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U.S. Department of Energy’s High-Temperature and High-Pressure Particulate Cleanup For Advanced Coal-Based Power Systems

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Introduction

The availability of reliable, low-cost electricity is a cornerstone for the United States' ability to compete in the world market. The Department of Energy (DOE) projects the total consumption of electricity in the U.S. to rise from 2.7 trillion kilowatt-hours in 1990 to 3.5 trillion in 2010. Although energy sources are diversifying, fossil fuel still produces 90 percent of the Nation's energy. Coal is our most abundant fossil fuel resource and the source of 56 percent of our electricity. It has been the fuel of choice because of its availability and low cost. A new generation of high-efficiency power systems has made it possible to continue the use of coal while still protecting the environment. Such power systems greatly reduce the pollutants associated with coal-fired plants built before the 1970s. To realize this high efficiency and superior environmental performance, advanced coal-based power systems will require gas stream cleanup under high-temperature and high-pressure (HTHP) process conditions.

Presented below are the HTHP particulate capture requirements for the Integrated Gasification Combined Cycle (IGCC) and Pressurized Fluidized-Bed Combustion (PFBC) power systems, the HTHP particulate cleanup systems being implemented in the PFBC and IGCC Clean Coal Technology (CCT) Projects, and the currently available particulate capture performance results.

Advanced Power Systems

IGCC and PFBC are two of this new generation of advanced coal-fired power plants. In these plants, coal-derived gases are cleaned at elevated temperatures and pressures prior to combustion in gas turbine power generation systems. Such gas turbine systems are expected to achieve exceptional efficiencies by the end of the decade, assisted in part by a government-sponsored advanced turbine system initiative.[1]

IGCC Power System

In an IGCC system, fuel gas, which is composed of hydrogen and carbon oxides, is generated in a gasifier under pressurized conditions by reacting coal with steam and air or oxygen. The pressurized fuel gas is typically cooled and then cleaned of particulate matter and sulfur at high temperature and fed to a high-efficiency combustion gas turbine. The hot turbine exhaust gas produces steam to drive a steam turbine. With the adaptation of hot gas cleanup, large-scale demonstration projects, capable of reaching efficiencies of 45 percent, are expected by the turn of the century. IGCC plant efficiencies will climb to 52 percent and greater as advanced turbine systems are incorporated.

One of several gasification processes can be employed in an IGCC system. The type of gasification process can be typified by the oxidant used — either air or oxygen — and the gasifier configuration — fixed-bed, fluidized-bed, or entrained-bed. The type of gasification process used will impact particle filtration operating conditions. The different types of gasifiers produce different filtration conditions where the significant parameters affected are filtration temperature, gas chemistry, char or dust morphology, and system material requirements.

PFBC Power System

In a PFBC system, jets of air suspend a mixture of coal and sorbent (limestone or dolomite) during combustion, converting it into a suspension of red-hot particles that flow like a fluid. The sorbent captures sulfur oxides that are released by the burning coal. By pressurizing the combustor, a combined cycle system can be created which increases power production. To realize this increased power production, the HTHP PFBC exhaust products must be cleaned of particulate matter. The HTHP filtered gas stream from the combusted coal is used to drive a gas turbine. Heat recovered from the exhaust of the gas turbine and the steam generated from the fluidized-bed drives a steam turbine.

To further improve PFBC plant efficiency, a partial gasification reactor (carbonizer) is added with an accompanying filter system. In this approach the production of a fuel gas permits topping combustion with the vitiated PFBC exhaust gas, thereby raising gas turbine inlet temperatures. Integrating combustion and gasification processes in this way results in a advanced PFBC system with more than 50 percent efficiency.

