Session 5

Advanced Filter Systems

5.1 Status of the Morgantown Energy Technology Center's Particulate Cleanup Program -- Enabling Technology for Advanced Coal-Based Power Systems

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Advanced coal-based power systems, such as integrated gasification and pressurized fluidized-bed combustion (PFBC), require particulate removal at high temperatures and high pressure (HTHP) to achieve their high efficiencies. In this enabling role, HTHP cleanup systems must provide particulate removal efficiencies greater than 99 percent, with high availability, and while operating under adverse conditions. These conditions include corrosive gases, thermal fatigue, and thermal transients. To facilitate the development of advanced coal-based power systems, the Morgantown Energy Technology Center (METC) has assembled a Particulate Cleanup Program, which conducts technology demonstration projects and applied research to address the adverse filtration conditions and filter system issues, as well as the future performance demands of these systems. A brief status of the program follows.

A look at past accomplishments will provide a good perspective for evaluating the present status of the METC particulate cleanup program. For discussion purposes, the past is viewed in a 10-year time frame where accomplishments of others establish bench marks. These bench marks can indicate the relative progress of the program.

Between 1985 and 1992, the Grimethorpe PFBC Establishment operated the largest ceramic filter system in the world on the exhaust from a nominal 10 megawatt-thermal (MW_{th}) PFBC (1). The filter system utilized up to 130 1.5-meter long, clay bonded silicon carbide candle filters suspended from a single tube sheet. Actual gas-flow rates were nominally 1.085 cubic meters per second. During several test campaigns 2300 hours of definitive operation were obtained. During this test program the limited filter failures were typically a result of a faulty filter hold-down and sealing assembly or failure of filter cleaning pulse valves. Candle filter elements used in these tests showed a significant loss in strength, which was attributed to high thermal stresses as a result of back-pulse cleaning with cold gas.

From 1986 to 1989, HTHP particulate control tests were conducted at the Department of Energy's New York University PFBC Test Facility. In this program three particulate control devices were tested, including an electrostatic precipitator (ESP), a granular bed filter (2), and cross flow filter systems (3). Gas-flow rates were nominally 0.5663 actual cubic meters per second from the 5-MW_{th} PFBC. Two-hundred hours of testing was planned for each device. Test results indicated delamination and sealing problems with the cross flow filter, voltage discharge problems with the ESP, and control and erosion problems with the granular bed filter.

During 1987 and 1988, HTHP particulate cleanup tests were conducted at the KRW fluidized-bed gasifier with ceramic candle filters (4). During this test period, over 650 hours of exposure were obtained on the clay bonded silicon carbide filter element. The filter vessel housed 33 1-meter long filter elements from a single tube sheet and filtered up to 0.160 actual cubic meters per second of dirty gas. During this test period, filter failure was attributed to system upsets and the candle filter hold-down assembly.

During 1992, eleven separate filter tests were conducted with the Texaco slagging entrained-flow gasifier located at Montebello, California (5). A total of 678 hours of test time was accumulated, with flow rates to the filter vessel ranging between 0.0472 and 0.0755 actual cubic meters per second. Tests were split between either four or eight cross-flow filters or nineteen candle filters. Both clay bonded silicon carbide and alumina/mullite candle filters were used. Candle filters were suspended from a single tube sheet. When the cross-flow filters were used, they were mounted to plenums and then suspended from a single tube sheet. Significant strength reduction was measured in all candle filter materials. The cross-flow filter showed signs of delamination.

In summary, past tests, both under PFBC and IGCC conditions, have been conducted at the pilot and sub-pilot scale. These tests clearly established the ability of the proposed technology to meet particulate removal, pressure drop, and heat loss requirements for the advanced coal-based power systems. It was through the success of these tests that the technical issues facing this technology were firmly established. In general, test results indicated a significant reduction in strength of both the clay bonded silicon carbide and alumina/mullite ceramic filter materials; a need for a better filter hold-down and sealing assembly; a need for longer and more continuous test times; the importance of coal, sorbent, and coal conversion process on dust cake performance; and a need to test and evaluate filter systems that exhibit commercial-scale features. These results established the issues and questions that needed to be addressed in order to bring HTHP particulate cleanup technology to fruition.

The present status of the particulate cleanup program is best ascertained by reading the papers presented in the Advanced Filter Systems and Filter Technical Issues sections of this conference's proceedings. These papers will show that significant accomplishments have been made towards the commercialization of HTHP particulate filter systems by addressing the technical issues developed over the past several years. Briefly these accomplishments include the long duration testing of candle filter systems, which represent commercial-scale subassemblies; the demonstrated ability to clean multiple filter elements from a single blow back nozzle; the development of a candle filter failsafe and thermal regenerator device; an improved understanding of dust cake behavior; a better understanding of candle filter strength degradation mechanisms; the advancement of alternate particulate control technologies; and the utilization of improved materials for ceramic filters. These advances will minimize the risk of future demonstration-scale testing of HTHP particulate control systems.

Our vision for the future is being shaped by our best made plans from the past and present. These plans include the demonstration of particulate cleanup technology at Southern Company Service's Power Systems Development Facility and the Clean Coal Demonstration Projects. The near-term aspect of these projects has set the cadence towards our future goals. The success of development and testing over the next 2 years will be critical to achieving these goals.

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5.2 Potential Industry Use of Continuous Fiber Ceramic Composites

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ABSTRACT

This presentation will introduce the Continuous Fiber Ceramic Composite (CFCC) Program, whose goal is to develop, in industry, the primary processing methods for the reliable and cost-effective fabrication of CFCC components for industrial applications. CFCC components are expected to be used in gas turbines, heat exchangers, radiant burners, and hot gas filters. The main focus of the presentation will be on how CFCC components in industry will benefit the environment and the economy, and the technical progress made by team members to date. The presentation will also cover the program strategies, status, and structure. The last section will discuss the impact of CFCC components on the market.

5.3 Ceramic Fiber Ceramic Matrix Filter Development

CONTRACT INFORMATION

Contract Numbers	DE-AC05-84OR21400 (ORNL) Field Work Proposal FEAA028 93X-SB482C (3M)
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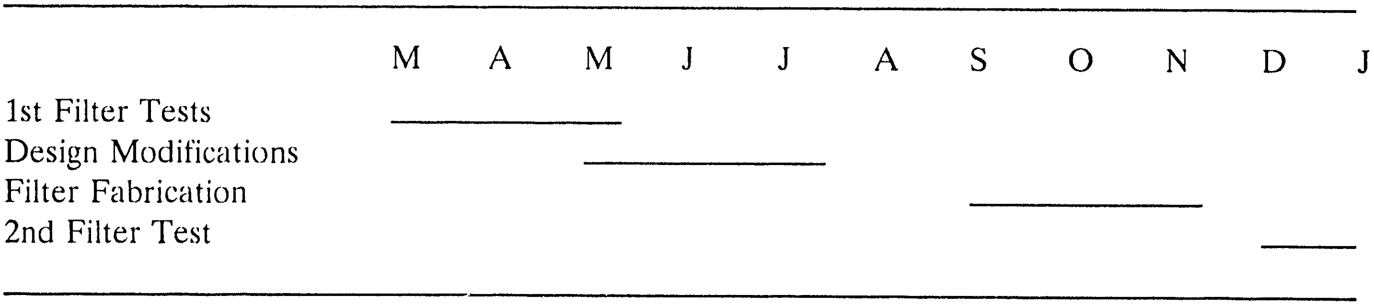
HQ Program Manager	James P. Carr
METC Project Manager	Richard A. Dennis
Period of Performance	October 1986 to Present

Schedule and Milestones

FY 1993/94 Program Schedule



OBJECTIVES

The objectives of this project were to develop a novel type of candle filter based on a ceramic fiber-ceramic matrix composite material, and to extend the development to full-size, 60-mm OD by 1-meter-long candle filters. The goal is to develop a ceramic filter suitable for use in a variety of fossil energy system environments such as integrated coal gasification combined cycles (IGCC), pressurized fluidized-bed combustion (PFBC), and other advanced coal combustion environments. Further, the ceramic fiber ceramic matrix composite filter, hereinafter referred to as the ceramic composite filter, was to be inherently crack resistant, a property not found in conventional monolithic ceramic candle filters, such as those fabricated from clay-bonded silicon carbide. Finally, the adequacy of the filters in the fossil energy system environments is to be proven through simulated and in-plant tests.

BACKGROUND INFORMATION

The successful development and deployment of several advanced coal-fueled gas turbine technologies depend greatly on the ability to clean fuel or combustion gas streams of particulates prior to these gases being passed through the turbines. These technologies include IGCC, PFBC, and direct coal-fired turbines. Rigid ceramic filters of a variety of designs are either commercially available or under development in programs around the world. Several filter designs are in use or are being developed. The most popular is the candle filter, which resembles a laboratory test tube in having one end closed and a flanged opening at the other.

Rigid ceramic candle filters are currently being developed to remove particulates from gas streams being introduced into hot-gas turbines. Filter systems large enough to handle the volume of gases for typical IGCC or PFBC systems will be extremely expensive. For example, a 300-MW(e) oxygen-blown IGCC power plant has a gas flow of about 8 m^3/s. In order to filter such a large volume of gas, approximately 130 m^2 of filter area or 1660 candle filters would be required. An air-blown gasifier would generate twice the gas flow and, therefore, require approximately 3300 candle filters. PFBC systems generate five times the volume of gas of an air-blown gasifier and would require 16,000 candle filters. Assuming candle filters could be purchased in large quantities for $300 to $600 each, the cost of one set of candles would range from $0.5 to $1.0 million for an oxygen-blown gasifier and from $5 to 2$10 million for a PFBC.[1]

Many different materials – oxides, nonoxides, and mixed – may be used for any of these ceramic filter types. The most popular oxide ceramics include alumina/mullite, cordierite, aluminosilicate foam/fibers, clay-bonded alumina, fireclay, and continuous fiber ceramic composites produced by chemical vapor infiltration (CVI). Nonoxide ceramics include clay-bonded silicon carbide, sintered silicon nitride, reaction-bonded silicon nitride, recrystallized silicon carbide, and CVI silicon carbide fiber-reinforced composite filters. Fabric filter materials include various grades of silica-alumina-boria, alumina-silica, and silicon carbide-silica. Most commercial and near-commercial ceramic filters are made of bonded ceramics. Several advanced concepts are being investigated and developed, including a ceramic composite filter developed at Oak Ridge National Laboratory (ORNL), which is being scaled to full-size by 3M Company of St. Paul, Minnesota. Ceramic composites have several properties that make them attractive for this application. They do not fail catastrophically as do monolithic ceramics; equivalent strengths can be achieved with much thinner and lighter structures; they have greater mechanical and thermal shock resistance; and they have greater resistance to chemical degradation compared to clay-bonded materials. In addition, they retain other properties of ceramics such as high strength (due to a silicon carbide matrix); refractoriness; good abrasion and corrosion resistance; and good oxidation resistance. Figure 1 provides a comparison of the failure characteristics of monolithic and fiber-reinforced composite ceramics.

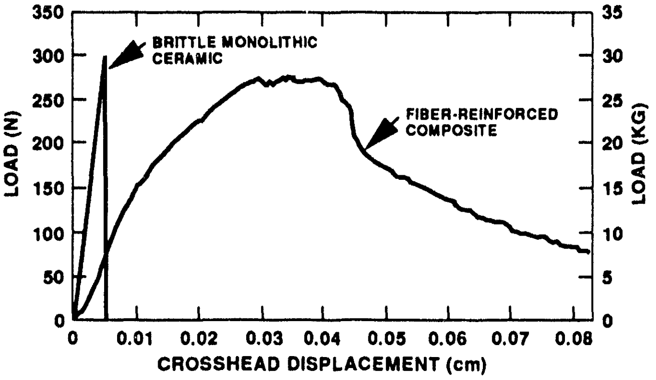


Figure 1. Load-displacement curves for monolithic and fiber-reinforced ceramics

PROJECT DESCRIPTION

This project was begun in FY 1986 as an exploratory effort derived from a project at ORNL on the development of dense ceramic composites for heat exchange applications. This project, which was funded by the U.S. DOE Office of Fossil Energy Advanced Research and Technology Development (AR&TD) Materials Program, involved the production of ceramic composites by CVI of a ceramic matrix into a structural form, hereinafter preform, of ceramic fibers. Several concepts for ceramic composite filters were examined at ORNL. Figure 2 is a schematic of the CVI process.

Based on initial results, the ORNL filter work was continued under DOE-Morgantown Energy Technology Center (METC) Surface Gasification Materials Program sponsorship in FY 1987, and the AR&TD Materials Program also continued to support CVI process development and the evaluation of the filters. Tests of filter specimens were conducted at ORNL, Acurex Corporation, and the Coal Research Establishment (United Kingdom). The ORNL work was continued from FY 1988 through 1991 under METC Advanced Research funding. In FY 1989, the 3M Company was awarded a contract on the AR&TD Materials Program through competitive bidding to scale the ORNL invention (Patent No. 5,075,160) to full-size candle filters.

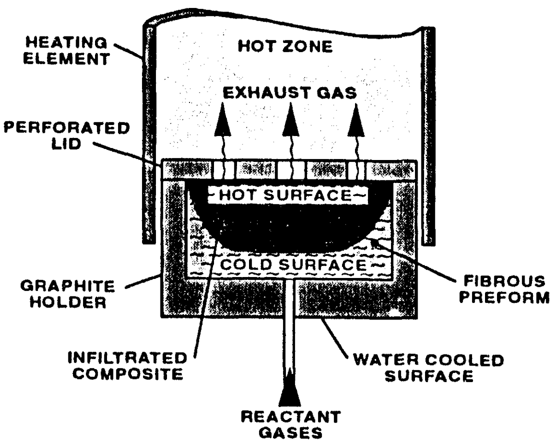


Figure 2. Chemical vapor infiltration process schematic

To aid the project in addressing relevant issues, a project was conducted by Acurex Corporation and Virginia Polytechnic Institute and State University to assess the causes of failure of ceramic filters.[2] Several common failure modes were identified. These included thermal and mechanical shock, strength degradation during use, plugging, cracking/breaking at the flange/candle body junction, and binder degradation due to chemical attack. Suspect causes of these failures were improper mounting techniques, tubesheet design, pulse cleaning, candle design, system transients, and corrosive contaminants in gas streams. Information from this project was incorporated into the 3M project to ensure that the filter developed by 3M would not suffer from the same deficiencies of other ceramic filters.

Many other tests and investigations of the suspected modes and causes of failures of ceramic candle filters as well as ceramic materials in other applications have been conducted.[3-16] The results of those investigations were also considered in the present work.

RESULTS

In mid-FY 1993, 3M Company completed the development of its first-generation ceramic composite candle filter. This first-generation filter, shown in Fig. 3, was a filament-wound structure with three plies of Nextel 312 with a filter surface on the exterior of the candle. The filter surface is a barrier layer of chopped fibers or felt. The binder for the filter is a silicon carbide matrix deposited by chemical vapor deposition (CVD).

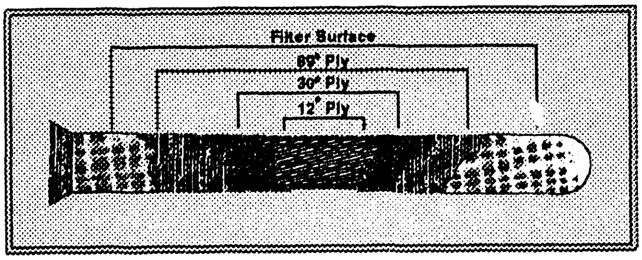


Figure 3. First-generation 3M Company Ceramic Composite Filter

Two of the first-generation 3M Company filters were tested at the Westinghouse Science and Technology Center (STC) in March 1993. These tests were conducted in a simulated PFBC environment at 815 to 830°C for a total of 136.4 operating hours. Ten turbine trip simulation thermal transients were made and the filters withstood these transients without cracking or failure. Filter performance was good and consistent with other ceramic candle filters. However, one candle filter experienced patchy cleaning and partial (≈75%) loss of the filter surface. Details of this phase of the filter development are presented in a 3M Company report entitled *Fabrication of Full-Scale Fiber Reinforced Hot-Gas Filters by Chemical Vapor Deposition*.[17]

Improvements in filter construction and fabrication processing were made by 3M. Among the most significant changes were strengthening of the flange seal area; elimination of the filament-wound structure; and the incorporation of a loosely woven outer layer to address the problem of sloughing off of the filter surface. The resultant structure incorporates a filter surface sandwiched between a tightly woven inner layer and the loosely woven outer layer of Nextel fibers. This loosely woven outer layer is evident in Fig. 4, which is a photograph of the 3M Company Ceramic Composite Filter and a clay-bonded silicon carbide filter.

Testing of six of the 3M Company's second-generation filters was conducted at Westinghouse STC in December 1993. As in the tests of the first-generation filters, these filters were tested in a simulated PFBC environment at 820°C and 0.7 MPa. Tests were conducted for 172 total operating hours using two lots of ash from the Grimethorpe (United Kingdom) PFBC. The first lot, from Grimethorpe Run 132, has been used in many filtration tests at Westinghouse STC and is generally considered to be a typical and relatively easy to filter PFBC ash. The second lot, from Grimethorpe Run 129, is a red ash that is particularly difficult to filter. As before, thermal transients were produced by simulated turbine trips. In these tests, 14 thermal shock tests were conducted.

The new, second-generation design 3M Ceramic Composite Filters met or exceeded all performance criteria for a successful test. They proved to be more durable than the previous design, and none of the filter surface came off during the tests. Dust removal efficiencies exceeded 99.8% with <4 wppm dust in the exit gas from the filters. The filters reached stable, conditioned permeability after 50 cleaning cycles. Permeance values and trends were consistent with clay-bonded filters. Acceptable cleaning of the filters was maintained using up to 300-psig pulses of cleaning gas. Mounting and gasketing maintained dust seals without apparent leakage. Post-test examination indicated significant but not excessive strength reductions. There was no damage (breakage, cracks, distortion, etc.) apparent to the 3M filters as a result of the test.

