**UNIVERSITY OF NORTH DAKOTA:
DEPARTMENT OF CHEMICAL ENGINEERING, AND
ENERGY & ENVIRONMENTAL RESEARCH CENTER**

Final Report

Electrostatically Enhanced Barrier Filter Collection

Period of Performance July 1, 1999 through September 30, 2002

Submitted to:

AAD Document Control

U.S. Department of Energy
National Energy Technology Laboratory
PO Box 10940, MS 921-107
Pittsburgh, PA 15236-0940

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U.S. Department of Energy Grant No.: DE-FG26-99FT40591

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June 2003

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ACKNOWLEDGMENT

This report was prepared with the support of the U.S. Department of Energy (DOE) National Energy Technology Laboratory Cooperative Agreement No. DE-FG26-99FT40591. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors(s) and do not necessarily reflect the views of DOE.

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ELECTROSTATICALLY ENHANCED BARRIER FILTER COLLECTION

ABSTRACT

This work was performed through the University of North Dakota (UND) Chemical Engineering Department with assistance from UND's Energy & Environmental Research Center. This research was undertaken in response to the U.S. Department of Energy Federal Technology Center Program Solicitation No. DE-PS26-99FT40479, Support of Advanced Coal Research at U.S. Universities and Colleges. Specifically, this research was in support of the UCR Core Program and addressees Topic 1, Improved Hot-Gas Contaminant and Particulate Removal Techniques, introducing an advanced design for particulate removal.

Integrated gasification combined cycle (IGCC) offers the potential for very high efficiency and clean electric generation. In IGCC, the product gas from the gasifier needs to be cleaned of particulate matter to avoid erosion and high-temperature corrosion difficulties arising with the turbine blades. Current methods involve cooling the gases to $\sim 100^{\circ}\text{C}$ to condense alkalis and remove sulfur and particulates using conventional scrubber technology. This "cool" gas is then directed to a turbine for electric generation. While IGCC has the potential to reach efficiencies of over 50%, the current need to cool the product gas for cleaning prior to firing it in a turbine is keeping IGCC from reaching its full potential.

The objective of the current project was to develop a highly reliable particulate collector system that can meet the most stringent turbine requirements and emission standards, can operate at temperatures above 1500°F , is applicable for use with all U.S. coals, is compatible with various sorbent injection schemes for sulfur and alkali control, can be integrated into a variety of configurations for both pressurized gasification and combustion, increases allowable face velocity to reduce filter system capital cost, and is cost-competitive with existing technologies.

The collector being developed is a new concept in particulate control called **electrostatically enhanced barrier filter collection** (EBFC). This concept combines electrostatic precipitation (ESP) with candle filters in a single unit. Similar technology has been recently proven on a commercial scale for atmospheric applications, but needed to be tested at high temperatures and pressures. The synergy obtained by combining the two control technologies into a single system should actually reduce filter system capital and operating costs and make the system more reliable. More specifically, the ESP is expected to significantly reduce candle filter load and also to limit ash reintrainment, allowing for full recovery of baseline pressure drop during backpulsing of the filters. Two major tasks were undertaken:

1. Design and construction of the EBFC – The bench-scale testing utilized an existing continuous fluid-bed reactor and hot-gas filter vessel. Runs were made at temperatures between 600°F and 1000°F, pressures from 50 psig to 120 psig, and face velocities from 5 to 7 ft/min. Gas composition (70% N₂, 15% CO₂ and 15% H₂O) emulated a combustor or gasifier in terms of ESP performance.
2. Experimental Testing – The testing was conducted in several steps: a) shakedown, b) Voltage-Current (V-I) curves to determine ESP performance, c) factorial experiments to evaluate overall system performance over the full range of likely operating conditions, and d) several long term runs (attempted).

The ESP performance tests primarily centered on developing sufficient corona for the ESP to function. High temperature was found to give a much smaller voltage window for corona to occur, but sufficient for the ESP to function. The system worked very well over the full range of conditions (see Figure ES-1). Backpulse frequency was dramatically reduced when the ESP was on, and the efficiency of the backpulse in reducing pressure drop across the candle filter was at least as good with the ESP on.

The only negative aspect of the testing was that the system only worked with ash that was fairly non-conductive (low in carbon). Purging of insulators allowed the system to function for a limited time with conductive ash, but the small size of the existing filter vessel precluded adequate purging. Improved design (which would require testing on a larger scale) should remedy that problem.

Figure ES-1. Typical ΔP vs. Time of the EBFC with the ESP on and off (1000°F, 50 psig).

