnation and encapsulation with low-viscosity epoxy.

ASH DATA BANK DEVELOPMENT

To date, Southern Research Institute has analyzed about 158 of the 358 particulate samples that have been collected from fifteen advanced generation or developmental power systems:

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

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

The data bank is structured about Microsoft Access 97®. Current plans call for a run-time version of Microsoft Access to be included with the data bank. The arrangement of information in the data bank allows the user to review a variety of information including photographs, scanned images, plots, figures, text, and numerical values. To facilitate

presentation of this wide variety of data formats, the data bank utilizes Adobe Acrobat® PDF (portable document format) files at various points in its construction. Therefore, software to install Adobe Acrobat Reader® is included with the data bank. Minimum system requirements for running the data bank are an IBM-compatible PC with a Pentium processor or higher, Microsoft Windows 95® or Windows 98® operating system, 16 megabytes of RAM, a 4X or faster CD-ROM drive, and a video card configured for a 1024 by 768 display with a minimum of 256 colors.

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

If the user has chosen to examine data and samples for specific facilities, a screen is displayed which permits the user to select one of the fifteen HGCU facilities to examine in detail. Once a facility has been selected, the data bank lists the primary participating organizations and principal contact personnel for the facility. The user can then select and review one of the six categories listed: brief description of the facility; process schematics; plant photographs; technical references; on-site inspections; or particulate sample analyses. Under the first category, brief descriptions, up to two pages of text, are provided for each of the facilities in the data bank from which the various particulate samples were obtained. Series of process schematics and plant photographs can be scrolled through by selecting the second or third category. Examples of the screens that are used to display process schematics and plant photographs are shown in Figures 37 and 38. The fourth category provides the user with references to more detailed information about the facility. The category for on-site inspections contains information gathered during filter inspection and sampling trips made by Southern Research Institute personnel. Information in this category covers four site visits to the Tidd PFBC, one visit to the MGCR at Morgantown, and five inspection and sampling trips to the PSDF. After the user selects a particular site visit to review, the data bank provides a brief summary of the condition of the filter, the sampling procedures and the particulate samples obtained, and some of the key data obtained during the visit. A series of photographs of the filter cakes and ash deposits observed during the visit can also be reviewed.

When the user wishes to review the analyses of samples obtained from a particular facility, a scroll-down list of the samples is displayed. Included with this listing are brief descriptions of the samples, and where and when they were obtained. Because not all of the samples archived in the data bank have been analyzed, this list will indicate which of the samples in the data bank have been tested. This screen is shown in Figure 39. After a sample is selected to examine in detail, a screen is displayed that summarizes the physical and chemical analyses that have been performed on that sample. Figure 40 presents this screen display for one of the Tidd samples. Physical attributes that have been measured and are included in this display include median particle size, specific surface area, particle morphology, bulk ash cohesivity, permeability, and tensile strength. This screen also provides access to scanning electron micrographs of many of the samples in the data bank. In general, these micrographs were obtained and can be viewed at four different magnifications. Chemical analyses of the selected sample are also summarized on this screen. Some of the samples collected which have unusual histories or unique characteristics have been analyzed with special techniques. When special analyses have been performed on the selected sample, the results of these analyses can also be accessed from this screen. This screen also provides a direct link to descriptions and explanations of the various analyses used to characterize the samples.

Each screen shown during operation of the data bank offers the user the option of exiting the program. When this option is selected, a final screen is displayed which credits the various organizations and individuals that made significant contributions to the data bank. Acquisition of particulate samples and analyses of their physical and chemical characteristics is an ongoing process. Therefore information will be added to the data bank throughout the duration of this project. The HGCU data bank is a final deliverable under this project. The option of placing the data bank on DOE/FETC's world-wide web home page will be investigated as the data bank and the project near completion.