Particulate Removal Performance Goals for High-Temperature and High Pressure-Particulate Cleanup Systems

New Source Performance Standards (NSPS) mandated by the Clean Air Act requires stationary power sources, greater than 70 MWe, to control particulate emissions to stringent levels. This level of particulate control will limit the emissions of particulate matter to below 0.03 pound of particulate emitted per million Btu of fuel consumed (0.03 lb/MMBtu, higher heating value). This level of cleanup can be attained with fabric bag-type filters and electrostatic precipitators presently deployed on conventional coal-fired power plants. Future regulations presently under consideration by the Environmental Protection Agency may tighten the present NSPS by a factor of ten. It is the intent of these particulate emission standards to have a positive effect on the environment. By most estimates, limitations on gas turbine inlet particulate concentrations are more stringent than existing NSPS and possibly future NSPS.

Gas turbine manufacturers are concerned with particulate inlet concentrations caused by deposition and erosion of gas turbine blades. Due to the uncertainty associated with the deposition and erosion mechanisms, particular turbine manufacturers tend to specify a range of particulate concentrations and particle size limits. Furthermore, the different manufacturers provide different specifications or ranges. In general, erosion limits stipulate that there should be no particles greater than 10 microns in diameter, 10 percent between 10 and 5 microns in diameter, and 90 percent less than 5 microns in diameter. Particle deposition appears to be a concern for concentrations greater than 100 ppm_w. Figure 1 illustrates both the turbine inlet and environmental limitations for particulate matter. Particulate removal requirements for gas turbines essentially determine the performance goals for particulate cleanup systems in the PFBC and IGCC coal-based power systems.

Meeting particulate concentration and size limitations for gas turbines will also provide other benefits. One benefit is the lack of fouling of post-turbine heat recovery steam generators. Furthermore, due to the absence of particulate matter, denser tube spacing with higher throughputs can be achieved, producing more efficient and compact heat transfer equipment. Additionally, conventional post-process particulate cleanup would no longer be required to meet environmental emission standards. This eliminates the need for an expensive bag house filter or an electrostatic precipitator.

HTHP Particulate Cleanup in the Clean Coal Technology Projects

The DOE is sponsoring several advanced technology demonstration projects through the CCT program. These projects cover a broad range of technology areas, from coal cleaning prior to utilization to advanced power systems. Presently, three of these projects are utilizing HTHP gas stream cleanup technology. These projects and the HTHP particulate cleanup systems are described below.

Piñon Pine Power Project

The Piñon Pine Power Project, near Reno, Nevada, was awarded to the Sierra Pacific Power Company (SPPCo) during Round 4 of the Department of Energy's Clean Coal Technology Program.[2] In this IGCC project, SPPCo will demonstrate the KRW air-blown gasification technology, hot gas desulfurization with zinc-based sorbents, Westinghouse Science & Technology Center's Advanced Particulate Filter (APF), and a General Electric frame 6FA combustion turbine. A depiction of the Piñon Pine process in block diagram form is shown in Figure 2. In this 100 MW IGCC project, coal and sorbent are fed to the gasifier. Generated fuel gas leaves the gasifier, where it enters a cyclone that removes entrained solids for recycle back to the gasifier. The fuel gas then enters a series of heat exchangers and is cooled from 1800 °F to 1000 °F. The coal gas then enters the external zinc oxide-based desulfurization system which removes sulfur, in the form of hydrogen sufide, down to a 20 ppm_v level. Process gas then enters a Westinghouse barrier filter system for particulate removal prior to combustion in the gas turbine. Steam is generated from the exhaust gas of the combustion turbine with a power split of about 60 percent and 40 percent between the gas and steam turbines, respectively.

In the Westinghouse APF design, shown in Figure 3, cluster assemblies are suspended from an uncooled tube sheet.[3] Each cluster supports a plenum assembly which physically holds the gasketed barrier filter. In this design, candle-type filter elements are used. The filter elements, together with the plenum, cluster, and tube sheet assembly, form the dirty side-to-clean side barrier. During the filtration process, dirty gas enters the pressure vessel and is forced to flow over a shroud which imparts a downward flow of gas parallel to the length of the cluster assemblies. Dirty gas then passes through the porous media, leaving the filtered dust as a cake on the surface of the filter element. The clean gas now inside the filter element is collected in the individual plenums and conveyed to the clean side of the tube sheet. Comingled process gas then exits the pressure vessel. Filters on individual plenums are cleaned periodically with a reverse pulse of high-pressure gas. Removed dust falls and is collected in the bottom of the vessel and discharged through a dust removal system.