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ELECTROSTATICALLY ENHANCED BARRIER FILTER COLLECTION

1.0 INTRODUCTION AND OBJECTIVES

This research is being undertaken in response to the U.S. Department of Energy Federal Technology Center Program Solicitation No. DE-PS26-99FT40479, Support of Advanced Coal Research at U.S. Universities and Colleges. This research is for the UCR Core Program and addressees Topic 1, Improved Hot-Gas Contaminant and Particulate Removal Techniques, introducing an advanced design for particulate removal.

1.1 Statement of Problem

Integrated gasification combined cycle (IGCC) offers the potential for very high efficiency and clean electric generation. In IGCC, the product gas from the gasifier needs to be cleaned of particulate matter to avoid erosion and high-temperature corrosion of the turbine blades. Current methods involve cooling the gases to $\sim 100^{\circ}\text{C}$ to condense alkalis and remove sulfur and particulates using conventional scrubber technology. This “cool” gas is then directed to the turbine for electric generation. While IGCC has the potential to reach efficiencies of over 50%, the current need to cool the product gas for cleaning prior to firing it to a turbine limits IGCC to 42%–45% efficiency.

The two primary gas cleanup steps that incur the most cost, both in terms of up-front capital and operation are sulfur removal and particulate removal. Efficient removal of H_2S using the current suite of sorbents is one of the primary forces driving the need for gas cooling prior to cleanup. The typical scheme for sulfur removal involves scrubbing the H_2S in methyl-diethanol-amine scrubbers (with Claus or sulfuric acid plants for sulfur recovery). Hot-gas desulfurization using zinc-based sorbents at $\sim 1000^{\circ}\text{F}$ is currently being developed for commercial application. Other approaches that have been considered and tried include the use of sorbents, either injected directly into the gasifier for in-situ sulfur capture or entraining the sorbent into the gas stream to be removed, along with the

sulfur, in the particulate control device (1, 2). Alkalies can likewise be captured with in-situ or entrained sorbents (3–5). While these methods have enjoyed some success, they are dependent upon the availability of cheap but effective sorbents, since sorbents cannot be easily collected and regenerated. The use of in-situ or entrained sorbents also causes a substantial increase in the particulate loading.

The primary state-of-the-art technology for particulate control at high temperatures is candle filters, either ceramic or sintered metal. Although they are very effective at removing particulate matter to the level required for safe turbine operation, they do have several limitations. They require a relatively low face velocity (2–6 ft/min) to allow operation at a reasonable pressure drop. This equates to a large collection area, with a relatively high capital cost. Filters are subject to blinding and/or bridging, forcing a very high pulse frequency and high baseline pressure drop, which hinders operation, decreases system efficiency, and in some cases leads to candle failures. Thermal shock, process upsets, and other forces can cause candle breakage (6, 7). Therefore, there is room for substantial improvement in the current state of the art for candle barrier filter devices.

1.2 Objective of Proposed Research

The objective of the proposed project is to develop a highly reliable particulate collector system that can meet the most stringent turbine requirements and emission standards, can operate at temperatures above 1000°F, is applicable for use with all U.S. coals, is compatible with various sorbent injection schemes for sulfur and alkali control, can be integrated into a variety of configurations for both pressurized gasification and combustion, increases allowable face velocity to reduce filter system capital cost, and is cost-competitive with existing technologies.

1.3 Solution to Problem

A new concept for particulate control should not only retain the best advantages of current technology, but should also make significant improvements. Therefore, any advanced concept should start where current barrier filter technologies leave off. A new concept in particulate control, called electrostatic barrier filter collection (EBFC), was tested that meets the objectives laid out here. As described in the following sections, this concept combines electrostatic precipitation (ESP) with candle filters in a single unit and is based on technology recently proven for atmospheric applications. This work was performed through the University of North Dakota (UND) Chemical Engineering Department with assistance from UND's Energy & Environmental Research Center (EERC).

2.0 TECHNICAL MERIT

2.1 Relevant Technical Issues and Barriers

The investigation of hot-gas filter systems for the control of particulate emissions from advanced power systems such as pressurized fluid-bed combustion (PFBC) and IGCC has been ongoing for approximately 20 years. The economic driving force for filtering the particulate under high-temperature, high-pressure (HTHP) operating conditions is the significant improvement in power efficiency that results from the combustion of a fuel gas or topped PFBC gases directly in an aero-derivative gas turbine. These high-efficiency gas turbines require particulate loadings of less than 10 ppm with a particle size of less than 5 μm and preferably less than 1 ppm. Efficiency gains of over 5% are possible if the fuel gas sensible heat can be retained.