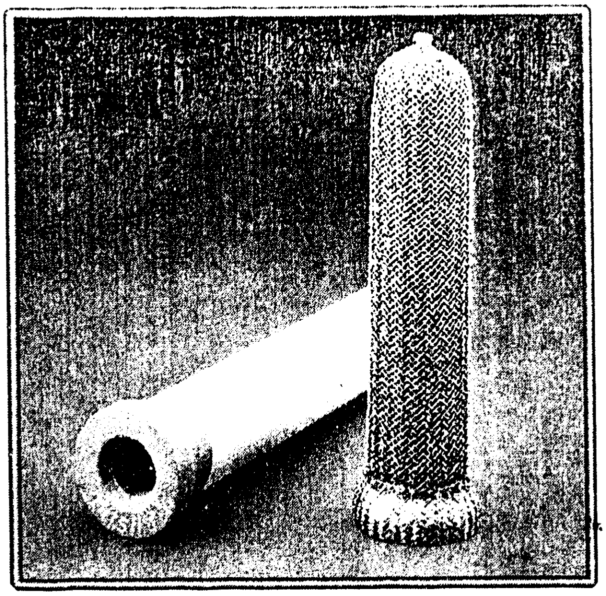


Figure 4. Second-generation 3M Ceramic Composite Filter and a clay-bonded silicon carbide filter

Based on the development and test results presented here, as well as additional studies at ORNL and elsewhere,[18] we have concluded that the 3M Company Ceramic Composite Filter is a viable filter for PFBC and IGCC applications, as well as other advanced coal combustion applications.

FUTURE WORK

The 3M Company Ceramic Composite Filter has performed well in PFBC simulation tests. Additional tests are needed in an operating PFBC and in an IGCC. To this end, three of the filters have been placed in the filter vessel at the Tidd PFBC for testing. At Tidd, approximately 7% of the process gas stream is diverted to the filter system. Filters have been, and are being, provided to many companies for testing in their specific applications. Testing in the Ahlstrom Pyropower Circulating Pressurized Fluidized Bed (CPFB) pilot plant in Karhula, Finland, is also being pursued. This would be an excellent test of the filters. The Karhula plant is a 10-MW(t) CPFB in which 100% of the process gas stream is directed through the filters, as opposed to the situation at the Tidd PFBC in which a small portion of the process gas flows through the filter vessel.

The 3M Company Ceramic Composite Filter is near to commercialization. It offers a viable and preferred alternative to clay-bonded ceramic filters for PFBC and IGCC applications.

This project provides an excellent example of cooperation between the Department of Energy-Fossil Energy AR&TD Materials Program, Coal Technology Programs, and industry. It also is a most successful example of technology transfer from a national laboratory to the industrial sector. This project also confirms the validity of the research and development (R&D) approach which involved good technical assessments of requirements and a disciplined approach to the R&D needed to satisfy those requirements.

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5.4

Westinghouse Advanced Particle Filter System

CONTRACT INFORMATION

Contract Number	DE-FC21-89MC21023 DE-FC21-89MC26042 DE-FC21-90MC25140
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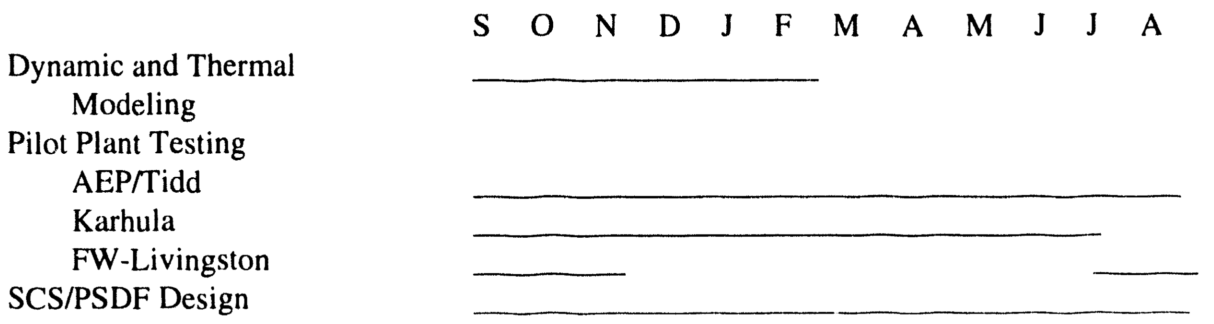
Principal Investigators	Gerald J. Bruck Zal N. Sanjana Richard A. Newby
METC Project Manager	Richard A. Dennis
Period of Performance	October 1992 thru September 1997

Schedule and Milestones

Schedule and Milestones FY94



OBJECTIVES

Integrated Gasification Combined Cycles (IGCC) and Pressurized Fluidized Bed Combustion (PFBC) are being developed and demonstrated for commercial, power generation application. Hot gas particulate filters are key components for the successful implementation of IGCC and PFBC in power generation gas turbine cycles. The objective of this work is to develop and qualify through analysis and testing a practical hot gas ceramic barrier filter system that meets the performance and operational requirements of PFBC and IGCC systems.

BACKGROUND INFORMATION

High temperature particulate filters are a key component in advanced, coal based gas turbine cycles (IGCC and PFBC) that are currently under development by DOE/METC for clean coal demonstration. In these applications the hot gas particulate filter protects the downstream heat exchanger and gas turbine components from particle fouling and erosion effects and cleans the gas to meet particulate emission requirements. Both PFBC and IGCC plants benefit because of lower cost downstream components, improved energy efficiency, lower maintenance and the elimination of additional and expensive flue gas treatment systems.

In IGCC systems, the hot gas particulate filter must operate in reducing gas conditions (i.e., presence of H_2, CH_4, CO), high system pressure (150 psi to 350 psi) and at operating temperatures usually determined by the method of sulfur removal, i.e., in bed, external or by cold gas scrubbing. Typically, these temperatures range around 1650°F (in bed), 900 to 1200°F (external) and 1000°F to 500°F (cold scrubbing).

In gasification applications, cold scrubbing of the fuel gas has been demonstrated as effective in cleaning the fuel gas to meet turbine and environmental requirements. However, with this process, plant energy efficiency is reduced, and higher capital costs are incurred. Incorporating a hot particulate filter upstream of the scrubbing unit reduces heat exchanger costs and provides for dry ash handling.

Hot fuel gas cleaning concepts (in bed and external) have also been proposed that utilize reactive solid sorbents to remove gas phase sulfur and hot gas filters to collect the ash and sorbent particles. This approach in IGCC provides for highest energy efficiency and lowest cost of electricity.

IGCC systems may utilize air or oxygen blown entrained or fluid bed gasifiers. Specific operating conditions of the hot gas particulate filter will vary depending on these choices. In general, hot gas filter pilot plant test experience suggests that gasifier ash/char is noncohesive with relatively high flow resistance. Thus, the potential for fines reentrainment and high filter pressure drop are reduced by selecting a relatively low design filter operating face velocity (<5 ft/min). Since the filter treats only the fuel gas component of the total gas flow, the choice of a low filter face velocity does not adversely impact economics. Typically, for a 100 MW_e IGCC system, the filter is required to treat only 6000 to 12,000 acfm, depending if the gasifier is oxygen or air blown. Inlet dust loadings may also vary widely, ranging from <1000 ppmw to 10,000 ppmw.

Bubbling bed PFBC technology is currently being demonstrated at commercial scale. Two PFBC units are located in Sweden (Stockholm Energi, Vartan Plant), another one at the Endesa's Escatron Plant in Spain and one in the United States at the American Electric Power's (AEP) Tidd Plant located in Brilliant, Ohio. The Tidd PFBC is a 70 MW_e demonstration plant awarded through the Round 1 U.S. DOE Clean Coal Technology Demonstration Program. Currently, all four plants utilize high efficiency cyclones to remove greater than 95% of the ash and a ruggedized gas turbine to tolerate ash carried over from the upstream cyclones. Economic and performance improvements in these first generation type PFBC plants can be realized with the application of hot gas particulate filters. Both the secondary cyclone(s) and stack gas ESP(s) could be eliminated saving costs and providing lower system pressure losses. The cleaner gas (basically ash free) provided with the hot gas filter, also permits a wider selection of gas turbines with potentially higher performance.

For these bubbling bed PFBC applications, the hot gas filter must operate at temperatures of 1580 °F and system pressures of 175 psia (conditions typical of the Tidd PFBC plant). Inlet dust loadings to the filter are estimated to be about 500 to 1000 ppm with mass mean particle diameters ranging from 1.5 to 3 μm. For commercial applications typical of the 70 MW_e Tidd PFBC demonstration unit, the filter must treat up to 56,600 acfm of gas flow. Scaleup to about 320 MW_e would require filtering over 160,000 acfm gas flow. For these commercial scale systems, multiple filter vessels are required. Thus, the filter design should be modular for scaling.

An alternative to the bubbling bed PFBC is the circulating bed concept. In this process the hot gas filter will in general be exposed to higher operating temperatures (1650 °F) and higher (factor of 10 or more) particle loading. Although the inlet particle loading is high, it contains a significantly coarser fraction (mass mean generally >15 μm) which helps mitigate the effect of the higher mass loading. For a 75 MW_e commercial scale circulating bed PFBC plant, gas flow to the filter is approximately 70,000 acfm. At this scale, multiple vessels with modular filter subassemblies are required.

Second generation (or advanced) PFBC is being developed and planned for demonstration and commercialization. In this plant, higher (than first generation PFBC) turbine inlet temperatures are achieved by partially devolatilizing the coal in a carbonizer unit producing a fuel gas. The char produced is transferred and burned in a circulating PFBC unit with high excess air. The hot (1600 °F) vitiated air produced is used to combust the hot fuel gas to raise the combustion gas temperature to as high as 2350 °F (Robertson, et al., 1989). With second generation PFBC, two hot gas filters are required. One filter is used to collect the ash and char material carried over from the carbonizer unit with the hot fuel gas. The second filter is used to remove ash and sorbent particles carried over with the hot vitiated air leaving the circulating pressurized fluidized bed combustor (CPFBC). Both filter units are required to operate at high temperatures (1200 to 1600 °F) and high particle loading. The fuel gas filter will operate in reducing gas while the CPFBC filter operates in oxidizing conditions. A 95 MW_e second generation PFBC demonstration plant requires a hot fuel gas flow to its filter of about 8000 acfm and hot vitiated air flow to its filter of approximately 64,000 acfm.

Westinghouse is currently evaluating candle and cross flow filter devices in subpilot and pilot scale PFBC facilities. These units are designed and operated to support the scaleup of these filters to commercial scale. Table 1 identifies the subpilot and pilot scale facilities that are currently operating (or plan to operate) with a ceramic barrier filter test system supplied by Westinghouse.

Foster Wheeler Advanced PFBC Facility

This testing is taking place at the Foster Wheeler Development Corporation (FWDC) pilot plant facility located at the John Blizard Research Center in Livingston, New Jersey. The second-generation PFBC development is divided into three phases. The first phase, already completed, developed a conceptual design of the commercial scale plant and identified R&D needs (Robertson et al., 1989). The second phase, completed in 1993, involved separate subscale pilot tests of the carbonizer/filter and circulating fluid bed combustor/filter components. The carbonizer/filter testing was initiated in June 1992 and completed in September (Newby et al., 1993). Following this test program, the facility was modified for CPFBC operation, utilizing the candle filter unit. Shakedown tests on the combustor/filter components were initiated in

February 1993. Initial results from this testing have been reported (Lippert et al., 1993). A brief summary of the final test run made in the Phase II activity is reported herein. In phase three of the project, an integrated second generation PFBC pilot plant facility is being constructed and operated. The integrated facility includes both carbonizer and combustor filter units. This testing is scheduled to begin in June 1994.

Advanced Particle Filter Hot Gas Filter Slipstream (AEP/APF)

In August 1989 a cooperative agreement was signed between Ohio Power Company, through its agent, the American Electric Power (AEP) Service Corporation and the U.S. DOE to assess the readiness and economic viability of high temperature and high pressure (HTHP) particulate filter systems for PFBC. The test facility is a one-seventh (1/7) slipstream taken from the Tidd 70 MW (electric) PFBC Clean Coal Demonstration Plant located in Brilliant, Ohio (Mudd et al., 1992). Results of this testing are reported in a companion paper.

Ahlstrom PCFB Facility

Ahlstrom Pyropower has built a 10 MW (thermal) pressurized circulating fluidized bed combustor (PCFB) - ceramic barrier filter test facility located in Karhula, Finland. Through the AEP-PFBC hot gas cleanup cooperative agreement, the U.S. DOE/METC, AEP, Pyropower, EPRI and Westinghouse have embarked on a program to test the Westinghouse candle filter system under PCFB conditions. Results of this work are reported in a companion paper.

Power System Development Facility (PSDF)

Southern Company Services, under a DOE Cooperative Agreement (DE-FC21-90MC25140), is designing and constructing a Power Systems Development Facility that is intended to test and evaluate advanced coal based power generation systems and components. One test module is a 4 MW_e, Advanced Pressurized Fluidized Bed Combustion (APFBC) System including hot gas filters and gas turbine components. A second test module is a dedicated hot gas filter test leg consisting of the M. W. Kellogg transport technology for pressurized combustion and gasification to provide either an oxidizing or reducing gas environment. The full description of the PSDF is given in a companion paper. Westinghouse is providing two hot gas filters for installation and operation at the PSDF. One filter is intended for the combustor leg of the APFBC module. The second filter will be installed on the M. W. Kellogg transport reactor module.

PROJECT DESCRIPTION

Westinghouse is developing a high temperature particulate filter system for application in IGCC and PFBC, advanced power generation systems.

The Westinghouse hot gas filter design, shown in Figure 1, consists of stacked arrays of filter elements supported from a common tubesheet structure. In this design, the arrays are formed by attaching individual candle elements (Item 1) to a common plenum section (Item 2). All the dirty gas filtered through the candles comprising this single array is collected in the common plenum section and discharged through a pipe to the clean side of the tubesheet structure. Each array of filter elements is cleaned from a single pulse nozzle source. The individual plenum assemblies (or arrays) are stacked vertically from a common support structure (pipe), forming a filter cluster (Item 3). The individual clusters are supported from a common, high alloy tubesheet structure and expansion assembly (Item 4) that spans the pressure vessel and divides the vessel into its "clean" and "dirty" gas sides. Each cluster attaches to the tubesheet structure by a specially designed split ring assembly. The cluster is free to grow down at temperatures. The plenum discharge pipes ducting the filtered gas to the clean gas side of the tubesheet structure are contained within the cluster support pipe and terminate at the tubesheet. Each discharge pipe contains an eductor section. Separate pulse nozzles are positioned over each eductor section. The eductors assist pulse cleaning. During cleaning, the pulse gas is contained within and ducted down the discharge pipe and pressurizes the respective plenum section.

The plenum assembly and cluster (stacked plenums) form the basic modules needed for constructing large filter systems indicative of PFBC requirements. The scaleup approach is:

- Increasing plenum diameter (more filter elements per array)
- Increasing the number of plenums per cluster
- Increasing the vessel diameter to hold more clusters

In general, vessel diameter will be limited by the tubesheet structure and desire to shop fabricate the vessel. Larger PFBC plants would utilize multiple vessels.

The pulse gas used to clean the filters is provided from a pressurized source and delivered and controlled through a series of pipes and valves that comprise the pulse delivery subsystem. The key operating component is the fast acting solenoid valve that controls the pulse action. Figure 2 shows a simplified schematic of a single back pulse module. The module consists of a pressurized gas source, the pulse gas control function and the pulse gas distribution manifold. The cleaning pulse is initiated by first selecting and opening (through the control logic) one of the pneumatic activated ball valves on the pulse gas distribution manifold. The control solenoid valve is then activated allowing a short, high pressure pulse to travel through the opened ball valve and discharge through the pulse nozzle. High reliability and maintainability of this system is obtained by providing a redundant pulse gas control leg and associated isolation valves that allow on-line maintenance. The control logic is developed to automatically switch to the redundant line should a failure signal be received. Control of the pulse cleaning system will be based on either a timing sequence or filter pressure drop signal. The practical operation of this system has been demonstrated in the Tidd PFBC 10 MW_e hot gas filter slipstream.

This paper updates the assessment of the Westinghouse hot gas filter design based on ongoing testing and analysis. Results are summarized from recent computational fluid dynamics modeling of the plenum flow during back pulse, analysis of candle stressing under cleaning and process transient conditions and testing and analysis to evaluate potential flow induced candle vibration.

RESULTS

Computational Fluid Dynamics Modeling. A transient flow analysis was conducted to evaluate the flow conditions within the clean gas plenum section during a pulse cleaning event. The objective of the analysis was to determine the time when the pressure drop (given criteria) across the ash cake of each candle (during cleaning) was sufficient to remove the cake deposit. Also of interest is how the flow field is affected after the first candle is cleaned. A fifty-two (52) candle element plenum array was chosen for analysis. Computations were carried out using a general purpose computational fluid dynamics code. The symmetry of the flow field permitted solution in only half the domain. The major physical features of the candle/plenum arrangement are illustrated in Figure 1. The flow solution was three-dimensional and included the effects of compressibility and turbulence. Figure 3 shows the three dimensional CFD model. For this initial analysis, it was assumed the dust cake to be uniform and that cleaning of any single candle was uniform over its length.

Results of the analysis show all 52 candles (considering symmetry) are cleaned within a 48.4 to 49.0 ms after start of the pulse cleaning event. Table 2 shows the sequence of candle element cleaning. It was found that the velocity and temperature fields did not vary significantly in the time interval when the candles are cleaned. The flow field is not affected in a manner that would disrupt the cleaning of the other candles and that the candles are all cleaned at relatively the same time. Additional analysis is being considered to evaluate effects of nonuniform candle cleaning, nonuniform cleaning between candles, assumptions on ash properties and impact of broken candles.

