Integrated System to Control Primary PM 2.5 From Electric Power Plants

Final Report

DOE Contract Number DC-FC26-OONT-40757
EPRI Contract Number EP-P4245/C2075

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Introduction

During this project, LSR Technologies, Inc. designed, built and tested the first Advanced ElectroCore particulate separator. The Advanced ElectroCore is an improvement over the conventional ElectroCore in that it contains a performance-enhancing central electrode. The unit was tested at Unit 4 of Alabama Power Company's E.C. Gaston Electric Generating Plant. The system was tested using a 6,000-acfm slipstream from the outlet of the unit's hot side ESP. The unit was burning low sulfur Alabama coal in a sub-critical boiler. The slipstream was directed to the Advanced ElectroCore where the particulate matter was separated and the efficiency measured. In addition to particulate efficiency tests, mercury capture tests were conducted by injecting activated carbon upstream of the Advanced ElectroCore and measuring the mercury removal efficiency.

Summary

The performance tests at E.C. Gaston showed how the Advanced ElectroCore field prototype performance changed as a function of the gas flow, inlet loading and the voltage applied to the central electrode in the separator. With the optimum voltage applied to the electrode, the unit achieved a maximum efficiency of 96.38 percent and a minimum outlet loading of 0.0021 grains/dscf while operating with a specific separating area (SSA) of 100 square feet per thousand acfm. The minimum outlet loading translates to about 0.00575 lb_m/million Btu or less than one fifth of the current NSPS standard of 0.03 lb_m/million Btu. The highest efficiency for the upstream ESP was about 99.75 percent. Together these two systems are capable of removing 99.991 percent of the particulate matter coming from the uncontrolled boiler. This efficiency is higher than the target efficiency of 99.99 percent and the outlet loading of 0.00575 lb_m/million Btu is almost half of the target emission rate of 0.01 lb_m/million stated in the program objectives. In terms of efficiency and outlet concentration, the tests showed that the Advanced ElectroCore can meet or exceed the program goals.

The mercury capture tests were conducted using the Ontario Hydro method. When injection activated carbon at the rate of 7 pounds per million cubic feet of gas, the measured removal efficiency was about 90 percent. At the time of this writing, LSR was unable to obtain the full report on the mercury testing. If it does become available, it will be included as an appendix to this report.

The results show that the ElectroCore has been successfully scaled up by a factor of 12 from the 500 acfm unit tested at Alabama Power Company's Plant Miller in the summer of 1997. The addition of the central electrode has improved the separation efficiency when inlet loadings get very low.

Discussion

The project was broken down into nine tasks as shown in Table 1.

Task 1 – ElectroCore Testing at SRI

The first task was to involve testing at Southern Research Institute to retrofit the ElectroCore unit used at Plant Miller in 1997 with a central electrode to enhance the performance. Instead, the ElectroCore unit was shipped to LSR's laboratory in Acton, Massachusetts where the work was performed by LSR personnel. The objective of the laboratory work was to determine what modifications to the ElectroCore would be

Table 1: Project Tasks

Number	*Description*
Task 1	ElectroCore Testing at SRI
Task 2	Component Design
Task 3	Fabrication/Construction
Task 4	Transport/Installation
Task 5	Shakedown Testing
Task 6	Field Testing at Site
Task 7	Data Analysis/Cost Estimate
Task 8	Dismantle/Site Restoration
Task 9	Project Management/Reporting

required to support the new electrode and achieve the proper flow distribution within the separator.

The ElectroCore unit from 1997 had been sitting unprotected outdoors at SRI and was badly rusted both inside and out. After cleaning the unit to the best of our ability, the internal walls of the separator were still very rough compared to when the unit was new. Restoring the unit to its original condition was estimated to cost about $30,000 and take about 16 weeks, so it was decided to modify the test procedures to be able to use the unit in its existing condition. Repairing the unit would put the project over budget and behind schedule.

The rough walls would have little impact on the electrical characteristics or on the details of the flow geometry. It was believed that the rough walls would have a large impact on particle performance because the particles are expected to bounce along the wall before being extracted from the bleed flow outlet slot. The device is designed to prevent particles from adhering to the walls and it would be impossible to keep particles from adhering to the now roughened surface. The approach was to use the unit for evaluating the central electrode installation and to look at the gas flows within the unit but not to use it to measure particle separation efficiency.

The first task was to modify the unit to accept an 8-inch diameter central electrode. The conventional ElectroCore had two end plates. It was deemed very desirable to eliminate these end plates when installing the central electrode. The end plates reduced the gap between the central electrode and the grounded separating electrode and thereby reduced the maximum voltage that could be applied before spark-over occurred. Even if these end plates were made of a dielectric material, such as Teflon®, there was still concern that the plates might eventually become coated with an electrically conductive material, such as damp fly ash, and again reduce the maximum operating voltage.

The second undesirable feature of the end plates is they create horizontal surface area onto which fly ash may collect. By eliminating the endplates, the separators form an unobstructed vertical tube from top to bottom without any horizontal surfaces for fly ash to accumulate. Eliminating the endplates would also make the separators easier to clean should tests show there is a material buildup on the vertical walls over time.
The conventional ElectroCore was installed with the end plates removed and the 8-inch diameter central electrode installed. The electrode was longer than the separators and extended into the upper and lower end caps. The ends of the electrode were fitted with corona shields made of ¾ inch diameter tubing rolled into a torus. The electrode was bottom-supported and electrified from the top through a ceramic feed-through bushing that also acted as a positioner for the electrode. The supports and electrical connections were shielded so that the maximum field strength occurred at the wall of the central electrode within the separating section. Tests showed the maximum voltage obtainable was 110 kV at ambient temperature. No corona was detected prior to spark-over as was desired. This maximum voltage was an 80 percent increase over the maximum voltage obtained earlier when tested with Teflon endplates and without carefully designed corona shields.

Removing the endplates improved the electrical characteristics of the unit but created the opportunity for particles entering the separator near the extreme top or bottom of the inlet slot and proceed directly out with the clean flow without being given time to be separated from the clean gas. It was clear that the inlet slot would have to be modified to prevent this “short circuit” from occurring. The approach used was to block the inlet slot some distance from the end so that the gas and particles would make at least a 180-degree turn in the separator before being lost out the ends of the separator. If the gas was able to make a 180-degree turn then the particles would be able to exit through the bleed flow outlet slot with the bleed flow.

Flow visualization tests were conduced to determine what length of inlet slot would be required to insure that the flow made at least a 180-degree turn. The top of the separator’s upper cap was replaced with a polycarbonate sheet so it was possible to see down into the separator. The view though this cap is shown in Figure 1. Flow visualization was accomplished by introducing white smoke though a probe placed in the inlet slot. The smoke generator generated white, non-toxic smoke with particles from 0.3 to 2.5 μm in diameter. In the first set of tests the probe position was moved up and down in the inlet slot and the rotation angle of the flow was observed. These tests were conducted without blocking the inlet slot. The results are shown in Figure 2. The results show, for example, that gas entering the separator 15 inches from the top of the separator makes a turn of 430 degrees (about 1.2 rotations) in the separator before exiting the end with the clean flow. This is essentially independent of the two bleed flow

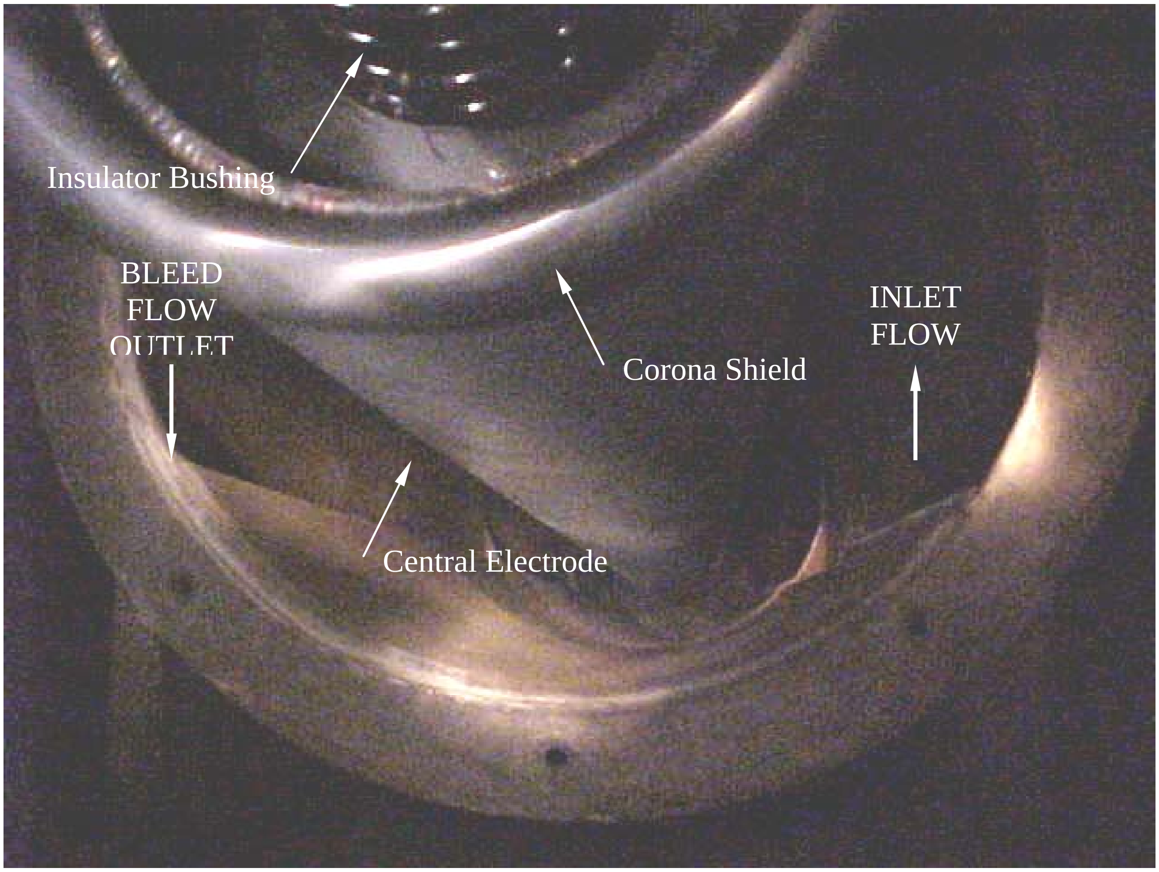

Figure 1: View Looking Down Into ElectroCore Separator Through Polycarbonate Top Cover

ratios tested. The bleed flow ratio, designated as ß, is the ratio of the flow rate of gas leaving through the bleed flow outlet slot to the gas inlet flow rate.

Figure 2 shows that gas entering closer than about 7 inches from the ends does not make at least a 180-degree turn so particles entering with this gas probably cannot be extracted with the bleed flow. This suggests that the length of inlet slot that is required to be blocked may be relatively small. In the second set of tests the inlet slot was blocked and the flow observations were repeated. The blocked inlet slot data are shown in Figure 3. In Figure 3 the gas rotation angle indicates the number of rotations the incoming gas makes before leaving the end of the cylinder with the clean flow. If the gas is introduced at the end of the separators, it will leave immediately without making any rotations. As the distance from the end increases, the gas has more time in the separator and therefore makes more revolutions before exiting. The parameter “a” used in Figure 3 is the length of inlet slot that has been blanked off. The smoke test data show the gas rotates about 40 percent of the value predicted by simple theory. For example, if the top and bottom 16.4 inches of the inlet slot are blanked off and operating at a bleed flow ratio of 9.07 percent, theory predicts the incoming gas will rotate at least 575 degrees before leaving the end of the separator. The experimental data showed the rotation was only 230 degrees. At a bleed flow ratio of 15.51 percent theory predicts

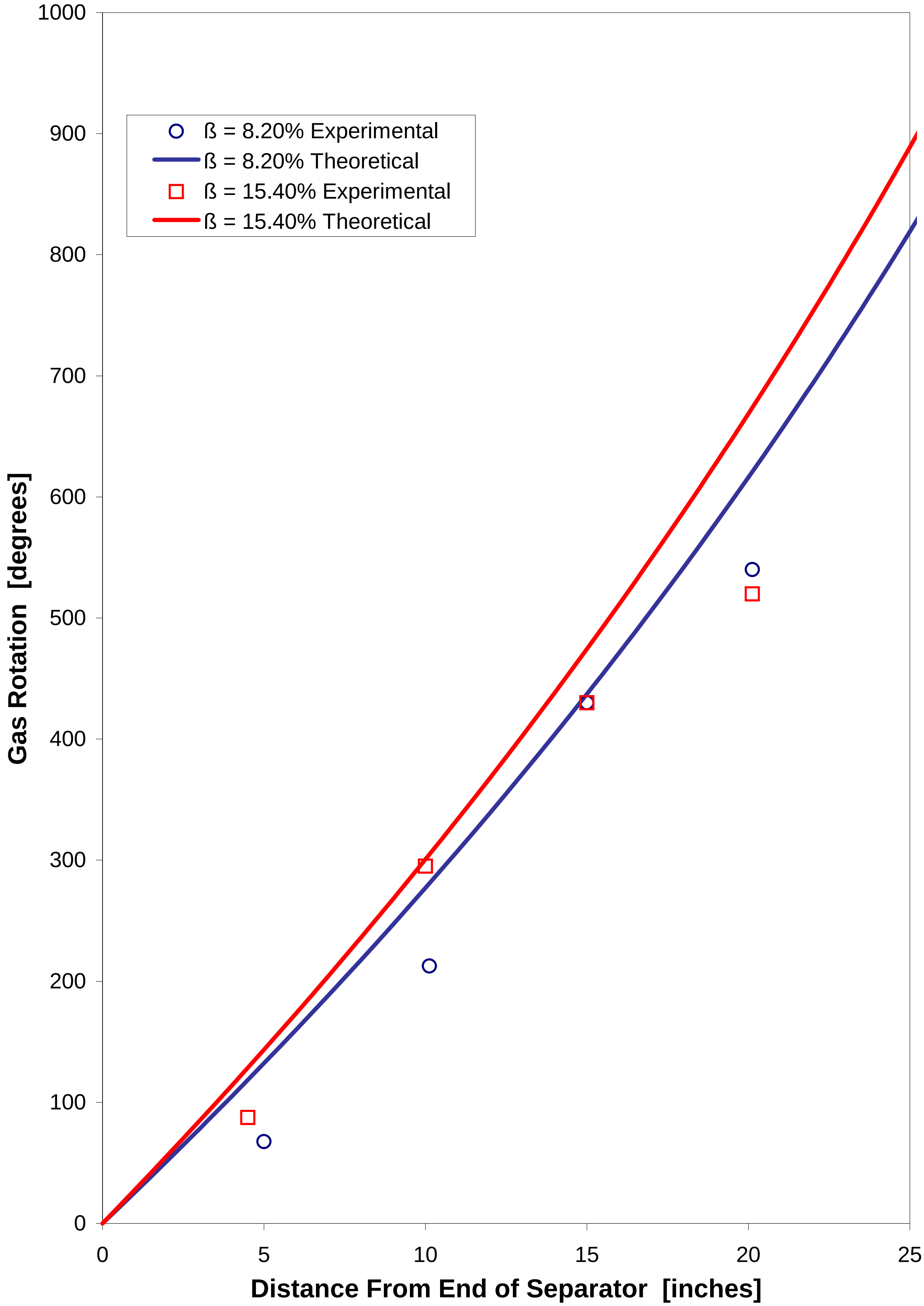

Figure 2: Gas Rotation Versus Distance Introduced From End of Separator – Unblocked Inlet

