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CATALYTIC FABRIC FILTRATION FOR SIMULTANEOUS NO_x AND PARTICULATE CONTROL

Final Report

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August 1994

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For
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Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania

By
University of North Dakota
Grand Forks, North Dakota

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ABSTRACT

The University of North Dakota (UND) Energy & Environmental Research Center (EERC), Owens-Corning Fiberglas Corporation (OCF), and Raytheon Engineers & Constructors (RE&C) conducted research to develop a catalytic fabric filter (CFF) for simultaneous control of NO_x and particulate matter. Funding for the project was provided by the U.S. Department of Energy Pittsburgh Energy Technology Center (DOE-PETC), Consolidated Edison Company of New York Inc. (Con Edison), and the Empire State Electric Energy Research Corporation (ESEERCO). OCF provided catalyst-coated bags, fabric samples, and technical support as a cost share.

The CFF concept employs a high-temperature woven-glass fabric (S2-glass), catalyst, and coating procedure developed by OCF. The woven fabric is coated with a catalyst capable of selectively reducing combustion flue gas NO_x to nitrogen and water, using ammonia as the reducing agent. Particulate control is accomplished as a result of conventional filtration mechanisms involving woven fabric and dust cake formation. Catalyst-coated bags are housed in a hot-side baghouse operating at air preheater inlet temperatures.

Bench-scale catalyst deactivation experiments demonstrated that strong acids (0.1 M HCl and H_2SO_4) and a strong base (0.1 M NaOH) destroy catalyst reactivity on used fabric samples having a light residual ash layer. Although the degree of catalyst reactivity loss was greater for residual ashes containing greater concentrations of alkali, the end result in all cases was a significant decrease in catalyst reactivity, which would require catalyst-coated bag replacement.

Results from the pilot-scale 100- and 500-hour pulse-jet tests have shown that catalyst loss or erosion from the fabric did not occur and 80% NO_x reduction is possible with an ammonia slip of 7.5% of the inlet NO_x concentration at an air-to-cloth ratio of 3 ft/min. Assuming a typical inlet NO_x concentration of 300 to 400 ppm (0.5 to 0.7 lb of NO_2/MMBtu), the resulting ammonia slip would be roughly 20 to 30 ppm. Decreasing the air-to-cloth ratio would result in an increase in NO_x reduction and a decrease in ammonia slip. Recent bench-scale tests with new fabric samples prepared using ten coats of catalyst rather than the seven coats used for the pilot-scale tests have shown improved reactivity. Assuming that further bench- and pilot-scale tests substantiate the improved performance, 80% NO_x reduction could be achieved with an ammonia slip of <10 ppm, or 95% NO_x reduction could be achieved with an ammonia slip of <20 ppm. These levels of ammonia slip meet ammonia emission limits (9 to 30 ppm) currently enforced in some areas of the United States.

Particulate collection efficiency was typically >99.9% during the 100- and 500-hour test periods, easily meeting the current New Source Performance Standards (NSPS) of 0.03 lb/MMBtu. Baghouse differential pressure was easily controlled at 4 to 6 in. W.C. using on-line pulse cleaning. Sulfur dioxide oxidation to sulfur trioxide was not observed to be a problem.

A single set of nine catalyst-coated DE992 bags were evaluated in a slipstream baghouse for 5136 hours, resulting in 13,820 cleaning cycles, while subbituminous coal was fired in a stoker-fired boiler at the UND steam plant. Supplemental ash injection

was used to augment fly ash from the stoker-fired boiler. Baghouse operating conditions included flue gas temperatures of 500°–700°F, filter face velocities of 3–5 ft/min, and differential pressures of 2–6 in. W.C. There were no catalyst-coated fabric failures as a result of the 5136 hours of normal baghouse operation. Data from MIT Flex, Mullen burst, and bench-scale reactivity tests with various fabric samples demonstrated that catalyst-coated fabric strength and reactivity did not degrade with time.

Particulate collection efficiency for the slipstream baghouse, as determined by a modified EPA Method 5, ranged from 99.96% to >99.9% for inlet mass loadings ranging from 1.5–5.7 gr/scf. Differential pressure across the slipstream baghouse was effectively controlled using on-line cleaning, a reservoir pulse pressure of 43 psig, and a pulse duration of 0.1 seconds.

To determine the commercialization potential of the CFF concept, a conceptual design was developed and an economic evaluation was prepared for the CFF process to estimate capital and levelized costs for two commercial pulverized coal-fired boiler applications, a new 500-MW plant, and an older 250-MW plant. In both cases, the CFF concept was compared to conventional hot-side selective catalytic reduction (SCR) for NO_x control and cold-side pulse-jet fabric filtration (PJFF) for particulate control. The economic analysis was prepared based on Electric Power Research Institute (EPRI) technical assessment guidelines.

The economic evaluation showed that the total installed plant investment for the CFF concept was 5% higher than the total installed plant investment for the SCR/PJFF combination, $145/kW versus $138/kW for the new 500-MW plant, and 4% lower for the 250-MW plant, $213/kW versus $221/kW. On a 30- and 15-year levelized cost basis, respectively, the CFF concept was somewhat less costly than the SCR/PJFF system for the new 500-MW plant, 5.91 versus 6.33 mills/kWh, and for the 250-MW retrofit, 9.15 versus 10.07 mills/kWh. These differentials represent an annual cost savings for the CFF of $1,400,000 and $1,300,000, respectively. Levelized costs for the CFF are driven by catalyst-coated bag replacement costs. Elements driving levelized costs for the SCR/PJFF included SCR catalyst replacement costs and the additional induced draft fan power requirements to offset the combined pressure losses across the SCR reactors and the PJFF. The conceptual design and economic evaluation indicates that the CFF is economically competitive with the SCR/PJFF, but further CFF development is necessary in order to compete commercially with the better developed technologies. Therefore, future CFF development efforts must focus on reducing the cost of catalyst-coated bags, demonstrating a bag and catalyst life of >2 years, and improving performance with respect to NO_x reduction and ammonia slip at air-to-cloth ratios equivalent to or higher than those used in this evaluation.

CATALYTIC FABRIC FILTRATION FOR SIMULTANEOUS NO_x AND PARTICULATE CONTROL

EXECUTIVE SUMMARY

Introduction

The University of North Dakota (UND) Energy & Environmental Research Center (EERC), Owens-Corning Fiberglas Corporation (OCF), and Raytheon Engineers & Constructors (RE&C) conducted research to develop a catalytic fabric filter (CFF) for simultaneous control of NO_x and particulate matter. Funding for the project was provided by the U.S. Department of Energy Pittsburgh Energy Technology Center (DOE-PETC), Consolidated Edison Company of New York Inc. (Con Edison), and the Empire State Electric Energy Research Corporation (ESEERCO). OCF provided catalyst-coated bags, fabric samples, and technical support as a cost share.

The DOE-PETC funding was secured as a result of a competitive award from the DOE-PETC Advanced NO_x Control Program. The objective of this program was to develop advanced concepts for the removal of NO_x from flue gas emitted by coal-fired utility boilers or for the control of NO_x formation by advanced combustion modification techniques. Funded projects were required to focus on the development of technology that significantly advanced the state of the art, using a process or a combination of processes capable of reducing NO_x emissions to 60 ppm or less. The concept must have successfully undergone sufficient laboratory-scale development to justify scaleup for further evaluation at the pilot scale (not to exceed 5 MW_e in size). Other requirements included production of a nonhazardous waste or a salable by-product. The concept was to have application to both new and retrofit coal-fired systems and show the potential for a 50% cost savings when compared to a commercial selective catalytic reduction (SCR) process capable of meeting the 60-ppm NO_x emission limit.

The EERC approach to meeting the program objective involved the development of a CFF for simultaneous NO_x and particulate control. This concept employs a high-temperature woven-glass fabric (S2-glass), catalyst, and coating procedure developed by OCF. The woven fabric is coated with a catalyst capable of selectively reducing combustion flue gas NO_x to nitrogen and water, using ammonia as the reducing agent. Particulate control is accomplished as a result of conventional filtration mechanisms involving woven fabric and dust cake formation. Catalyst-coated bags are housed in a pulse-jet hot-side baghouse operating at air preheater inlet temperatures.

The overall objective of the project proposed by the EERC was to evaluate the catalyst-coated fabric filter concept for effective control of NO_x and particulate emissions simultaneously. General goals included demonstrating high removal efficiency of NO_x and particulate matter, acceptable bag and catalyst life, and that process economics show a significant cost savings in comparison to a commercial SCR process and conventional particulate control. Specific goals included the following:

- Reduce NO_x emissions to 60 ppm or less

- Demonstrate particulate removal efficiency of >99.5%

- Demonstrate a bag/catalyst life of >1 year

- Control ammonia slip to <25 ppm

- Show that catalytic fabric filtration can achieve a 50% cost savings over conventional fabric filtration and SCR control technology

- Determine compatibility with SO_2 removal systems

- Show that the concept results in a nonhazardous waste product

Approach

Development of the catalytic fabric filter concept required further evaluation of air-to-cloth ratio effects, ammonia slip, SO_2 oxidation to SO_3, temperature cycling, catalyst-coated fabric preparation, fuel impacts, fabric cleaning (reverse gas versus pulse jet), catalyst life (poisoning and resistance to erosion), and filter performance and life (particulate control, differential pressure, and durability). The specific approach used to address these issues is defined by the following five tasks:

Task 1 – Program Definition
Task 2 – Design and Construction of Test Unit
Task 3 – Experimental Program and Data Reduction
Task 4 – Conceptual Design and Economic Evaluation
Task 5 – Test Unit Removal

Task 1, Program Definition, required preparation of a project management plan. This document contained a detailed scope of work, project schedule, and project budget; identified key project personnel; and presented the quality assurance/quality control (QA/QC) plan for the project.

Task 2, Design and Construction of Test Unit, was divided into three subtasks. Subtask 2.1, Reverse-Gas System, involved the design and construction of a new reverse-gas chamber in addition to upgrading an existing reverse-gas chamber to minimize temperature and flue gas flow control problems. Construction of the new chamber was necessary to permit operation over a range of air-to-cloth ratios (1.5, 2.0, 3.0, and 4.0 ft/min) without having to slipstream a significant portion of the flue gas. Upgrading the existing chamber was necessary to permit baghouse operation in the temperature range of 500° to 750°F. In combination, the chambers house two 12-in. × 26-ft bags providing a total filter area of 157 ft^2.

Subtask 2.2, Pulse-Jet System, involved the design and construction of a pulse-jet fabric filter system for use in Subtask 3.3, as well as for filtering the flue gas during off-line cleaning of the reverse-gas system. Construction of a new pulse-jet fabric filter system was necessary to obtain adequate temperature control over the range of interest (500° to 750°F) and to operate at the appropriate range of air-to-cloth ratios (2, 3, 4, and 6 ft/min), with minimal flue gas flow rate adjustments and slipstreaming. The pulse-jet fabric filter houses twelve bags, 6 in. in diameter by 8.25 ft long, providing a total cloth area of 151 ft^2. The pulse-jet system is a single compartment capable of cleaning both on-line and off-line.

Subtask 2.3, Catalytic Fabric and Filter Bag Preparation, involved the preparation of catalyst-coated fabric for use in the experimental phase of the project. This work was done by or under the direction of OCF personnel. Specific activities included manufacturing the high-temperature S2-glass fabric, coating the fabric for abrasion resistance, coating the fabric with catalyst, and manufacturing the filter bags for the reverse-gas and pulse-jet baghouses. A total of 27 reverse-gas and 94 pulse-jet bags were manufactured for the pilot-scale experimental effort.

Task 3, Experimental Program and Data Reduction, had four subtasks. Subtask 3.1, Fundamental Testing, was a bench-scale support effort to the primary experimental test plan. This effort was intended to supply information needed to understand the process mechanism thoroughly, allow screening of additional fabric samples, address the issue of catalyst poisoning, and generally support the pilot-scale effort.

Subtask 3.2, Process Testing/Reverse-Gas System, included the bulk of the pilot-scale experimental effort. This subtask involved twelve 100-hr test periods, one 500-hr test period, and four 1- to 2-day test periods. Each of the 100-hr test periods was performed while coal was fired and catalyst-coated filter bags were evaluated in a pilot-scale reverse-gas baghouse. The shorter test periods involved firing either natural gas or coal. Based on the results obtained during the 100-hr reverse-gas and pulse-jet tests, the 500-hr reverse-gas test originally planned was replaced with a 500-hr pulse-jet test.

Subtask 3.3, Process Testing/Pulse-Jet System, involved three 100-hr test periods and one 500-hr test period. Two 100-hr test periods and the 500-hr test period were performed while coal was fired. The third 100-hr test period involved oil firing. All four test periods used a pilot-scale pulse-jet baghouse to evaluate the catalyst-coated filter bags.

Subtask 3.4, Fabric Durability Testing/Pulse-Jet System, evaluated the performance of a single set of catalyst-coated filter bags in a pilot-scale pulse-jet baghouse for more than 5000 hours. The test involved slipstreaming flue gas from a stoker-fired boiler at the UND steam plant during parts of two heating seasons. The primary purpose of this activity was to determine filter bag performance (particulate control, baghouse differential pressure, and fabric cleanability) for an extended operating period.

Based on the results of Task 3, a technical and economic assessment of the catalytic fabric filter concept, Task 4, Conceptual Design and Economic Evaluation, was completed. Task 4 was based on a reference 500-MW$_e$ greenfield plant burning high-sulfur coal and a 250-MW$_e$ plant with the catalytic fabric filtration system added as a retrofit. The basis for the economic evaluation was the Electric Power Research Institute (EPRI) Technical Assessment Guide (TAG).

Task 5, Test Unit Removal, required the identification of all major test facilities, equipment, instruments, and hardware and their condition, ownership, and proposed disposition. With the exception of some instrumentation upgrades, the reverse-gas baghouse (Subtask 2.1) and the pulse-jet baghouse (Subtask 2.2), all of the equipment and facilities necessary to perform the experimental program were available at the EERC. Therefore, the Task 5 effort was minimal and primarily involved preparing an equipment disposition plan, documenting ownership of equipment acquired and fabricated in Task 2, and maintaining control of the equipment until final disposition was determined by DOE and other funding organizations.

The EERC, as the primary contractor for the project, was responsible for the management and direction of all technical and administrative project activities. EERC personnel performed all work associated with Task 1, Subtasks 2.1 and 2.2, Task 3, and Task 5.

OCF personnel performed and/or supervised all work associated with Subtask 2.3, including manufacturing the S2-glass fabric, coating the fabric, and manufacturing the filter bags for the reverse-gas and pulse-jet systems. This effort, as well as technical support, was provided by OCF as a cost share to the project.

RE&C, as a subcontractor to the EERC, provided technical support for Task 1 and performed Task 4. EERC and OCF personnel involved in Task 3 provided input to RE&C Task 4 activities.

The project schedule was based on a start date of October 1, 1990, with an assumed project duration of 36 months. Therefore, the planned project completion date was September 30, 1993. Because of delays encountered in completing Subtask 3.4, a request was made and approved to extend the project completion date through August 31, 1994. The 11-month extension permitted the continuation of Subtask 3.4 into December 1993 and allowed participation in a July 1994 contractors' review meeting at no additional cost to the project sponsors.

Results

Although all of the project objectives were not achieved, significant progress was made concerning the development of the CFF concept. Also, project results documented in this report demonstrate that the CFF concept has commercial potential. Data presented in the report demonstrate the potential to reduce NO_x emissions to 60 ppm (0.1 lb of NO_2/MMBtu) or less and control ammonia slip to <25 ppm. Particulate collection efficiency for the woven S2-glass fabric was $>99.5\%$. Although fabric and catalyst life were not specifically demonstrated for >1 year, there was no evidence that fabric and catalyst life would not be >1 year based on the 5136 hours of flue gas exposure completed.

Specific, experiments were not completed to verify the compatibility of the CFF concept with SO_2 removal options. However, no data were developed or observations made that would indicate that the CFF concept, when operating within design parameters, would interfere with the performance of a downstream spray dryer or wet scrubber. Also, the hot-side CFF baghouse presents an ideal temperature regime for the use of sodium-based sorbents to control SO_2 emissions resulting from the use of low-sulfur fuels. CFF reaction products are nitrogen and water. Therefore, the CFF concept does not generate a hazardous waste. Data show that catalyst erosion from the fabric does not occur and the vanadium component in the catalyst is not vanadium pentoxide. Also, disposal of spent catalyst-coated bags is factored into the OCF estimated purchase price, with OCF reprocessing the used fabric and catalyst.

The economic evaluation completed demonstrated that the CFF concept is competitive with a combination of conventional SCR and cold-side pulse-jet fabric filtration (PJFF). However, the project objective of a 50% cost savings was not achieved. On a levelized cost basis, the CFF concept was 7% to 10% cheaper than the SCR/PJFF combination. A more detailed summary of specific conclusions and recommendations is presented in the following paragraphs and in Section 4.0.

Catalyst-Coated Fabric Heat Treatment

As part of the catalyst-coating process, a fugitive organic lubricant is added to protect the catalyst and fabric and to facilitate sewing of the bags. Therefore, to obtain optimum performance of the catalyst-coated fabric, the fabric must be heat-treated to remove the lubricant and complete catalyst curing. Since the optimum heat treatment time and temperature for each of the fabrics was unknown, bench-scale tests were completed to evaluate the effect of heat treating on catalyst reactivity. The results of these tests were then used to select the heat treatment conditions for the catalyst-coated filter bags used in the pilot-scale tests.

From the bench-scale results, it was determined that each set of new bags would be heat-treated in the pilot-scale baghouse at 700°–725°F for 4 hours using flue gas containing 2–4 vol% O_2 resulting from the combustion of natural gas. The heat treatment procedure developed for these pilot-scale tests was appropriate for this project. However, further development of heat treatment procedures will be necessary prior to commercialization of the catalyst-coated fabric filter concept.

Catalyst Deactivation

Catalyst deactivation experiments were designed to represent a worst-case scenario, where the catalyst-coated fabric filters are wetted as a result of an upset condition, such as a tube leak. During such an upset condition, water may leach various components from the ash layer onto the fabric, creating an alkali, acid, or sulfur-rich solution. Depending on the nature of the upset condition, the wetted fabric would either dry quickly because of CFF operating temperatures or remain wetted for an extended period in the event of a forced system shutdown.

Results of the bench-scale catalyst deactivation experiments demonstrated that strong acids (0.1 M HCl and H_2SO_4) and a strong base (0.1 M NaOH) destroy catalyst reactivity on clean fabric samples. However, in the case of the acid-coated fabric, thoroughly washing the samples with water resulted in a complete recovery of catalyst reactivity. These results imply that the strong base chemically destroys catalyst reactivity, while the acid merely interferes with the catalyst site.

Strong acids and a strong base were found to destroy catalyst reactivity on used fabric samples having a light residual ash layer. Although the degree of catalyst reactivity loss was greater for residual ashes containing greater concentrations of alkali, the end result in all cases was a significant decrease in catalyst reactivity, which would require catalyst-coated bag replacement.

Exposure of clean catalyst-coated fabric to a severe moisture dew point showed little or no effect on catalyst reactivity. However, for used fabric samples having a light residual ash layer, catalyst reactivity was permanently reduced to a level requiring replacement of the catalyst-coated bags.

Catalyst-coated fabric samples coated with any one of several chemical forms of alkali (Na, Ca, and K) and then exposed to a severe moisture dew point demonstrated a significant loss of catalyst reactivity. Independent of chemical form, sodium had a greater effect than calcium, and calcium a greater effect than potassium, consistent with the increasing Brønsted acidity of the ions.

Catalyst-Coated Fabric-Screening Tests

Five new fabric types were prepared by OCF for screening near the end of the project. The fabric samples were identified as Fabric 205, 206, 207, 208, and 209. Based on the bench-scale data, Fabric 208 appears to be significantly more reactive than the DE992 fabric used for the pilot-scale pulse-jet tests. Assuming future bench- and pilot-scale tests substantiate the improved performance of Fabric 208, 80% NO_x reduction could be achieved with an ammonia slip of <10 ppm, or 95% NO_x reduction could be achieved with an ammonia slip of <20 ppm.

Fabric 208 represents a standard DE992 woven S2-glass fabric prepared using ten coats of the standard 0.2 M V–Ti catalyst coating rather than the seven coats used previously. The purpose of applying ten coats of catalyst was to simply increase the amount of catalyst on the fabric in the hope of increasing NO_x reduction and reducing ammonia slip. If successful, the cost of the CFF concept could be reduced as a result of being able to operate the CFF at a higher face velocity and could reduce the operating and maintenance (O&M) costs associated with ammonia slip.

Pilot-Scale Parametric Tests

Testing of catalyst-coated fabric filters with the reverse-gas and pulse-jet systems included fabric-screening tests, fuel effects tests, operating temperature tests, and dew point exposure tests. Sixteen reverse-gas test periods and six pulse-jet test periods were completed. With the exception of the two 500-hr pulse-jet tests, test duration was 100 hours or less. Specific observations made as a result of the pilot-scale parametric tests include the following:

- Pilot-scale 100-hr fabric-screening tests demonstrated that the 22-oz/yd^2 woven S2-glass fabric, prepared using seven coats of a vanadium–titanium catalyst and applied using an organic-based coating process, resulted in higher NO_x reduction and lower ammonia slip than the other four catalyst-coated fabric types tested. However, differences observed between the 14- and 22-oz/yd^2 fabric prepared using the same catalyst and organic-based coating process may be simply due to the greater catalyst concentration on the 22-oz/yd^2 fabric. Therefore, further development or testing of the catalyst-coating process would be appropriate to maximize the quantity of the catalyst that can be effectively applied to an S2-glass fabric.

- During 100-hr test periods using both the pulse-jet and reverse-gas baghouses, 90% NO_x reduction and <25-ppm ammonia slip were demonstrated. Air-to-cloth ratio had a significant effect on catalyst-coated fabric performance. An air-to-cloth ratio of <4 ft/min and a flue gas temperature of 650°–700°F were necessary to achieve 80% NO_x reduction and control ammonia slip adequately.

- Flue gas temperature also had an effect on catalyst-coated fabric performance. As flue gas temperatures were decreased from 650°F, ammonia slip increased and NO_x reduction decreased, while temperatures of >750°F are known to permanently deactivate the catalyst.

- The pilot-scale data from the 100-hr test periods indicate that fuel type (oil and coal) may have some effect on NO_x reduction and ammonia slip. However, the short duration of these tests and range of operating parameters experienced prevent the formulation of specific conclusions.

- In order to minimize the effect of fly ash characteristics on CFF performance, future development activities should evaluate a catalyst-coated S2-glass felt. The catalyst-coated felt would not be affected by pinholing to the degree a woven fabric is affected. Therefore, dust cake characteristics, such as pinholes, would have less effect on NO_x reduction and ammonia slip.

- Results from the 100-hr oil-fired test were similar to the 100-hr coal-fired tests. However, NO_x reduction was slightly lower and ammonia slip, as a percentage of inlet NO_x concentration, was slightly higher. Lower NO_x reduction and higher ammonia slip probably resulted from a very low fly ash mass loading entering the baghouse, resulting in very little dust cake development and a low operating differential pressure (<3 in. W.C.).

- Particulate collection efficiency was >99.5% for both the 14- and 22-oz/yd^2 woven S2-glass fabrics for all 100-hr coal-fired test periods when the ammonia was turned off. However, with the ammonia on, the calculated particulate collection efficiency for tests with high ammonia slip (>40 ppm) was lower because of ammonium sulfate or bisulfate formation on the particulate sampling filters artificially increasing measured outlet mass loadings.

- Baghouse differential pressure was controlled at reasonable levels, 4–8 in. W.C., during the 100-hr coal-fired test periods at all air-to-cloth ratios tested. Baghouse differential pressure was controlled using off-line cleaning during reverse-gas tests and on-line cleaning during pulse-jet tests. Pulse-cleaning frequency ranged from 10 to 60 minutes, depending on specific operating conditions.

- N_2O concentrations in the flue gas were measured at both the inlet and outlet of the CFF baghouse during several test periods to verify that nitric oxide and nitrogen dioxide were not being converted to N_2O. For all coals tested, N_2O concentrations were <10 ppm at the CFF baghouse inlet and outlet, demonstrating that N_2O was not being formed as a result of flue gas exposure to the catalyst-coated bags.

- Based on the catalyst-coated fabric and baghouse hopper ash samples analyzed, no significant catalyst loss or erosion occurred that would affect performance with respect to NO_x reduction or ammonia slip or create concern with respect to fly ash disposal. This observation was made during the 100- and 500-hr pilot-scale parametric tests as well as the fabric durability test where catalyst-coated fabric was exposed to flue gas in a pilot-scale baghouse for 5136 hours. Therefore, the CFF concept meets the DOE–PETC Advanced NO_x Control Program objective concerning the production of a nonhazardous waste product. However, vendors of both the CFF concept and conventional SCR systems will need to address the recycle and/or disposal of spent catalyst in commercial applications.

- Measurements were made to determine SO_3 concentrations downstream of the CFF baghouse with the ammonia injection system turned off to avoid interference. Results from the 100- and 500-hr tests while various fuels were fired (oil, bituminous coal, subbituminous coal, and lignite) demonstrated that the CFF was not oxidizing SO_2 to SO_3.

- The 500-hr bituminous coal-fired tests demonstrated that the reactivity of the catalyst-coated fabric decreased slightly during the first 100 hours of operation. After 100 hours, performance was stable, demonstrating 80% NO_x reduction, with an ammonia slip of 7.5% of the inlet NO_x concentration at an air-to-cloth ratio of 3–3.5 ft/min. Assuming an inlet NO_x concentration of 300–400 ppm (0.5 to 0.7 lb of NO_2/MMBtu), which is greater than, if not typical of, pulverized coal (pc)-fired boilers with low-NO_x burners, the resulting ammonia slip would be 20–30 ppm. These results demonstrate the potential to meet the DOE–PETC Advanced NO_x Control Program objective of reducing NO_x emissions to 60 ppm (0.1 lb of NO_2/MMBtu) or less and meet ammonia emission limits (9 to 30 ppm) currently enforced in some areas of the United States.

- Analysis of baghouse hopper ash collected during the 500-hr tests showed that ammonia concentrations in the ash were <30 μg/g when 80% NO_x reduction was attempted. At this level, <30 μg/g, ammonia concentrations in the ash are not expected to interfere with ash disposal or utilization options.

- Particulate collection efficiency was typically $>99.9\%$ during the 500-hr tests, easily meeting the current New Source Performance Standard of 0.03 lb/MMBtu. Exceptions were observed when ammonia slip exceeded 40 ppm, resulting in the formation of a sulfate or bisulfate. Baghouse differential pressure was easily controlled between 4 and 6 in. W.C. using on-line pulse cleaning.

Pilot-Scale Fabric Durability Test

Nine pulse-jet bags were installed in the slipstream baghouse at the UND steam plant in July 1992. These bags represented nine of the twelve bags used for the first 100-hr pulse-jet test (PTC-BV-429) successfully completed for Subtask 3.3. Results from the 100-hr test (PTC-BV-429) showed NO_x reduction ranging from 73% to 92% for air-to-cloth ratios and ammonia-to-NO_x molar ratios of 2 to 6 ft/min and 0.7 to 0.96, respectively. Measured ammonia slip was $<7.5\%$ of the inlet NO_x concentration, which averaged 747 ppm (1.24 lb of NO_2/MMBtu).

Completion of the 100-hr test and the resulting data established an excellent baseline from which to evaluate fabric performance and durability in the pulse-jet baghouse at the steam plant. Operation of the slipstream baghouse was initiated on July 16, 1992, and continued intermittently through December 3, 1993, at which time system operation was terminated because of funding limitations. Specific observations made as a result of slipstream baghouse operation include the following:

- A single set of nine catalyst-coated DE992 bags was evaluated in a slipstream baghouse for 5136 hours, resulting in 13,820 cleaning cycles, while subbituminous coal was fired in a stoker-fired boiler at the UND steam plant. Supplemental ash injection was used to augment fly ash from the stoker-fired boiler. Baghouse operating conditions included flue gas temperatures of 500°–700°F, filter face velocities of 3–5 ft/min, and differential pressures of 2–6 in. W.C. No catalyst-coated fabric failures occurred as a result of the 5136 hours of normal baghouse operation. Because of project funding limitations and steam plant downtime, the project objective of demonstrating a bag/catalyst life of >1 year was not achieved. However, there were no data collected or observations made that would indicate a bag/catalyst life of <1 year.

- Particulate collection efficiency for the slipstream baghouse, as determined by a modified EPA Method 5, ranged from 99.96% to $>99.99\%$ for inlet mass loadings ranging from 1.5–5.7 gr/scf. An inlet mass loading of 3 gr/scf resulted in cleaning cycle frequencies of 20–30 minutes.

- Differential pressure across the slipstream baghouse was effectively controlled using on-line cleaning, a reservoir pulse pressure of 43 psig, and a pulse duration of 0.1 seconds. These pulse system conditions resulted in a pulse air volume of roughly 0.3 ft^3 per bag.

- Sampling at the outlet of the slipstream baghouse demonstrated that the catalyst-coated bags did not oxidize SO_2 to SO_3. Measured SO_3 concentrations were <1 ppm. These data are consistent with the results observed for the 100- and 500-hr pilot-scale parametric tests.

- Data from MIT Flex, Mullen burst, and bench-scale reactivity tests demonstrated that catalyst-coated fabric strength and reactivity did not degrade with time. Fabric samples tested represented 840, 1642, and 5136 hours of flue gas exposure.

Conceptual Design and Economic Evaluation

Although the initial focus of a process development effort is to evaluate technical performance, successful technology commercialization is ultimately dependent on achieving technical performance goals at an economic advantage over competing technologies. One objective of the DOE-PETC Advanced NO_x Control Program was to demonstrate that concepts selected for evaluation have application to both new and retrofit coal-fired systems and show the potential for a 50% cost savings when compared to a commercial SCR process capable of meeting the program objective of a 60-ppm NO_x emission limit.

To determine the commercialization potential of the CFF concept, RE&C was asked to develop a conceptual design and prepare an economic evaluation of the CFF process to estimate capital, operating, maintenance, and levelized costs for two commercial pc-fired boiler applications: a new 500-MW plant and an older 250-MW plant with moderate retrofit constraints. In both cases, the CFF concept was compared to conventional hot-side

CATALYTIC FABRIC FILTRATION FOR SIMULTANEOUS NO_x AND PARTICULATE CONTROL

1.0 INTRODUCTION

The University of North Dakota (UND) Energy & Environmental Research Center (EERC), Owens-Corning Fiberglas Corporation (OCF), and Raytheon Engineers & Constructors (RE&C) conducted research to develop a catalytic fabric filter (CFF) for simultaneous control of NO_x and particulate matter. Funding for the project was provided by the U.S. Department of Energy Pittsburgh Energy Technology Center (DOE-PETC), Consolidated Edison Company of New York Inc. (Con Edison), and the Empire State Electric Energy Research Corporation (ESEERCO). OCF provided catalyst-coated bags, fabric samples, and technical support as a cost share.

The DOE-PETC funding was secured as a result of a competitive award from the DOE-PETC Advanced NO_x Control program. The objective of this program was to develop advanced concepts for the removal of NO_x from flue gas emitted by coal-fired utility boilers or for the control of NO_x formation by advanced combustion modification techniques. Funded projects were required to focus on the development of technology that significantly advanced the state of the art, using a process or a combination of processes capable of reducing NO_x emissions to 60 ppm or less. The concept must have successfully undergone sufficient laboratory-scale development to justify scaleup for further evaluation at the pilot scale (not to exceed 5 MW_e in size). Other requirements included production of a nonhazardous waste or a salable by-product. The concept was to have application to both new and retrofit coal-fired systems and show the potential for a 50% cost savings when compared to a commercial selective catalytic reduction (SCR) process capable of meeting the 60-ppm NO_x emission limit.

The EERC approach to meeting the program objective involved the development of a CFF for simultaneous NO_x and particulate control. This concept employs a high-temperature woven-glass fabric (S2-glass), catalyst, and coating procedure developed by OCF. The woven fabric is coated with a catalyst capable of selectively reducing combustion flue gas NO_x to nitrogen and water, using ammonia as the reducing agent. Particulate control is accomplished as a result of conventional filtration mechanisms involving woven fabric and dust cake formation. Catalyst-coated bags are housed in a pulse-jet hot-side baghouse operating at air preheater inlet temperatures.

The overall objective of the project proposed by the EERC was to evaluate the catalyst-coated fabric filter concept for effective control of NO_x and particulate emissions simultaneously. General goals included demonstrating high removal efficiency of NO_x and particulate matter, demonstrating acceptable bag and catalyst life, and demonstrating that process economics show a significant cost savings in comparison to a commercial SCR process and conventional particulate control. Specific goals included the following:

- Reduce NO_x emissions to 60 ppm or less
- Demonstrate particulate removal efficiency of >99.5%
- Demonstrate a bag/catalyst life of >1 year

- Control ammonia slip to <25 ppm

- Show that catalytic fabric filtration can achieve a 50% cost savings over conventional fabric filtration and SCR control technology

- Determine compatibility with SO_2 removal systems

- Show that the concept results in a nonhazardous waste product

This document represents the final project report for DOE Contract No. DE-AC22-90PC90361, Catalytic Fabric Filtration for Simultaneous NO_x and Particulate Control. In addition to presenting the results of the bench- and pilot-scale experimental activities, this document summarizes the key findings of the conceptual engineering and economic evaluation and identifies areas in which further development of the catalyst-coated fabric filter concept is necessary in order to improve performance and reduce costs.

1.1 Background

The idea of applying either permanent or throwaway catalysts to a high-temperature fabric filter for NO_x control is not new (1–4). Initial work at OCF began in the early 1980s and was carried out and funded exclusively in-house to develop a catalyst-coated fabric to be used in filter bags for simultaneous NO_x and particulate control. The key to this research effort was the development of novel methods for producing highly active catalysts on high-temperature glass fibers. In 1984, OCF contracted with the EERC to assist with the development effort. Because of funding constraints, the developmental work was discontinued in the fall of 1986.

In April of 1988, the developmental effort was resumed by OCF and the EERC. OCF activities were funded by OCF and primarily involved preparation of catalyst-coated fabrics for bench-scale experiments that were performed at the EERC. EERC activities, funded within a Cooperative Agreement program with the U.S. Department of Energy (DOE), focused on bench-scale experiments designed to show continuity with previous work and screen a large number of catalyst-coated fabric samples. The properties and performance of the materials developed are summarized in the following discussion.

1.2 Early Fabric Performance

1.2.1 OCF Laboratory Results

A block diagram of the OCF laboratory apparatus used initially to evaluate catalytic activity is shown in Figure 1-1. The flow rates of the gases used were individually controlled by mass-flow controllers (Matheson Model 10) to achieve the desired chemical composition and total gas flow rate. The gas mixture was passed through a Pyrex glass heat exchanger, then through a single thickness of the test cloth contained in a glass filter holder, and held within an oven. An all-glass assembly was required, because other materials, such as 316 stainless steel, nickel, and copper, are slightly catalytic at elevated temperatures (5, 6) and can interfere with the evaluation of catalyst reactivity. After passing through the test fabric, the simulated flue gas entered a sample conditioner (Thermoelectron Model 90) and, finally, a chemiluminescent nitric oxide (NO) analyzer (Thermoelectron Model 10A). NO_x and ammonia concentrations were also measured using

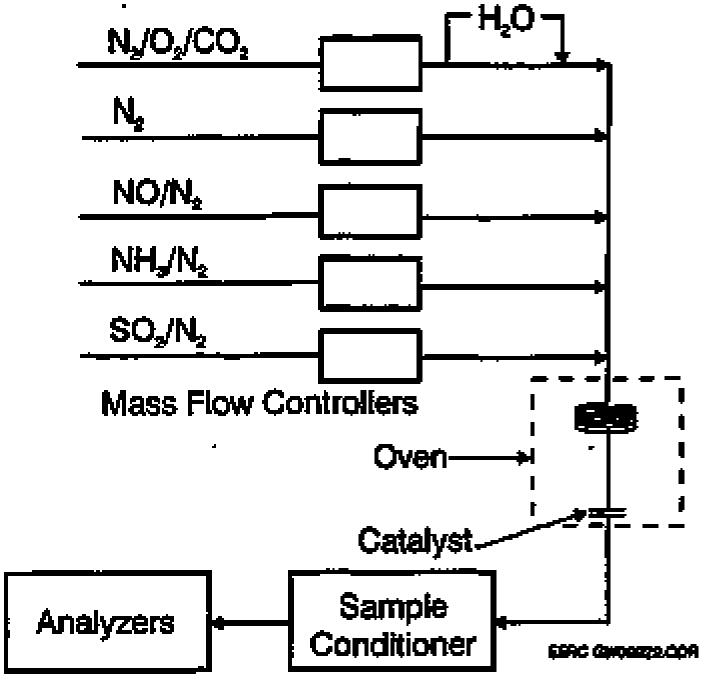

Figure 1-1. Block diagram of OCF laboratory apparatus used to evaluate catalyst-coated fabric activity.

catalytic converters that converted these species to NO. This specific experimental apparatus was dismantled and is no longer available to support bench-scale development efforts.

The steady-state catalytic activity of a sample was typically measured at seven different temperatures, each at four different face velocities. The composition of the simulated flue gas chosen for the laboratory tests is listed in the third column of Table 1-1. Although the simulated flue gas did not contain water, particulates, and minor flue gas components, it did contain ammonia, which is the reducing agent required for catalytic NO_x reduction. Typical NO_x reduction reactions include the following:

$$6NO + 4NH_3 + \text{Catalyst} \rightarrow 5NH_2 + 6H_2O$$

$$4NO + 4NH_3 + O_2 + \text{Catalyst} \rightarrow 4N_2 + 6H_2O$$

$$6NO_2 + 8NH_3 + \text{Catalyst} \rightarrow 7N_2 + 12H_2O$$

$$2NO_2 + 4NH_3 + O_2 + \text{Catalyst} \rightarrow 3N_2 + 6H_2O$$

TABLE 1-1

Flue Gas Compositions (vol%)

Component	Typical Flue Gas	Simulated Flue Gas
N_2	73.76	78.1
O_2	4.88	6.0
CO_2	12.31	15.7
SO_2	0.24	0.0
SO_3	0.0024	0.0
NO	0.06	0.1
NH_3	0.0	0.1
HCl	0.01	0.0
H_2O	8.79	0.0
Particulates	15 g/m_3	0.0

Typical results for the OCF catalyst-coated fabric are shown in Figure 1-2. The fractional decreases in NO_x concentration are plotted as a function of temperature and face velocity. For example, at a temperature of 662°F (350°C) and a face velocity of 2 ft/min (0.67 m/min), the fabric will reduce 90% of the NO_x in the gas stream. It should be noted that the OCF catalyst-coated fabric exhibits an extraordinary degree of catalytic activity. If the fabric is 1 mm thick, a face velocity of 2 ft/min is equivalent to a space velocity of 40,000 hr^{-1}. Typical SCR catalysts operate at much lower space velocities, ranging from 3000 to 10,000 hr^{-1}. The high degree of catalytic activity was expected and is attributed to the mass-transfer advantages inherent in using a high external surface area fiber and in exploiting novel materials and processing techniques developed at OCF for producing catalytic materials.

The primary difference between the catalyst-coated filter bag concept and conventional SCR technology is the catalyst support. Conventional SCR technology generally uses a honeycomb support structure. The catalyst-coated fabric is prepared by coating the surface of an S2-glass (high-temperature) cloth, resulting in a catalyst bonded to the surface of the fabric. The catalyst coating consists of a chemical source of titanium and vanadium, generally referred to as "sol-gel" materials. After the fabric has been coated, the sol-gels hydrolyze during air drying, resulting in a highly porous layer. The fabric is then cured at a low temperature to drive off any residual organic material and partially densify the coating. The final product is a highly porous catalyst coating that is strongly bonded to the surface of the glass fabric.

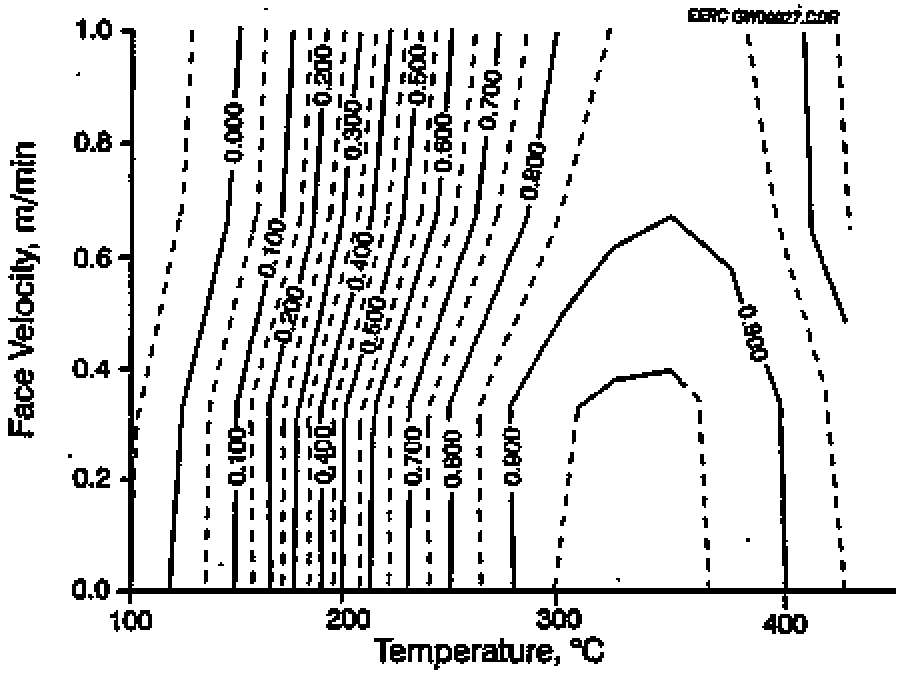

Figure 1-2. Fractional decreases in NO_x concentration as a function of temperature and face velocity.

OCF determined that catalyst pickup during the coating process was 22.4 g/yd^2 of fabric. Catalyst pickup was measured for a 13.6-oz/yd^2, nontexturized style 484 weave. Based on this information and the numbers presented in Table 1-2, OCF determined that the weight of the glass and catalyst was roughly 91 kg/MW. A similar calculation for a 22-oz/yd^2 S2-glass woven fabric results in a 73-kg/MW value.

These numbers (91 and 73 kg/MW) are relatively small when compared to values (630 to 1050 kg/MW for catalyst and support) reported in the literature for conventional SCR technology (5, 7). Therefore, these data indicate that by using a fibrous support, levels of NO_x reduction comparable to those observed for conventional SCR technology may be observed using the CFF concept with 7 to 14 times less catalyst and support mass.

Catalyst composition and the unique method of applying the catalyst to high-temperature glass fabric are proprietary to OCF (8). Other catalyst and coating procedure options will continue to be evaluated by OCF in order to improve CFF performance and minimize cost.

1.2.2 Slipstream Sample Trials at the EERC

While early in-house conversion efficiency results were promising, several critical flue gas conditions could not be duplicated in the OCF laboratory. For example, the effects of fly ash, sulfur, water vapor, and trace constituents on the catalyst-coated cloth remained unknown. For these reasons, OCF contracted with the EERC to evaluate the

TABLE 1-2

Catalyst Pickup on Woven S2-Glass Fabric

Fabric Weight, oz/yd^2	13.6	22
Flue Gas Flow Rate (scfm/MW)	1900	1900
Operating Temperature (°F)	660	660
Flue Gas Flow Rate (acfm/MW)	4026	4026
Air-to-Cloth Ratio (ft/min)	2	4
Catalytic Fabric Area (ft^2/MW)	2013	1007
Weight of Fabric (g/yd^2)	386	624
Weight of Catalyst (g/yd^2)	22.4	29.4
Weight of Fabric and Catalyst (g/yd^2)	408.4	653.8
Weight of Fabric and Catalyst (kg/MW)	91	73

NO_x reduction capability of the fabric while fly ash was filtered from a pilot-scale pulverized coal-fired (pc-fired) furnace. Velva North Dakota lignite was fired in the EERC's particulate test combustor (PTC) to produce fly ash for the testing. A description of the PTC is given in Appendix A.