Flow Induced Vibrations. The Westinghouse hot gas filter design utilizes free hanging candles fixed at one end to a metal plenum section. The possibility of damaging flow included vibration in the candle element caused by either normal gas filtration or pulse cleaning has been evaluated. The natural frequencies of the candle and mounting system were calculated and measured. The measurement was conducted by fastening accelerometers to the end of one of the candle elements mounted in the Westinghouse filter unit installed at the AEP/Tidd PFBC plant. Experiments were performed by "bumping" the candle and recording response; including frequencies and damping characteristics. From this testing, the largest spikes on the power spectra occurred at 84.37 and 114.45 Hz. Results of finite element mode frequency analysis that modeled the candle/holder system confirmed the measured natural frequencies. Four potential flow included effects were evaluated; Vortex shedding, jet switching, circumferential skimming and turbulence, Table 3. Failure criteria for each mode was established and then compared to the estimated effect based on the filter flow conditions, geometry and natural frequency. The turbulence parameter was estimated based on the results of computational fluid modeling done for one specific installation and flow arrangement. Results of the analysis show that the estimated effect of each flow mode fall significantly below the failure criteria. In general, therefore, flow induced vibration during the normal filtration process is not expected to be a significant factor in the mechanical durability of the candle filter system.

Following the "bump" tests on the accelerometer instrumented candle element in the Tidd filter unit, a series of cold back pulse tests were conducted to measure the candle acceleration and damping as a function of pulsing pressure. In these tests, as expected, the maximum acceleration (e.g., loading) increases with increased pulse tank pressure, Figure 4. The maximum measured acceleration was 0.7 g's at 700 psi under ambient conditions.

Since the g acceleration is expected to vary directly with modulus of elasticity, actual g loading under operating conditions are expected to be decreased. Calculations show that the reaction force at the candle caused by a 1-g loading results in a candle bending stress of less than 200 psi, well within the modulus of rupture limits of candidate candle materials.

Filter Thermal Stressing. Thermal stressing of the filter media occurs with cold backpulsing and whenever there is a sudden and rapid change in the process gas temperature. Such changes may be associated with plant startup, shutdown, plant trip or some unanticipated plant upset.

During filter cleaning, relatively large quantities of (cold) pulse gas flow through the porous ceramic wall causing rapid cooling within the ID wall region and high local tension stressing. Westinghouse calculations, given in Figure 5, show that local wall stresses are well in excess of the modulus of rupture (MOR) of current commercial candle filters. However, the ID wall stresses quickly, dissipate as the pulse gas is heated by the filter. As a result, microcracking of the ID surface may occur. The propensity of these microcracks to grow quickly and cause catastrophic filter failure is a property of the material (critical threshold stress intensity, K_{1c}). K_{1c} values are estimated by using a combination of two experimental techniques – the stressing rate dependence of strength and interrupted static fatigue tests.

Accelerated pulse cycling tests are currently being conducted to identify microcracking and confirm the integrity of candle elements.

Process thermal transients generally last several minutes or longer, subjecting the full filter body to temperature change. Pilot plant testing has shown that process thermal transients may range from $< \pm 10\,^\circ$C/min to over $\pm 100\,^\circ$C/min. Thermal process transients that cycle, i.e., first increase temperature then decrease temperature, even through relatively low in magnitude, cause the filter body (from OD to ID) to cycle between tension and compression stressing, Figure 6. Such conditions may cause pre-existing flaws or cracks to grow, causing catastrophic failure of the filter element. Although large demonstration and commercial PFBC and IGCC plants are expected to be well controlled and process upsets minimized, tolerance to process thermal transients is a primary requirement of any filter material.

Pilot Plant Testing - Foster Wheeler APFB. The Phase II APFB pilot testing was completed in early December 1993. Filter testing has included separate operation on both the carbonizer and circulating pressurized fluid bed (CPFB) units (Lippert et al., 1993). The same 22-element candle filter unit was utilized for both the carbonizer and CPFB testing, Figure 7. The CPFB testing included a significant shakedown period (approximately 400 hours, representing nine different test runs) to evaluate CPFB operation and control. During this period the CPFB was tested on both coke and coal and the filter was exposed to severe upset events and process conditions that would vary widely. Candle breakage was incurred in some of the shakedown runs.

The final CPFB test run, following shakedown in the Phase II program, included a 180 hour continuous test period in which the CPFB and filter operated under char and coal fired conditions, Table 4. In this test, the filter was configured with 14 candle elements to operate at a face velocity of about 7.8 ft/min. the filter inlet dust loading ranged from about 1000 ppmw to 40,000 ppmw (depending on coal/char feedstock). Filter operating pressure drop was stable throughout the test run. The CPFB operated smoothly and without major upset. Inspection of the filter following completion of the test run showed the 14 candle element to be undamaged. No indication of dust leaks to the clean side could be identified. The residual filter cake was relatively uniform in appearance and did not show any crusty sublayer of sodium or potassium sulfate eutectic that had been experienced in one of the earlier shakedown runs.

Following the Phase II component testing, Foster Wheeler has now reconfigured the pilot plant to include integrated carbonizer and CPFB operation. The Westinghouse Phase II candle filter unit will be integrated with the carbonizer. A second hot gas candle filter unit has been designed and supplied for the CPFB. Table 5 summarizes the design and expected operating conditions for the two Westinghouse filter units. Phase II operation is expected to be initiated in late June or early July, 1994.

SCS/PSDF - Hot Gas Filters. Westinghouse is designing two hot gas particle control devices (PCD) for installation at the Southern Company Services Power System Development Facility located in Wilsonville, Alabama. Table 1 summarizes the basis for the two PCD designs. PCD 352 will be installed and integrated with the Foster Wheeler circulating PFBC unit. The filer is designed to utilize candle filter elements. Operating experience gained from the Karhula PCFB and Tidd PFBC filter testing have been factored into the PCD 352 design. Improvements include increased spacing between the candle elements and plenum pipe support structure, redesign of the plenum dust shields to enlarge and improve the path for ash discharge; recessing the candle filter holders into the clean gas plenum sections thus eliminating the region where dust can bridge and form clumps that ultimately can break off and get trapped between the candle elements. A steeper cone angle and large outlet flange are also employed in the vessel ash hopper region to promote ash discharge. The PCD 352 is scheduled to be delivered to the PSDF in the first quarter of 1995.

The PCD 301 unit will be initially installed and operated on the M. W. Kellogg transport reactor test module. The PCD 301 is designed to interchange the test cluster to accommodate a variety of filter types including:

- Advanced Candles
- Cross Flow
- CeraMem Axial Cross Flow
- Ceramic Bags

FUTURE WORK

Continued testing of Westinghouse hot gas filter system is planned this summer at the Foster Wheeler APFBC pilot plant facility. Testing of the Advanced design PCD 301 and 352 at the SCS/PSDF is scheduled to be initiated in the second or third quarter in 1995. Results of these and other ongoing filter testing will be utilized to demonstrate and qualify the Westinghouse Advanced Particle Filter for Clean Coal and commercial application.

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Newby, R. A. et al., 1993. Cross Flow Filter Performance with Second-Generation PFBC Carbonizer Fuel Gas. Paper presented at the 1993 International Fluidized Bed Combustion Conference, May 18-23, 1993 in San Diego, CA.

Robertson, A. et al., 1989. Second-Generation Pressurized Fluidized Bed Combustion Plant: Research and Development Needs. Foster Wheeler Development Corporation, Livingston, NJ. Phase 1 Task 2 Report FWC/FWDC-TR-89/06 to the U.S. DOE under contract DE-AC21-86MC21023.

Table 1. Hot Gas Filter Pilot Plant Test Facilities

	Advanced PFBC (Foster Wheeler)				Southern Companies Services Power Systems Development Facility	
	Carbonizer	Combustor	PFBC (AEP-Tidd)	PCFB Ahlstrom	APFB Foster Wheeler	Transport Reactor, MWK
Facility Size	2 MWt	1.2 MWt	10 MWe	10 MWt	4 MWe	2 MWt
Coal Feed	Dry	Dry	Paste	Paste	Dry	Dry
Operating Temperature	1400-1600°F	1400-1650°F	1300-1550°F	1500-1650°F	1650°F	1800°F
Operating Pressure	100 - 200 psi	100 - 200 psi	130 - 150 psi	130 - 150 psi	200 psi	350 psi
Gas	Reducing	Oxidizing	Oxidizing	Oxidizing	Oxidizing	Reducing (Oxidizing)
Gas Flow (Nominal)	120 acfm	750 acfm	7500 acfm	3100 acfm	6000 acfm	1000 acfm
Precleaning	None	None	Cyclone	None	Cyclone	Cyclone

Table 2. Candle Cleaning Times

Time (sec)	Candle Numbers
0.04844	4
0.04845	5
0.04847	6
0.04848	1
0.04850	7
0.04852	8
0.04853	9, 16, 20
0.04855	10, 17, 19
0.04857	11, 21, 22
0.04858	12, 18
0.04859	13
0.04861	14
0.04862	15
0.04873	3
0.04877	2
0.04880	27
0.04882	26
0.04886	25
0.04884	28
0.04893	24
0.04899	23

Table 3. Summary of Candle Flow Induced Vibration Evaluation

Flow Mode	Criteria		Estimated	Comment
Vortex Shedding	At Critical Frequency (84 Hz)		~0.34 Hz	0.34<<84 Hz No Issue
Jet Switching	u/fD ≥100		0.2	0.2<<100 No Issue
Circumferential Skimming	Velocity >590 ft/s		<<590 ft/sec	No Issue
Turbulence ($0.5\ m^2/sec^2$)	Work Energy From Turbulence	>Energy Lost in Damping	$W_T<2\%W_D$	No Issue

Table 4. Summary of CPFB TR5 Test Run

Operating Temperature	1550° F (Nominal)
Pressure	100 to 130 psi
Face Velocity	7 to 8 ft/min
Baseline ΔP	25 - 30 in wg
Dust Loading	1000 to 40,000 ppmw
Test Hours	183

Table 5. Summary of Hot Gas Filter Design and Operating Conditions for Phase III APFBC Testing

PHASE 2 FILTER - CARBONIZER

- Design Gas Flow (acfm) - 120
- Number Candles: 14 (max. 22)
- Face Velocity (ft/min): 2 - 3
- Pressure (psig): 100 - 200
- Temperature (° F): 1400 - 1600
- Dust Loading (ppmw): 2,000 - 20,000

CPFB FILTER

- Design Gas Flow (actual = 750)
- Number Candles: 36 (max 48)
- Face Velocity (ft/min): 5 - 8
- Pressure (psig): 100 - 200
- Temperature (° F): 1400 - 1650
- Dust Loading (ppmw):