Numerous problems in HTHP filtration have been identified and resolved; however, some technical and economic issues remain that have limited the widespread advancement of these

systems into the marketplace. Some, such as filter performance, strength, and longevity, are being addressed in current programs with filter manufacturers and at large-scale test facilities such as the U.S. Department of Energy (DOE)-funded Power Systems Development Facility operated by Southern Company Services at its Wilsonville, Alabama, location.

Other programs at the EERC and the Southern Research Institute have examined filter ash and filter cake properties to determine their effects on filter bridging, blinding, cake permeability and re-entrainment. Some of these filter ash properties can result in the formation of low-permeability or hard-to-clean filter cakes, which results in frequent back pulsing and/or a substantial increase in baseline pressure drop across the filter. Increased dust loadings to the filter can also result in a higher pulsing frequency. Because of the relatively low permeability of the filter elements themselves and to counteract some of these filter cake properties, filter system designers limit the ratio of the actual gas flow rate to the total filter surface area (called the face velocity) to between 2 and 12 ft/min. For combustion systems, face velocities in the upper end of this range are generally achievable; however, for gasification systems, face velocities in the range of 2 to 6 ft/min are more typical. These low face velocities result in increased filter vessel size and capital cost.

2.2 Description of Proposed Concept

2.2.1 Electrostatic Barrier Filter Collection

Proprietary Information – See Appendix A.

2.2.2 Issues Related to Concept

Many of the issues related to the use of ESPs or barrier filters are resolved by the EBFC. The ESP limits ash re-entrainment, allowing for full recovery of baseline pressure drop during backpulsing of the candle filters. Reductions in ash loadings to the barrier filter will reduce pressure drop and backpulse frequency. Directional electrodes may be used to limit back corona. Conductive

metal filters can be used to further limit back corona. The barrier filter can handle higher loadings if required to handle poorer collectability of low-resistivity ashes in the ESP portion of the EBFC. Alkali can be controlled with the use of in-bed or in-duct sorbents. These “conditioned” sorbents should collect well in the ESP portion of the EBFC. The compact nature of the EBFC should keep size and cost low.

Issues to be resolved in the final design of an EBFC include mechanical stability of the materials used, including the insulators, at the operating temperature of the EBFC. A number of iron-based alloys are available at moderate cost that can provide good mechanical properties at temperatures over 1500°F. Cooling of the insulators has been proposed (8) and, if required, could be accomplished with only a small flow of inert gas such as nitrogen. Advances in the ceramic industry are also making high-temperature insulating materials available.

2.3 Relation to Past and Current Research Practice

2.3.1 Previous Developments in HTHP Filtration

Tests conducted on a pilot-scale transport reactor gasifier system with a hot-gas barrier filter system at the EERC have seen some filtration problems due to ash properties (9, 10). These problems included a significant increase in the filter baseline differential pressure from 20 to 90 in. of H₂O. Another observed problem was a rapid buildup of pressure drop across the filters, resulting in a pulse frequency as short as every 5 to 6 min. The average particulate loading going into the hot-gas filter vessel (HGFV) was approximately 4500 ppm, with a d_{50} of 6 μm when the primary cyclone was not spoiled, and approximately 11,000 ppm with a d_{50} of 12 μm when the cyclone was spoiled. Carbon in the filter ash ranged from 45% to 60% depending on the conditions.

Off-line cleaning tests were completed using a high-temperature ball valve to bypass the filter vessel every time it was to be backpulsed. Total off-line cleaning times were varied from 160 to

330 sec to 450 to 690 sec, and back pulse pressure was varied from 180 to 240 to 300 psig. This testing showed that as back pulse reservoir pressure was increased, the length of time until the next back pulse trigger increased slightly, by approximately 30 sec with each increase. Traces that were obtained with a 240-psig back pulse reservoir pressure show that at a settling time above 330 sec, there was not much difference in the pressure traces. However, when the settling time was dropped to 160 sec, two back pulse sequences were observed in the time for one back pulse sequence at the higher settling times. These tests showed that reducing the re-entrainment of filter ash resulted in a 20- to 30-in. H₂O decrease in the baseline filter differential pressure and doubled the time between filter backpulsing (9, 10).

2.3.2 Advanced Hybrid Particulate Collector

Proprietary Information – See Appendix A.

2.3.3 Previous Development of ESP at Pressure

ESP was considered for filtering particles from gases at HTHP in the 1980s for several emerging electric generation technologies, including IGCC and PFBC (11). The advantage of ESP is that since, from a gas dynamics point of view, the precipitator is virtually an open duct, it cannot plug, and it has a negligible pressure drop. The high gas densities enable high electric fields to be sustained across the electrodes, leading to a small specific collection area (SCA). Such an ESP promises to be compact in comparison to an ESP treating the same mass flow of gas at atmospheric pressure (8).