Since full bag samples of the test fabrics were not immediately available, a special slipstream sampler was designed and constructed by the EERC to test fabric samples of about 0.5 ft^2 in size. The fabric sample was housed in an oven that kept the samples at 650° ± 25°F, and flue gas was drawn through the filter sample at a face velocity of 2 ft/min. After passing through the filter, the flow was split, with about 10 scfh going to a gas pump and dry gas meter for control of the total flow. The sampling scheme is shown in Figure 1-3. For these tests, ammonia was injected into the system well upstream of the sample point to ensure sufficient mixing with the flue gas stream prior to its being sampled with the slipstream sampler.

In all, 15 different cloth samples were tested in 8- to 11-hr runs. The samples represented variations in cloth composition, weave, and coating procedure. Average experimental conditions under which the samples were run are listed in Table 1-3. Conversion efficiencies, or percent NO_x reduction for the 15 samples, are presented in Table 1-4. Overall, NO_x reduction ranged from 70% to 93% at an ammonia-to-NO_x molar ratio of ≤ 1.0. A noncatalytic blank was included to eliminate the possibility of NO_x removal because of 1) reaction with ammonia, 2) reactions with stainless steel surfaces, or 3) interaction with the fly ash or dust cake. Conversion efficiencies did not decrease with time during short-term tests because of catalyst blinding or fly ash buildup on the fabric. If anything, removal efficiency increased during the first few hours of testing and then stabilized. Cloth durability also appeared to be good for all catalyst-coated fabric samples.

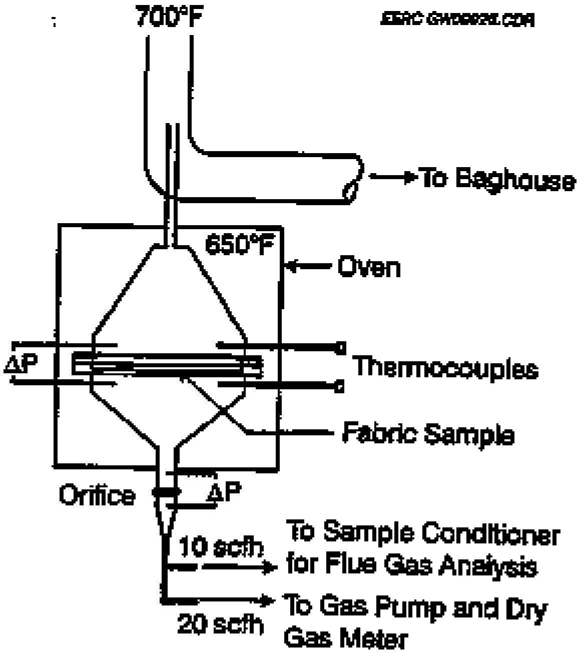

Figure 1-3. Schematic of slipstream sampler.

TABLE 1-3

Slipstream Sample Test Conditions

Temperature, °F	650
NO_x, inlet concentration, ppm	800
SO_2, inlet concentration, ppm	300
Vol% O_2	5
Vol% CO_2	15.5
Air-to-Cloth Ratio, ft/min	2
Ammonia-to-NO_x Molar Ratio	≤1.0
Test Duration, hr	11

TABLE 1-4

NO_x Reduction Efficiencies for EERC Slipstream Samples

Sample	NO_x Reduction, %
EERC 1	83
EERC 2	93
EERC 3[a]	4
EERC 4	87
EERC 5	92
EERC 6	77
EERC 7	85
EERC 8	82
EERC 9	85
EERC 10	86
EERC 11	76
EERC 12	80
EERC 13	82
EERC 14	81
EERC 16	70

[a] Blank, noncatalytic glass cloth.

1.2.3 Bag Trial at the EERC

The next logical step for proof-of-concept testing for the catalyst-coated filter bags was construction and testing of bags. Nine bags approximately 4 ft long and 7 in. in diameter were constructed and placed in operation. Experimental conditions were similar to those used for the slipstream samples (see Table 1-2). Test duration was planned to be approximately 100 hours, and the primary objectives were to demonstrate NO_x reduction and bag durability with time.

Low conversion efficiency (roughly 50% NO_x reduction) was observed early in the test, caused at least in part by an air leak in the baghouse. It was also noted that the conversion efficiency dropped each time the bags were cooled and reheated; the cooling–reheating cycle occurred 3 times during testing. SEM analyses of a used bag revealed the presence of fibrils on the cloth surface that were not observed on the surface of catalyst-coated fabric with good activity. Further analysis using x-ray diffraction (XRD) indicated the presence of sodium sulfite, which probably condensed on the cloth as the flue gas cooled. Speculation at that time was that the sodium sulfite covered the catalyst surface, reducing activity. Both alkaline metal poisoning and deposition of ammonium bisulfate have been reported to reduce the activity of SCR catalysts when rapid cooling occurs in the presence of flue gas or ammonia and SO_x (9, 10). However, this can be avoided by purging the catalyst prior to cooling. Subsequent work by EERC personnel has shown that silicone gasket material may have been the cause of reduced catalyst activity. This issue is discussed in more detail later in this section.

Later in the test, the original bags were removed, and three new bags were installed. The temperature was not changed during the course of this run. Even though the air-to-cloth ratio was higher than in earlier tests (approximately 4 rather than 2 ft/min) and the baghouse temperature lower, NO_x reduction averaged about 77%. After 2 days of operation, NO_x reduction had not decreased, and equally important, no holes or tears were found in the bags. These results indicated that good NO_x reduction and bag durability were possible, at least in a short test period. Results also indicated that temperature cycling in the presence of ammonia should be avoided, although it is not expected to be a major obstacle, since conventional baghouses cannot tolerate excessive temperature cycling without bag damage.

1.2.4 EERC Bench-Scale Experiments

In April of 1988, the catalyst and fabric development effort was resumed by OCF and the EERC. OCF activities were funded by OCF and primarily involved preparation of catalyst-coated fabrics for bench-scale experiments that were performed at the EERC. EERC activities, funded within a Cooperative Agreement program with DOE, focused on bench-scale experiments designed to show continuity with the previous work and to screen a large number of catalyst-coated fabric samples.

Prior to initiating the experimental effort, a bench-scale experimental system was designed and constructed for catalyst-coated fabric-screening tests. The fabric filter holder was designed to be housed in an oven and hold a 0.8-ft^2 sample of catalyst-coated fabric. The operating procedure for the bench-scale experimental system involved heating the oven to 650°F with nitrogen flowing through the system. Once the oven was heated, the CO_2, H_2O, and O_2 levels were set at 15%, 5%, and 5% by volume, respectively. The SO_2 was then adjusted to the desired level. For the initial bench-scale experiments performed, SO_2 levels ranged from 300 to 3000 ppm. Flow rates for NO were adjusted to achieve a concentration of about 300 to 1000 ppm. Once all the flue gas constituent levels had stabilized, the ammonia was added to achieve ammonia-to-NO_x molar ratios ranging from 0.6 to 1.2. System temperatures, along with flue gas data, were monitored continuously and recorded every 2 minutes using a Kaye data logger. In most cases, 4 hours of data was collected for each set of experimental conditions. A schematic of the bench-scale experimental system is presented in Figure 1-4.

During the period April 1988 through June 1989, numerous bench-scale experiments were completed (11). Results from the initial experiments were poor, with only 10% to 30% NO_x reduction observed. After a thorough review of the system and the experimental procedure and discussions with OCF personnel and others, the EERC determined that the poor results were caused by the decomposition of the silicone gasket material used to seal the filter holder. At 650°F, the silicone gasket material decomposed into silicon dioxide and D8 and D4 siloxanes, which reacted with the catalyst, permanently reducing its reactivity. Based on this observation, the EERC believes that

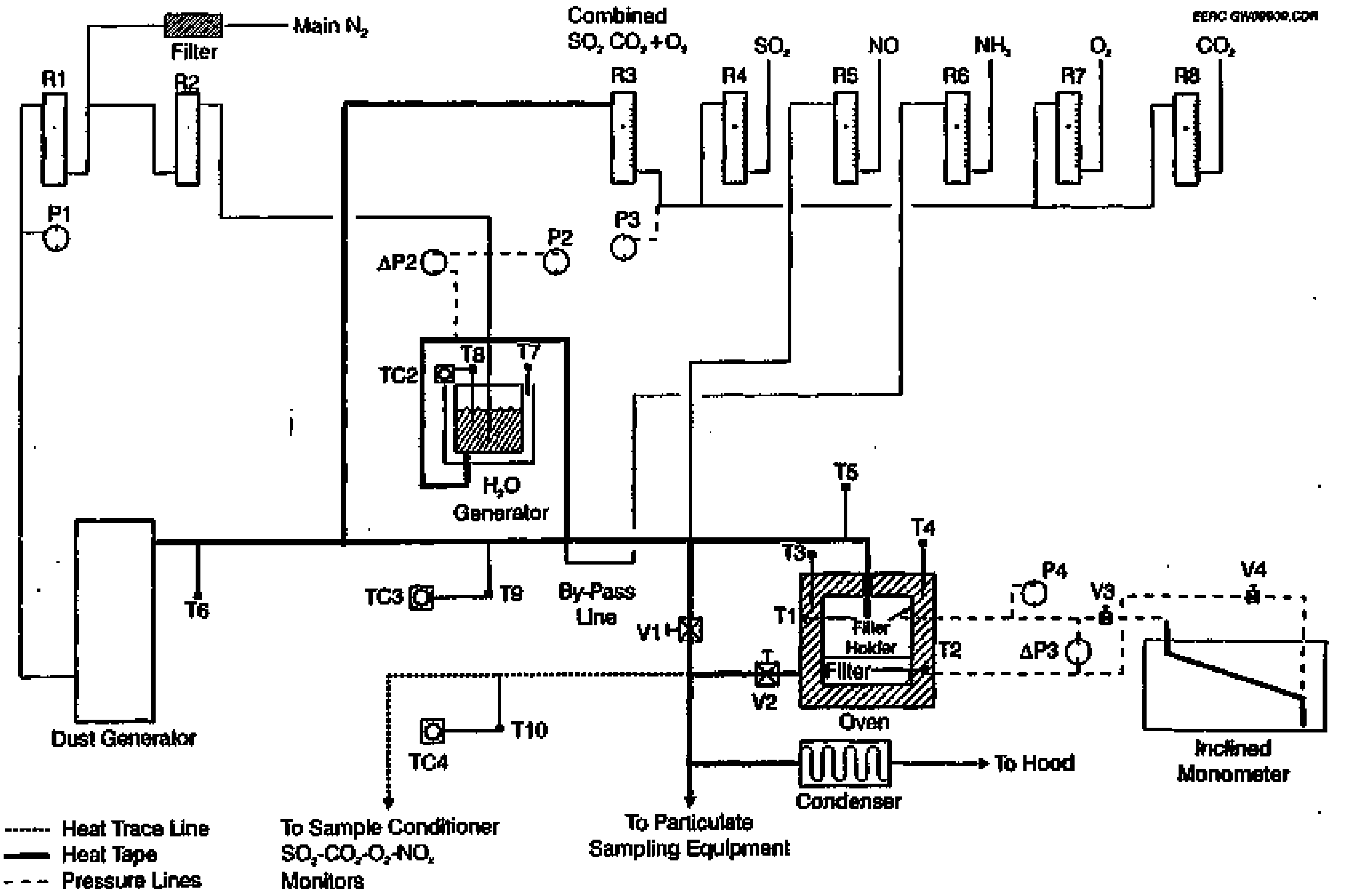

Figure 1-4. Bench-scale experimental system for screening catalyst-coated fabric samples.

results from bag tests performed in 1986 were affected by the silicone gasket material used to seal the pilot-scale baghouse.

An experimental test matrix completed in March 1989 demonstrated NO_x reduction in the range of 58% to 92% for a single fabric and a range of operating conditions. The statistically designed experimental matrix evaluated the significance of parameters such as flue gas SO_2 and NO_x concentration, ammonia-to-NO_x molar ratio, and air-to-cloth ratio. Temperature was not included as an independent parameter in this series of experiments, since it had been shown to have a significant effect on NO_x reduction during initial OCF work. Results from this experimental effort demonstrated that flue gas NO_x concentration, air-to-cloth ratio, and the interaction of these two parameters have a significant impact on NO_x reduction. Results from these tests demonstrated continuity with previous work completed by OCF and the EERC.

A second series of bench-scale catalyst-coated fabric-screening experiments was completed in May 1989. Each of sixteen fabric samples was evaluated in terms of NO_x reduction, ammonia slip, and SO_3 production. The operating conditions at which each fabric sample was tested are presented in Table 1-5. Replicate experiments were performed to determine data variability. For individual fabric samples, NO_x reduction ranged from 3% to 93%, with ammonia slip values ranging from 2 to 340 ppm. SO_3 concentrations downstream of the catalyst-coated fabric samples ranged from 4 to over 200 ppm. Previous work sponsored by OCF had not shown that oxidation of SO_2 to SO_3 would be a problem. It is possible that the high SO_3 concentrations measured during bench-scale tests using simulated flue gas were an artifact of the experiments. Subsequent experiments using flue gas from a pc-fired pilot-scale combustion system demonstrated SO_3 levels downstream of the catalyst-coated fabric filter to be <15 ppm. Because of the potential operability problems associated with the production of SO_3, the EERC monitored SO_3 concentrations downstream of the catalyst-coated fabric filter samples during most bench-scale tests and during all of the subsequent pilot-scale tests completed.

TABLE 1-5

Operating Conditions for Catalyst-Coated Fabric-Screening Experiments

Temperature, °F	650
NO_x, inlet concentration, ppm	800
SO_2, inlet concentration, ppm	300
Vol% O_2	5
Vol% H_2O	5
Vol% CO_2	15
Air-to-Cloth Ratio, ft/min	2
Ammonia-to-NO_x Molar Ratio	0.9
Test Duration, hr	4

Eight of the sixteen catalyst-coated fabrics were screened a second time using the bench-scale experimental system as a sample system in conjunction with a pilot-scale, pc-fired combustion system. This approach allowed testing of the fabric samples under actual flue gas conditions. It was critical that the fabric be tested in an actual flue gas stream produced from the combustion of coal, since submicron particles, volatile species, and trace elements that may affect the catalyst would be present. Testing in a simulated flue gas stream with reentrained fly ash would not produce the same effect, since volatile species would not be present, and submicron fly ash particles are not easily reentrained as separate particles.

This series of tests involved the use of four different coals: two eastern bituminous coals, a western subbituminous coal, and a lignite. Dependent variables measured included NO_x reduction, ammonia slip, SO_3 production, and particulate collection efficiency. This approach allowed testing of a maximum number of fabric samples in an actual flue gas environment at a minimum cost. Since the bench-scale fabric filter holder/slipstream sampler could test fabric samples of 0.8 ft^2 in size, the cost of making multiple sets of full bags was avoided. This experimental test series was initiated in late 1989 and was completed in early 1990. The results of these catalyst-coated fabric-screening experiments were the basis for the selection of catalyst-coated fabrics used to manufacture catalyst-coated filter bags for pilot-scale experiments.

Results from this series of bench-scale experiments identified five catalyst-coated fabric samples with sufficiently high catalyst reactivity (80% to 90% NO_x reduction and <25 ppm ammonia slip) to warrant further testing (12, 13). Other observations included that for the short duration of each test period (8 hours), there was no apparent change in catalyst reactivity and NO_x reduction decreased significantly with increasing air-to-cloth ratio. Specifically, for the fabric samples tested in the bench-scale system, the maximum air-to-cloth ratio at which 85% to 90% NO_x reduction was achieved was 3 ft/min. Figure 1-5 presents results for one of the more reactive catalyst-coated fabric samples tested.

These bench-scale tests also attempted to determine the effect of coal type on catalyst-coated fabric performance. Although three of the coals, the two bituminous coals and the subbituminous coal, resulted in similar catalyst-coated fabric performance, there appeared to be a decrease in NO_x reduction for the lignite. This is believed to have been caused by pinhole formation in the dust cake, resulting in gas channeling and limited contact between the flue gas and catalyst. Since the distribution of flue gas through the catalyst-coated fabric is dictated by the fuel-specific characteristics of the dust cake on the fabric surface, fuel impacts on NO_x reduction and ammonia slip would be expected. These effects are best demonstrated during pilot-scale and demonstration tests of significant duration allowing for an equilibrium to be achieved between dust cake development and release as a result of multiple bag-cleaning cycles.

Analysis of catalyst-coated fabric samples before and after exposure to flue gas has shown that there is a decrease in both the quantity of catalyst on the fabric and the total surface area. However, the percentage decrease in surface area is greater, indicating that a high percentage of the total reactive sites is located at or near the surface of the catalyst coating. Therefore, the catalyst coating is not highly porous, or the porosity decreases as a result of exposure to flue gas. Figure 1-6 illustrates NO_x reduction versus surface area and catalyst concentration for several catalyst-coated fabric types. A

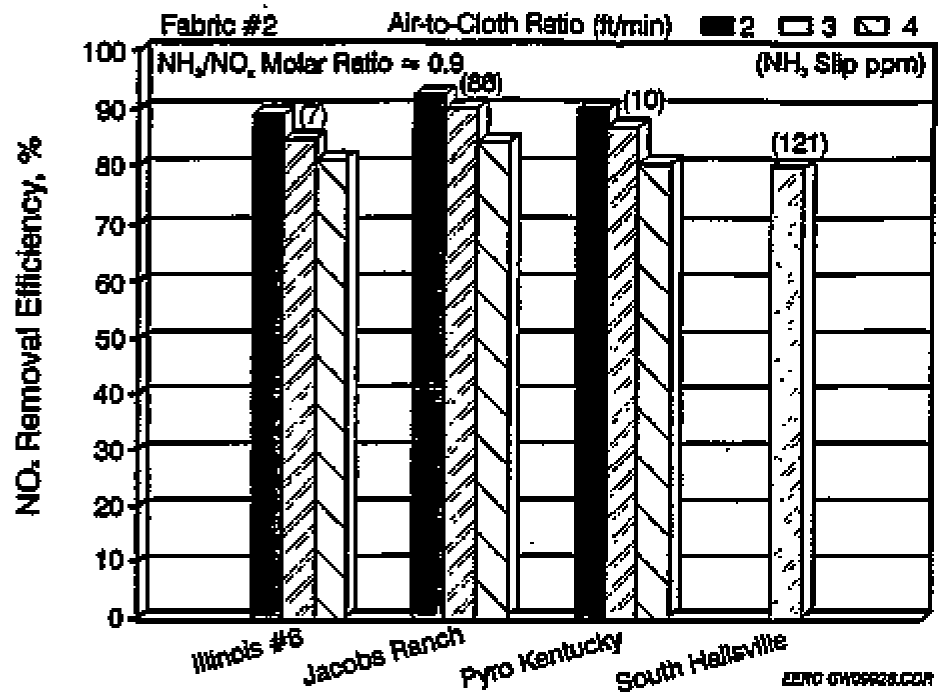

Figure 1-5. NO_x removal efficiency versus air-to-cloth ratio and coal type.

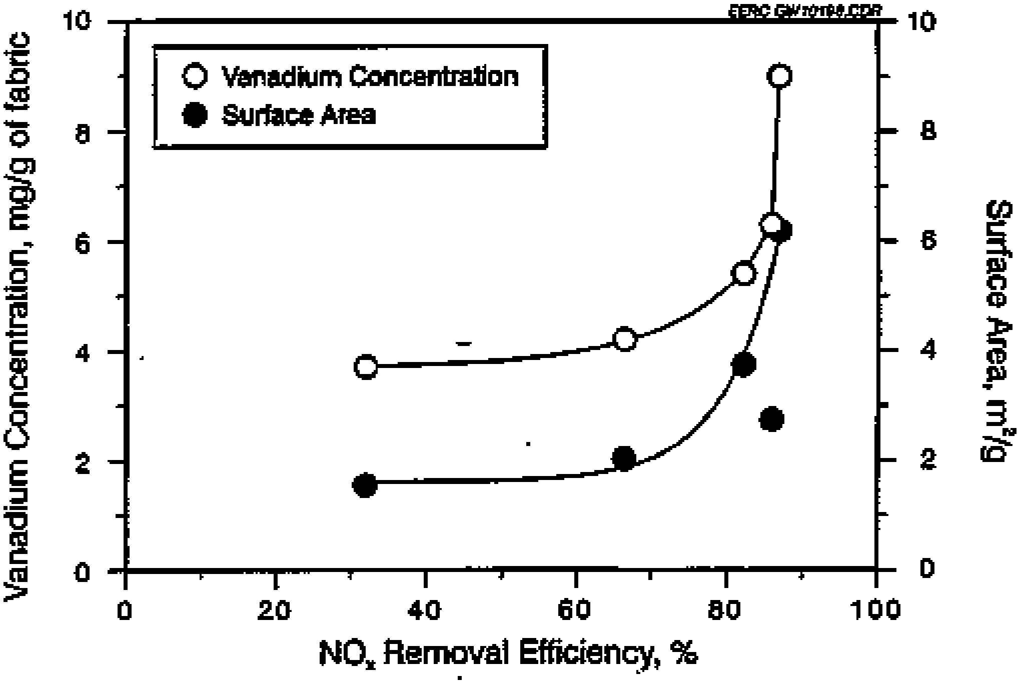

Figure 1-6. NO_x removal efficiency versus surface area and catalyst concentration.

minimum surface area of 4.5 to 5 m^2/g of fabric and a vanadium concentration of 6.5 to 7 mg/g of fabric appear necessary to provide good fabric reactivity. Therefore, it would be beneficial to maximize the surface area of the catalyst and the catalyst concentration on the fabric within processing and economic constraints.

1.2.5 Catalyst Deactivation

Performance of the catalyst-coated fabric can be decreased in two ways: by a physical defect such as a hole in the fabric or physical blinding of the fabric weave and by catalyst poisoning from a flue gas or fly ash constituent. The bulk of SCR catalyst deactivation data from industrial experience and from pilot- and laboratory-scale studies has focused on available commercial V_2O_5/TiO_2 catalysts supported on ceramic materials. The catalyst coating tested in this project is coated on S2-glass fabric by the "sol gel" process. The OCF catalyst is vanadium/titanium based, but does not contain V_2O_5. While both types of catalyst are utilized for NO_x reduction, the exact chemical composition and structure are slightly different. This detailed information is proprietary to OCF.

The following contains a short summary of SCR catalyst deactivation data (14). SCR experience in Germany has shown that gaseous arsenic oxide or very fine arsenic oxide covered dust particles cause catalyst deactivation in wet-bottom boiler flue gases upstream of the air preheater where concentrations are about 100 times higher than in dry-bottom boiler flue gas. Since arsenic concentrations in European coal ashes are higher than in most American coal ashes, arsenic poisoning is not of great concern in the United States. The arsenic deactivation mechanism begins with vaporization of arsenic in the combustion chamber followed by condensation and absorption of gaseous arsenic oxide on fly ash particles, which then deposit on the catalyst surface.

Arsenic oxide preferentially condenses in the smallest pores of the catalyst, physically blocking gas flow and causing chemical attack of the catalyst, as has been characterized by infrared spectroscopy. One abatement measure is to add limestone to the wet-bottom boiler to simultaneously improve slag flow characteristics as well as bind gaseous arsenic oxide and other volatile metals.

Post-flue gas desulfurization (FGD) SCR pilot plant tests were conducted on a medium-sulfur coal with two V–Ti catalysts: an extruded homogeneous catalyst, and a composite catalyst in a parallel-flow honeycomb design (15). These tests showed that silicon, sodium, potassium, phosphorous, and sulfur penetrated the catalyst-coated surface, while calcium and iron remained concentrated at the surface. While compounds containing these ions are normally solid at these process temperatures, the contamination showed patterns consistent with vapor or liquid deposition and also liquid mobilization of solid-phase contaminants. Dissolved species in the SO_2 scrubber mist upstream of the SCR and exposure to moisture from ambient air during shutdowns were two likely sources of the vapor and liquid phases. Other data from these tests pointed to loss of catalyst reactivity by poisoning rather than by catalyst degradation. It can be concluded from these data that exposure to moisture has a significant negative impact on the V–Ti catalysts.

The presence of SO_2 in the flue gas can have both a promoting and poisoning effect on V–Ti catalysts depending upon the chemical composition and structure of the catalyst, binder, and support (16). Tests conducted with several deactivation agents, in the absence of SO_2, showed the strongest poisons were KCl > NaCl > K_2SO_4 > Na_2SO_4, but indicated that poisoning effects were nonexistent in the presence of SO_2 (17).

Much of the laboratory-scale data produced on V–Ti catalyst deactivation was done by Chen, Yang, and Buzanowski at the State University of New York at Buffalo (18). They have concluded that alkali oxides most strongly deactivate the V–Ti catalysts in the following order: Cs_2O > Rb_2O > K_2O > PbO > Na_2O > Li_2O > > CaO. One possible deactivation mechanism is the formation of alkali–vanadium oxides formed by acid–base reactions causing changes in surface properties (19). As_2O_5 and P_2O_5 were considered weaker deactivation agents than the other common alkalies. One explanation for the more apparent SCR poisoning by arsenic, especially in wet-bottom boilers, is that while the other alkali components are captured as slag, arsenic vaporizes into the flue gas. However, alkali constituents still make up a significant part of the composition of fly ash, especially the fine particulates (20). Alkali chlorides were shown to be less deactivating than the corresponding alkali oxides. It was concluded that the chlorine atom had a strong promoting effect and that NaCl in small amounts had a promoting effect. Hydrogen chloride was shown to be a strong deactivation agent at 300°C and less so at 350°C. The HCl reacted with the NH_3 to form NH_4Cl and also produced a red-brown liquid, VCl_4, and a green liquid, VCl_2. At 300°C, the NH_4Cl formation rate was greater than its sublimation rate; whereas, at 350°C, the sublimation rate was greater, accounting for the greater decreased reactivity at 300°C.

Chen, Yang, and Buzanowski describe the V_2O_5 SCR reaction mechanism as an Eley-Rideal type that occurs stepwise with 1) chemisorption of NH_3 on a Brønsted acid site, binding of NO to the chemisorbed NH_3 desorption of N_2 and H_2O, followed by oxidation of a surface hydroxyl group to a vanadyl group. It has been shown that the SCR activity is directly related to the Brønsted acidity of the V_2O_5 catalyst. Even though water is a product of the SCR reaction, the effect of accumulated adsorbed water vapor on SCR reactivity is to weaken the Brønsted acidity and hence weaken the SCR reactivity. Comparison of poisoned catalysts, both dry and wetted, validated this concept. In cases where SO_2 had a promoting effect, it was attributed to SO_2 increasing the Brønsted acidity of the surface.

1.2.6 Abrasion Resistance

While catalyst reactivity is the focus of development for the catalyst-coated filter bag, the durability of the woven fabric is also critical. Because of the higher (600° to 750°F) operating temperature of the bags, conventional Teflon coatings for abrasion resistance cannot be utilized. Therefore, other high-temperature abrasion-resistant coatings had to be developed.

Nextel 312, manufactured by 3M Company, has been used in high-temperature filtration applications, and its abrasion resistance appears acceptable (21, 22). Nextel was used as a standard against which OCF candidates for abrasion-resistant cloth were compared. The method of comparison was the room-temperature MIT flex test, in which a cloth is repeatedly folded until failure occurs. Results are reported as the number of cycles to failure. For comparison, Table 1-6 presents the MIT flex numbers for Nextel and a catalyst-coated woven fabric. Results are reported for both as-received samples and heat-treated (8 hours at 650°F) cloths. For both cases, the catalyst-coated fabric appeared to perform better than Nextel.

TABLE 1-6

MIT Flex Data for Catalyst-Coated S2-Glass and Nextel Fabrics
(reported as number of cycles to failure)

Sample	As-Received	Heat-Treated (8 hr at 650°F)
Catalyst-Coated S2-glass	140	135
Nextel	32	25

In a program completed at the EERC, Nextel fabric was tested for over 16,000 hours in a nine-bag slipstream baghouse without bag failure (23). This shows that a high-temperature fabric can sustain long-term operation when filtering coal fly ash. Since the catalyst-coated woven fabric performed better than the Nextel fabric in the MIT flex tests, it is expected that the catalyst-coated fabric life would be at least as good as the Nextel fabric.

2.0 SCOPE OF WORK

Development of the catalytic fabric filter concept required further evaluation of air-to-cloth ratio effects, ammonia slip, SO_2 oxidation to SO_3, temperature cycling, catalyst-coated fabric preparation, fuel impacts, fabric cleaning (reverse-gas versus pulse-jet), catalyst life (poisoning and resistance to erosion), and filter performance and life (particulate control, differential pressure, and durability). The specific approach used to address these issues is represented by the following:

Task 1 – Program Definition
Task 2 – Design and Construction of Test Unit
Task 3 – Experimental Program and Data Reduction
Task 4 – Conceptual Design and Economic Evaluation
Task 5 – Test Unit Removal

Task 1, Program Definition, required preparation of a project management plan. This document contained a detailed scope of work, project schedule, project budget; identified key project personnel; and presented the quality assurance/quality control (QA/QC) plan for the project.

Task 2, Design and Construction of Test Unit, was divided into three subtasks: Subtasks 2.1 and 2.2 involved the detailed design of the test facility, the construction of the test facility, and shakedown of the system prior to initiating the experimental effort. Subtask 2.3 involved OCF's preparation of the catalyst-coated fabric filters that were to be evaluated.

Task 3, Experimental Program and Data Reduction, had four subtasks. Subtask 3.1, Fundamental Testing, was a support effort to the primary experimental test plan. This effort was intended to supply information needed to understand the process mechanism thoroughly, allow screening of additional fabric samples, address the issue of catalyst poisoning, and generally support the pilot-scale effort. Subtask 3.2, Process Testing/ Reverse-Gas System, was intended to evaluate process performance in a pilot-scale reverse-gas fabric filter, identify and optimize important process variables, and provide data for a conceptual design. Subtask 3.3, Process Testing/Pulse-Jet System, evaluated process performance in a pilot-scale pulse-jet fabric filter. Subtask 3.4, Fabric Durability Testing/Pulse-Jet System, evaluated catalyst-coated fabric durability and performance in a slipstream pulse-jet baghouse.

Based on the results of Task 3, a technical and economic assessment of the catalytic fabric filter concept, Task 4, Conceptual Design and Economic Evaluation, was completed. Task 5, Test Unit Removal, required the identification of all major test facilities, equipment, instruments, and hardware and their condition, ownership, and proposed disposition.

The EERC, as the primary contractor for the project, was responsible for the management and direction of all technical and administrative project activities. The EERC performed all work associated with Task 1, Subtasks 2.1 and 2.2, Task 3, and Task 5.

OCF performed and/or supervised all work associated with Subtask 2.3, including manufacturing the S2-glass fabric, coating the fabric, and manufacturing the filter bags for the reverse-gas and pulse-jet systems. This effort, as well as technical support, was provided by OCF as a cost share to the project.

RE&C, as a subcontractor to the EERC, provided technical support for Task 1 and performed Task 4. EERC and OCF personnel involved in Task 3 provided input to RE&C Task 4 activities.

The project schedule was based on a start date of October 1, 1990, and originally assumed a project duration of 36 months. Therefore, the planned project completion date was September 30, 1993. Because of delays encountered in completing Subtask 3.4, a request was made and approved to extend the project completion date through August 31, 1994. The 11-month extension permitted the continuation of Subtask 3.4 into December 1993 and allowed participation in a July 1994 contractors' review meeting at no additional cost to the project sponsors.

2.1 Task 1 – Program Definition

Task 1, Program Definition, was initiated in early October 1990 shortly after the contract was signed by the U.S. DOE and UND. Specific activities associated with Task 1 included preparation of the Project Management Plan, which included a Project Work Plan. Following submission of the Project Management Plan in November 1990, a project kickoff meeting was held in Pittsburgh in December 1990.

In addition to the Project Work Plan, the Project Management Plan presented information describing administrative systems in place at UND that assisted the EERC Project Manager with day-to-day project management. These management and administrative systems addressed general organization, accounting, budgeting, auditing, security, health and safety, personnel, legal, procurement, data processing, property management, and subcontractor controls.

The Project Work Plan included a scope of work, milestone schedule, cost plan, labor plan, project work chart identifying key personnel and company affiliation, and a QA/QC program. The Project Work Plan was intended to be detailed enough to explain thoroughly the methods and procedures used to accomplish the goals and objectives of each task or subtask. Changes to the Project Work Plan were recommended by the EERC Project Manager when necessary and then implemented upon approval by the DOE Project Manager. Therefore, the Project Work Plan was used as a dynamic document.

EERC personnel consulted with OCF and RE&C personnel during the preparation of the Project Work Plan with respect to their performance of Subtask 2.3 and Task 4, respectively.

OCF involvement in Task 1 was critical for planning and scheduling the preparation of the catalyst-coated bags that were used during the experimental phase of the project. Coordination of subtasks within Task 2 was necessary to ensure that the construction of the test unit and preparation of the catalyst-coated bags were completed within the same time frame to avoid a delay in Task 3 activities.

RE&C involvement was necessary during Task 1 to ensure that the appropriate data was collected during Task 3 to permit a proper economic evaluation in Task 4. To accomplish this, RE&C personnel reviewed the Project Work Plan to ensure that the experimental program as outlined would provide the information needed.

Figure 2-1 illustrates the approach to completing the work as well as key decision points. Although Tasks A and B were performed within a previous EERC/DOE Cooperative Agreement, they were the development steps upon which this project was based. Early bench-scale results met the goal of 90% NO_x reduction and <25-ppm ammonia slip (12). Therefore, the decision was made to proceed with the pilot-scale development effort (Tasks 1 through 5). Task 1 was completed in January 1991, when the Project Management Plan, including the Project Work Plan, was approved in writing by the DOE Project Manager.

2.2 Task 2 – Design and Construction of Test Unit

All experimental activities associated with the project were performed using facilities on-site at EERC or other UND locations. Although much of the equipment/facilities required to successfully complete the planned effort were already available at the EERC, it was necessary to upgrade some of the existing equipment (flue gas instrumentation, the data acquisition system, and a reverse-gas baghouse) and construct a new reverse-gas baghouse and a new pulse-jet baghouse. The preliminary test unit design for Subtask 2.1 was submitted for review and approved in March 1991.

During and after completion of the construction activities, the EERC disposed of all wastes in accordance with applicable federal, state, and local laws and regulations. Hazardous wastes were not a product of the construction effort; therefore, scrap metal was recycled where appropriate, and all nonrecyclable wastes were properly landfilled. If hazardous wastes had resulted from the construction effort, the EERC hazardous waste disposal policy would have been implemented.

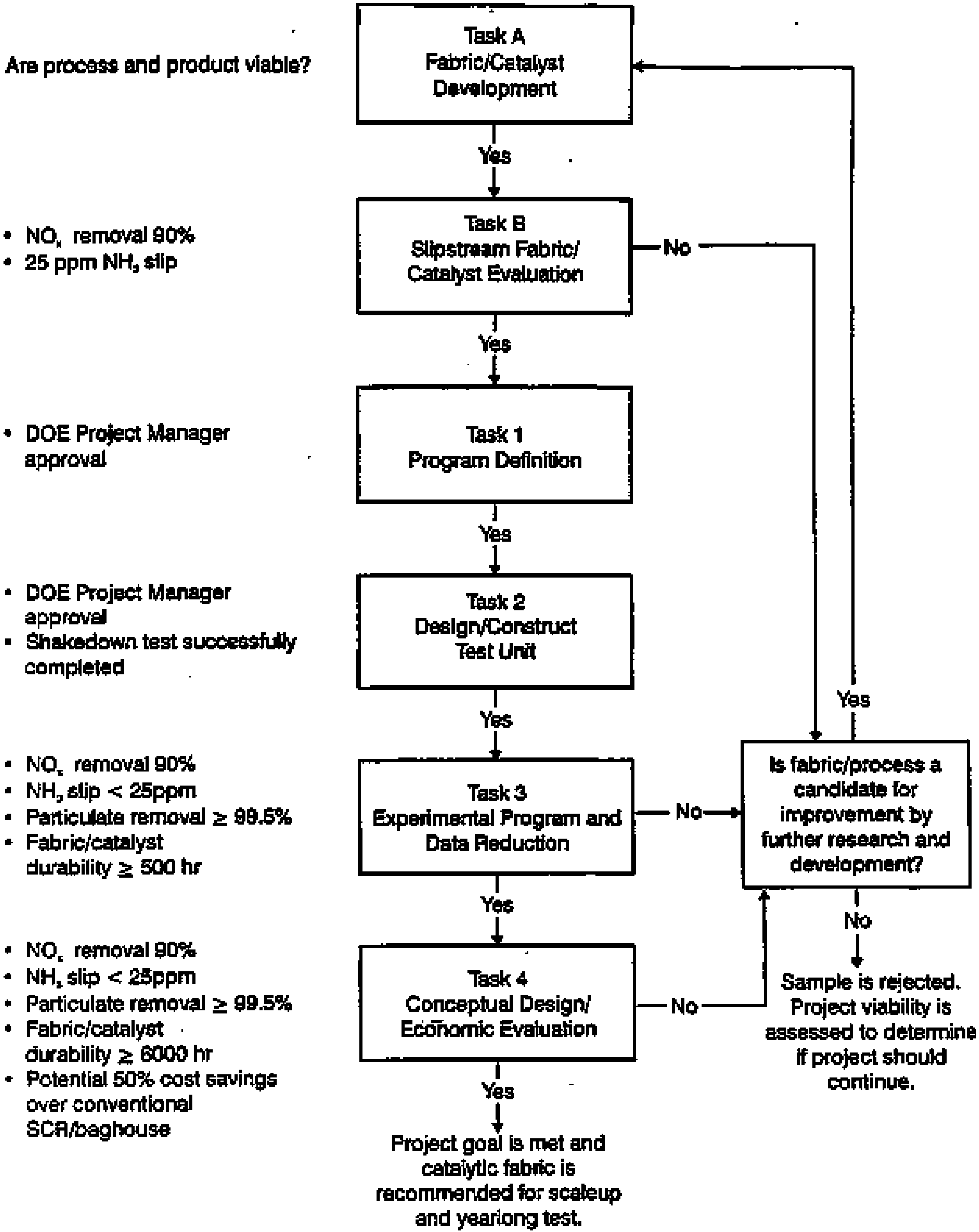

Figure 2-1. Project development logic.

Following completion of construction activities, all process equipment, process controls, flow measurement systems, instrumentation, and data acquisition systems were put through a rigorous shakedown procedure to demonstrate safe operation and develop equipment calibration and detailed operating procedures.

The final as-built drawings and equipment lists for the pilot-scale reverse-gas and pulse-jet baghouses were prepared in conjunction with the construction effort. This information, along with system operating data from the shakedown tests, was documented in the July through September 1991 quarterly technical progress. This document, entitled "Catalytic Fabric Filter Test Unit Design," is included in Appendix A.

2.2.1 Subtask 2.1 – Reverse-Gas System

Subtask 2.1, Reverse-Gas System, involved the design and construction of a reverse-gas fabric filter very similar to a device previously constructed and in use at the EERC. The reverse-gas baghouse is shown in Figure 2-2. The purpose for duplicating the existing reverse-gas chamber was to permit operation over a range of air-to-cloth ratios (1.5, 2.0, 3.0, and 4.0 ft/min) without having to slipstream a significant portion of the flue gas. This approach minimized temperature and flue gas flow control problems.

In addition to building a new reverse-gas chamber, the existing reverse-gas chamber was upgraded to permit operation in the temperature range of 500° to 750°F and minimize temperature gradients. This upgrade primarily involved installation of new electrical heaters and additional insulation to minimize heat loss. Each chamber houses a catalyst-coated filter bag approximately 12 in. in diameter by 26 ft long (25 linear feet of filtration surface), providing a total cloth area of 157 ft^2. The reverse-gas chambers used tube sheet-mounted bags and were cleaned off-line.

Flue gas sample conditioning equipment, instrumentation, and the data acquisition system were also upgraded as part of Subtask 2.1. Specific attention was paid to monitoring requirements for NO, NO_2, N_2O, SO_2, SO_3, and ammonia. The EERC had previously purchased an on-line N_2O monitor that was made available for use during the experimental phase of the project (Task 3).

Acquisition of an on-line ammonia monitor had a high priority. Although commercially available instrumentation was not readily available, several companies were developing instruments, and their progress was monitored. In March 1991, an on-line ammonia analyzer was ordered from Siemens Energy & Automation, Inc. A detailed description of the analyzer and support components is presented in Appendix A. Instrumentation was already available to adequately monitor NO, NO_2, O_2, SO_2, CO_2, and CO; therefore, no instrument upgrades for these flue gas constituents were required. Measurement techniques for SO_3 and NH_3 involved wet chemistry methods in addition to the on-line NH_3 analyzer.

The available data acquisition system, with the exception of a computer, was adequate to meet the needs of the project. Therefore, the only upgrade was the acquisition of a new computer for on-line data acquisition and off-line data editing and reduction. The computer and peripherals had sufficient capability to meet all data acquisition, storage, and reduction needs. Subtask 2.1 was federally funded, and all procurement, construction, and installation activities were performed by EERC personnel with input from OCF and RE&C personnel.

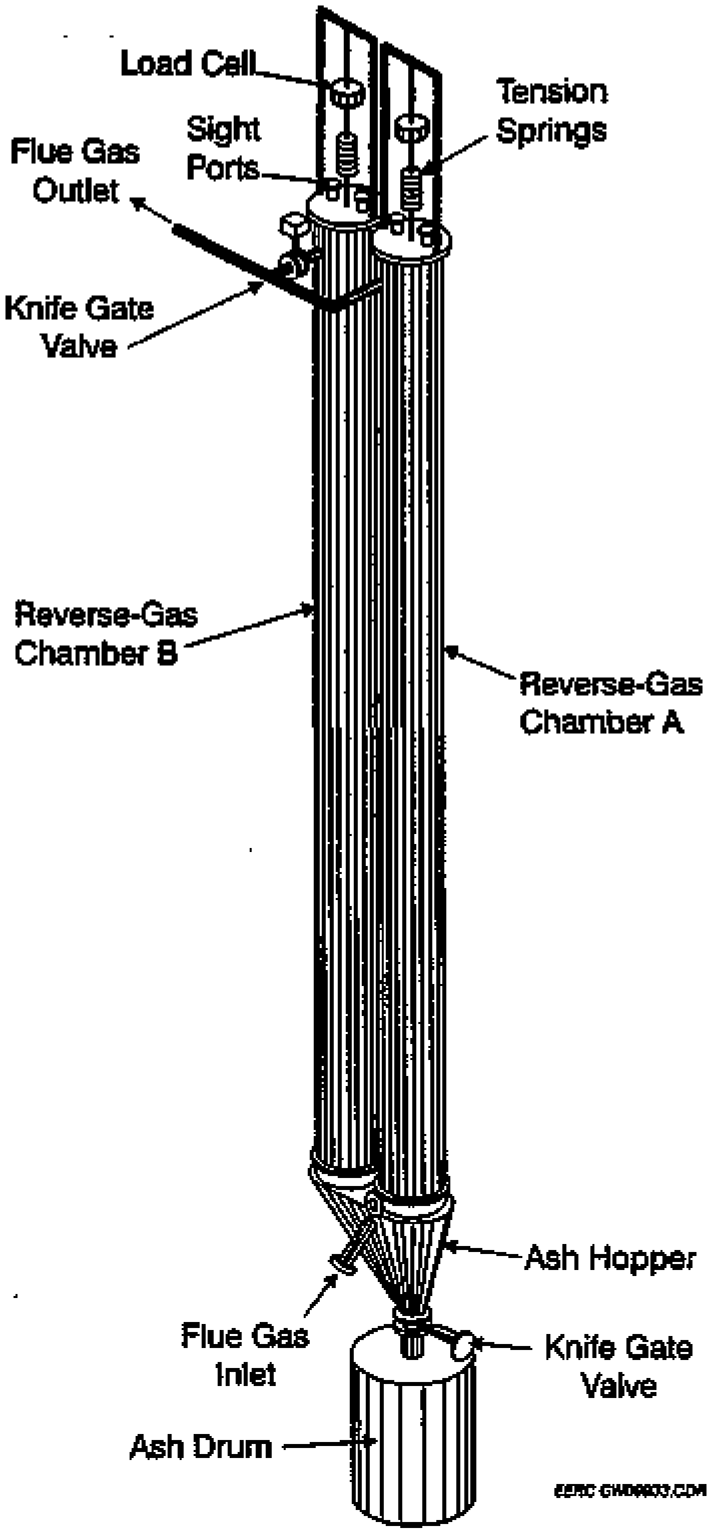

Figure 2-2. Reverse-gas fabric filter chambers.