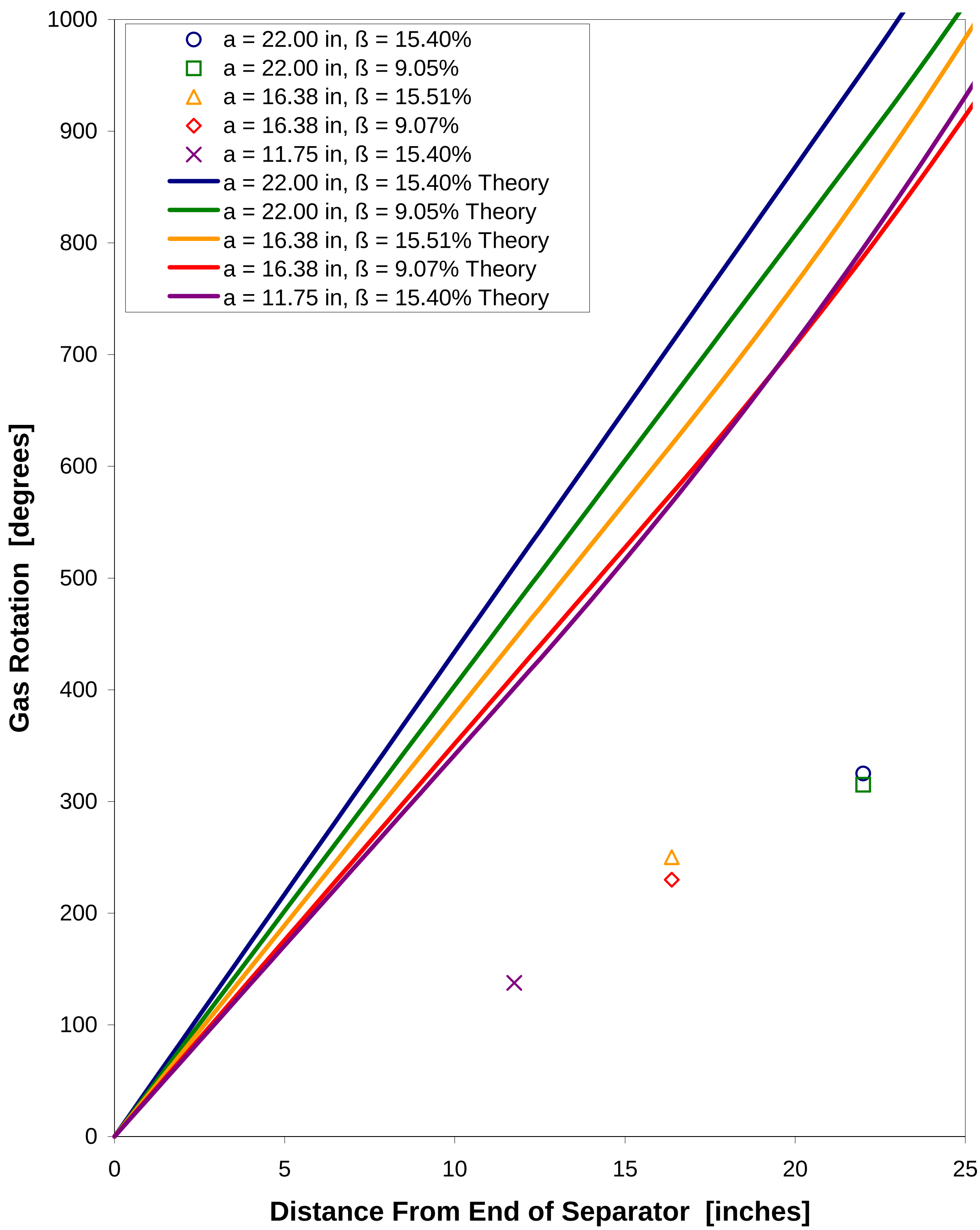

Figure 3: Gas Rotation Versus Distance Introduced From End of Separator – Blocked Inlet

a minimum rotation of 620 degrees while the experimental data showed 250 degrees. The difference between theory and experimental data is due primarily to viscosity effects not considered by the theory.

The objective is to make sure the gas rotates at least 180 degrees, so a slot blanking distance of 16 inches was selected. In the field prototype the inlet slot length will be 32 inches shorter than the separator length. It will stop 16 inches from each end of the separator. It is important to note that during these tests the flow rate of the clean gas remained constant as the inlet slot was shortened. In other words, the gas inlet velocity increased as the length of the inlet slot was shortened. Once the inlet slot geometry was determined our attention shifted to the bleed flow outlet slot.

It is apparent that, for a constant inlet gas velocity, as the length of ElectroCore separator increases, the axial velocity of the gas leaving the end of the separator gets larger as well. This axial gas flow creates an axial pressure gradient. The static pressure is at its maximum at the symmetry plane half way between the two ends and decreases toward each end. Work with the computational fluid dynamics (CFD) computer model showed that if this pressure gradient gets too large, flow begins to recirculate from the bleed flow outlet slot. For large pressure gradients, flow comes back out of the bleed flow slot near the ends where the static pressure is a minimum. This returning bleed flow enters the separator just at the ends and then leaves axially with the clean flow. If, as expected, this flow contains particles then this recirculation zone acts as a pathway for particles to penetrate through the separator. Using both smoke and threads, the flow in the ends of the bleed flow slot was investigated.

The smoke tests were conducted by pushing the smoke probe upstream into the bleed flow outlet slot until it just entered the separator. A small recirculation zone was identified at the extreme top of the slot. The details of the zone were revealed by placing a 1 inch length of thin white tread on the end of a rod and inserting it into the separator through a small holed drilled in the polycarbonate the top cover. Although the zone was small it was decided to segregate this portion of the outlet slot and independently extract bleed flow to see if the recirculation could be stopped and what kind of flow would be required.

A divider that had been slipped into the bleed flow outlet slot segregated the top 4 inches of the slot. The flow in this 4" tall slot was termed secondary bleed flow. Tests were conducted by running at various bleed flow ratios and then determining how much secondary bleed flow was required to just eliminate the backflow. The results are shown in Figure 4.

The results are plotted versus bleed flow ratio. Bleed flow ratio is defined as the sum of the primary and secondary bleed flow divided by the separator inlet flow. What is plotted is the amount of secondary bleed flow just required to stop backflow, so this plot represents a bleed flow stability map. Operating points above the line will have no back flow in the bleed flow slot while points below the line can expect to have backflow occurring. The data have been plotted in two ways. On the left axis the average

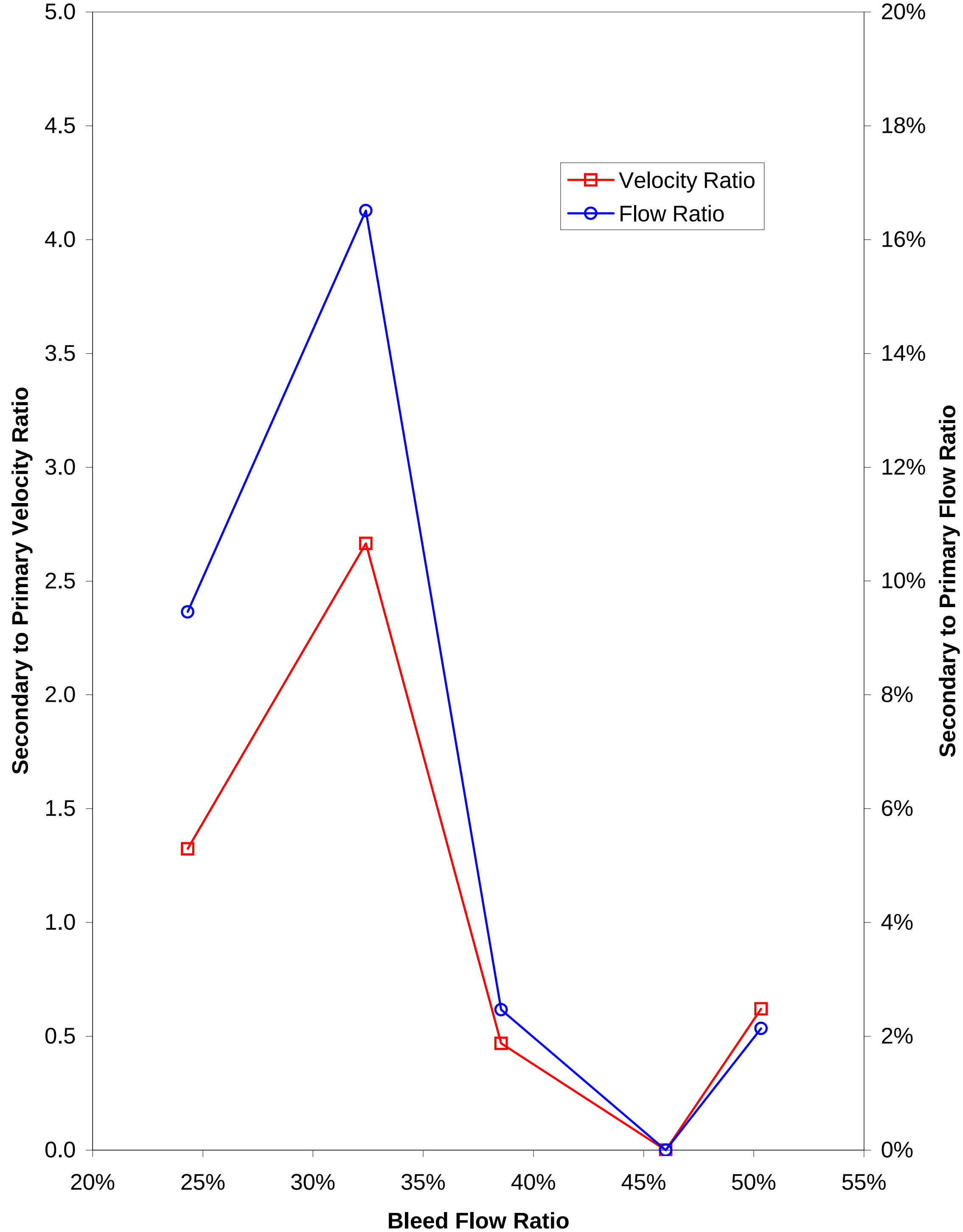

Figure 4: Secondary Bleed Flow Required to Stop Backflow

velocity in the secondary bleed flow slot has been divided by the average velocity in the primary bleed flow slot. On the right axis the results are expressed as the ratio of the secondary bleed flow rate to the primary bleed flow rate.

The data show that a minimum amount of secondary bleed flow is required when the ElectroCore is operated at a 45 percent bleed flow ratio. The maximum required secondary bleed flow occurs at a bleed flow ratio of about 32 percent and in this case the secondary bleed flow is about 16.5 percent of the primary bleed flow. At lower bleed flow ratios the required amount of secondary bleed flow decreases again.

Up to now, the discussion has been about flow geometry. The important issue however is particle separation efficiency. Backflow in the bleed flow slot is not important if the returning flow contains no particles. There was enough concern about backflow that LSR has decided to build the 6,000 acfm Advanced ElectroCore field prototype with the secondary bleed flow slots. One of the important tasks in the field test is to determine how best to operate the secondary bleed flow. At least by Figure 4, the ratio of secondary to primary bleed flow should not be set lower than 10 percent when operating at low bleed flow ratios.

Task 2 – Component Design

The second task was to design the precharger, Advanced ElectroCore Module and the dry scrubber that make up the 6,000 acfm Advanced ElectroCore field prototype. The system is shown schematically in Figure 5. LSR produced a set of eleven design drawings for the ElectroCore module and the water-cooled precharger and sent them to Merrick Environmental Technology, Inc. who turned them into a set of about 50 fabrication drawings. Ken Olen designed the dry scrubber and his company, Global Energy Services Corp., produced the scrubber fabrication drawings.

The process of developing the precharger and Advanced ElectroCore separator module fabrication involved taking LSR's design drawings and developing detailed part drawings as well as an overall system assembly drawing. In the process of going from design drawing to fabrication drawing, issues involving cost and manufacturability were considered. For example, the design drawings of the Advanced ElectroCore module showed an outer support frame with stiffeners made of relatively light gauge material. Tim Mallory at Merrick suggested that it would be more cost effective to use heavier stiffeners in the outer frame and make the frame simpler by reducing the amount of cross bracing required. The cost of the heavier material was more than offset by the labor saved in constructing the simpler frame. Insight into these kinds of practical matters has made Merrick a very valuable member of this project team.

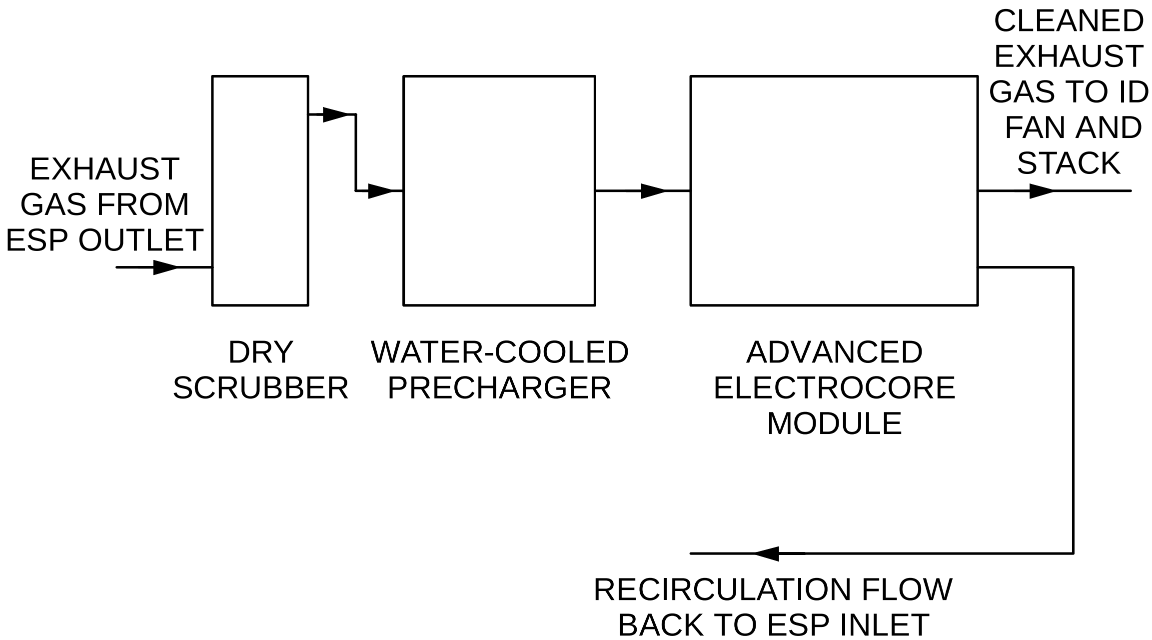

Figure 5: Schematic of Advanced ElectroCore Field Prototype

Similar improvements were made in the design of the water-cooled precharger. The original design concept came from a paper entitled *Proof or Concept Testing of ESP Retrofit Technologies for Low and High Resistivity Fly Ash* by George Rinard of the University of Denver; Marlin Andersen, a consultant from Hopkinsville, Kentucky; and by Ralph Altman of the Electric Power Research Institute. Given the basic geometry, LSR adapted the design to give the required particle residence time and to make the cross-section compatible with the requirements of the Advanced ElectroCore module connected downstream. Merrick then took the design drawings and determined the best method of supporting the unit. As with the Advanced ElectroCore module, it was decided to top-support the precharger. Top supporting the unit allowed it to expand and contract with changing gas temperature without inducing thermal stresses.

