Contract No. DE-AC21-94MC31160--34

PARTICULATE HOT GAS STREAM CLEANUP TECHNICAL ISSUES

Task 1 ASSESSMENT OF ASH CHARACTERISTICS

FINAL REPORT
October 1994 - September 1999

including the

QUARTERLY REPORT
July 1999 - September 1999

and the

ANNUAL REPORT
October 1998 - September 1999

Prepared for

UNITED STATES DEPARTMENT OF ENERGY
Federal Energy Technology Center - Morgantown
Post Office Box 880, 3610 Collins Ferry Road
Morgantown, West Virginia 26505

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SOUTHERN RESEARCH INSTITUTE
2000 NINTH AVENUE SOUTH
Post Office Box 55305
BIRMINGHAM, ALABAMA 35255-5305
Principal Investigator: D. H. Pontius
Task Leader: T. R. Snyder

for

UNITED STATES DEPARTMENT OF ENERGY
Federal Energy Technology Center - Morgantown
Post Office Box 880, 3610 Collins Ferry Road
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Contract No. DE-AC21-94MC31160
Project Manager: Thomas P. Dorchak

Abstract

This is the final technical report describing the activities performed under Task 1 of Contract No. DE-AC21-94MC31160. The analyses of hot gas stream cleanup (HGCU) particulate samples and descriptions of filter performance studied under this contract were designed to address problems with filter operation that have been linked to characteristics of the collected particulate matter. One objective of this work was to generate an interactive, computerized data bank of the key physical and chemical characteristics of ash and char collected from operating advanced particle filters and to relate these characteristics to the operation and performance of these filters. The interactive data bank summarizes analyses of over 160 ash and char samples from fifteen pressurized fluidized-bed combustion and gasification facilities utilizing high-temperature, high pressure barrier filters. As a deliverable item under this contract, the HGCU data bank was to be submitted to the Department of Energy by the closing date of the contract (September 30, 1999). All of the data measured and activities conducted under Task 1 of Contract DE-AC21-94MC31160, and a significant proportion of data and activities generated under a prior contract with DOE/FETC (Contract No. DE-AC21-89MC26239) are presented in this final report.

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1.0 EXECUTIVE SUMMARY

This is the final technical 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 were designed to address problems with filter operation that have been linked to characteristics of the collected ash. Task 1 was designed to generate an interactive, computerized data bank of the key characteristics of ash and char samples collected from pressurized fluidized-bed combustion (PFBC) and gasification facilities. This task was also designed to relate these characteristics to the operation and performance of operating advanced particle filters (APFs). 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, concerned testing and failure analyses of ceramic filter elements currently used in operating APFs and the characterization and evaluation of new ceramic materials.

Ceramic barrier filters operating in HGCU environments face several potential challenges that may result from the characteristics of the ash or char being collected. The condition that has received the most attention since the first testing of these filters is the formation of tenacious ash deposits in the filter vessel that can form bridge-like structures that often result in lateral mechanical forces being exerted on the filter elements. Ash bridging can become extensive enough to significantly reduce active filter area, and ash deposits can become large enough to cause damage to filter elements if the deposits dislodge and fall to the hopper. Observations of the formation of high-strength ash deposits and ash bridging under this task were confined to PFBC facilities. Although experiences at American Electric Power Service Company's 70 MWe Tidd Pressurized Fluidized-Bed Combustor (Tidd) and Foster Wheeler's 10 MWt Pressurized Circulating Fluid Bed Facility in Karhula, Finland (Karhula) led to improved filter elements and filter system design to minimize the damaging effects of these ash deposits, operating experiences and supporting laboratory studies indicate that these improvements are not sufficient to completely remove the potential for ash bridges to form.[1] Residence time in the filter vessel, combined with filter temperature, and ash and flue gas chemistry, can provide conditions sufficient for strong PFBC ash deposits to form in HGCU filters. Although the fundamental mechanisms controlling the formation and strengthening of these ash deposits have not been completely verified, a great deal of information has been compiled characterizing PFBC ash deposits. Based on these characterizations, this task developed and presented a model of deposit growth based on the formation of eutectic compounds in PFBC ash.