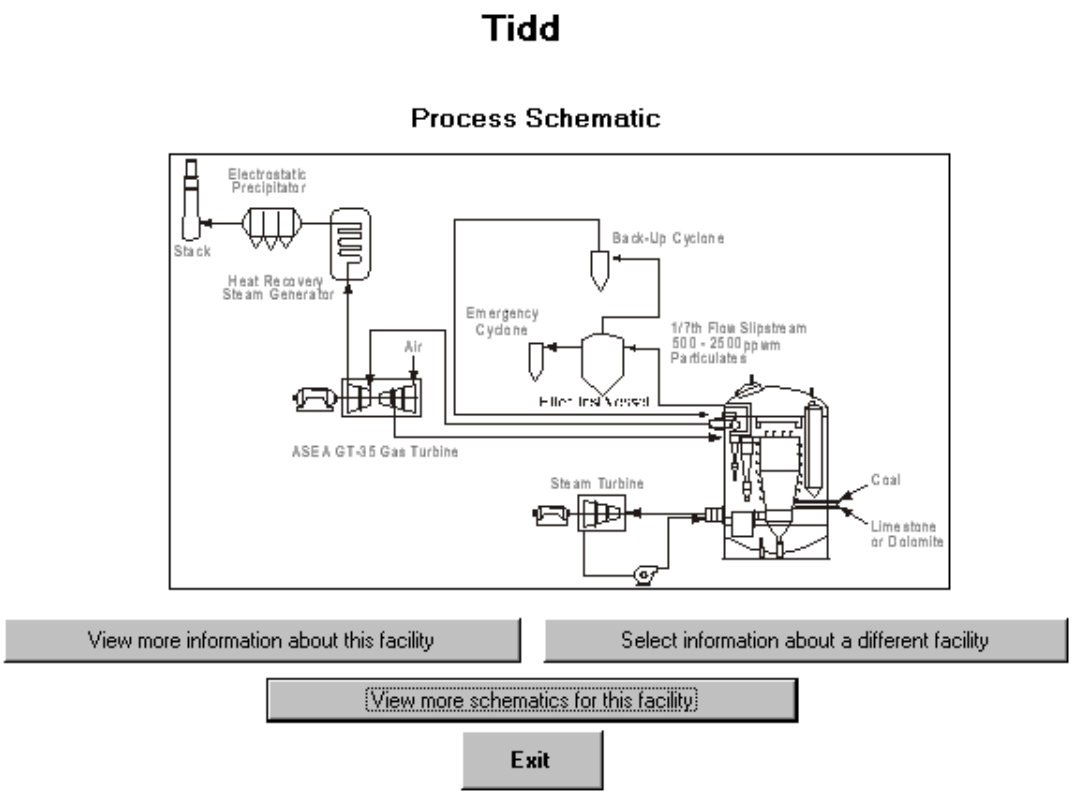


Figure 37. Example of the screen used to display process schematics.

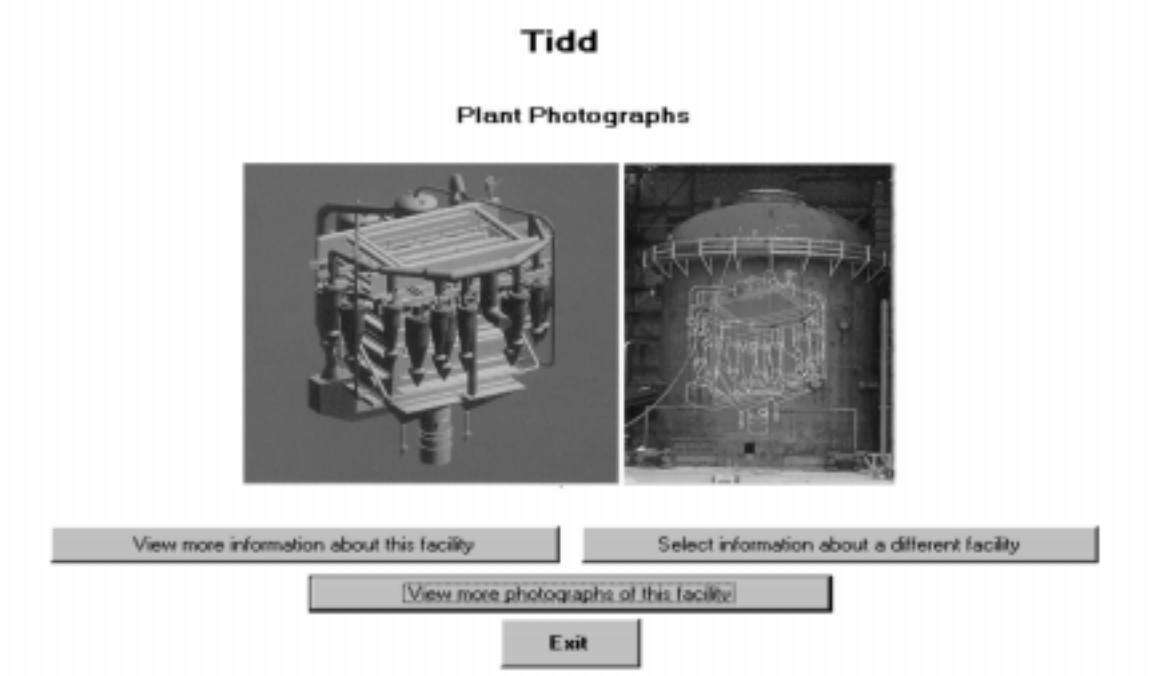


Figure 38. Example of the screen used to display plant photographs.