It was also decided to construct the gas-touched surfaces out of Type 304 stainless steel. Stainless steel provided protection against corrosion and meant that the unit would not have to be painted. The frame from which the unit was hung was carbon steel and was painted to protect the steel from rust and corrosion. After receipt of appropriate approvals, LSR placed the logos of the National Energy Technology Laboratory, the Electric Power Research Institute, the U.S. Environmental Protection Agency and the Alabama Power Company on the sides of the Advanced ElectroCore module to acknowledge the support of these organizations. The general arrangement drawing of the assembled system is shown in Figure 6. The applied logos are shown on the side of the Advanced ElectroCore module in Figure 7.

One important consideration in designing the Advanced ElectroCore field prototype was making the unit easy to transport and install. At the conclusion of this project, LSR

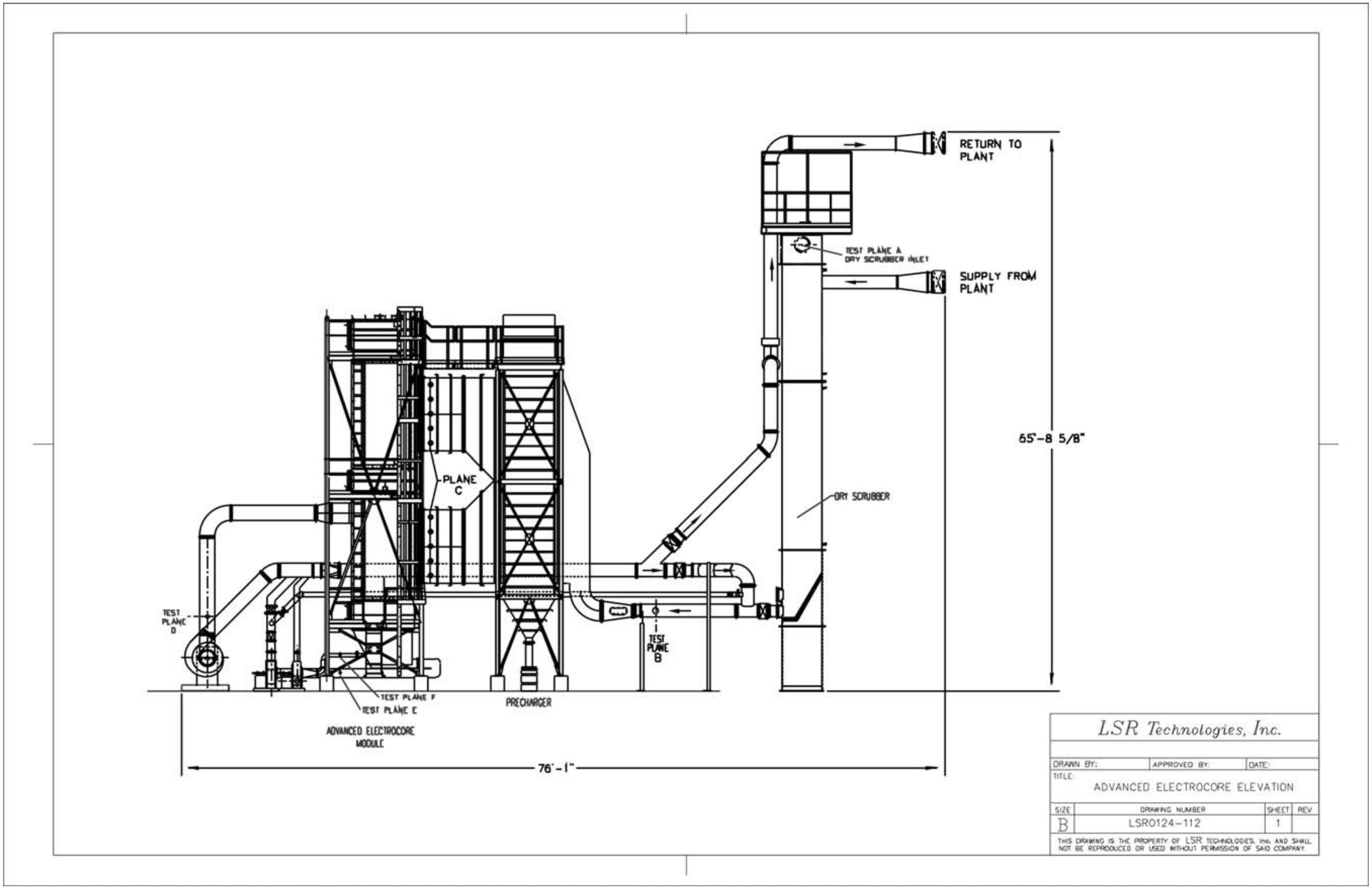

Figure 6: Elevation View of Advanced ElectroCore Field Prototype

Figure 7: Logos of Program Sponsors on Side of Advanced ElectroCore Module

would like to use the prototype as a mobile demonstration unit or for further investigation of its usefulness in capturing mercury or other hazardous air pollutants. The hope is to take the unit to the plants of potential customers and treat a 6,000 acfm slipstream from the plant to demonstrate the effectiveness of the technology and to help determine what size of unit would be required to meet the customer's needs. LSR believes that this will be an important sales tool and will help speed the commercial development of the both the conventional and Advanced ElectroCore technologies. This strategy proved helpful in developing LSR's Core Separator technology. LSR built and tested a 6,600 acfm Core Separator in a biomass application and when that project ended, LSR has used that unit to demonstrate the technology to potential Core Separator customers.

Task 3 – Fabrication/Construction

The fabrication drawings for the Advanced ElectroCore module and the water-cooled precharger were sent to four fabrication shops as part of a bid package. Of the three companies that chose to participate, the contract to fabricate the two components was awarded to Advanced Fabrication Services of Lemoyne, PA. Construction of the unit began on 10 November 2000. The following photos show the unit at various stages of completion.

The cost to build the precharger, including all work order changes, was $62,043 including electrodes, thermal insulation, electrical insulators, support frame and catwalks. The amount budgeted in Figure C-2 on page 62 of the original Technical and Cost Proposal was $79,322. The precharger was produced for $17,279 below the original estimate. The cost to build the Advanced ElectroCore module was $118,690 including electrodes, thermal insulation, electrical insulators and support frame. The amount budgeted for the module in the original Technical and Cost Proposal was $101,572. The module was produced for $17,118 above the original estimate. The combined module and precharger was under budget by $161.

The dry scrubber and the connecting ductwork were fabricated by Southern Metal Fabricators in Albertville, Alabama and shipped directly Wilsonville on their own trailers.

Figure 8: Partially Assembled Advanced ElectroCore Module

Figure 9: Precharger Assembly

Figure 10: Advanced ElectroCore Module Support Frame After Painting

Figure 11: Advanced ElectroCore Module Ready For Shipping

Task 4 – Transport and Installation

The Advanced ElectroCore module and its support frame were transported from Lemoyne, Pennsylvania to Wilsonville, Alabama on two flatbed trailers. AFS did not feel comfortable placing the module inside the support frame so they were shipped separately on two trailers then assembled at Wilsonville. The support frame was too wide so it had to be specially permitted as a wide load.

The precharger and its support frame were shipped separately as well. These were both wide loads. The final piece was a support frame required to straddle a pipe trench at the installation site. The cross-trench support frame was designed by LSR, built by AFS and shipped to Wilsonville. The following figures show the unit being installed at Wilsonville, Alabama.

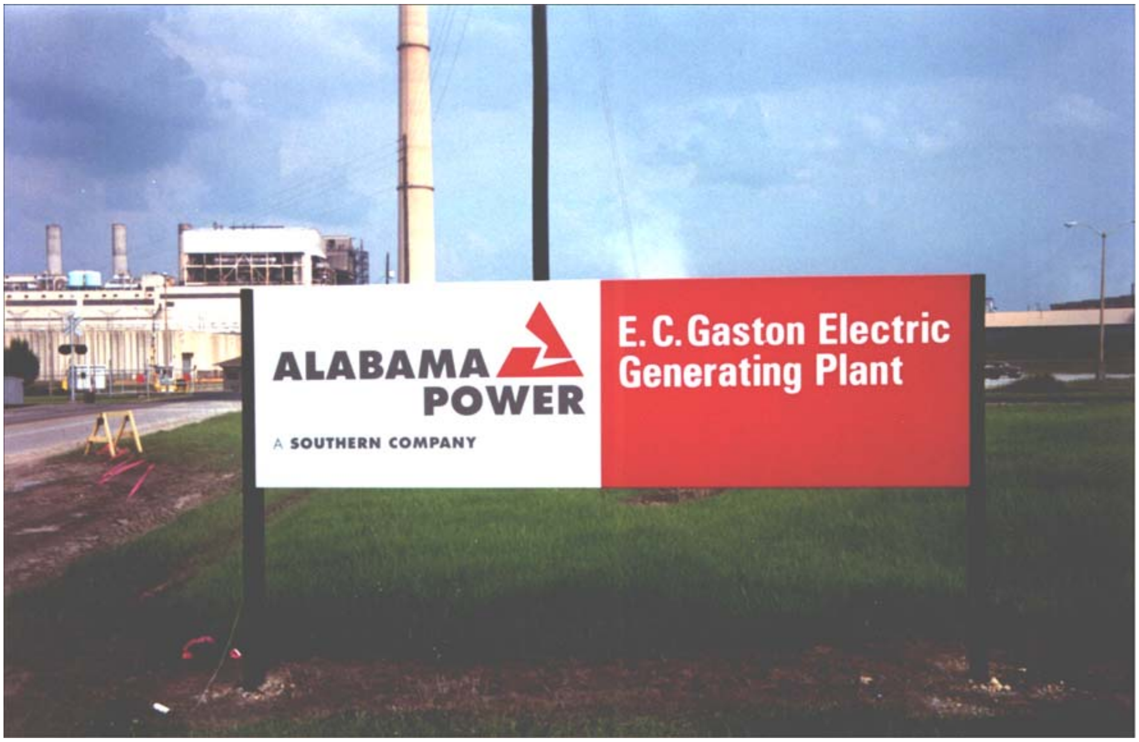

Figure 12: Advanced ElectroCore Installation Site in Wilsonville, Alabama

One of the more difficult aspects of the installation was that the Advanced ElectroCore module had to be installed partway under the coal conveyor. The system installation was carried out by Alstom. The steps in installing the unit are described below.

1 The first task was to pour nine concrete foundations that the Advanced ElectroCore module, the precharger and the dry scrubber would be anchored to.

2 The second task was to install the cross-trench support frame. The frame was required because the precharger installation site lay on top of a pipe trench and the trench cover was insufficient to carry the weight of the precharger. The frame was welded to the steel plates bolted to the top of the concrete foundations.

3 Next, the precharger support frame was mounted on the cross-trench support frame. The support frame was bolted to the cross-trench support frame using sixteen extra-strong bolts. The bolts were designed to withstand the uploads required to resist the tipping forces generated by a 100 mile per hour wind.

4 Next, the Advanced ElectroCore module support frame was stood up on the road next to the installation site. The frame is shown being erected in Figure 13. The Advanced ElectroCore module had to be inserted into its support

frame before being placed on the foundations due to clearance issues under the coal conveyor. The support frame is show standing up in Figure 14.

5 The Advanced ElectroCore module was inserted into the Advanced ElectroCore support frame. The start of this process is shown in Figure 15 The top of the module had to be lifted about 80 feet in the air and then slowly lowered into the frame. The 4” channels at the top of the module were bolted into the support frame with a 1” spacer placed between the support frame and channels. The spacers were used to pick the module up an additional inch in the frame.

6 After the Advanced ElectroCore module was secured in its support frame, the assembly was picked up and maneuvered onto its foundations under the coal conveyor. The unit is shown on its foundations in Figure 16. There was only about 3 inches of clearance between the bottom of coal conveyor truss and the top of the handrail on the support frame. The installers did a remarkable job of shoehorning the unit into position.

7 Next, the two connecting walkway sections between the precharger support frame and Advanced ElectroCore module support frame were installed in order to make the unit more stable.

8 The precharger was lifted into place on the precharger support frame and bolted to the two cantilevered 8” wide flange beams near the top of the frame. The precharger is shown being lifted into place in Figure 17. Again, some 1” thick spacers were inserted between the precharger channels and the support frame beams to ensure that the precharger outlet lined up with the separator module inlet.

9 The next step was to bolt the precharger inlet duct to the precharger inlet. RTV silicone was used between the flanges for gasketing. The Advanced ElectroCore module, precharger and precharger inlet duct are shown in Figure 18

10 The next step was to connect the outlet of the precharger to the inlets of the Advanced ElectroCore module. This involved lifting a breeching duct into place and bolting on to it two connect ducts and two flexible joints to accommodate the thermal expansion between units.

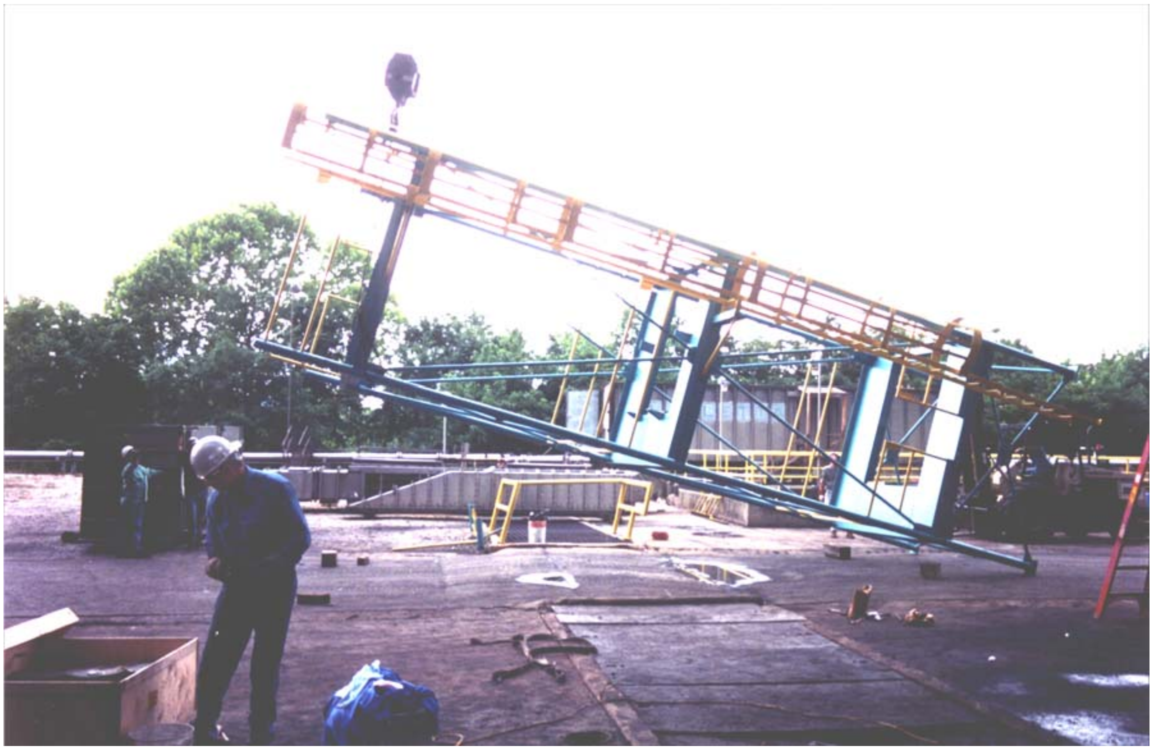

Figure 13: Standing Up the Advanced ElectroCore Module Support Frame

Figure 14: Advanced ElectroCore Module Frame Erected

Figure 15: Advanced ElectroCore Module Ready to be Inserted Into its Support Frame

Figure 16: Advanced ElectroCore Module in Place on Foundations

Figure 17: Precharger Being Lifted Onto Precharger Support Frame

11 The dry scrubber was assembled on the ground and the entire 47 foot tall unit was picked and placed on the foundation. Figure 19 shows the dry scrubber being lowered into place.