2.2.2 Subtask 2.2 – Pulse-Jet System

Subtask 2.2, Pulse-Jet System, involved the design and construction of a pulse-jet fabric filter system for use in Subtask 3.3, as well as for filtering the flue gas during off-line cleaning of the reverse-gas system. Pulse-jet fabric filtration technology has been applied primarily to industrial systems; however, interest has developed recently in its application to utility boiler systems, specifically for cases where existing electrostatic precipitators (ESPs) are only marginally effective in meeting particulate control requirements. Construction of a new pulse-jet fabric filter system was necessary to obtain adequate temperature control over the range of interest (500° to 750°F) and to operate at the appropriate range of air-to-cloth ratios (2, 3, 4, and 6 ft/min), with minimal flue gas flow rate adjustments and slipstreaming. The pulse-jet fabric filter houses twelve bags, 6 in. in diameter by 8.25 ft long (8 linear feet of filtration area), providing a total cloth area of 151 ft^2. The pulse-jet system is a single compartment capable of cleaning both on-line and off-line. Figure 2-3 is a schematic of the pulse-jet baghouse. An important feature of the pulse-jet baghouse is its ability to effectively seal off individual bags in order to adjust the air-to-cloth ratio on-line.

An existing fabric filter device at the EERC was dismantled to make room for the new pulse-jet baghouse. Parts salvaged from the existing unit were used in the construction of the new pulse-jet baghouse as well as the new reverse-gas baghouse to minimize the cost of construction. Subtask 2.2 was commercially funded, and all procurement, construction, and installation activities were performed by EERC personnel with input from OCF and RE&C personnel.

2.2.3 Subtask 2.3 – Catalytic Fabric and Filter Bag Preparation

Subtask 2.3, Catalytic Fabric and Filter Bag Preparation, involved the preparation of catalyst-coated fabric for use in the experimental phase of the project. This work was done by or under the direction of OCF personnel. Specific activities included manufacturing the high-temperature S2-glass fabric, coating the fabric for abrasion resistance, coating the fabric with catalyst, and manufacturing the filter bags for the reverse-gas and pulse-jet baghouses. Table 2-1 presents a summary of the number and type of filter bags prepared in support of the project. A more detailed discussion of catalyst-coated fabric and bag characteristics is presented in the discussion of experimental results. Subtask 2.3 activities were funded by OCF.

2.3 Task 3 – Experimental Program and Data Reduction

Task 3 was divided into four subtasks. Subtask 3.1, Fundamental Testing, was a bench-scale support effort to the primary experimental program. This subtask involved experiments required to answer technical questions concerning the process mechanism, investigate factors that may affect catalyst life, and screen additional fabric samples developed by OCF.

Subtask 3.2, Process Testing/Reverse-Gas System, included the bulk of the pilot-scale experimental effort. This subtask involved twelve 100-hr test periods, one 500-hr test period, and four 1- to 2-day test periods. Each of the 100-hr test periods was performed while coal was fired and catalyst-coated filter bags were evaluated in a pilot-scale reverse-gas baghouse. The shorter test periods involved firing either natural gas or coal. Based

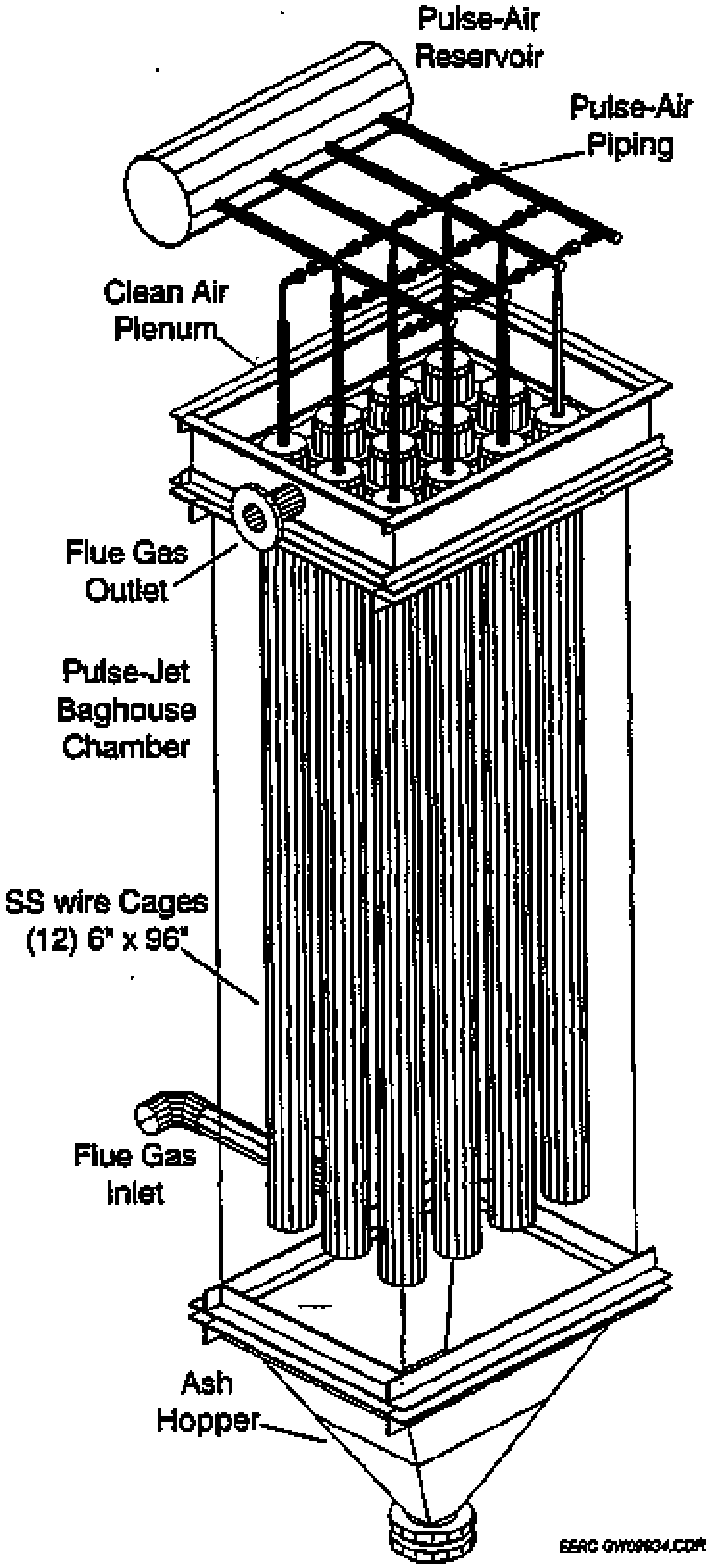

Figure 2-3. Pulse-jet fabric filter chamber.

TABLE 2-1

Catalyst-Coated Filter Bags Prepared for Catalytic Fabric Filter Project

	Reverse-Gas Bags[a]	Pulse-Jet Bags[b]
Task 1	–	–
Task 2[c]	3	12
Subtask 3.1[d]	–	–
Subtask 3.2	24	–
Subtask 3.3	–	82
Subtask 3.4[e]	–	–
Task 4	–	–
Task 5	–	–
Total	27	94

[a] Reverse-gas filter bags were 12 in. in diameter by 26 ft long and had a fabric weight of 14 or 22 oz/yd^2.

[b] Pulse-jet filter bags were 6 in. in diameter by 8.25 ft long and had a fabric weight of 22 oz/yd^2.

[c] Filter bags used for Task 2 equipment shakedown were not catalyst-coated. Pulse-jet filter bags used in Task 2 were also used during Subtask 3.2 to filter flue gas when the reverse-gas system was bypassed for cleaning.

[d] Although no filter bags were required, samples of catalyst-coated fabric were prepared in order to complete appropriate bench-scale experiments.

[e] Catalyst-coated bags used during a 100-hr pulse-jet test (Subtask 3.3) were subsequently used for Subtask 3.4.

on the results obtained during the 100-hr reverse-gas and pulse-jet tests, the 500-hr reverse-gas test was replaced with a 500-hr pulse-jet test.

Subtask 3.3, Process Testing/Pulse-Jet System, involved three 100-hr test periods and one 500-hr test period. Two 100-hr test periods and the 500-hr test period were performed while coal was fired. The third 100-hr test period involved oil firing. All four test periods used a pilot-scale pulse-jet baghouse to evaluate the catalyst-coated filter bags.

Subtask 3.4, Fabric Durability Testing/Pulse-Jet System, evaluated the performance of a single set of catalyst-coated filter bags in a pilot-scale pulse-jet baghouse for more than 5000 hours. The test involved slipstreaming flue gas from a stoker-fired boiler at the UND steam plant during parts of two heating seasons. The primary purpose of this activity was to determine filter bag performance (particulate control, baghouse differential pressure, and fabric cleanability) for an extended operating period.

Following completion of the Task 3 experimental effort, all used and unused catalyst-coated fabric samples and filter bags were returned to OCF for proper storage or disposal. All wastes generated as a result of the experimental program were disposed of in accordance with approved EERC waste disposal practices and applicable federal, state, and local laws and regulations.

2.3.1 Subtask 3.1 – Fundamental Testing

Subtask 3.1, Fundamental Testing, was a bench-scale support activity to the pilot-scale experimental effort. The purpose of this activity was to perform experiments necessary to answer technical questions concerning the process mechanism, as well as to support the pilot-scale test program. Additional experiments were performed to screen new fabric samples developed by OCF. Experiments were also performed using catalyst-coated fabric samples to determine the factors that may affect catalyst life. Specifically, experiments were performed to evaluate the effect of flue gas temperature on catalyst reactivity and the potential for chemical deactivation of the catalyst. A schematic of the bench-scale experimental apparatus is shown in Figure 2-4. Primary components include mass flow controllers, a tube furnace assembly, quartz glass reactors, and an NO_x analyzer. After several months of work with the bench-scale experimental system, it was apparent that modifications were necessary to obtain the range of operating conditions desired and to obtain acceptable data. The change involved replacing the tube furnace and quartz glass reactor with three stainless steel reactors housed in an electrically heated oven. Figure 2-5 illustrates the modified system. Detailed discussions of the individual systems and the experimental approach used with each are presented in subsequent sections of this report.

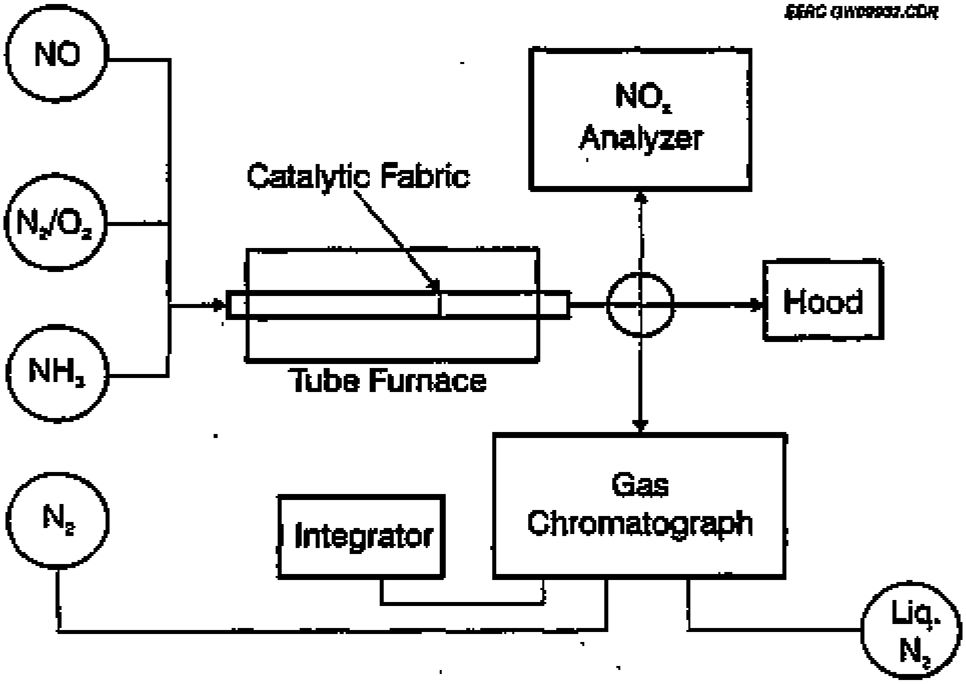

Figure 2-4. Bench-scale reactor system and gas chromatograph.

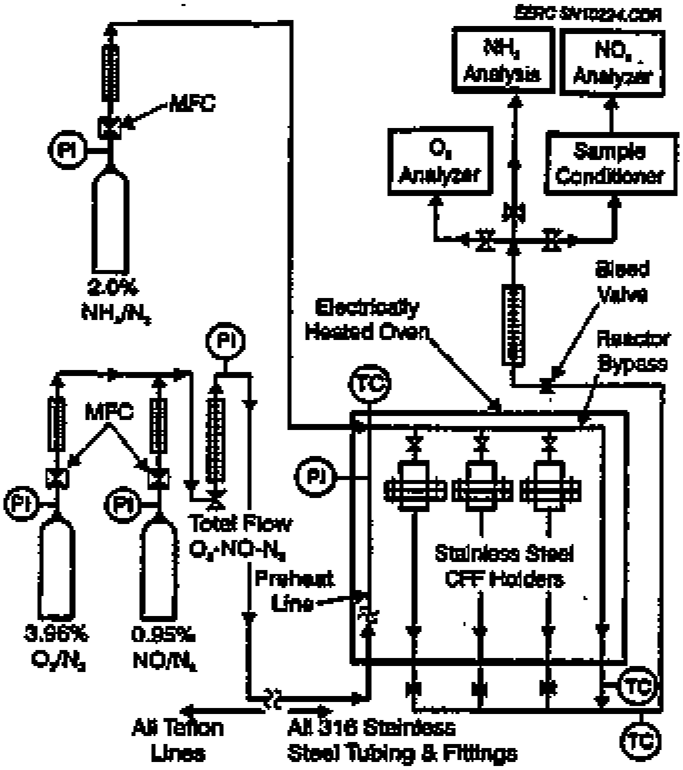

Figure 2-5. Schematic of modified bench-scale reactor system.

All bench-scale tests were performed on a simulated flue gas stream prepared from certified calibration gases. Specific flue gas components for bench-scale experiments included NO, anhydrous ammonia, O_2, and N_2. The ammonia-to-NO_x molar ratio was typically <1.0. Flue gas temperature was normally 650°F, but temperatures ranging from 500° to 750°F were used for certain experiments. Flue gas flow rates were controlled to achieve air-to-cloth ratios in the range of 2 to 6 ft/min.

Setup of the initial experimental apparatus was completed, and experimental activities were initiated in August 1991. Bench-scale experiments continued off and on through January 1994. Subtask 3.1 activities and results are discussed in Section 3.1 of this report. Subtask 3.1 activities involving EERC personnel were federally funded, and activities involving OCF personnel were funded by OCF.

2.3.2 Subtask 3.2 – Process Testing/Reverse-Gas System

Subtask 3.2, Process Testing/Reverse-Gas System, involved the bulk of the pilot-scale experimental effort, including twelve 100-hr tests, one 500-hr test, and four 1- to 2-day test periods using the pulverized coal-fired PTC. The reverse-gas fabric filter system was used for these tests with the exception of the 500-hr test, which utilized the pulse-jet baghouse. The PTC, shown in Figure 2-6, is a vertically oriented, pulverized coal-fired combustor (550,000 Btu/hr) that has been used extensively in past years and continues to be used on process development projects addressing environmental control issues. A detailed description of the PTC and its operation is presented in Appendix A.

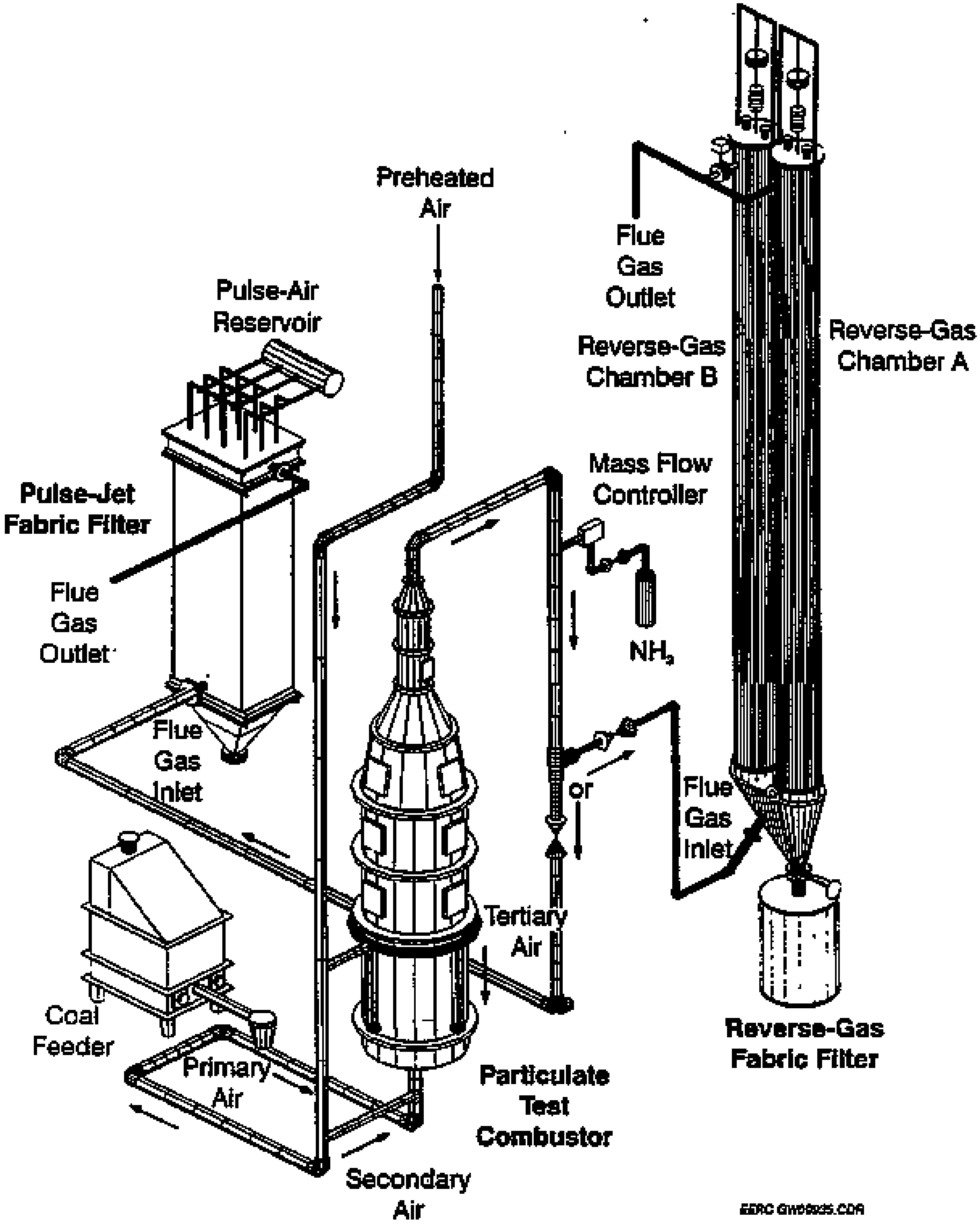

Figure 2-6. Particulate test combustor: pulverized coal-, oil-, or gas-fired at 550,000 Btu/hr.

Table 2-2 presents the test conditions for Subtask 3.2. One purpose of these tests was to evaluate the NO_x reduction capability of five catalyst-coated fabrics. The five fabrics were selected based on results from bench-scale tests completed in 1990 as part of the DOE Cooperative Agreement Flue Gas Cleanup project. Results from Subtask 3.1's bench-scale fabric screening also aided in the selection process. Each of the five fabrics was made into filter bags and evaluated during a 100-hr test period. A washed Illinois No. 6 bituminous coal was fired during each of the initial fabric tests. The baghouse temperature was maintained at 650°F and an oxygen concentration of 4.5% ± 0.5% by volume. Variable operating parameters included ammonia-to-NO_x molar ratio (0.73 to 1.4) and air-to-cloth ratio (1.3 to 4.2 ft/min), with a baseline ammonia-to-NO_x molar ratio of 0.9 and an air-to-cloth ratio of 2 ft/min.

A mass flowmeter and rotameter were used to adjust and control the ammonia injection rate into the flue gas upstream of the fabric filter. Accurate control of the ammonia was important to obtain the desired level of NO_x reduction and minimize ammonia slip.

The air-to-cloth ratio was controlled by making minor adjustments to the flue gas flow rate and using one or both of the reverse-gas chambers. Bench-scale results had previously shown that air-to-cloth ratio has a significant effect on overall NO_x reduction, ammonia slip, and the cost of the technology. Therefore, the effect of air-to-cloth ratio was thoroughly evaluated for each of the five catalyst-coated fabrics tested.

During Subtask 3.2, four different coals and natural gas were used: two eastern bituminous coals, a western subbituminous coal, and a lignite. The baseline coal was an eastern bituminous coal having a high sulfur content (a washed Illinois No. 6). Selection of four coals for testing was important to the overall evaluation of the catalyst-coated fabric. For example, it is known that coal sulfur content has an impact on SO_3 concentration in the flue gas and that chlorine present in the fuel can result in the formation of HCl in the flue gas, both of which are highly corrosive. The ash characteristics of eastern and western fuels were expected to have an effect on catalyst performance since conventional SCR experience in Europe and Japan has shown that arsenic and alkali ash components can poison SCR catalysts (24–26). In addition, fabric filter performance (particulate removal efficiency and pressure drop) has been shown to be dependent on coal type (27–29).

Flue gas temperature has been found to be an important operating parameter with respect to catalyst performance. Previous experimental work by OCF and the EERC has shown that if the flue gas temperature is too high, permanent deterioration of the catalyst will result, and if too low, NO_x reduction will not take place. Rapid changes in temperature have also been observed to decrease the activity of the catalyst-coated fabric. Two tests were designed to determine the effect of temperature on catalyst performance.

A 500-hr test was necessary to evaluate the performance of a specific catalyst-coated fabric over an extended test period. The objective of the 500-hr test was to evaluate the performance of the catalyst-coated bags with respect to NO_x reduction, ammonia slip, SO_3 production, particulate collection efficiency, baghouse pressure drop, fabric cleanability, and durability.

TABLE 2-2

Test Conditions for Subtask 3.2 – Process Testing/Reverse-Gas System

Test Number[a]	Purpose of Tests	Fabric Sample	Coal[b]	Baghouse Temperature, °F	Variable Test Parameters[c]
PTC-IL6-408	Comparative tests of five catalyst-coated fabric types	DE484	IL6	650	SR, A/C
PTC-IL6-414		DE992	IL6	650	SR, A/C
PTC-IL6-415		DE484	IL6	650	SR, A/C
PTC-IL6-416		DE484 (aqueous)	IL6	650	SR, A/C
PTC-IL6-417		G143	IL6	650	SR, A/C
PTC-IL6-418		G143	IL6	650	SR, A/C
PTC-IL6-419		DE992 (undercoat)	IL6	650	SR, A/C
PTC-NG-420		G143	NG	650	SR, A/C
PTC-NG-421		DE484	NG	650	SR, A/C
PTC-NG-422		DE484	NG	650	SR, A/C
PTC-IL6-428		DE992	IL6	650	SR, A/C
PTC-BV-423	Determine the effect of coal type on catalytic fabric performance	DE484	BV	650	SR, A/C
PTC-BT-424		DE484	BT	650	SR, A/C
PTC-BU-425		DE484	BU	650	SR, A/C
PTC-IL6-426	Determine the effect of temperature on catalytic fabric performance	DE484	IL6	500–750	SR
PTC-IL6-427		DE484	IL6	250–700 cycling	SR
PTC-BV-432	500-hr performance test	DE992	BV	650	SR

[a] Runs PTC-IL6-408 through PTC-IL6-428 were 2- to 4-day test periods using the pilot-scale reverse-gas baghouse. Run PTC-BV-432 was a 500-hr test using the pilot-scale pulse-jet baghouse.

[b] The coals used included two eastern bituminous coals (a washed Illinois No. 6 [IL6] and a Blacksville bituminous coal [BV]), a western subbituminous coal (Black Thunder [BT]), and a western lignite (Beulah [BU]). Natural gas (NG) was also used during several test periods.

[c] SR (ammonia-to-NO_x molar ratio) = 0.73 to 1.4, A/C (air-to-cloth ratio) = 1.3 to 4.2. ft/min.

In addition to NO_x reduction and ammonia slip, pressure drop and particulate emissions were important indicators of overall fabric filter performance. Pressure drop was monitored continuously using pressure transducers during each 100-hr test and the 500-hr test. At the conclusion of the each test, the bags were carefully weighed to determine residual dust cake weight, and comparisons were made to bag weights for conventional pulse-jet baghouses. Careful inspection of the bags followed each test to determine that pinholes or tears had not developed and that fraying had not occurred. This was especially important following the 500-hr test.

Particulate emissions were measured during each test period. A modified EPA Method 5 was used to determine overall particulate collection efficiency. In addition, real-time techniques (aerodynamic particle sizer [APS] and differential mobility particle sizer [DMPS]) were used to determine particulate emissions in the size range of 0.01 to 30 microns. Particle-size distribution was measured using multicyclone and Coulter counter techniques. Table 2-3 lists the particulate sampling techniques used.

Flue gas concentrations of O_2, SO_2, and NO_x were monitored continuously throughout each test at the inlet and outlet of the fabric filter to evaluate NO_x reduction. Concentrations of CO_2 and CO were monitored at the combustor exit to determine overall system operability. Continuous monitoring of ammonia in the flue gas was attempted, but the results were not acceptable. Wet chemistry techniques were used to measure ammonia and SO_3 concentrations in the flue gas at various times during each test period. Table 2-4 lists the instrumentation and sampling techniques that were used.

Samples of the catalyst-coated fabric and bulk samples of fuel and ash were characterized using standard analytical methods. The types of samples collected for analysis and the methods that were applied are listed in Table 2-5. In addition to routine ash analyses, several ash samples were collected and analyzed for vanadium to determine if the catalyst had been eroded from the catalyst-coated fabric.

Subtask 3.2 data reduction and analysis focused on flue gas data and baghouse performance data. Flue gas data were recorded continuously on circular charts and logged as a function of time using a Kaye data logger. Manual data were collected by operations personnel on a 30-minute basis as a backup to the data-logging system. Data from the data logger were downloaded directly to a computer. After completion of a run or test period, data downloaded to the computer were reviewed and edited according to identifiable equipment malfunctions or other system anomalies. For example, the flue gas sample conditioners were purged periodically during operation to remove condensed moisture. For a short period of time after purging (<5 minutes), flue gas constituent data were incorrect because of purge air entering the gas analyzers.

NO_x removal was calculated based on baghouse inlet and outlet values, corrected to 4% O_2, and reported as percent NO_x reduction. Calculated values for NO_x reduction, ammonia-to-NO_x molar ratio, ammonia slip data, and fly ash nitrogen content were compared to verify results based on the nitrogen balance. Detailed flue gas data and calculated results were presented in both graphical and tabulated formats in the quarterly technical progress reports. For weekly test and monthly status reports, general results were presented in a discussion format. Copies of the raw data downloaded to the computer during each run or test period were copied on 5.25-in. floppy disks and are available for review upon request.

TABLE 2-3

Particulate Sampling Techniques for Task 3

Sampling Technique	Sampling Location	Resulting Data
Modified EPA Method 5	Fabric filter inlet and outlet	Total mass loading/efficiency
Flow Sensor Multicyclone.	Fabric filter inlet	Total mass loading/size distribution
Aerodynamic Particle Sizer (APS)	Fabric filter outlet	Size distribution (0.5 to 30 μm) Respirable mass
Differential Mobility Particle Sizer (DMPS)	Fabric filter outlet	Size distribution (0.01 to 1.0 μm)

TABLE 2-4

Flue Gas Instrumentation and Sampling Techniques for Task 3[a]

Instrument or Sampling Technique	No. of Instruments Available	Flue Gas Constituent Measured	Sampling Location
Thermo Electron Model 10	2	NO/NO_x	Combustor Exit/Baghouse Outlet
DuPont Model 400	2	SO_2	Combustor Exit/Baghouse Outlet
Beckman Model 755	2	O_2	Combustor Exit/Baghouse Outlet
Beckman Model 864	1	CO_2	Combustor Exit
Beckman 880	1	CO	Combustor Exit
Siemens Ultramat 5E	1	N_2O	Baghouse Inlet/Outlet
Wet Chemistry			
Selective Condensation	–	SO_3	Baghouse Inlet/Outlet
Specific Ion Electrode	–	NH_3	Baghouse Inlet/Outlet
Acid/Base Titration	–	HCl	Baghouse Inlet/Outlet

[a] The EERC purchased an on-line ammonia monitor, but its performance was not acceptable.

TABLE 2-5

Solid Samples Collected and Types of Analyses Applied[a]

Sample Type	Type of Analysis
Coal	Proximate/ultimate, sulfur forms, sieve, heating value, vanadium determination
Oil	Proximate/ultimate, heating value
Coal Ash	X-ray fluorescence (XRF), vanadium determination, ash fusion temperature
Baghouse Ash	NH_3 analysis, vanadium determination, XRF, ash fusion temperature, loss on ignition (LOI), Coulter counter
EPA Filter Ash	Vanadium determination, NH_3 analysis
New Catalyst-Coated Fabric	Vanadium determination, BET surface area
Exposed Catalyst-Coated Fabric	Vanadium determination, BET surface area

[a] Scanning electron microscopy (SEM) was used as a trouble-shooting analytical tool when needed.

The EERC did not perform extensive computer modeling. Trends for dependent variables such as NO_x reduction and ammonia slip are presented graphically as a function of independent variables such as fabric type, air-to-cloth ratio, temperature, and ammonia-to-NO_x molar ratio. Subtask 3.2 was federally funded and performed in the EERC combustion pilot plant.

2.3.3 Subtask 3.3 – Process Testing/Pulse-Jet System

Subtask 3.3, Process Testing/Pulse-Jet System, involved three 100-hr tests and one 500-hr test similar to those performed in Subtask 3.2. Table 2-6 presents actual test conditions for Subtask 3.3. Results from Subtask 3.2 were used to select the catalyst-coated fabric used in Subtask 3.3. The purpose of the first two tests was to evaluate the performance of the catalyst-coated fabric in a pulse-jet system with respect to NO_x reduction, ammonia slip, SO_3 production, particulate control, baghouse pressure drop, and bag cleaning for two different coals. Variable operating parameters included the ammonia-to-NO_x molar ratio (0.6 to 1.2) and the air-to-cloth ratio (2.0, 3.0, 4.0, and 6.0 ft/min). The third test used residual oil (RO) to fire the PTC to evaluate the effect of fuel type on catalyst-coated fabric performance. The physical, chemical, and morphological characteristics of the fly ash from the three fuels were very different, providing an interesting comparison.

The fourth test was a 500-hr coal-fired test intended to evaluate catalyst-coated fabric performance (NO_x reduction, ammonia slip, SO_3 production, particulate control, baghouse pressure drop, and fabric cleanability) in a pulse-jet baghouse over an extended operating period. This test was run in a manner similar to that used in Subtask 3.2. The

TABLE 2-6

Test Conditions for Subtask 3.3 – Process Testing/Pulse-Jet System

Test Number[a]	Purpose of Test(s)	Fabric Sample	Fuel[b]	Baghouse Temperature, °F	Variable Test Parameters[c]
PTC-BV-429	Determine the effect of cleaning cycle	DE992[d]	BV	650	SR, A/C
PTC-BT-430	on catalytic fabric performance	DE992	BT	650	SR, A/C
PTC-RO-431	Determine the effect of fuel type on catalytic fabric performance	DE992	Residual Oil	650	SR, A/C
PTC-BV-434	Complete 500-hr performance test	DE992	BV	650	SR

[a] The first three tests were 100-hr tests, and the fourth was a 500-hr test. All four test periods involved pulse-jet baghouse operation.

[b] "BV" represents Blacksville bituminous coal; "BT" represents Black Thunder subbituminous coal; "RO" represents residual oil.

[c] SR (ammonia-to-NO_x molar ratio) was 0.6 to 1.2; A/C (air-to-cloth ratio) was 2 to 6 ft/min for the 100-hr tests and 3 ft/min for the 500-hr test.

[d] The DE992 catalyst-coated fabric is a 22-oz woven S2-glass fabric prepared using seven coats of a vanadium–titanium catalyst.

only variable operating condition was the ammonia-to-NO_x molar ratio (0.6 to 1.2). The air-to-cloth ratio, 3.0 ft/min, was selected based on results from the 100-hr tests.

Results from 100- and 500-hr tests were reported in weekly test reports, monthly status reports, quarterly technical progress reports, as well as the final technical report. Subtask 3.3 was commercially funded and performed in the EERC combustion pilot plant.

2.3.4 Subtask 3.4 – Fabric Durability Testing/Pulse-Jet System

Subtask 3.4 was an attempt to demonstrate the performance and durability of the catalyst-coated fabric in a pulse-jet system. The test was performed using a pulse-jet baghouse operating as a slipstream device at the UND steam plant. The baghouse housed nine catalyst-coated fabric filters 6 in. in diameter by 8 ft in length. A slipstream of flue gas was removed from a stoker-fired boiler with supplemental ash injection used to maintain an adequate ash loading at the baghouse inlet. Catalytic filter bag performance was measured in terms of durability, particulate control, fabric cleanability, and NO_x reduction potential for over 5000 hours of operation. Figure 2-7 is a schematic of the baghouse slipstream system. A more detailed discussion of the system is presented in Appendix B.

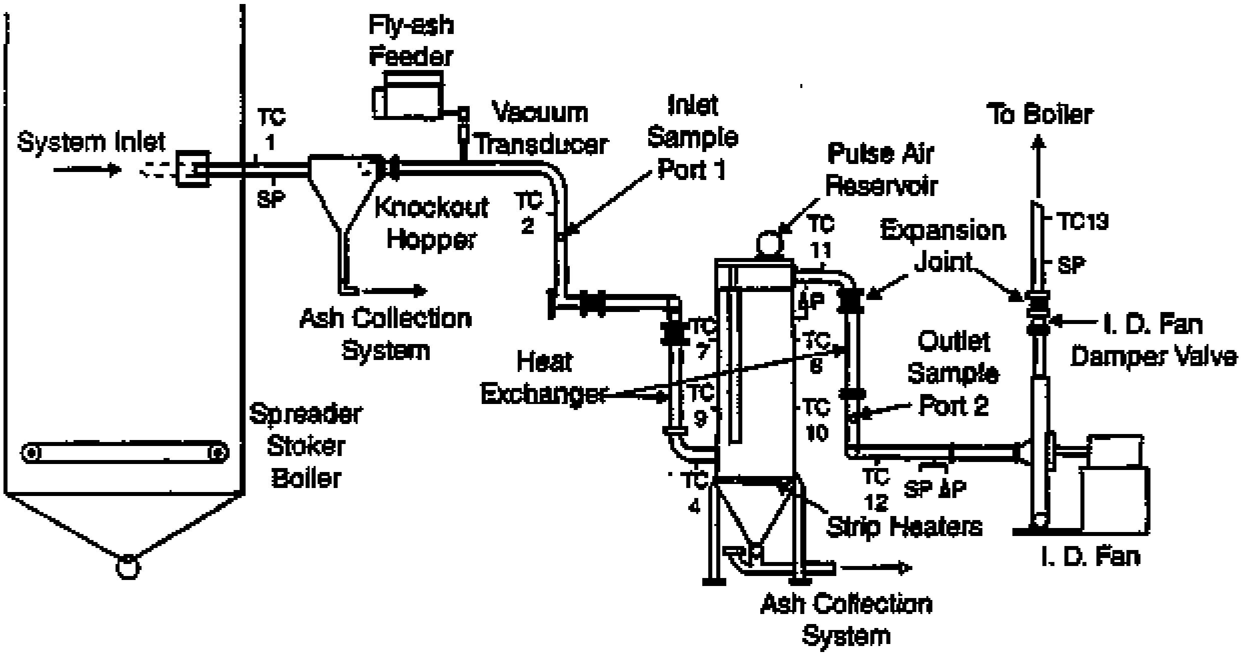

Figure 2-7. Baghouse slipstream system at UND steam plant.

Particulate emissions were measured once a month at the inlet and outlet of the pulse-jet baghouse to evaluate the catalyst-coated fabric's ability to control particulate emissions effectively. Sampling techniques were identical to those identified in Table 2-3. Baghouse differential pressure was monitored on a continuous basis to determine whether the catalyst-coated filter bags were effectively cleaned and the differential pressure controlled.

Fabric durability was determined using the MIT flex test and Mullen burst measurements of new fabric and catalyst-coated fabric samples from filter bags removed from the baghouse after 840, 1642, and 5136 hours of operation. These physical fabric characteristics were measured by OCF personnel.

The performance and durability of the catalyst-coated fabric in terms of NO_x reduction capability was evaluated by conducting a bench-scale NO_x reduction test with new fabric and fabric samples from filter bags removed from the baghouse after 840, 1642, and 5136 hours of operation. The baghouse was operated at temperatures ranging from 500° to 640°F and air-to-cloth ratios of 3 to 6 ft/min.

In order to select a catalyst-coated fabric for this subtask, it was necessary to have successfully completed at least one of the 100-hr tests planned for Subtask 3.3. Therefore, Subtask 3.4 did not begin until July 1992. Results from this activity were reported in monthly status reports and quarterly technical progress reports and are summarized in this final technical report. Subtask 3.4 was commercially funded.

2.4 Task 4 - Conceptual Design and Economic Evaluation

Based on the results of Task 3, RE&C developed a conceptual design and performed an economic evaluation of the catalytic fabric filtration process. As part of the Task 4 economic evaluation, a preliminary assessment was performed early in the project (concurrent with Task 1 activities) to identify which variables are most important from an economic standpoint. This early assessment helped focus the project to address and optimize those items that potentially drive the overall cost of the technology. This information was particularly useful in developing the Task 3 test plans.

The conceptual design and economic evaluation was based on a reference 500-MW_e greenfield plant burning high-sulfur coal, as well as a 250-MW_e plant with the catalytic fabric filtration system added as a retrofit. The format for the economics was the Electric Power Research Institute (EPRI) Technical Assessment Guide (TAG) (30).

The first step in performing the economic evaluation was to develop design criteria upon which to base a conceptual design. The design criteria were based on Task 3 results. Important design criteria for the catalytic fabric filtration process include the following:

- Bag life – 2 years
- Bag cost – developed by OCF
- Inlet NO_x level – A fixed outlet emission of 60 ppm NO_x will also set NO_x removal. Higher inlet NO_x concentration typically requires more catalyst for selective catalytic reduction technology.

- Ammonia slip – Lower ammonia slip typically requires greater catalyst quantity for selective catalytic reduction technology.

- SO_2/SO_3 oxidation – affects catalyst formulation and cost

- Air-to-cloth ratio (gross, net, services) – greatly impacts cost, typically 4 ft/min for pulse-jet

- Type of cleaning – pulse jet, intermediate pressure

- Bag diameter

- Bag length

- Bags per compartment

- Compartments per baghouse

- Number of baghouses

- Insulation thickness

- Bag spacing

Similar design criteria were also developed for conventional selective catalytic reduction technology in order to provide a benchmark from which to compare costs. Since RE&C had previously completed a project for EPRI evaluating costs for conventional selective catalytic reduction technology, this comparison was made both cost-effectively and on a consistent basis.

The next step in the evaluation was the development of process flow diagrams and material and energy balances. The process flow diagrams for this evaluation reflected the complexity of the ductwork required to operate a hot-side baghouse.

A systems description was written to reflect the process flow diagram and to describe the process. The technology was summarized and its level of development discussed and assessed. The level of process development was important for the selection of an appropriate process contingency according to EPRI guidelines.

Equipment lists were prepared reflecting new equipment for the greenfield plant and both new and modified equipment for the retrofit. The lists contain pertinent information such as equipment sizes, capacities, performance, materials of construction, and number of operating units and spares.

General arrangement drawings were prepared reflecting the layout of all major equipment items. This was particularly important for addressing requirements for both the greenfield and retrofit cases. Both a plan and elevation view were required to evaluate the ductwork requirements accurately.

The capital, operating, and maintenance costs were estimated using standard EPRI TAG guidelines. Vendor quotes were obtained for all major equipment items. Installation factors were developed by the RE&C cost estimating department. Contingencies were developed on an area basis in accordance with EPRI standards. Other costs such as preproduction costs, interest during construction, royalties, etc., were also developed in accordance with the EPRI guidelines.

Since the catalytic fabric filtration process is a combined particulate and NO_x control technology, it was necessary to develop economics for combined NO_x and particulate control (applicable to either retrofit with inadequate particulate control or a greenfield plant). The comparative economics use selective catalytic reduction for NO_x control and a cold-side pulse-jet fabric filter for particulate control.

Overall cases were estimated as follows:

	Catalytic Fabric Filter	Comparative Case
New 500-MW Plant	Costs assessed for both NO_x and particulate control	Selective catalytic reduction + baghouse
Existing 250-MW Plant (inadequate particulate removal)	Costs assessed for both NO_x and particulate control	Selective catalytic reduction + baghouse

This effort was performed by RE&C personnel with input from EERC and OCF staff involved with the project. Task 4 began after completion of the 500-hr tests. The results were documented in a separate report and are summarized in this final technical report in Section 3.5. Task 4 was federally funded.

2.5 Task 5 – Test Unit Removal

With the exception of some instrumentation upgrades, the reverse-gas baghouse (Subtask 2.1), and the pulse-jet baghouse (Subtask 2.2), all of the equipment and facilities necessary to perform the experimental program were available at the EERC. Therefore, the Task 5 effort was minimal and primarily involved preparing an equipment disposition plan, documenting ownership of equipment acquired and fabricated in Task 2, and maintaining control of the equipment until final disposition has been determined by DOE and other funding organizations. There is no site demolition anticipated.