In order to resolve key questions of achievable voltage stresses and electrical energy consumption, pilot plant and bench-scale tests have been performed in several centers – the most widely reported being those from West Germany (12) and the United States (13–15). In the United States, Cottrell Environmental System (CES) took the lead in the development of the HTHP ESP.

CES had installations at six different pilot-scale test sites. In addition, the Denver Research Institute (DRI), supported by DOE has performed pilot-scale ESP tests at elevated temperature and pressure (10).

At DRI, Rinard and colleagues performed a series of tests on a single-tube ESP operated at 6.4 to 10 bar and at 760°–900°C (15). The best performance was at 760°C. At 900°C, the performance obviously deteriorated as a result, it was thought, of possible electron or ion emission from the hot ash. The beneficial effect of elevated gas densities was seen in electric fields of 13.5 kV/cm that were established at 845°C and 10 bar. Tests performed at the Union Carbide PFBC using a CES ESP demonstrated the improvement due to increasing gas density (pressure). Feldman and Kumar (14) point out the rapid improvement in collection efficiency with increasing electric field strength. Collection efficiencies ranged from 95% to 99.5% at the Curtiss-Wright PFBC, depending upon the rapping cycles and the corona power, for a SCA of 66 to 74 m²/m³/s (11).

The general conclusion from previous HTHP pilot-plant ESP testing is that the feasibility of operation at 5–10 bar and up to 850°C has been demonstrated. Stable coronas have been generated whose voltage-current characteristic can be related to the gas density. However, for a successful HTHP ESP to be designed and developed, the following factors need careful consideration:

- The combination of low ash resistivity at high operating temperatures, together with the correspondingly high current densities, will not necessarily lead to back corona, since the high gas densities should suppress it.
- The suitability and integrity of the material used at temperatures $\geq 1000^{\circ}\text{C}$ has to be considered carefully. For long-term application at elevated temperatures, the creep behavior of the material has to be taken into account.

- For some materials, at temperatures above 700°C the region of forgeability starts. This can become a problem if rapping is done by conventional hammer systems. Cleaning by pulse jet, analogous to those used in baghouses or by ultrasonic horns, is under discussion.
- The electrical resistivity of most insulator materials drastically decreases at temperatures above about 300°C. An application of advanced ceramics for insulating material for the extreme requirements of both temperature and pressure should be investigated.
- Electric power consumption as a fraction of the total electric output from a PCFB electric generating plant has been observed to be between 1.5% and 2% (11). The low required collection efficiency (90%) of the EBFC will greatly reduce the electric load. Another solution might be to use power-conserving means on the transformer rectifier sets, such as intermittent electrical energization.

Tassicker (11) concludes that “the data available would be sufficient for the commercial-scale of an ESP for conditions of 5–15 bar and 400–700°C. The available data are less definite for a firm design at 850–900°C. More pilot-plant work is needed before a commercial-scale plant in this range could be confidently sized.”

2.3.4 Technical Issues Resolved by EBFC

- EBFC is expected to greatly reduce the problem of higher pressure drop and frequent pulsing for conventional candle filters when the face velocity is increased.
- EBFC is expected to solve the problem of re-entrainment and recollection of dust in conventional filter collection devices caused by the close candle spacing.
- EBFC is expected to break down the barriers that prevent operation of candle filters at high face velocities.
- EBFC is expected to require significantly less total collection area than conventional devices.

- EBFC is expected to improve the potential for alkali capture with sorbents.
- EBFC is expected to be suitable for new installations or as a retrofit replacement technology for existing particulate collectors.
- EBFC is expected to be applicable to both gasification and PBFC technologies.

3.0 EXPERIMENTAL APPROACH

3.1 Overall Approach

The EBFC concept is a new technology that had never been tested at HTHP, even at the bench scale. However, there was a strong theoretical basis for the concept, as described in Section 2.0. The intent of the current work was to take this concept from the conceptual stage through the laboratory demonstration step, i.e., proof of concept. The test program was designed to test whether the theory and the practical experience gained from low-temperature, ambient-pressure applications could be successfully applied to HTHP particulate removal.

The bench-scale testing utilized the continuous fluid-bed reactor (CFBR) and HGFV described in Section 3.2.2 of this report (and in more detail in Appendix A of the first status report on this project dated April 5, 2000). The bulk of the tests used electric heat for heating synthetic fuel gas and filter ash, which were fed into the HGFV. This filter vessel contained one centrally located candle filter of the appropriate length to achieve a baseline face velocity of approximately 6 ft/min. Since maintaining a given velocity in the CFBR is not required, the total system gas flow was changed in order to vary filter face velocity. Initial tests were conducted to determine the collection efficiency of the filter vessel itself as a settling chamber. These tests were followed by a series of tests with the ESP operating without a candle filter present. This allowed the collection efficiency of the ESP under a variety of operating conditions to be determined.