12 The final step was to install the connecting ductwork, install the fans and then thermally insulate them both. The high voltage power supplies were installed last. The completed unit is shown in Figure 20.

Task 5 – Shakedown Testing

The first test conducted during the shake down test was to measure the voltage versus current characteristic of the precharger. Tests were conducted by measuring the electrode current while increasing the electrode voltage. The first run was at ambient temperature with all fans off. The second test was with the fans running and the unit operating in the recirculation mode The two results were essentially the same. The current versus voltage curve for the new, clean precharger with fans running is shown in Figure 22.

The recirculation configuration is defined by looking at the flow schematic in Figure 21 and using the following valve positions from Table 2.

Table 2: Valve Positions For Shake Down Tests in Recirculation Mode

Valve Number	*Description*	*Position*
V1	Dirty Gas Inlet Valve	Shut
V2	Dry Scrubber Outlet Valve	Shut
V3	ID Fan Discharge Damper	Open
V4	Return Gas Throttling Valve	Shut
V5	Dirty Gas Return Valve	Shut
V6	Secondary Bleed Fan Discharge Damper	Open
V7	Primary Bleed Fan Discharge Damper	Open
V8	Primary Bleed Flow Cross-Over Valve	Open
V9	Primary Bleed Flow Recycle Valve	Shut
V10	Clean Flow Recycle Valve	Open
V11	COHPAC Inlet Valve	Shut