Samples of new and used catalyst-coated fabric remaining after completion of the experimental effort were returned to OCF for proper storage or disposal. Task 5 activities performed by EERC personnel were federally funded. Catalytic fabric storage or disposal costs incurred by OCF were the responsibility of OCF.

3.0 RESULTS AND DISCUSSION

3.1 Bench-Scale Fundamental Testing

3.1.1 The Effect of Heat Treatment Temperature on Catalyst-Coated Fabric Reactivity

As part of the catalyst-coating process, an organic fugitive lubricant is added to protect the catalyst and fabric and to facilitate sewing of the bags. Therefore, to obtain optimum performance of the catalyst-coated fabric, the fabric must be heat-treated to remove the lubricant and complete catalyst curing. Since the optimum heat treatment time and temperature for each of the fabrics were unknown, bench-scale tests were completed to evaluate the effect of heat treatment on catalyst reactivity. The results of these tests were then used to select the heat treatment conditions for the catalyst-coated filter bags used in the pilot-scale tests.

In the initial bench-scale system, fabric samples were inserted into a glass tube and heated to temperature using several tube furnaces (a schematic of the initial bench-scale system is shown in Figure 2-4). The tube furnaces and glass sample holder were long enough to ensure that the gas(es) were well mixed and brought to temperature prior to coming into contact with the fabric sample. Once the desired temperature had been reached, the fabric samples were maintained at that temperature for a specified length of time. All of the heat treatment tests were done in air or in a mixture of 4% O_2 in nitrogen.

Three types of catalyst-coated fabric were tested. The first was a lightweight, 14-oz/yd^2 fabric with a single-beam weave (DE484). The second type of fabric was a heavier weight, 22-oz/yd^2 with a double-beam weave (DE992). Both of these fabrics used a DE-fiber (6.5 μm). However, the third fabric tested was woven from G-fibers that had an average diameter of 9.0 μm (G143). The weight of the G143 fabric was 14 oz/yd^2.

The results of these bench-scale heat treatment tests are shown in Figure 3-1. For each test, the air-to-cloth ratio, ammonia-to-NO_x molar ratio, and operating temperature were constant at 2 ft/min, 0.9, and 650°F, respectively. The data indicate that the general trend for each of the three fabrics was the same. In all cases, an increase in catalyst reactivity occurred from 500°–700°F. From 700°–750°F, the reactivity was relatively constant, and at heat treatment temperatures exceeding 750°F, a decrease in catalyst reactivity occurred that became significant at temperatures exceeding 800°F. Although this trend was the same for each of the fabrics, there was a difference in the catalytic reactivity of the fabrics. At lower heat treatment temperatures, the DE992 was the most effective. Once a temperature of about 750°F was reached, the DE992 and DE484 demonstrated similar levels of reactivity. For the G143 fabric, the catalyst reactivity was lower; however, no tests were made at temperatures above 800°F. It did not appear from the bench-scale tests that the catalytic reactivity of the fabrics was affected by the duration of the fabric heat treatment. Test duration ranged from 1 to 25 hours, and the results were about the same. From the bench-scale results, it was determined that prior to each pilot-scale test, the bags would be heat-treated in the pilot-scale baghouse at 700°–725°F for 4 hours using flue gas containing 2–4 vol% O_2 resulting from the combustion of natural gas.

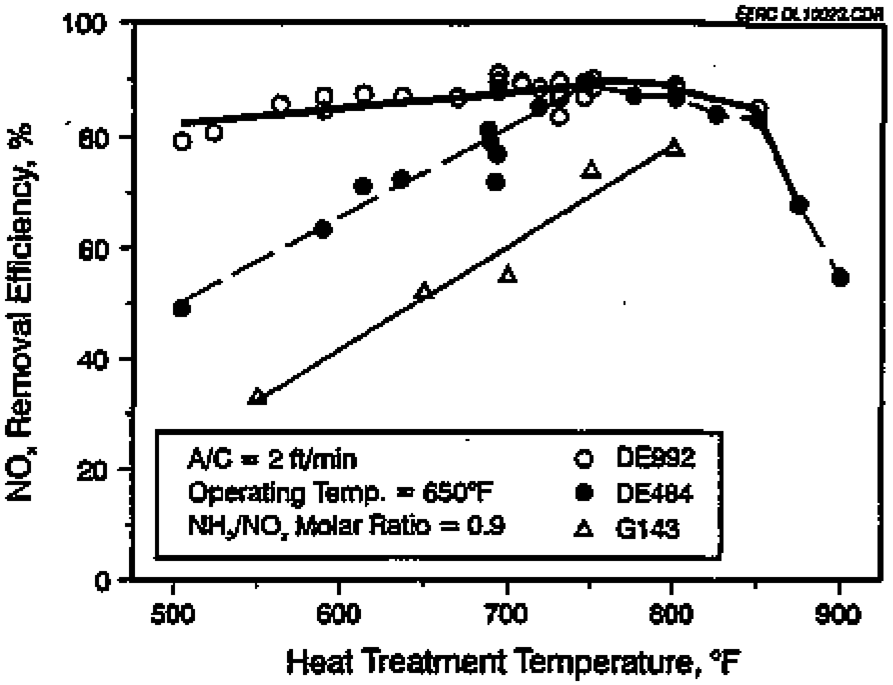

Figure 3-1. The effect of heat treatment temperature on NO_x removal for three different fabrics.

The heat treatment procedure developed for these pilot-scale tests was appropriate for this project. However, further development of heat treatment procedures will be necessary prior to commercialization of the catalyst-coated fabric filter concept.

3.1.2 The Effect of Various Chemical Species on Catalyst-Coated Fabric Reactivity

A small bench-scale unit illustrated in Figure 2-5 was assembled to perform catalyst deactivation and fabric-screening experiments. Primary system components include three parallel stainless steel reactors housed in an electrically heated oven; multiple gas cylinders supplying the simulated flue gas components (oxygen, ammonia, and nitric oxide, with the balance nitrogen); and instrument calibration gases, mass flow controllers, flow indicators, and on-line analyzers for measurement of oxygen and nitric oxide concentrations. Ammonia concentrations were measured using colorimetric techniques. All fabric samples were 2.8-in. diameter circles. The unit was operated after the fabric samples were sealed in the bolted-flange reactors and a heatup period of 3–4 hours with no gas flow to bring the internal operating temperature to 650°F. After operating temperature was reached, simulated flue gas flow was initiated and ammonia, NO_x, and oxygen concentrations verified. Fourier transform infrared (FT-IR) analyses using clean, heat-treated fabric determined that approximately 95% of maximum NO_x reduction was achieved in the first 5 minutes of operation and that maximum NO_x reduction was achieved in 15 minutes. The FT-IR instrument was not used during catalyst deactivation experiments because of contamination of the FT-IR cell with products offgassing from the contaminated fabrics. Inlet concentrations were verified for each reactor. Each set of three experiments required 2 to 3 hours to collect and verify the inlet and outlet gas data. Specifically, multiple ammonia measurements were necessary during each experiment to ensure reliable data and to document good ammonia closure. Inlet flue gas pressure was 10–15 in. W.C. The pressure differential across the reactors was 5 in. W.C., depending on the amount of deactivation agent coated on the fabric. The outlet product gas pressure was maintained at atmospheric using a bleed valve between the reactor and gas analyzers.

Catalyst deactivation experiments were designed to represent a worst-case scenario, where the catalyst-coated fabric filters are wetted as a result of an upset condition, such as a tube leak. During such an upset condition, water may leach various components from the ash layer onto the fabric, creating an alkali, acid, or sulfur-rich solution. Depending on the nature of the upset condition, the wetted fabric would either dry quickly because of CFF operating temperatures or remain wetted for an extended period in the event of a forced system shutdown.

Fabric samples treated with an acid or base solution were tested after the solution was dried at 240°F on the fabric surface and then tested a second time after thorough washing with distilled water. Fabric samples treated with a slurry of the deactivation agent, resulting in a dried dust cake on the surface, were lightly washed with distilled water prior to testing in order to prevent simple fabric blinding from contributing to observed catalyst deactivation. Fabric samples treated with coal ash were also wetted and then dried. These bench-scale tests were designed to evaluate the effect of a severe upset condition on the reactivity of the catalyst-coated fabric with respect to NO_x reduction and ammonia slip.

The catalyst-coated fabric type used for the catalyst deactivation experiments was a 22-oz woven S2-glass fabric consisting of DE-fibers (6.5 micron) with seven layers of a vanadium–titanium catalyst bonded to the fabric using the sol-gel process with an organic solvent. This is the same fabric type as was used during the pilot-scale pulse-jet tests. For the catalyst deactivation experiments, reactor temperatures varied between 650°–660°F, and the filter face velocity was 4 ± 0.15 ft/min. The simulated flue gas stream contained 700–725 ppm nitric oxide, sufficient ammonia to achieve a roughly 0.8 ammonia-to-NO_x molar ratio, roughly 3.5% oxygen, and a balance of nitrogen.

Table 3-1 summarizes the results from the catalyst deactivation and fabric-screening experiments. Each data set in the table represents a single experiment. Ammonia closure was typically 97% to 103%. As presented in the table, the potential catalyst deactivation agents used included distilled water, tap water, HCl, H_2SO_4, NaOH, CaO, $CaSO_4$, K_2SO_4, Na_2SO_4, Na_2SO_3, NaCl, $CaCl_2$, SiO_2, and three ash samples.

Baseline fabric performance was observed to be 71.5% NO_x reduction and 5.6% ammonia slip at an ammonia-to-NO_x molar ratio of 0.78. Results from the catalyst deactivation tests showed that distilled water (70.4% NO_x reduction and 5.6% ammonia slip) had no effect on catalyst reactivity and that tap water (68% NO_x reduction and 6.9% ammonia slip) may have had a minor effect. Both acids, 0.1 M HCl and 0.1 M H_2SO_4, appeared to totally destroy catalyst reactivity initially, but when the fabric samples were

TABLE 3-1

Bench-Scale Catalyst Deactivation Test Results[a,b]

Deactivation Agent	NH_3/NO_x Molar Ratio	NO_x Removal, %	NH_3 Slip, % of inlet NO_x
DE992 Fabric, baseline	0.78	71.5	5.6
Distilled H_2O	0.78	70.4	5.6
Tap H_2O	0.78	68.0	6.9
0.1 M HCl	1.16	0.0	86.0
0.1 M HCl, washed thoroughly[c]	0.85	73.4	2.76
0.001 M HCl	0.81	71.4	–
0.1 M H_2SO_4	0.85	1.0	80.7
0.1 M H_2SO_4, washed thoroughly	0.85	71.4	2.48
0.001 M H_2SO_4	0.81	58.4	–
0.1 M NaOH	0.81	2.1	82.1
0.1 M NaOH, washed thoroughly	0.85	6.5	80.0
0.001 M NaOH	0.81	58.4	–
CaO, washed lightly[d]	0.82	11.3	66.8
$CaSO_4$, washed lightly	0.86	70.4	17.8
K_2SO_4, washed lightly	0.86	74.1	9.2
Na_2SO_4, washed lightly	0.86	26.5	57.0
Na_2SO_3, washed lightly	0.82	2.4	74.1
NaCl, washed lightly	0.81	8.7	70.2
$CaCl_2$, washed lightly	0.81	14.9	68.9
NaCl, washed thoroughly	0.79	24.3	54.7
$CaCl_2$, washed thoroughly	0.79	28.3	49.9
SiO_2, washed thoroughly	0.80	12.1	53.5
Blacksville Bituminous Ash (low Ca and Na)	0.82	37.6	43.8
Falkirk Lignite Ash (high Ca, low Na)	0.82	34.7	44.6
Beulah Lignite Ash (high Ca and Na)	0.82	3.28	80.7

Continued . . .

TABLE 3-1 (continued)

Deactivation Agent	NH_3/NO_x Molar Ratio	NO_x Removal, %	NH_3 Slip, % of inlet NO_x
500-hr Fabric (PTC-BV-434)			
Baseline	0.80	75.8	3.72
Wetted (tap H_2O)	0.80	73.8	4.16
Acid (0.1 M H_2SO_4)	0.80	≈20	Unmeasurable
Acid-Washed	0.80	<3	97.3
1640-hr Fabric			
Baseline	0.82	72.8	3.5
Wetted (tap H_2O)	0.82	70.8	4.6
Acid (0.1 M H_2SO_4)	0.82	≈36	Unmeasurable
Acid-Washed	0.80	<10	83.3
5136-hr Fabric			
Baseline	0.79	75.4	4.0
Wetted (tap H_2O)	0.80	70.3	6.9
Acid (0.1 M H_2SO_4)	0.80	≈47	Unmeasurable
Acid-Washed	0.80	23	18.7
Clean Fabric and Ash (wetted)	0.80	58.3	–
PTC-BV-432 Fabric (wetted)	0.80	71.7	–
Used Fabric and Ash (wetted)	0.80	50.1	–
DE992 Fabric			
Blackeville Bituminous Ash (low Ca and Na) and Tap H_2O	0.80	58.3	–
PTC-BV-432 Fabric			
Tap H_2O	0.80	71.7	–
PTC-BV-432 Fabric			
Blacksville Bituminous Ash (low Ca and Na) and Tap H_2O	0.80	50.1	–

[a] Typical reactor operating conditions for the catalyst deactivation experiments were a temperature of 650°–660°F, a face velocity of 4 ft/min, an inlet NO_x concentration of 700–725 ppm, and an NH_3/NO_x molar ratio of roughly 0.8.

[b] Each data set in the table represents a single experiment. Closure on NH_3 was typically 97% to 103%.

[c] "Washed thoroughly" refers to removal of deactivation agent to the greatest possible extent with distilled water.

[d] Fabric was wetted, coated with deactivation agent, and dried. "Washed lightly" refers to minimal removal of caked deactivation agent with distilled water to allow for gas flow through the fabric without significant pressure drop.

thoroughly washed with distilled water and retested, catalyst reactivity was observed to be effectively recovered.

Deactivation experiments with 0.1 M NaOH resulted in complete loss of catalyst reactivity, 2% NO_x reduction, and >80% ammonia slip. Washing this fabric sample did not produce any recovery of catalyst reactivity. Even when the NaOH concentration was decreased to 0.001 M, NO_x reduction decreased to 58%. Ultimately, all of the sodium-based catalyst deactivation agents (NaOH, Na_2SO_4, Na_2SO_3, and NaCl) tested severely reduced the reactivity of the catalyst-coated fabric.

Of the three calcium-based catalyst deactivation agents tested (CaO, $CaSO_4$, and $CaCl_2$), CaO and $CaCl_2$ resulted in the most significant decrease in catalyst reactivity, 11% to 15% NO_x reduction and 66.8% to 68.9% ammonia slip, respectively. The $CaSO_4$ did not decrease NO_x reduction as significantly as the sodium-based materials or the other calcium-based materials tested, but there was a significant increase in the ammonia slip observed, with that value approaching 18% of the inlet NO_x concentration. Potassium sulfate also had an effect on catalyst reactivity, although substantially less significant than that of the other alkali species. In this case, ammonia slip increased to over 9% of the inlet NO_x concentration, as opposed to the 5% to 6% observed for the baseline fabric.

Two general conclusions can be drawn from these data. First, condensation of an acid on the surface of the clean catalyst-coated fabric interferes with the reactivity of the catalyst. However, catalyst reactivity can be recovered by simply washing the acid from the surface of the catalyst-coated fabric. Second, exposing the catalyst-coated fabric to an alkali solution will result in varying degrees of catalyst deactivation. A strong base, such as NaOH, will destroy catalyst reactivity. Alkaline solutions in general appear to have a more severe negative effect than acidic solutions on the catalyst reactivity of clean fabric. Solutions containing sodium ions reduce catalyst reactivity more dramatically than calcium ions and calcium ions more dramatically than potassium ions. The degree of catalyst deactivation also varies, depending on the negative ion associated with the sodium or calcium.

Sodium chloride and calcium chloride opposed this trend of stronger alkali causing greater deactivation, with the NaCl decreasing NO_x reduction to 14.9% and $CaCl_2$ decreasing NO_x reduction to 8.7%. Chlorine has been reported to have a promoting effect in V_2O_5–TiO_2 catalysts (19). During fabric preparation, all of these slurried compounds formed a solid crystalline layer on the surface of the fabric during the drying step. This solid material was partially removed prior to testing by careful washing with distilled water. Care was taken not to bend the stiffened fabric. The fabrics treated with NaCl and $CaCl_2$ were retested after a vigorous, thorough washing with distilled water. The—respective NO_x reduction rates rose to 24.3% and 28.3%, with ammonia slips around 50% of inlet NO_x concentration. One other solid deactivation agent, SiO_2, was tested after both light and thorough washings, with corresponding NO_x removal rates of 6.7% and 12.1%. During this test, the ammonia closure was poor, possibly because of a chemical reaction with the SiO_2.

Additional tests to delineate the effects of chlorine as it exists in tap water were not completed after discussing with the local water department the water purification process steps which contain chlorine. The residual chlorine in the tap water is not in the form of chlorinated salts or metals; rather, it is in the form of NH_2Cl at 2–2.5 ppm concentration.

Chloramine is formed when ammonia is added to the water after it has been contacted with chlorine. This process is used to avoid the formation of trihalomethanes. The city water used to deactivate the samples is moderately hard, containing 140–160 mg/L of calcium carbonates, bicarbonates, and sulfates. Since we have shown that $CaSO_4$ deactivates the catalyst, it is presumed that the $CaSO_4$ is the contributing factor causing 2% less NO_x reduction with a corresponding 1%–2% higher ammonia slip (as percent of inlet NO_x) with the tap water than with the distilled water-treated fabrics.

The three ash samples used in the series of experiments represent a bituminous coal and two lignites. Table 3-2 summarizes the chemical composition for each ash type. The bituminous coal ash contained very little alkali; one lignite ash contained a high level of calcium; and the other lignite ash contained high levels of both calcium and sodium. Results from these three experiments are consistent with those observed for the pure chemical deactivation agents tested. Catalyst reactivity was dramatically decreased for all three fabric samples, with the high-sodium ash demonstrating the greatest effect—3.28% NO_x reduction and 80.7% ammonia slip. The two low-sodium ash samples decreased NO_x reduction to roughly 35% and increased ammonia slip to 44%. However, these data contradicted the final set of deactivation experiments described below that evaluated used catalyst-coated fabric.

The final set of deactivation tests involved three catalyst-coated fabrics: 1) a PTC pulse-jet bag with 500 hours of operation, 2) a UND steam plant pulse-jet bag with 1642 hours of operation, and 3) a steam plant pulse-jet bag with 5136 hours of operation. The steam plant ash contained a higher concentration of alkali constituents than the ash from the 500-hr test. Two pieces of each fabric were used; the first was a baseline fabric sample, and the second fabric sample was tested twice, once after treatment with 0.1 M H_2SO_4 and once after a thorough washing with distilled water. The baseline tests, conducted at an ammonia-to-NO_x molar ratio of 0.8 ± 0.025 and performed similarly to previous baseline tests, demonstrated from 72%–75% NO_x reduction, with ammonia slips less than 5% of inlet NO_x. Also, the data indicate that no detectable loss in catalytic reactivity was observed from 500 to 1642 to 5136 hours of operation. When the samples were wetted with tap water, the NO_x reduction decreased 2%–5%, as reported for previous samples. Although previous tests had been run successfully with 0.1 M H_2SO_4 on clean fabric, the tests with the acid and dust cake continued to offgas throughout the test,contaminating the reactors and tubing and almost instantaneously plugging the NO_x analyzer. The initial NO_x readings taken indicated that maximum NO_x conversion was 20% for the 500-hr fabric, 36% for the 1640-hr fabric, and 47% for the 5136-hr fabric. Ammonia slip measurements could not be made because of the reaction between the acid residue in the system and the ammonia. After the fabric samples had been thoroughly washed, the NO_x reduction was 3% for the 500-hr, <10% for the 1640-hr, and 23% for the 5136-hr fabrics. These rates of recovery show the opposite trend to that expected for ashes with increasingly higher alkali content, but the overall conclusion is that NO_x reduction cannot be adequately recovered after the ash-coated bags have been exposed to a severe acid dew point, even after thorough washing. In general, the results from the bench-scale catalyst deactivation experiments show that exposure of dust-laden fabric to a severe moisture or acid dew point will permanently reduce catalyst reactivity to a level requiring replacement of the catalyst-coated bags.

Comparison of the above data indicates strongly that preparation of the fabric sample is a critical parameter. The fabric samples cut from the filter bags used on the pilot-scale

TABLE 3-2

Coal Ash Analyses for Catalyst Deactivation Tests

	Blacksville Bituminous Coal	Beulah Lignite	Falkirk Lignite
Oxides, wt% of ash			
SiO_2	46.87	25.5	42.2
Al_2O_3	22.58	12.3	12.1
Fe_2O_3	18.92	11.2	12.6
TiO_2	0.88	1.1	0.9
P_2O_5	0.32	0.5	0.0
CaO	5.40	18.1	20.8
MgO	1.01	4.3	7.0
Na_2O	0.77	13.07	0.6
K_2O	1.44	0.6	1.5
SO_3	1.81	12.9	1.8

unit and tested in the bench-scale unit showed a marginal trend of 2% less NO_x reduction. The data verify that results from the bench-scale unit approximate data from the pilot-scale system. However, results from deactivation experiments were drastically different between fabric samples from the filter bags and fabric samples prepared from clean, heat-treated fabric in the laboratory. For example, fabric samples from the pilot-scale runs that were treated with water showed much less damage than clean fabric samples coated with a greater quantity of the same ash as on the used fabric and wetted. To determine if the difference in results was caused by excess ash on the fabric, three additional tests were run. Two fabric samples were cut from a bag representing a 500-hr run (PTC-BV-434), one wetted and the other coated with a known quantity of excess ash and wetted. The third sample was clean, heat-treated fabric coated with the same quantity of ash as the used sample. Results from these runs, presented in Table 3-1, indicate that the wetted used fabric showed a decrease of 2% in NO_x reduction from the used fabric. Both clean and used fabrics, when coated with ash, showed a substantial decrease in NO_x reduction, 58.3% and 50.1%, respectively. Therefore, the process of coating the clean fabric with ash and wetting under laboratory conditions does not produce a fabric sample that performs in the bench-scale system in a manner similar to the pilot-scale system. The remainder of the deactivation experiments were performed with clean, heat-treated fabric samples treated with the given deactivation agent in the same manner as those samples with added ash. While lesser quantities of the deactivation agents may have resulted in better NO_x reduction, it is reasonable to assume that the deactivation trend is valid even if the percentage loss of NO_x reduction is exaggerated. Other conclusions drawn from the deactivation studies are that 1) some catalytic reactivity can be regained after fabric washing, 2) sodium > calcium > potassium in deactivation strength, and 3) chlorine in alkali salt form is detrimental to the reactivity of the catalyst-coated fabric. Previous data by Chen, Buzanowski, and Yang indicated that the chlorine in alkali salts had a promoting effect on ceramic-supported V–Ti catalysts (19).

Several differences aside from scale stand out between the bench-scale test unit and the pilot-scale baghouse. From the standpoint of inlet gas composition, the pilot-scale baghouse used flue gas and corresponding particulate matter from the PTC. The bench-scale test unit used a simulated flue gas containing only NO, NH_3, O_2, and N_2, excluding all other major combustion products such as CO_2, CO, SO_2, SO_3, and H_2O. These gases could affect the catalytic reactivity, especially SO_2, which has been shown to both inhibit and enhance, depending on various conditions, V–Ti catalysts. Water in the flue gas has the potential to change the acidity of the active catalyst sites, which has been shown to be directly related to catalyst reactivity. While the particulate collection efficiency of the catalytic filter fabric is a function of the presence of a dust cake, it is possible that the presence and chemical composition of a dust cake layer may also affect NO_x reduction performance, especially in the presence of SO_2.

Another difference between the pilot- and bench-scale systems is the difference in reactor geometry. The main difference is the ratio of exposed stainless steel surface area to the catalytic fabric surface area. In order to minimize the contact of ammonia to the stainless steel and to minimize the contact time between the NO and ammonia before they reach the catalytic fabric, the ammonia was injected into the NO–N_2–O_2 stream just before the reactor inlet. Since stainless steel can react with ammonia, several runs were made with no fabric in the reactor to determine whether ammonia was lost before crossing the fabric. The results were that no perceptible difference in ammonia or NO_x concentrations from reactor inlet and outlet was detected. No NO_2 was detected in the inlet stream, and measurements made after the outlet stream was scrubbed with a mild peroxide solution showed no detectable amounts of NO_2, typically less than 5 ppm. After several runs with the peroxide solution, this practice was discontinued, and all NO_x measurements were made using the NO option of the NO_x analyzer. Ammonia balances were typically within 96%–104% prior to runs using fabric treated with 0.1 M H_2SO_4. During these runs, the outlet tubing became contaminated with acid residue and ammonia balances fell. Even after some replacement and washing of the outlet tubes, baseline samples showed identical NO_x reduction numbers, but poor ammonia closure. Acid residue observed in the NO_x analyzer capillary tubes appeared to be reddish brown and highly viscous in nature. Other residue swabbed from the stainless steel tubing appeared to be more greenish black. The quantities of these materials were not large enough to collect and analyze. However, Chen, Buzanowski, and Yang also observed a red-brown liquid when treating ceramic-supported V–Ti catalysts in a fixed-bed reactor. They showed the reddish material to be VCl_4 and the greenish material to be VCl_2 and also showed the presence of NH_4Cl in the product gas (19). The ammonia analysis method used with the bench-scale reactor does not detect NH_4Cl.

Another factor that potentially alters NO_x reduction performance is the air-to-cloth ratio. In the bench-scale system, the air-to-cloth ratio was nominally 4 ft/min ± 0.2. On an average, the pilot-scale runs showed a decrease of approximately 2% NO_x reduction as air-to-cloth ratios increased from 2 to 8 ft/min. The cylinder gas concentrations used were calculated to produce an air-to-cloth ratio of 4 ft/min at 650°F given the standard fabric sample size, a nominal oxygen concentration of 3.5%, and inlet NO_x of between 700 and 725 ppm with corresponding NH_3 to achieve an ammonia-to-NO_x molar ratio of 0.8. Under these restrictions, it was not possible to vary the air-to-cloth ratio without varying at least one other parameter.

3.1.3 Catalyst-Coated Fabric-Screening Tests

Five new fabric types were prepared by OCF for screening. The fabric screening data given in Table 3-3 represent the data set with the best ammonia balance. The fabric samples were identified as Fabric 205, 206, 207, 208, and 209. Fabric 205 was prepared using an S2-glass felt and eight coats of a 0.1 M V–Ti catalyst-coating. The use of a felt rather than a woven fabric may be an advantage at filter face velocities of >3 ft/min. Successful development of a catalyst-coated felt would limit the effect of dust cake characteristics/properties on particulate emissions and ammonia slip.

Fabric 206 represented the standard DE992 woven S2-glass fabric prepared using seven coats of catalyst, but the catalyst-coating was prepared using a higher-viscosity titania source. The purpose of the higher-viscosity titania source was an attempt to increase the quantity of V–Ti catalyst on the surface of the fabric.

Fabric 207 represented two layers of woven DE484 fabric prepared using seven coats of the standard 0.2 M V–Ti coating on the clean-side layer of fabric and two coats of an abrasion-resistant Si–Ti coating on the dirty-side layer of fabric. This approach would simulate a double bag.

Fabric 208 represents a standard DE992 woven S2-glass fabric prepared using ten coats of the standard 0.2 M V–Ti catalyst coating rather than the seven coats used previously. The purpose of applying ten coats of catalyst was simply to increase the amount of catalyst on the fabric in the hope of increasing NO_x reduction and reducing ammonia slip. If successful, the cost of the overall concept could be reduced as a result of

TABLE 3-3

Bench-Scale Fabric-Screening Test Results

Fabric	NH_3/NO_x Molar Ratio	NO_x Removal, %	NH_3 Slip, % of inlet NO_x
DE992	0.78	71.5	5.6
205	0.83	25.4	61.9
206	0.83	76.1	5.6
207	0.80	77.8	1.7
207	1.02	94.4	7.7
208	0.80	80.4	1.9
208	0.85	84.9	2.1
208	0.91	91.0	2.8
208	0.95	95.0	2.6
208	1.02	97.0	5.6
209	0.83	81.0	1.4
209	1.02	95.4	7.6

being able to operate the catalytic fabric filter at a higher face velocity and reduce the operating and maintenance costs associated with ammonia slip.

The final fabric sample, 209, represented a standard DE992 woven S2-glass fabric prepared using seven coats of the standard 0.2 M V–Ti catalyst coating with a high molecular weight polymer added. Again, the objective of this change to the catalyst coating was to increase catalyst concentration on the fabric.

Fabric 205 performed very poorly in three trials, with 25.4% NO_x reduction and an ammonia slip of 61.9% of the inlet NO_x concentration. Fabric 209 performed well, with 81.0% NO_x reduction at an ammonia-to-NO_x molar ratio of 0.83 and an ammonia slip of 1.4% of the inlet NO_x concentration. At an ammonia-to-NO_x molar ratio of 1.02, Fabric 209 showed a NO_x reduction of 95.4% and an ammonia slip of 7.6% inlet NO_x concentration. Fabric 208 was tested at ammonia-to-NO_x molar ratios ranging from 0.8 to 0.95 with ammonia slips of approximately 1.9% to 2.8% of the inlet NO_x concentration. At an ammonia-to-NO_x molar ratio of 1.02, Fabric 208 demonstrated 97.0% NO_x reduction and an ammonia slip of 5.6% inlet NO_x concentration. Fabric 206, with the high-viscosity titania source, appeared to be discolored over portions of the sample. The sample was tested using two differently colored areas of fabric. The maximum NO_x reduction was 76.1% at an ammonia-to-NO_x molar ratio of 0.83. The corresponding ammonia slip was 5.6% of the inlet NO_x concentration. Fabric 206 performed better than the clean DE992 fabric previously tested, which had an average of 71% NO_x reduction at an ammonia-to-NO_x molar ratio of 0.78 and an ammonia slip of about 5.6% of inlet NO_x concentration. Fabric 207 also performed better than clean DE992 fabric, with an ammonia slip of 1.7% and NO_x reduction of 77.8% at a stoichiometric ratio of 0.80.

Based on this preliminary bench-scale data, Fabrics 207, 208, and 209 appear to be more reactive than the DE992 fabric used for the pilot-scale pulse-jet tests. If these observations can be substantiated with further bench-scale testing, Fabric 208 may be able to reduce the level of ammonia slip observed during pilot-scale pulse-jet tests from 7% to <5% of the inlet NO_x concentration. Further testing would be required in order to determine potential performance.

3.2 Process Testing/Reverse-Gas System

Testing of catalyst-coated fabric filters with the reverse-gas system included fabric-screening tests, coal effects tests, operating temperature tests, and dew point exposure tests. A 500-hr reverse-gas test was also planned, but was replaced by a second pulse-jet test. Table 2-2 presents the test conditions for Subtask 3.2.

The vanadium catalyst used on the fabric filters was similar to the catalyst used to oxidize SO_2 to SO_3 in ESP flue gas conditioning systems. Although the oxidation of SO_2 to SO_3 takes place at 800°F, there was concern that a certain level of oxidation would occur at SCR temperatures (650°F). Therefore, it was necessary to determine the level of oxidation of SO_2 to SO_3 due to the presence of the vanadium catalyst. SO_3 measurements were made with the ammonia injection turned off during each test to avoid interference by ammonia and maximize the potential for SO_3 formation. Concentrations during the reverse-gas tests ranged from 0.3 ppm with the Black Thunder subbituminous coal to 43.8 ppm with the Illinois No. 6 bituminous coal. The higher concentrations were in the expected range for a 3% sulfur bituminous coal (Illinois No. 6). All but a few of the SO_3

concentrations were less than 1% of the inlet SO_2 concentration and indicate little oxidation of SO_2 due to the catalyst-coated fabric.

A second concern with the use of catalyst-coated bags was the possibility of catalyst erosion resulting in an increase in the vanadium content of the fly ash. Although vanadium itself is not identified by RCRA (Resource Conservation and Recovery Act) to be a hazardous element, some vanadium compounds are considered hazardous materials. Therefore, it was important to monitor the vanadium concentration in the fly ash. Table 3-4 presents the vanadium content of the coal, fly ash from the inlet to the reverse-gas or pulse-jet baghouses, and ash from the baghouse hoppers as determined by atomic absorption (AA) analysis. The differences in vanadium concentration in the baghouse ashes for the different coals appeared to be caused by differences in the coals, and not a loss of vanadium catalyst from the bags. When the vanadium concentration in the baghouse ash was compared to the theoretical concentration based on the concentration of the vanadium and ash in the coal, there was an increase in the vanadium in the baghouse ash in some cases. An explanation is that vanadium is known to be enriched in the fine particulate matter as a result of initial vaporization in the flame zone and the subsequent condensation on fine ash particles (31). Although the concentration of the vanadium in the combustor bottom ash was not known, it was expected to be less than the concentration in the fly ash. In general, the variability of vanadium concentration in baghouse ash samples for a single coal appears to be due to the vanadium variability in the coal. The data indicate that catalyst erosion from the bags was not a problem for the type and duration of tests completed.

3.2.1 NO_x Control with Catalyst-Coated Fabric

Nine reverse-gas baghouse tests ranging from roughly 40 to 100 hours in duration were completed to screen different types of catalyst-coated fabrics. Each 100-hr test consisted of 12 individual test periods in order to address the effects of air-to-cloth ratio (1.5, 2.0, 3.0, and 4.0 ft/min) and ammonia-to-NO_x molar ratio (0.80, 0.90, and 1.00).

The catalyst-coated fabrics tested were a 14-oz/yd^2 single-beam weave, woven from DE-fibers (6.5 microns), designated DE484; a 14-oz/yd^2 single-beam weave, woven from G-fibers (9 microns), designated G143; and a 22-oz/yd^2 double-beam weave, woven from DE-fibers, designated DE992. All fabrics were woven from an S2-glass yarn. The DE484, DE992, and G143 fabrics were prepared with seven coats of catalyst applied with an organic-based coating process. One DE484 fabric was also prepared with seven coats of catalyst applied with an aqueous-based coating process. Also a DE992 fabric treated with three coats of an undercoat before being coated with the vanadium/titanium catalyst was tested. All catalyst-coated fabrics were selected based on previous bench-scale performance. The fabric types, characteristics, and the tests in which they were used are presented in Table 3-5.

OCF provided all fabric filter bags for the reverse-gas baghouse and pulse-jet baghouse tests. For the reverse-gas system, two filter bags (12 in. in diameter by roughly 26 ft long) were used for each test. Prior to testing, it was necessary to heat-treat the bags in order to remove a lubricant used in the manufacture of the bags and maximize catalyst reactivity. Deficiencies in the initial heat treatment procedure used for the first two test periods (PTC-IL6-408 and PTC-IL6-414) were identified and corrected, resulting in the bags being heat-treated in the baghouse chambers, using flue gas generated by firing

TABLE 3-4

Vanadium Concentration Analyses Results for Coal and Ash Samples

	Coal Composite, ppm	Coal Ash, ppm	Inlet, ppm	Baghouse Ash, ppm	Sample Conditions
PTC-IL6-408		160			Calculated theoretical (11.89% ash)
	19		220	240	
			250	250	
PTC-IL6-414				260	A/C ratio = 2.0 ft/min
PTC-IL6-415		240			Measured value in ashed coal sample
				270	A/C ratio = 1.5 ft/min
				260	A/C ratio = 2.0 ft/min
				260	A/C ratio = 3.0 ft/min
				260	A/C ratio = 4.0 ft/min
PTC-IL6-416				260	A/C ratio = 1.5 ft/min
				250	A/C ratio = 4.0 ft/min
				290	A/C ratio = 2.0 ft/min
PTC-IL6-417				230	A/C ratio = 1.5 ft/min
				220	A/C ratio = 2.0 ft/min
				250	A/C ratio = 2.0 ft/min
				250	A/C ratio = 3.0 ft/min
				250	A/C ratio = 4.0 ft/min
PTC-IL6-419				260	A/C ratio = 1.5 ft/min
				230	A/C ratio = 2.0 ft/min
				250	A/C ratio = 2.0 ft/min
				240	A/C ratio = 3.0 ft/min
				240	A/C ratio = 4.0 ft/min
PTC-BV-423	18	203			Calculated theoretical (8.85% ash)
				160	A/C ratio = 1.5 ft/min
				200	A/C ratio = 2.0 ft/min
				140	A/C ratio = 3.0 ft/min
				170	A/C ratio = 4.0 ft/min
PTC-BT-424	13	270			Calculated theoretical (4.86% ash)
				240	A/C ratio = 1.5 ft/min
				240	A/C ratio = 2.0 ft/min
				240	A/C ratio = 3.0 ft/min
				250	A/C ratio = 4.0 ft/min

Continued . . .

TABLE 3-4 (continued)

	Coal Composite, ppm	Coal Ash, ppm	Inlet, ppm	Baghouse Ash, ppm	Sample Conditions
PTC-BU-425	<5.0	61			Calculated theoretical 8.19% ash)
				38	A/C ratio = 2.0 ft/min
				55	A/C ratio = 4.0 ft/min
				44	A/C ratio = 3.0 ft/min
				46	A/C ratio = 1.5 ft/min
				36	A/C ratio = 2.0 ft/min
PTC-IL6-426	30	270			Calculated theoretical (10.91% ash)
				240	Baghouse temp. = 700°F
				250	Baghouse temp. = 650°F
				240	Baghouse temp. = 600°F
				240	Baghouse temp. = 550°F
				230	Baghouse temp. = 500°F
				230	Baghouse temp. = 750°F
				220	Baghouse temp. = 650°F
PTC-IL6-427				230	Upset Condition 1
				220	Upset Condition 2
PTC-IL6-428				220	A/C ratio = 2.0 ft/min
PTC-BV-429				240	A/C ratio = 4.0 ft/min
				230	A/C ratio = 1.5 ft/min
				240	A/C ratio = 3.0 ft/min
				260	A/C ratio = 2.0 ft/min
				160	A/C ratio = 2.0 ft/min
				180	A/C ratio = 4.0 ft/min
				190	A/C ratio = 3.0 ft/min
				180	A/C ratio = 1.5 ft/min
				210	A/C ratio = 2.0 ft/min
PTC-BT-430				260	A/C ratio = 4.0 ft/min
				260	A/C ratio = 3.0 ft/min
				260	A/C ratio = 2.0 ft/min
				260	A/C ratio = 6.0 ft/min
				260	A/C ratio = 2.0 ft/min
PTC-BV-432	13	163			Calculated theoretical (7.98% ash)
				180	Week 1
				180	Week 2
				190	Week 3
PTC-BV-434				190	Week 1
				190	Week 2
				190	Week 3

TABLE 3-5

Catalyst-Coated Fabric Filter Characteristics

Fabric Designation	Runs	Vanadium Concentration, g/ft^2	Fabric Weight, oz/yd^2	Catalyst Coating[c]	Fiber Diameter, µm
DE484	PTC-IL6-408 PTC-IL6-415 PTC-NG-421 PTC-BV-423 PTC-BT-424 PTC-BU-425 PTC-IL6-426 PTC-IL6-427	0.348[a]	14.0	7 coats	6.5
DE992	PTC-IL6-414 PTC-IL6-428 PTC-BV-429 PTC-BT-430 PTC-RO-431 PTC-BV-432 PTC-BV-433 PTC-BV-434	0.465[b]	22.0	7 coats	6.5
DE992	PTC-IL6-419	0.471	22.0	3 coats undercoating before 7 catalyst coats	6.5
DE484	PTC-IL6-416	NA	14.0	7 coats aqueous-based	6.5
G143	PTC-IL6-417 PTC-NG-420	0.234	14.0	7 coats	9.0

[a] Average of two concentrations.

[b] Average of four concentrations.

[c] Except where noted, all bags were coated with seven coats of a vanadium–titanium catalyst.

natural gas. The flue gas used to heat-treat the bags nominally contained 4.5% oxygen, and the bulk gas temperature was maintained at 700°–725°F for 4 hours. This resulted in adequate heat treatment for all bags used in either the reverse-gas or pulse-jet baghouse.

For the fabric-screening tests, flue gas was generated by firing a washed Illinois No. 6 bituminous coal. The average ultimate, proximate, and sieve analyses for the coal are presented in Table 3-6. The coal was typical of midwestern bituminous coals: high fixed carbon (48.42%) and heating value (11,501 Btu/lb), moderate ash (11.18%) and sulfur (3.26%), and low moisture (5.89%) content. The coal ash was characterized by high silica (49.24%), alumina (19.35%), and iron (18.73%) and low alkali content.

3.2.1.1 PTC-IL6-408

The catalyst-coated fabric filters used for Run PTC-IL6-408 were made from a 14-oz/yd^2 S2-glass woven fabric coated with seven coats of a vanadium–titanium catalyst. For the pilot-scale tests, this fabric was designated DE484.

The results from the 100-hr test were poor due to inadequate temperature control in the reverse-gas baghouse and inadequate heat treatment of the catalyst-coated fabric filter bags. Originally, 12 individual experimental periods were planned in order to address the effects of air-to-cloth ratio (1.5, 2, 3, 4 ft/min) and ammonia-to-NO_x molar ratio (0.8, 0.9, 1.0). However, because of the heat treatment and temperature control problems, no useful NO_x reduction data were collected. The ammonia slip concentrations measured (187–511 ppm) confirmed the poor NO_x removal performance of the fabric filters. The bags were heat-treated again and retested at a later date (PTC-IL6-415).

3.2.1.2 PTC-IL6-414

The catalyst-coated fabric filters used for this test were made from a 22-oz/yd^2 double-beam weave fabric coated with seven coats of the vanadium–titanium catalyst. For the pilot-scale tests, this fabric was designated DE992. The bags were heat-treated for 4 hours at 730°F in a convective oven.

Results from the 100-hr test were poor, with deteriorating NO_x removal efficiency throughout the test. After approximately 36 hours of operation, it was determined the bags were not performing as expected, and the test was terminated. When the bags were inspected after the test, several holes were found in the bags. At first it was thought the bags were damaged by thermocouple probes in the reverse-gas baghouse during bag installation. However, it is believed the bags were damaged when they came in contact with a hot metal grate in the convective oven during the heat-treating process. In subsequent tests, the bags were heat-treated in the baghouse chamber using flue gas generated by firing natural gas. This fabric type was retested at a later date (PTC-IL6-428) using a new set of bags.

Because of the damage to the bags, no meaningful NO_x reduction data were collected. Results from the ammonia slip measurements using wet chemistry techniques (350–860 ppm NH_3) confirm the low NO_x reduction values observed.