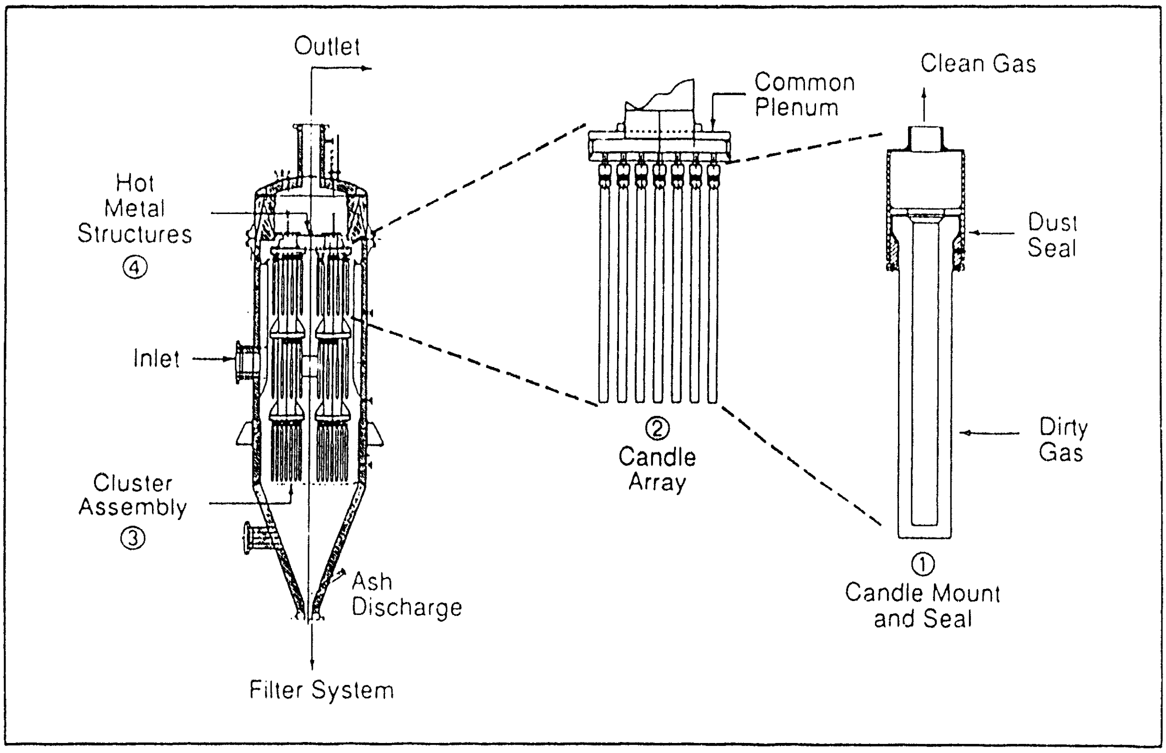


Figure 1. Hot Gas Cleaning Systems - Westinghouse Candle Filter System

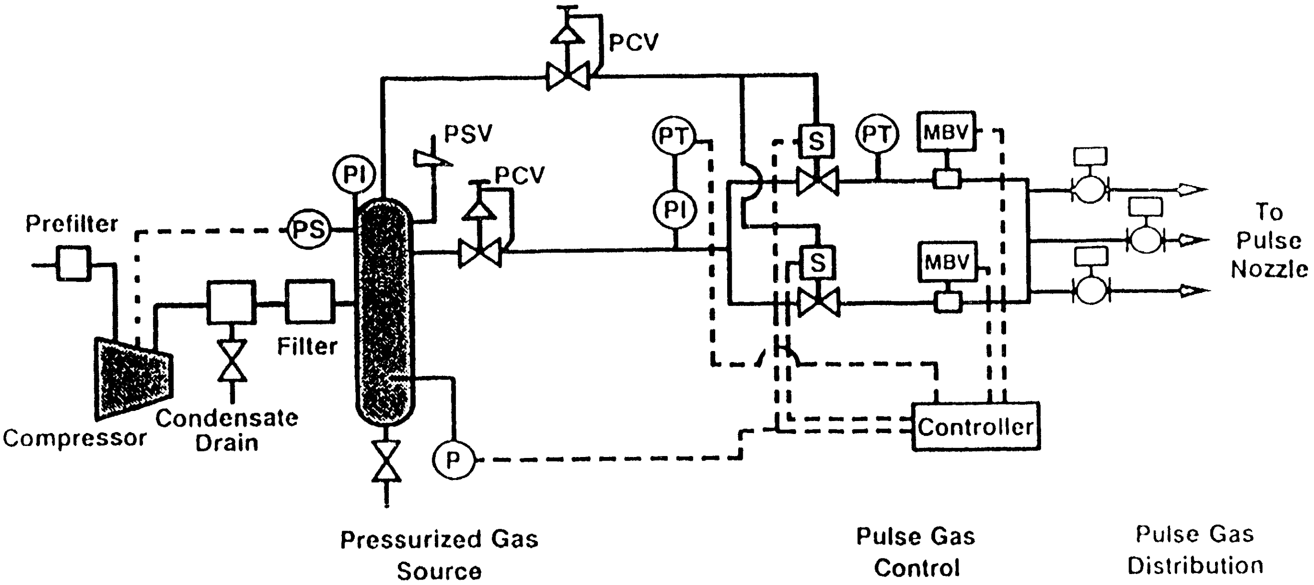


Figure 2. Pulse Gas System Schematic

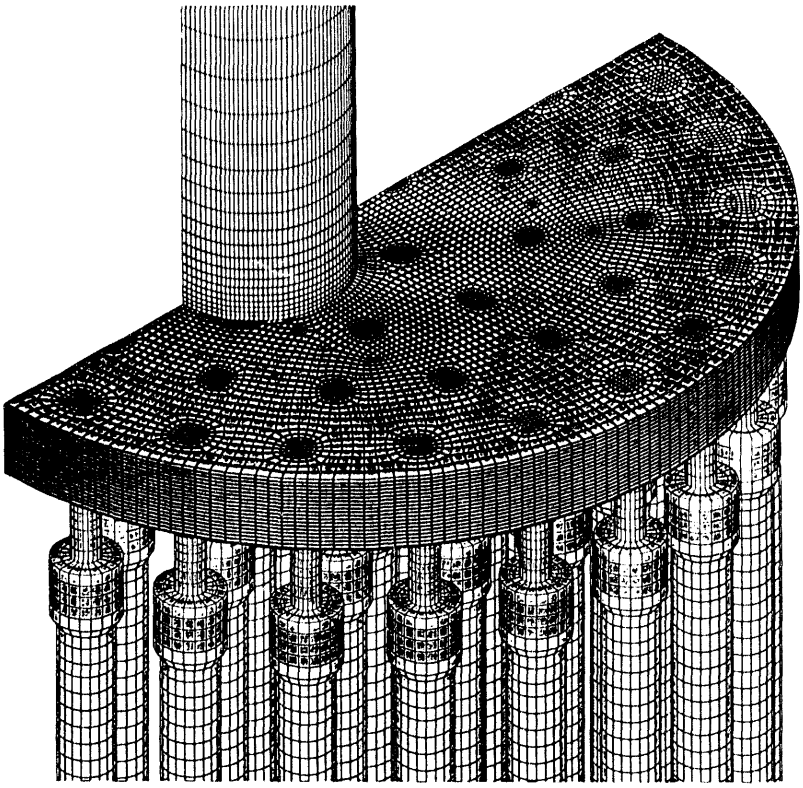


Figure 3. Westinghouse Candle Filter System

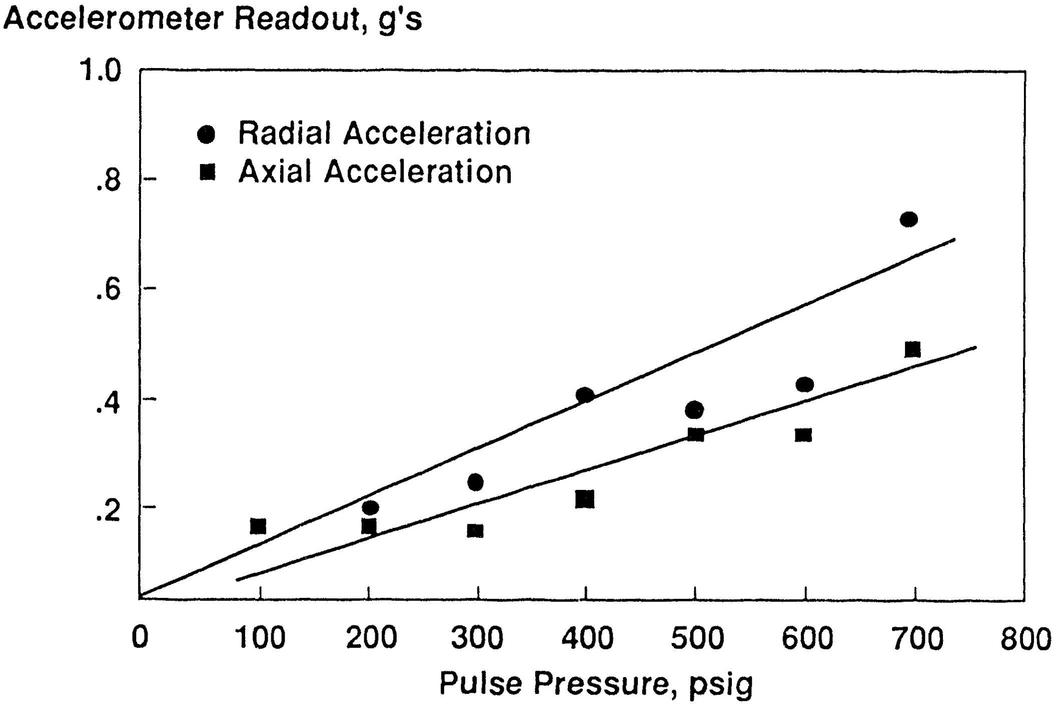


Figure 4. Pulse Induced Vibrations - Test Results

- High Candle ID Wall Tension Stresses - > MOR
- Potential ID Wall Damage (i.e. Microcracks)
- High Stressing Limited to 1 mm Wall Thickness
- Bulk of Filter Wall in Compression

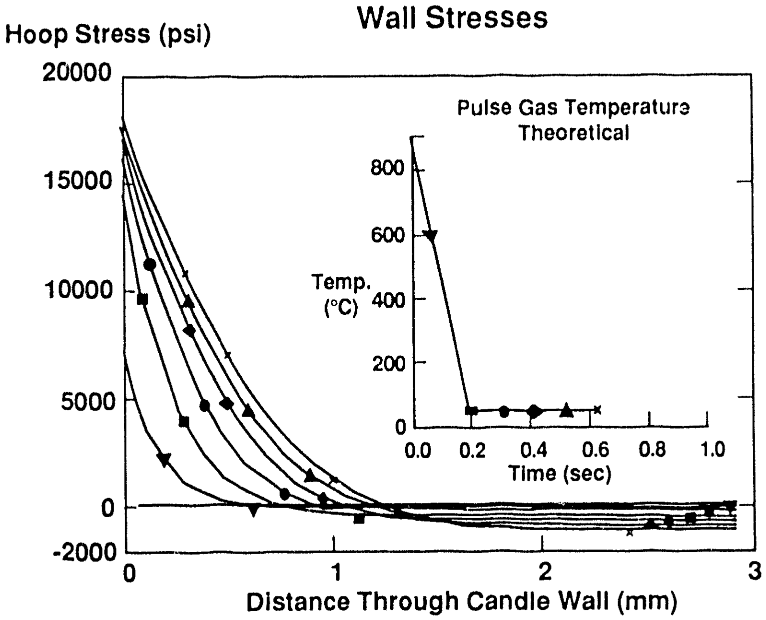


Figure 5. Filter Element Stressing - Cold Pulse Cleaning

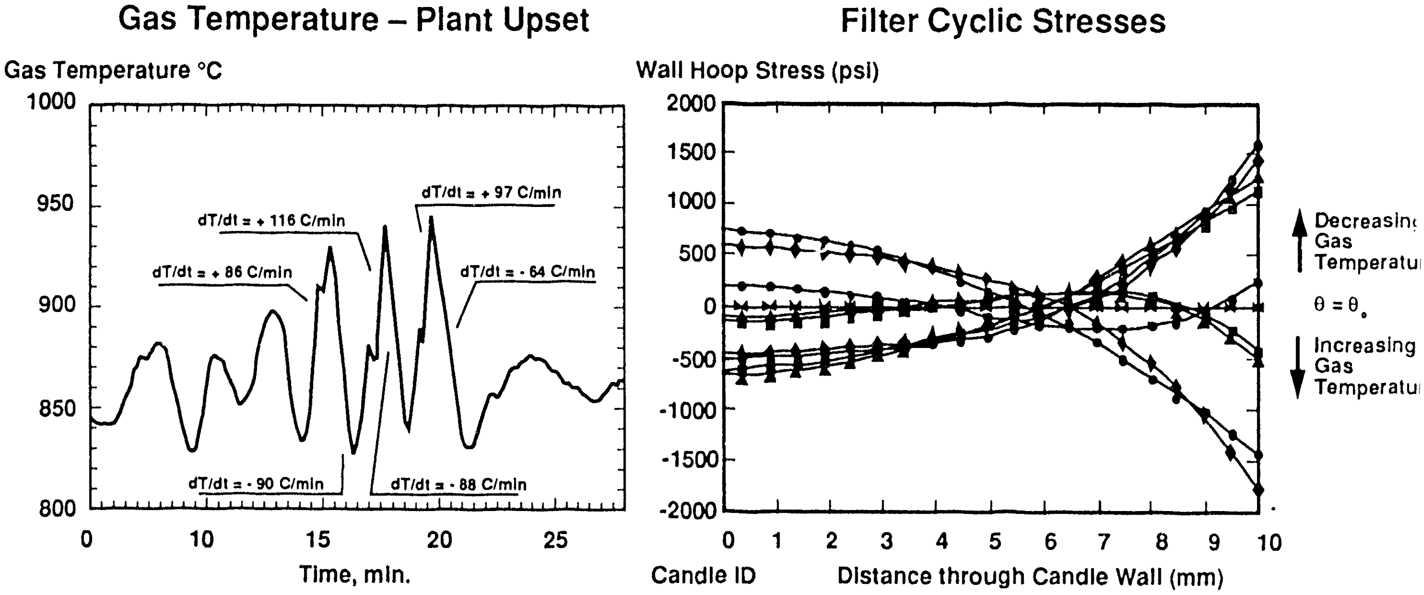


Figure 6. Filter Element Stressing - Process Transients

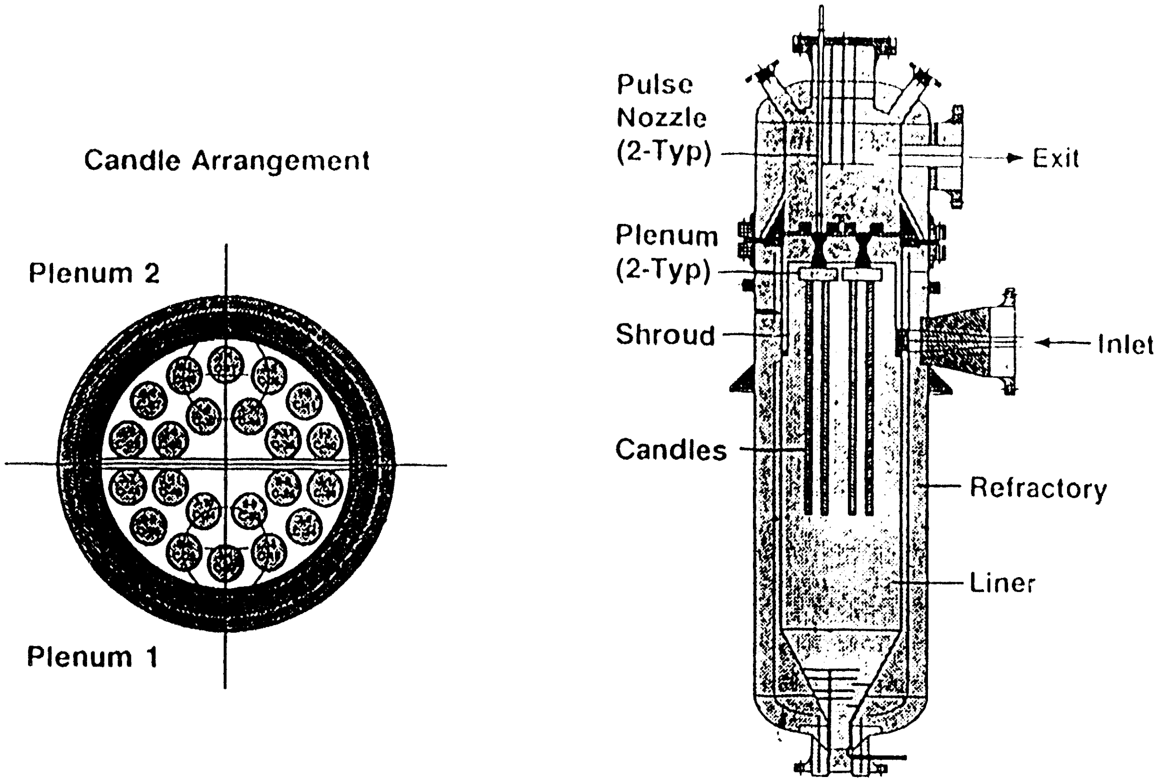


Figure 7. Schematic of 22-Element Candle Filter Installation

5.5

IF&P Fibrosic™ Filters

CONTRACT INFORMATION

Contract Number DE-FG02-92ER81349

Contractor
Industrial Filter & Pump Mfg. Co., Inc.
5900 Ogden Avenue
Cicero, IL 60650
(708)656-7800

Contract Project Manger Paul M. Eggerstedt

Principal Investigator Paul M. Eggerstedt

METC Project Manager Norman T. Holcombe

Period of Performance July 27, 1992 to February 17, 1995

Schedule of Milestones

Program Schedule

	1992	1993	1994	1995
Phase 1	**********			
Phase 2		************************		
Candle Strength Testing		**************		
Tubesheet Strength Testing		***************		
Corrosion Studies			*****	

OBJECTIVES

The primary objective of this SBIR research program is to increase the performance, durability, and corrosion resistance of lightweight filter candles and filter tubesheet components (Fibrosic™), fabricated from vacuum formed chopped ceramic fiber (VFCCF), for use in advanced coal utilization applications. Phase I results[1] proved that significant gains in material strength and particle retentivity are possible by treatment of VFCCF materials with colloidal ceramic oxides. Phase II efforts will show how these treated materials tolerate high temperature and vapor-phase alkali species, on a long-term basis. With good durability and corrosion resistance, high temperature capability, and a low installed and replacement cost, these novel materials will help promote commercial acceptance of ceramic candle filter technology, as well as increase the efficiency and reliability of coal utilization processes in general.

BACKGROUND INFORMATION

Ceramic candle filtration is an attractive technology for particulate removal at high temperatures. Due to their simple and cost effective design, temperature capability, and high filtration efficiency, ceramic candles are one of the few clean-up technologies which can consistently meet gas turbine manufacturer's inlet particulate requirements and Clean Air Act mandates. Unfortunately, traditional ceramic candles, made from granular silicon carbide, etc., can be prone to failure from physical and thermal shock as well as chemical attack. These candles also tend to be expensive and, owing to their weight, present internal filter design problems.

VFCCF Filter Materials

Unlike traditional filter candles, VFCCF filter candles offer unique properties for use in HGCU applications, as shown below:

VFCCF Filter Candle Properties:

- Formed from stable ceramic oxides
- Lightweight
- High temperature capability
- Fibers & binder share similar thermochemical properties
- "Knitted" pore matrix

Typically, VFCCF filter candles are formed from commercially available fibers and binders, using existing vacuum forming technology, resulting in a low cost product with excellent manufacturing uniformity and quality control. Because the fibers and binders are essentially a blend of stable, pure ceramic oxides, such as alumina and aluminosilicate materials, the amount of contaminants, organics, etc. which might be reactive in certain applications is negligible.

With apparent density values in the range of 17-22 lbs/ft^3, VFCCF candles are much lighter in weight than their granular ceramic counterparts. This low density, which translates into a weight savings of 70-80% over isostatically pressed silicon carbide filter elements, results in a highly permeable filter with roughly twice the pore volume as granular filter candles. Additionally, as a direct result of the weight savings, the design and construction of the tubesheet and supporting hardware becomes a much easier task, not to mention the reduced stress on the filter candle flange.

VFCCF fibers and binders are typically rated for a maximum temperature of 2600°F to 2800°F, and do not exhibit significant physical changes, such as shrinkage, until a temperature of about 2300°F. is reached. As a result, they are suitable for use in nearly all IGCC and PFBC applications, where temperatures are generally 2000°F. or lower.

Because VFCCF binders are nearly identical in chemical composition to that of the fibers, differences in thermochemical properties between the binder and fiber are negligible, resulting in excellent thermal shock and thermal spalling resistance, as well as resistance to microcracking caused by differences in the thermal expansion coefficients of the fiber and binder. As a consequence of the fiber geometry within the VFCCF matrix, these candles also have an inherently high crack resistance, due to the "knitting" tendency of the fibers during fabrication, and their random orientation which tends to blunt microcrack propagation. Table 1 summarizes these important properties of VFCCF materials.

In the course of fabrication of VFCCF candles, it was found that such materials respond extremely well to treatment with colloidal ceramic oxide materials, which can increase strength, add corrosion resistance to suit a given application, and allow for the particle retention of the filter element to be controlled, all of which have led to the research effort discussed in this report. With their combined high temperature capability, low thermal expansion, corrosion resistance, and resistance to catastrophic failure, VFCCF materials show promise for use as filter candles and other internal filter hardware, such as a tubesheet, with proper colloidal treatment.

Table 1. VFCCF Material Properties

Typical Chemistry	35-60% Al_2O_3 40-65% SiO_2
Apparent Density	17-22 lbs/ft^3
Maximum Use Temperature	2800°F
Thermal Conductivity (1500°F)	1.26 BTU-in/ft^2-°F-hr
Permanent Lineal Shrinkage (2000°F)	less than 0.8%
Coefficient of Thermal Expansion	2.8 x 10^{-6} in/in-°F

PROJECT DESCRIPTION

Phase 1 Efforts

The overall objective of the Phase 1 effort was to determine which colloidal ceramic oxides of those tested exhibited the greatest increase in the strength of VFCCF filter candle and tubesheet specimens. In the case of VFCCF filter candles, strength increases were valued as important, but not at the expense of acceptable permeability. A total of five different colloidal ceramic oxides, applied using two distinctly different methods, were investigated as shown in Table 2.

Table 2. Colloidal Ceramic Oxide Tests

Materials Tested	Application Methods
Silica Alumina Zirconia Yttria Ceria	Spray Infusion

The materials above were selected on the basis of their temperature capability, corrosion resistance, thermal expansion compatability with VFCCF materials, commercial availability, and cost. Application methods were approached from the standpoints of reproducibility of results, relative cost, and minimal complexity. In both application methods, variations in the colloidal material concentrations as well as the total amount of material applied to the candle and tubesheet test specimens were evaluated in an effort to optimize a technique for producing filtration components with superior performance characteristics.

Phase 2 Efforts

Several goals of the Phase 2 effort are expected to be met as a result of this ongoing research, namely:

- Selection of the most suitable colloidal ceramic oxide material for use in increasing VFCCF material strength and corrosion resistance, without greatly sacrificing permeability (in the case of filter candle applications);

- Development and optimization of the most promising colloidal ceramic oxide application methods, suitable for mass production of VFCCF components;

- Development and refinement of other means of increasing strength and durability of VFCCF materials, including such techniques as:

  -Filter candle flange, end-cap, and forming die modifications;
  -Investigating the effect of varying fiber type and fiber length on VFCCF material strength;
  -Investigation of lamination and joining techniques for structural VFCCF uses.

Descriptions of each of the above aspects of this research effort follow.

Colloidal Ceramic Oxide Material Selection. In addition to the colloidal oxide materials cited earlier, Phase 2 tests involving colloidal mullite were performed, and appear to be particularly promising. Colloidal mullite has good thermochemical properties and corrosion resistance, adds considerable strength, and tends to form a desirable divergent, acicular pore structure within the VFCCF candle matrix after infusion and subsequent curing. Several VFCCF filter candle specimens prepared in this manner were tested in a PFBC application at Argonne National Laboratory, through funding from the Illinois Clean Coal Institute (ICCI), with excellent results[2], other similarly prepared candles are being tested for permeability decay and durability at Acurex Corp. in Mountain View, CA.

Colloidal Ceramic Oxide Treatment of VFCCF Materials; Spray Application Trials. In continuation of the Phase 1 effort, colloidal ceramic oxides have been applied to aluminosilicate VFCCF matrices, both singularly and in combination, by spraying and immersion application techniques in the Phase 2 effort. In the case of application of colloidal oxides by spraying directly onto VFCCF specimens, a number of problems were encountered, including clogging of the spray nozzles due to drying of the ceramic oxide solids within the nozzle during application. Another problem noted during spraying was a gradual but evident dimensional change of the spray nozzle, presumably due to erosion caused by the ceramic oxide's high velocity through the nozzle orifice. This resulted in an increase in deposited material on subsequent samples, over time.