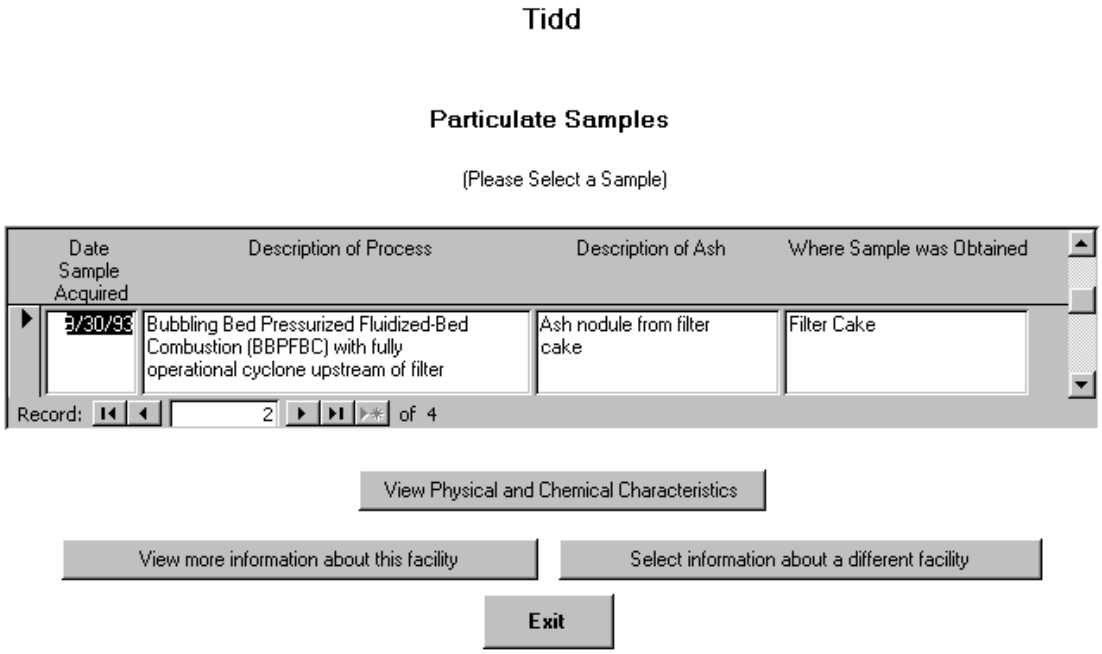


Figure 39. Samples are selected for subsequent examination of their characteristics using this screen. This screen is being modified to list more samples.

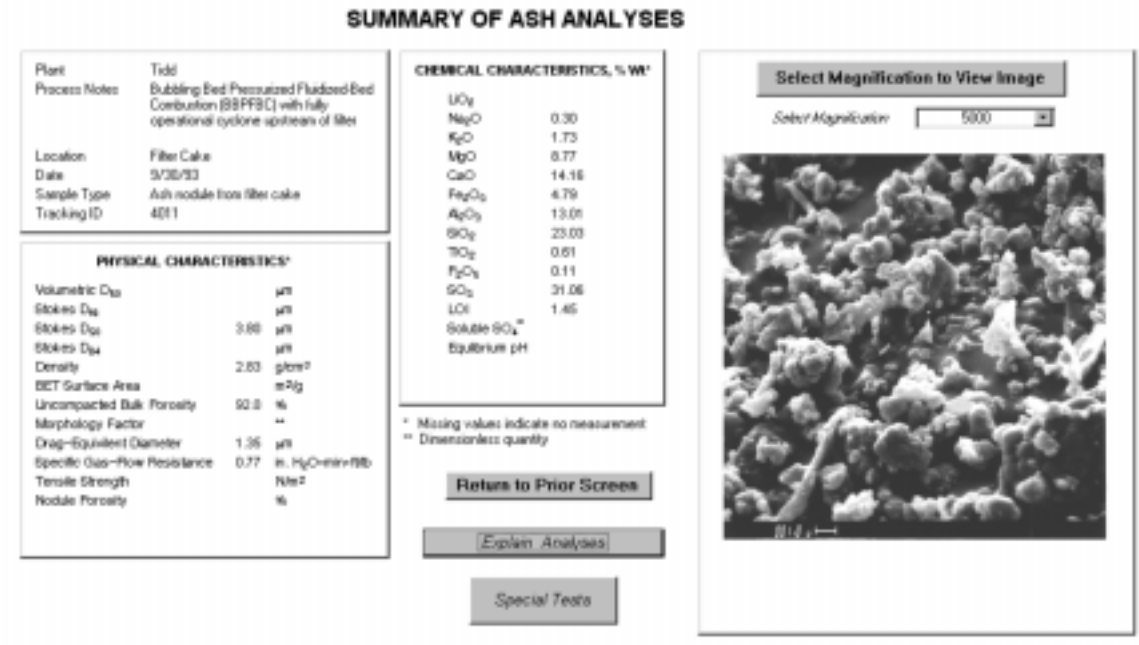


Figure 40. Measured sample characteristics are displayed on this screen.