The Westinghouse APF located at the Piñon Pine Project and shown in Figure 4 will represent the largest IGCC hot gas filtration demonstration of its kind in the world.[4] The Westinghouse filter will process the full gas stream under reducing conditions at 1011 °F and 260 psig. The APF, positioned downstream of the external desulfurization system, will process 318,000 lb/hr of process gas with an estimated dust loading of 17,700 ppm_w. In the Westinghouse design 748 porous-ceramic clay-bonded silicon carbide candle-type filter elements, each 1.5 meters long, will be suspended from 16 plenums. The tube sheet will support four cluster assemblies with four plenums on each cluster. The bottom plenums on each cluster will hold 61 filter elements with the other 12 plenums holding 42 elements each. The hot metal structure of the filter assembly will be housed in a ten-foot diameter by approximately 40-foot tall refractory-lined pressure vessel. The dust cake in the Piñon Pine application will be periodically cleaned with a high-pressure pulse of cleaned and recycled fuel gas.

The Piñon Pine project is scheduled for startup by April 1997.

Lakeland McIntosh Unit 4 Demonstration Project

The City of Lakeland, Florida, Foster Wheeler Development Corporation, and Westinghouse Electric Company have embarked on a technology demonstration project.[5] The project, sponsored through the Department of Energy's Clean Coal Technology Program, will demonstrate Advanced Pressurized Circulating Fluidized Bed Combustion (PCFBC) technology jointly developed by Foster Wheeler and Westinghouse. Foster Wheeler will supply the combustion technology and Westinghouse will supply the hot gas filter and gas turbine technology. The project will first demonstrate non-topped PCFBC technology and later demonstrate the topped PCFBC cycle. Figure 5 depicts, in block format, the Lakeland CCT project as a topped PCFBC process.

In the PCFBC technology, coal is combusted in a pressurized circulating fluidized-bed combustor at temperatures of approximately 1550-1650 °F and pressures from 150 to 235 psig. Sorbent, such as limestone or dolomite, is injected into the combustor to capture sulfur released from the coal. Combustion exhaust gas, along with entrained coal ash and sorbent fines, leaves the combustor and is passed on to a ceramic barrier filter. In the filter, particulate matter is removed at approximately 1550 °F and at high pressure. Clean process gas is than expanded through a gas turbine. After the gas turbine the process gas is used to raise steam in a heat recovery unit. This steam is combined with steam generated in the combustor.

In the topped PCFBC application, an air-blown carbonizer (similar to a fluidized-bed gasifier) and a gas turbine combustor are added to the PCFBC cycle. In this modification, coal is fed to a fluidized-bed-type carbonizer reactor under reducing conditions, thereby generating a low-Btu fuel gas and a char. The char is then fed to the combustor for complete oxidation. The low-Btu fuel gas is passed through a separate barrier filter at approximately 1400 °F. The low-Btu fuel gas is then mixed with the combustor exhaust gas, which contains excess oxygen, and the mixture is fired in a gas turbine topping combustor. This approach effectively allows the gas turbine inlet temperature to be raised, thereby increasing the power output and improving the cycle heat rate.

In the fully evolved topped PCFBC technology, two separate barrier filter systems will be required, one for the combustor and one for the carbonizer. While the project is still in the initial design phase, estimates suggest that the filter system on the combustor would be equivalent, on a size basis, to four Piñon Pine project-size filter vessels. The carbonizer would potentially have one filter vessel of significantly smaller size. Other differences in the two filter systems will be metallurgical and filter material selection to accommodate the oxidizing-versus-reducing gas conditions, the particulate matter morphology, and the higher temperature of the combustor filter.