TABLE 3-6

Results of Coal and Coal Ash Analyses for Reverse-Gas System Tests[*]

	Illinois No. 6 Bituminous	Blackville Bituminous	Black Thunder Subbituminous	Beulah Lignite
Proximate Analysis, wt%				
Moisture	5.89	1.40	24.50	31.60
Volatile Matter	34.50	32.81	36.70	30.36
Fixed Carbon	48.42	56.92	33.92	29.84
Ash	11.18	8.85	4.86	8.19
Ultimate Analysis, wt%				
Hydrogen	4.98	4.40	6.50	6.47
Carbon	64.84	74.76	52.23	43.61
Nitrogen	1.22	1.36	0.65	0.54
Sulfur	3.26	2.31	0.36	0.94
Oxygen	14.49	8.31	35.37	40.23
Ash	11.18	8.85	4.86	8.19
Heating Value, Btu/lb	11,501	12,794	8940	7158
Percent as Oxides, wt%				
SiO_2	49.24	44.30	32.60	27.58
Al_2O_3	19.35	20.67	15.50	13.77
Fe_2O_3	18.73	20.48	5.49	7.86
TiO_2	0.82	1.01	1.13	0.47
P_2O_5	0.30	0.38	1.17	0.83
CaO	3.92	5.58	22.16	16.21
MgO	1.21	1.18	8.06	7.66
Na_2O	0.79	0.61	1.10	6.31
K_2O	1.72	1.11	0.30	0.28
SO_3	3.69	4.69	12.48	19.02
Ash Fusion Temp., °F				
Initial	2096	2292	2186	2226
Softening	2170	2357	2234	2279
Hemisphere	2251	2390	2249	2289
Fluid	2343	2425	2263	2308
Sieve Analysis				
Screen Mesh Size	wt% Retained			
100	19.00	17.18	26.80	24.66
140	12.77	12.94	13.60	13.11
200	9.78	13.82	13.50	11.26
230	9.64	9.03	5.10	5.83
270	8.85	14.85	5.30	3.86
325	1.72	0.33	1.90	3.98
Pan	37.26	30.86	30.10	34.71
Total %	99.07	99.01	96.30	97.41

[*] Coal analyses are presented on an "as-fired" basis.

3.2.1.3 PTC-IL6-415 and PTC-NG-421

The catalyst-coated fabric filters used for the 100-hr Run PTC-IL6-415 were the same bags used for Run PTC-IL6-408, which were inadequately heat-treated. The bags were heat-treated a second time by exposing them to flue gas generated by firing natural gas. The average bulk gas temperature was maintained at roughly 700°F for 4 hours, resulting in adequate heat treatment of the fabric.

Air-to-cloth ratios ranged from 1.8 to 3.6 ft/min and the ammonia-to-NO_x molar ratio ranged from 0.7 to 1.2. A 2-day test (PTC-NG-421) with the same set of bags was run at a later date to determine if decreasing NO_x removal efficiency was due to pinholes or decreasing catalyst reactivity. Air-to-cloth ratios ranged from 1.5 to 4.1 ft/min, and ammonia-to-NO_x molar ratios ranged from 0.78 to 1.12 during the 2-day test. A nominal bulk gas temperature of 660°F in the baghouse chamber was maintained during all test periods.

NO_x removal efficiency for PTC-IL6-415 ranged from 68% (air-to-cloth ratio = 3.6, ammonia-to-NO_x molar ratio = 0.92) to 90% (air-to-cloth ratio = 1.7, ammonia-to-NO_x molar ratio = 1.18). NO_x removal efficiencies and ammonia slip values were similar during PTC-NG-421. Figure 3-2 presents the NO_x removal efficiency and the ammonia slip (as a percent of the inlet NO_x concentration) data as a function of ammonia-to-NO_x molar ratio for tests PTC-IL6-415 and PTC-NC-421. The results show a definite effect due to air-to-cloth ratio. Comparing NO_x removal efficiency for average air-to-cloth ratios of 1.8 ft/min and 3.7 ft/min, the data indicate a decrease in NO_x removal efficiency of 10% at the higher air-to-cloth ratios. As a basis of comparison with other fabrics tested, the NO_x removal efficiency at an air-to-cloth ratio of 2.0 ft/min and an ammonia-to-NO_x molar ratio of 0.80 was roughly 75%, and the ammonia slip was roughly 3% of the inlet NO_x concentration.

Ammonia slip ranged from <1% of the inlet NO_x concentration at an air-to-cloth ratio of 2.0 ft/min to 40% of the inlet NO_x at an air-to-cloth ratio of 4.1 ft/min (average inlet NO_x during the different test periods ranged from 684 to 1021 ppm). Because of the limited ammonia slip data available, it is difficult to determine if the increased ammonia slips at higher air-to-cloth ratios during natural gas firing were due to higher gas velocities or the lack of a dust cake on the filters and the potential for permanent pinhole development. Pinhole development is believed to be the most probable cause of higher ammonia slip during gas-fired tests.

Used (exposed to flue gas) and unused (not exposed to flue gas) samples of the catalyst-coated fabric were submitted for analysis to determine the concentration of vanadium on the fabric. Results showed a vanadium concentration of 7900 μg/g on the unused sample and 7533 μg/g on the used sample. The vanadium concentration of the used fabric would be somewhat less due to the dilution effect of fly ash particles trapped in the weave of the fabric. Therefore, because of the ash dilution effect and the variability of vanadium concentration as a function of the coating process, the data do not indicate any loss of catalyst from the bags.

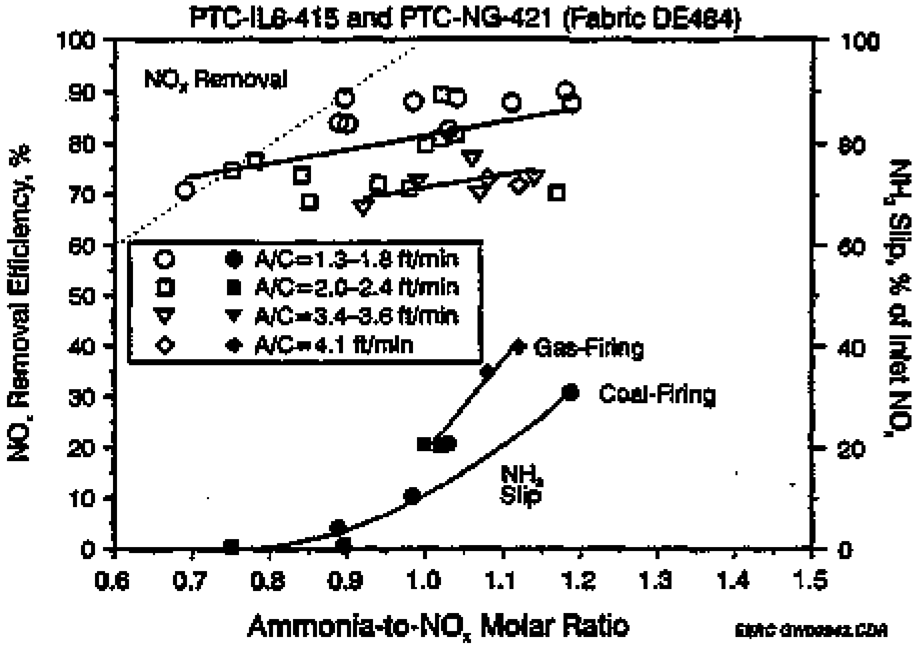

Figure 3-2. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Runs PTC-IL6-415 and PTC-NG-421: average inlet NO$_x$ = 818 ppm, average baghouse temperature = 660°F.

3.2.1.4 PTC-IL6-416

The catalyst-coated fabric filters used for Run PTC-IL6-416 were made from a DE484 fabric with seven coats of the vanadium–titanium catalyst applied using an aqueous-based coating process. It was anticipated that the aqueous-based catalyst coating process would be more economical, more environmentally acceptable, and more easily managed from an industrial health and safety perspective than the organic-based coating process. Bench-scale experimental results, with the catalyst applied by the aqueous-based process, had demonstrated NO$_x$ reduction and ammonia slip values comparable to the catalysts applied by the organic-based process.

The NO$_x$ reduction results from the 100-hr test were initially good, but degraded with time. Figure 3-3 plots the NO$_x$ removal efficiency as a function of time for the 100-hr test. Nitric oxide removal averaged 90% (air-to-cloth ratio = 1.7, ammonia-to-NO$_x$ molar ratio = 1.02, ammonia slip = 11.4% of inlet NO$_x$ concentration) for the first 10 hours. At this point, the bags were cleaned for the first time, and the NO$_x$ removal efficiency dropped to less than 80% (maintaining the same operating conditions as prior to cleaning). As the dust cake developed on the bags, the NO$_x$ removal efficiency increased to approximately 90%. When the bags were cleaned a second time, the NO$_x$ removal efficiency again dropped below 80%. The pattern of decreased NO$_x$ reduction after cleaning followed by increasing NO$_x$ reduction with dust cake development is clearly

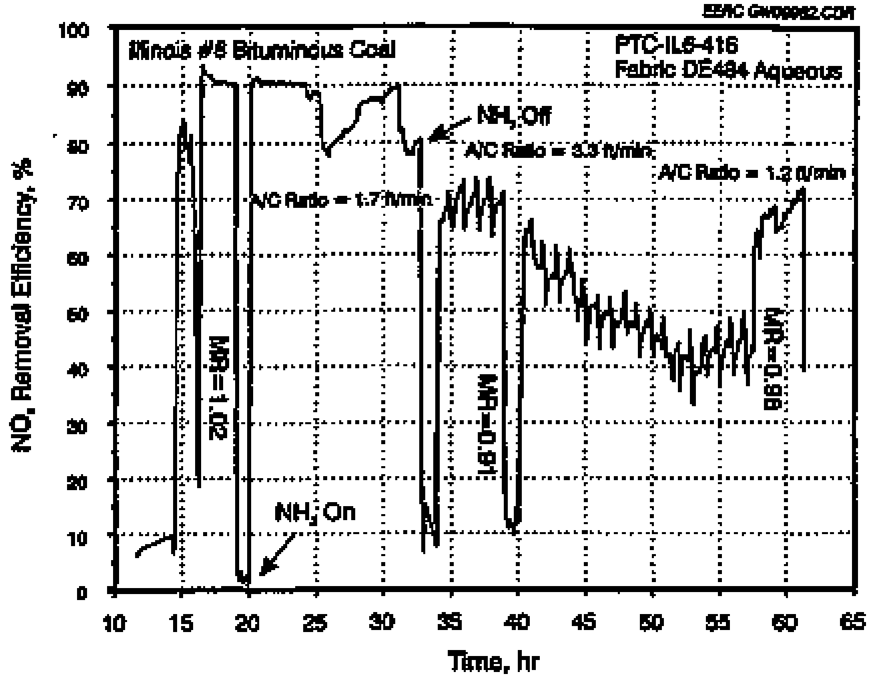

Figure 3-3. NO$_x$ removal efficiency as a function of time for Run PTC-IL6-416.

demonstrated in Figure 3-3. However, as the test progressed, the levels of NO$_x$ removal efficiency before and after cleaning steadily decreased. The lowest NO$_x$ removal efficiency was 36% (an air-to-cloth ratio = 3.3 ft/min, ammonia-to-NO$_x$ molar ratio = 1.11), and the corresponding maximum (before the cleaning cycle) was 46% NO$_x$ removal.

The ammonia slip values also indicate deteriorating NO$_x$ removal with time. The initial ammonia slip was 19 ppm, and the ammonia slip at the end of the test was 278 ppm at comparable air-to-cloth ratios.

Used and unused samples of the catalyst-coated fabric were submitted for analysis to determine the concentration of vanadium on the fabric. Results showed a vanadium concentration of 10,900 μg/g on the unused sample and 6710–7320 μg/g on the used sample. This difference is not consistent with the ash dilution effect anticipated and does not appear to fall within the variability of the coating process. Therefore, the results indicate a loss of catalyst from the bags, explaining the decrease in catalyst reactivity observed with time. Although the aqueous catalyst-coating process needs further development in order to produce results comparable to the organic catalyst-coating process, further consideration of the aqueous process is warranted in order to improve overall CFF economics.

3.2.1.5 PTC-IL6-417 and PTC-NG-420

The fabric filters used for the 100-hr Run PTC-IL6-417 were woven from G-fibers (9 microns) having a 14-oz/yd^2 fabric weight and coated with seven coats of the vanadium–titanium catalyst. The single-beam weave fabric was designated G143.

This set of bags was used for a 100-hr coal-fired test (PTC-IL6-417) and a short test (PTC-NG-420) where flue gas was generated by firing natural gas. The 2-day test (PTC-NG-420) was run at a later date to determine if additional heat treatment would result in improved NO_x removal. Air-to-cloth ratios for the two tests ranged from 1.3–3.7 ft/min during the coal-fired test and 3.9 to 4.0 ft/min during the gas-fired test. The ammonia-to-NO_x molar ratio ranged from 0.82 to 1.15 for all tests.

NO_x removal efficiency for PTC-IL6-417 ranged from 66% (air-to-cloth ratio = 3.5, ammonia-to-NO_x molar ratio = 0.93) to 87% (air-to-cloth ratio = 1.3, ammonia-to-NO_x molar ratio = 1.03). NO_x removal efficiencies during PTC-NG-420 were poor, ranging from 54% (air-to-cloth ratio = 3.9, ammonia-to-NO_x molar ratio = 1.07) to 65% (air-to-cloth ratio = 3.9, ammonia-to-NO_x molar ratio = 1.02). The results did not indicate any benefit from additional heat treatment. Figure 3-4 plots the NO_x removal efficiency and the NH_3 slip (as a percentage of the inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio for Runs PTC-IL6-417 and PTC-NC-420. These results, as did previous data presented, showed a definite effect due to air-to-cloth ratio, resulting in decreasing NO_x reduction and increasing ammonia slip with increasing air-to-cloth ratio. Earlier results with the DE484 fabric had shown NO_x removal efficiency, at an air-to-cloth ratio of 2.0 ft/min and an ammonia-to-NO_x molar ratio of 0.8, was roughly 75% and the ammonia slip was roughly 3% of the inlet NO_x concentration. The data from PTC-IL6-417 (75% NO_x reduction with 7.5% ammonia slip), extrapolated because of the lack of data at these specific conditions, showed similar performance with respect to NO_x reduction, but ammonia slip levels for the G143 fabric were significantly higher than the values for the DE484 fabric.

Ammonia slip for the G143 fabric ranged from 8% of the inlet NO_x concentration (air-to-cloth ratio = 3.4 ft/min, ammonia-to-NO_x molar ratio = 0.82) during coal firing to 91% of the inlet NO_x concentration (air-to-cloth ratio = 4.0 ft/min, ammonia-to-NO_x molar ratio = 1.45) during natural gas firing, (average inlet NO_x concentration during the coal-fired and natural gas-fired test periods were 710 ppm to 943 and 239 to 286 ppm, respectively). From the data, it is difficult to determine if air-to-cloth ratio is the dominating effect on ammonia slip, or if the difference when firing natural gas is due to the lack of a dust cake on the filters and pinholing. Again, it is believed pinholing is having the greatest effect.

Used and unused samples of the catalyst-coated fabric were submitted to determine the concentration of vanadium on the fabric. Results showed a vanadium concentration of 5300 μg/g on the unused sample and 5000 μg/g on the used sample. The vanadium concentration of the used fabric would be somewhat less owing to the dilution effect of fly ash particles trapped in the weave of the fabric. Therefore, because of ash dilution and the variability of the coating process, the data do not indicate any loss of catalyst from the bags.

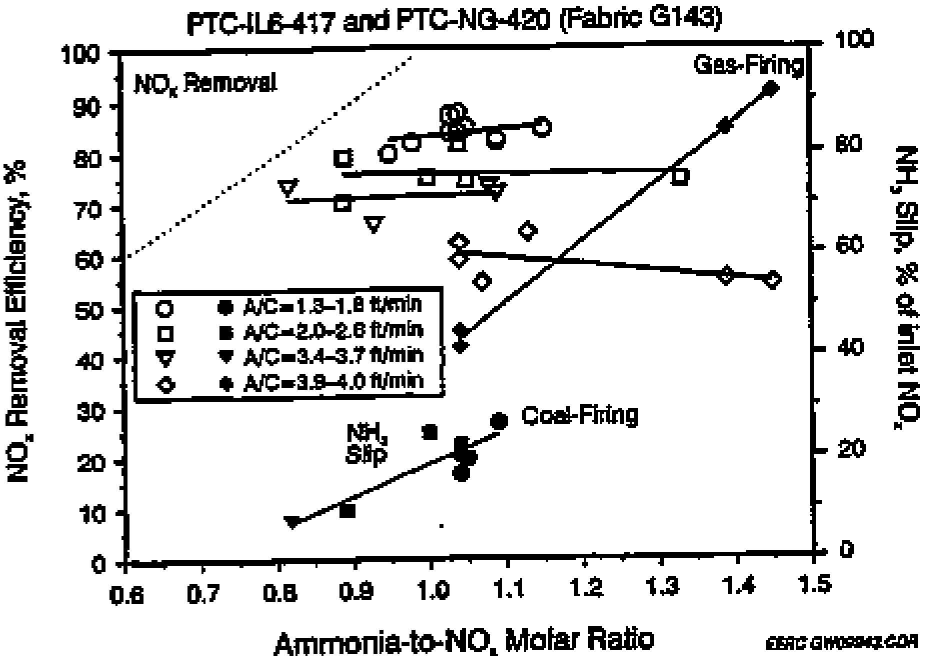

Figure 3-4. NO_x removal efficiency and ammonia slip versus ammonia-to-NO_x molar ratio for Runs PTC-IL6-417 and PTC-NG-420: average inlet NO_x = 825 ppm, average baghouse temperature = 657°F.

3.2.1.6 PTC-IL6-419

The catalyst-coated fabric filters used for the 100-hr Run PTC-IL6-419 were constructed from the 22-oz/yd^2 woven fabric (DE992). Three coats of an undercoat were applied to increase fabric surface area and possibly improve fiber abrasion resistance before seven coats of the vanadium–titanium catalyst were applied.

NO_x removal efficiency for PTC-IL6-419 ranged from 62% (air-to-cloth ratio = 2.8, ammonia-to-NO_x molar ratio = 0.99) to 90% (air-to-cloth ratio = 1.8, ammonia-to-NO_x molar ratio = 1.00). Figure 3-5 plots the NO_x removal efficiency and the NH_3 slip (as a percentage of the inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio. The air-to-cloth ratio tests were performed in the following order: 2.0, 4.0, 1.5, and 3.0 ft/min (nominal air-to-cloth ratios). In Figure 3-5 the NO_x removal efficiency at a nominal air-to-cloth ratio of 2.0 ft/min is higher than the NO_x removal efficiency at a nominal air-to-cloth ratio of 1.5 ft/min. The same relationship is true for NO_x removal efficiencies at nominal air-to-cloth ratios of 3.0 and 4.0 ft/min. The results show a definite effect due to air-to-cloth ratio, but it also appears the reactivity of the catalyst degraded with time during the 100-hr run. However, it is not possible to separate the effects of air-to-cloth ratio and decreasing catalyst activity. Figure 3-6 plots NO_x removal efficiency as a function of time. This figure shows more clearly the decreasing NO_x removal efficiency with time.

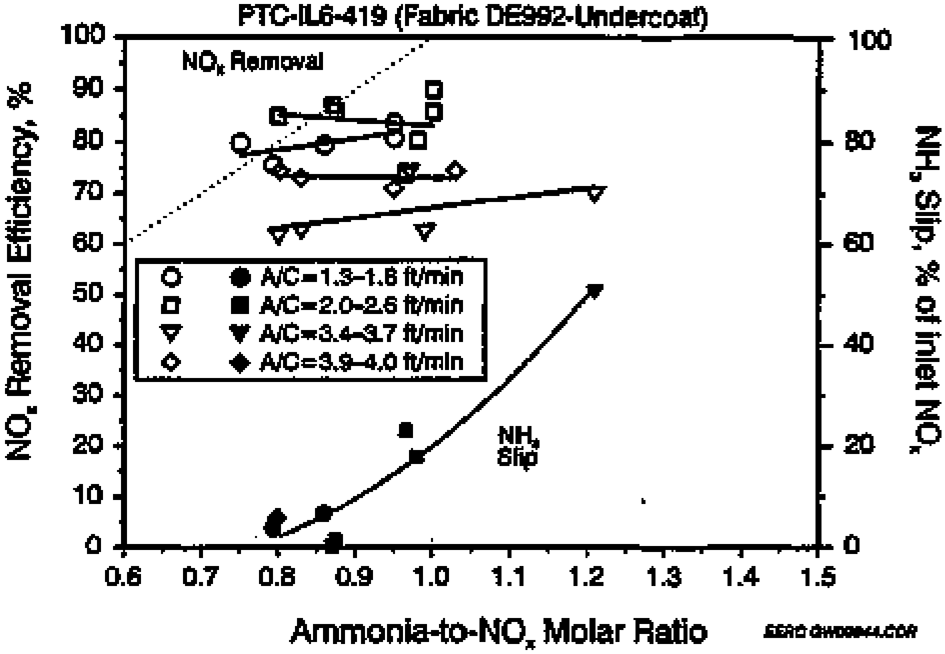

Figure 3-5. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Run PTC-IL6-419: average inlet NO$_x$ = 828 ppm, average baghouse temperature = 687°F.

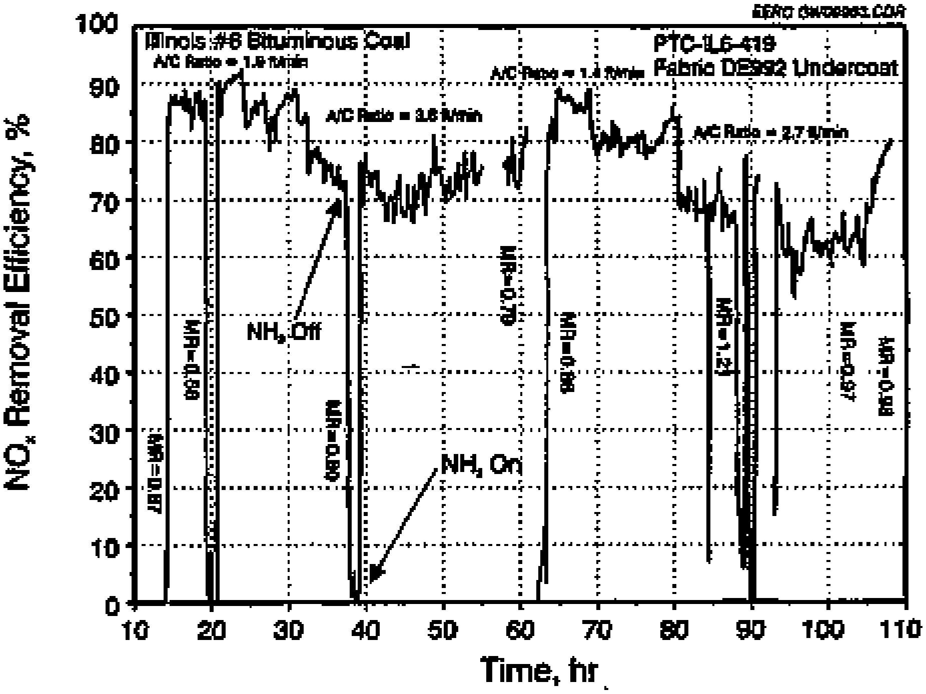

Figure 3-6. NO$_x$ removal efficiency as a function of time for Run PTC-IL6-419.

At an ammonia-to-NO_x molar ratio of 0.80 and an air-to-cloth ratio of 2.0 ft/min, the NO_x removal efficiency was roughly 80%, and the ammonia slip was roughly 5% of the inlet NO_x concentration. The initial results were better than those observed with the DE484 and G143 fabric filters. This was probably due to the increased amount of catalyst on the DE992 bags.

Ammonia slip ranged from <1% of the inlet NO_x at an air-to-cloth ratio of 2.2 ft/min early in the test to 51% of the inlet NO_x at an air-to-cloth ratio of 2.7 ft/min near the end of the test (average inlet NO_x concentration during the different test periods ranged from 632 ppm to 936 ppm). The ammonia slip values also indicate a decrease in NO_x removal efficiency with time. The three highest slip measurements were taken near the end of the 100-hr test at lower air-to-cloth ratios.

Used and unused samples of the catalyst-coated fabric were submitted for analysis to determine the concentration of vanadium on the fabric. Results showed a vanadium concentration of 6200 μg/g on the unused sample and 5033 μg/g on the used sample. This difference is not consistent with the ash dilution effect anticipated and does not appear to fall within the variability of the coating process. Therefore, the results indicate a loss of catalyst from the bags and an explanation for the observed decrease in catalyst reactivity with time. These data may indicate that the undercoat applied to the fabric prior to the catalyst coating resulted in a weaker bond between the catalyst and undercoat or the undercoat and fabric than observed for the catalyst coatings applied to the DE484 and G143 fabrics.

3.2.1.7 PTC-IL6-428

The catalyst-coated fabric filters used for Run PTC-IL6-428 were made from a 22-oz/yd^2 double-beam weave fabric (DE992) coated with seven coats of the vanadium–titanium catalyst. New bags were used for this 100-hr test, which was a repeat of a previous test (PTC-IL6-414) in which the bags were damaged during heat treatment.

Results from this 100-hr test were very good when compared to previous tests. NO_x removal efficiency ranged from 79% (air-to-cloth ratio = 3.0, ammonia-to-NO_x molar ratio = 0.68) to 96% (air-to-cloth ratio = 2.0, ammonia-to-NO_x molar ratio = 0.98). Figure 3-7 plots the NO_x removal efficiency and the ammonia slip (as a percentage of the inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio. At lower ammonia-to-NO_x molar ratios, NO_x removal efficiency was greater than theoretically possible based on Reactions 1, 2, and 3:

$$4NH_3 + 4NO + O_2 \rightarrow 6H_2O + 4N_2 \qquad [1]$$

$$4NH_3 + 2NO + 2O_2 \rightarrow 6H_2O + 3N_2 \qquad [2]$$

$$NO + NO_2 + 2NH_3 \rightarrow 3H_2O + 2N_2 \qquad [3]$$

It was originally thought that some of the NO or NO_2 was being reduced as a result of Reaction 4:

$$4NH_3 + 6NO \rightarrow 6H_2O + 5N_2 \qquad [4]$$

However, it was possible the ammonia flowmeter was delivering more ammonia than indicated, leading to higher ammonia-to-NO_x molar ratios than previously thought. Ammonia-to-NO_x molar ratios were calculated based on the following equation, assuming the ammonia slip concentrations were accurate and the difference between the inlet and outlet NO_x concentrations was due solely to Reactions 1–3. In light of the ammonia injection problems, the NO_x removal efficiency and ammonia slip data were reevaluated using the following equation:

$$NH_3/NO_x \text{ molar ratio} = \frac{(NH_3 \text{ slip [ppm]} + NO_x \text{ removal [\%]} \times \text{Inlet } NO_x \text{ [ppm]})}{\text{Inlet } NO_x \text{ (ppm)}}$$

Based on these values, the NO_x removal efficiencies during this 100-hr test were very near theoretical levels. The NO_x removal efficiencies and the ammonia slip values gave no indication of loss of catalyst from the bags or deactivation of the catalyst with time. An extrapolated value (due to lack of data at this ammonia-to-NO_x molar ratio) for NO_x removal efficiency at an ammonia-to-NO_x molar ratio of 0.80 and an air-to-cloth ratio of 2.0 ft/min was roughly 80%, and the ammonia slip was roughly 1% or less of the inlet NO_x concentration. This result is better than those observed with the DE484 and G143 fabrics and similar to the initial results with the undercoated DE992 fabric.

Figure 3-8 plots the NO_x removal efficiency as a function of time for the 100-hr test. Near the end of the 100-hr test, at a nominal air-to-cloth ratio of 3.0 ft/min, the NO_x removal efficiency rises and falls with the bag-cleaning cycle. The data showed that the NO_x removal efficiency dropped from roughly 86% to 80% each time the bags were cleaned. It is not clear if this is due to the frequent cleaning cycles and general dust cake characteristics or the formation of pinholes.

Ammonia slip ranged from 1.3% of the inlet NO_x concentration at an air-to-cloth ratio of 2.0 ft/min to 14% of the inlet NO_x concentration at an air-to-cloth ratio of 4.0 ft/min (average inlet NO_x concentration during the different test periods ranged from 796 to 916 ppm).

Results from the five 100-hr fabric-screening tests established the 22-oz/yd^2 (DE992) catalyst-coated fabric most reactive with respect to high NO_x removal and low ammonia slip. The DE484- and DE992-undercoat fabrics showed similar performance at ammonia-to-NO_x molar ratios of 0.8 and air-to-cloth ratios of 2.0 ft/min, but the DE992 filter bags showed no degradation with time and had consistently higher NO_x removal efficiencies and lower ammonia slips. Based on these results, the DE992 catalyst-coated fabric was selected for use in preparation of filter bags for the pulse-jet tests.

The difference between the NO_x reduction and ammonia slip results from the tests using the DE484 catalyst-coated fabric and the DE992 catalyst-coated fabric may be due to the amount of catalyst on the bags. Therefore, it is recommended that further development work be completed to determine an optimum number of catalyst coats for both the DE484 and DE992 fabrics.

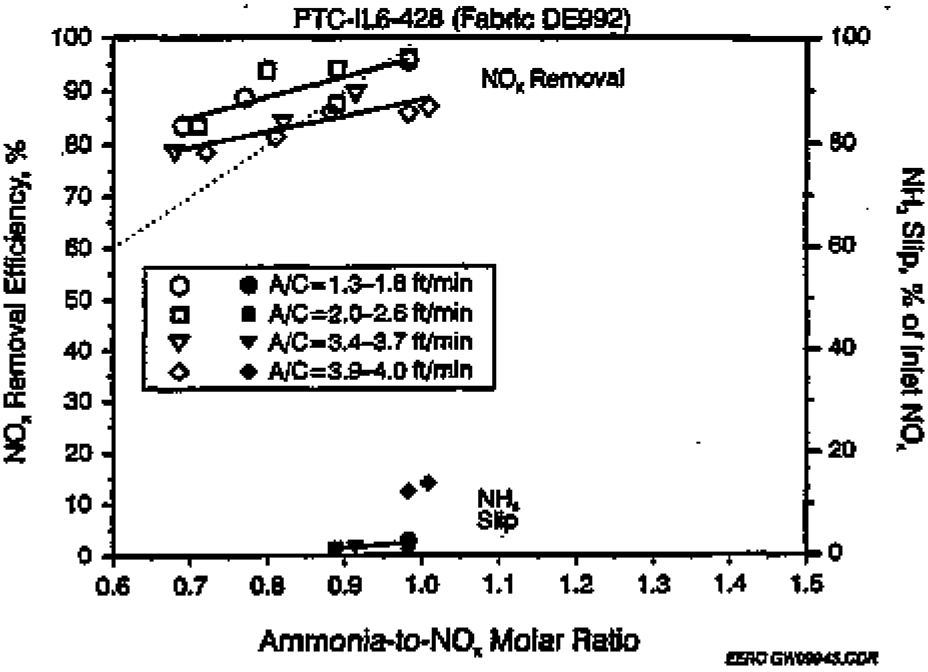

Figure 3-7. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Run PTC-IL6-428: average inlet NO$_x$ = 840 ppm, average baghouse temperature = 650°F.

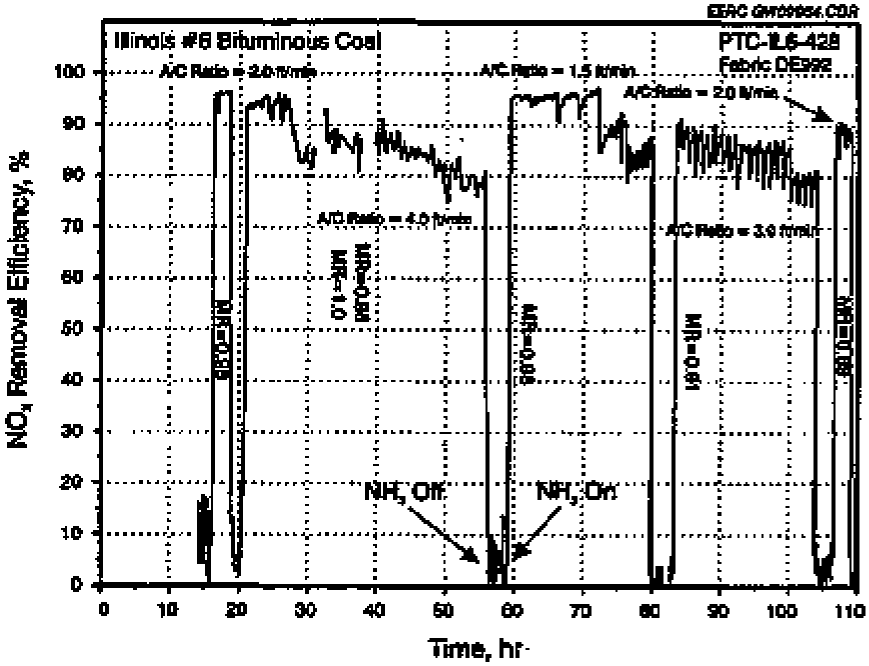

Figure 3-8. NO$_x$ removal efficiency as a function of time for Run PTC-IL6-428.

3.2.2 Fuel Impacts on Catalyst-Coated Fabric Performance

Four 100-hr reverse-gas test periods were completed to evaluate the effects of coal type on the ability of the catalyst-coated fabric to control particulate and NO_x emissions. Flue gas was generated by firing a washed Illinois No. 6 bituminous coal (PTC-IL6-415), a Blacksville bituminous coal (PTC-BV-423), a Black Thunder subbituminous coal (PTC-BT-424), and a North Dakota Beulah lignite (PTC-BU-425) in a pilot-scale pc-fired combustor. The average ultimate, proximate, and sieve analyses for each coal used are presented in Table 3-6. The four fuels used during this series of experiments represent a broad range of fuel characteristics in terms of moisture content (<2% to 32%), ash content (5% to 11%) and chemical characteristics (low and high alkali content), sulfur content (0.3% to 3.3%), and heating value (7000 to 13,000 Btu/lb). Each 100-hr test was to consist of 12 individual test periods in order to address the effects of air-to-cloth ratio (1.5, 2.0, 3.0, and 4.0 ft/min) and ammonia-to-NO_x molar ratio (0.80, 0.90, and 1.00).

The catalyst-coated fabric filters used for these tests were made from the 14-oz/yd^2 single-beam weave (DE484) fabric, coated with seven coats of the vanadium–titanium catalyst. Heat treatment for all bags consisted of a 3.5- to 5-hr period during which the baghouse temperature was raised from roughly 350° to 690°F, followed by a heat treatment period of roughly 4 to 7 hours at 700°F and 2.0% to 4.5% oxygen. The flue gas used for heat treatment was generated by firing the pilot-scale combustor on natural gas.

3.2.2.1 PTC-IL6-415

Results from Run PTC-IL6-415 demonstrated NO_x removal efficiencies ranging from 68% (air-to-cloth ratio = 3.6, ammonia-to-NO_x molar ratio = 0.92) to 90% (air-to-cloth ratio = 1.7, ammonia-to-NO_x molar ratio = 1.18). Figure 3-9 plots the NO_x removal efficiency and the ammonia slip (as a percent of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio. As a basis of comparison with other fuel tests, the NO_x removal efficiency at an air-to-cloth ratio of 2.0 ft/min and an ammonia-to-NO_x molar ratio of 0.80 was roughly 75%, and the ammonia slip was roughly 3% of the inlet NO_x concentration. A complete discussion of the results from this 100-hr test is provided in Section 3.2.1.3.

3.2.2.2 PTC-BV-423

The results from the 100-hr test PTC-BV-423 showed that the NO_x reduction ranged from 74% (air-to-cloth ratio = 3.1 ft/min, ammonia-to-NO_x molar ratio = 0.83) to 89% (air-to-cloth ratio = 2.0 ft/min, ammonia-to-NO_x molar ratio = 1.00). Figure 3-10 plots the NO_x removal efficiency and the ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio. The effect of air-to-cloth ratio is evident in the NO_x removal data as well as the ammonia slip data.

3.2.2.3 PTC-BT-424

The results from Run PTC-BT-424 were similar to the previous 100-hr test. The NO_x reduction ranged from 76% (air-to-cloth ratio = 4.2 ft/min, ammonia-to-NO_x molar ratio = 0.84) to 90% (air-to-cloth ratio = 2.0 ft/min, ammonia-to-NO_x molar ratio = 1.05). Figure 3-11 plots the NO_x removal efficiency and the ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio. The effect of air-to-cloth ratio on NO_x removal efficiency is not as pronounced as with previous data, but the

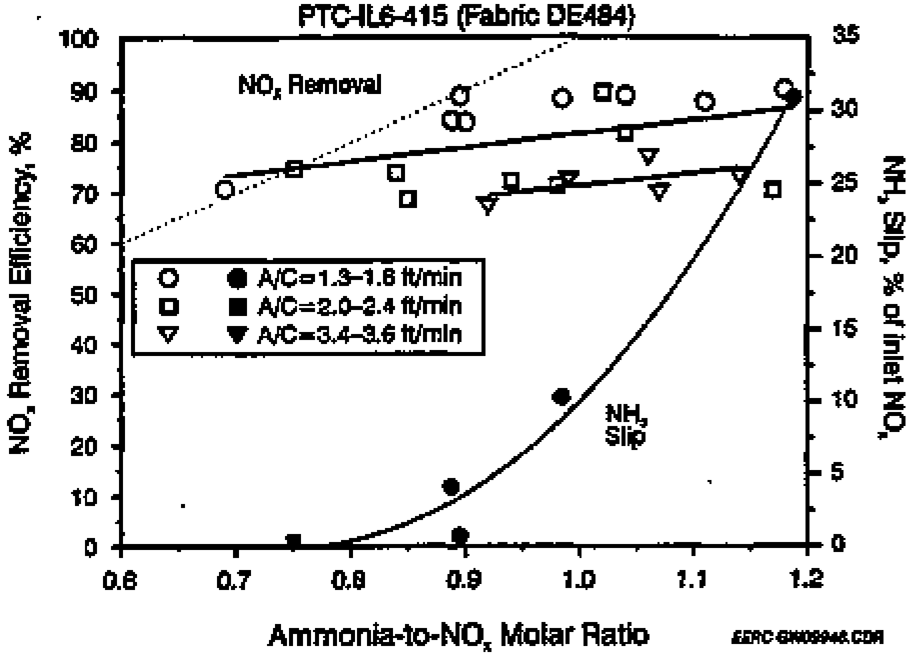

Figure 3-9. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Run PTC-IL6-415: average inlet NO$_x$ = 818 ppm, average baghouse temperature = 660°F.

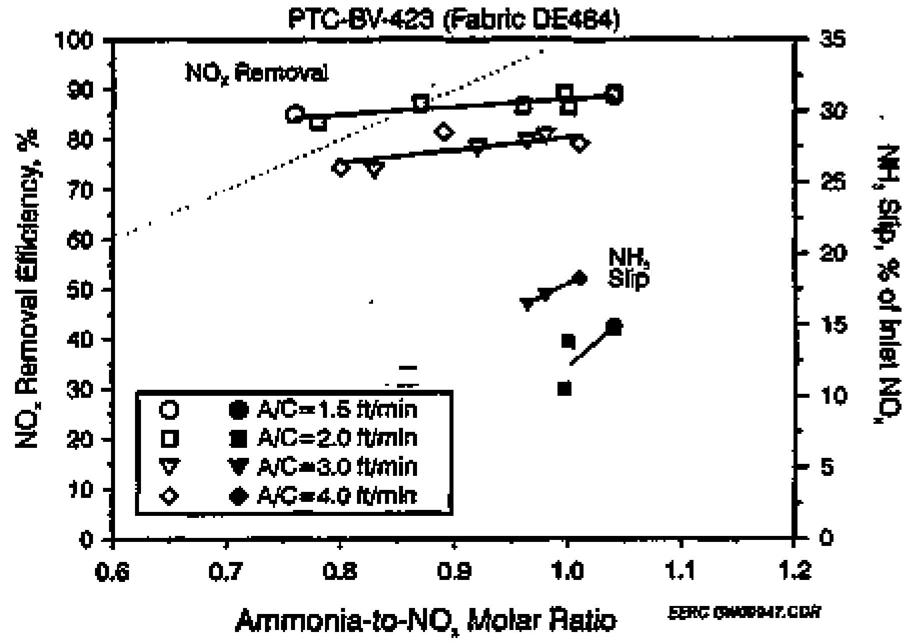

Figure 3-10. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Run PTC-BV-423: average inlet NO$_x$ = 857 ppm, average baghouse temperature = 663°F.

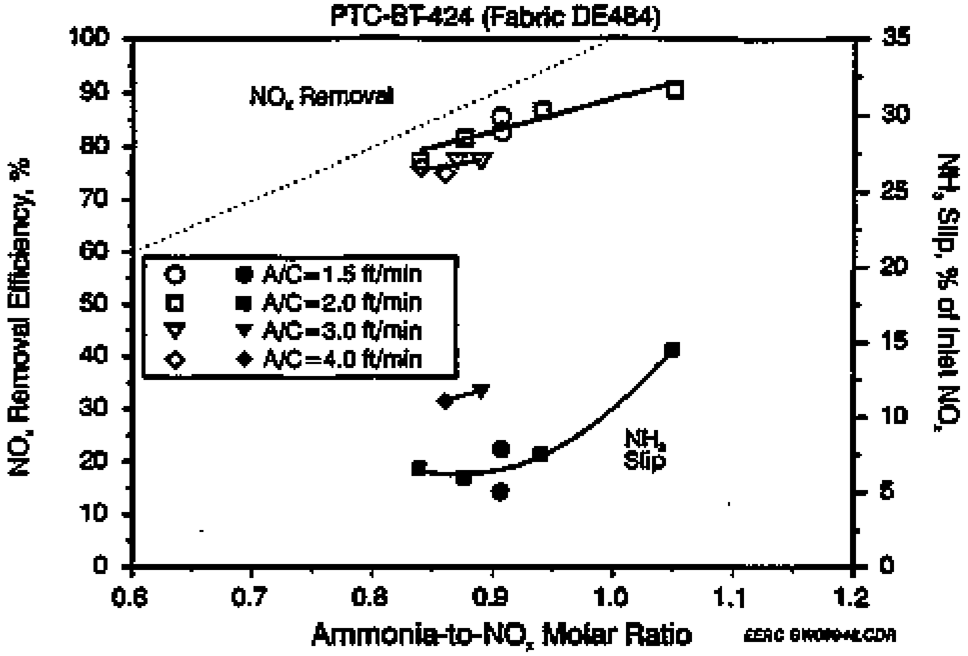

Figure 3-11. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Run PTC-BT-424: average inlet NO$_x$ = 799 ppm, average baghouse temperature = 664°F.

effect on ammonia slip is consistent as with previous data. A less pronounced air-to-cloth ratio effect may be due to dust cake characteristics resulting from combustion of a subbituminous coal as opposed to a bituminous coal. Figure 3-12 plots the NO$_x$ removal efficiency as a function of time for the 100-hr test. It appears the NO$_x$ removal efficiency decreased from the first to the last test period (nominal air-to-cloth ratio of 2.0 ft/min), but the ammonia-to-NO$_x$ molar ratio was 1.05 and 0.95 during the first and second test periods and 0.84 during the last test period. There are no other indications of a decrease in catalyst reactivity or loss of catalyst from the bags.