A third problem noted with the spraying technique was that it provided only a very superficial coating of ceramic oxide material onto the sample. This was alleviated partially by the use of a slight amount of vacuum on the downstream side of the specimen, but the additional amount of ceramic oxide coating observed on each specimen was very small. Efforts were made to produce very fine spray patterns for greater penetration of the colloidal oxides into the VFCCF matrices, but this was found to be troublesome and produced substantial amounts of "overspray" due to the fineness of the spray droplets.

Immersion (Infusion) Application Trials. By comparison, application of the colloidal ceramic oxides by means of simple immersion (infusion) was much more successful and easier to control. Limited to only a few variables, namely the concentration of the ceramic oxide material and the infusion duration, the application from one specimen to the next was found to be much more uniform and predictable than application by spraying techniques.

VFCCF Filter Candle Development Program. In addition to the work involving colloidal ceramic oxides, other means of increasing the durability of VFCCF filter candles has been ongoing, as part of this research grant. Geometry changes in the critical flange and end cap zones has been one successful approach. A female vacuum forming die was constructed to permit forming of an integral candle flange, in order to eliminate the original bonded flange design, which subjected the flange joint to shear when positioned in a tubesheet. In so doing, it was believed that the filter element would be inherently stronger in the flange area, by the complete elimination of the ceramic adhesive joint. Several dozen filter candles were made using the new forming die, but it was found that in every case, the tapered flange section of the filter candles did not form sufficiently thick to permit machining to the traditional (rectangular or hemispherical) flange shapes which are accepted commercially. In spite of repeated attempts using different vacuum forming pressures, flowrates, and slurry concentrations, a wall thickness of only 7-10mm resulted in the tapered (flange) section of the die.

In view of the above, the approach whereby the outside flange taper would simply be machined to the desired flange geometry was modified. Numerous designs and procedures were tested, but the most promising approach involved the following flange assembly steps:

- Truncating of the "as formed" filter candle at a point 25mm from the onset of the flange taper;

- Machining of a flange "ring" from VFCCF board stock. The outside surfaces of the flange ring can be easily machined into a hemispherical, reverse hemispherical, or rectangular flange geometry from the flat (board) stock, while the inner surface of the ring is machined to the same pitch as the outer taper of the filter candle flange. In so doing, it was found that machining from VFCCF flat stock, subjected to an immersion (infusion) treatment of colloidal ceramic oxide material resulted in a smoother outer machined surface, as compared to flanges machined from untreated VFCCF flat stock;

- "Roughing" the filter candle tapered surface as well as the flange ring inner surface to provide the best "bite" for the ceramic adhesive, followed by vacuuming of fiber debris;

- Affixing the flange ring to the tapered section of the filter candle by slipping it across the distal candle end and into place at the candle taper. A properly selected aluminosilicate ceramic adhesive, designed specifically for VFCCF materials is applied to both mating surfaces, which are first prewetted with colloidal silica for maximum adhesive penetration.

- Compression is applied to the flange joint during the curing step, at temperature, per the adhesive manufacturer's recommendations.

By following the above procedure, a substantially stronger filter flange results, since the flange adhesion joint is no longer subjected solely to shear and tension but is instead in compression, due to the flange taper. Also, unlike the "integral" flange concept, turning of the filter candle flanges to their desired final geometry (on a lathe) is not required.

In destructive testing of the compressive flange joint described above, a downward (shear) load of 73 lbs. was applied to the filter candle flange before failure occurred. Additionally, as hoped, the failure did not occur at the glue joint seam but instead failed within the porous section of the candle. This compares quite favorably to earlier flange designs tested in Phase 1, which had an average flange strength of 53 lbs. Further efforts are underway to increase the flange strength to an even greater degree; ceramic adhesives using reconstituted fiber, for example, appear to show promise in creating a unique "ceramic weld" between the joined surfaces.

With the above advances made in the flange area of the filter candle, it became apparent that similar candle fabrication techniques would be applicable to the end cap section of VFCCF candles. Capitalizing on the techniques used above, a compressive-state glue joint in the end cap area was developed. By rewetting the open filter candle end temporarily, it became possible to insert a conical VFCCF plug into the softened end to serve as an end cap, much like a stopper in a flask. By inserting the plug backwards (i.e., widest end first), however, the softened cylinder could then be drawn or "puckered" around the conical taper of the plug, after which it would reharden upon drying. Further use of some of the techniques used during flange assembly resulted in a design which places the end cap joint in compression, rather than shear, during the critical jet pulse cleaning of the filter candle.

RESULTS

Phase 1 Efforts

Phase 1 test results showed that the bending and compressive strength characteristics of VFCCF materials can increase substantially as a direct result of the infusion of colloidal ceramic oxide suspensions into the VFCCF matrix. In some instances, it was possible to increase strength of typical VFCCF tubesheet specimens eight-fold, in comparison to the strength of untreated specimens. By variation in colloidal solution application techniques and curing methods, it was also possible to greatly increase VFCCF filter candle strength in critical flange and end cap areas, with a minimal decrease in overall candle permeability. Table 3 provides the highlights of some of the infusion trials, which were quite successful.

Table 3. Results of Phase 1 Testing

Aluminosilicate VFCCF Tubesheet Specimen Strength Test Results After Colloidal Ceramic Oxide Infusions

Infusion Description	Apparent Density (lbs./ft.^{3})	Modulus of Rupture (lbs./in^2)
Untreated Aluminosilicate	17.02	52.68
Single Immersion, SiO_2	36.83	274.11
Single Immersion, Al_2O_3	32.67	127.84
Double Immersion, SiO_2, then Al_2O_3	47.06	440.45
Single Immersion, ZrO_2	32.08	61.79
Single Immersion, Y_2O_3	28.81	168.15
Single Immersion, CeO_2	30.84	86.1

Phase 2 Efforts

Single Infusion Studies. Because of the problems cited earlier with the application of colloidal ceramic oxides by means of spraying, Phase 2 efforts focused primarily on infusion (immersion) as the method of application. Numerous single infusions of VFCCF (aluminosilicate) fiber specimens were made; in each case, the solids concentration of the various colloidal suspensions used was as follows:

•	Silica	40% w/w
•	Mullite	28% w/w
•	Yttria	14% w/w
•	Alumina	20% w/w

While it would have been desirable to test using identical concentrations of each suspension, the number and significance of other variables (e.g., pH, viscosity, particle size distribution, etc.), combined with the relative instability of the suspensions, made this an impossible task. Also, unlike Phase 1 testing, ceria and zirconia colloidal ceramic oxides were eliminated in the Phase 2 tests, due to their relatively small resultant strength enhancement of VFCCF matrices.

In the case of silica, a single immersion appeared to increase weight and also strength of the aluminosilicate fiber matrix considerably more than any other material, but at the same time appeared to "seal" the outer pores of each specimen so as to prevent further penetration of colloidal oxides after a subsequent immersion. Although silica is known to increase VFCCF material strength dramatically, because of its susceptibility to corrosion in high temperature environments (from steam, alkali and other corrosive attack mechanisms), it became apparent that another additional ceramic oxide must be applied over the silica layer to produce a durable product. Because of the sealing tendency of the silica, however, it became questionable if suitable penetration by a subsequent corrosion resistant material such as alumina, yttria, or mullite would in fact take place.

Another material which was tested in a single treatment immersion application was that of colloidal mullite. While the mullite applications did not see the rather dramatic weight or strength increases observed with the silica treatment, it was noted that the mullite treatment penetrated very uniformly in each specimen tested, and did not have the tendency to seal or "blind" the pores, as was noted in the silica immersion trials. This observation seems to indicate that subsequent immersions in colloidal mullite, or other colloidal ceramic oxides might lead to greater overall penetration than was noted in the silica trials. Given the advantage mullite has over silica in terms of corrosion resistance, (particularly against vapor phase alkali species in a hot gas environment), combined with good thermal shock resistance and low thermal expansion, mullite is considered to be a choice colloidal material for VFCCF treatment. In each test case involving mullite, a weight increase of 45-85% was noted.

Still another material which was tested in a single treatment immersion study was that of alumina. Alumina has a very high corrosion resistance with regard to vapor phase alkali species, but it was noted that the amount of alumina infused into the VFCCF specimens resulted in a weight increase less than that of mullite, in the range of 45-65%. Based on Phase 1 bending strength test data, alumina did not significantly increase strength, so it was concluded that the use of colloidal alumina for VFCCF materials would be limited to that of a final corrosion resistant treatment only.

The last colloidal ceramic oxide material which was applied by means of single immersion techniques in the Phase 2 effort was that of yttria. Yttria has high thermal stability and good corrosion resistance, but exhibited relatively small weight increases, generally averaging about 40%.

In summary then, the strength of structural VFCCF aluminosilicate materials can be substantially increased by a single immersion in silica, whereas strength and corrosion resistance may be increased in one (or more) immersions using mullite colloidal ceramic oxide material, possibly in conjunction with colloidal yttria or alumina.

For filter candle applications, in contrast to structural ceramic applications, it appears as though the mullite colloidal material also provides a strength increase without a dramatic reduction in pore size,which relates inversely to the pressure differential across a filter candle in operation. Specifically, in the case of the single mullite immersed filter candle specimens, it was found that a weight increase occurred on the order of 60-80%, for immersion durations of 10-15 seconds. Unlike silica, however, it was found that the pore structure of the material did not change dramatically and decreased only from approximately 55 microns to 45-50 microns, from which it can be concluded that filter candle specimens could undergo dramatic increases in strength and durability, as well as corrosion resistance, using a colloidal mullite material, without greatly compromising the pore size (and consequently the pressure differential) across the filter candle. Ongoing tests seem to show that even diluted concentrations (as low as 12%) of mullite are very effective in enhancing candle strength, with almost no loss in permeability.

VFCCF Fiber Length Variation; Mullite and High Alumina Fiber Testing. Efforts involving variations in VFCCF fiber length, as well as forming of filter components using mullite fiber and alumina fiber, rather than aluminosilicate fiber, were performed to see what effect these changes might have on VFCCF material strength. The comparative testing was limited to three-point modulus of rupture (M.O.R.) bend tests, performed on specimens having dimensions of 3" x 2" x 12" (span). The average strength values from these tests are shown in Tables 4 and 5.

Table 4. VFCCF Fiber Length vs. Strength

Nominal Fiber Length (mm)	Modulus of Rupture (psi)
30	55.35
15*	55.65
7.50	85.95

*This material is our VFCCF "standard" material.

Table 5. VFCCF Fiber Type vs. Strength

Fiber Type (Nominal Length, mm)	Modulus of Rupture (psi)
Aluminosilicate, 15mm	55.65
Mullite, 15mm	24.30
High Alumina, 15mm	48.15

The above results indicate that longer aluminosilicate fiber lengths, which produce a lower density product, do not increase strength in comparison to the standard (medium length) aluminosilicate fiber normally used. Shorter, high density aluminosilicate fibers, however, appear to increase strength substantially, by approximately 55%. In the case of the various fiber types tested, both the pure mullite fibers and high alumina fibers show lower strength values than the standard medium length aluminosilicate fiber.

Ceramic Fiber Composite Materials (for structural applications). Investigation of a commercially available pressure-laminated aluminosilicate fiber composite material has also been underway as a result of this research effort, for use as a suitable material for hot gas filter structural components. The composite material closely matches the chemical composition of VFCCF aluminosilicate boards, but has improved properties both in compression (10,000 psi strength) and tension (8,000 psi strength)

Thicknesses are commercially available up to a maximum of 1", and sizes of up to 36" square can be obtained. Because of the size limitations, however, the joining of sections of this material is required to fabricate ceramic tubesheets, etc. in excess of about 36" in diameter. For filter applications involving large tubesheet designs, a joined tubesheet eliminates several drawbacks associated with monolithically formed tubesheets, namely:

- The tendency for formation of air pockets, poor fiber "knitting", etc. in VFCCF specimens thicker than about 2";
- Inability to vacuum form, dry, and cure large diameter specimens, due to existing equipment size limitations (tanks, dies, ovens, etc.);
- Inability to physically handle large specimens while wet, due to their fragility.

In view of the above, the concept of laminating and joining composite ceramic fiber board sections to create a larger final product is being pursued; the 18" x 30" laminated tubesheet specimen shown in Figure 1 is currently being tested for high temperature creep strength at Acurex Corp. of Mountain View, CA.

In addition to high strength, advantages of laminated and joined composite ceramic tubeheets include:

- Utilization of "off-the-shelf" VFCCF and composite board materials for maximum product uniformity, tolerances, etc.;
- No special oversize dies, ovens, tankage, etc. required;
- Attractive cost;
- No special one-of-a-kind tooling required for each particular product design;
- Chemical stability, corrosion resistance, and thermal expansion properties similar to VFCCF materials;
- The need to stock only laminated boards and ceramic adhesive for virtually any tubesheet application.

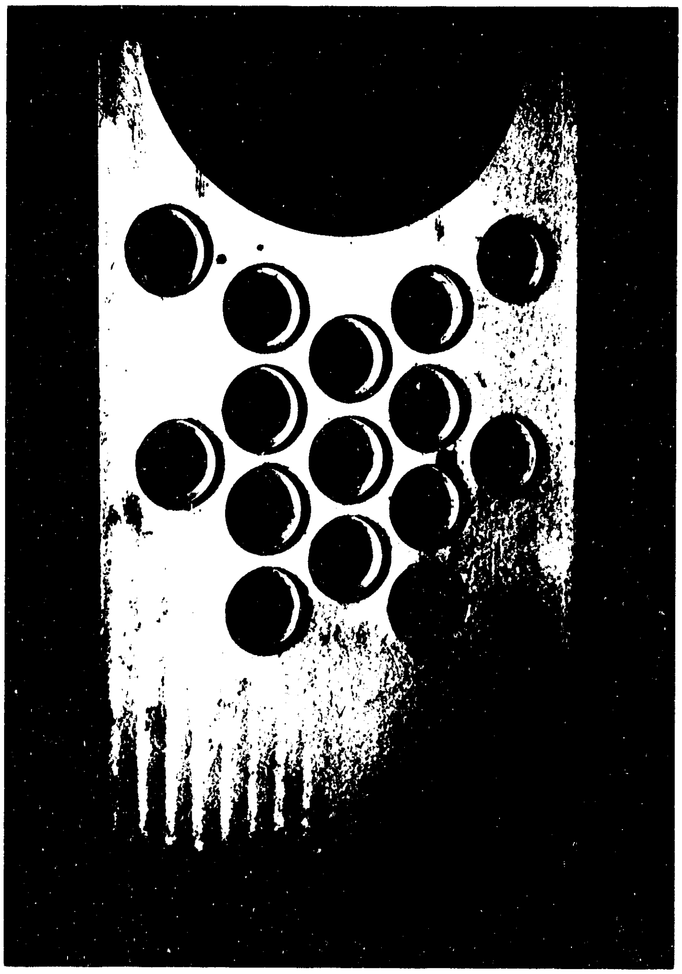


Figure 1. Laminated Composite Ceramic Tubesheet Section

Conclusions

As evidenced from the preceding sections, mullite appears to be the most promising colloidal ceramic oxide treatment material for VFCCF matrices. When applied by means of infusion techniques, considerable process control can be maintained with relative ease, for consistency of final product. Colloidal mullite can be used to increase the strength of VFCCF filter candles without a significant decrease in candle permeability, and creates a desirable divergent, acicular pore geometry during high temperature curing.

The development of a new flange and end cap design approach and joining technique appears to be very promising; continued efforts in ceramic adhesives development should lead to even greater filter candle integrity.

Aluminosilicate fiber composite materials, for use as lightweight ceramic structural components, offer high strength and can be successfully laminated for even greater strength, using proper joining techniques and ceramic adhesives suited for VFCCF materials.

FUTURE WORK

Future VFCCF filter candle developmental efforts will consist of:

- Investigation of multiple infusions of colloidal mullite material, as well as successive mullite/alumina and mullite/yttria infusions, to maximize filter candle strength and corrosion resistance without the premature sealing of pores and possible corrosion, as was noted with colloidal silica;
- Continued development of critical filter flange and end cap areas;
- Further investigation of shorter (7.5 mm) length aluminosilicate VFCCF fibers for use in increasing filter candle strength;
- Application of a finely chopped ceramic fiber "membrane" layer on the filter candle, to produce superior filtration characteristics;
- Corrosion and alkali exposure studies of the most promising filter candle specimens as a result of the above.

Regarding VFCCF and aluminosilicate composite materials, for structural (tubesheet) applications, future efforts will include:

- Development of the optimum lamination, joining, and curing procedures for maximum strength and integrity of these critical components.

REFERENCES

1) Eggerstedt, P. M., (1993) Final Technical Report of Phase 1 Project Entitled: "Durable, Low Cost Ceramic Materials for Use in Hot Gas Filtration Equipment"; USDOE SBIR Grant No. DE-FG02-92ER61349, Cicero, Illinois

2) Lee, S.H.D., (1994), "Evaluate FIBROSIC$^{\text{TM}}$ Candle Filter for Particle Control In PFBC", Illinois Clean Coal Institute Final Technical Report for September 1, 1992 through December 31, 1993, Argonne National Laboratory, Argonne, IL.