The Lakeland PFBC project is scheduled for startup at the end of the year 2000, with the topped portion of the cycle scheduled for 2002.

Tampa Electric Company's Polk Power Station

The Tampa Electric Company and the United States Department of Energy are jointly funding a project awarded under Round 3 of the U.S. DOE's Clean Coal Technology Program.[6] The project, known as the Polk Power Station (Unit No. 1), will demonstrate a 250-MW integrated, oxygen-blown, entrained-flow gasification process with advanced combined cycle technology. The Polk Power Station will demonstrate fuel gas generation with the Texaco entrained gasification technology. The power station will utilize 95 percent pure oxygen from a highly integrated air separation unit and a General Electric 7F combustion turbine technology. A conventional cold gas cleanup system, capable of treating 100 percent of the process gas, will be utilized upstream of the gas turbine. Figure 6 depicts, in block form the Polk Power Station Unit No. 1 CCT process.

Hot gas cleanup technology developed by General Electric Environmental Services, Inc. (GEESI) will also be demonstrated at the Polk Power Station. The purpose of the HGCU system is to demonstrate the potential for higher IGCC system efficiencies. In this demonstration, a nominal 10 percent slip-stream will be extracted from the Polk Power Station process gas for direct cleanup from the gasifier at temperatures between 900-1000 °F. The HGCU system essentially consists of gross particulate removal via cyclones, halogen removal, sulfur removal, and fine particulate removal via barrier filtration.

The barrier filter system used in the GEESI HGCU train was designed and fabricated by Pall Corporation. The barrier filter system is positioned downstream of the sulfur removal system and upstream of the combustion turbine. Operating conditions for the filter are on the order of 900 °F and 400 psig, processing 1300 actual cubic feet per hour of dust-laden gas. The filter is designed with a single tube sheet capable of holding on the order of 60 candle-type filter elements. The barrier filter system will utilize either high-alloy porous-metal candle filter elements or clay-bonded silicon carbide porous ceramic candle filter elements. The filter elements are periodically cleaned with a high-pressure pulse of gas. The filter will be removing dust at a rate of 3 to 5 pounds per hour with an efficiency greater than 99.5 percent. Process fuel gas from the barrier filter will then be combusted prior to entering the gas turbine.

Operation of the Polk Power Station is presently underway.

Particulate Cleanup Performance Results in Pilot-Scale Applications

To facilitate the evolution and development of coal-based combined-cycle power systems, efficient and reliable particulate cleanup systems are required. Without this enabling technology, the high system efficiencies of the PFBC and IGCC power systems would not be possible. These system efficiencies are dependent on high levels of particulate capture at high temperature, where the sensible heat contained in both the fuel and or flue gases is preserved. Ultimately, the particulate capture performance of these filter systems will be based not only on the performance of individual filter elements but on the performance of the fully integrated filter systems.

Filter-element suppliers are offering filters with efficiencies greater than 99.9 percent for a 2-to-4-micron size range.[7,8] Filter elements functioning at this level of performance were a prerequisite for the design and development of commercial-scale systems. Filter element capture efficiencies have shown some dependence on filter body conditioning. In application, this filter-conditioning phenomena would probably be a one-time occurrence.

Several bench-scale tests of barrier filter systems have been conducted these are described below, where capture efficiencies have been reported. In these tests, determining the collection efficiency is equally dependent on knowing the inlet and outlet dust concentrations. Here, particulate capture efficiency, in percentage, can be defined as the difference between the inlet loading and the outlet loading, divided by the inlet loading, times 100 percent.

In a bench-scale simulator reactor, Westinghouse conducted long-term 3000-hr. and 2000-hr. tests simulating PFBC and gasification conditions, respectively.[9] These tests were conducted with ceramic cross-flow-type filters; however, the particulate capture performance should be representative of candle-type filters. In these tests, filter inlet loadings were between 1000 and 1500 ppm_w with an average outlet loading less than 1 ppm_w. This translates into a capture efficiency greater than 99.90 percent.