These tests showed that the ESP was very inefficient and needed to be redesigned. This was done, incorporating some new findings from the advanced hybrid particulate collector (AHPC). Then the EBFC was reassembled with a candle filter element in place and the test conditions repeated. With the filter element installed, the collection efficiency was assumed to be 100%, and the filter operational variables (primarily pressure drop and pulse frequency) were monitored. The baseline pressure drop after a backpulse (pressure drop recovery) was also used as an indication of the amount of re-entrainment on the filters.

Since the ash injection tests exhibited excellent performance, an actual 50-hr coal gasification test using the CFBR was attempted to generate a dirty gas stream for the bench-scale EBFC. This long term test was unsuccessful due to rapid (within 4-6 hours) coating of the insulators with conductive ash. This caused arcing which required the ESP to be turned off. It is assumed that better mechanical design of the system (which was not possible with the current setup) would eliminate this problem.

3.2 Basis for Experimental Test Program

3.2.1 Scale of Testing

Initial testing has been done on as small a scale as practical, but large enough not to compromise the data quality. The UND EERC operates a 4-lb/hr fluid-bed gasification test rig (CFBR) that is equipped with a HGFV. This small-scale filter vessel has been used to mimic conditions of the EERC's larger transport reactor (300 lb/hr) and of other larger fluid-bed gasifiers with good results (16). The EERC has conducted 50-hr gasification tests on the CFBR with the bench-scale hot-gas filter system utilizing some of the same feedstocks tested in the 300-lb/hr transport gasifier. Hot-gas filter performance was markedly different from the transport reactor even though similar temperatures, face velocities, particulate loadings and particle size distributions were

achieved. Results were similar to those reported from operation of a fluid-bed gasifier. However, when filter ash from the transport reactor was injected into the CFBR, the same rapid back pulsing that occurred in the pilot-scale system was observed—back pulsing intervals decreased from approximately every 2 hr to every 7 min. Operation in both the fluid-bed and transport regime was therefore demonstrated (16).

3.2.2 Test Equipment

The CFBR, shown in Figure 1, was used for these experiments. It is constructed of 316H stainless steel Schedule 80 pipe. The first (bottom) section is made of 3-in. pipe and is 33 in. long. The next (top) reactor section is made of 4-in pipe, 18.75 in. long. The top of the fluid bed lies 33 in. above the coal injection point. The reactor currently has two ceramic fiber heaters to maintain the vessel's temperature. The reactor is capable of operation at a maximum of 155 psig and 840°C. A 3-in.-diameter electrically heated cyclone capable of operating at a temperature of 1650°F (900°C) and 200 psia is ordinarily used for solids removal from the gas stream, but if was filled with sand for these tests.

The bench-scale HGFV is approximately 9.75 in. inside diameter and 60 in. long (including cone, vessel and cap), and it can handle a gas flow up to 30 scfm at 1550°F and 150 psig. Heat-traced stainless steel piping to connects the bench-scale HGFV between the cyclone and the quench train. Ports are added in the filter vessel that allow temperature and pressure measurements to be obtained. These same ports can be utilized to insert a water-cooled boroscope probe for visually inspecting the filter elements and looking for signs of back corona. The ash letdown station consists of a high-temperature valve to isolate the ash hopper from the filter vessel. The nitrogen back pulse system is designed to supply a minimum of three candle volumes per pulse. The nitrogen is capable of being heated up to 1500°F before entering the filter vessel.

A more detailed description of this test equipment is given in Appendix A of the first status report for this project (April 5, 2000).

3.2.3 Realism of Operating Conditions

Previous operating experience with the bench-scale filter vessel on bench-scale PFBC and gasification test rigs has provided operating conditions that are similar to full-scale operating systems (5, 9, 16). Previous work has also shown that filter operating conditions achieve steady state very quickly so that 4–6-hr tests were sufficient to verify significant differences in the operation of the filter system versus the EBFC.

3.3 Relevance to UCR Program

The EBFC concept clearly meets the stated objectives of the UCR Core Program. First, the concept is a truly advanced approach that offers significant improvements in collection of particulates over existing technologies. With the EBFC, system efficiency is not only gained

Figure 1 – CFBR for Gasification and Filtration Testing

through higher-temperature operation, but also reduced pressure drop and less frequent backpulse cleaning. The EBFC concept is also fully compatible with the technology for control of alkali and sulfur with sorbents in a particulate control device. In the worst case, the cost of the EBFC is expected to be competitive with existing technology, but will provide far superior operability. More likely, the cost for the EBFC will be significantly lower than that of conventional barrier filter technology because the total collection area is likely to be reduced by a minimum of 69%.