FUTURE WORK

Plans for the remainder of the project include characterization of additional samples collected during site visits to the Department of Energy / Southern Company Services Power Systems Development Facility (PSDF). Additional samples obtained from other high-temperature, high-pressure filters will also be analyzed and included in the HGCU data base. The device described in this report for the preservation of filter cakes is being constructed and will be tested. Providing the technique and device work as planned, fully encapsulated filter cake/filter element specimens should be available for distribution and analysis. The HGCU data base will be completed and delivered to DOE/FETC-MGN by the end of this contract.

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7. Swanson, M.L. and M.D. Mann, “Advanced High-Temerature, High-Pressure Transport Gasifications,” Proceedings of the Advanced Coal-Based Power and Environmental Systems ’98 Conference, Federal Energy Technology Center, Morgantown, WV, July 21-23, 1998.

APPENDIX A SAMPLE INFORMATION FORMS

SAMPLE INFORMATION
(Provided by Facility Operator)
Tracking ID # 4324

FACILITY

1	Name	Transport Reactor Demonstration Unit
2	Type of Gasifier	2.7 MM Btu/hr Pilot Plant
3	Plant Heat Rate (Btu/kWh)	
4	Plant Firing Rate (MWe)	
5	Maximum Continuous Rating (MWe)	
6	Site Altitude (ft)	850 ft

FUEL Wyodak P051

7	Type	Subbituminous
8	Source	Wyodak Seam from Belle Air Mine near Gillette, WY
9	Higher Heating Value (Btu/lb)	9360

10 Proximate analysis

	as received	dry basis
% moisture	~20	NA
% ash	4.68	5.85
% volatile	36.38	45.48
% fixed carbon	38.94	48.67
totals	100.00	100.00
Btu/lb.	9360	11705
% sulfur	0.35	0.44

11 Ultimate analysis

	as received	dry
% moisture	~20	NA
% carbon	55.25	69.06
% hydrogen	6.39	5.19
% nitrogen	0.67	0.84
% chlorine	ND	
% sulfur	0.35	0.44
% ash	4.68	5.85
% oxygen (diff.)	32.66	18.63
totals	100	100

12 Fly ash fraction (% wt.)

13 Chemical analysis of coal (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
	1.3	0.3	7.0	26.6	5.5	13.1	27.8	1.3	1.0	16.0	NA

14 Is sorbent added to fuel? yes

15 Type of sorbent Plum run dolomite from Greenfield formation @ 5 wt%

16 Chemical analysis of added sorbent (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
	0.3	0.3	27.5	66.6	1.3	1.0	2.7	0.0	0.0	0.3	43.1

PARTICULATE CONTROL DEVICE

17	Type	candle
18	Cleaning initiated on	30 in H_2O above baseline
19	Hopper pulling schedule (h)	0.5 hr
20	Normal operating temperature (°F)	1000
21	Normal operating pressure (psig)	120
22	Normal gas flow	20,100 scfm @ 1atm & 60 °F
23	Normal operating tubesheet pressure drop (in. H_2O)	20
24	Normal pressure drop prior to cleaning (in. H_2O)	100
25	Normal pressure drop following cleaning (in. H_2O)	80
26	Total active filtering surface (ft^2)	26.52

SAMPLE FOR ANALYSIS

27	Type of sample	filter hopper sample
28	Source of ash in plant layout	
29	Date 2/25/97 time 12:00 - 24:00	
30	Sample taken by Bill Sulkalski	
31	Description of operation prior to sample collection: no recirculation of dipleg solids (e.g. steady-state full load, boiler upset, ramping, etc.)	steady-state
32	How was sample obtained	scooped from hopper

ANALYSIS AND REPORTING

33	Sample sent to SRI by Mike Swanson	Phone 701-777-5239
34	Request for sample analysis initiated by Rich Dennis (DOE/FETC)	
35	Goal of laboratory analyses	
36	Specific tests requested	
37	Send report to	
38	Send copies of report to	
39	Special instructions	

SAMPLE INFORMATION
(Provided by Facility Operator)
Tracking ID # 4325

FACILITY

1	Name	Transport Reactor Demonstration Unit
2	Type of Gasifier	2.7 MM Btu/hr Pilot Plant
3	Plant Heat Rate (Btu/kWh)	
4	Plant Firing Rate (MWe)	
5	Maximum Continuous Rating (MWe)	
6	Site Altitude (ft)	850 ft