Westinghouse conducted filter performance tests on a 15-element cross-flow filter system.[10] The filter system was processing the effluent from a subpilot-scale 10-MW (thermal) PFBC. Particulate grab and impactor samples were taken over a 50-hr. and 30-hr. period, respectively. Both sampling procedures typically indicated loadings under 6 ppm_w , corresponding to 0.004 lb of particulate per million Btu of fuel consumed. Efficiencies were typically only slightly better than 99.1 percent due to low filter inlet loadings.

Schiffer et al. conducted a series of simulated and actual candle filter exposure tests over a range of temperatures, pressures, dust-loading and filter-cleaning parameters.[11] Over 5000 hours of exposure were conducted. Testing at times simulated PFBC conditions, but was often conducted at temperatures lower than typical PFBC temperatures and at atmospheric pressure. Collection efficiency was always greater than 99.71 percent, even for the low inlet loadings. The average efficiency was 99.85 percent for the five measurements performed, with outlet loading always less than 1 ppm_w.

Westinghouse also conducted a test program in which a single candle-type filter was subjected to 2005 cleaning cycles under simulated PFBC conditions.[12] In this test, the filter element was subjected to a range of process variables including face velocity, dust concentration, pulse source pressure, and pulse duration. In this test, both the candle filter element and the gasketing and filter hold-down assembly were subjected to repeated thermal cycles. Dust outlet concentrations were measured by isokinetically sampling the gas stream. The sampled gas was passed through an absolute filter. For the 19 reported measurements, the average collection efficiency was 99.45 percent, with an average outlet loading of 10.9 ppm_w. Ten of the measurements for outlet loading were at or below 5 ppm_w. The large variation in outlet loading is attributed to filter element sealing issues.

In 1990, American Electric Power Service Corporation, through a cooperative agreement with the U.S. DOE, awarded the Westinghouse Science & Technology Center a contract to install a HTHP advanced particulate filter (APF) on a one-seventh flow slipstream from the Tidd 70 MWe PFBC.[13] The Tidd PFBC CCT Demonstration Project, in Brilliant, Ohio, operated from late 1990 through March 1995.[14] At the time, this was the largest HTHP filter test ever conducted. During the APF operation 34 discrete operational periods were conducted with over 5800 hours of accumulated operation. Several of these operational periods accumulated over 400 hours of continuous operation. The filter design used in this test is similar to the design shown in Figures 3 and 4, but with only three clusters and three plenums per cluster. This assembly contains 384 candle filter elements of 1.5-meter length. The filter processed approximately 7600 actual cubic feet per minute of PFBC exhaust gas. As part of a study to assess the hazardous air pollutants emitted from the Tidd plant, Radian Corporation was contracted to conduct particulate sampling at the inlet and outlet of the APF.[15]

Sampling was conducted in triplicate toward the end of run number 18, a 443-hour continuous test of the APF. During each sampling period on the outlet of the APF, over 1300 dry standard cubic feet of gas was collected. As a result of this sampling, the Westinghouse APF was found to have a particulate collection efficiency of 99.993 percent.

In an effort to further characterize the particulate capture efficencies of pilot-scale barrier filter systems, additional measurements are planned.[16] These measurements will continue to establish the particulate capture performance of fully integrated filter systems and to provide an understanding of the chemical and physical properties of the char or ash derived from the IGCC and PFBC power systems.

Conclusions

IGCC and PFBC power systems will provide the technology for the continued generation of reliable and low-cost electricity. The ability of these advanced coal-based power systems to achieve these goals is made possible, in part, through the use of advanced turbine systems. The use of advanced turbines and the deployment of other efficiency-enhancement options in these advanced power systems has been enabled through the use of particulate-control technology. In addition, barrier filter systems have clearly demonstrated particulate capture efficiencies significantly greater than existing NSPS. These filter systems offer the potential to meet or exceed future regulations regarding particulate emission.