This research program has allowed two students from the UND chemical engineering Master's program (one of whom has continued in the Engineering Ph.D. program) as well as three undergraduates to receive top-notch training on coal-related research using state-of-the-art equipment.

4.0 RESULTS AND DISCUSSION

The project is divided into three activities: design and modification of equipment, experimental testing, and conceptual design of a full-scale plant.

4.1 Task 1 – Design and Construction of EBFC

The primary purpose of Task 1 was to design, construct, and install a working EBFC model on the existing EERC CFBR HGFV system described in Section 3.2.2 and Appendix A of the first status report on this project (April 5, 2000).

As intended, the EBFC was constructed with one centrally located candle filter surrounded by a circular wire high-voltage cage. The vessel wall was grounded and served as the collecting electrode. See Figure 2 for a general schematic of the EBFC. To accommodate one centrally located candle, a new tube sheet and filter hold down plug were machined for the EBFC out of stainless steel. See Figure 3 for a schematic diagram of the tube sheet.

Figure 2 – Schematic Diagram of Electrostatically Enhanced Barrier Filter Collector (EBFC)

After completing the necessary calculations, the electrode cage was constructed entirely from 1/16-in. diameter stainless steel welding rod. The diameter of the wire for the cage was critical for developing the appropriate corona discharge. The spacing from the wires to the vessel wall was 1.5 in. while the spacing from the wires to the candle was approximately 2.2 in. The smaller wire-to-wall spacing helped to force any sparking from the wires to the wall rather than to the candle. Isolating the high-voltage electrode cage from the grounded vessel wall required the use of high-temperature ceramics. Due to the compact size of the EBFC, all insulators needed to be small (2 inches in length) and thus required a ceramic with extremely high electrical resistance. Very high purity alumina (99.8% Al_2O_3) was chosen as the material of construction for the insulators.

Calculations were completed to size all insulators and estimate the current loss through each. Three vertical insulators were used to suspend the electrode cage from the bottom of the tube sheet. The high-voltage wire that connected the power supply to the electrode cage also needed to be isolated from the vessel wall. A cylindrical feed-through insulator was machined to isolate the power cable. The power cable also needed to be isolated from the flange where it gained access to the vessel wall. A high-pressure, high-voltage feed-through plug was purchased as an “off the shelf” item from a manufacturer. This feed-through plug was then welded into the flange. Figure 4 shows a general schematic of the feed-through plug. Finally, a means of connecting the high-voltage power cable to the electrode cage was constructed. Putting the electrode cage in place required sealing the vessel. Thus, the only access to the cage and power cable was through the flange at the bottom of the vessel. A connector was constructed and welded to the cage so that a set screw holding the high voltage wire to the cage could be tightened from the bottom of the vessel.

Figure 3 – Tube Sheet Modified for Vertical Insulator Purge (with Candle Not in Place)

Figure 4 – Feed-Through Plug for High Voltage Electrode

4.2 Task 2 – Experimental Testing

The overall approach to this program, including the experimental testing, was summarized briefly in Section 3.1. The testing was to be conducted in four steps: 1) shakedown, 2) testing to determine variables important to ESP performance, 3) testing of overall system performance, and 4) long-term proof of concept.

4.2.1 Shakedown Testing

A number of problems were uncovered during the shakedown testing. Among the most serious, were the following: (1) The computer data acquisition and control system would frequently reboot when the ESP arced. Since arcing was a regular occurrence, this was not tolerable. To rectify the situation, the computer system had to be as far as possible from the ESP power supply and system, and the two needed to be on two different AC circuits. (2) The feed-through plug arced to the

surrounding pipe regularly. To prevent that, all gaps (no matter how small) between the insulator (which shielded the wire to the electrode cage) and the feed-through plug had to be filled in with insulating paste. In addition, a nitrogen purge was still found to be necessary to prevent dust, which is conductive, from collecting on the insulator and causing shorting. The purge stream, which was added to the original design, is also shown in Figure 4. (3) The vertical insulators which isolate the ESP electrode cage from the vessel (i.e. the tube sheet) were found to get covered in conductive dust very rapidly. This resulted in shorting of the ESP. To prevent this, a nitrogen purge was added to the tube sheet as shown in Figure 3. The purge was added through the center of the tube sheet temporarily, just to make sure that it would be effective. It was. As a permanent measure, individual purge lines were eventually added to flow around the base of each of the three vertical insulators. The central purge was only useful while no candle was installed.