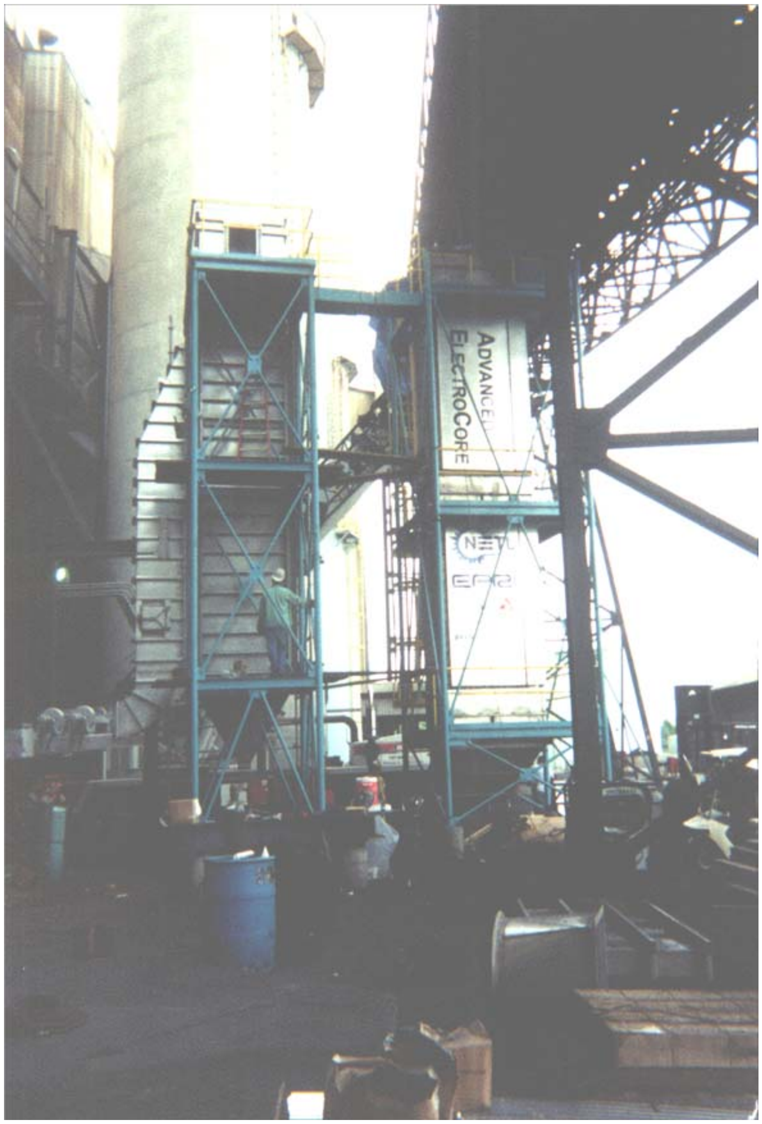

Figure 18: Assembled Precharger and Advanced ElectroCore Module

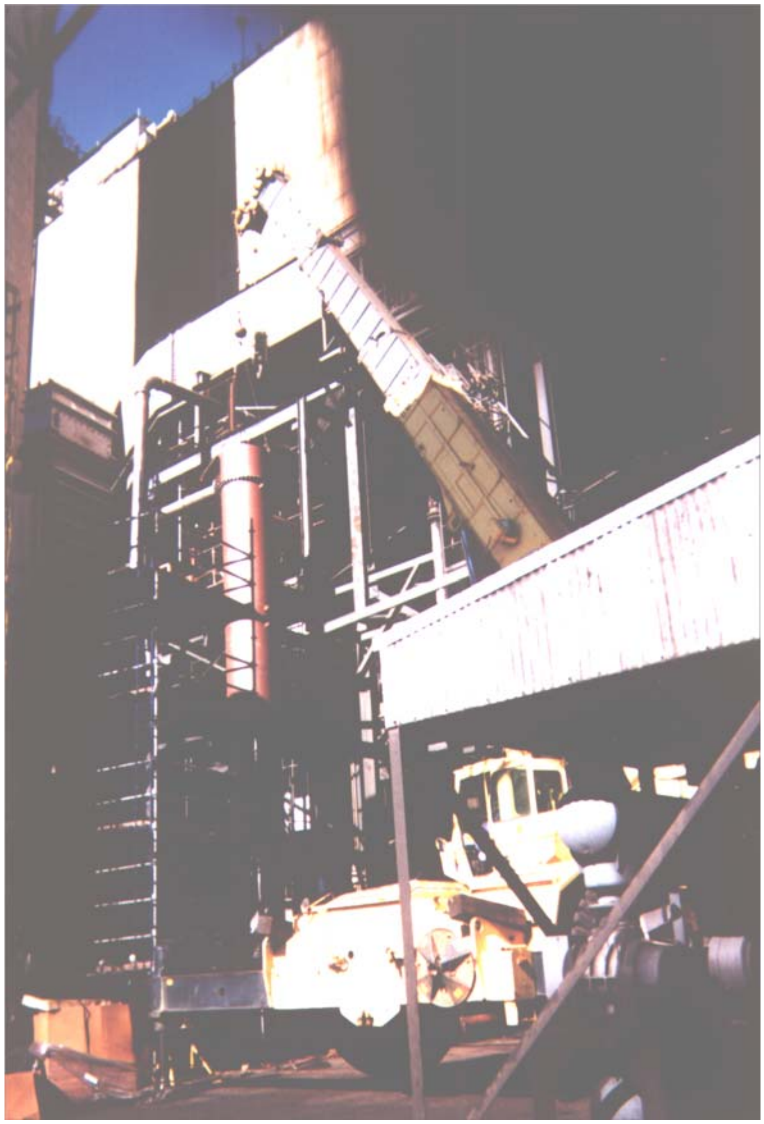

Figure 19: Dry Scrubber Being Lifted and Set in Place on Concrete Foundation

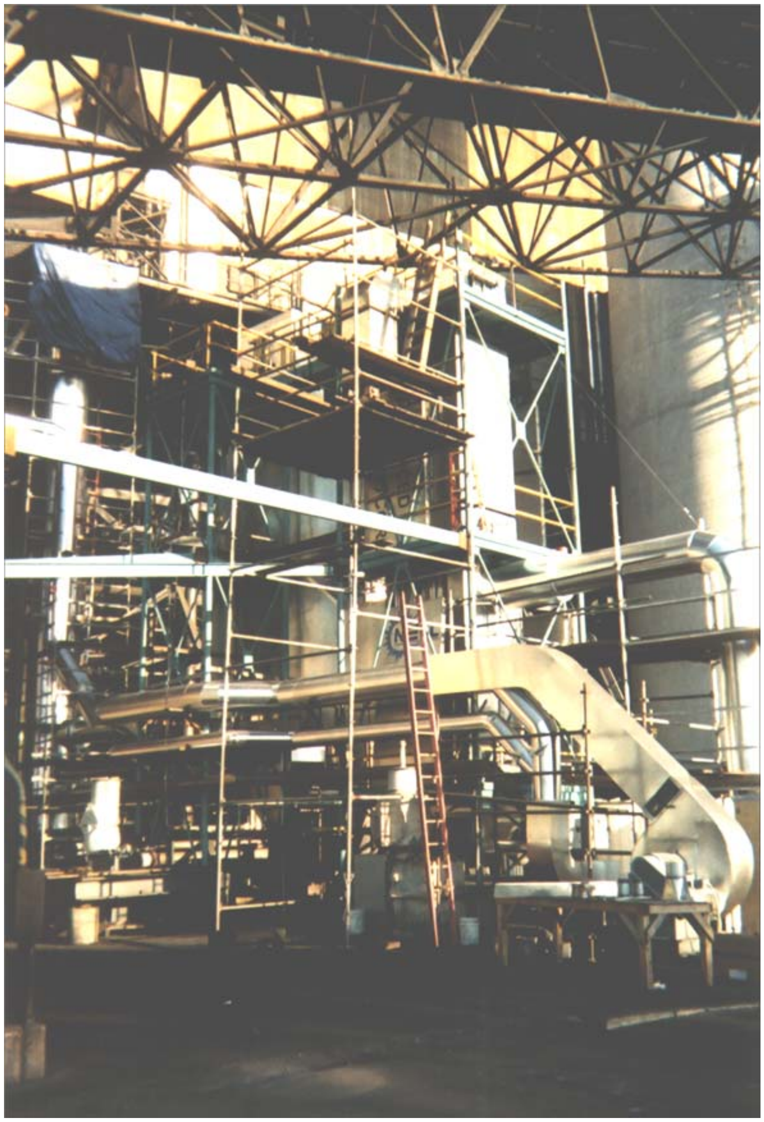

Figure 20: Complete System With Fans and Connecting Ductwork

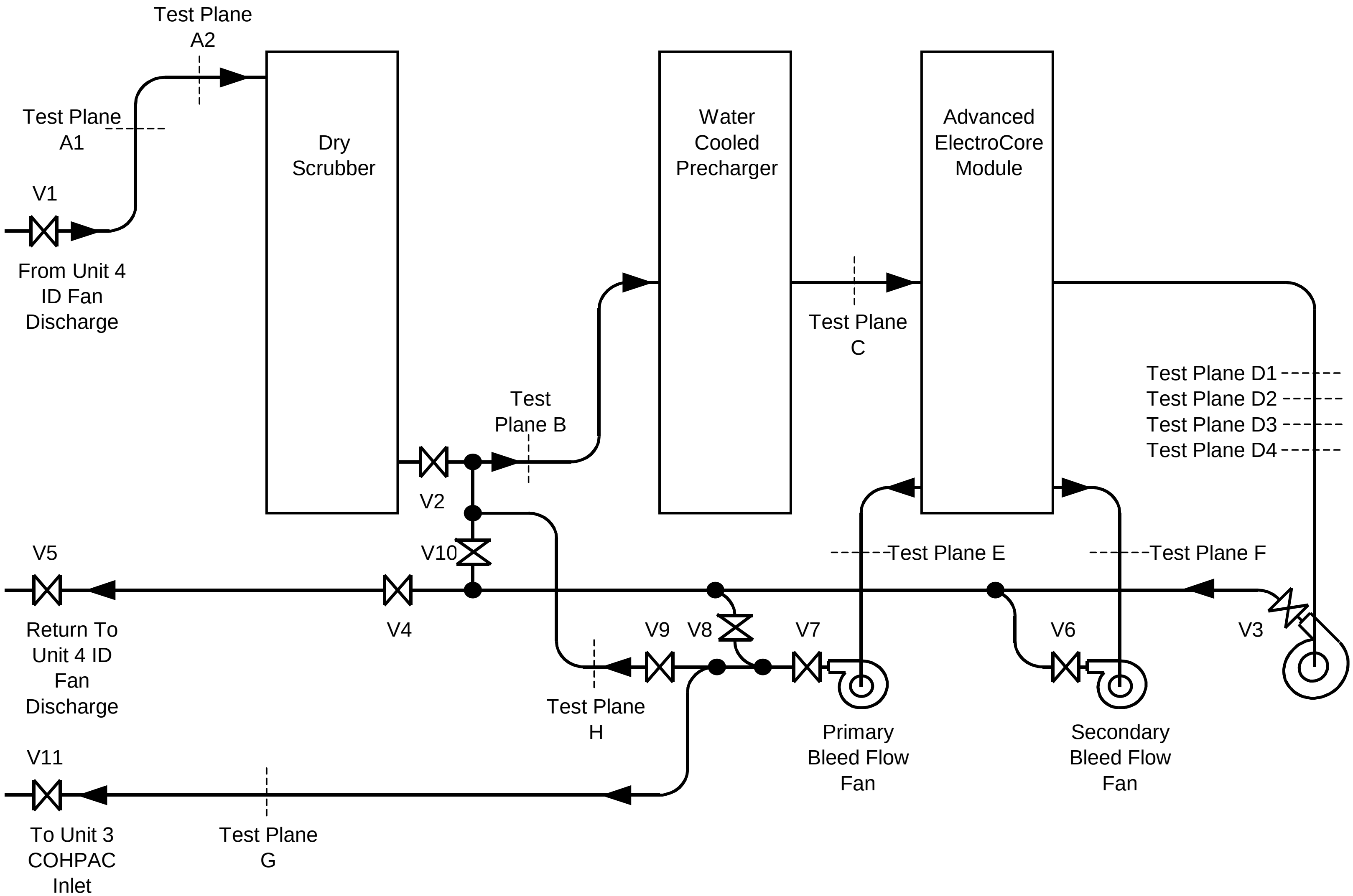

Figure 21: Advanced ElectroCore Field Prototype Flow Schematic

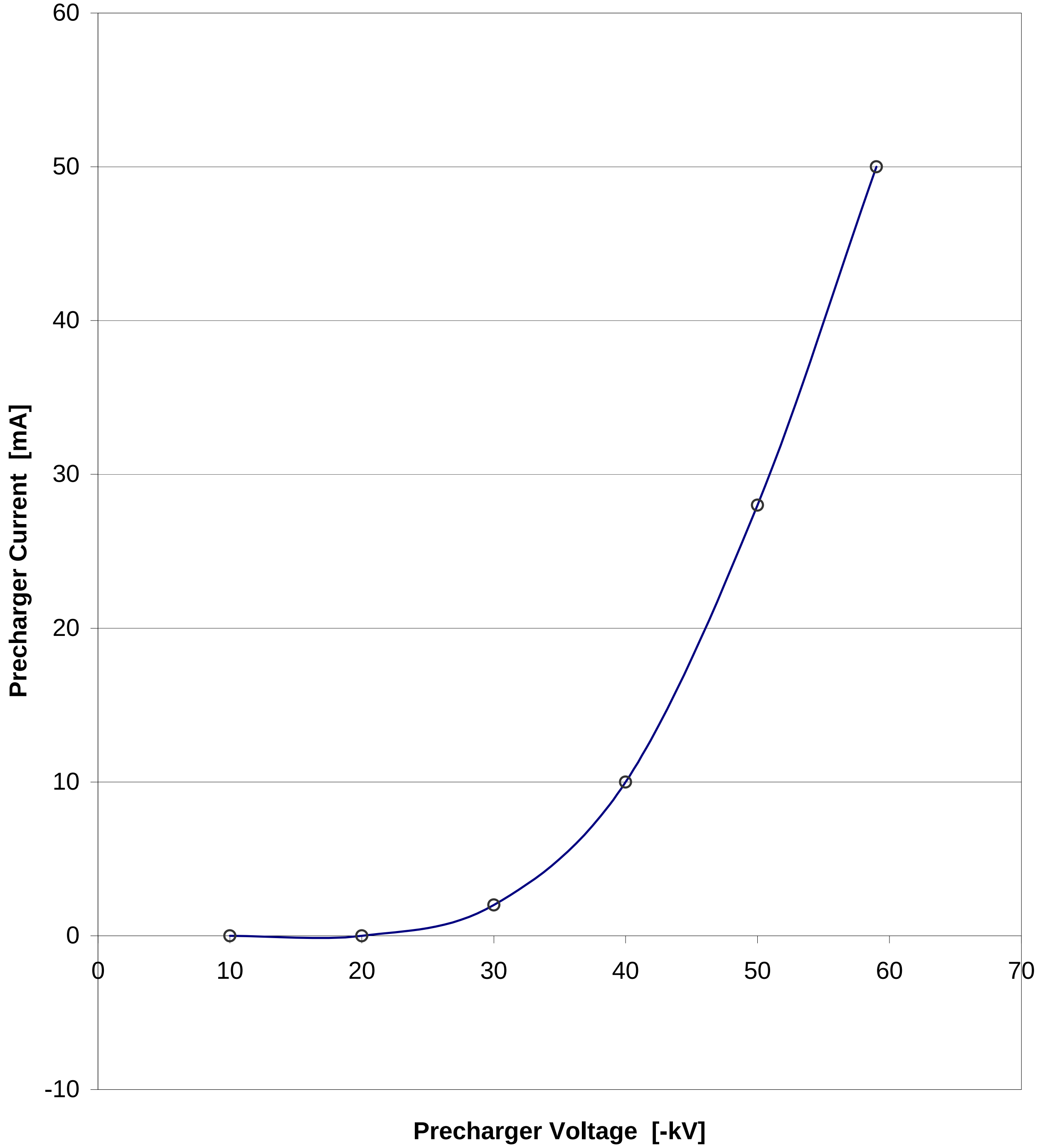

Figure 22: Precharger V-I Curve – As New

Shakedown flow tests involved running the fans at their maximum speed to determine the maximum flow rate that could be obtained by the system. The design flow rate was for 6,000 acfm and the maximum flow rate achieved was 6,162 acfm.

Task 6 – Field Testing at Site

Three types of tests were conducted on the Advanced ElectroCore field prototype. The first type was stack sampling using EPA Method 5 to measure the particulate concentrations at Test Planes A1, B, C and D1. The maximum number of stack samplers operating at any one time was three. They were moved to the different sampling planes depending on the nature of the test being conducted. The second type of test was cascade impactor tests to determine the particle sized distribution at the system inlet and outlet. The third type of test was the mercury capture test using the continuous emission monitor loaned to the project by the U.S. Environmental Protection Agency and by the Ontario Hydro tests conducted by the Southern Research Institute. In addition to the EPA Method 5 data, the Advanced ElectroCore module clean flow outlet was monitored using a P5A particle detector. The instrument detects particles by measuring how much light is scattered by a beam of light in the duct. It provides a continuous output that proved very useful in monitoring the performance of the Advanced ElectroCore during testing.

Testing was conducted over two separate time periods. The first period was from 12 November though 28 November 2001. After analyzing the results from these tests and making some minor adjustments to the system, a second round of tests was conducted from 5 February though 8 February 2002.

During the week of November 12, a total of fourteen Advanced ElectroCore tests were performed using EPA Method 5 and three tests for particulate sizing with University of Washington cascade impactors. The test conditions during these tests are shown in Table 7. In addition to the particle size and concentration measurements, some mercury sorbents were injected at the top of the dry scrubber in order to determine the efficiency of mercury removal. The mercury tests were performed by Southern Research Institute (SRI).

LSR believed that the operating conditions that existed during these first set of tests were not optimum, and that the results obtained were not the best that could be achieved. Nonetheless, the overall performance of the Advanced ElectroCore during this week of testing was very encouraging. On the first day of testing, a rubber boot in the precharger cooling water line failed. Therefore, test numbers 3 through 6 were run without cooling water. Also, the high voltage power cable for the Advanced ElectroCore module TR set began to spark and had to be replaced. While this was being repaired, test numbers 2 though 7 were run without power to the Advanced ElectroCore module's central electrodes.

The EPA Method 5 tests were used and compared with data from the P5A continuous emission monitor. The P5A was calibrated against the Method 5 measurements by SRI. Since the P5A output depends on the particle concentration, particle size distribution and the optical properties of the particles, the P5A has to be calibrated to produce outlet loadings in terms of pounds of particles per cubic foot of exhaust gas for each application in which it is used.

During the second group of tests conducted from 5 February to 8 February 2002, eleven Advanced ElectroCore tests were performed using EPA Method 5 with one sampling train measuring the particulate concentration at Test Plane B and another measuring the concentration at Test Plane D_2. These test planes can be seen in Figure 6 and schematically in Figure 21. The test conditions during these tests are shown in Table 3. The objective of the second set of tests was to see how changes in operating conditions affected the particle separation efficiency. Issues such as how long the unit ran recirculating clean air prior to testing was investigated. This was done to determine the effect of initial cleanliness on performance. The effect of separator electrode voltage on efficiency was investigated. The effect of specific separating area on performance was measured as well as the effect of gas residence time in the precharger. The results of these investigations described in Task 7 below.

Table 3: Summary of Advanced ElectroCore Field Prototype Test Conditions for February 2002 Tests

Test No.	*Clean Flow [acfm]*	*Clean Flow Gas Temp [°F]*	*Specific Separating Area [ft^2/kacfm]*	*Bleed Flow Ratio [percent]*	*Average Precharger Voltage [kV]*	*Precharger Current Density [nA/cm^2]*	*Average Advanced ElectroCore Voltage [kV]*	*Comments*
16	4274	185	125.4	10.93	-38	223.8	0	Test to determine effect of increased SSA
17	3600	182	149.0	9.23	-38	231.8	0	Test to determine effect of increased SSA
18	2961	162	181.0	10.80	-40	247.8	0	Test to determine effect of increased SSA
19	5129	181	104.5	10.77	-38	223.8	-60.03	Test after 3 hrs of high velocity cleaning
20	5198	185	103.1	10.42	-38	207.8	-36.90	Test with reduced separator voltage
21	5261	191	101.9	10.73	-38	215.8	-55.03	Test after 2 hrs of high velocity cleaning
22	5276	192	101.6	10.71	-38	223.8	-54.98	Test after 1 hour of high velocity cleaning
23	5151	192	104.1	10.91	-38	223.8	-15.05	Test with reduced separator voltage
24	5231	188	102.5	9.98	-38	239.8	-6.99	Test with reduced separator voltage
25	2637	182	203.3	12.05	-38	231.8	0	Test to determine effect of increased SSA
26	2665	184	201.2	12.05	-38	191.8	0	Reduced precharger residence time

Task 7 – Data Analysis/Cost Estimate

P5A Versus EPA Method 5

The EPA Method 5 tests were used and compared with data from the P5A continuous emission monitor. The P5A was calibrated against the Method 5 measurements by SRI, since the instrument readings depend on the particle size and other physical properties of the solid material.

Table 4 summarizes the Advanced ElectroCore efficiency measurement results from November 2001. The data show that the particle separation efficiency of the unit averaged about 85 percent when using EPA Method 5 and about 95 percent when using the P5A to measure the particulate concentration at the clean flow outlet. This difference is probably due to the fact that the P5A has a reduced sensitivity to particles about 7 micrometers in stokes diameter and above. The only impactor run conducted at the clean flow outlet shows that about 60 percent of the particles are above 7 micrometers as shown in Figure 23. Both the outlet size distribution and the disparity between EPA Method 5 and the P5A suggest that there may be a significant amount of particle agglomeration taking place within the Advanced ElectroCore system.

The first step in being able to use the P5A data to estimate the concentration of particles in the clean flow outlet is to run simultaneous P5A and Method 5 tests. Figure 25 shows the Method 5 results plotted as a function of the P5A output voltage. The data from the first two test days show an excellent straight-line correlation with an R^2 value of over 0.99. The data from the final three days, however, shows poor correlation. The most significant difference in the operation of unit over the two time periods is that electrodes in the separator were energized during all tests in the last three days but energized only during one test during the first two days. It is supposed that energization of the electrodes in the separator encourages particle agglomeration by the phenomenon known as the “pith ball effect” described in *Electrostatic Precipitation* by Oglesby and Nichols.

For the purposes of analysis, the correlation from the first two days was used to correlate the P5A output to the EPA Method 5 results. This causes the P5A determined efficiency to be greater than the Method 5 efficiency for those tests where the Advanced ElectroCore electrode is energized. It represents an estimate of the efficiency if the agglomeration process could be controlled or eliminated. This P5A efficiency versus inlet loading is shown in Figure 24.

Efficiency Results

Figure 26 and Figure 27 show examples of the P5A output traces. Figure 26 shows the trace for Test 2, which had the lowest outlet emission of all tests conducted in November and Figure 27 shows the trace for Test 4, which had the highest outlet loading. The first trace shows a consistently low output level with only eight significant spikes, all but one of short duration. The middle spike correlates to the midpoint of the Method 5 test where the probes are taken out and inserted into the sampling port 90 degrees away. The second trace shows the output is very unsteady with many peaks saturating the P5A output. Observations during the test indicated that the plant was having combustion problems as indicated by periodic puffs coming from the Unit 4 stack.

Table 4: Advanced ElectroCore Field Prototype Particle Separation Efficiency Results for November 2001 Tests

Test No.	*EPA Method 5 Inlet Loading at Test Plane B [grains/scf]*	*EPA Method 5 Outlet Loading at Test Plane D_2 [grains/scf]*	*P5A Outlet Loading at Test Plane D_2 [grains/scf]*	*EPA Method 5 Concentration Efficiency [percent]*	*Bleed Flow Ratio [percent]*	*EPA Method 5 Mass Efficiency [percent]*	*P5A Mass Efficiency [percent]*
1	0.0440	0.0141	0.0113	67.94	9.42	70.96	76.78
2	0.0243	0.0065	0.0067	73.37	8.22	75.56	74.68
3	Impactor	Run					
4	0.7798	0.1182	0.1167	84.85	9.08	86.22	86.40
5	0.1172	0.0156	0.0202	86.67	11.20	88.16	84.71
6	0.1390	0.0186	0.0236	86.58	10.83	88.03	84.86
7	0.3542	0.0597	0.0247	83.16	10.42	84.91	93.76
8	0.0933	0.0521	0.0044	44.21	29.31	60.56	96.65
9	0.1899	0.0250	0.0092	86.83	11.19	88.30	95.68
10	0.3094	0.0581	0.0150	81.22	11.52	83.38	95.71
11	0.6252	0.0747	0.0387	88.05	11.41	89.42	94.52
12	0.3419	0.0953	0.0208	72.13	10.86	75.16	94.57
13	0.1275	0.0596	0.0275	53.28	11.30	58.56	80.85
14	0.1947	0.0240	0.0064	87.65	14.81	89.48	97.18
15	0.1628	0.0296	0.0080	81.85	15.66	84.69	95.85

In order to interpret the November data points, a number of observations were made which affect their quality and accuracy. The most important of these observations were:

(1) The conditions of the boiler flue gas were such that there were many operational upsets during test runs. These upsets may have been caused by soot blowing of the boiler backpass, rapping of the ESPs last field, or irregular boiler control. As evidence of the variations in stack opacity, the particulate carryover from the boiler showed wide variations.

(2) The P5A calibration depends on particle size and composition, which changed frequently with test conditions. For example, in addition to boiler upsets, some tests were performed with and without sorbents, and with and without recycle return.

(3) Like other collection devices, the Advanced ElectroCore system has a tendency for solids to buildup, accumulate, and then release cyclically. Hence, due to the dynamic changes in the system and shifting of solids, it was difficult to find steady-state run conditions during the tests.

(4) During the Method 5 tests, several of the filters at the ElectroCore outlet (Test Plane D) were very white and clean (usually signifying very low outlet emissions) except for a small buildup of loose granules. The loose material could have been dislodged from wall surfaces. It also represented the major fraction of the filter weight in these tests, which was only 40-50 mg. Thus, the loose material may not be representative of normal Advanced ElectroCore conditions and may in effect be a source of error in the data.

(5) It was also observed that when the Method 5 probe at the precharger inlet (Test Plane B) was repositioned, there was an immediate response on the P5A showing heavy solids carryover. These spikes undoubtedly affected the Method 5 outlet result as well. Each of the phenomena described above contributed to the difficulty of data analysis and interpreting data.

These results were for the first set of tests conducted in November of 2001 and were not expected to represent the Advanced ElectroCore's best performance. LSR was (and still is) learning how to best operate the system and finding out what operating conditions gave the best performance. In the second set of tests, effects such as the residence time in the precharger, specific separating area, and separator voltage were all investigated to find the best operating condition for the Advanced ElectroCore field prototype.