3.2.2.4 PTC-BU-425

The results from Run PTC-BU-425 were similar to results from the previous 100-hr tests. The NO$_x$ reduction ranged from 71% (air-to-cloth ratio = 3.0 ft/min, ammonia-to-NO$_x$ molar ratio = 0.73) to 91% (air-to-cloth ratio = 2.0 ft/min, ammonia-to-NO$_x$ molar ratio = 0.99). Figure 3-13 plots the NO$_x$ removal efficiency and the ammonia slip (as a percentage of inlet NO$_x$ concentration) as a function of ammonia-to-NO$_x$ molar ratio. Again, the effect of air-to-cloth ratio on NO$_x$ removal efficiency is evident in the NO$_x$ removal data as well as in the ammonia slip data. Figure 3-14 plots the NO$_x$ removal efficiency as a function of time for the 100-hr test. It appears the NO$_x$ removal decreased from the first to the last test period (nominal air-to-cloth ratio of 2.0 ft/min), but the ammonia-to-NO$_x$ molar ratio was 1.1 during the first test period and 0.90 during the last

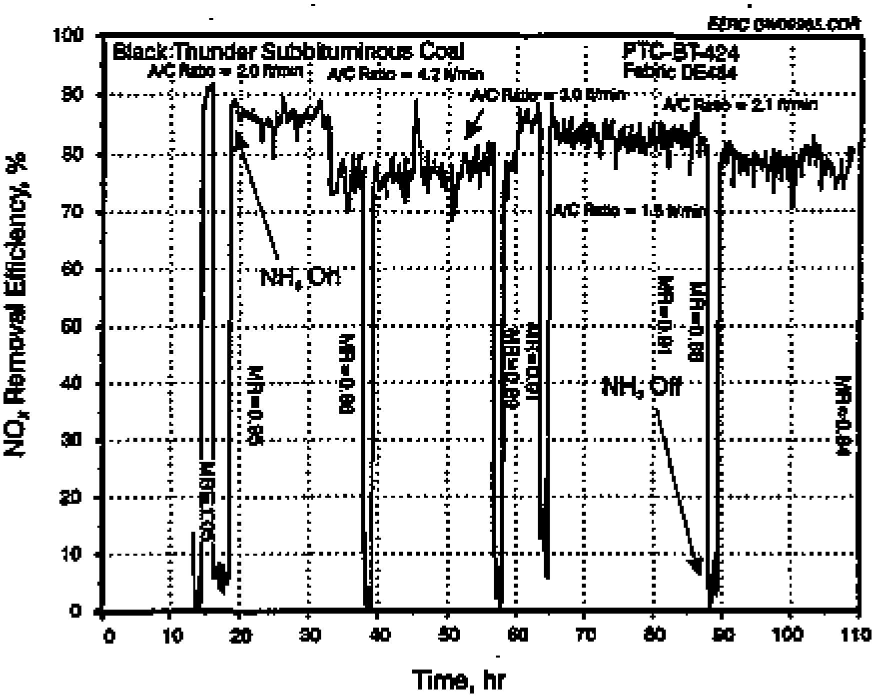

Figure 3-12. NO_x removal efficiency as a function of time for Run PTC-BT-424.

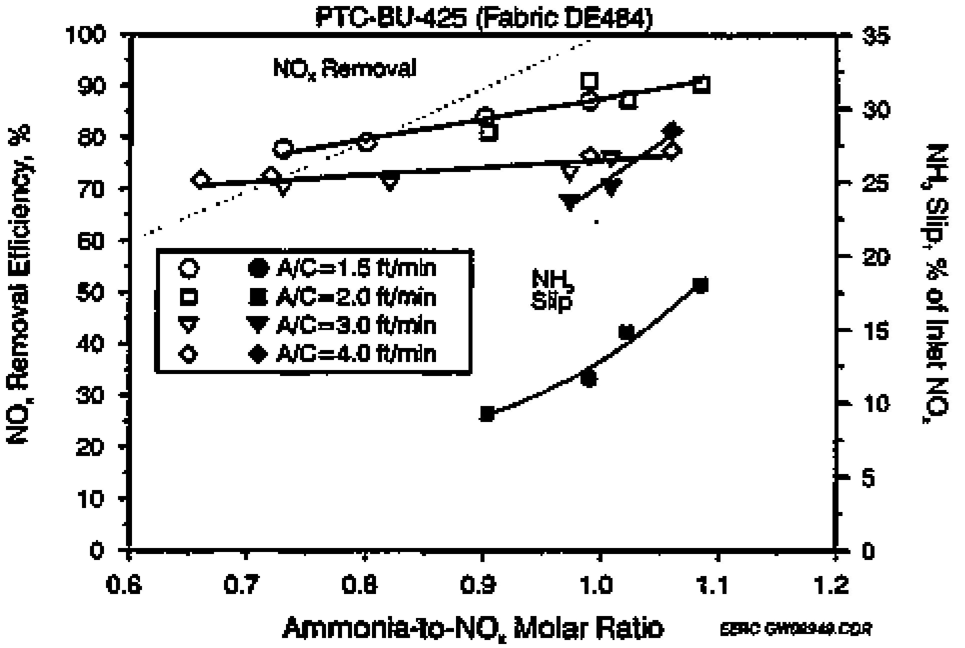

Figure 3-13. NO_x removal efficiency and ammonia slip versus ammonia-to-NO_x molar ratio for Run PTC-BU-425: average inlet NO_x = 645 ppm, average baghouse temperature = 650°F.

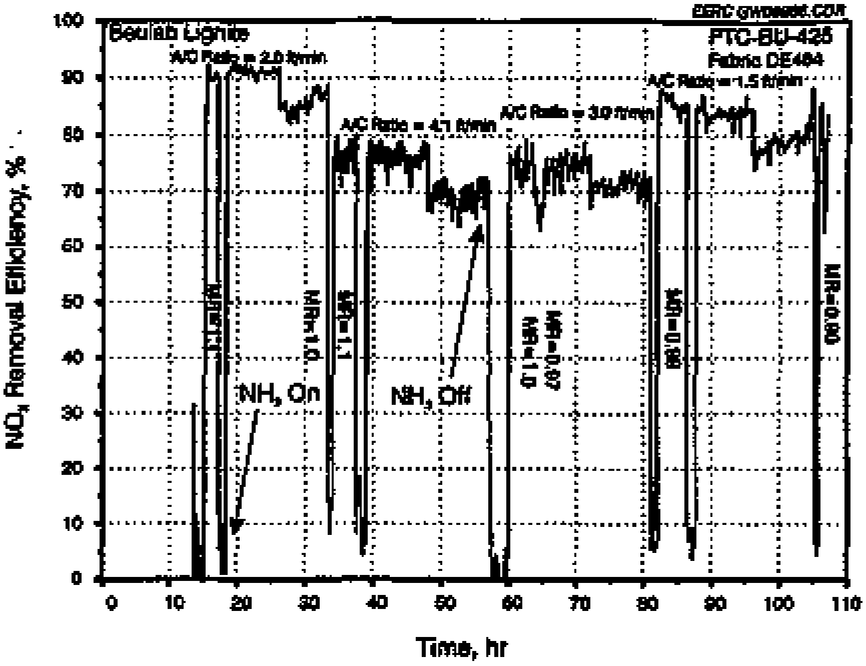

Figure 3-14. NO_x removal efficiency as a function of time for Run PTC-BU-425.

test period. There are no other indications of a decrease in catalyst reactivity or loss of catalyst from the bags.

Figure 3-15 plots the NO_x removal efficiency and the ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio for the four 100-hr tests (PTC-IL6-415, PTC-BV-423, PTC-BT-424, and PTC-BU-425). This figure indicates coal type had no discernable effect on NO_x removal, which is consistent with earlier bench-scale tests (12). The effect of air-to-cloth ratio was possibly due to its effect on dust cake development and residual dust cake characteristics. Since the pilot-scale reverse-gas baghouse was cleaned off-line and operated over a relatively narrow range of air-to-cloth ratios, the effect of dust cake properties on NO_x reduction and ammonia slip may be less significant than the effects observed during operation of the pulse-jet baghouse with on-line cleaning.

3.2.3 Flue Gas Temperature Effects on Catalyst-Coated Fabric Performance

3.2.3.1 PTC-IL6-426

During Run PTC-IL6-426, seven individual experimental periods were completed in order to address the effects of bulk gas baghouse temperature (500°, 550°, 600°, 650°, 700°, and 750°F) on NO_x removal efficiency using DE484 catalyst-coated fabric. For all tests, air-to-cloth ratio was held constant at 2 ft/min, and the ammonia-to-NO_x molar ratio was nominally 0.9. Flue gas was generated by firing a washed Illinois No. 6 bituminous coal in the pilot-scale pc-fired combustor.

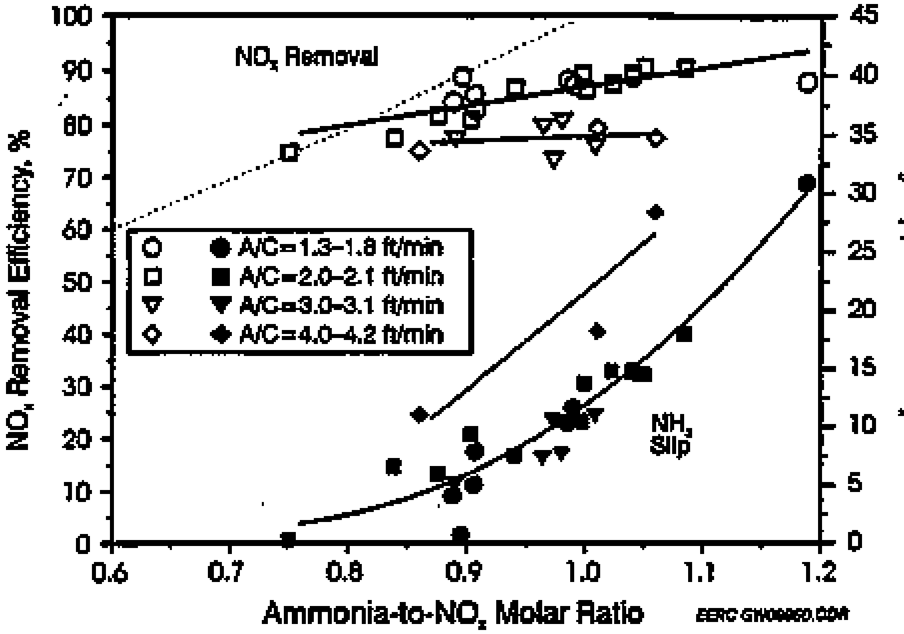

Figure 3-15. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Runs PTC-IL6-415, PTC-BV-423, PTC-BT-424, and PTC-BU-425.

Figure 3-16 plots the NO$_x$ removal efficiency as a function of time for the 100-hr test. The NO$_x$ reduction showed a strong dependence on temperature. Figure 3-17 plots the NO$_x$ removal efficiencies for Run PTC-IL6-426 and additional test periods at the ends of Runs PTC-IL6-428, PTC-BV-429, and PTC-BT-430 as a function of bulk gas baghouse temperature.

During Run PTC-IL6-426, at a nominal bulk gas baghouse temperature of 500°F, the NO$_x$ removal efficiency averaged 16%, the calculated ammonia-to-NO$_x$ molar ratio was 0.73, and the corresponding ammonia slip was 458 ppm. The average NO$_x$ removal efficiency increased to 24% at a nominal bulk gas baghouse temperature of 550°F, the ammonia-to-NO$_x$ molar ratio was 0.89, and the corresponding ammonia slip was 556 ppm. The NO$_x$ removal efficiency continued to increase with increasing bulk gas baghouse temperature until roughly 650°F. At the higher temperatures, NO$_x$ removal efficiency leveled out and appeared to decrease slightly at 750°F. However, the observed decrease was consistent with decreases in catalyst reactivity observed during previous tests. Therefore, it is not clear whether the decrease was due to temperature or simply a decrease in catalyst reactivity with time. The NO$_x$ removal efficiencies at nominal bulk gas baghouse temperatures of 650°–700°F range from 78% at 650°F to 87% at 700°F at molar ratios of 0.96 and 0.91, respectively.

In order to verify the results, additional data were generated by completing short test periods at the end of Runs PTC-IL6-428, PTC-BV-429, and PTC-BT-430 using DE992 catalyst-coated fabric. During Run PTC-IL6-428 at an air-to-cloth ratio of 1.91 ft/min, an

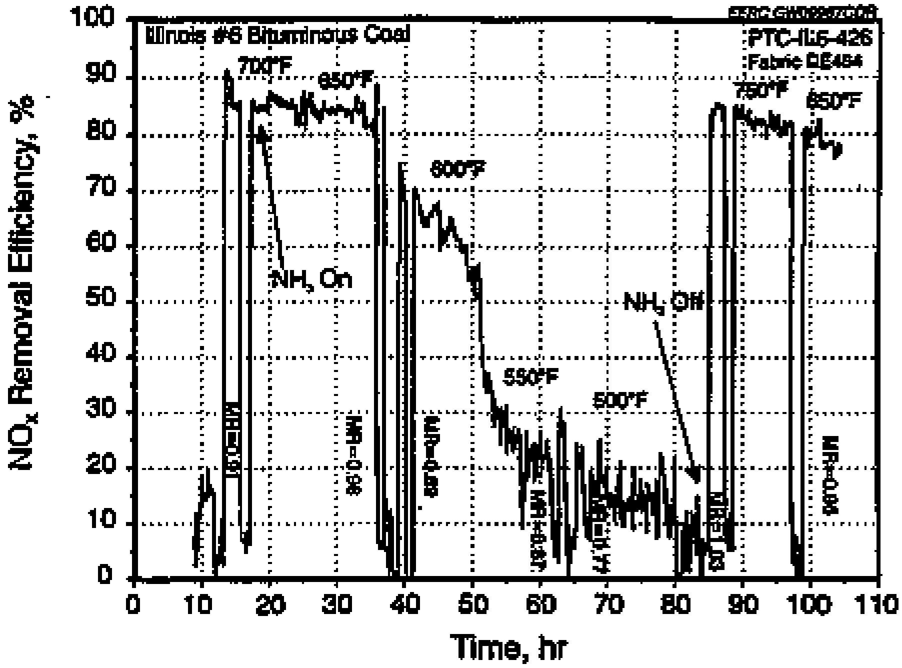

Figure 3-16. NO_x removal efficiency as a function of time for Run PTC-IL6-426.

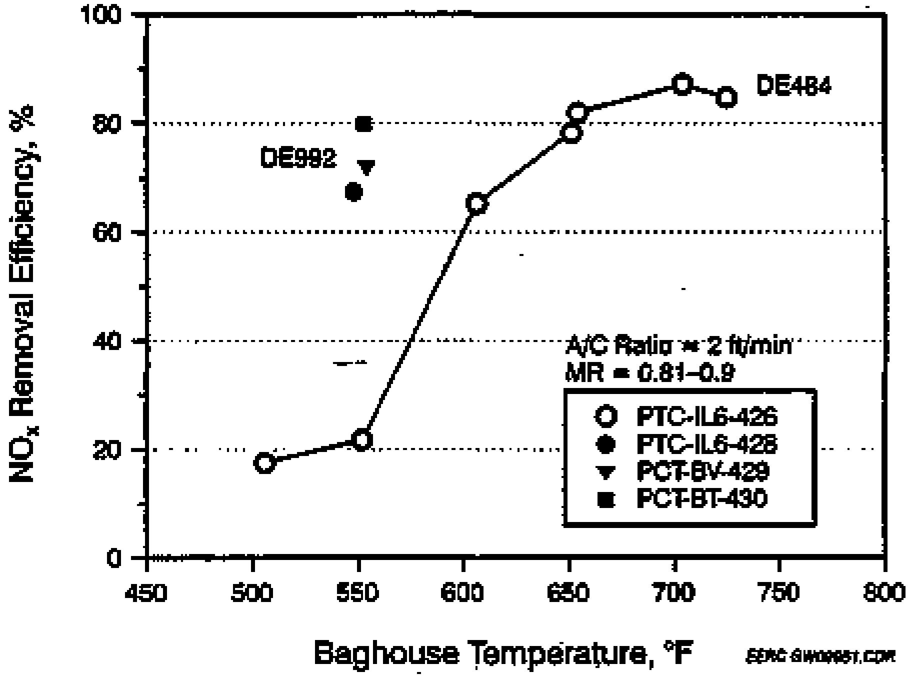

Figure 3-17. NO_x removal efficiency as a function of baghouse temperature.

average baghouse bulk gas temperature of 548°F, and an ammonia-to-NO_x molar ratio of 0.81, NO_x removal averaged 67%. During Run PTC-BV-429, at an air-to-cloth ratio of 2 ft/min, an ammonia-to-NO_x molar ratio of 0.87, and an average baghouse bulk gas temperature of 554°F, NO_x removal averaged 72%, and the ammonia slip was 13% of the inlet NO_x concentration. During Run PTC-BT-430, at an ammonia-to-NO_x molar ratio of 0.86 and an average baghouse bulk gas temperature of 553°F, NO_x removal averaged 80%, and the ammonia slip was 5.9% of the inlet NO_x concentration.

The operating temperature affects the NO_x removal efficiency, but the data indicate the effect is not as severe with the DE992 fabric (Runs PTC-IL6-428, PTC-BV-429, and PTC-BT-430). This may be due to the increased amount of catalyst available to promote the reduction reaction on the DE992 fabric. The DE992 fabric has over 33% more vanadium catalyst than the DE484 fabric (0.465 g/ft^2 versus 0.348 g/yd^2). Further bench-scale testing may be appropriate to better evaluate the effect of temperature on various catalyst-coated fabric types.

3.2.3.2 PTC-IL6-427

The bags used for Run PTC-IL6-427 were the same bags that were used for the previous 100-hr test (PTC-IL6-426). Two individual experimental periods were completed in order to address the effects of an upset condition on NO_x removal efficiency. The bags were exposed to temperatures below the acid (H_2SO_4) dew point (approximately 150°F) and the water dew point (approximately 140°F). Air-to-cloth ratio was held constant at 2 ft/min, and the ammonia-to-NO_x molar ratio was nominally 0.9.

To expose the bags to an acid dew point, the bulk gas baghouse temperature was lowered to roughly 150°F for more than three hours. In addition, SO_3 was injected for two hours to achieve a flue gas concentration of roughly 20 ppm. The NO_x removal efficiency was affected by the exposure of the catalyst-coated fabric to an acid dew point. After the first upset condition, the average bulk gas baghouse temperature was raised to roughly 655°F, and NO_x reduction averaged 65%. In a previous test (PTC-IL6-426), at similar operating conditions with the same set of bags, NO_x removal efficiency averaged 84%. This represents a 23% decrease in NO_x removal efficiency.

After exposure to the water dew point for two hours, NO_x removal efficiency averaged 66% at an average bulk gas baghouse temperature of 658°F. Exposure to the water dew point did not have an additional effect on NO_x removal efficiency.

It can be concluded that exposure to the acid dew point adversely affected the catalyst-coated fabric, but no conclusion can be made with respect to these data concerning the effect of the water dew point.

Used (after Run PTC-IL6-427) and unused samples of the catalyst-coated fabric were submitted to determine the concentration of vanadium on the bags. Results showed a vanadium concentration of 7900 μg/g on the unused sample and 5900 μg/g on the used sample. This difference does not appear to fall within the variability of the coating process or the dilution effect of ash on the bags and indicates loss of catalyst from the bags. Another possibility is that the condensed acid also had a dilution effect on the vanadium measurements.

Bench-scale results for clean fabric treated with sulfuric acid showed a complete loss of catalyst reactivity for 0.1 M H_2SO_4 and only 58.4% NO_x reduction for fabric treated with 0.001 M H_2SO_4. Ammonia slip could not be measured in the presence of H_2SO_4. Catalyst reactivity was completely recovered after washing the H_2SO_4-treated fabric with distilled water, 70.4% NO_x reduction versus 71.5% for clean fabric and 68% NO_x reduction for clean fabric treated with tap water.

Ash-coated fabric samples from PTC-BV-434 and the 1642- and 5136-hr steam plant bags treated with 0.1 M H_2SO_4 showed better NO_x removal than the acid-treated clean fabric. However, NO_x measurements were difficult to make because of acid residues blocking the capillary tubes in the NO_x analyzer. After thorough washing of these fabrics with distilled water, catalyst reactivity was not recovered, see Table 3-1.

Both clean and ash-coated fabric samples treated with tap water showed a 2%–5% decrease in NO_x reduction. Distilled water showed a 1% decrease in NO_x reduction. City tap water contains 140–160 mg/L of calcium carbonates, bicarbonates, and sulfates. These compounds were shown to cause catalyst deactivation as reported in Section 3.1.2 on catalyst reactivity.

When both the bench-scale and pilot-scale data are considered, moisture dew points do not appear to have a detrimental effect on catalyst reactivity for either clean fabric or catalyst-coated fabric with a residual dust layer. Acid dew points do have a negative effect on catalyst reactivity, but reactivity can be recovered by thoroughly washing a clean fabric surface, indicating that the condensed acid is physically inhibiting reactivity and no permanent chemical attack is occurring. However, exposure of a catalyst-coated fabric, having a residual dust layer, to an acid dew point will result in permanent catalyst damage, requiring the replacement of the catalyst-coated bags.

3.2.4 Fabric Filter Performance

Conventional fabric filter performance is usually determined by its particulate collection efficiency and operating pressure drop. These performance characteristics were also measured to determine the overall performance of the catalyst-coated fabric filter. Particulate collection efficiency was calculated from measured mass emissions using a modified EPA Method 5. In addition, an aerodynamic particle sizer (APS) was also used intermittently. Multicyclones and Coulter counter were used to determine the particle-size distribution. The reverse-gas baghouse was cleaned off-line using a set time period. If the pressure drop began to rise uncontrollably, the time period was shortened. In general, the time period was set at 1–2 hours. Pressure drop across the baghouse was monitored continuously using pressure transducers, with the data recorded on a strip chart and data logger.

Several factors made the particulate collection efficiency and pressure drop data difficult to interpret. The first is that the operating conditions, air-to-cloth ratio and ammonia-to-NO_x molar ratio, were being changed during each run. Air-to-cloth ratio is one of the primary variables determining the pressure drop across the fabric filter. In general, it was varied from 1.5 to 4.0 ft/min. Although the ammonia-to-NO_x molar ratio does not have much impact on the pressure drop, it can skew EPA Method 5 results. If the ammonia-to-NO_x molar ratio is high or NO_x removal is so low that there is a substantial amount of ammonia slip present in the flue gas, SO_3 will react with the ammonia at the cooler temperatures of the EPA Method 5 filters, resulting in higher-than-expected measured dust loadings. At the outlet side, depending on the ammonia slip, up to 25% of the total particulate can be ammonium sulfate or bisulfate. In almost all cases where the baghouse operating temperature was 650°F and the ammonia slip was high (>100 ppm), the particulate collection efficiency was less than 99.8%. Although it was difficult to totally quantify the pressure drop and particulate collection efficiency within each test, the impact of fabric type, coal type, and temperature could be determined qualitatively by comparing the results from various tests.

3.2.4.1 Fabric Filter Performance for Catalyst-Coated Bag-Screening Tests

Three different fabrics were tested on the reverse-gas baghouse. The first fabric was designated DE484. This fabric is woven from DE-fibers (6.5 μm) having a fabric weight of 14 oz/yd^2 in a single-beam weave. The second type of fabric (G143) was woven from G-fibers (9.0 μm) having a 14-oz/yd^2 fabric weight and a single-beam weave. The third fabric type (DE992) was again woven from a DE-fiber; however, the fabric weight was 22 oz/yd^2 and had a double-beam weave. Table 3-5 presents the fabric and catalyst coating applied to each of the different types of bags screened. The coal used for these screening tests was a washed Illinois No. 6 bituminous coal.

Although the air-to-cloth ratio varied from 1.2 to 4.0 ft/min during the fabric-screening tests, there did not appear to be much difference in particulate collection efficiency between the three fabrics. For the DE484 fabric, the particulate collection efficiency was in the range of 99.09%–99.90%; for G143 fabric, the particulate collection efficiency was in the range of 99.13%–99.85%; and 99.15%–99.98% collection efficiency was observed for the DE992 fabric. Figure 3-18 shows a comparison of the average particulate collection efficiency with error bars (based on a 95% confidence interval) for each of the three fabric types tested. The data in the figure illustrate that there is no statistical difference in the average particulate collection efficiency for the three fabric types.

In Figure 3-19, the APS data show that at a nominal air-to-cloth ratio of 3 ft/min, the G143 and DE484 respirable mass emissions were very similar. For fabric DE992, the respirable mass emissions did appear to be somewhat lower. Several reasons may be possible for this. First, since the DE992 fabric is heavier, it may have been more effective at collecting fine particles than the lighter-weight fabrics even though the overall emissions were about the same. Second, the data for the DE992 fabric were collected about 20 hours further into the run than those for the DE484 and G143, which may have resulted in a better-developed dust cake.

As would be expected, since the coal was an Illinois No. 6 bituminous coal in all cases, the Coulter counter data showed that the inlet particle-size distribution was approximately the same for each of the tests, with an average volumetric mean diameter of 21 μm. The multicyclone and Coulter counter data for each of the coal types used during the project are presented in Appendix C.

In addition to the particulate collection efficiency, the operating pressure drop is an important parameter determining overall fabric filter performance. Although the varying air-to-cloth ratio made data interpretation difficult, there did not appear to be any significant differences between the DE484 and G143 fabrics, which were the same weight

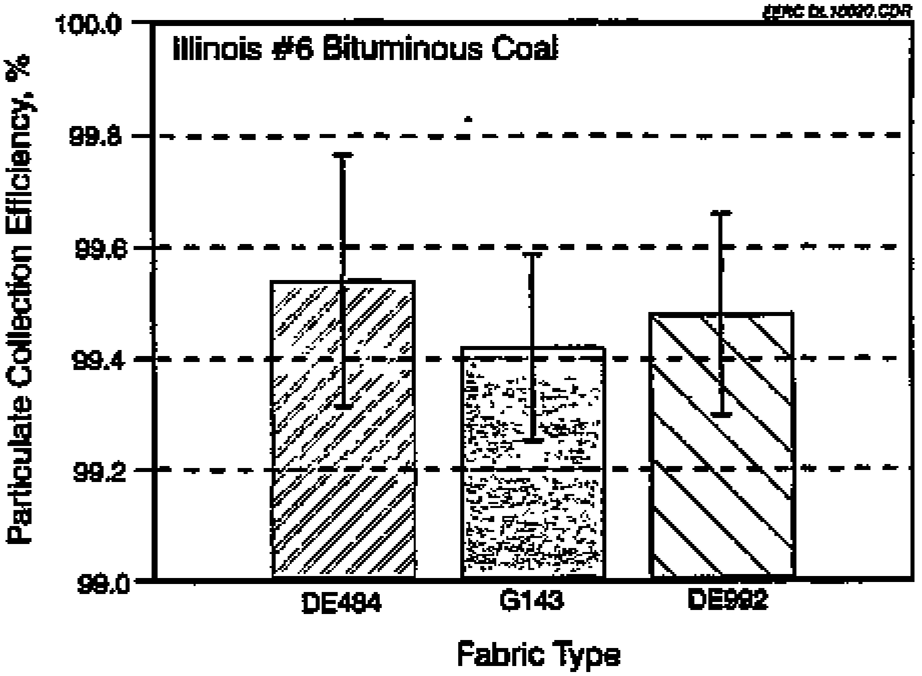

Figure 3-18. The effect of fabric type on the average particulate collection efficiency for three types of catalyst-coated fabric.

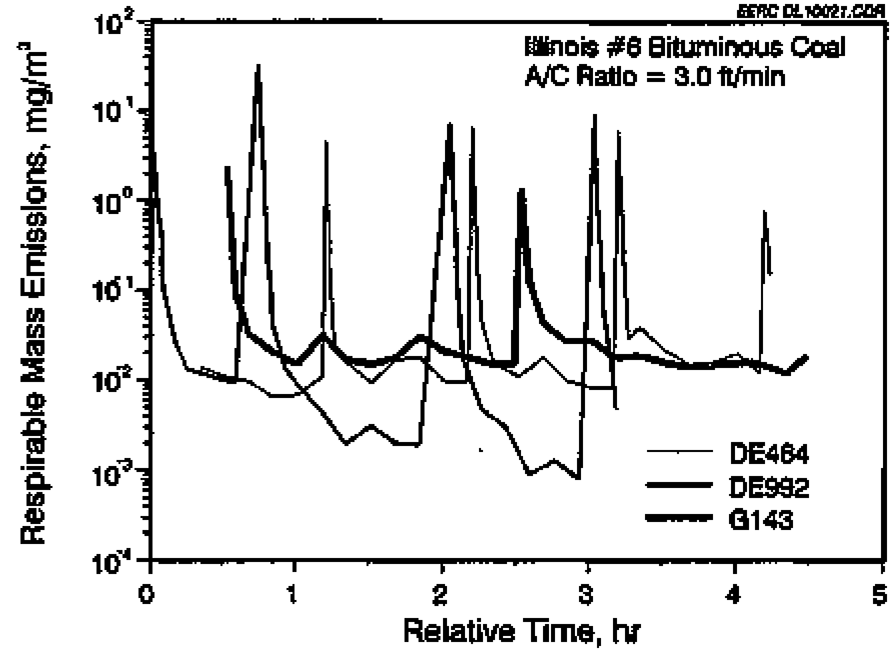

Figure 3-19. The effect of fabric type on respirable mass emissions for three types of catalyst-coated fabric.

and weave (14 oz/yd^2 with a single-beam weave). However, it does appear that for the DE992 fabric, which was a 22-oz/yd^2 fabric with a double-beam weave, the pressure drop was more difficult to control. This may be a result of the heaver fabric being more difficult to clean, since reverse-gas cleaning is a very gentle method. Even though the pressure drop was more difficult to control for the DE992 fabric than for the other types, in general, the pressure drop was much more influenced by time and air-to-cloth ratio than by fabric type. In all cases, the pressure drop was increasing with time when the air-to-cloth ratio was greater than 3.5 ft/min, making it necessary to increase cleaning frequency. At lower air-to-cloth ratios, the pressure drop appeared to stabilize within a few hours. Figures 3-20 to 3-22 show the pressure drop data for the three different fabrics.

3.2.4.2 Fuel Impacts on Fabric Filter Performance

Figure 3-23 illustrates a statistical difference in the particulate collection efficiency between the four coals tested using the DE484 fabric. The first two coals, the Illinois No. 6 and the Blacksville, are both eastern bituminous coals. The Black Thunder is a Powder River Basin subbituminous coal, and the Beulah is a North Dakota lignite. These results were not surprising, since previous fabric filter tests at the EERC have shown that ash chemistry does have a significant impact on fabric filter performance (27, 29). The two western low-rank fuels appear to have a higher collection efficiency than the two eastern bituminous coals. This may be because of the different ash chemistry. Low-rank western fuels produce a much more alkaline ash than the higher-rank eastern coals. It is possible that a higher alkali content may make the ash more cohesive, resulting in a more stable dust cake. In addition, both the eastern fuels, as was shown in Table 3-6, had higher sulfur contents than the western fuels. Lower sulfur content in the coal will normally mean less SO_3 is generated. Also, the alkali in the western fuels will react with the SO_3, resulting in less ammonia sulfate and bisulfate formation on the dust-loading filter as a result of high ammonia slips. The range of particulate collection efficiencies for each of the four coals is as follows:

- Illinois No. 6 – 99.08% to 99.98%
- Blacksville – 99.35% to 99.66%
- Black Thunder – 99.81% to 99.91%
- Beulah – 99.86% to 99.95%

APS data shown in Figure 3-24 indicate that the DE484 fabric collected fine particles more effectively when the Black Thunder subbituminous coal was fired than when the two eastern bituminous coals were fired (no data were available for the Beulah lignite). This is in agreement with the overall collection efficiencies determined using the modified EPA Method 5.

Although the subbituminous coal and lignite had higher collection efficiencies than the two eastern bituminous coals, it appears from the data that controlling pressure drop was more difficult. As illustrated in Figures 3-25 to 3-28 at air-to-cloth ratios greater than 3.0 ft/min, it was difficult to maintain a pressure drop under 4 in. W.C., even though the cleaning cycle was reduced from 1 hr to 30 min. In the case of the Black Thunder, when the air-to-cloth ratio was 4.2 ft/min, the pressure drop was 10 in. W.C. with continuous cleaning. In contrast, for the test firing Blacksville coal, the pressure drop was easily maintained at 4 in. W.C. with a 1-hr cleaning cycle, even at an air-to-cloth

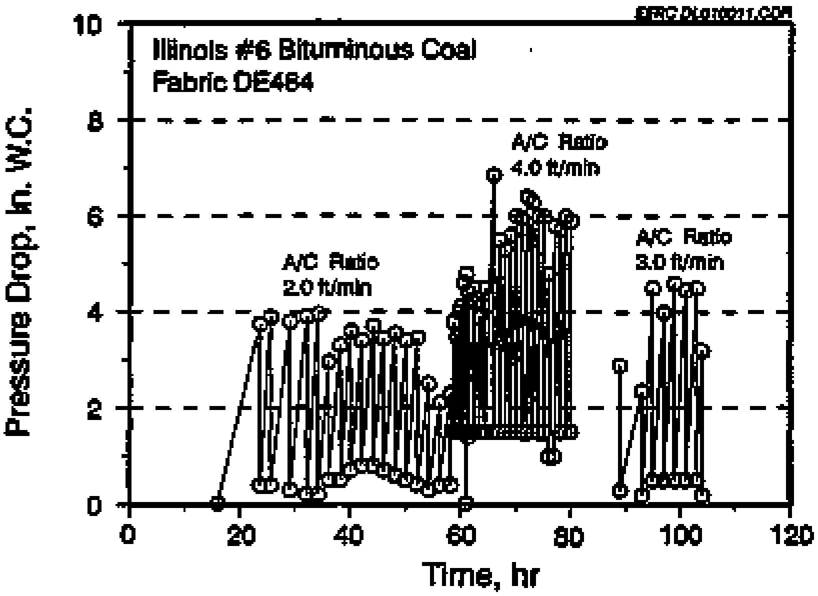

Figure 3-20. Pressure drop as a function of time using DE484 fabric.

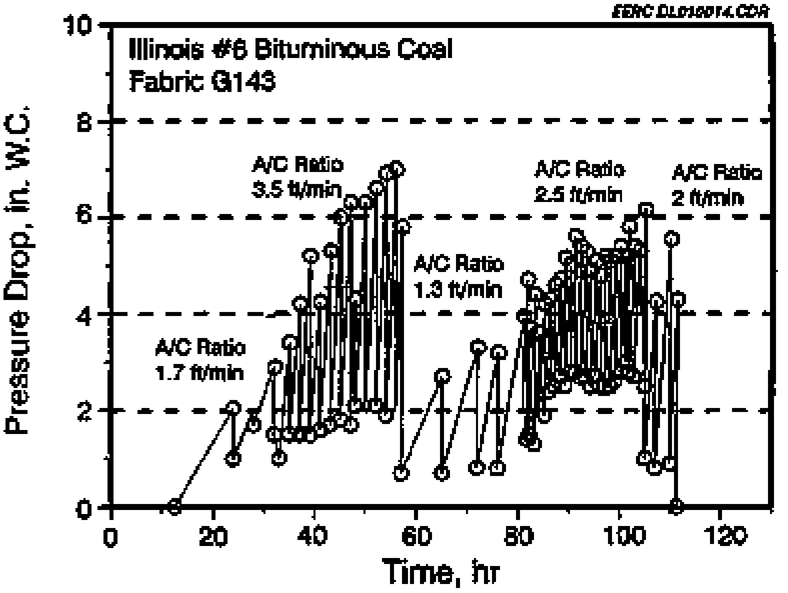

Figure 3-21. Pressure drop as a function of time using G143 fabric.

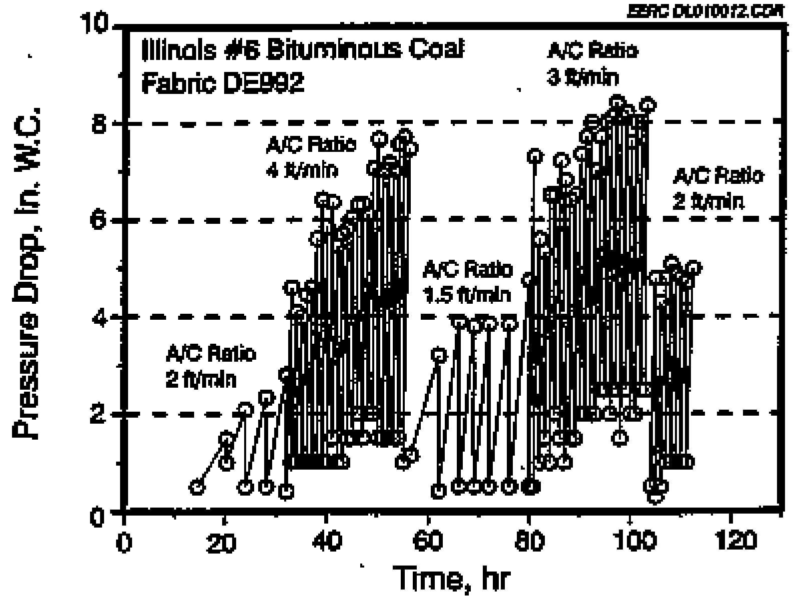

Figure 3-22. Pressure drop as a function of time using DE992 fabric.

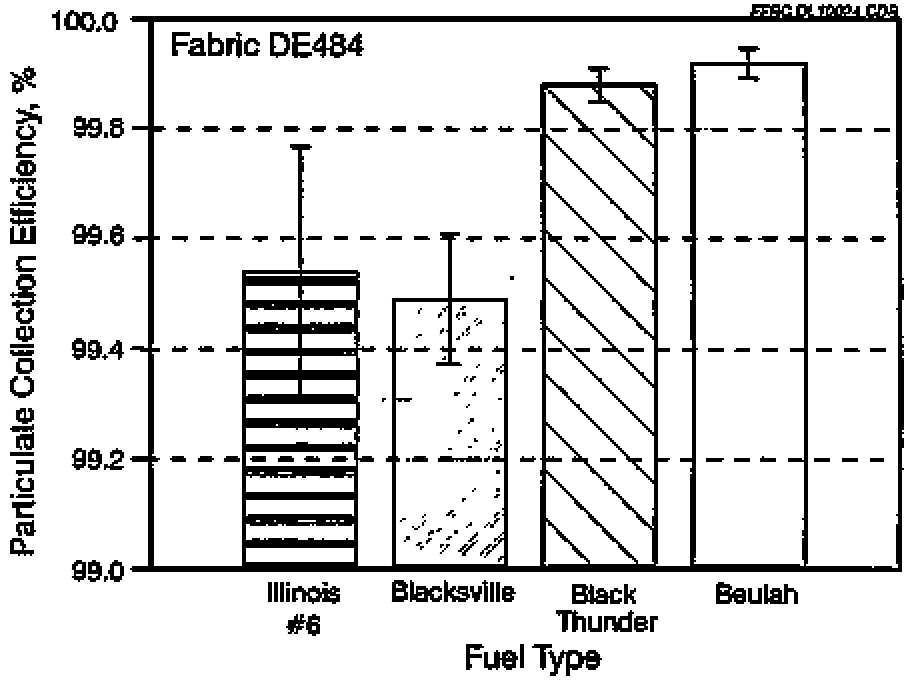

Figure 3-23. The effect of coal type on the average particulate collection efficiency for DE484 catalyst-coated fabric.

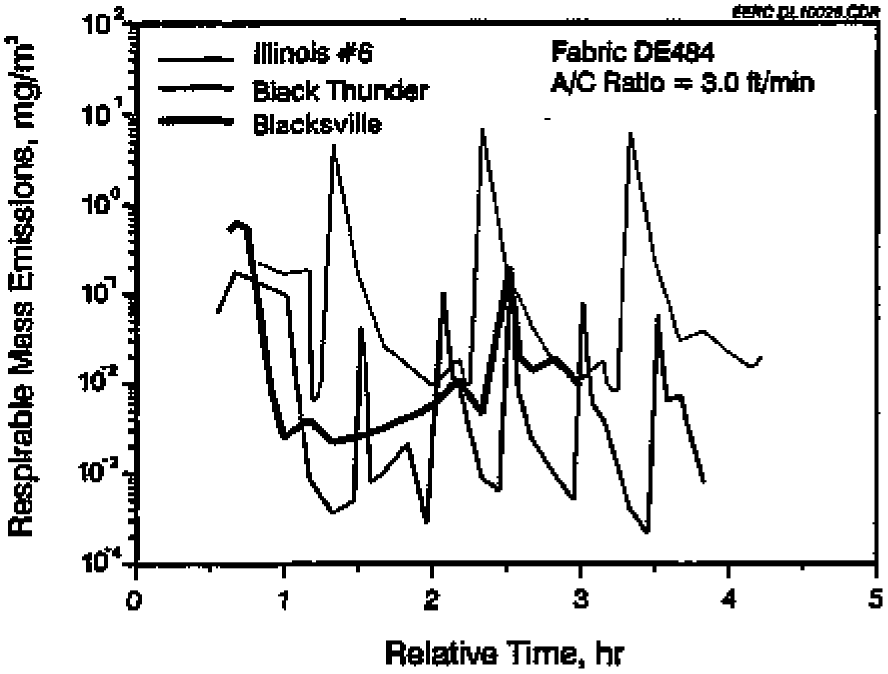

Figure 3-24. The effect of coal type on respirable mass emissions for DE484 catalyst-coated fabric.

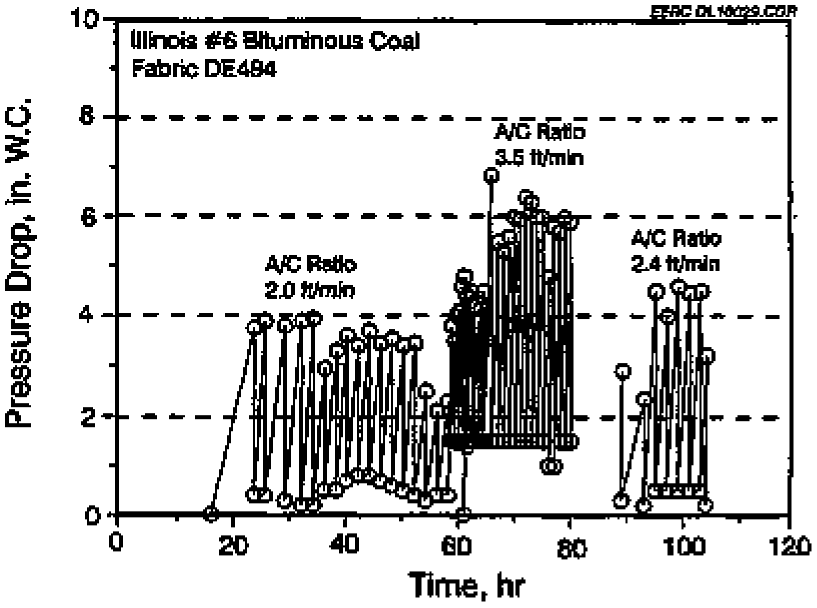

Figure 3-25. Pressure drop as a function of time across the DE484 catalyst-coated fabric while an Illinois No. 6 bituminous coal was fired.

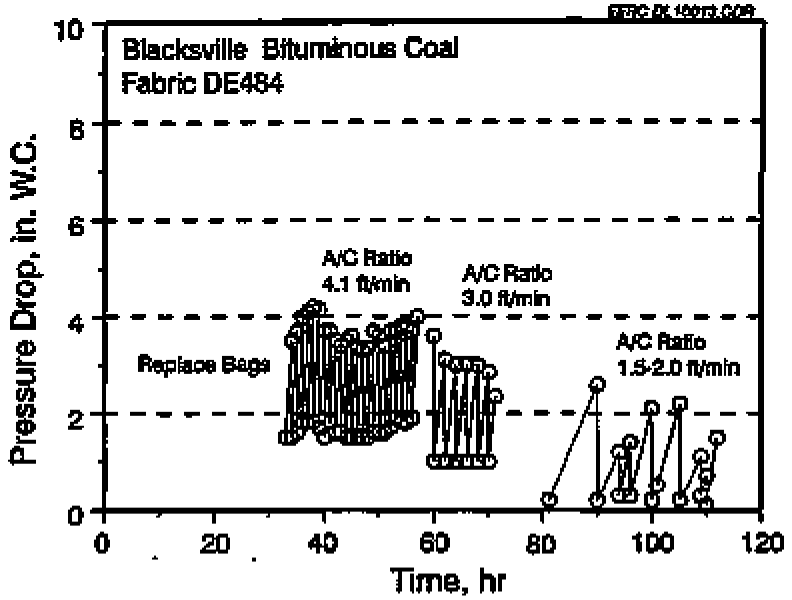

Figure 3-26. Pressure drop as a function of time across the DE484 catalyst-coated fabric while a Blacksville bituminous coal was fired.