To bring this technology to fruition, the U.S. Department of Energy, through the Federal Energy Technology Center, will continue to support the development and deployment of these advanced coal- based technologies. This approach to developing and deploying cleaner, more efficient, and cost-effective power systems for the continued utilization of fossil fuel is consistent with the national energy strategy.

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Figure 1. Particulate loading and size distribution guidelines for gas turbines and NSPS.

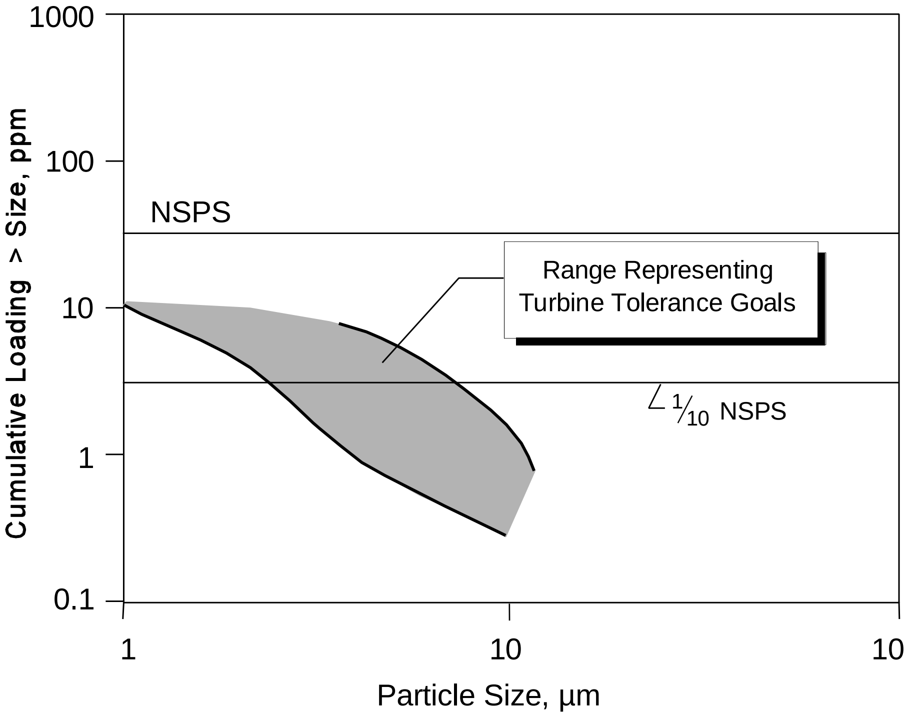

Figure 2. Block flow diagram of the Piñon Pine CCT process.