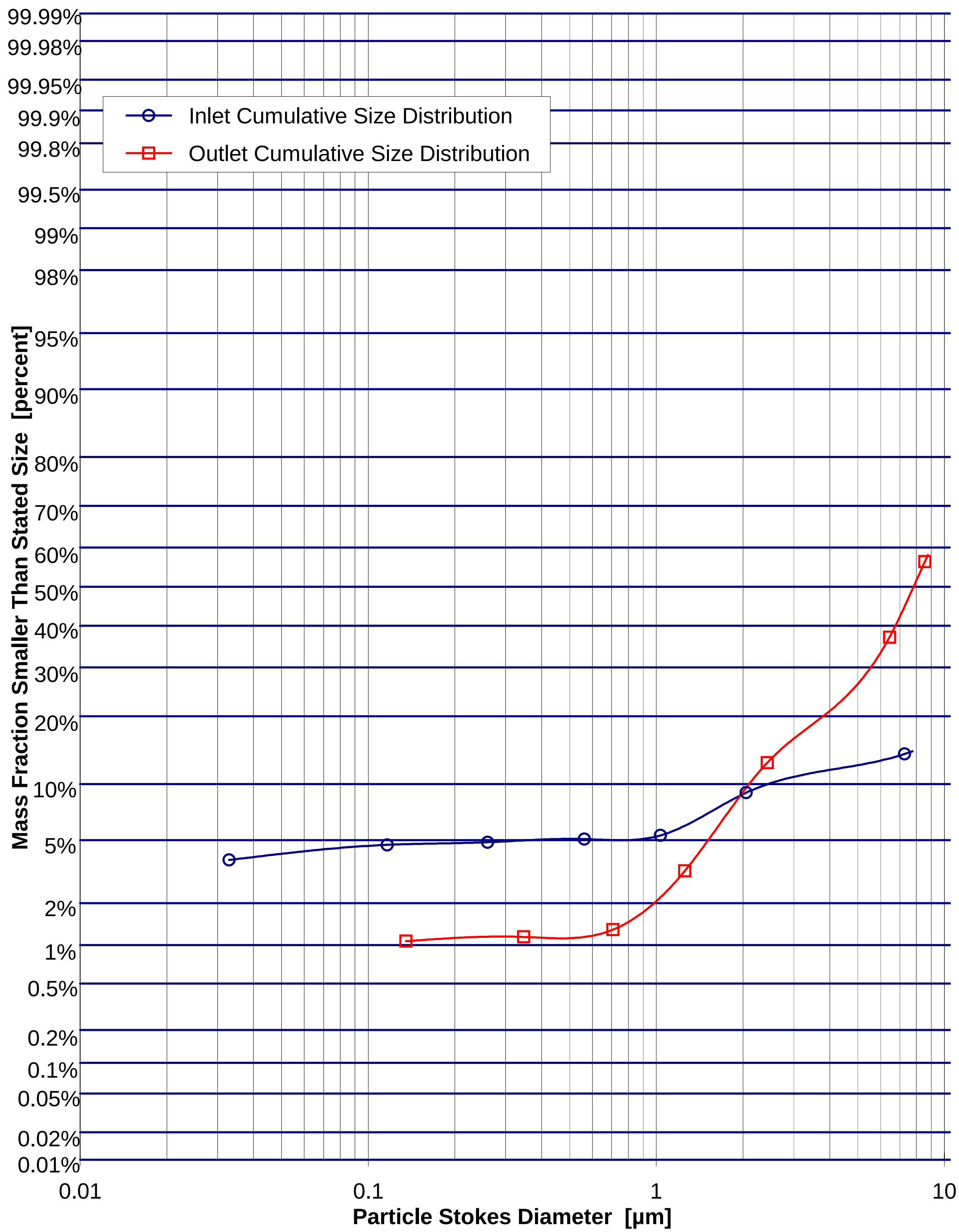

Figure 23: Inlet and Outlet Cumulative Particle Size Distribution

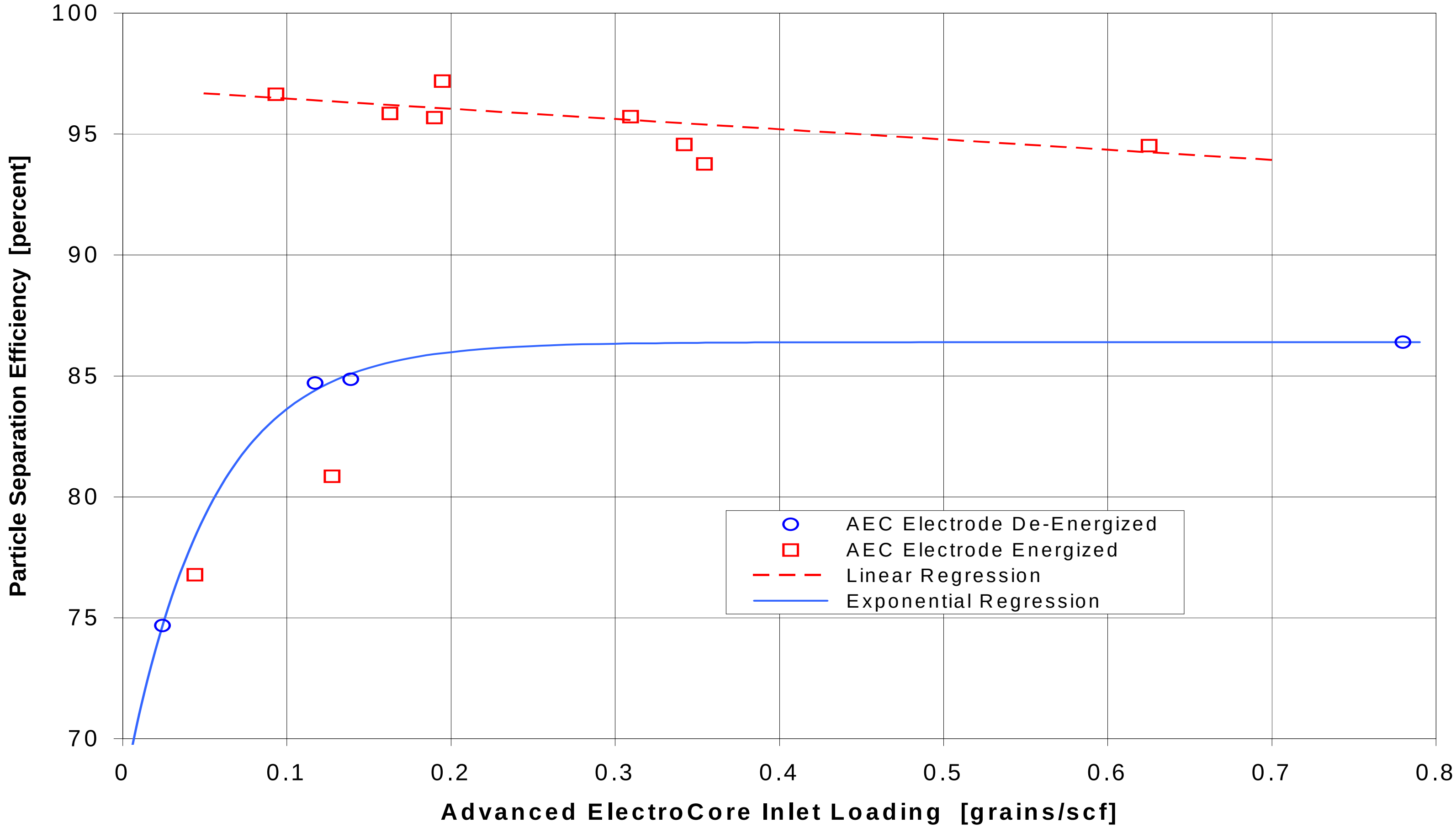

Figure 24: Efficiency of Advanced ElectroCore Field Prototype From P5A Analysis

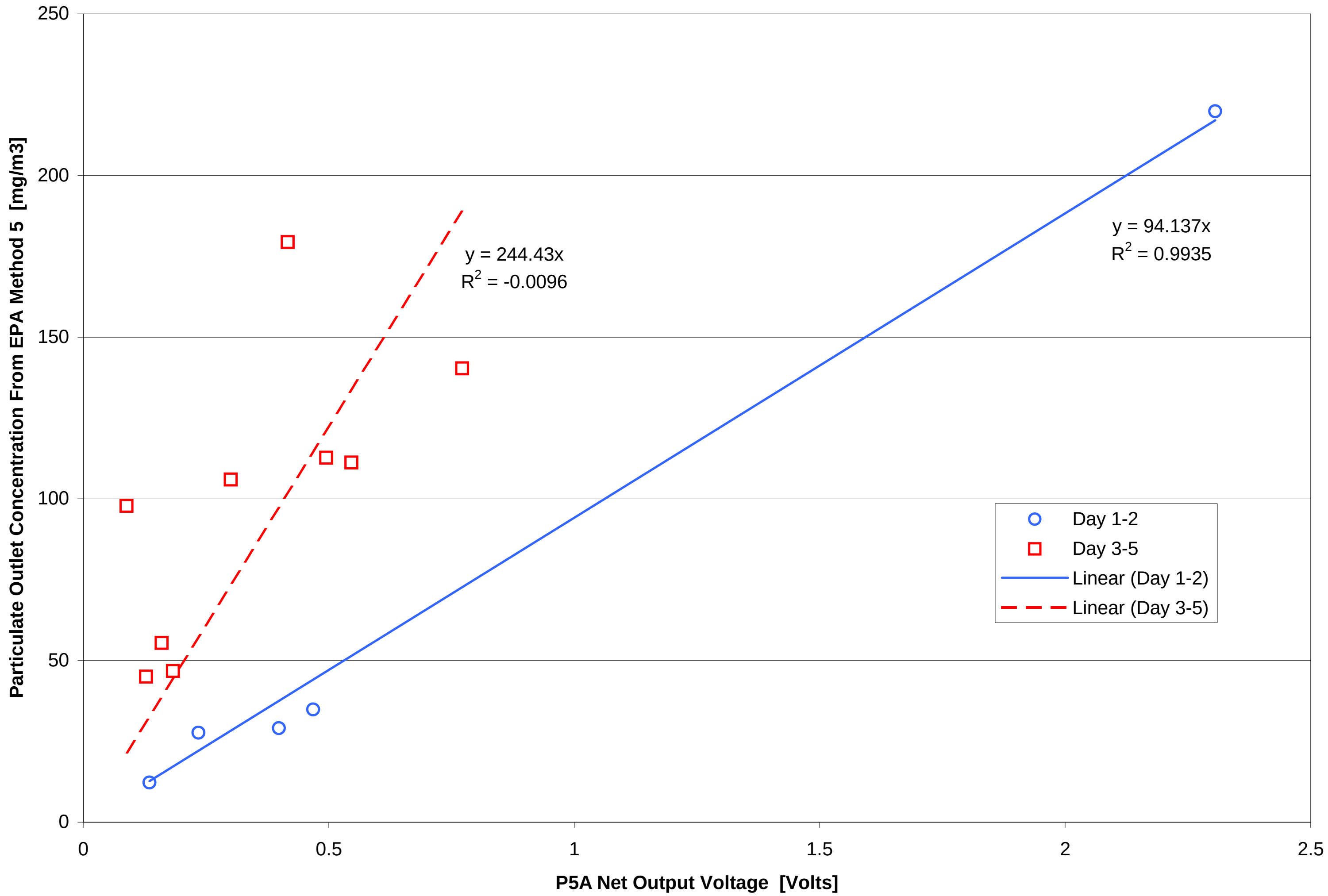

Figure 25: Correlation of P5A Output to EPA Method 5 Data

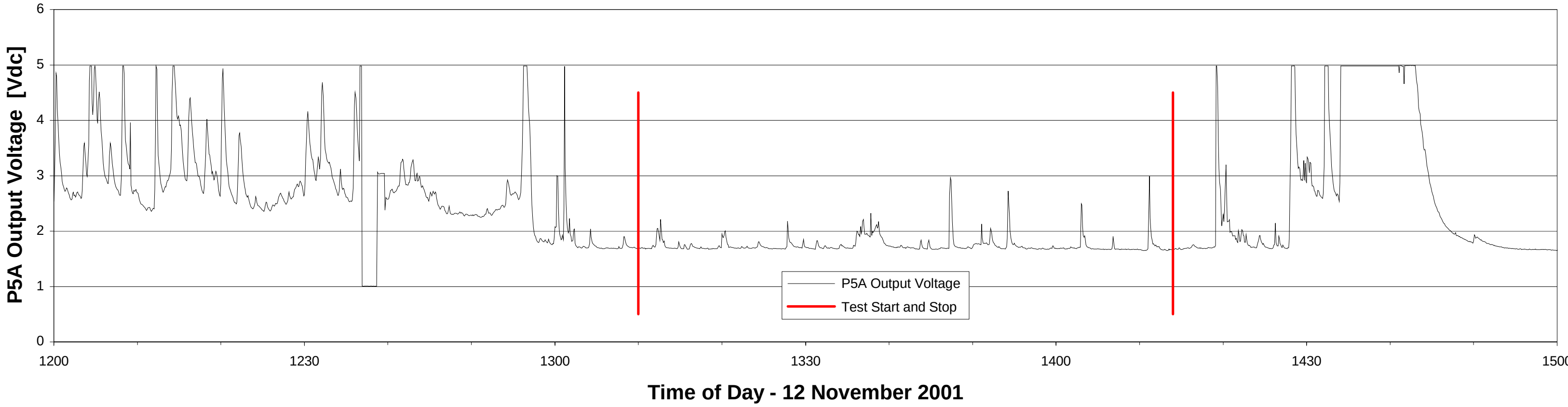

Figure 26: P5A Output Voltage For Test Number 2

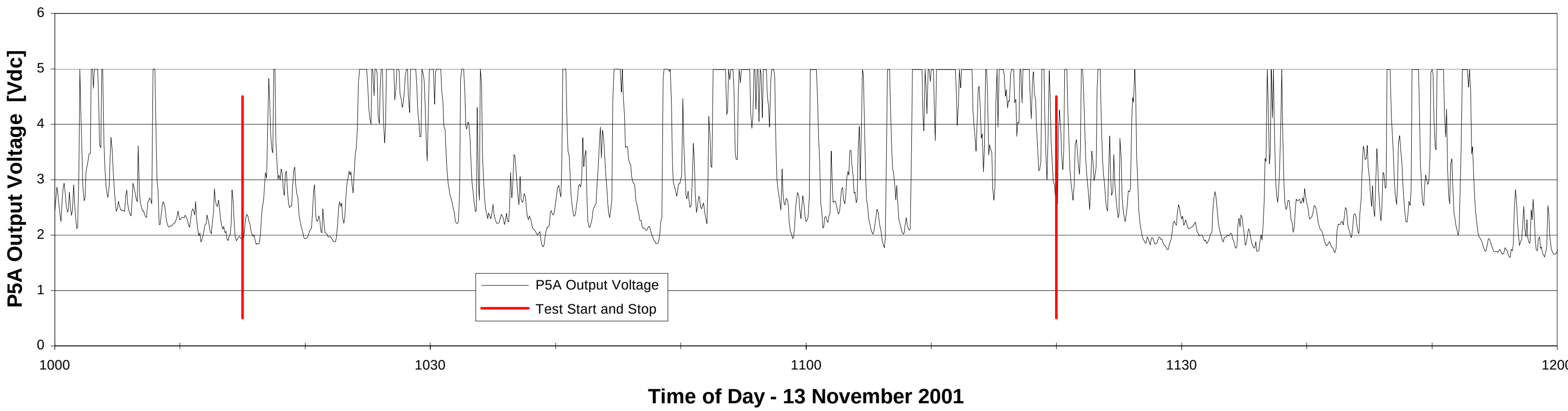

Figure 27: P5A Output Voltage For Test Number 4

As expected, the results from the second set of tests, conducted in February 2002, were better than the first set as LSR began to understand how best to operate the unit. Test conditions for the second set of data are summarized in Table 3, and the results for these tests are shown in Table 5. The results show that the efficiency of the Advanced ElectroCore is a function of the inlet loading, the specific separating area and the voltage applied to the separator electrode. The performance data can be understood by looking at penetration is defined as

$$P = 1 - \eta \qquad \text{Equation 1}$$

Where:

- P Penetration
- η Advanced ElectroCore particle separation efficiency

Good performance is indicated by low penetration. The data show a general trend of increasing penetration with decreasing inlet loading. Points 23, 24 and 25 all fall below the general trend line and represent better than average performance. The low penetration of Point 15 can be partially explained by the high SSA, 203 ft^2/kacfm. Points 23 and 24 have typical SSA values but low penetration due to the moderate voltage used in the Advanced ElectroCore separator. The data show that using the highest voltage in the separator results in higher penetration and therefore lower separation efficiency. The results also show that the performance improvement achieved by a moderate electrode voltage increases as the inlet loading decreases. At an inlet loading of 0.067 grains/ft^3, moderate voltage reduces the particulate penetration about half. By 0.015 grains/ft^3, the reduction is about 70 percent. This is probably due to the fact that, as the electric field due to space charge diminishes, the electric field due to the applied electrode voltage becomes more and more dominant. This tends to make the curve flatter than the no-voltage line. The reason that the highest separator electrode voltages do not result in the highest separation efficiency is believed to be explained by the pith ball effect as described by Oglesby and Nichols in *Electrostatic Precipitation*. When there is no current flowing through a layer of material on the separator wall then the negatively charged central electrode will induce a positive surface charge on the material that can cause it to leap back into the bulk flow. This repelling force goes as the square of the electrode voltage as shown in Equation 2.

$$f = \frac{1}{2}\,\varepsilon_o \left[\left(\frac{j\rho\varepsilon_1}{\varepsilon_o} \right)^2 - \left(\frac{V - (\mathrm{R}_2 - t)\, j\,\rho\;\mathrm{Ln}\left(\frac{\mathrm{R}_2}{\mathrm{R}_2 - t} \right)}{(\mathrm{R}_2 - t)\,\mathrm{Ln}\left(\frac{\mathrm{R}_2 - t}{\mathrm{R}_1} \right)} \right)^2 \right] \qquad \text{Equation 2}$$

Where:

f	Force per unit area holding dust layer to inside of separator wall
ε_o	Permittivity of free space
j	Current density at the gas to ash layer interface
ρ	Ash resistivity
ε_1	Permittivity of ash layer
V	Voltage on separator central electrode
t	Thickness of ash layer
R_1	Central electrode radius
R_2	Radius of inner wall of separator

In Figure 28 the penetration versus inlet loading for points 23 and 24 have been plotted against the data taken at Plant Miller in 1997 with the conventional ElectroCore, that is with a single separator without an energized central electrode. The laboratory data points shown are data points from the Plant Miller unit taken while it was still in the laboratory. The laboratory points have the same configuration and nominal SSA as the Miller and Gaston test data. The results show a continuum of increasing penetration with decreasing inlet loading. Figure 28 shows that the performance of the Advanced ElectroCore is comparable to the efficiency of the single separator tested at Plant Miller even though the Advanced ElectroCore processes 12 times the gas flow processed by the Miller unit. This means that the scaling up ElectroCore has not resulted in lower system performance, as long as the separators are equipped with central electrodes operating at moderate voltages.

In Figure 29 the outlet loading is shown versus the inlet loading for the two Gaston points, the Miller points and the laboratory data. Even though the penetration is increasing with decreasing inlet loading, the outlet loading continues to decrease with decreasing inlet loading. The ElectroCore is not behaving as a constant output device. This is probably due to the fact that the applied separator electrode voltage keeps the efficiency higher than a device that relies almost exclusively on space charge and centrifugal effects to collect or separate particles.

Table 6 shows the test results from February 2002 expressed in terms of pounds of particulate emissions per million Btu. The conversion to lbm/million Btu was done using Equation 19-1 from EPA Method 19. The dry oxygen-based F factor for Bituminous coal was used which has a value of 9780 dscf/million Btu. The results show that the highest ESP efficiency was 99.75 percent which occurred during Test 21. The highest efficiency for the Advanced ElectroCore was 96.38 percent which occurred during Test 25. The results indicate that the Advanced ElectroCore had been configured to operate at its peak efficiency during the same time that the ESP achieved its peak efficiency then the overall system efficiency would have been 99.991 percent which is above the performance target of 99.99 percent. Since the ElectroCore efficiency was changing with each test as the test matrix proceeded, and the ESP efficiency was changing due to operating conditions at the power plant, it was unlikely that the test with the best

ElectroCore performance would occur at the same time as the best ESP performance. By using the best ESP performance and the best ElectroCore performance it is possible to estimate the system performance for the test condition when both were operating optimally.

In Figure 30, the ElectroCore results are plotted in terms of pounds per million Btu to show how the results compare to current particulate emission standards. The results show the Advanced ElectroCore should be able to achieve a 0.03 lb_m/million Btu outlet loading as long as the inlet loading is below about 4.0 lb_m/million Btu.

Figure 31 shows the P5A outlet voltage during Test Point 23. High output voltage corresponds to high outlet loading. Due to the zero offset, with ambient air the P5A output voltage is about 1 volt. The trace shows that a series of small spikes in the outlet loading occurred during the test. The largest spike occurred at about 1749. The second largest spike occurred at 1745. Figure 32 shows the stack opacity for the combined flues of Gaston Unit 3 and Unit 4. The opacity scale is not shown so it is usable only to indicate relative changes in stack opacity. The highest stack opacity occurred at 1751. The second highest occurred at 1747. These spikes correlate well with the spikes in the P5A trace after correcting for an apparent 2-minute time difference between the clock in the control room which generated the opacity data, and the clock on the P5A data acquisition computer.

The fact that each bump up in the P5A output correlates to bump in the stack opacity trace indicates that the source of the P5A spikes were increases in inlet loading due to changes in boiler operating conditions. This means that the output spikes are not being produced by instability inherent in the Advanced ElectroCore but are due to external factors.

The P5A output spike that occurred at 1824 was due to shutting off the precharger power. The decay after 1830 was due to the fact that the unit had been placed the gas recirculation mode so no additional stack gas was being introduced.

Test Point 25 was conducted with a nominal SSA of 200 ft^2/kacfm and all four precharger discharge electrodes operating. In Point 26, only two of the four precharger electrodes were energized, thereby reducing the residence time in the precharger by 50 percent. Although, from Table 5, the penetration with two electrodes is higher than with four, it is still in line with the expected performance degradation that would be anticipated due to the effect of reduced inlet loading alone. This would suggest that the two-electrode configuration might provide an adequately long residence time to achieve sufficient particle charging.

Table 5: Advanced ElectroCore Field Prototype Particle Separation Efficiency Test Results From February 2002

Test No.	*EPA Method 5 Inlet Loading at Test Plane B [grains/dscf]*	*EPA Method 5 Outlet Loading at Test Plane D_2 [grains/dscf]*	*P5A Outlet Loading at Test Plane D_2 [grains/dscf]*	*EPA Method 5 Concentration Efficiency [percent]*	*Bleed Flow Ratio [percent]*	*EPA Method 5 Mass Efficiency [percent]*	*P5A Mass Efficiency [percent]*
16	0.0246	0.0105	0.0120	57.32	10.93	61.98	56.60
17	0.0167	0.0089	0.0113	46.71	9.23	51.62	38.80
18	0.1612	0.0196	0.0113	87.84	10.80	89.15	93.76
19	0.0387	0.0095	0.0117	75.45	10.77	78.10	73.10
20	0.0303	0.0107	0.0089	64.69	10.42	68.37	73.61
21	0.0145	0.0049	0.0079	66.21	10.73	69.83	51.66
22	0.0192	0.0122	0.0076	36.46	10.71	43.26	64.52
23	0.0149	0.0021	0.0086	85.91	10.91	87.44	48.38
24	0.0670	0.006	N/A	91.04	9.98	91.94	N/A
25	0.3209	0.0132	N/A	95.89	12.05	96.38	N/A
26	0.1186	0.0135	N/A	88.62	12.05	89.99	N/A

Table 6: Advanced ElectroCore Field Prototype Test Results From February 2002 in Terms of Pounds per Million Btu

Test No.	*Estimated Uncontrolled Boiler Normalized Emission Rate [lb_m/million Btu]*	*ESP Outlet Normalized Emission Rate [lb_m/million Btu]*	*ESP Efficiency [percent]*	*Advanced ElectroCore Outlet Normalized Emission Rate [lb_m/million Btu]*	*Advanced ElectroCore Mass Efficiency [percent]*	*Overall System Efficiency [percent]*
16	13	0.0557	99.57	0.0238	61.98	99.837
17	13	0.0378	99.71	0.0201	51.62	99.859
18	13	0.3649	97.19	0.0444	89.15	99.696
19	13	0.0876	99.33	0.0215	78.10	99.852
20	13	0.0686	99.47	0.0242	68.37	99.833
21	13	0.0328	99.75	0.0111	69.83	99.924
22	13	0.0435	99.67	0.0276	43.26	99.810
23	13	0.0337	99.74	0.0048	87.44	99.967
24	13	0.1517	98.83	0.0136	91.94	99.906
25	13	0.7264	94.41	0.0299	96.38	99.798
26	13	0.2685	97.93	0.0306	89.99	99.793