Several approaches to limiting the potential for bridging have been tried. Bridging was significantly reduced at Tidd by limiting the time that ash remained in the APF.[1] At Karhula, various combinations of coals and sorbent materials were evaluated with one of the objectives being to minimize ash bridging.[2] At the Kellogg Brown & Root Advanced Transport Reactor at the Department of Energy / Southern Company Services Power Systems Development Facility (PSDF), the temperature of the filter vessel has not been allowed to approach the levels where severe bridging was encountered at Tidd. It is clear from the experiences at these facilities that understanding and optimizing ash characteristics is one of the keys to successful and optimized HGCU filter operation on PFBC systems.

In addition to bridging in HGCU filters, other key issues that are strongly dependent on the characteristics of the particles collected in the filter are pressure loss across the filter, the development of filter cakes that may be hard to remove during reverse-pulse cleaning, and the reentrainment and recollection on the filter cake of previously collected particles following their removal by cleaning pulses.

For a given filter design, the permeability of the filter cake is the primary variable determining overall pressure loss across the filter. (Although inlet mass concentration, filtering face velocity, gas viscosity, and the permeability of clean ceramic filter elements also contribute to the overall pressure loss, these factors are set by the system design.) Given these design factors, the pressure loss through the filter cake is determined by the amount of cake on the filter surface (usually expressed in terms of its areal density), and the morphology of the filter cake. This morphology is a combination of the porosity of the cake structure, and the morphology of the particles composing the cake. As with the other factors set by the system design, the morphology of the particles reaching the filter cake is determined by operating variables of the combustion or gasification system. Precollectors, such as cyclones upstream of the barrier filter can also modify particle morphology by preferentially removing the larger entrained particles.

Mathematical models of filtration, including the semi-empirical model refined under Task 1 of this contract describing the permeability of filter cakes composed of fine, irregular particles, demonstrate the sensitivity of flow resistance to cake porosity [3, 4, 5, 6, 7]. Factors that can decrease the porosity of filter cakes in barrier filters include cake collapse caused by filtering pressure drop, alteration of particle morphology and rearrangement of the collected particles as a result of the formation of eutectic melts, and the filling of interparticle voids by the additional formation of sulfate salts on the surfaces of incompletely reacted sorbent particles.

Because the relationships between chemical constituents and particulate behavior are not yet established for gasification processes, the effect on filtration behavior of the various chemical compounds present in gasification particulate samples are not yet known. Chemical reactions such as tar formation and chemical sintering between particles have the potential to create problems such as bridging in filters collecting gasification particulates.

Some of the gasification chars studied under this task comprised irregularly-shaped particles with very high specific surface areas, and often exhibited extremely fine size distributions. Chars with very high surface areas (> 100 m^2/g) have the potential to generate filter cakes that have extremely low permeabilities. In addition, there is a potential for some filter cakes comprising gasifier char to compact, which would adversely affect permeability. Also, many of the gasification char samples studied under this task exhibited relatively low tensile strengths. The low tensile strengths measured for these samples may indicate that char particles dislodged from filter elements during pulse cleaning cycles may break up into very small agglomerates. If this type of breakup occurs, reentrainment of previously collected gasification residues may pose a significant problem. Continued observation of the behavior of gasifier char filter cakes in HGCU filters is needed to assess to what extent these phenomena (the formation of low permeability filter cakes, filter cake compaction, and particle reentrainment) occur.

This task has catalogued many characteristics of PFBC ashes and gasification chars, and has studied the fundamental ways in which these characteristics ultimately affect filter operation. Figure 1-1 summarizes the ranges measured for some of the key physical characteristics of the filter cake samples discussed in this report. As can be seen in this figure, there are several distinct differences between these two types of filter cake material. This report examines these data in detail, and discusses the implications of these characteristics on HGCU filter performance. In addition to this report, the interactive data bank issued as a deliverable to DOE/FETC under this task serves as an important tool for advancing these studies. (The reader of this report is referred to the DOE/FETC Project Manager, Thomas P. Dorchak, for access to the interactive data bank.)

In order to maximize the benefit of the characterization and analysis of particulate properties for HGCU technology, additional samples should be analyzed as they become available, operating data and observations from operating HGCU facilities should continue to be compiled, and critical analysis of these data must continue to be performed and communicated to the users of these filters. Tasks like the one described in this report, and especially the interactive data bank it produced, provide excellent means for achieving these continuing objectives.