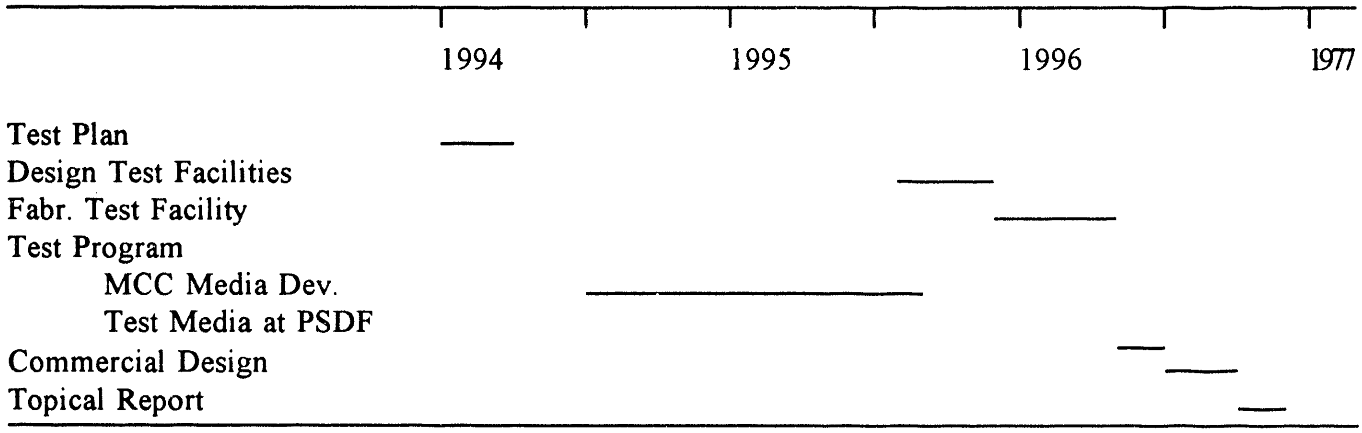
5.6 Multi-Contaminant Control Granular Bed Filter

CONTRACT INFORMATION

Contract Number	DE-AC21-90MC27423
Contractor	Combustion Power Company 2101 Webster Street #1700 Oakland, CA 94612 510-286-8820
Contractor Project Manager	Keith B. Wilson
Principal Investigators	John C. Haas Cheryl Anne Olivo
METC Project Manager	Heather M. McDaniel
Period of Performance	October 1992 to April 1994

Schedule and Milestones

FY94-96 Program Schedule



OBJECTIVES

The objective of this phase of the Moving Granular Bed Filter (GBF) Development Program is to develop a GBF for the control of particulates and other contaminants found in high pressure and high temperature coal-derived gas streams. The filter should be able to remove particulates and one or more contaminants such as sulfur compounds, nitrogen compounds, alkali compounds, halogenated compounds, heavy metals and tars. The multi-contaminant control granular bed filter should be applicable to reducing and/or oxidizing conditions.

Specific objectives of the program are:

- To identify and define an approach to multi-contaminant control using a moving granular bed filter. The approach chosen for multi-contaminant control is justified with supporting data and information from the literature.

- To develop a test plan which includes the conceptual design of component test facilities, a description of tests which includes experimental procedures, operating conditions, duration of tests, number of tests and data to be collected.

- To design, procure and install experimental test facilities.

- To conduct tests to evaluate the moving granular bed filter for multi-contaminant control.

- To develop a commercial-scale design and economic analysis for a multi-contaminant control granular bed filter in PFBC or IGCC applications.

BACKGROUND INFORMATION

The granular bed filter was developed through low pressure, high temperature (1600°F) testing in the late 1970's and early 1980's (Guillory, 1980). Collection efficiencies over 99% were obtained. In 1988, high pressure, high temperature testing was completed at New York University, Westbury, N.Y., utilizing a coal-fired pressurized, fluidized bed combustor. High particulate removal efficiencies were confirmed as it was shown that both New Source Performance Standards and turbine tolerance limits could be met (Wilson, 1989).

The early scale-up work of the granular bed filter indicated potential limitations due to size, cost, and mechanical complexity. These limitations were addressed in the base contract of the present program (Wilson et al, 1992). It is currently proposed to use large diameter filters with 6 mm spherical filter medium to increase filtration capacity and reduce system complexity. Figure 1 shows a granular bed filter designed for a 100 MWe KRW (air) gasifier. The filter has an inside diameter of 14 ft with a nominal bed depth of 5 ft.

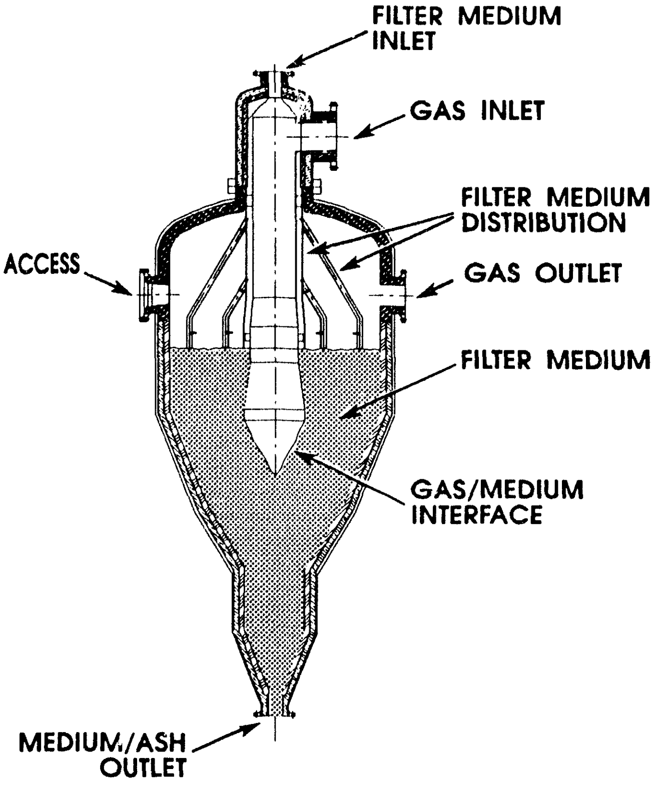


Figure 1. Granular Bed Filter for 100 MWe KRW (Air) Gasifier

PROJECT DESCRIPTION

A multi-contaminant control filter requires that either a chemically reactive sorbent be added to the gas stream and then removed in the filter or that the filter medium itself be chemically reactive. An application in which a fine grained sorbent is added to the gas stream and is then removed with the filter would be applicable to a granular bed filter as well as other types of filtration processes. We have chosen to use a chemically reactive filter medium to take advantage of the inherent characteristics of a granular bed filter which are long residence times for both the filter medium and the gas which is in contact with the filter medium.

The chemically reactive filter medium can be either a regenerable or non-regenerable sorbent. Others are currently working on the development of regenerable zinc titinate sorbents (Ayala et al, 1992). Such a sorbent would have potential use as a granular bed filter medium if it possesses sufficient strength and attrition resistance for many cycles through a granular bed filter and a sorbent regenerator. Another approach is to use a sorbent which has a finite life and is removed from the filter system after it is spent.

We propose to investigate a non-regenerable filter medium composed of a mixture of limestone and clay for the control of sulfur and alkali contaminants in coal-derived gas streams. Such a sorbent would also have the potential for the control of halogenated compounds, trace metals and tars.

In this concept, the filter medium would be composed of 6 mm chemically reactive spheres which are the same size as the filter medium used for particulate control. The rate of circulation of the filter medium in the GBF for particulate control is much greater than the rate at which reactive filter medium would need to be added to the filter for multi-contaminant control. Fresh reactive filter medium would be added to the circulating filter medium before it enters the filter. After the filter, spent filter medium would be removed from the circulation loop at the rate at which it is added.

Limestone for Sulfur Control

Limestone is widely used for the control of sulfur contaminants in both coal gasification and combustion processes because of its effectiveness, low cost and wide availability. Crushed limestone may not be an effective GBF filter medium because its irregular shape does not have the solids flow characteristics needed for a GBF and may have high attrition rates due to the loss of edges and corners formed in the crushing process.

Rather than using crushed limestone as the filter medium, it will first be pulverized, mixed with clay for alkali control, and then agglomerated into 6 mm spheres using suitable binders. The agglomerated limestone/clay spheres have the advantages of an improved shape for flow in a GBF, an increased micro-pore size and improved attrition properties.

Previous investigators have found that agglomerating finely powdered limestone improved its chemical reactivity and the temperature range of its reactivity, and that the addition of binders during agglomeration could improve mechanical strength. Shen and Albanese (1978), Voss (1983), and Spitsbergen et al. (1988) all demonstrated that calcined agglomerates of powdered limestone have considerably higher reactivity than calcined, similar-sized particles of the naturally occurring stone and may have increased mechanical strength. Zhang et al. (1989) demonstrated that not only is the chemical reactivity of calcined limestone improved by agglomeration, but also the temperature range for chemical reactivity.

Limestone can react directly with H_2S by the reaction route shown in equation 1. If the temperature is high enough, the limestone first calcines to calcium oxide and reacts by the route shown in equations 2 and 3.

$$CaCO_3 + H_2S = CaS + CO_2 + H_2O \quad (1)$$

$$CaCO_3 = CaO + CO_2 \quad (2)$$

$$CaO + H_2S = CaS + H_2O \quad (3)$$

$$CaO + COS = CaS + CO_2 \quad (4)$$

$$CO + H_2O = CO_2 + H_2 \quad (5)$$

Carbonyl sulfide also reacts with calcium oxide as shown in equation 4. The extent of the above reactions are limited by the equilibrium concentrations.

Figure 2 shows the calculated equilibrium concentrations for H_2S and COS in the presence of limestone for fuel gas resulting from the KRW (air) gasifier. The equilibrium H_2S concentration decreases with temperature until a minimum value of 90 ppmv is reached at the calcination temperature of calcium carbonate, 1692°F. After the calcium carbonate calcines to calcium oxide, the equilibrium concentration of H_2S increases with temperature. The equilibrium concentration of COS depends on the concentration of H_2S. The minimum equilibrium COS concentration is 11 ppmv and it also occurs at 1692°F.

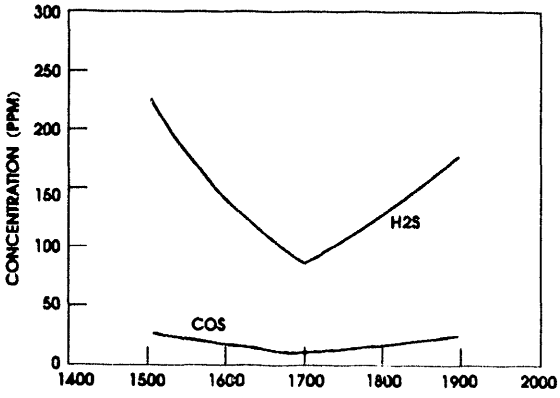


Figure 2 Equilibrium Concentration for H_2S and COS for KRW (Air) Gas

Pilot plant tests conducted at IGT (Goyal, 1988) showed that in their gasifier, it is possible to achieve 85% or more approach to the equilibrium concentration of H_2S. Assuming an 85% approach to the equilibrium concentration of H_2S, the H_2S concentration at the outlet of the GBF would be 106 ppmv. If the COS has the same approach to its equilibrium concentration, its concentration would be 13 ppmv. The combined concentration of H_2S and COS would be 119 ppmv which corresponds to 97.3% sulfur removal for the 2.68% sulfur coal used in the Wansley study (Southern Company Services, 1991).

Unlike the control of hydrogen sulfide with limestone, the control of sulfur dioxide is not thermodynamically limited in a pressurized fluidized-bed combustor operating at 10 atmosphere pressure at temperatures below 1050°C (Newby et al., 1989). Assuming that the PFBC has a limestone bed, a GBF with limestone medium would be used as a polishing sulfur dioxide absorber and as a particulate filter. In such an application, the limestone/clay medium would circulate through the GBF many times since the inlet concentration of sulfur dioxide would be low. The medium would have to have a high attrition resistance to be able to circulate many times through the filter.

Clay for Alkali Control

Several investigators have reported successful alkali removal from high temperature gas streams with sorbents of activated bauxite, attapulgus clay, calcium montmorillonite clay, diatomaceous earth, kaolin clay, and emathlite clay.

Emathlite, a type of fullers earth, was found to be a leading getter of alkali (Bachovchin et al., 1986). The clay had a high capacity for sodium and binds the sodium irreversibly. At extreme conversions, the clay was found to become sticky. This could be a problem but is unlikely to occur as these extreme conversions are not realistically obtained and the anticipated fraction of clay within the agglomerated pellet is small. Kaolin, bauxite, and emathlite were all found to be capable of removing alkali from coal conversion streams (Uberoi et al., 1990). Kaolin and emathlite sorption of alkali was an irreversible process. The maximum sorption capacity of the kaolin was about 25% while that of bauxite and emathlite was about 15%. During screening of alkali sorbents, calcium montmorillonite clay was found to be superior and was chosen for further investigation (McLaughlin, 1990).

All of these sorbents are capable of alkali removal but only a few can be considered within the scope of this program. Of these alkali sorbents tested, bauxite was reported to be fractionally irreversible with alkali removal being 10% chemical sorption and 90% physisorption (physically absorbed as water soluble alkali) (Lee and Johnson, 1980) while only kaolin and emathlite were reported to react irreversibly with alkali (Bachovchin et al., 1986; Uberoi et al., 1990). Because bauxite is also a relatively expensive sorbent which would not be suitable as a non-regenerable sorbent. Work on limestone agglomeration found attapulgus clay to be an effective binding agent (Voss, 1983). With these points in mind, an alkali sorbent of kaolin, attapulgus or emathlite clay in conjunction with limestone will be investigated.

Trace Metal Control

Work at the University of Arizona indicates the potential of porous solids such as bauxite, kaolin or activated alumina for the absorption of heavy metals such as lead or cadmium (Uberoi and Shadman, 1991a). Results have shown that bauxite was considerably more effective than kaolinite for the sorption of cadmium vapors (Uberoi and Shadman, 1991b). The lower effectiveness of kaolinite was explained during examination of the particle which showed an almost completely reacted surface with an unreacted interior. This surface reaction is also typical of dense, natural limestones reacting with sulfur. Therefore, the use of kaolinite in an agglomerated pellet with large micro-pores may allow higher utilization just as it does for the sorption of sulfur species by limestone agglomerates. The kaolinite had a lower water soluble fraction of sorbed cadmium than the bauxite which is desirable from the point of view of ultimate disposal. Also studied was the sorption of lead vapors by various sorbents and kaolinite was found to be the most effective (Uberoi, 1990).

Limestone and dolomite were found to be effective for the removal of zinc and lead vapors from simulated flue gases (Mojtahedi et al., 1989). Dolomite, with its more open pore structure, removed 82% of the lead vapors and 19% of the zinc vapors. Limestone removed 41% of the lead vapors and 81% of the zinc vapors. The sorption of lead vapors may possibly be improved by the agglomeration of limestone to give a more open pore structure similar to dolomite.

From the work of these investigators, a high temperature sorbent composed of kaolinite, bauxite, limestone or dolomite could be capable of heavy metals removal from coal process streams. These same materials have proven to be effective for the capture of alkalies and sulfur species.

Filter Media Preparation, Characterization and Evaluation

In order to evaluate the concept of a GBF multi-contaminant control filter medium, a bench scale laboratory program is planned to be followed by testing in a pilot scale GBF. The bench-scale laboratory program consists of filter media preparation, physical characterization and evaluation of chemical reactivity.

The filter media will be prepared from pulverized limestone, either 80% minus 150 microns or 80% minus 44 microns, an alkali absorbing clay and suitable binders. A disc pelletizer will be used to prepare 6 mm and 2 mm spherical pellets. Major emphasis will be on evaluation of 6 mm media. The 2 mm media will be evaluated only if the 6 mm media does not have suitable properties. Should disk pelletizing not produce a suitable filter medium, extruded pellets which are rounded into spherical shapes with a disc pelletizer would then be evaluated.

The clay to be used in the filter medium as an alkali sorbent will be determined on the basis of a screening test developed by McLaughlin (McLaughlin, 1990). The candidate clays to be evaluated are: kaolin clay, bauxitic kaolin clay, ematholite (calcium montmorillonite clay), attapulgite clay and low swelling bentonite clay. A mixture of clay and NaCl is heated in a thermogravimetric analyzer (TGA). The mixture with the lowest weight loss would be the best alkali sorbent. Mixtures of limestone, clay and NaCl will also be evaluated. The preferred clay will be mixed with limestone at 5% weight concentration to form the multi-contaminant control filter medium.

In order to make a strong, attrition resistant filter medium from the clay and limestone mixture, a binder may be needed. The following lists the binders which will be evaluated and their weight concentration.

- 15% attapulgus clay with 2% boric acid
- 2% and 4% sodium silicate
- 2% and 4% corn starch
- 2% sodium bentonite with 10% calcium sulfate
- 2% and 5% sodium bentonite
- 2% and 5% calcium montmorillonite
- 5% and 10% calcium sulfate hemihydrate
- 10% and 15% portland cement
- 10% and 15% FBC bed ash

The filter media prepared from the above combinations will be evaluated in terms of their physical properties. Pellet green strength is evaluated by a drop test which relates to the ability of the pellet to be handled before curing. After curing, calcined pellets are subjected to a crush test which relates to the ability of the pellets to maintain shape in the GBF. Pellet attrition resistance is measured using ASTM D4164-88 procedure. The attrition resistance of the most promising formulation will be evaluated in a special test apparatus which simulates the particle motion in a GBF. The apparatus consists of a lift pipe and return seal leg.

For the five most promising formulations more extensive physical characterizations will be performed. These include bulk density measurements, measurement of pore volume and pore diameter, determination of optimum pellet moisture for maximum strength and SEM microstructure of reacted pellets.

Media reactivity will be evaluated in sulfidation, sulfation and alkali absorption tests. Initial TGA sulfidation tests will be run on 15 formulations of 6 mm pellets and 3 sample of 2 mm pellets. The five best formulations will then be sulfided in a larger batch apparatus so that the reacted medium can be evaluated for crush strength and ASTM attrition resistance. For the most promising formulation, additional TGA will be run to obtain detailed kinetic data. In these tests, gas composition and temperature will be varied. A series of pressurized TGA tests will be run to access the effects of pressure on reaction kinetics. A larger scale fixed bed reactor will be used to sulfide filter medium for large scale attrition tests and to obtain kinetic data for comparison with the TGA data. This test series will evaluate the medium's reactivity with respect to the sorption of H_2S.