FUEL Wyodak P051

7	Type	Subbituminous
8	Source	Wyodak Seam from Belle Air Mine near Gillette, WY
9	Higher Heating Value (Btu/lb)	9360

10 Proximate analysis

	as received	dry basis
% moisture	~20	NA
% ash	4.68	5.85
% volatile	36.38	45.48
% fixed carbon	38.94	48.67
totals	100.00	100.00
Btu/lb.	9360	11705
% sulfur	0.35	0.44

11 Ultimate analysis

	as received	dry
% moisture	~20	NA
% carbon	55.25	69.06
% hydrogen	6.39	5.19
% nitrogen	0.67	0.84
% chlorine	ND	
% sulfur	0.35	0.44
% ash	4.68	5.85
% oxygen (diff.)	32.66	18.63
totals	100	100

12 Fly ash fraction (% wt.)

13 Chemical analysis of coal (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
	1.3	0.3	7.0	26.6	5.5	13.1	27.8	1.3	1.0	16.0	NA

14 Is sorbent added to fuel? yes

15 Type of sorbent Plum run dolomite from Greenfield formation @ 5 wt%

16 Chemical analysis of added sorbent (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
	0.3	0.3	27.5	66.6	1.3	1.0	2.7	0.0	0.0	0.3	43.1

PARTICULATE CONTROL DEVICE

17	Type	candle
18	Cleaning initiated on	30 in H_2O above baseline
19	Hopper pulling schedule (h)	0.5 hr
20	Normal operating temperature (°F)	1000
21	Normal operating pressure (psig)	120
22	Normal gas flow (acfm)	~ 20,100
23	Normal operating tubesheet pressure drop (in. H_2O)	20
24	Normal pressure drop prior to cleaning: 20-30 in H_2O above baseline (up to 100 in max)	
25	Normal pressure drop following cleaning (in. H_2O)	ranging from 30 up to 80
26	Total active filtering surface (ft^2)	26.52

SAMPLE FOR ANALYSIS

27	Type of sample	filter cake
28	Source of ash in plant layout	
29	Date 2/28/97 time end of test	
30	Sample taken by Mike Swanson	
31	Description of operation prior to sample collection: no recirculation of dipleg solids (e.g. steady-state full load, boiler upset, ramping, etc.)	steady-state until off-line
32	How was sample obtained	scraped off surface of candle

ANALYSIS AND REPORTING

33	Sample sent to SRI by Mike Swanson	Phone 701-777-5239
34	Request for sample analysis initiated by Rich Dennis (DOE/FETC)	
35	Goal of laboratory analyses	
36	Specific tests requested	
37	Send report to	
38	Send copies of report to	
39	Special instructions	

SAMPLE INFORMATION
(Provided by Facility Operator)
Tracking ID # 4326

FACILITY

1	Name	Transport Reactor Demonstration Unit
2	Type of Gasifier	2.7 MM Btu/hr Pilot Plant
3	Plant Heat Rate (Btu/kWh)	
4	Plant Firing Rate (MWe)	
5	Maximum Continuous Rating (MWe)	
6	Site Altitude (ft)	850 ft

FUEL Wyodak P056

7	Type	Subbituminous
8	Source	Wyodak Seam from Belle Air Mine near Gillette, WY
9	Higher Heating Value (Btu/lb)	9360

10 Proximate analysis

	as received	dry basis
% moisture	~20	NA
% ash	4.68	5.85
% volatile	36.38	45.48
% fixed carbon	38.94	48.67
totals	100.00	100.00
Btu/lb.	9360	11705
% sulfur	0.35	0.44

11 Ultimate analysis

	as received	dry
% moisture	~20	NA
% carbon	55.25	69.06
% hydrogen	6.39	5.19
% nitrogen	0.67	0.84
% chlorine	ND	
% sulfur	0.35	0.44
% ash	4.68	5.85
% oxygen (diff.)	32.66	18.63
totals	100	100

12 Fly ash fraction (% wt.)

13 Chemical analysis of coal (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
	1.3	0.3	7.0	26.6	5.5	13.1	27.8	1.3	1.0	16.0	NA

14 Is sorbent added to fuel? yes

15 Type of sorbent Plum run dolomite from Greenfield formation @ 5 wt%

16 Chemical analysis of added sorbent (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
	0.3	0.3	27.5	66.6	1.3	1.0	2.7	0.0	0.0	0.3	43.1