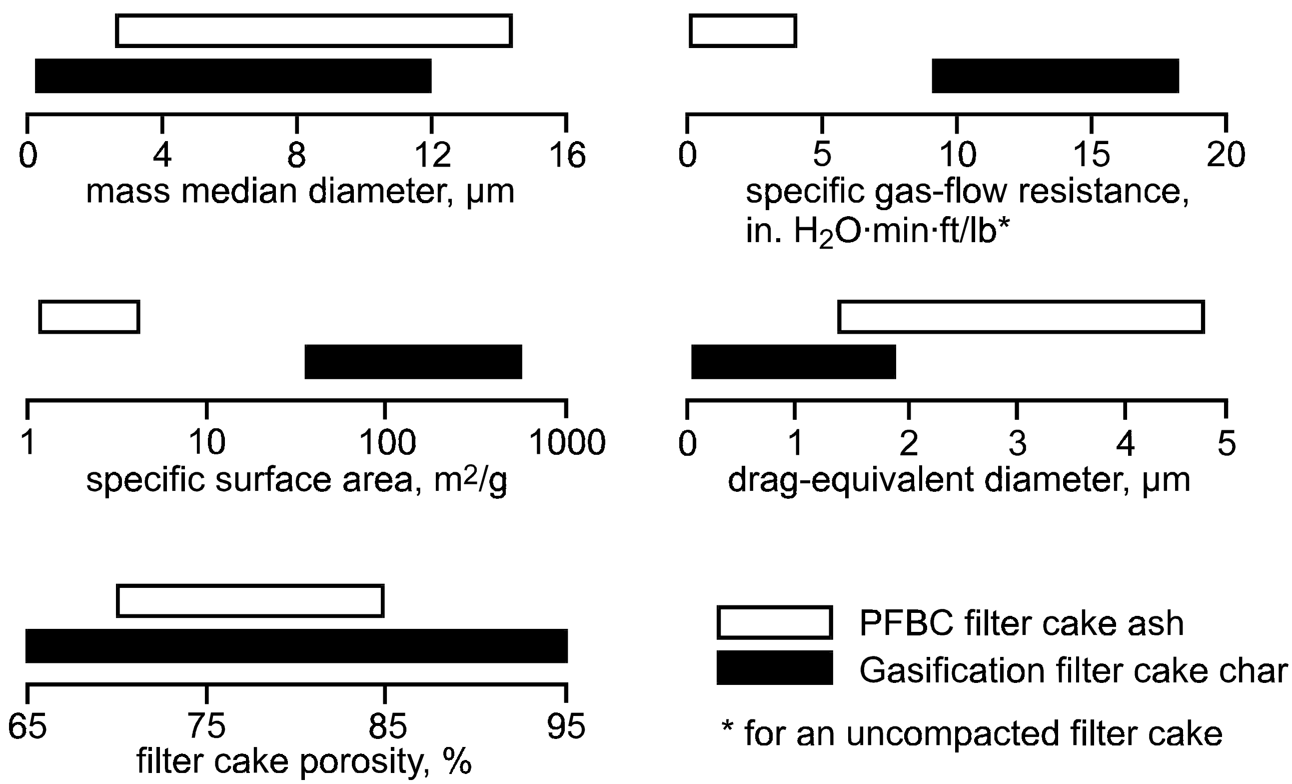

Figure 1-1. Ranges measured for some of the key physical characteristics of the filter cake samples discussed in this report.

2.0 INTRODUCTION

This is the final technical report describing the activities performed under Contract No. DE-AC21-94MC31160. Task 1 of this contract concerned analyses of HGCU ashes and descriptions of filter performance that were designed to address problems with filter operation linked to characteristics of the collected particulate matter. Much of the work conducted under Task 1 built 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 are presented under separate cover, and concern 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 they also have characteristics that might negatively affect filtration. Specifically, gasifier particulates form filter cakes that could accumulate in thickness quite rapidly, might compact as a result of the filtering pressure drop across them, and also may tend to reentrain following cleaning pulses.

To identify which particulate characteristics can lead to problems with filtration, 375 particulate samples from fourteen facilities involved in FETC's HGCU program have been assembled into an interactive, computerized data bank. Three samples from gasification studies carried out by Herman Research Pty Ltd. (HRL) of Melbourne, Australia have also been studied under this task and are included in the data bank. An overview of these facilities and samples is provided in Table 2-1. Many of the samples 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, the Power Systems Development Facility, and Foster Wheeler's pilot-scale combustion facility located in Livingston, New Jersey have also been performed. The data obtained in these studies were assembled into an interactive, computerized data bank to help the manufacturers and operators of high-temperature barrier filters tailor their designs and operations to the specific characteristics of the particulate materials to be collected. This report describes the methods used to analyze the HGCU particulate samples, presents the data measured for these samples, and discusses the implications these data have for HGCU filter operation at PFBC and gasification facilities.