4.2.2 *Testing ESP Performance* (See Appendix A for Proprietary Information.)

The best diagnostic tool for ESP's is the voltage-current (V-I) curve. As the name suggests, this curve shows the relationship between current and voltage for an ESP at specified conditions. The most important factor addressed by the V-I curve is the generation of corona. Without corona, an ESP will not precipitate any ash. A V-I curve shows whether or not any corona is present. Figure 5 shows an example of a desirable V-I curve. When voltage is initially applied to the ESP, there is no current draw. This means that the insulators are doing their job and preventing any current from leaking to ground. Then, at a voltage known as the corona onset voltage, corona begins and a measurable current is drawn. The gas ions are transporting electrons to the grounded collecting surface. Finally, a maximum voltage is reached where arcing occurs between the discharge and collecting electrodes.

It is normal for corona to suddenly begin at a specific voltage. Corona current is also not linear in relation to applied voltage. The V-I curve of Figure 5 is desirable because the corona current increases gradually with voltage. This gives the ESP a broad window of voltage within which to work. If the curve is too steep, the voltage window is too narrow to work within. In a narrow window, sufficient corona is difficult to maintain without severe arcing. It is also desirable that the corona current be large enough for the size (collection area) of the ESP. In most cases, this is in the area of several milliamps. During operation of an ESP, it is generally desirable to use as high a voltage as possible with an acceptable frequency of arcing.

A broad range of conditions were examined for onset of corona via V-I curves. These V-I curves were all reported in a previous status report of this project (April 13, 2001). Suitable corona was found to be achievable under the HTHP conditions being studied. This result is consistent with findings reported by other researchers (17).

Figure 5 – An Example of a Desirable V-I Curve

However, based on settling tests which were run with dust loading to determine the effectiveness of the ESP at removing dust over and above that of just the vessel itself acting as a settling chamber, it was found that the ESP was not filtering as much of the dust as expected. These results were also reported in that same status report (April 13, 2001), and are summarized below in Table 1 for convenience. The status report can be referenced for more particulars on the exact conditions which were run in each case. The main result from the tests is that the collection efficiency obtained with the ESP was better than without the ESP, but the collection efficiency was lower than expected (69% vs 90%). The cause of this poorer than hoped for efficiency was presumed to be “sneakage”. Sneakage is the ability of the dirty gas to pass through an inactive zone of the ESP. It is any area in the ESP in which there is no electric field and thus no precipitation (or the precipitation is directed toward the barrier filter). Based on the dimensions of the discharge electrode cage and the vessel wall, approximately 48% of the vessel’s volume is inactive when it comes to precipitation. Good ESPs have absolutely no sneakage.

TABLE 1. Results of Testing with Dust Loading

Run	Flow rate (ACFH)	Collection Efficiency (%)
Settling Chamber-1	298	55
Settling Chamber-2	264	58
ESP on	339	69

The other modification that needed to be made to the equipment was to replace the temporary purges for the vertical insulators shown in Figure 3, which went through the center of the tube sheet. With the candle in place, that purge system could not be used, so purge lines were drilled into the tube sheet that ended at fittings to mount the vertical insulators. Each of the insulators was placed

into a fitting in the tube sheet about 1/4 inch, held in place with three set screws, and had a small gap all around it for the purge stream to flow.

After the modifications to the ESP had been made, the shake-down testing of the ESP had to be performed a second time. V-I curves were determined at a wide range of gas compositions and temperatures and pressures. The gas composition was eventually fixed at 75% nitrogen, 15% carbon dioxide, and 10% steam for all subsequent runs. It was felt that this composition was reasonably close to what would be encountered in combustion systems, and that it behaved in the ESP much like the gas from air fired gasification systems. V-I curves for this gas mixture at 600°, 800°, and 1000°F are given in Figures 6, 7, and 8 respectively. It can be seen from these curves that corona was established at the whole range of temperatures and pressures. Thus, the new design of the ESP worked (at least in terms of being able to establish a corona current).

4.2.3 Testing for Overall System Performance

The third phase of experimentation focused on the whole EBFC system, examining the effects of various operating variables on filter performance—specifically the back pulse frequency and the

Figure 6 – V-I Curves at 600°F

Figure 7 – V-I Curves at 800°F

Figure 8 – V-I Curves at 1000°F

baseline pressure drop. The system efficiency with the filter in place is assumed to be 100%, but the frequency of back pulsing and the baseline pressure drop impact the economics of the system significantly.