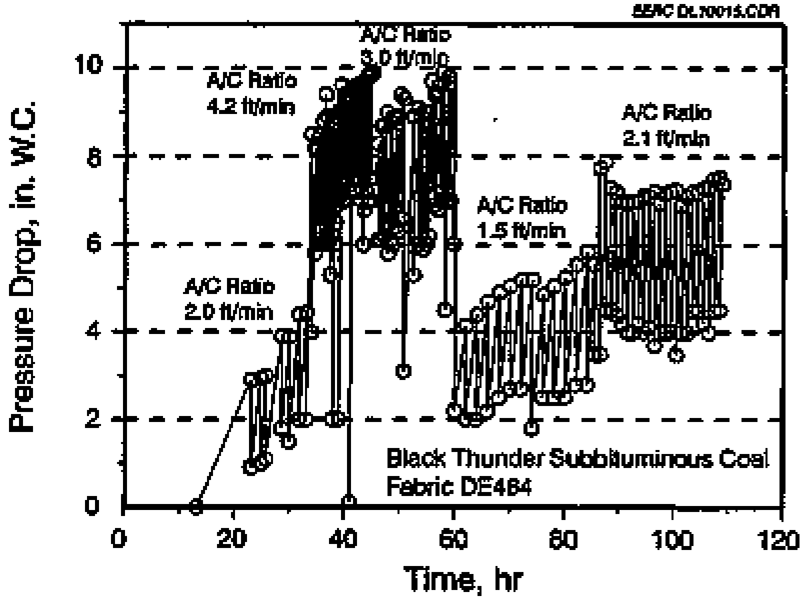

Figure 3-27. Pressure drop as a function of time across the DE484 catalyst-coated fabric while a Black Thunder subbituminous coal was fired.

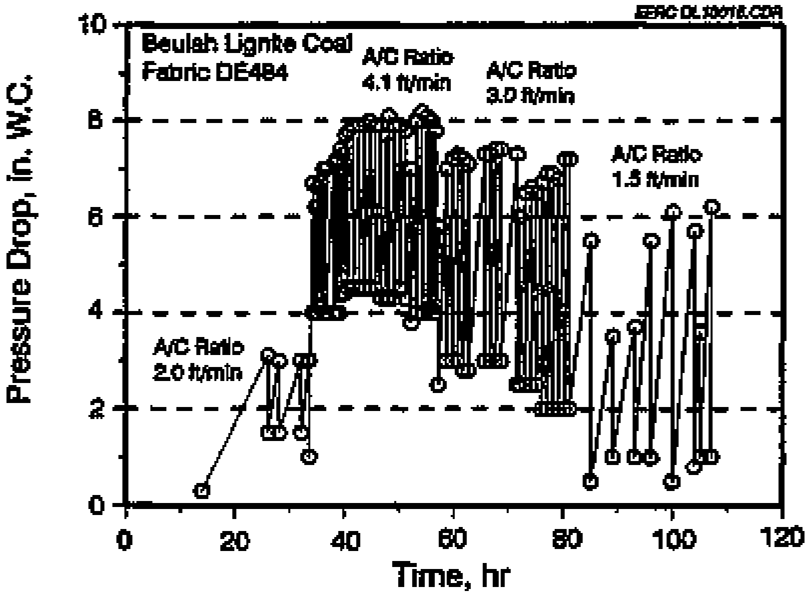

Figure 3-28. Pressure drop as a function of time across the DE484 catalyst-coated fabric while a Beulah lignite was fired.

ratio of 4.1 ft/min. For the Illinois No. 6 coal, the pressure drop was maintained at 6 in. W.C. at an air-to-cloth ratio of 3.5 ft/min and a 1-hr cleaning cycle.

The Coulter counter and multicyclone data showed little difference in the volumetric mean diameter of the baghouse fly ash between the four coals. The range was a low of 17 μm for the Blacksville to a high of 22 μm for the Beulah. This difference, however, was within the data variability and is not statistically significant.

3.2.4.3 Flue Gas Temperature Effects on Fabric Filter Performance

There appears to be a temperature impact on particulate collection efficiency, as shown in Figure 3-29. At low temperatures (500° and 550°F), the particulate collection efficiency was >99.9% (99.95% at 500°F and 99.94% at 550°F), compared to 99.29% to 99.75% for tests at temperatures >600°F. The NO_x removal efficiency was also low for the low-temperature tests, 24% and 16% respectively, resulting in very high (>400 ppm) ammonia slip. This would seem to be the opposite of what was expected. In most other tests (at 650°F), when the ammonia slip was high, the particulate collection efficiency was low. However, at the lower baghouse operating temperatures, two effects were probably taking place. First, some fly ash conditioning effect was possibly being caused by ammonia and SO_3 present in the flue gas (32). Second, the conversion of SO_2 to SO_3 is directly related to the flue gas temperature, resulting in a lower SO_3 concentration in the

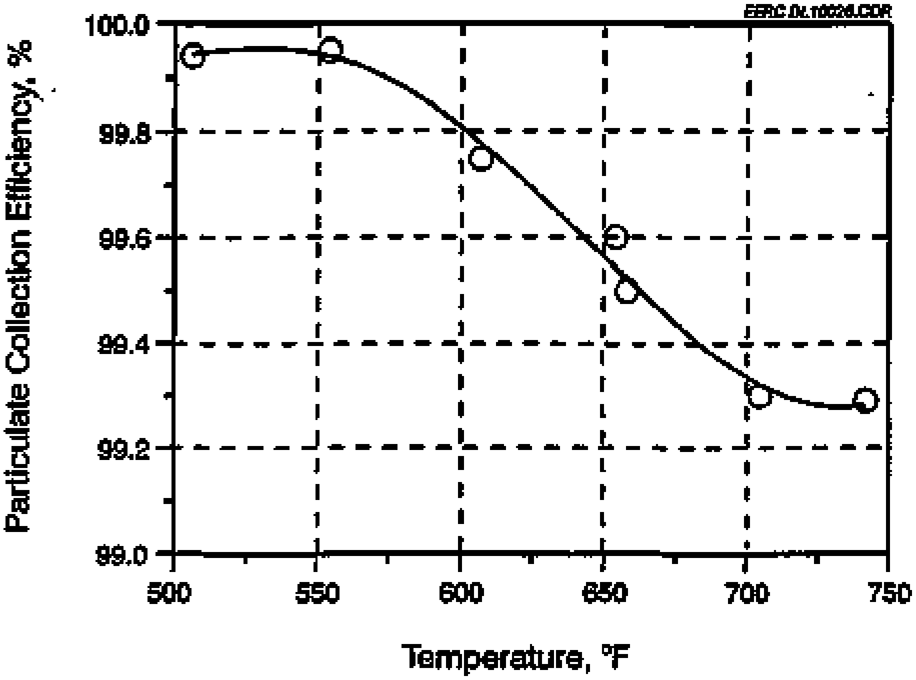

Figure 3-29. Effect of temperature on particulate collection efficiency for DE484 catalyst-coated fabric.

flue gas at the lower temperatures. With less SO_3 present, there would also be less ammonium sulfate and bisulfate on the modified EPA Method 5 outlet filter.

The only APS data taken during these test periods were taken at the beginning and end of the 100 hours (nominally 650°F). It does show that the fine-particle mass emissions had increased from about 0.1 mg/m^3 to 0.6 mg/m^3 by the end of the test. There was also a corresponding decrease in catalyst reactivity, resulting in higher ammonia slips. This increase in fine-particle mass emissions may have been the result of ammonium sulfate and bisulfate formation. Since APS measurements were taken over a relatively short period of time, it is also possible that the increase may have been only a transitory condition.

As shown in Figure 3-30, the pressure drop was reasonably controlled (<4 in. W.C.) during the entire 100 hours using a 2-hr cleaning cycle; however, there was a decrease from 4 in. to about 3 in. W.C. at about 70 hours. This would correspond with the tests at the lower temperature, again indicating a conditioning effect. The pressure drop did not increase again as the temperature was increased to 740° and then finally lowered to 650°F. This could have been a result of the residual conditioning effect on the filter dust cake.

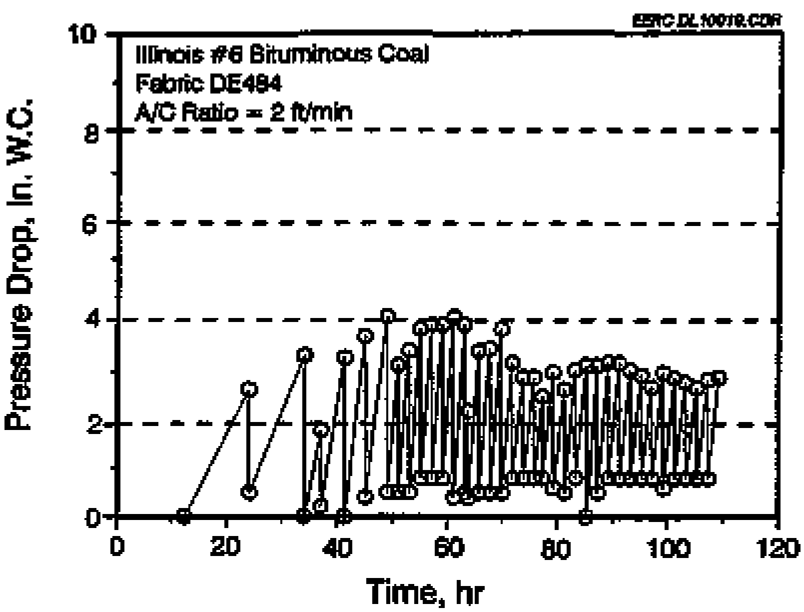

Figure 3-30. Pressure drop as a function of time for tests evaluating temperature effects on DE484 catalyst-coated fabric performance.

3.3 Process Testing/Pulse-Jet System

Tests were completed to determine fuel effects on NO_x removal and ammonia slip in a pilot-scale pulse-jet baghouse. Two 500-hr tests were also completed to address the effect of ammonia-to-NO_x molar ratio at a constant air-to-cloth ratio. Table 2-6 presents the test conditions for Subtask 3.3.

SO_3 measurements were made with the ammonia injection turned off during each test to avoid interference as a result of ammonia and SO_3 reactions. Concentrations during the pulse-jet tests ranged from 0.2 to 19.6 ppm. The higher levels of SO_3 were a result of firing the Blacksville bituminous coal and residual oil, both higher in sulfur than the Black Thunder subbituminous coal. All but a few of the SO_3 concentrations were less than 1% of the inlet SO_2 concentration and were well within expected levels. From the data (reverse-gas and pulse-jet), no oxidation of SO_2 to SO_3 was caused by the presence of the vanadium catalyst on the surface of the S2-glass fabric.

Analysis of ash samples collected from the baghouse hopper showed ammonia concentrations in the ash ranging from 26 to 92 μg/g, respectively, for NO_x reduction levels of 80% to 90%. Literature sources indicate that, based on European experience, ammonia concentrations in the ash of <100 μg/g do not create ash handling, disposal, or reuse problems (33). An earlier EPRI report stated that ammonia concentrations of <30 μg/g were necessary to avoid potential problems (34). Based on these data, it appears that the use of the CFF concept to achieve 80% NO_x reduction would not create ash handling, disposal, or reuse problems.

Based on the reverse-gas fabric filter screening tests, the 22-oz/yd^2 double-beam woven glass consisting of DE-fibers (6.5 micron) was selected for all pulse-jet baghouse tests. Seven coats of the vanadium–titanium catalyst were applied to the fabric. This is the same type of fabric used during the 100-hr reverse-gas Run PTC-IL6-428. Heat treatment for all bags consisted of a 4-to 4.5-hour heatup period followed by a heat treatment period of roughly 4 to 5.5 hours at 710°F and 2.7% to 4.5% oxygen. The flue gas for the heat treatment was generated by firing natural gas in the pilot-scale test combustor.

3.3.1 NO_x Control with Catalyst-Coated Fabric Filter

Three 100-hr pulse-jet baghouse tests were completed to determine the effects of fuel type on catalyst-coated fabric performance (PTC-BV-429, PTC-BT-430, and PTC-RO-431). The effects of air-to-cloth ratio (2, 3, 4, and 6 ft/min) and ammonia-to-NO_x molar ratio (0.7, 0.8, and 0.9) were also determined. The nominal baghouse temperature was held constant at 650°F. Flue gas was generated by firing a pulverized Blacksville bituminous coal (PTC-BV-429), a pulverized Black Thunder subbituminous coal (PTC-BT-430), and a residual oil (PTC-RO-431) in the pilot-scale combustor. The average ultimate, proximate, and sieve analyses for each of the 100-hr test coals, as well as the ultimate and proximate analysis for the residual oil, are presented in Table 3-7. The data show that the three fuels used during this series of tests represent a broad range of fuel characteristics in terms of moisture content (<2% to 24%), ash content (0.2% to 8.04%) and characteristics (low and high alkali content), sulfur content (0.37% to 2.32%), and heating value (8941 to 18,066 Btu/lb). Ash analysis was not available for the oil-fired test (PTC-RO-431) because of the dilution effect of dolomite used to precoat the catalyst-coated bags. The dolomite coating was applied to provide an initial dust cake and to protect the bags from damage in the event of spontaneous combustion of the carbon in the ash.

3.3.1.1 PTC-BV-429

A pulverized Blacksville bituminous coal was used to generate flue gas for the 100-hr Run PTC-BV-429. Results from the test showed that the NO_x removal efficiency ranged from 88% (air-to-cloth ratio = 3 ft/min, eight bags on-line, ammonia-to-NO_x molar ratio = 0.88) to 92% (air-to-cloth ratio = 2 ft/min, twelve bags on-line, ammonia-to-NO_x molar ratio = 0.95). Figure 3-31 plots the NO_x removal efficiency and the ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio. Because of a calibration error associated with the ammonia flowmeter (resulting in uncertain ammonia-to-NO_x molar ratios), only NO_x removal data with corresponding ammonia slip data are presented. All NO_x removal is near stoichiometric based on a calculated ammonia-to-NO_x molar ratio, and the corresponding ammonia slip concentrations are low (<7% of the inlet NO_x concentration).

It is difficult to determine from these data if NO_x reduction and ammonia slip are affected by air-to-cloth ratio. The highest ammonia slip occurs at an air-to-cloth ratio of 6 ft/min, but this also corresponds to the highest ammonia-to-NO_x molar ratio. Therefore, it is not possible to separate the effect of air-to-cloth ratio and ammonia-to-NO_x molar ratio on NO_x reduction and ammonia slip for this small data set. Based on the high NO_x

TABLE 3-7

Results of Coal and Coal Ash Analysis for Pulse-Jet System Tests*

	Blacksville Bituminous	Black Thunder Subbituminous	Residual Oil
Proximate Analysis, wt%			
Moisture	1.77	24.30	1.60
Volatile Matter	38.82	35.68	94.35
Fixed Carbon	51.36	35.01	3.83
Ash	8.04	5.00	0.20
Ultimate Analysis, wt%			
Hydrogen	5.04	6.74	10.26
Carbon	74.78	52.18	88.65
Nitrogen	1.30	0.70	0.25
Sulfur	2.32	0.37	1.96
Oxygen	8.50	35.01	–
Ash	8.04	5.00	0.20
Heating Value, Btu/lb	13,406	8941	18,066
Percent as Oxides, wt%			
SiO_2	42.04	33.65	NA
Al_2O_3	20.79	15.29	NA
Fe_2O_3	21.04	5.69	NA
TiO_2	0.90	1.08	NA
P_2O_5	0.49	1.19	NA
CaO	5.72	21.15	NA
MgO	2.35	7.69	NA
Na_2O	0.95	1.10	NA
K_2O	0.87	0.29	NA
SO_3	4.75	12.90	NA
Ash Fusion Temp., °F			
Initial	2158	2183	NA
Softening	2235	2213	NA
Hemisphere	2308	2228	NA
Fluid	2366	2244	NA
Sieve Analysis			
Screen Mesh Size	wt% Retained		
100	3.09	25.31	NA
140	6.79	13.81	NA
200	11.92	13.87	NA
230	7.08	4.99	NA
270	5.84	4.99	NA
325	2.33	1.21	NA
Pan	62.14	33.44	NA
Total %	99.19	97.60	NA

* Fuel analysis is presented on an "as-fired" basis.

reduction and relatively low ammonia slip observed, nine of the bags used during Run PTC-BV-429 were installed in the slipstream pulse-jet baghouse at the UND steam plant. These bags were evaluated for longer-term durability and performance as discussed in Section 3.4 (Subtask 3.4–Fabric Durability Testing/Pulse-Jet System).

3.3.1.2 PTC-BT-430

A pulverized Black Thunder subbituminous coal was fired in the pilot-scale pc-fired test combustor to generate flue gas for Run PTC-BT-430. Results from this test demonstrated NO_x removal efficiency ranging from 86% (air-to-cloth ratio = 4 ft/min, six bags on-line, ammonia-to-NO_x molar ratio = 0.89) to 92% (air-to-cloth ratio = 2 ft/min, twelve bags on-line, ammonia-to-NO_x molar ratio = 0.95). Figure 3-32 plots the NO_x removal efficiency and the ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio. Because of a calibration error associated with the ammonia flowmeter (resulting in uncertain ammonia-to-NO_x molar ratios), only NO_x removal data with corresponding ammonia slip data are presented. All NO_x removal is near stoichiometric based on a calculated ammonia-to-NO_x molar ratio, and the corresponding ammonia slip concentrations are low (<7% of the inlet NO_x concentration).

As before, it is difficult to determine if NO_x reduction and ammonia slip are affected by air-to-cloth ratio. The highest ammonia slip again occurs at an air-to-cloth ratio of 6 ft/min. At air-to-cloth ratios of 2 and 3 ft/min and higher ammonia-to-NO_x molar ratios, the ammonia slip is lower, but the difference is not statistically significant. The NO_x removal efficiency at an air-to-cloth ratio of 6 ft/min is also lower than at air-to-cloth ratios of 2 and 3 ft/min at slightly higher ammonia-to-NO_x molar ratios, but the difference is not statistically significant owing to the small size of the data set. Based on the reverse-gas data previously discussed, lower NO_x reduction and higher ammonia slip would be expected at an air-to-cloth ratio of 6 ft/min.

Fabric samples from the bags used during Run PTC-BT-430 were tested in the bench-scale unit. Three samples, one each from the top, middle, and bottom of a bag were tested at ammonia-to-NO_x molar ratios of 0.86 and 0.80. The higher ammonia-to-NO_x molar ratio (0.86) showed a NO_x reduction of 83% with an ammonia slip of 5% of the inlet NO_x concentration. The lower ammonia-to-NO_x molar ratio (0.80) showed a NO_x reduction of 73% with an ammonia slip of 3% of the inlet NO_x concentration. The pilot-scale data at a stoichiometric ratio of 0.89 was 86% NO_x reduction with an ammonia slip of 3.2% of the inlet NO_x concentration. Pilot-scale data extrapolated back to an ammonia-to-NO_x molar ratio of 0.80 indicates comparable levels of NO_x reduction and ammonia slip. These bench-scale results verify the corrected ammonia-to-NO_x molar ratios calculated for the pilot-scale data from the measured NO_x reduction and ammonia slip values.

Used and unused samples of the catalyst-coated fabric were analyzed to determine the vanadium concentration on the fabric. Results showed a vanadium concentration of 6800 $\mu g/g$ on the unused sample and an average of 6945 $\mu g/g$ on four used samples. The data indicate no catalyst loss from the bags. Although the anticipated dilution effect of residual ash is not apparent, the data are consistent within the variability of vanadium concentrations observed for DE992 fabric.

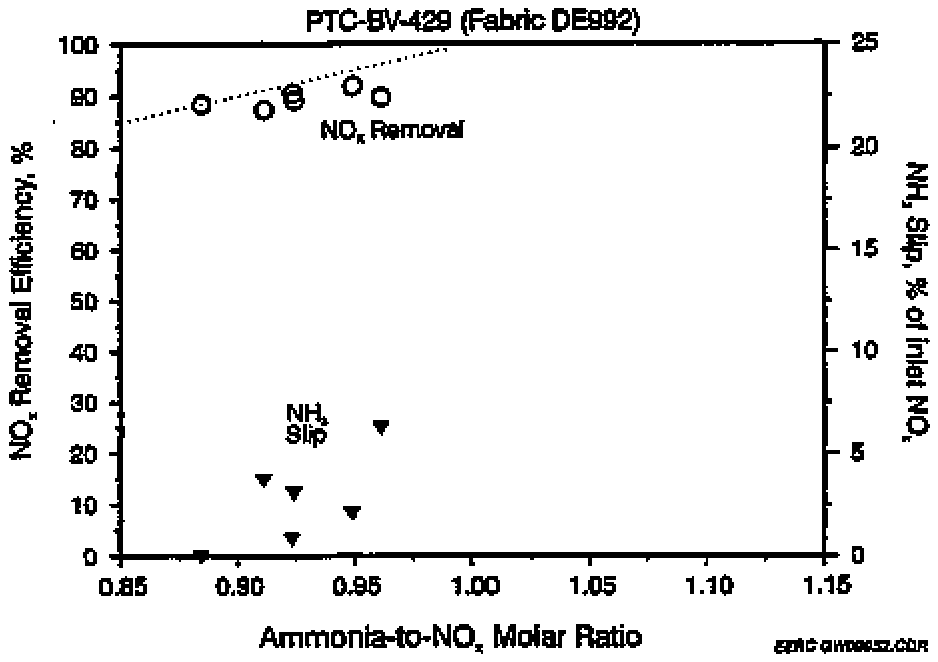

Figure 3-31. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Run PTC-BV-429: average inlet NO$_x$ = 747 ppm, average baghouse temperature = 655°F.

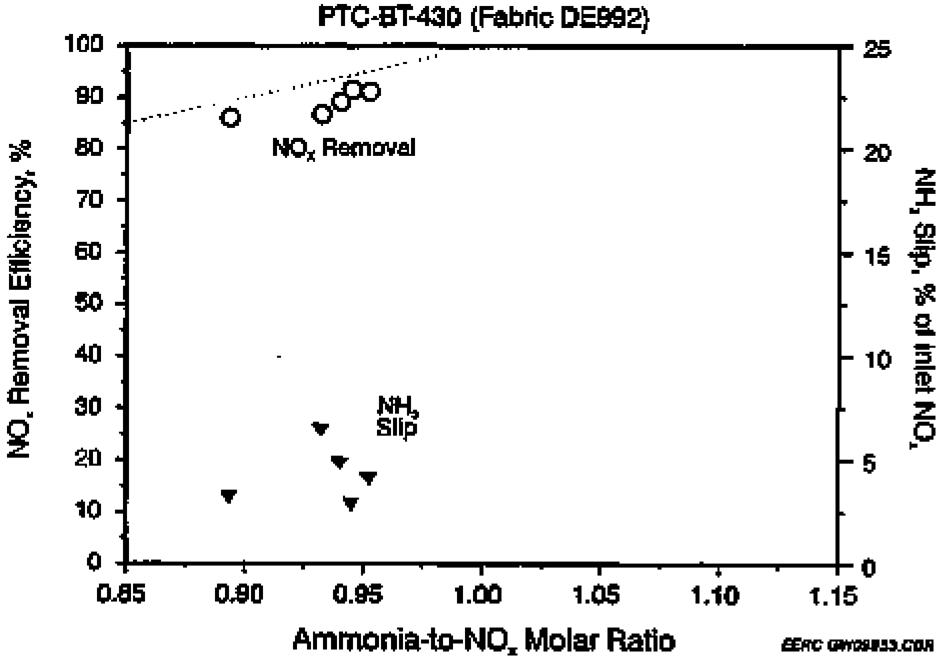

Figure 3-32. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Run PTC-BT-430: average inlet NO$_x$ = 759 ppm, average baghouse temperature = 653°F.

3.3.1.3 PTC-RO-431

A residual oil was used to generate flue gas for the 100-hr test PTC-RO-431. Results from this test showed that the NO_x removal efficiency ranged from 82% (air-to-cloth ratio = 4 ft/min, six bags on-line, ammonia-to-NO_x molar ratio = 0.86) to 95% (air-to-cloth ratio = 3 ft/min; eight bags on-line, ammonia-to-NO_x molar ratio = 1.05). Figure 3-33 plots the NO_x removal efficiency and the ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio. All NO_x removal is near stoichiometric, and the corresponding ammonia slip concentrations range from 4% to 23% of the inlet NO_x concentration. Again there appears to be little to no effect of air-to-cloth ratio on the NO_x reduction or ammonia slip. It is important to point out that the catalyst-coated bags were precoated with dolomite to develop a dust cake prior to oil firing. No real change in baghouse differential pressure occurred during the 100-hr test because of the low ash content of the fuel.

Bench-scale results from fabric samples cut from the bags used during Run PTC-RO-431 show 73% NO_x reduction with an ammonia slip of 5.2% of the inlet NO_x concentration at an ammonia-to-NO_x molar ratio of 0.80. No test periods were performed at an ammonia-to-NO_x molar ratio of 0.8 during Run PTC-RO-431. However, extrapolating back to an ammonia-to-NO_x molar ratio of 0.80 suggests the NO_x reduction would have been approximately 75% and the corresponding ammonia slip would have been <5% of the inlet NO_x concentration. These results should be viewed as statistically similar in light of the differences in the experimental systems.

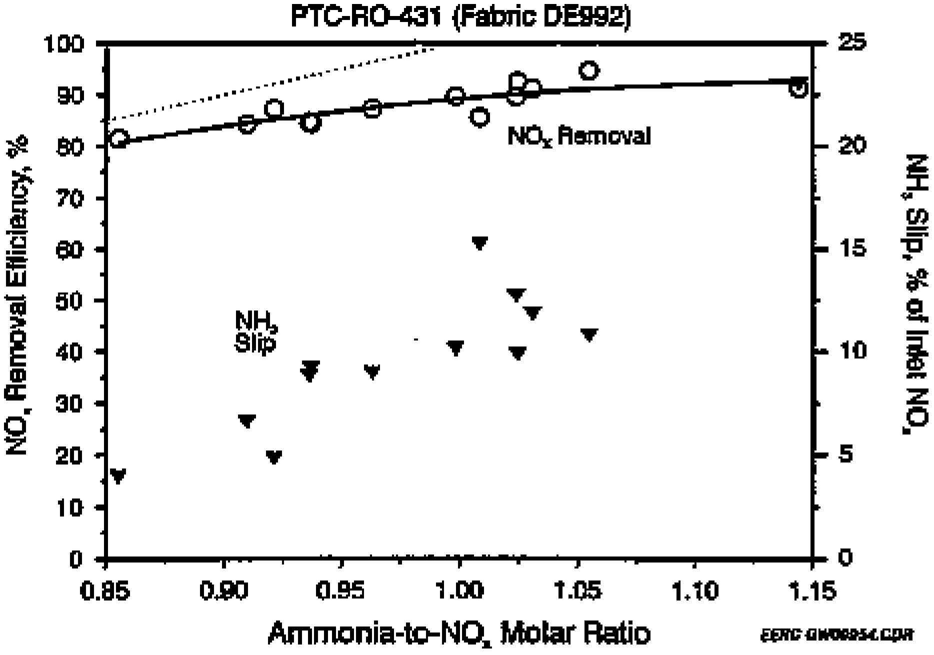

Figure 3-33. NO_x removal efficiency and ammonia slip versus ammonia-to-NO_x molar ratio for Run PTC-RO-431: average inlet NO_x = 278 ppm, average baghouse temperature = 652°F.

Used and unused samples of the catalyst-coated fabric were analyzed to determine the concentration of vanadium on the fabric. Results showed a vanadium concentration of 6800 μg/g on the unused sample and 6868 μg/g on the used sample. The data indicate no loss of catalyst from the bags as a result of the 100-hr test period and the data are consistent with data previously discussed for Run PTC-BT-430.

Figure 3-34 plots the NO_x removal efficiency and the ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio for the three 100-hr pulse-jet tests (PTC-BV-429, PTC-BT-430, and PTC-RO-431). The NO_x removal efficiencies for the oil-fired tests are slightly lower than those observed for the coal-fired tests. The ammonia slip values were generally higher during the oil-fired tests, but there is no statistical difference between the coal-fired tests. The difference between the oil-fired test and coal-fired tests may be due to the residual dust cake characteristics and/or the lack of a residual dust cake on the bags during the oil-fired tests. The catalyst-coated bags for the oil-fired test were precoated with dolomite, and firing the fuel oil generated very little ash. If pinholes developed during the oil-fired test, they would not have been bridged over as a result of dust cake development.

3.3.2 Catalyst-Coated Bag Performance During 500-hr Test Periods

Two 500-hr pulse-jet tests were completed to address the effect of ammonia-to-NO_x molar ratio (0.6, 0.7, 0.8, and 0.9) at a constant air-to-cloth ratio of 3.0–3.5 ft/min (eight and seven bags on-line, respectively). Baghouse temperature was nominally 650°F, and flue gas was generated by firing natural gas or a Blacksville bituminous coal in the pilot-scale pc-fired combustor. The average ultimate, proximate, and sieve analyses for the coal are presented in Table 3-7. The DE992 fabric with seven coats of the vanadium–titanium catalyst were used for these tests.

3.3.2.1 PTC-BV-432

Seventeen individual experimental periods were planned and completed during Run PTC-BV-432 to address the effect of ammonia-to-NO_x molar ratio (0.6, 0.7, 0.8, and 0.9) at a constant air-to-cloth ratio of 3.5 ft/min (seven bags on-line). Baghouse temperature was nominally 650°F, and flue gas was generated by firing natural gas or a Blacksville bituminous coal in the EERC pilot-scale pc-fired combustor.

Approximately 114 hours into the run, baghouse differential pressure began to increase uncontrollably; therefore, routine combustor maintenance was moved ahead one day. Inspection of the baghouse revealed that one of the pulse-air nozzles was plugged and others were partially plugged by what appeared to be corrosion deposits. As a result, the effective air-to-cloth ratio was increased from 3.5 to 4 ft/min, and the overall performance of the cleaning system was reduced. The piping in the pulse-air system was dismantled and thoroughly cleaned prior to resuming system operation. Although the condition of the pulse nozzles was a reasonable explanation for the difficulty encountered with respect to controlling baghouse differential pressure, it was speculated that the bags may have become somewhat blinded. Based on the observations made, it was decided to replace this set of bags with seven bags used during the 100-hr oil-fired test (PTC-RO-431), which had performed well in terms of NO_x reduction and ammonia slip and had been precoated with dolomite. Since this set of bags already had experienced 100 hours of operation, 500 hours of operation on one set of bags was achieved.

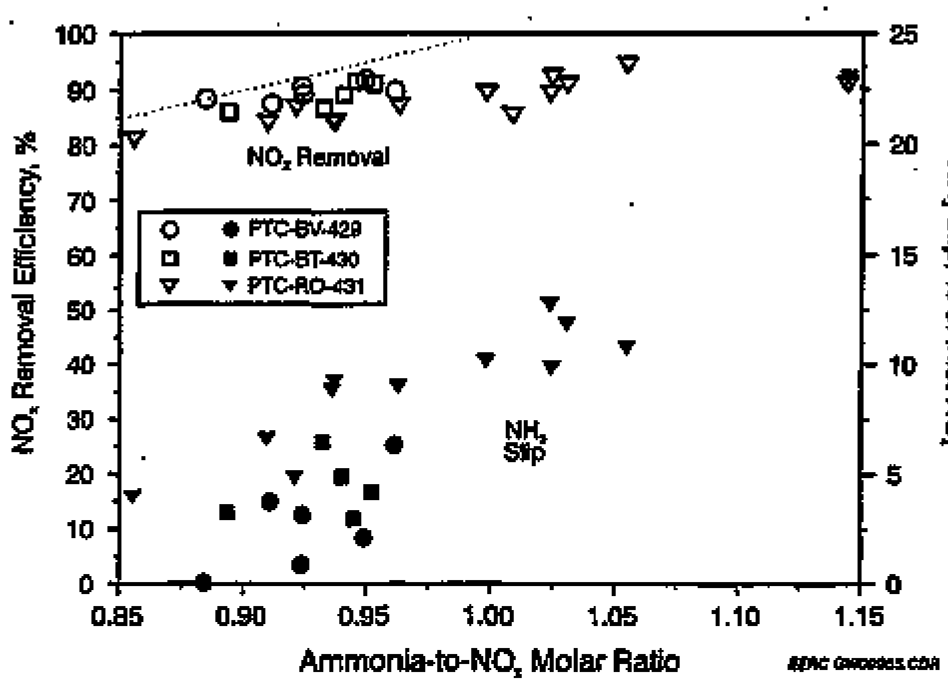

Figure 3-34. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Runs PTC-BV-429, PTC-BT-430, and PTC-RO-431.

Figure 3-35 plots the NO$_x$ removal efficiency and ammonia slip (as a percentage of inlet NO$_x$ concentration) as a function of ammonia-to-NO$_x$ molar ratio for the four gas-fired test periods completed. During the first gas-fired test period (clean fabric), the NO$_x$ reduction ranged from 76% at an ammonia-to-NO$_x$ molar ratio of 0.83 to 93% at an ammonia-to-NO$_x$ molar ratio of 1.14. The average baghouse bulk gas temperature was 658°F, and the inlet NO$_x$ concentration averaged 139 ppm. Ammonia slip concentrations for this test period also indicated good bag performance, ranging from 6.8% to 20.8% (9.7 to 32.3 ppm) of the inlet NO$_x$ concentration. The NO$_x$ removal efficiency during the final three gas-fired test periods was lower than the initial gas-fired test period, ranging from 75% (ammonia-to-NO$_x$ molar ratio = 0.94) to 89% (ammonia-to-NO$_x$ molar ratio = 1.45). Ammonia slip concentrations also increased from the initial gas-fired test period, ranging from 16% to 55% (27.3 to 84.4 ppm) of ~~the inlet~~ NO$_x$ concentration. Baghouse bulk gas temperature averaged 654°F, and the average inlet NO$_x$ was 161 ppm.

Figure 3-36 plots the NO$_x$ removal efficiency and ammonia slip (as a percentage of inlet NO$_x$ concentration) as a function of ammonia-to-NO$_x$ molar ratio for the coal-fired test periods during Run PTC-BV-432 and additional tests from PTC-BV-433. The results are consistent with data from the previous 100-hr pulse-jet tests. For the coal-fired test periods during Run PTC-BV-432, the NO$_x$ removal efficiencies ranged from 62% (ammonia-to-NO$_x$ molar ratio = 0.63) to 91% (ammonia-to-NO$_x$ molar ratio = 1.09). The ammonia slip concentrations while firing coal ranged from <1.0% to 17.7% (7.6 to 170.1 ppm) of the inlet NO$_x$ concentration, with an average baghouse bulk gas temperature of 650°F and an average inlet NO$_x$ concentration of 821 ppm.

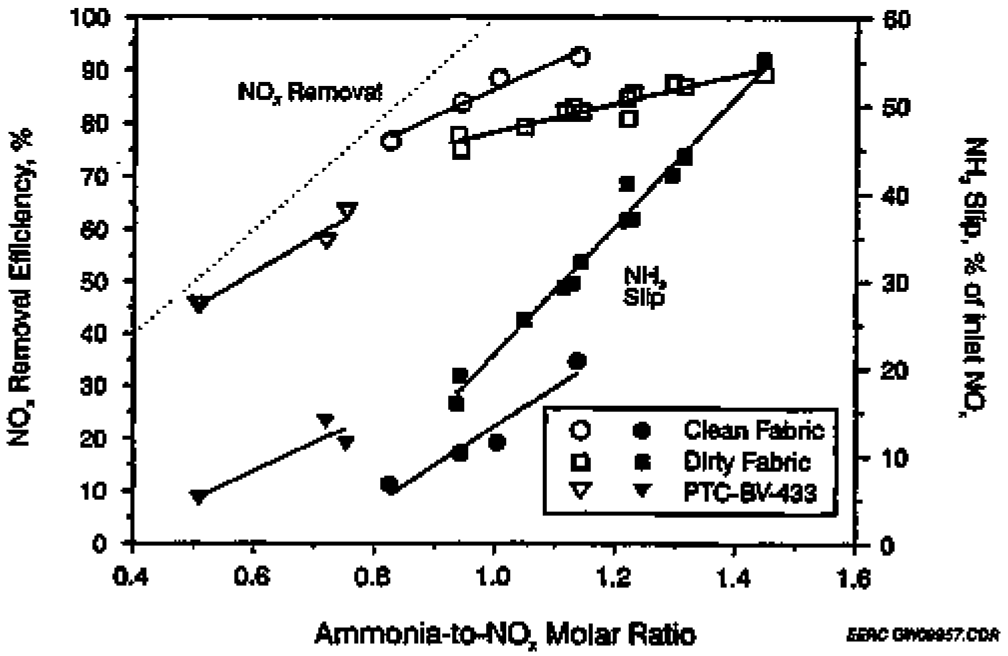

Figure 3-35. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Runs PTC-BV-432 and PTC-BV-433, natural gas-fired tests: average inlet NO$_x$ = 162 ppm, average baghouse temperature = 655°F.

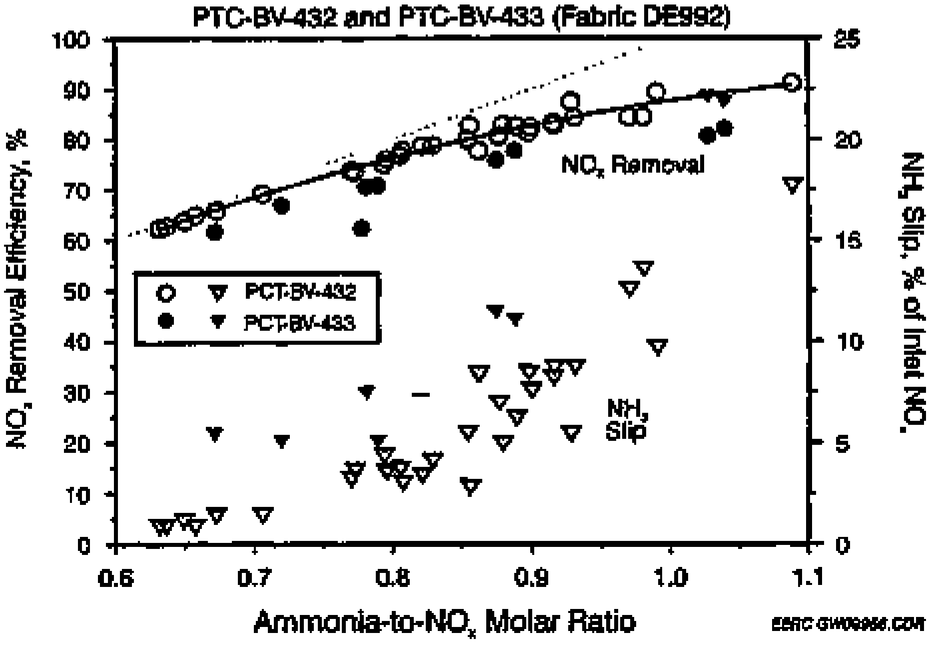

Figure 3-36. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Runs PTC-BV-432 and PTC-BV-433, coal-fired tests: average inlet NO$_x$ = 797 ppm, average baghouse temperature = 653°F.

It was speculated that there may have been a leak across the tube sheet of the baghouse that would result in reduced NO_x removal efficiencies and the increased ammonia slips. Therefore, a new tube sheet was fabricated, and additional test periods were completed: Run PTC-BV-433. Nine individual test periods were completed: four firing natural gas (ammonia-to-NO_x molar ratios of 0.6, 0.7, 0.8, and 0.9) and five firing Blacksville bituminous coal (ammonia-to-NO_x molar ratios of 0.6, 0.7, 0.8 [twice], and 0.9).

For the coal-fired test periods during Run PTC-BV-433, the NO_x removal efficiencies ranged from 61.7% (ammonia-to-NO_x molar ratio = 0.67) to 82.1% (ammonia-to-NO_x molar ratio = 1.04). The ammonia slip concentrations while firing coal ranged from 5.1% to 22.1% (36.0 to 160.1 ppm) of the inlet NO_x concentration, with an average baghouse bulk gas temperature of 657°F and an average inlet NO_x concentration of 744 ppm. The data indicated a decrease in NO_x removal efficiency and an increase in ammonia slip. However, it is not clear if these changes were due to catalyst deactivation or loss of catalyst from the bags as a result of the additional handling.

Bench-scale results for samples cut from the bags used for Run PTC-BV-432 were 2% lower NO_x reduction than the pilot-scale data: 67% versus 69% NO_x reduction, respectively, with similar ammonia slips of roughly 3% of the inlet NO_x concentration. The bench-scale results from fabric samples of bags from Run PTC-BV-433 showed identical NO_x reduction with the pilot-scale data: 74% NO_x reduction at an ammonia-to-NO_x molar ratio of 0.8. Ammonia slip values for both pilot and bench scale were approximately 4% of the inlet NO_x concentration.

3.3.2.2 PTC-BV-434

After the test results and the operational problems (pulse nozzle plugging and high baghouse differential pressure) encountered during the first 500-hr pulse-jet (PTC-BV-432) were reviewed, a second 500-hr pulse-jet test was completed rather than the 500-hr reverse-gas test originally proposed in the scope of work.

Three coal-fired experimental periods were planned in order to address the effect of ammonia-to-NO_x molar ratio (0.8 [twice] and 0.9) at a constant air-to-cloth ratio of 3 ft/min. Baghouse temperature was nominally 650°F, and flue gas was generated by firing a Blacksville bituminous coal in the pilot-scale pc-fired combustor. During a few short test periods, the combustor was fired using natural gas.

Figure 3-37 plots the NO_x removal efficiency and ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio for the gas-fired test periods. These tests were performed prior to initial coal firing and after weekly maintenance periods prior to reinitiating coal firing. The first gas-fired test period was performed with clean fabric (no residual dust cake). The NO_x reduction ranged from 51% at an ammonia-to-NO_x molar ratio of 0.52 to 72% at an ammonia-to-NO_x molar ratio of 0.79. The average baghouse bulk gas temperature was 652°F, and the inlet NO_x concentration averaged 174 ppm. Ammonia slip concentrations for these test periods indicated good bag performance, ranging from 2.3% to 7.5% (4 to 19 ppm) of the inlet NO_x concentration.

The results from the final three gas-fired test periods were very consistent. These tests were performed after 1, 2, and 3 weeks of coal firing with a dust cake on the bags.

The NO_x reduction ranged from 50% at an ammonia-to-NO_x molar ratio of 0.55 to 85% at an ammonia-to-NO_x molar ratio of 1.02. The average baghouse bulk gas temperature was 656°F, and the inlet NO_x concentration averaged 174 ppm during the first two gas-fired test periods and 289 ppm during the last test period.

Ammonia slip was higher for the last three gas-fired test periods than the first gas-fired test period with clean fabric. Ammonia slip ranged from 3.7% to 17.7% (7 to 49 ppm) of inlet NO_x concentration. These ammonia slip values are consistent with the results from the first 500-hr test (PTC-BV-432). Again, it is unclear whether the difference in ammonia slip is due to a decrease in catalyst reactivity or an effect of the residual dust cake on the bags.