2.1 OBJECTIVES

Task 1 had two primary objectives. The first was to generate a readily accessible data bank of the key characteristics of particulate samples collected from operating advanced particle filters. The second objective was to relate these measured properties and the contents of the data bank to the operation and performance of the advanced particle filters and filter components. The first objective included formatting the data bank and collecting, analyzing, and maintaining particulate samples from operating HGCU facilities. The second objective of this task involved 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.

Table 2-1
Overview of Facilities and Particulate Samples

# of samples	HGCU facility	Process
7	New York University	bubbling bed PFBC
8	Kellogg Brown & Root	circulating PFBC
14	Kellogg Brown & Root	gasification
2	Texaco Montebello Research Lab	gasification
11	Grimethorpe	circulating PFBC
9	KRW	gasification
2	Allison	coal-fired combustion turbine
10	Foster Wheeler	carbonizer
7	Foster Wheeler	circulating PFBC
3	Iowa State University	AFBC
61	Karhula	circulating PFBC
116	Tidd	bubbling bed PFBC
12	DOE/FETC	gasification
7	UNDEERC transport reactor	gasification
2	UNDEERC transport reactor	circulating PFBC
3	Herman Research Pty Ltd.	gasification
101	PSDF transport reactor	circulating PFBC
3	Piñon Pine Power Project	gasification

3.0 FIELD SAMPLING AND ON-SITE MEASUREMENTS

Site visits were made to three HGCU filters which included observations, on-site measurements, documentation of the condition of the filter, and collection of samples for analysis. Descriptions of the conditions of these filters during each of these visits are presented in this section, along with brief descriptions of the HGCU facility visited. (Descriptions of the other HGCU facilities from which particulate samples were received for analysis under this task are presented under section *4.0 Analyses of Particulate Samples*.)

Each site visit conducted under this task began with photographic documentation of the condition of the filter vessel. The ranges of on-site measurements and samples that can be obtained during site visits depend on the types of particulate deposits in the vessel, the condition of the filter elements, and the constraints of the sampling location. During several of these visits, areal density determinations and cake thickness measurements were made at various locations on the surfaces of the filter elements. (When both of these measurements can be made close to one another, filter cake porosity can be calculated.) These measurement techniques, which are described below, were limited to elements located on the outer perimeter of the filter arrays.

The measurement of areal density is made with a thin-walled core sampling tube that has a leading edge shaped to conform to the outer surface of the cylindrical filter elements. After a representative region is selected for this measurement, the sampling tube is pressed laterally through the filter cake until it firmly and evenly contacts the surface of the filter element. While it is held in place, the filter cake adjacent to the area isolated within the tube is brushed away to expose the surface of the filter element. A small catch basin shaped to conform to the outer surface of the filter element is placed below the core sampling tube, and the tube is gently removed so that any particulate material falling out of the tube is caught in the basin. Once the sampling tube has cleared the surface of the cake, its contents are added to any material already in the basin. Finally, the filter cake adhered to the surface of the element is brushed into the catch basin. The areal density of the sampled region is calculated by dividing the weight of the material collected by the cross-sectional area of the sampling tube.

A traversing transverse laser gauge is used to measure the thickness of filter cakes. After a region of the filter cake is selected, the gauge, which is mounted on a tripod, is positioned so that the horizontally-directed laser beam is tangent to the curvature of the filter element for the region of interest. The laser is mounted on a linear traversing mechanism so the beam can be moved horizontally at a right angle to its direction. The traversing mechanism includes a scale to record the location of the beam. Two positions of the beam are needed for a thickness measurement. The first is when the beam just contacts the surface of the filter cake. After this position is recorded, the filter cake between the contact point of the beam with the cake and the element surface is brushed away to expose the surface of the filter element. Then the beam is traversed laterally until it just contacts the surface of the cleaned region of the filter element. This second position is recorded, and the thickness of the cake is the difference between these two readings.

Other measurement and sample preservation techniques that have been made on site include preservation of nodules and deposits with epoxy (described under *Nodule Porosity* in section *4.1 Laboratory Methods Used to Characterize Samples*), and preservation of the filter cakes on the surface of a candle removed from the filter vessel to an on-site laboratory. This technique is described in *Appendix A Technique for Preserving Filter Cakes*.