PARTICULATE CONTROL DEVICE

17	Type	candle filter
18	Cleaning initiated on	30 in H_2O above baseline
19	Hopper pulling schedule (h)	0.5 hr
20	Normal operating temperature (°F)	1000
21	Normal operating pressure (psig)	120
22	Normal gas flow	19,885 scfm @ 1atm & 60 °F
23	Normal operating tubesheet pressure drop (in. H_2O)	20
24	Normal pressure drop prior to cleaning (in. H_2O)	60
25	Normal pressure drop following cleaning (in. H_2O)	30
26	Total active filtering surface (ft^2)	26.52 (13 one-meter candles)

SAMPLE FOR ANALYSIS

27	Type of sample	filter hopper sample
28	Source of ash in plant layout	
29	Date 2/22/98 time 08:00 - 16:15	
30	Sample taken by Bill Sulkalski	
31	Description of operation prior to sample collection: with recirculation of dipleg solids (e.g. steady-state full load, boiler upset, ramping, etc.)	steady-state
32	How was sample obtained	scraped from barrel

ANALYSIS AND REPORTING

33	Sample sent to SRI by Mike Swanson	Phone 701-777-5239
34	Request for sample analysis initiated by Rich Dennis (DOE/FETC)	
35	Goal of laboratory analyses	
36	Specific tests requested	
37	Send report to	
38	Send copies of report to	
39	Special instructions	

SAMPLE INFORMATION
(Provided by Facility Operator)
Tracking ID # 4327

FACILITY

1	Name	Transport Reactor Demonstration Unit
2	Type of Gasifier	2.7 MM Btu/hr Pilot Plant
3	Plant Heat Rate (Btu/kWh)	
4	Plant Firing Rate (MWe)	
5	Maximum Continuous Rating (MWe)	
6	Site Altitude (ft)	850 ft

FUEL — Illinois #6

7	Type	Bituminous
8	Source	Seam 6 from Baldwin Mine, near Baldwin, IL
9	Higher Heating Value (Btu/lb)	12080

10 Proximate analysis

	as received	dry basis
% moisture	8.5	NA
% ash	10.7	11.7
% volatile	36.02	39.38
% fixed carbon	44.78	48.92
totals	100.00	100.00
Btu/lb.	11.289	12.341
% sulfur	3.24	3.55

11 Ultimate analysis

	as received	dry
% moisture	8.5	NA
% carbon	63.36	69.27
% hydrogen	5.55	5.03
% nitrogen	1.01	1.10
chlorine, µg/g	609	
% sulfur	3.24	3.55
% ash	10.7	11.7
% oxygen (diff.)	16.13	9.34
totals	100	100

12 Fly ash fraction (% wt.)

13 Chemical analysis of coal (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
ND	1.1	1.9	1.6	3.2	13.6	21.2	53.9	0.9	0.2	2.5	NA

14 Is sorbent added to fuel? yes

15 Type of sorbent Plum run dolomite from Greenfield formation @ 17 wt%

16 Chemical analysis of added sorbent (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
ND	0.3	0.3	27.5	66.6	1.3	1.0	2.7	0.0	0.0	0.3	43.1

PARTICULATE CONTROL DEVICE

17	Type	candle filter
18	Cleaning initiated on	30 in H_2O above baseline
19	Hopper pulling schedule (h)	0.33 hr
20	Normal operating temperature (°F)	1000
21	Normal operating pressure (psig)	120
22	Normal gas flow	16,300 scfh @ 1atm & 60 °F
23	Normal operating tubesheet pressure drop (in. H_2O)	20
24	Normal pressure drop prior to cleaning (in. H_2O)	20
25	Normal pressure drop following cleaning (in. H_2O)	40
26	Total active filtering surface (ft^2)	26.52 (13 one-meter candles)

SAMPLE FOR ANALYSIS

27	Type of sample	filter hopper sample
28	Source of ash in plant layout	
29	Date 2/25/98 time 06:40 - 10:00	
30	Sample taken by Bill Sulkalski	
31	Description of operation prior to sample collection: with recirculation of dipleg solids (e.g. steady-state full load, boiler upset, ramping, etc.)	steady-state
32	How was sample obtained	scooped from barrel

ANALYSIS AND REPORTING

33	Sample sent to SRI by Mike Swanson	Phone 701-777-5239
34	Request for sample analysis initiated by Rich Dennis (DOE/FETC)	
35	Goal of laboratory analyses	
36	Specific tests requested	
37	Send report to	
38	Send copies of report to	
39	Special instructions	