Twelve 6-hr tests were conducted in a fractional factorial arrangement (eight runs) plus center points (four runs). The center points gave an estimate of error for tests of statistical significance. The variables studied are given in Table 2.

TABLE 2. Operating Variables Studied in EBFC System Experiments

Variables Which Were Studied		Low Level	High Level	Units
1.	Temperature	600	1000	°F
2.	Pressure	50	120	psig
3.	Face Velocity (gas flow rate)	5	7	ft/min
4.	ESP System	Off	On	
Variables Which Were Fixed				
1.	Gas Composition	N ₂ (70%), CO ₂ (15%), H ₂ O (15%)		
2.	Pulse-Cleaning Pressure	System plus 100 psig		
3.	Pulse Duration	500 ms		
4.	Dust Loading	20,000 ppm		
5.	ESP Electrode Voltage	Maximum (just below frequent arcing)		
6.	Ash Carbon Content	< 1%		
7.	Ash Particle Size Distribution	< 15 microns		

The results of the testing are summarized in Figures 9–13, which show the primary variable, pressure drop across the filter, as a function of time.

The conclusions to be drawn from this experimental testing are as follows:

1. Corona can be established under gasification conditions (high temperature and pressure).

Figure 9 – System Test at Temperature = 600°F, Pressure = 120 psig, and Face Velocity = 5 ft/min.

Figure 10 – System Test at Temperature = 600°F, Pressure = 50 psig, and Face Velocity = 7 ft/min.

Figure 11 – System Test at Temperature = 800°F, Pressure = 85 psig, and Face Velocity = 6 ft/min.

Figure 12 – System Test at Temperature = 1000°F, Pressure = 50 psig, and Face Velocity = 5 ft/min.

Figure 13 – System Test at Temperature = 1000°F, Pressure = 120 psig, and Face Velocity = 7 ft/min.

2. The EBFC has a large impact on pressure drop build-up. With the ESP on, the pressure drop took dramatically longer to increase. Backpulse frequency was therefore reduced by a large factor (>10).
3. The baseline pressure drop was also improved with the ESP on. This shows that the ESP helped cut down on re-entrainment of the ash after back-pulsing (as was noticed in the AHPC).
4. An EBFC cuts down on the required number of barrier filters, since most of the ash is being removed by the ESP.
5. This concept is ready to be demonstrated at the next scale (pilot scale).

4.2.4 Long Term Testing

Since the experiments were successful up to this juncture and an EBFC system with good performance has been found, a long-term confirmation run was attempted. This was hoped to be a run of at least 50 hr at gasification conditions, using actual gas from the gasification of a selected coal on the CFBR. Unfortunately, the run had to be terminated after only several hours. The problem was arcing of the ESP. The purging of the insulators was not sufficient to keep the conductive ash from depositing on them to a limited extent. Once a slight film of ash built up on the insulators, the system began to arc repeatedly. Although this was a major problem in the system tested, it is not expected to be a problem at the next scale. The purge system that was used was the best that could be done given the constraints of the HGFV that was used to house the system. But, if a system is being designed from scratch, a better purge system could be implemented, and there is every reason to believe that the system would work well even with conductive (higher carbon content) ashes.

4.3 Task 3 – Design Considerations for Full-Scale EBFC

One of the main operating variables for a commercial scale EBFC is the potential (voltage) required to obtain corona current. Corona current is, of course, the driving force for ESP operation. This potential is proportional to gas density. If the data from the V-I curves from this work (which

had a maximum gas density of about 0.36 lb/ft³) is extrapolated to commercial scale conditions, which are assumed to be 400 psig and 100°F (corresponding to a gas density of 0.72 lb/ft³), then the potential required for corona is almost 110,000 volts. This is a very high potential, but not out of the question. The data and extrapolation are shown in Figure 14.

5.0 CONCLUSIONS

The ESP performance tests primarily centered on developing sufficient corona for the ESP to function. High temperature was found to give a much smaller voltage window for corona to occur, but sufficient for the ESP to function. The system worked very well over the full range of conditions. Backpulse frequency was dramatically reduced when the ESP was on, and the efficiency of the backpulse in reducing pressure drop across the candle filter was at least as good with the ESP on.

Figure 14 – Potential Required to Obtain 1 ma of Corona Current vs. Gas Density

The only negative aspect of the testing was that the system only worked with ash that was fairly non-conductive (low in carbon). Purging of insulators allowed the system to function for a limited time with conductive ash, but the small size of the existing filter vessel precluded adequate purging. Improved design (which would require testing on a larger scale) is expected to remedy that problem, since ESPs are currently used in some situations to remove conductive ash.

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