3.1 TIDD

The objective of the test program carried out at Tidd was to evaluate the design and obtain operating experience for a commercial size Advanced Particle Filter (APF) through long-term testing on a slipstream at Ohio Power Company's Pressurized Fluidized Bed Combustion (PFBC) Demonstration Plant. The 70 MWe Tidd PFBC Demonstration Plant in Brilliant, Ohio was completed in late 1990, and operated through March 1995 as part of the Department of Energy's Clean Coal Technology Program. The original design of the Tidd Plant utilized seven strings of primary and secondary cyclones to remove 98% of the particulate matter from the gases between the fluidized bed and the gas turbine. A HGCU slipstream replaced one of the seven secondary cyclones by taking the discharge gas of one of the primary cyclones to outside of the combustor vessel and into the APF.[1] The general features of the APF are shown in Figure 3-1. The filter was designed to operate with 384 filter elements, each nominally 2.36 in. (6 cm) O.D. and 4.92 feet (150 cm) long.[8]

Under the original maximum design load conditions, gas at approximately 150 psig, 1550 °F flowed into the filter at 7600 acfm with a dust loading of 600 ppmw. In January 1994, the dust loading was increased to 3400 ppmw by detuning the primary cyclone upstream of the APF. During the tests conducted in 1994, the APF generally operated between 1350 and 1450°F. In January 1995, the primary cyclone was bypassed which increased the loading to approximately 20,000 ppmw. This change was made to take advantage of a larger particle size distribution, as described later in this section. The operating temperature of the APF was allowed to reach 1550 °F for a significant portion of its operation with the cyclone bypassed.[1]

Southern Research Institute personnel made four site visits to the Tidd APF to inspect and document the condition of the filter vessel and to collect for analysis representative samples of the various deposits of ash found in the APF. The first two of these visits were made on an earlier contract (No. DE-AC21-89MC26239). All four site visits are discussed in this section. In addition, a topical report entitled *Analyses of Ashes from the Tidd PFBC Advanced Particulate Filter* summarizing on-site observations and the results of on-site and laboratory ash analyses was submitted in August 1995 to DOE/FETC-MGN.