SAMPLE INFORMATION
(Provided by Facility Operator)
Tracking ID # 4328

FACILITY

1	Name	Transport Reactor Demonstration Unit
2	Type of Gasifier	2.7 MM Btu/hr Pilot Plant
3	Plant Heat Rate (Btu/kWh)	
4	Plant Firing Rate (MWe)	
5	Maximum Continuous Rating (MWe)	
6	Site Altitude (ft)	850 ft

FUEL SUFCo P057

7	Type	Bituminous
8	Source	Bituminous seam at SUFCo mine in Salina, UT
9	Higher Heating Value (Btu/lb)	11040

10 Proximate analysis

	as received	dry basis
% moisture	9.5	NA
% ash	7.56	8.35
% volatile	39.10	43.20
% fixed carbon	43.84	48.45
totals	100.00	100.00
Btu/lb.	11040	12200
% sulfur	0.33	0.36

11 Ultimate analysis

	as received	dry
% moisture	9.5	NA
% carbon	69.78	77.10
% hydrogen	5.23	4.61
% nitrogen	1.17	1.29
chlorine, µg/g	69	
% sulfur	0.33	0.36
% ash	7.56	8.35
% oxygen (diff.)	15.93	8.29
totals	100	100

12 Fly ash fraction (% wt.)

13 Chemical analysis of coal (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
ND	4.6	0.2	3.0	16.3	6.1	9.3	38.3	0.8	0.2	21.1	NA

14 Is sorbent added to fuel? yes

15 Type of sorbent Plum run dolomite from Greenfield formation @ 5 wt%

16 Chemical analysis of added sorbent (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
ND	0.3	0.3	27.5	66.6	1.3	1.0	2.7	0.0	0.0	0.3	43.1

PARTICULATE CONTROL DEVICE

17	Type	candle filter
18	Cleaning initiated on	30 in H_2O above baseline
19	Hopper pulling schedule (h)	0.5 hr
20	Normal operating temperature (°F)	1000
21	Normal operating pressure (psig)	120
22	Normal gas flow	20,100 acfm @ 1atm & 60 °F
23	Normal operating tubesheet pressure drop (in. H_2O)	20
24	Normal pressure drop prior to cleaning (in. H_2O)	60
25	Normal pressure drop following cleaning (in. H_2O)	25
26	Total active filtering surface (ft^2)	26.52 (13 one-meter candles)

SAMPLE FOR ANALYSIS

27	Type of sample	filter hopper sample
28	Source of ash in plant layout	
29	Date 4/4/98 time 14:00 - 18:00	
30	Sample taken by Bill Sulkalski	
31	Description of operation prior to sample collection (e.g. steady-state full load, boiler upset, ramping, etc.)	steady-state
32	How was sample obtained	scooped from barrel

ANALYSIS AND REPORTING

33 Sample sent to SRI by Mike Swanson Phone 701-777-5239
34 Request for sample analysis initiated by Rich Dennis (DOE/FETC)
35 Goal of laboratory analyses
36 Specific tests requested
37 Send report to

38 Send copies of report to

39 Special instructions

SAMPLE INFORMATION
(Provided by Facility Operator)
Tracking ID # 4329

FACILITY

1	Name	Transport Reactor Demonstration Unit
2	Type of Gasifier	2.7 MM Btu/hr Pilot Plant
3	Plant Heat Rate (Btu/kWh)	
4	Plant Firing Rate (MWe)	
5	Maximum Continuous Rating (MWe)	
6	Site Altitude (ft)	850 ft

FUEL SUFCo P057

7	Type	Bituminous
8	Source	Bituminous seam at SUFCo mine in Salina, UT
9	Higher Heating Value (Btu/lb)	11040

10 Proximate analysis

	as received	dry basis
% moisture	9.5	NA
% ash	7.56	8.35
% volatile	39.10	43.20
% fixed carbon	43.84	48.45
totals	100.00	100.00
Btu/lb.	11040	12200
% sulfur	0.33	0.36

11 Ultimate analysis

	as received	dry
% moisture	9.5	NA
% carbon	69.78	77.10
% hydrogen	5.23	4.61
% nitrogen	1.17	1.29
chlorine, µg/g	69	
% sulfur	0.33	0.36
% ash	7.56	8.35
% oxygen (diff.)	15.93	8.29
totals	100	100

12 Fly ash fraction (% wt.)

13 Chemical analysis of coal (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
ND	4.6	0.2	3.0	16.3	6.1	9.3	38.3	0.8	0.2	21.1	NA

14 Is sorbent added to fuel? yes

15 Type of sorbent Plum run dolomite from Greenfield formation @ 5 wt%

16 Chemical analysis of added sorbent (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
ND	0.3	0.3	27.5	66.6	1.3	1.0	2.7	0.0	0.0	0.3	43.1