Prior to disposal, sulfided filter medium will have to be converted to the sulfate form. It is expected that the larger micro-pores of the pelletized limestone will facilitate the conversion of sulfide to sulfate as occurs with dolomite. Atmospheric TGA tests will be used to determine the kinetics of the oxidation of the sulfide filter medium.

The multi-contaminant control GBF could be used with combustion gases to remove particulate, sulfur dioxide, and alkali compounds. The five best formulations determined from the sulfidation tests will be evaluated for SO_2 removal. TGA tests will evaluate the kinetics of the sulfation reaction. Batch sulfation tests will generate sufficient quantities of reacted filter medium for crush strength tests and ASTM attrition tests.

Fixed-bed alkali absorption tests will be used to obtain kinetic data on the reactivity of the prepared sorbents with respect to the absorption of alkali and sulfur compounds. A heated sample holder whose change in weight is monitored with a micro balance heats salt crystals which vaporize into a carrier stream. The rate of evaporation is controlled by the temperature of the sample holder. The alkali vapors are mixed with either a gas stream containing H_2S or one containing SO_2 and are carried into the packed bed of sorbent. The packed bed section will be 3 inches in diameter by 12 inches long, in a tube of alumina which is inert with respect to the alkali vapors. Test durations are between 24 and 100 hours. The first tests use a carrier gas containing N_2, 5% H_2O, and additives of H_2S and HCl. In later tests, the carrier gas contains 95% CO_2 and 5% H_2O with additives of SO_2 and HCl. The first five tests use a shallow bed which will be analyzed for the average alkali and sulfur sorption. After the first five tests, the bed will be sectioned into ninths and analyzed for alkali and sulfur content as a function of the position in the bed. In some of the tests, the carrier gas will contain HCl which is know to inhibit the sorption of alkali.

The kinetic data collected on sorbent reactivity will be used to create a model of the sorbent's chemical reactivity in a GBF. The model will take into account the sorbent reactivity with respect to sulfur species and alkali. The model will provide information on the required bed depth of the GBF, the expected outlet concentration of sulfur and alkali species and the extent of reaction of the sorbent.

Pilot Plant Testing

Bench scale tests are used to develop and evaluate multi-contaminant control media. The developed media is evaluated in terms of its chemical and physical properties in a bench scale environment. The next phase of evaluation will be at the pilot plant scale. Combustion Power Co. is participating in the DOE sponsored tests at the Power Systems Development Facility (PSDF) to be installed in a Southern Company Services Facility in Wilsonville, AL. The first year of testing at the PSDF will be dedicated to the evaluation of the GBF for particulate control. For these tests, the GBF is connected to M.W. Kellogg's transport reactor which can be operated in either a gasification or combustion mode. After the evaluation of a GBF for particulate control, the opportunity exists to evaluate the GBF with a reactive medium for the control of sulfur and alkali compounds.

The modification necessary to allow testing at the PSDF GBF are relatively straight forward. Lock hoppers will be installed for the addition and removal of multi-contaminant control filter medium. The additional feed and removal systems can be accommodated within the existing structure. Nine tons of clay/limestone filter medium will be prepared for the test series which will provide for 80 hours of testing.

Cost Estimate for Production of GBF Multi-Contaminant Filter Medium

To evaluate sorbent feasibility, plant scale processes were developed to estimate the capital and operating costs to produce a GBF medium of limestone and clay at three different production rates. The production rates chosen were 5,000, 50,000 and 500,000 ton/yr.

To develop the plant processes and cost estimates for the three production rates, assumptions were made concerning the medium composition, i.e. the sorbent formulation. Of the 68 possible formulations to be evaluated, a single formulation was chosen as the base case. This formulation is 6 mm pellets of 80% less than 149 micron limestone with 5% montmorillonite clay and 10% dry binder addition of portland cement (PC III). The pellets would be formed by disc pelletization requiring 20% pellet moisture and moist environment curing for 72 hours. Cost estimates were also made for lower and upper limits based on different formulations and pelletizing procedures.

Table 1 shows the cost estimates; for the base case, the production cost for 50,000 tons/year would be $39.72 per ton.

FUTURE WORK

The first task in the GBF multi-contaminant development program of identifying a concept and a test plan is completed. The next phase will be the execution of bench scale tests to determine the feasibility of the proposed approach to multi-contaminant control using a GBF. Following bench scale testing, testing will be conducted on a pilot scale GBF at the PSDF. After completion of testing, the cost and design of a commercial scale GBF with multi-contaminant control will be determined.

Table 1 Cost Estimate for GBF Medium Production

Production Rate ton/yr	Capital Cost M$		Operating Cost $/ton	
	Base	Range	Base	Range
5,000	2.5	2.1 - 2.8	152.0	137.8 - 200.3
50,000	4.3	3.6 - 5.1	39.7	31.1 - 86.0
500,000	15.2	12.3 -17.0	26.9	190.2- 71.9

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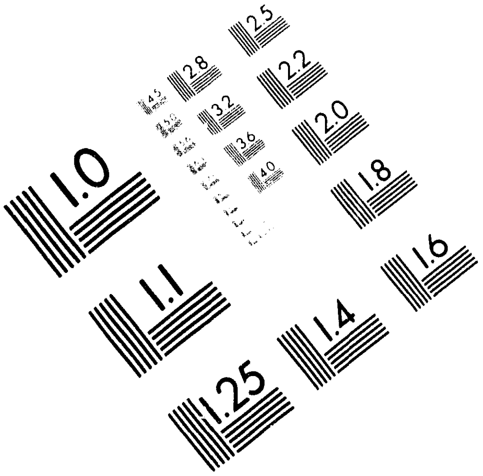

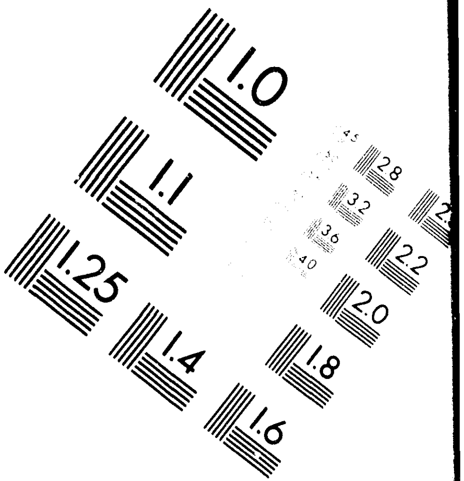

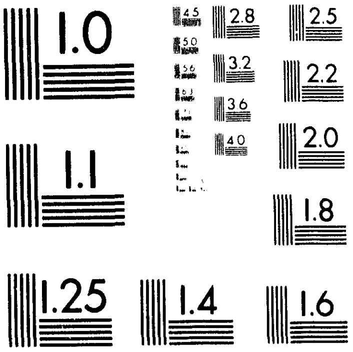

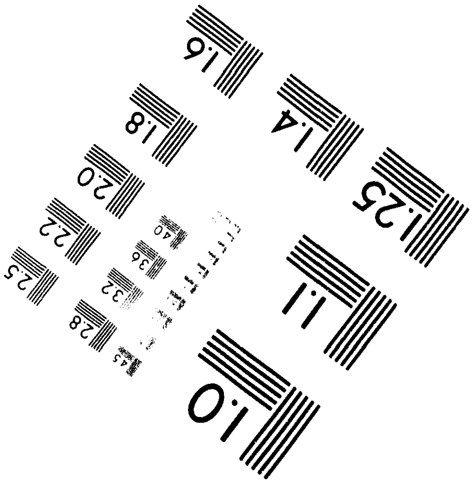

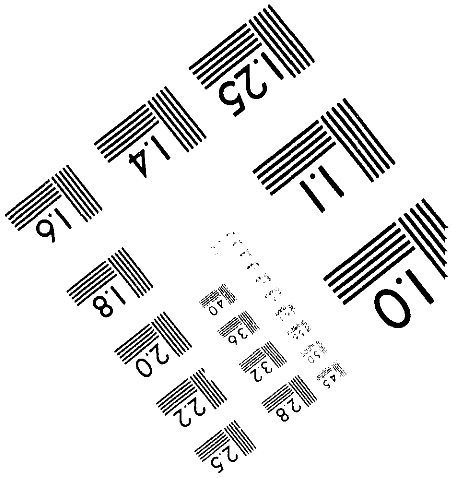

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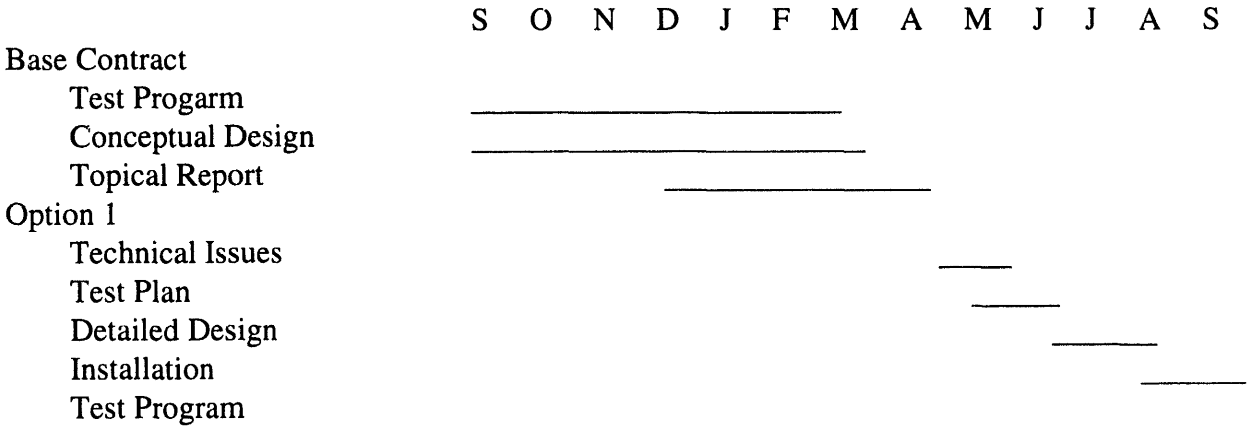
5.7 Westinghouse Standleg Moving Granular Bed Filter Development Progam

CONTRACT INFORMATION

Contract Number	DE-AC21-91MC27259
Contractor	Westinghouse Electric Corporation Science & Technology Center 1310 Beulah Road Pittsburgh, PA 15235 (412) 256-2210
Contractor Project Manager	Richard A. Newby
Principal Investigators	Wen-Ching Yang Eugene E. Smeltzer Thomas E. Lippert
METC Project Manager	Heather M. McDaniel
Period of Performance	May 13, 1991 to December 15, 1994

Schedule and Milestones

FY94 Program Schedule



OBJECTIVES

The overall goal of the Standleg Moving Granular Bed Filter (SMGBF) development program is to establish a moving granular bed filter system that meets all of the performance requirements and design constraints imposed by advanced power generation applications, and is economically competitive with ceramic barrier filter systems. In the recently completed, Base Contract period, it was the objective of the program to identify barrier technical issues for the SMGBF technology and to perform critical testing and evaluation to resolve those key issues. This paper summarizes the activities and conclusions from the Base Contract period.

BACKGROUND INFORMATION

Advanced, coal-based, power plants, such as IGCC and Advanced-PFBC, are currently nearing commercial demonstration. These power plant technologies require hot gas filtration as part of their gas cleaning trains. Ceramic barrier filters are the major filter candidates being developed for these hot gas cleaning applications. While ceramic barrier filters achieve high levels of particle removal, there are concerns for their reliability and operability.

An alternative hot gas filtration technology is the moving granular bed filter. These systems are at a lower state of development than ceramic barrier filters, and their effectiveness as filters is still in question. Their apparent attributes, relative to ceramic barrier filter systems, result from their much less severe mechanical design and materials constraints, and the potential for more reliable, failure-free particle removal operation.

The Westinghouse Science & Technology Center has proposed a novel moving granular-bed filter concept, the Standleg Moving Granular-Bed Filter (SMGBF) system, that may overcome the deficiencies of the current state-of-the-art moving granular-bed filter technology. The SMGBF is a compact unit that uses cocurrent gas-pellet contacting in an arrangement that greatly simplifies and enhances the distribution of dirty, process gas to the moving bed and allows effective disengagement of clean gas from the moving bed.

The SMGBF vessel concept is elucidated in Figure 1. Dirty process gas is introduced into the top chamber of the filter vessel through a tangential entry. The moving bed media is introduced into the same chamber through a single, vertical dipleg pipe, where it spills from the base of the dipleg pipe to form a free surface having the normal media angle of repose. The dirty process gas enters the moving bed media through this free surface. Cocurrent flow of gas and bed media through the short, vertical standleg promotes intimate contact between the flowing gas stream and the moving bed media, resulting in excellent separation of fly ash particles. The cocurrent gas/solids operation also prevents fluidization at the bottom of the standleg and permits high flow throughput (3 to 6 ft/s through the standleg), with relatively small ratios of bed media-to-fly ash (mass ratio of about 10). The cleaned gas is then allowed to flow out through the free surface of the bed formed naturally below the standleg. Special design features are built into the region at the base of the standleg to permit disengagement of the cleaned gas from the moving bed media without significant fly ash re-entrainment. The bed media and captured fly ash withdrawal from the filter vessel is controlled by a water-cooled, rotary valve or screw conveyor located below the vessel. The SMGBF vessel design is relatively simple, and it employs well-known standpipe design technology, making it cost effective, reliable, and easy to scaleup.

Two approaches for handling the bed media can be applied to the SMGBF: "Once-Through" media operation, and "Recycle" media operation. Once-Through media operation applies pelletization technology to generate filter pellets from the power plant solid waste materials, and uses these pellets as a "once-through" filtering media to eliminate the need for costly, complex, and large filter media recycling equipment. This pelletizing step also generates a more environmentally acceptable solid waste product

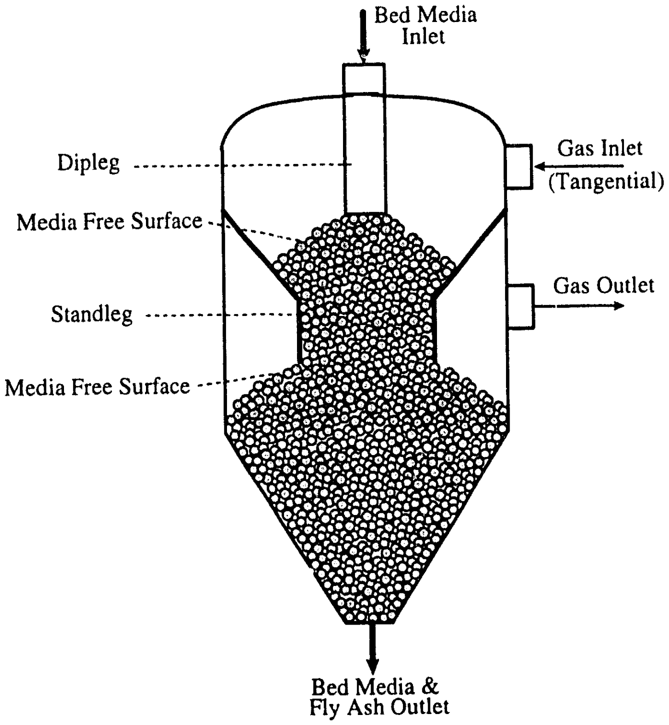


Figure 1. SMGBF Configuration Concept

and provides the potential to incorporate gas-phase contaminant sorbents into the filtering media. Recycle media operation recirculates granules from the SMGBF bottom withdrawal point to a top feed point, much as in the traditional moving granular bed filter approach. The SMGBF system performs this media circulation function by applying standleg, dense-phase flow and pneumatic transport that uses the dirty process gas to carry the granules. The granules are purchased bed media selected for its attrition resistance and it performance as a filtering media.

A general schematic diagram of the Once-Through SMGBF system in PFBC and IGCC applications is shown in Figure 2. The Once-Through SMGBF system is closely integrated with the power plant because of its need to utilize the power plant solid waste as the moving bed filter media while maintaining high power plant performance and economics. The major system components are:

- The SMGBF modules and their connecting piping
- The plant solid waste handling system (solids cooling and heat recovery, depressurization, transport)
- The pelletization system
- The pellet handling system (pressurization, transport, feeding and distribution)
- The pellet/dust cake handling system (cooling and heat recovery, depressurization, transport)

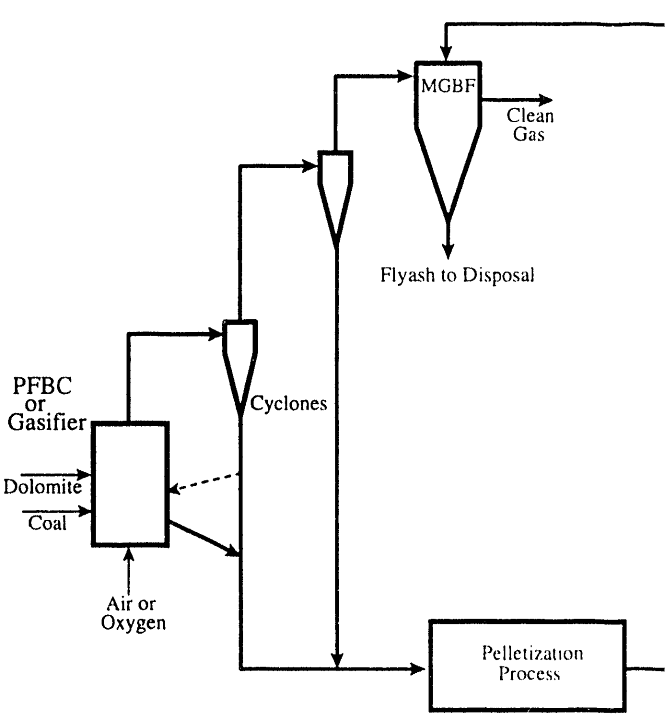


Figure 2. Once-Through SMGBF System Concept

There are several equipment options for each of these system components. The solids handling systems and pelletization system are generally commercially available components, but their selection is highly dependent on the nature of the solid waste streams, and they may need to be adapted to environments (eg., high pressure) where they have not been previously demonstrated. The pelletization system is a key system, and many pelletization techniques are available. The pelletization system must be integrated into the power plant to minimize complexity and to maximize energy efficiency, as well as being selected to produce sufficiently durable pellets for the SMGBF system.