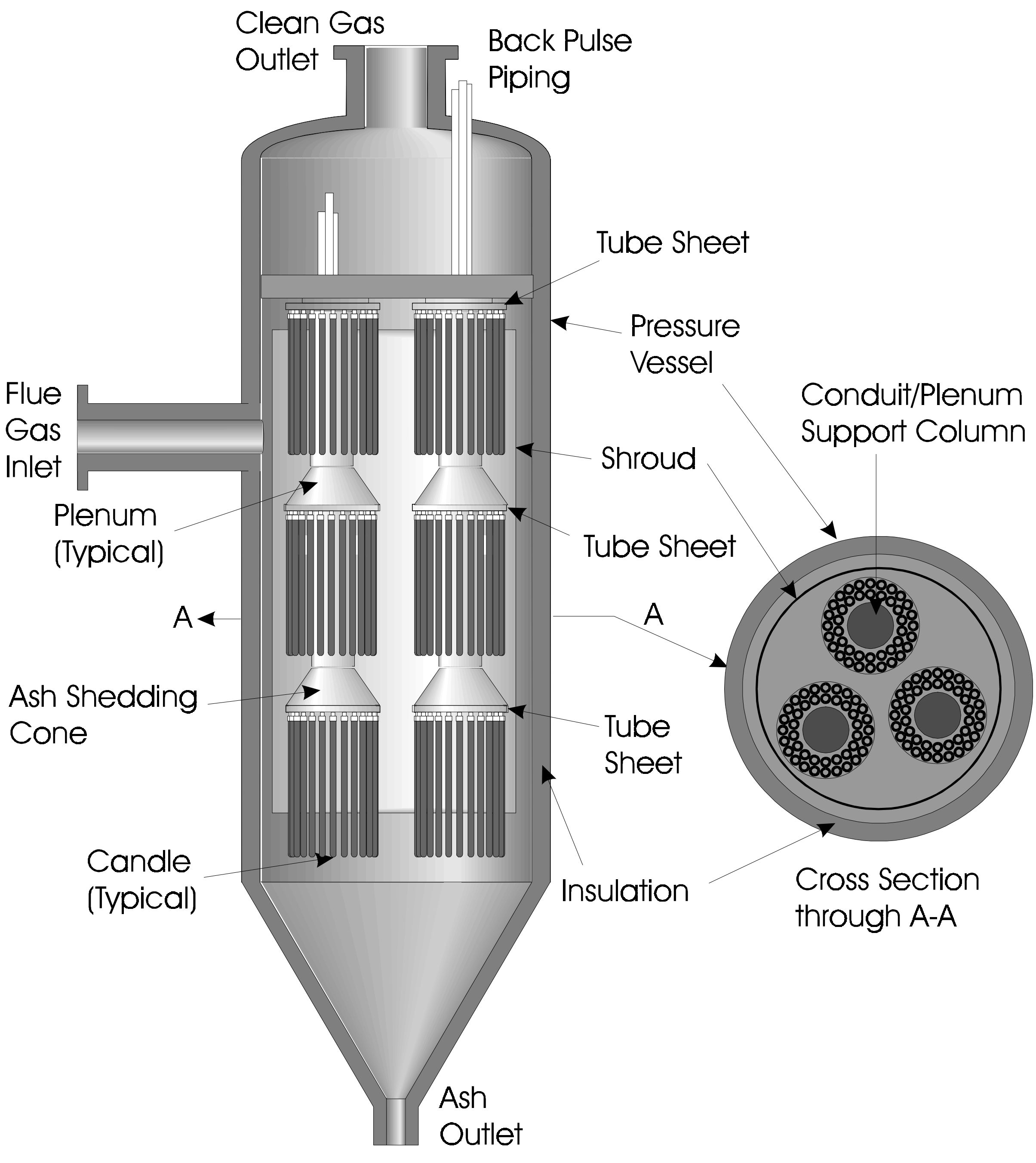

Figure 3-1. General features of the APF at the Tidd Demonstration Plant.

3.1.1 September 30, 1993

When the filter assembly was opened on September 30, 1993, extensive deposits of ash were found on candle surfaces, bridged between candles, and on non-filtering surfaces (ash sheds, plenum support conduits, and on the underside of the tube sheet). Deposits found on these non-filtering surfaces were formed by the gradual deposition of particles as a result of turbulent diffusion. Some of these passive deposits were up to six inches thick, with high tensile strength. Many of the candle filter elements were covered by filter cakes up to one inch thick. Like the passively deposited agglomerates of ash, these filter cakes also had high tensile strength. Figures 3-2 through 3-5 provide representative views of the condition of the APF as observed on this site visit. Figure 3-6 shows one of the thick, strong filter cake specimens collected while on site.

Figure 3-2. Severe ash bridging was evident as the top two plenums were lifted into view.


Figure 3-3. Thick, patchy cakes were present throughout the filter vessel.


Figure 3-4. Ash almost completely enveloped many of the candle filter elements.

Figure 3-5. The appearance of these candles is believed to be the result of patchy cleaning and the loss of cake during cooling down of the filter vessel.

Figure 3-6. A number of laboratory analyses were performed on this thick filter cake deposit (ID # 4012). The deposition layers formed during filtration are clearly visible in this specimen.

3.1.2 May 5, 1994

The filter vessel was again opened for inspection and refitting on May 5, 1994. Despite the relative cleanliness of the candles, significant deposits of ash were observed at several other locations in the assembly. The undersides of all of the nine tube sheets were coated with deposits of ash about eight inches thick. Although the outer (presumably the most recently deposited) portions of these deposits were fairly fluffy, the inner regions were hard, strong, and well consolidated. Similar deposits were found on the ash sheds above the middle and bottom plenums. These deposits were about three inches thick, and were also strong and well consolidated. Strong, thick deposits were present on the plenum support conduits positioned in the center of the top and middle plenum assemblies. These deposits were thick enough (over four inches) in most areas to envelop the inner ring of candles in these plenum assemblies. Many of the innermost candles in the top and middle plenums were bent away from the plenum support conduits. The regions between these candles and the plenum support conduits were almost completely filled with ash. Figures 3-7 through 3-23 document the condition of the APF on this site visit.

Observations of the APF during this site visit indicated that severe bridging of ash between adjacent candles was still a serious problem. Many ash bridges were present, some of which extended from the deposit on the underside of the tube sheet all the way down to the conical surface of the ash shed below the bottom ends of the candles. Ash bridges were identified in many different stages of formation. Most ash bridges were found in the top and middle plenums, which were also the locations where most of the severely bent candles were found. The bottom plenums had the fewest ash bridges, and the fewest bent or broken candles. As was observed previously, the ash deposits throughout the APF had high tensile strength. However, the filter cakes observed during this second site visit were only about 0.4 inch thick, compared with the one-inch thick cakes present in September 1993.