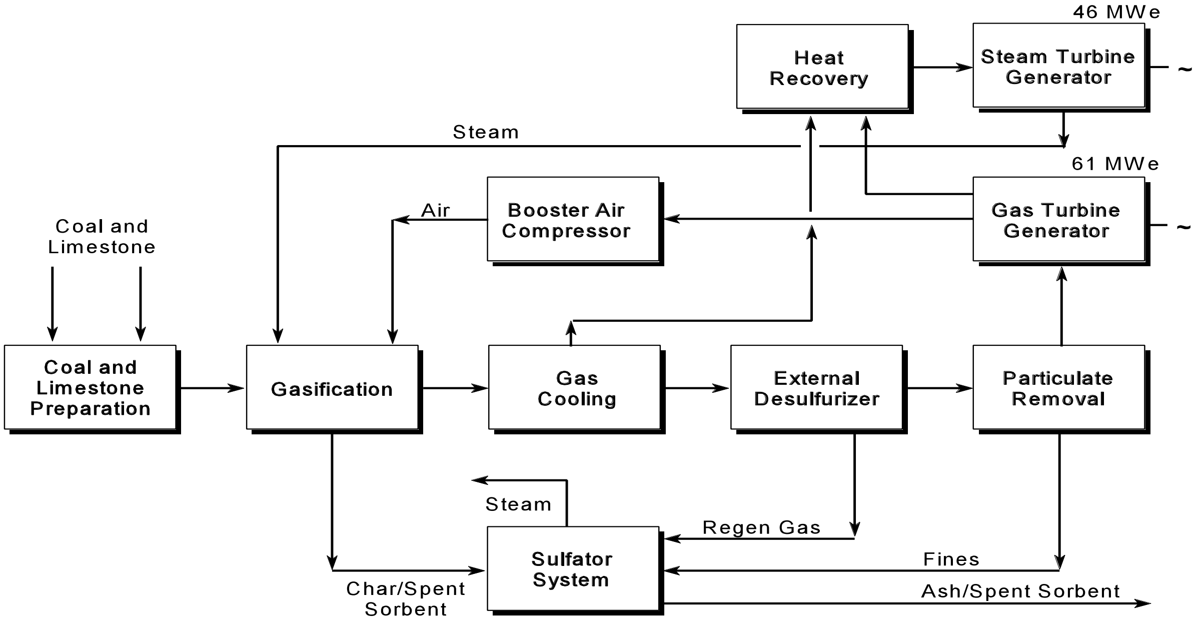

Figure 3. Conceptual design of the Westinghouse Advanced Particulate Filter.

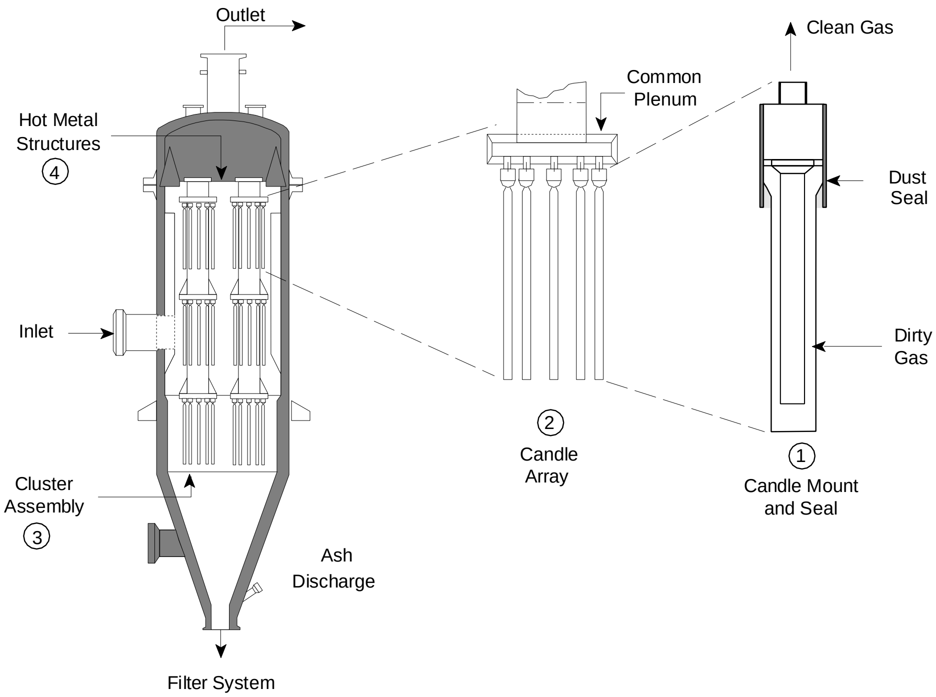

Figure 4. Westinghouse Advanced Particulate Filter design for the Piñon Pine CCT project.