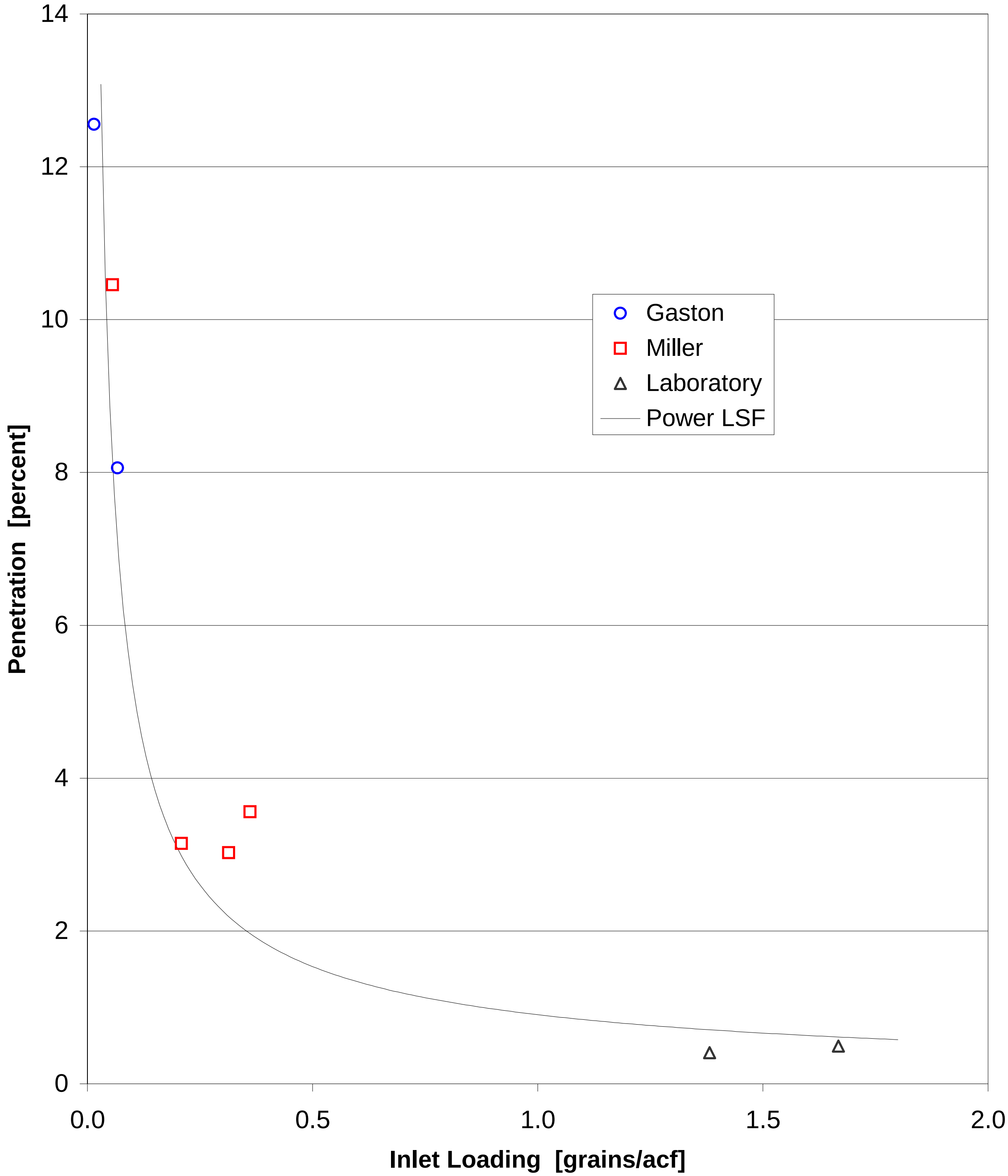

Figure 28: Effect of Inlet Loading on Particulate Penetration

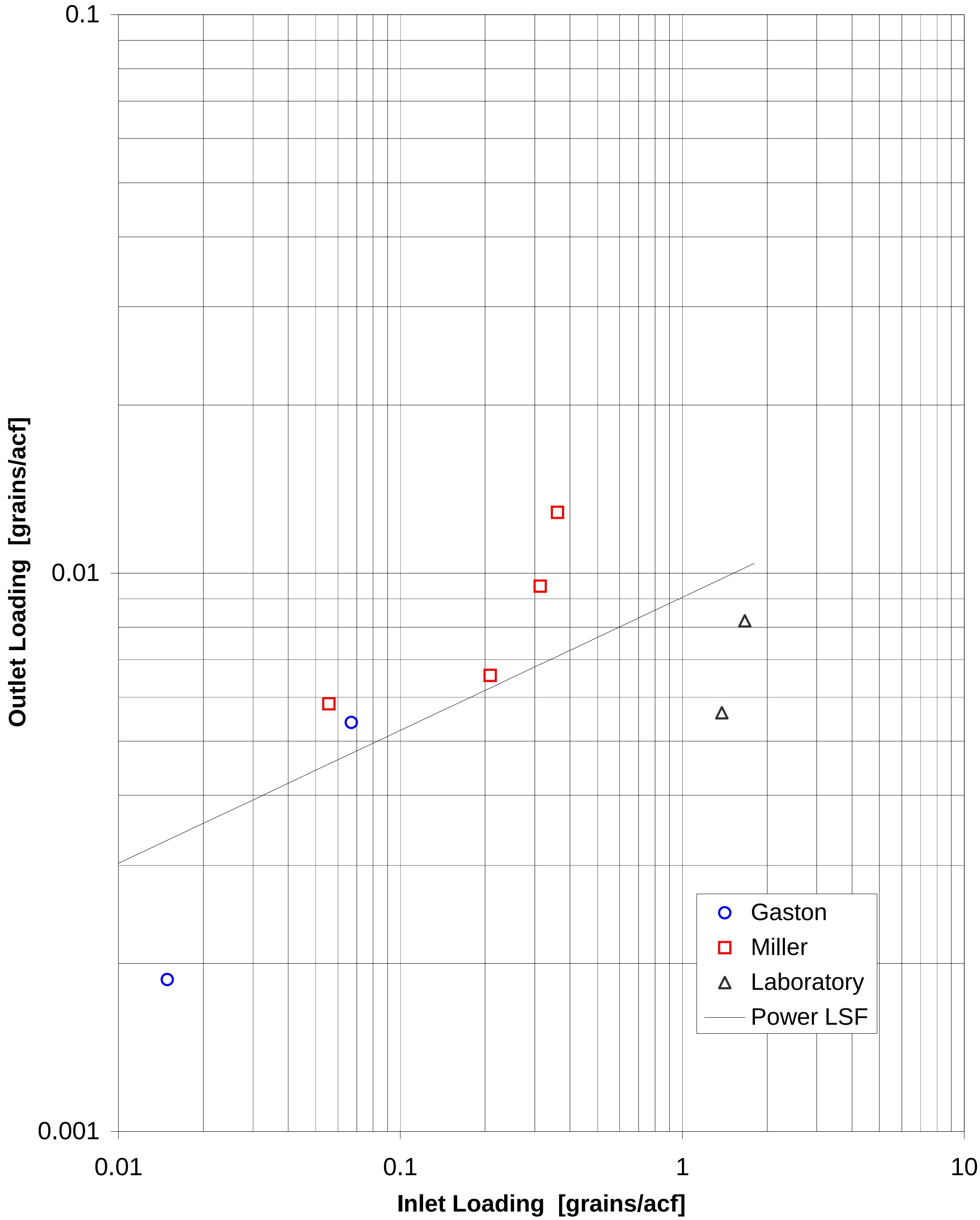

Figure 29: Effect of Inlet Loading on Particulate Outlet Loading

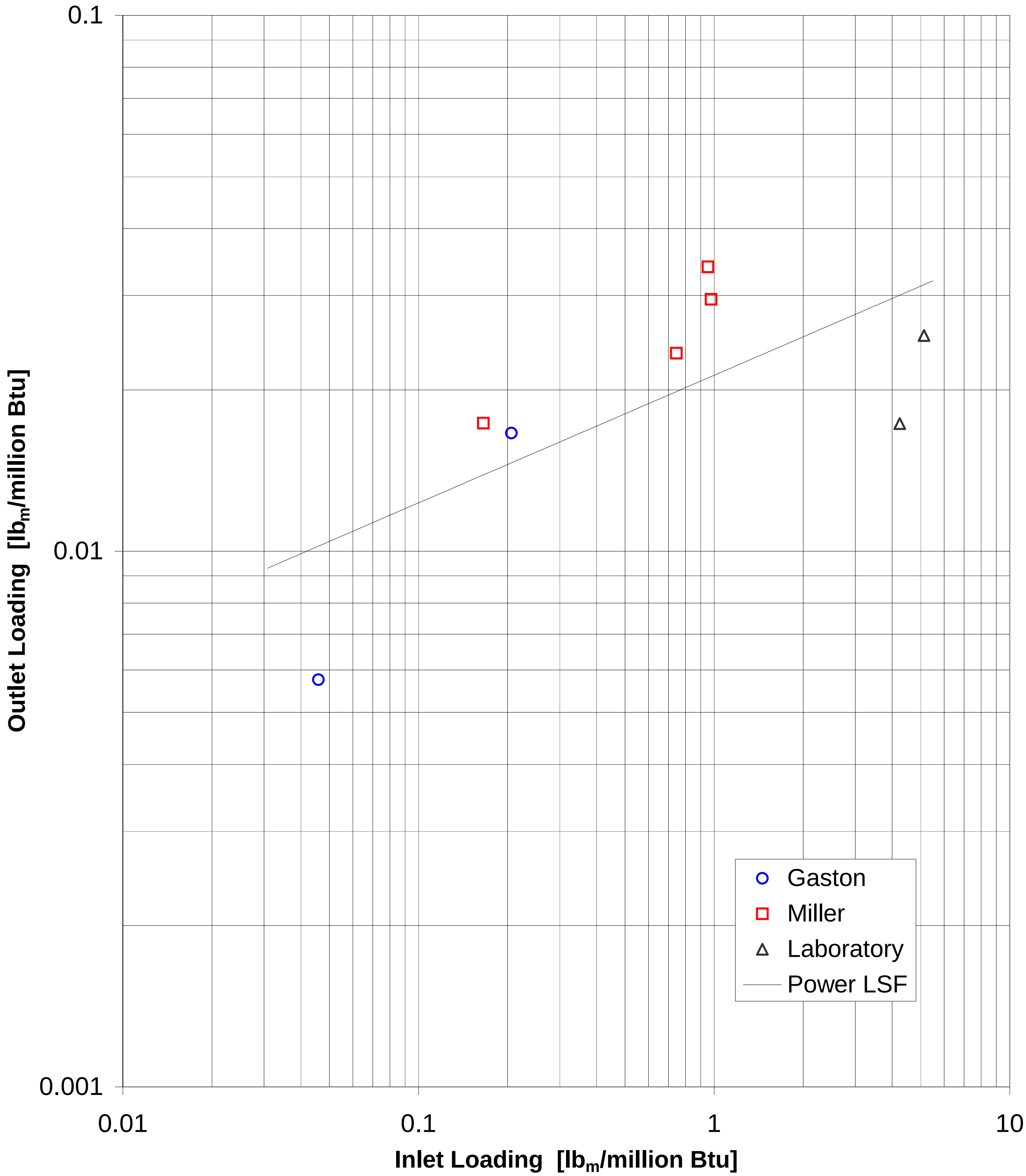

Figure 30: Effect of Inlet Loading on Particulate Outlet Loading Expressed in Pounds per Million Btu

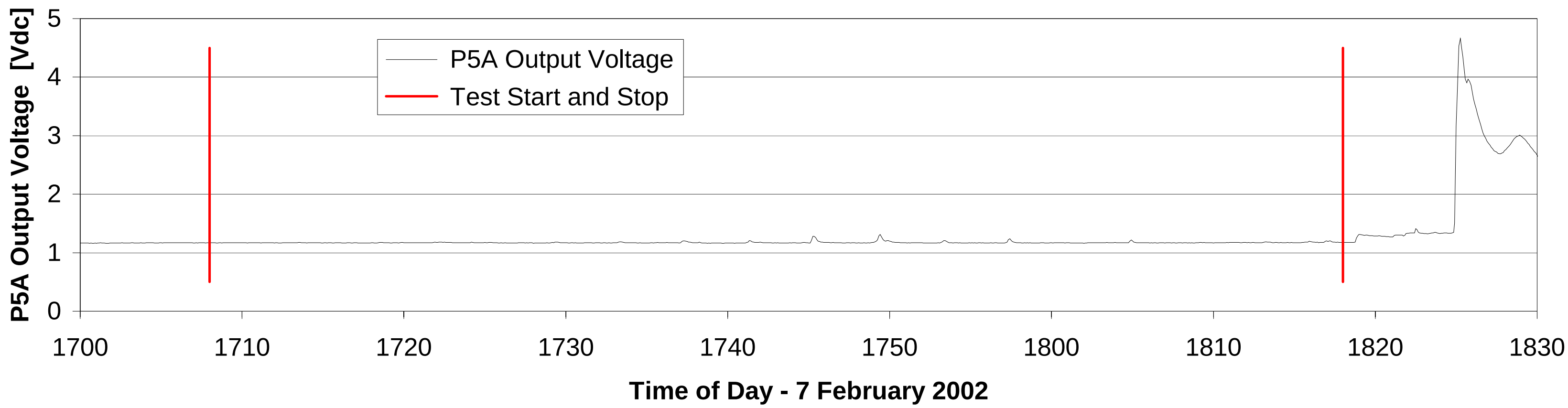

Figure 31: P5A Output Voltage For Point 23

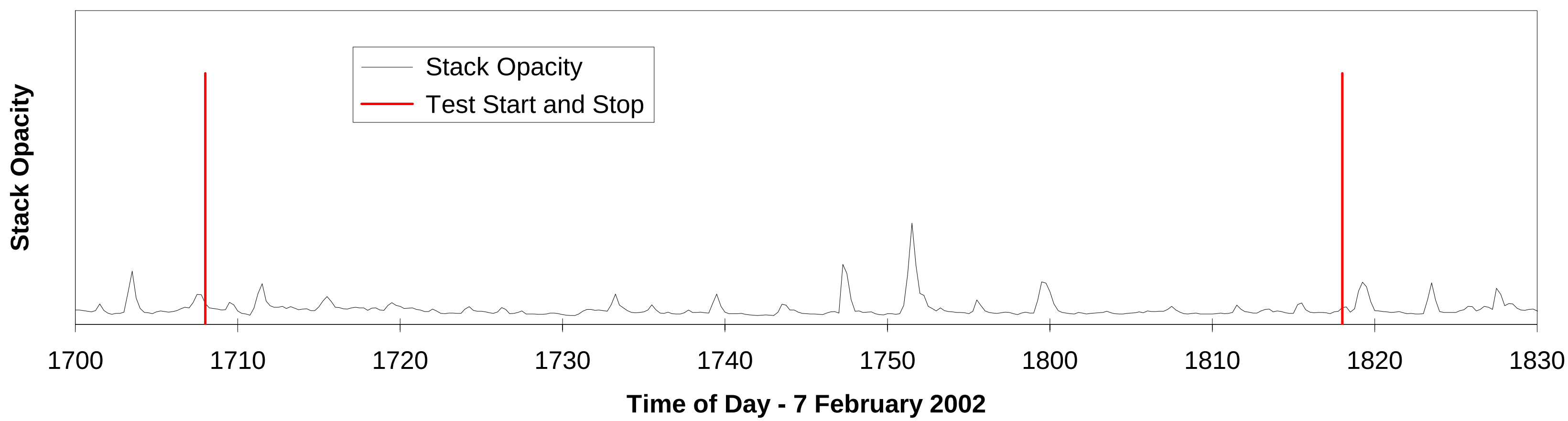

Figure 32: Stack Opacity During Point 23

Table 7: Summary of Advanced ElectroCore Field Prototype Test Conditions During Week of 12 November 2001

Test No.	*Clean Flow [acfm]*	*Clean Flow Gas Temp [°F]*	*Specific Separating Area [ft²/kacfm]*	*Bleed Flow Ratio [percent]*	*Average Precharger Voltage [kV]*	*Precharger Current Density [nA/cm²]*	*Average Advanced ElectroCore Voltage [kV]*	*Comments*
1	6064.2	156.5	88.4	9.42	-50	735.5	-60.5	Test ended early when HV cable failed
2	6161.8	176.7	87.0	8.22	-50	639.5	N/A	Joint on water-cooled precharger failed
3	5918.2	182.7	90.6	10.28	-45	495.6	N/A	Test conducted with cascade impactors
4	5870.4	189.6	91.3	9.08	-39.5	319.8	N/A	Still no precharger cooling water
5	5346.3	190.1	100.3	11.20	-38	247.8	N/A	100% of bleed flow directed to precharger
6	5151.4	186.4	104.1	10.83	-37	215.8	N/A	50% of bleed flow directed to precharger
7	5999.5	179.5	89.4	10.42	-40	279.8	-61.4	Cooling water and HV cable restored
8	4831.7	183.4	111.0	29.31	-40	279.8	-62.1	Test conducted with high bleed flow ratio
9	5327.1	188.3	100.6	11.19	-40	287.8	-60.9	Activated carbon sorbent injection
10	5282.4	179.6	101.5	11.52	-39	255.8	-62.2	Test again without sorbent
11	5248.2	183.2	102.2	11.41	-39	255.8	-62.2	Duplicate of previous test number
12	5273.0	182.1	101.7	10.86	-35	183.9	-61.8	Precharger voltage reduced to -35kV
13	5313.9	187.0	100.9	11.30	-36	197.2	-55.0	Test with "Sorbent 2" and "Sorbent 3"
14	5191.7	185.0	103.3	14.81	-34	127.9	-52.7	No sorbent and 15% bleed flow ratio
15	5224.1	183.9	102.6	15.66	-34	143.9	-52.9	Repeat of test number 15

The second part of Task 7 is to evaluate the cost of an Advanced ElectroCore system. The method for estimating the cost is to use as a basis the Black and Veatch cost study prepared in August of 1999 then update it based on changes in the ElectroCore made since that time. The basis of the original cost is the following.

Table 8: Cost Comparison Basis - Original Case

Parameter	*Value*
Capacity of Unit	1,000,000 acfm
Specific Separation Area	100 ft^2/kacfm
Contingency	20 percent
Installed Cost	16.63 $/kW

Since the Black and Veatch report, done in August of 1999, the ElectroCore separator endplates have been eliminated and the inlet slot shortened. These changes were the result of the testing described in Task 1 and implemented in Task 2. The savings in material and construction costs due to the elimination of the endplates is almost entirely offset by the costs associated with the shortening of the inlet slots. Although the performance of the Advanced ElectroCore is better than for the conventional ElectroCore at very low inlet loadings, they are, for the purposes of the cost estimate anyway, equivalent at the higher inlet loadings. Therefore, no cost savings will be considered for the Advanced ElectroCore over the conventional ElectroCore. The only significant cost change is in the contingency, which was 20 percent for the ElectroCore which was tested only at 500 acfm. Since the successful demonstration of a 12 times scale up, this contingency could be expected to be reduced due to the greater certainty of scale up. Although a contingency of only 15 percent might be considered more reasonable now, to be conservative LSR will still continue to use the 20 percent figure. To install a 310 MWe still requires a further 150 times scale up. The results of the testing of the Advanced ElectroCore at E.C. Gaston Steam Plant still show that the ElectroCore technology is still on track to have an installed cost of about $17/kW.

Conclusion

The tests of the Advanced ElectroCore at E.C. Gaston Steam Plant show that an efficiency of 99.991 percent can be achieved when an optimally performing Advanced ElectroCore is operating downstream of an ESP. The test results show that the upstream ESP operated with a maximum efficiency of 99.75 percent and that the Advanced ElectroCore operated with a maximum efficiency of 96.38 percent. Taken together, they comprise a system that can remove 99.991 percent of particulates coming for an uncontrolled boiler.

The tests also show that the performance of the ElectroCore system could be maintained when the system was scaled up by a factor of 12. The fact that the 12 Advanced ElectroCore separators performed as well as the single conventional ElectroCore separator indicates that a reasonably uniform flow distribution was achieved among the 12 separators. The results also show that the Advanced

ElectroCore's central electrode improved the separator efficiency when the ElectroCore inlet loading dropped below about 0.07 grains/dscf. Above that, the Advanced ElectroCore and conventional ElectroCore performed similarly. Although they cannot be presented at this time, the mercury capture data indicate that the Advanced ElectroCore is capable of capturing about 90 percent of mercury with activated carbon injection rates of about 7 pounds of activated carbon per million cubic feet of exhaust gas. This represents a baseline utilization of activated carbon. By placing a classifier in the bleed flow line to separate course un-spent activated carbon from fine fly ash particles, it is hoped that by recirculating the activated carbon to the Advanced ElectroCore inlet one can achieve the same mercury reduction with even lower sorbent injection rates. These tests have shown that the potential of the Advanced ElectroCore system to become a leading air pollution control solution is even bigger than it was at the start of the project.