The Recycle SMGBF system is Conceptually illustrated in Figure 3. Granules and captured fly ash are drained from the SMGBF and ash-granule separation is performed to remove a large portion of the captured fly ash. the SMGBF. The SMGBF configuration allows the transport to be accomplished by the dirty, process gas, and fly ash not separated from the granules in the ash-granule separator are reintroduced to the SMGBF.

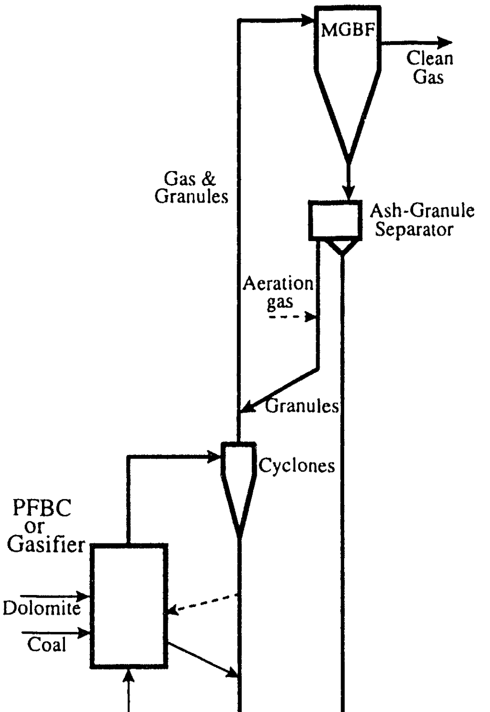


Figure 3. Recycle SMGBF System Concept

PROJECT DESCRIPTION

The Standleg Moving Granular Bed Filter (SMGBF) development program is a four-phase program, a Base Contract and 3 Optional phases. The program has successfully completed the initial, Base Contract period, identifying and resolving barrier technical issues, and demonstrating conceptual feasibility. The Option 1 program has been initiated, confronting the major technical issues remaining for the SMGBF by conducting key component tests to optimize the SMGBF performance. Option 3 will demonstrate the SMGBF at an advanced, coal-fired power plant, pilot facility to be selected. Option 4 is devoted to development of multi-contaminant control features for the SMGBF, incorporating gas-phase contaminant sorbents into the moving bed media.

RESULTS

The SMGBF development program has completed the initial, Base Contract period. The barrier technical issues identified were:

- The ability to achieve sufficient levels of fly ash removal to meet environmental standards and turbine protection criteria,
- The ability to generate sufficiently durable pellets from plant solid wastes, using commercial, economical pelletization techniques integrated with advanced power plants.

The technical approach applied to achieve the Base Contract objective was to conduct commercial plant conceptual design evaluation, in combination with laboratory and bench-scale testing that focused directly on the barrier issues. These activities were performed in parallel to ensure that each had the appropriate perspective to provide significant results.

Two major test efforts were undertaken to establish the conceptual feasibility of the SMGBF with respect to its ability to achieve sufficient fly ash removal, a cold flow model test program, and a high-temperature, high-pressure (HTHP) test program. The cold flow model test program was conducted first to investigate several design and operating features of the SMGBF in a facility where performance phenomena within the SMGBF unit could be visualized, where detailed probing could be easily performed, and where equipment changes could be easily made. The HTHP testing was then conducted to show that the cold model trends were reproducible at HTHP conditions, and to demonstrate the SMGBF performance at small-scale, prototypic conditions. In parallel to the cold model test program, an effort to identify viable solid waste pelletization techniques, and to test pellet durability was conducted.

A new, cold flow model facility was designed and constructed, as shown in Figure 4. The model was constructed primarily of Plexiglas, with a vessel OD of 36", and a 36" long standleg having 12" OD. The test unit was designed to be highly sectionalized so that internal modifications could easily be performed, and was of a size that represented a reasonable scaling to commercial dimensions. Support facilities for the cold model test included a large bed media feed hopper located above the SMGBF vessel, a screw feeder and weight scale located below the SMGBF vessel to control and record the flow rate of bed media, a fly ash feed system

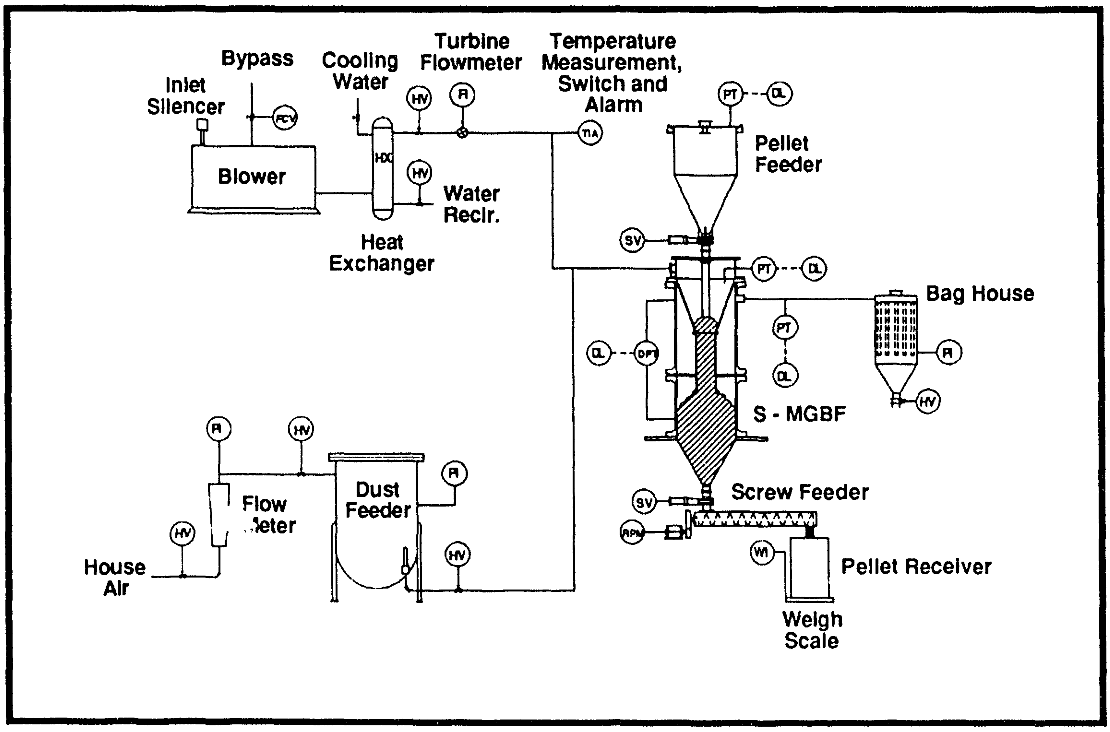


Figure 4. SMGBF Cold Model Facility

(K-Tron, loss-in-weight screw feeder) to inject fly ash into the inlet gas, a fabric filter to capture the fly ash in the SMGBF outlet gas so that its particle removal performance could be monitored, and instrumentation to measure the pressure drop profile within the SMGBF unit.

The cold flow model testing was performed with crushed acrylic particles, having an average diameter of about 3800 μm, as the bed media. The acrylic was selected because it had a density low enough to provide proper scaling to the actual, high-pressure SMGBF environment. A series of cold flow model tests were performed to characterize the gas flow and bed pressure drop characteristics, and the bed media flow characteristics, without fly ash feed. No visible fluidization of the bed media could be detected at standleg velocities up to 6 ft/s, exceeding the bed media minimum fluidization velocity of 5 ft/s. The clean bed pressure drop was consistent with existing packed bed pressure drop correlations. Fly ash injection testing was performed with fly ash from a PFBC pilot plant. Three SMGBF configurations were tested: the simple standleg configuration, a skirt section added at the base of the standleg, and a secondary, or topping bed added to surround the standleg skirt. Operating with a standleg gas velocity of about 3 ft/s, a bed media to fly ash mass feed ratio of about 10, and an inlet fly ash loading of about 6400 ppmw, total unit pressure drop was acceptable at less than 40 in-wg, and the particle removal performance achieved was:

- >97% removal with the simple standleg configuration,
- >99% removal with the added skirt section,
- >99.95% with the added topping bed.

Test durations were extended to relatively long periods of time to ensure that steady levels of performance were achieved. The cold flow model testing identified the key phenomena controlling the SMGBF performance, established the design features needed to achieve high levels of performance, and demonstrated the potential performance capabilities of the SMGBF. The cold flow model testing was representative of both the Once-Through and Recyle SMGBF performance capabilities.

Pelletization studies were performed by collecting representative solid waste samples from various advanced, coal-fired power plant units, and having commercial vendors prepare pellets from these wastes by several commercial techniques. Solid waste samples from both IGCC plants and PFBC plants were collected, as well as from some AFBC plants. All of these were successfully pelletized by several vendors. The generated pellets were then tested for durability by simple furnace heating tests, as well as a standard, rotary pellet attrition test rig that was adapted to high-temperature conditions. The attrition test subjected the pellets to much more severe attrition conditions than they would see in the SMGBF application. The results indicated that sufficiently durable pellets can be produced with advanced power plant solid wastes using conventional pelletization methods, but more evaluation is required to develop optimum techniques for solid waste sizing, water and binder content, mixing, and curing.

An existing HTHP test facility previously used to test ceramic barrier filter elements was adapted to test the SMGBF, as illustrated in Figure 5. The pressure vessel used had an OD of 40" and a total vessel height of about 10 feet. A new vessel head was constructed with a tangential gas inlet nozzle, and the natural gas-fired combustion system was moved to the head gas inlet location. The standleg internals inserted in

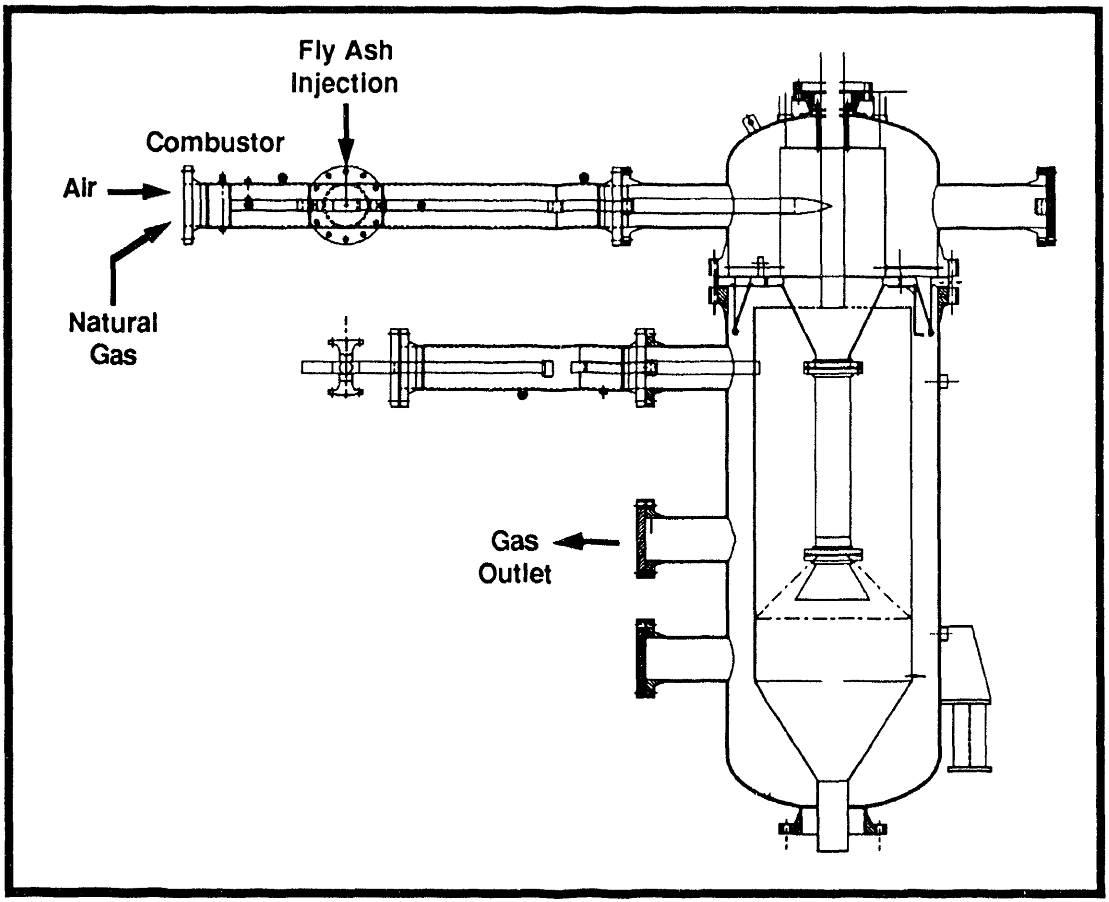


Figure 5. SMGBF HTHP Facility

the vessel had a 6" diameter, and were operated at a standleg velocity of about 3 ft/s in most of the testing. The standleg was constructed with a skirt section attached at its base, with its design based on the cold flow model results. A pressurized, water-cooled screw conveyor was added to the facility to control the flow of bed media through the unit. A batch feed hopper for bed media was located over the SMGBF vessel. The tests were performed under conditions simulating a PFBC application:

- Temperature of 1500 to 1600 ° F,
- Pressure of 100 psig,
- Injected PFBC fly ash at inlet loadings of 1000 to 7000 ppmw.

A total of 18, high-temperature test runs were completed. The tests were arranged in three major series:

1. On-off bed media flow with pelletized fly ash,
2. Continuous bed media flow with alumina beads,
3. Continuous bed media flow with pelletized fly ash.

The pelletized fly ash used in the tests was Aardelite, a commercial, pelletized conventional pulverized coal (PC) power plant fly ash product. The on-off bed media flow testing showed very high levels of particle removal performance, with outlet loadings of 2 to 20 ppmw, but operational problems would not permit representative, steady operation to be achieved. Subsequent, continuous bed media flow testing with alumina beads, a mixture of 1/4" and 3/8" diameter beads, was performed without operational problems, but the higher density, more uniform sized and shaped alumina beads resulted in poorer particle removal performance, with outlet loadings of 6 to 250 ppmw. The final series of continuous bed media flow, pelletized fly ash tests achieved good performance, with acceptable unit pressure drop and outlet loadings of 8 to 14 ppmw. The HTHP testing showed a clear trend for higher particle removal performance as the mass ratio of bed media to fly ash flow was increased, and demonstrated a particle removal performance acceptable for commercial applications. Mass ratios of bed media to fly ash were in the range of 10 to 20 for acceptable performance.

Conceptual design evaluations were conducted for IGCC and Advanced-PFBC applications of the SMGBF technology, and comparisons were made with ceramic barrier filter technology by applying Reference Studies conducted previously for ceramic barrier filter applications (Ciliberti, et al, 1986; Foster Wheeler Development Corp., 1989). Process flow diagrams and material & energy balances were developed for the IGCC and Advanced-PFBC applications using SMGBF hot gas cleaning. Both Once-Through and Recycle SMGBF were evaluated. The SMGBF system equipment was sized and specified to the extent needed to develop equipment delivered and installed cost estimates and to produce rough plant equipment layouts. The impact of the SMGBF system on the power plant thermal efficiency was estimated based on estimated heat losses, SMGBF system gas pressure drop, and auxiliary power consumption. Finally, total power plant capital requirements, annual operating costs and cost-of-electricity (COE) estimates were made, updating the Reference Studies to the current plant economic premises.

The evaluation results show that the SMGBF system is economically competitive with ceramic barrier filters for IGCC and Advanced-PFBC applications. The installed equipment costs of the SMGBF system are comparable to those of the ceramic barrier filter systems, although the pelletization system adds a significant equipment cost to the Once-Through SMGBF system:

- Installed equipment cost for IGCC application
    - Once-Through SMGBF: 32 - 41 $/kW
    - Recycle SMGBF: 17 - 22 $/kW
    - Ceramic barrier filter:, 11 - 19 $/kW

- Installed equipment cost for Advanced-PFBC application
    - Once-Through SMGBF: 31 $/kW
    - Recycle SMGBF: 18 $/kW
    - Ceramic barrier filter: 17 $/kW

The Once-Through SMGBF system has a higher total power plant capital cost, annual operating cost, and COE than the ceramic barrier filter system for IGCC and Advanced-PFBC, but these cost increases are small, about 1% for IGCC, and about 3-5% for Advanced-PFBC. The waste material issued from the plants using Once-Through SMGBF potentially has a superior environmental character, or even byproduct possibilities. The Recycle SMGBF system total power plant capital cost, annual operating cost and COE is nearly identical with that of the ceramic barrier filter system.

The Base Contract conclusions reached are:

- Design features have been identified in the cold flow model testing that optimize the SMGBF particle removal performance.

- Cold flow model and HTHP testing trends are consistent.

- Particle penetration levels of 6 to 14 ppmw are representative performance levels based on the HTHP testing, with the cold flow model testing indicating that even higher performance levels can be achieved.

- Particle removal performance increases and the unit pressure drop decreases as the mass feed ratio of bed media to fly ash increases. Ratios of 10 to 20 are required for acceptable performance.

- Sufficiently durable pellets can be generated from advanced power plant solid waste using conventional pelletization techniques, but further evaluation of optimum solid waste sizing, water and binder content, mixing, and curing procedures is needed.

- The pelletized solid waste may provide particle removal performance superior to more regular shaped and uniformed sized purchased granules.

- The Once-Through SMGBF total power plant capital requirement and COE are only marginally higher (1 to 5%) than that for ceramic barrier filter systems in both IGCC and Advanced-PFBC applications.

- The Recycle SMGBF system is comparable in capital cost and COE to the ceramic barrier filter system for both IGCC and Advanced-PFBC applications.

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