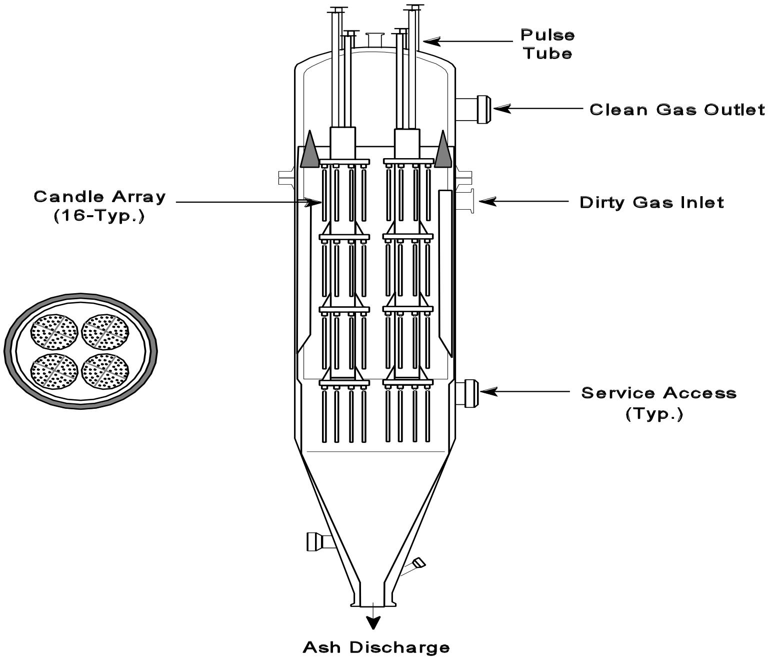

Figure 5. Block flow diagram of the Lakeland CCT process (Topped version).

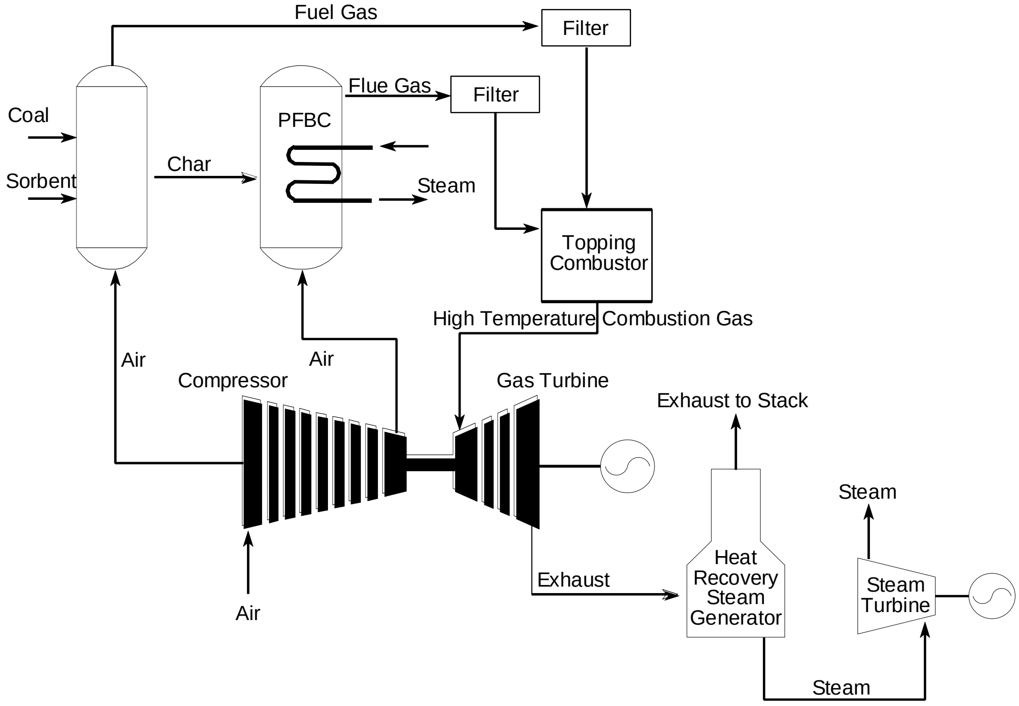

Figure 6. Block flow diagram of the Polk Power Station CCT process.