PARTICULATE CONTROL DEVICE

17	Type	candle filter
18	Cleaning initiated on	30 in H_2O above baseline
19	Hopper pulling schedule (h)	0.5 hr
20	Normal operating temperature (°F)	1000
21	Normal operating pressure (psig)	120
22	Normal gas flow	20,100 acfm @ 1atm & 60 °F
23	Normal operating tubesheet pressure drop (in. H_2O)	20
24	Normal pressure drop prior to cleaning (in. H_2O)	20
25	Normal pressure drop following cleaning (in. H_2O)	50
26	Total active filtering surface (ft^2)	26.52 (13 one-meter candles)

SAMPLE FOR ANALYSIS

27	Type of sample	filter hopper sample
28	Source of ash in plant layout	
29	Date 4/7/98 time 08:50 - 12:00	
30	Sample taken by Bill Sulkalski	
31	Description of operation prior to sample collection (e.g. steady-state full load, boiler upset, ramping, etc.)	steady-state
32	How was sample obtained	scooped from barrel

ANALYSIS AND REPORTING

33 Sample sent to SRI by Mike Swanson Phone 701-777-5239
34 Request for sample analysis initiated by Rich Dennis (DOE/FETC)
35 Goal of laboratory analyses
36 Specific tests requested
37 Send report to

38 Send copies of report to

39 Special instructions

SAMPLE INFORMATION
(Provided by Facility Operator)
Tracking ID # 4330

FACILITY

1	Name	Transport Reactor Demonstration Unit
2	Type of Gasifier	2.7 MM Btu/hr Pilot Plant
3	Plant Heat Rate (Btu/kWh)	
4	Plant Firing Rate (MWe)	
5	Maximum Continuous Rating (MWe)	
6	Site Altitude (ft)	850 ft

FUEL Pet Coke P058

7	Type	Pet Coke
8	Source	Hunt Oil Refinery in Tuscaloosa, AL
9	Higher Heating Value (Btu/lb)	15150

10 Proximate analysis

	as received	dry basis
% moisture	0.90	NA
% ash	0.98	0.99
% volatile	9.62	9.71
% fixed carbon	88.50	89.30
totals	100.00	100.00
Btu/lb.	15150	15300
% sulfur	5.44	5.49

11 Ultimate analysis

	as received	dry
% moisture	0.90	NA
% carbon	89.83	90.65
% hydrogen	3.96	3.89
% nitrogen	1.68	1.70
chlorine, µg/g	ND	
% sulfur	5.44	5.49
% ash	0.98	0.99
% oxygen (diff.)	-1.89	-2.72
totals	100	100

12 Fly ash fraction (% wt.)

13 Chemical analysis of coal (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
ND	1.0	0.2	5.1	11.9	7.6	4.8	18.9	0.0	0.1	13.8	NA

14 Is sorbent added to fuel? yes

15 Type of sorbent Plum run dolomite from Greenfield formation @ 20 wt%

16 Chemical analysis of added sorbent (% wt.)

Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	LOI
ND	0.3	0.3	27.5	66.6	1.3	1.0	2.7	0.0	0.0	0.3	43.1

PARTICULATE CONTROL DEVICE

17	Type	candle filter
18	Cleaning initiated on	2 hour intervals
19	Hopper pulling schedule (h)	2 hr
20	Normal operating temperature (°F)	1050
21	Normal operating pressure (psig)	110
22	Normal gas flow	13950 acfh @ 1atm & 60 °F
23	Normal operating tubesheet pressure drop (in. H_2O)	20
24	Normal pressure drop prior to cleaning (in. H_2O)	27
25	Normal pressure drop following cleaning (in. H_2O)	24
26	Total active filtering surface (ft^2)	26.52 (13 one-meter candles)

SAMPLE FOR ANALYSIS

27	Type of sample	filter hopper sample
28	Source of ash in plant layout	
29	Date 5/5-8/98 time	
30	Sample taken by Bill Sulkalski	
31	Description of operation prior to sample collection (e.g. steady-state full load, boiler upset, ramping, etc.)	steady-state
32	How was sample obtained	scooped from barrel

ANALYSIS AND REPORTING

33 Sample sent to SRI by Mike Swanson Phone 701-777-5239
34 Request for sample analysis initiated by Rich Dennis (DOE/FETC)
35 Goal of laboratory analyses
36 Specific tests requested
37 Send report to

38 Send copies of report to

39 Special instructions

PARTICULATE HOT GAS STREAM CLEANUP TECHNICAL ISSUES

Task 1 ASSESSMENT OF ASH CHARACTERISTICS

ANNUAL REPORT

October 1997 - September 1998

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November 30, 1998

Approved by

Duane H. Pontius, Principal Investigator