As shown in Figure 3-37, the results indicated a slight decrease in NO_x reduction and an increase in ammonia slip when comparing the clean catalyst-coated fabric to the same fabric with a dust cake on the surface. Two explanations are possible for this difference. The first is that the simple presence of a dust cake limits the contact between the flue gas and catalyst or the possibility of pinhole effects. The second explanation may be that there is a decrease in catalyst reactivity after 1 week of operation. Despite the reason, the result is an increase in the measured ammonia slip.

Figure 3-38 plots the NO_x removal efficiency and ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio for the coal-fired test periods. During the first week, the ammonia-to-NO_x molar ratio averaged 0.85; daily average NO_x reduction ranged from 80.3% to 82.7%. The average baghouse bulk gas temperature was 658°F, and the inlet NO_x concentration averaged 946 ppm. Ammonia slip concentrations ranged from 0.9% to 7.3% (9 to 70 ppm) of inlet NO_x concentration and appeared to increase on average over the week.

During the second week of coal firing, the ammonia-to-NO_x molar ratio averaged 0.95, and average daily NO_x reduction ranged from 81% to 87%. The first day of this test period, NO_x reduction started at roughly 89% and dropped to roughly 83% by the end of the day. This drop corresponds to a decrease in the ammonia-to-NO_x molar ratio from 1.04 to 0.94 during the first day. The next four days, the NO_x reduction remained relatively constant at 81%, and the ammonia-to-NO_x molar ratio was also relatively constant at roughly 0.93. The average baghouse bulk gas temperature was 659°F, and the inlet NO_x concentration averaged 953 ppm. Ammonia slip concentrations ranged from 9.0% to 17.0% (86 to 157 ppm) of the inlet NO_x concentration.

For the first six hours of the third-week, the ammonia-to-NO_x molar ratio was 0.92. Again, NO_x reduction dropped from roughly 90% to 85% during the short test period. For the remainder of the week, the ammonia-to-NO_x molar ratio averaged 0.86, and the average daily NO_x reduction ranged from 77.6% to 79.6%. The average baghouse bulk gas temperature was 659°F, and the inlet NO_x concentration averaged 941 ppm. The ammonia slip concentrations ranged from 5.42% to 8.6% (50 to 79 ppm) of the inlet NO_x concentration.

Although the ammonia slip concentrations (9 to 157 ppm) measured during the 500-hr test ranged from 0.9% to 17% of the inlet NO_x concentration when firing coal, the results show that 80% NO_x reduction can be achieved with an ammonia slip of 7.5% of the inlet

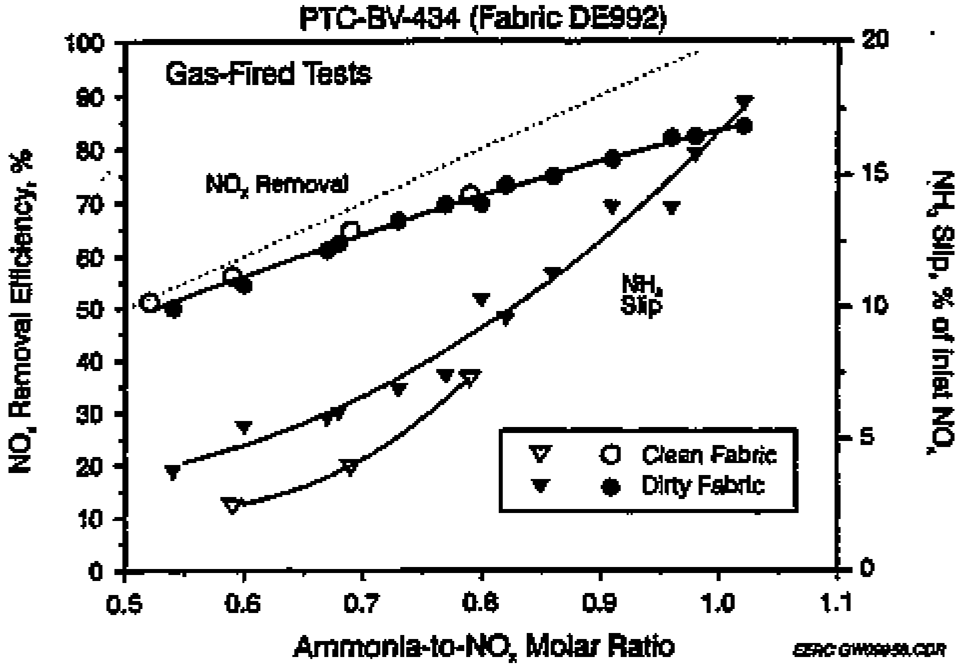

Figure 3-37. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Run PTC-BV-434, natural gas-fired test: average inlet NO$_x$ = 254 ppm, average baghouse temperature = 657°F.

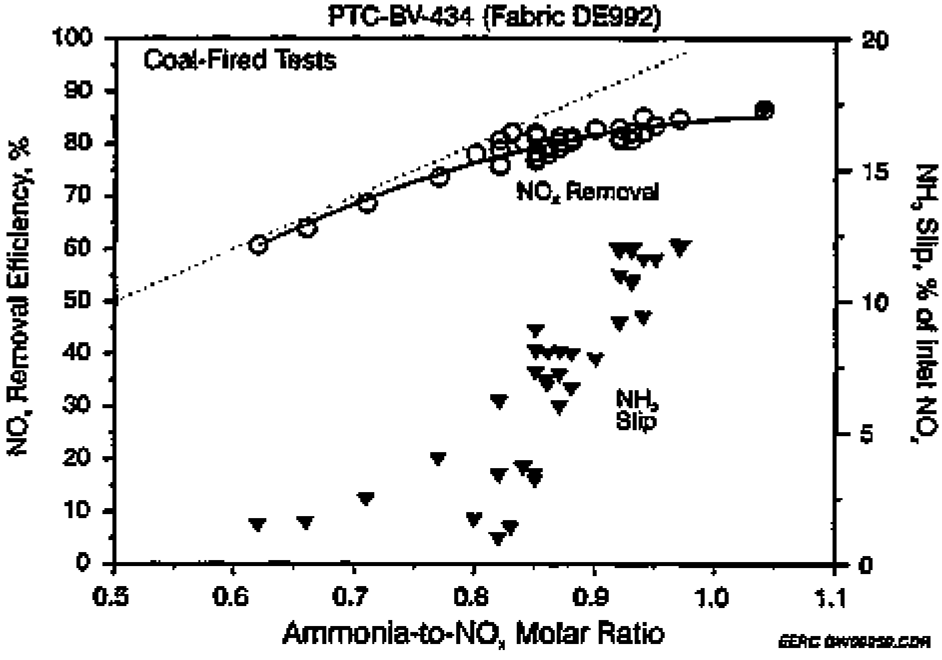

Figure 3-38. NO$_x$ removal efficiency and ammonia slip versus ammonia-to-NO$_x$ molar ratio for Run PTC-BV-434, coal-fired tests: average inlet NO$_x$ = 940 ppm, average baghouse temperature = 659°F.

NO_x concentration. Assuming an inlet NO_x concentration of 300–400 ppm (0.5–0.7 lb of NO_2/MMBtu), which is greater than if not typical of pc-fired boilers with low NO_x burners, the resulting ammonia slip would be 20–30 ppm.

An ammonia slip level of 20–30 ppm is significantly higher than the <10 ppm values typically reported for conventional SCR systems. A paper presented at a recent conference on NO_x control for utility boilers concluded that the stringent ammonia emission limits currently in place around the United States (9 to 30 ppm) were significantly lower than the allowable occupational exposure levels (25 ppm for an 8-hr continuous period) (35). Therefore, an ammonia concentration at the stack of <100 ppm would not result in risk to human health or create an odor problem at ground level. However, in order to avoid plant impacts such as increased stack opacity and air heater fouling, users of ammonia-based NO_x control systems will effectively control ammonia slip at levels far below concentrations that could pose a hazard to human health. Therefore, there is no risk-based need to stringently regulate ammonia emissions. However, it is unlikely that ammonia emission limits exceeding those currently in place will be acceptable.

In general, the overall performance of the bags was good during the second 500-hr test. However, the catalyst reactivity decreased during the first week of operation. This was evidenced by an increase in ammonia slip. Catalyst performance appeared stable during the second and third weeks. Also, the average daily NO_x reduction decreased from 82% the first week to 78% the third week at a nominal ammonia-to-NO_x molar ratio of 0.85. Figure 3-39 plots the NO_x removal efficiency and ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio for the gas-fired test periods during both 500-hr test periods. Figure 3-40 plots the NO_x removal efficiency and ammonia slip (as a percentage of inlet NO_x concentration) as a function of ammonia-to-NO_x molar ratio for the coal-fired test periods during both 500-hr tests. Despite the pressure drop control problems during the first 500-hr test, the results are very consistent for the gas- and coal-fired tests. There is a definite difference between NO_x reduction from clean to dirty fabric while natural gas was fired. The scatter in the coal-fired data may be due to differences in air-to-cloth ratios or catalyst reactivity.

Clean (unused) DE992 fabric was tested in the bench-scale system and compared to results from the pilot-scale system while natural gas was fired with new bags. At an ammonia-to-NO_x molar ratio of 0.81, the bench-scale NO_x reduction observed was 75%, 2% lower than the pilot-scale results. Ammonia slip was 4% of the inlet NO_x concentration for the bench-scale system, as opposed to 7% of the inlet NO_x concentration for the pilot-scale system. The ammonia measurement on the bench-scale unit was made using a calorimetric method that samples a total of 50 or 100 cm^3 of gas in one minute, whereas the pilot-scale system uses a titration method that samples a slipstream of the flue gas over a 1- to 2-hr period.

The bench-scale data for Run PTC-BV-434 fabric samples again showed 2% less NO_x reduction than the pilot-scale data: 77% versus 79%. Ammonia slip values were 5.2% versus 7.5% of the inlet NO_x concentration at an ammonia-to-NO_x molar ratio of 0.84 for the bench- and pilot-scale data, respectively.

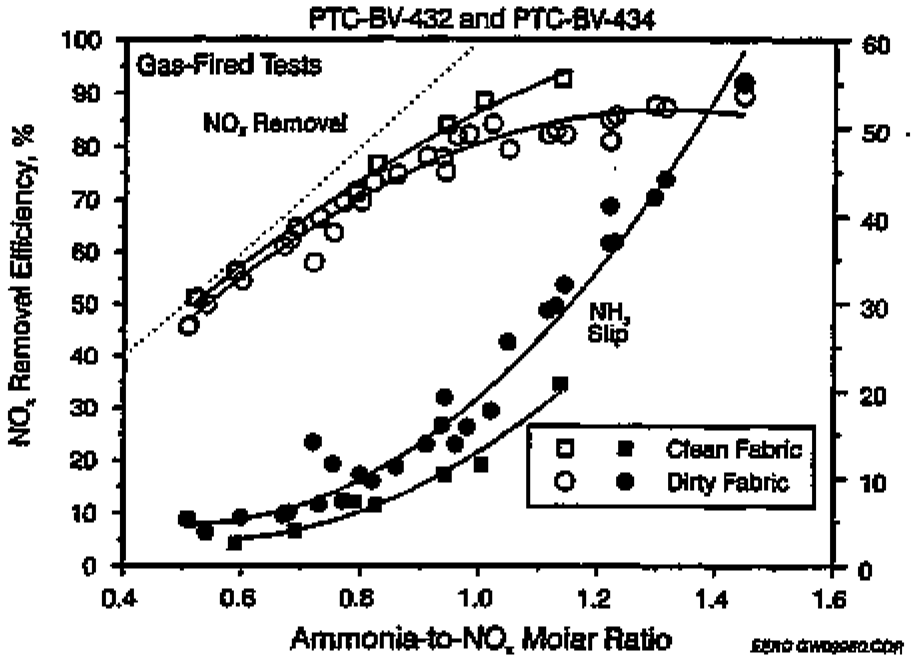

Figure 3-39. NO_x removal efficiency and ammonia slip versus ammonia-to-NO_x molar ratio for Runs PTC-BV-432 and PTC-BV-434, natural gas-fired tests.

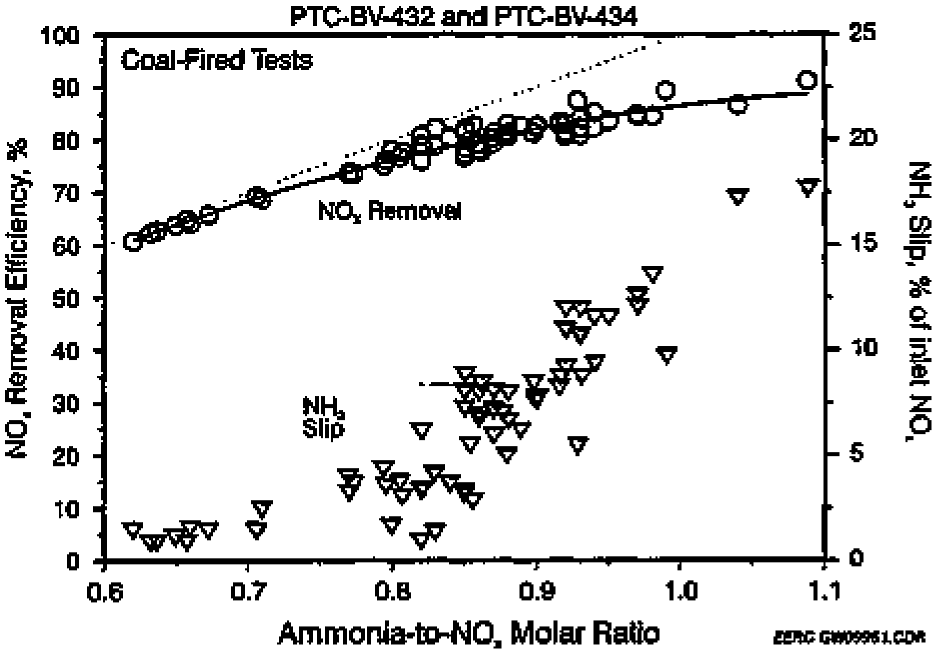

Figure 3-40. NO_x removal efficiency and ammonia slip versus ammonia-to-NO_x molar ratio for Runs PTC-BV-432 and PTC-BV-434, coal-fired tests.

3.3.3 Fabric Filter Performance

Tests were completed using catalyst-coated filter bags in a pulse-jet system with three different fuels (Blacksville bituminous coal, Black Thunder subbituminous coal, and a residual oil). In addition, two 500-hr tests were completed to better assess catalyst-coated fabric performance. The bags were cleaned on-line using a pulse of compressed air for which the pressure and duration of the pulse could be adjusted, depending on the allowable pressure drop.

As was the case with the reverse-gas fabric filter tests, particulate emissions were measured using a modified EPA Method 5 and the APS. Multicyclones and a Coulter counter were used to measure particle-size distribution.

3.3.3.1 Fuel Impacts on Fabric Filter Performance

Three different fuels, Blacksville bituminous coal, Black Thunder subbituminous coal, and a residual oil, were fired in the PTC while catalyst-coated bags were being tested in the pulse-jet baghouse. The bags were cleaned on-line on a timed basis with the pressure drop maintained at less than 8 in. W.C.; however, in several tests at the higher air-to-cloth ratios, it was necessary to intermittently clean the bags off-line. Pressure drop as a function of time is shown in Figures 3-41 and 3-42 for the two coals. The ammonia-to-NO_x molar ratio ranged from 0.8 to 1.1.

Figure 3-43 shows the average particulate collection efficiency for the Blacksville bituminous and the Black Thunder subbituminous coals, measured both with the ammonia injection off and with it on. No statistical difference was found between the coals with the ammonia injection off. However, there is a statistical difference between the two coals when the measurements were made with the ammonia injection on. In this case, as with the reverse-gas baghouse tests, the particulate collection efficiency was lower for Blacksville bituminous coal than for Black Thunder subbituminous coal. The average collection efficiency for the Blacksville coal dropped from 99.96% to 99.51% when the ammonia injection was turned on. However, when the Black Thunder coal was fired, the average particulate collection efficiency remained at 99.95% with and without ammonia injection. This is directly attributable to the higher concentration of sulfur in the Blacksville coal, resulting in a higher SO_3 concentration in the flue gas to react with ammonia and form fine particulate. Because of the alkaline nature of the subbituminous coal ash, any SO_3 that is formed will react to form calcium or sodium sulfate before the flue gas cools enough to allow it to react with excess ammonia.

As stated earlier, in addition to the two coals, the pulse-jet catalyst-coated filter bags were also evaluated while a residual oil was fired. Because residual oil can produce a large number of submicron monosized particles, there was concern that the bags could become blinded with time. In addition, there was concern that soot particles might form and burn on the catalyst-coated bags at the planned operating temperature (650°F). To help alleviate these concerns, the bags were precoated with pulverized dolomite. Controlling pressure drop during this test was no problem, as it was maintained at under 3 in. W.C., and the bags were not cleaned throughout the test because of the low inlet ash loading. When the particulate collection efficiency of the residual oil is compared with that of the two coals, as shown in Figure 3-44 (the ammonia is turned off in all three cases), the collection efficiency does appear to be lower. However, one difficulty in

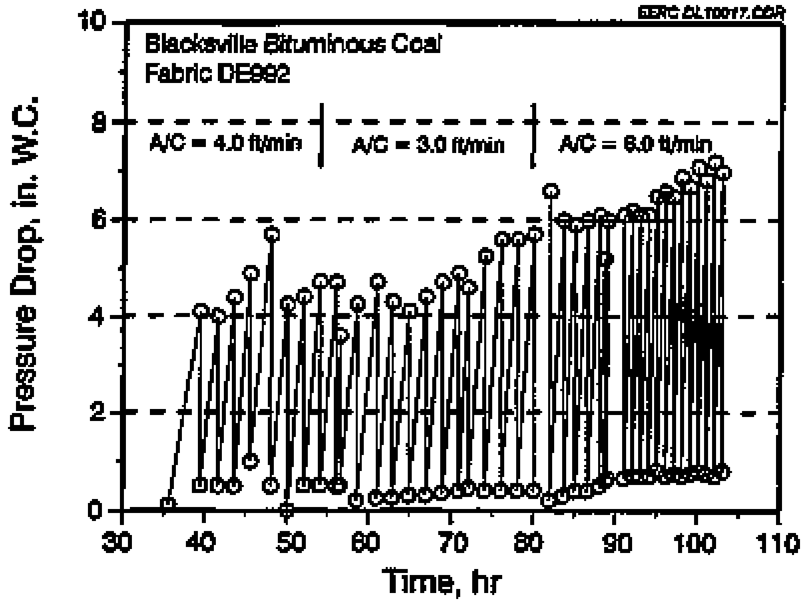

Figure 3-41. Pressure drop as a function of time across the DE992 catalyst-coated fabric while a Blacksville bituminous coal was fired.

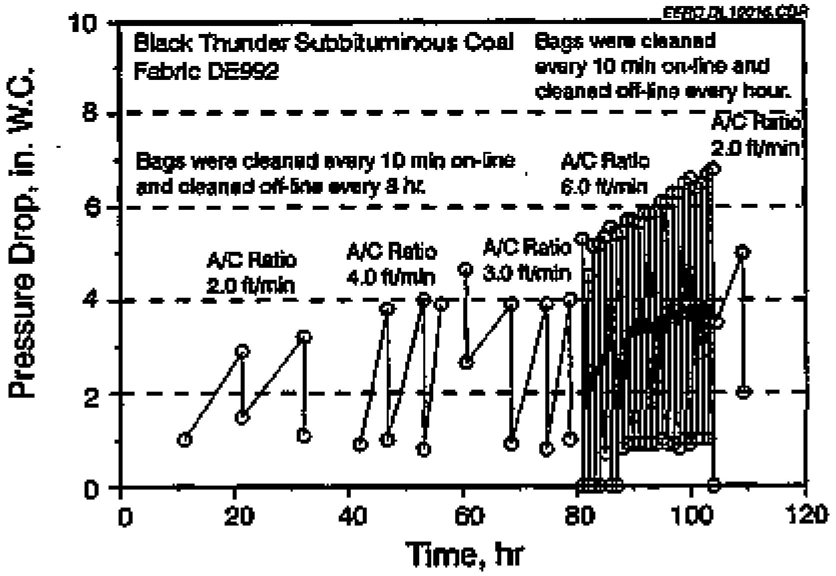

Figure 3-42. Pressure drop as a function of time across the DE992 catalyst-coated fabric while a Black Thunder subbituminous coal was fired.

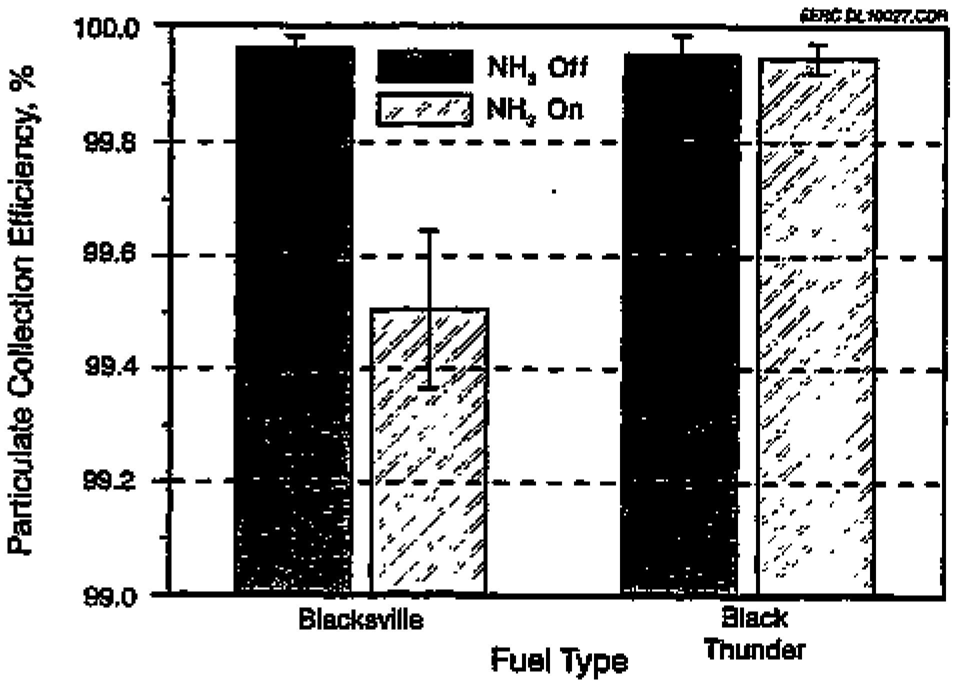

Figure 3-43. The effect of coal type on the average particulate collection efficiency for DE992 catalyst-coated fabric.

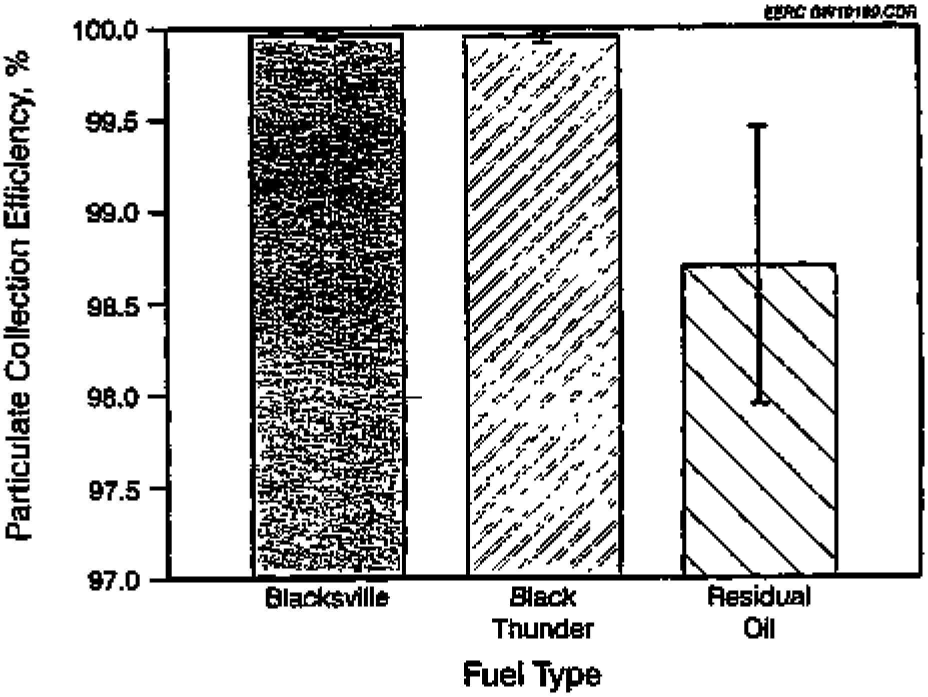

Figure 3-44. The average particulate collection efficiency for a residual oil compared to two different coal types for a DE992 catalyst-coated fabric.

determining the particulate collection efficiency for the residual oil was very low inlet particulate concentrations, about 2 orders of magnitude lower than for the two coals (0.018 gr/scf compared to 1.8 gr/scf). This resulted in more uncertainty in the overall particulate collection efficiency, as shown by the relatively large error bar in Figure 3-44. Although the overall collection efficiency was lower (an average of 98.77%), the actual mass emissions (gr/scf) were about the same for all three fuels. Also, the collection efficiency was affected by the dolomite, which was not part of the inlet dust loading, bleeding through the bags and on to the outlet filters during sampling periods.

3.3.3.2 Fabric Filter Performance During 500-hr Test Periods

Two 500-hr tests (PTC-BV-432 and PTC-BV-434) were completed using the pulse-jet baghouse to evaluate the performance of the catalyst-coated filter bags on a longer-term basis. These two tests were run at air-to-cloth ratios of 3.5 and 3.0 ft/min, respectively, and a baghouse temperature of 650°F while firing Blacksville bituminous coal. The primary parameter was the ammonia-to-NO_x molar ratio, which varied from 0.6 to 1.1. For both tests, the bags were cleaned based on the pressure drop, a maximum of 5–6 n. W.C. and a minimum of 3–4 in. W.C.

During the first of the two 500-hr tests (PTC-BV-432), after approximately 114 hours, the pressure drop (shown in Figure 3-45) began to increase uncontrollably even after pulse pressure, pulse duration, and cleaning frequency were increased. Inspection of the baghouse revealed that one of the pulse nozzles had plugged and others were partially plugged, thereby effectively changing the air-to-cloth ratio from 3.5 to 4 ft/min and reducing the performance of the cleaning system overall. It was speculated at the time that the bags may have been blinded as a result of the poorly performing pulse system. The initial set of catalyst-coated bags was then replaced with the bags that had been pretreated with dolomite and used successfully during the testing with residual oil. After the catalyst-coated filter bags had been changed, there was still some difficulty in cleaning the bags. However, after about 350 hours, the pressure drop appeared to stabilize. As shown in Figure 3-45, the bags were cleaned when the differential pressure drop reached 5 in. W.C., and on-line cleaning continued until a differential pressure drop of about 3 in. W.C. was reached. At the very end of the test, the pressure drop again could not be adequately controlled, and the run was terminated. Following the test, it was found that two of the pulse nozzles were completely plugged and four others were partially plugged. The nozzles were being plugged by corrosion deposits developing in the carbon steel pulse lines because of flue gas condensation. It was decided that for future tests, a small amount of air (1 scfh) would be used to continuously flush the pulse nozzles to prevent flue gas condensation and the corrosion and plugging problems.

During the 500-hr test (PTC-BV-432), four inlet and ten outlet modified EPA Method 5 dust-loading measurements were made. For all of the measurements, the ammonia injection was turned on. The outlet data are shown in Figure 3-46. Particulate collection efficiency in several cases was very low and would not effectively control emissions to meet the New Source Performance Standard (NSPS) of 0.03 lb/MMBtu). The particulate collection efficiencies ranged from 97.69% to 99.89%. The very low collection efficiencies (those resulting in emissions exceeding 0.03 lb/MMBtu) were always associated with high ammonia slip. Although there were no measurements taken with the ammonia injection turned off, it was expected that the particulate collection efficiency would be significantly better, >99.9%, based on the 100-hr test with Blacksville bituminous coal.

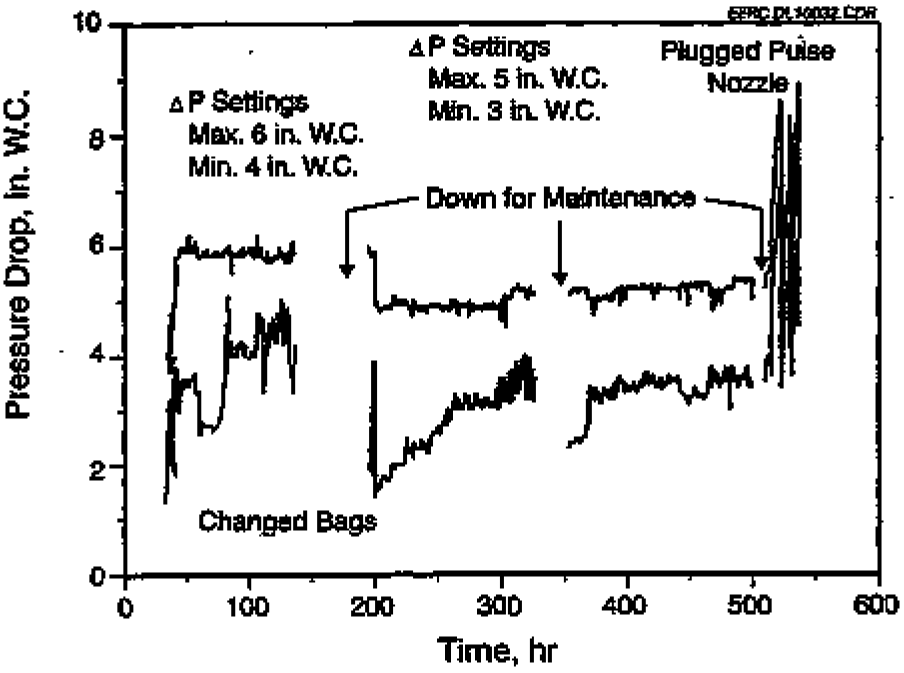

Figure 3-45. Pressure drop as a function of time for the first 500-hr test, PTC-BV-432.

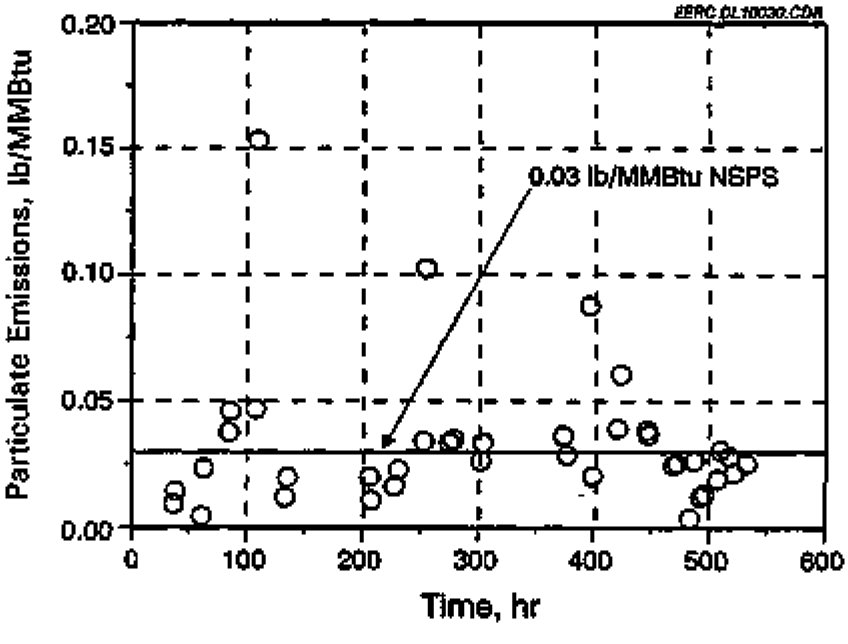

Figure 3-46. Modified EPA Method 5 particulate emissions for the first 500-hr test, PTC-BV-432.

Using the APS, an integrated average (one sample over an entire cleaning cycle) of respirable mass emissions was taken each day. These data are plotted in Figure 3-47. Based on an inlet respirable mass of 300 mg/m^3, the respirable mass collection efficiency ranged from 97% to 99.9%, which is in agreement with the modified EPA Method 5 results.

Because of some of the operational problems that occurred during the first 500-hr pulse-jet test (PTC-BV-432), a second 500-hr test (PTC-BV-434) was completed. As in the first test, Blacksville bituminous coal was fired in the pulverized coal-fired combustor and the air-to-cloth ratio and temperature were constant at 3.0 ft/min and 650°F. The only variable tested was the ammonia-to-NO$_x$ molar ratio, which was nominally 0.8 or 0.9, with a few tests completed at ammonia-to-NO$_x$ molar ratios of 0.6 and 0.7.

Although the pressure drop problems associated with plugging of the nozzles did not occur during the second 500-hr test, the pressure drop was very similar to that of the first test. Figure 3-48 presents the pressure drop data as a function of time for the second 500-hr test. The initial setting was for the bags to clean when the pressure drop reached 5 in. W.C. and to continue to clean on-line until 3 in. W.C. was reached. Figure 3-48 shows that there was a slow increase in after-cleaning pressure drop with time. Initially, the bags were easily cleaned to less than 3 in. W.C. with a single-pulse cycle. However, after about 400 hours, the increase in after-cleaning pressure drop required that the pressure drop settings be changed to a maximum of 6 in. W.C. and cleaned down to 4 in. W.C. For the remainder of the test, the pressure drop appeared to be stable.

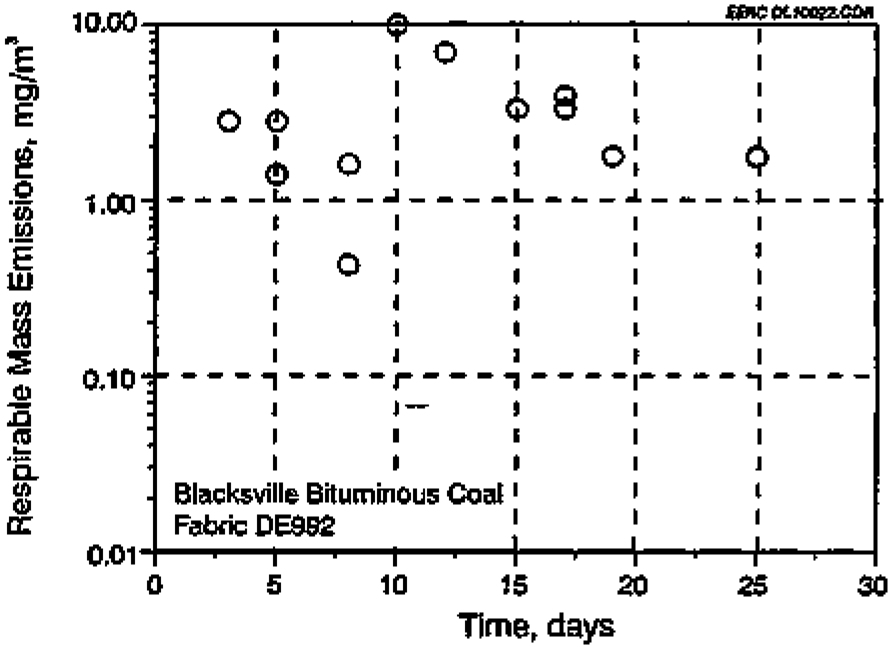

Figure 3-47. Integrated average respirable mass emissions for the first 500-hr test, PTC-BV-432.

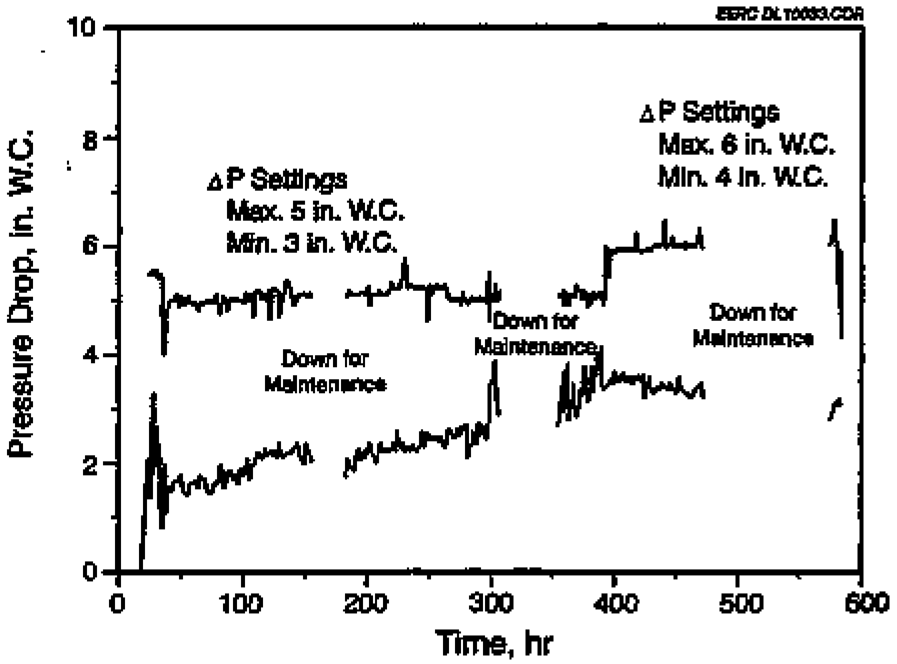

Figure 3-48. Pressure drop as a function of time for the second 500-hr test, PTC-BV-484.

As in the first 500-hr test, four inlet and ten outlet modified EPA Method 5 dust-loading measurements were completed each week, most with the ammonia injection on. The outlet data are plotted in Figure 3-49. Comparing the particulate collection efficiencies obtained during the first 500-hr test to those obtained during the second 500-hr test (Figure 3-46 compared to Figure 3-49) shows that some of the data are similar. However, during the second 500-hr test, there were no data points above the NSPS for particulate emissions. This improvement in filter performance was the result of better overall system stability with respect to filter cleaning, pressure drop, and air-to-cloth ratio during the second 500-hr test. As shown in Figure 3-49, six outlet EPA Method 5 dust-loading measurements were made with the ammonia injection turned off. In each case, the particulate collection efficiencies were high, ranging from 99.84% to 99.99%, resulting in low particulate emissions. Particulate emissions approaching the 0.03-lb/MMBtu NSPS limit were observed during test periods when ammonia slip was >40 ppm.

The integrated respirable mass averages using the APS are plotted in Figure 3-50. Again assuming an inlet respirable mass of 300 mg/m^3, the respirable mass collection efficiency ranged from 99.63% to 99.98%. This is in good agreement with the modified EPA Method 5 sampling data.

In general, the 500-hr pulse-jet tests provided consistent data while natural gas and coal were fired. At an ammonia-to-NO$_x$ molar ratio of 0.80, a NO$_x$ reduction of roughly 75% and an ammonia slip of 5% of the inlet NO$_x$ concentration can be expected. To achieve 80% NO$_x$ reduction, an ammonia-to-NO$_x$ molar ratio of 0.85 will be necessary, and

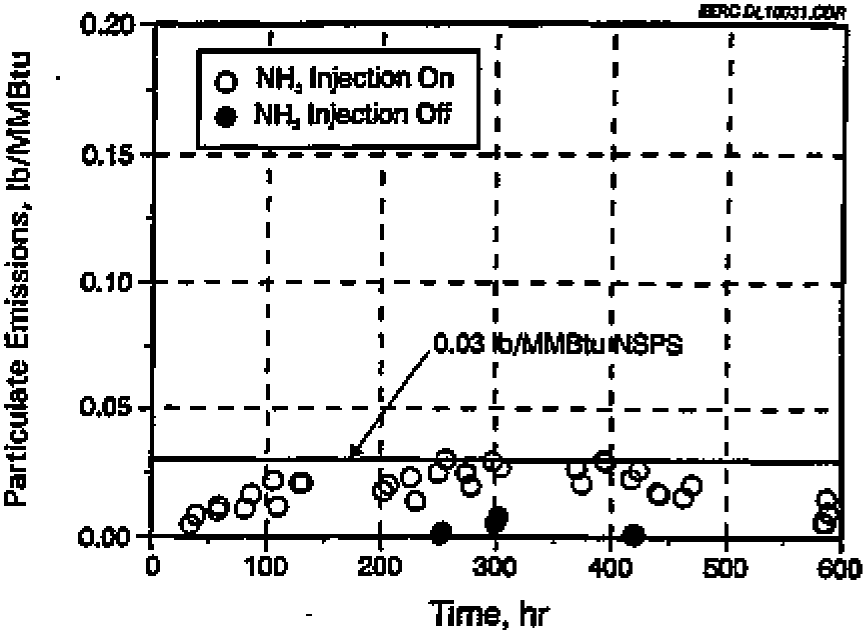

Figure 3-49. Modified EPA Method 5 particulate emissions for the second 500-hr test, PTC-BV-434.

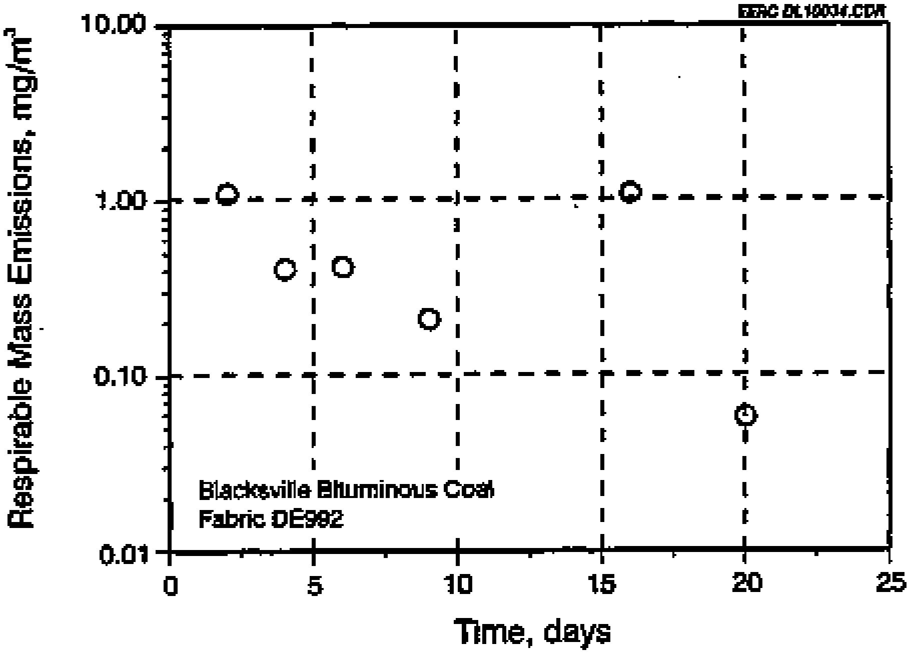

Figure 3-50. Integrated average respirable mass emissions for the second 500-hr test, PTC-BV-434.

the ammonia slip will be 7.5% of the inlet NO_x concentration (23-ppm ammonia slip for a 300-ppm, 0.5 lb of NO_2/MMBtu inlet NO_x concentration). Further development of the CFF concept should focus on improving catalyst reactivity in order to reduce ammonia slip and allow operation at higher air-to-cloth ratios while achieving NO_x reduction levels of 80% or more.

3.4 Subtask 3.4 – Fabric Durability Testing/Pulse-Jet System

Subtask 3.4 activities were initiated in September 1991 in order to prepare the baghouse slipstream system at the UND steam plant for operation. Selection of a catalyst-coated fabric for Subtask 3.4 was discussed during a project review meeting held on March 3, 1992. Participants agreed that the 22-oz/yd^2 woven S2-glass fabric (DE992) would be used for pulse-jet applications.

Pulse-jet bags were installed in the slipstream baghouse at the UND steam plant in July 1992. EERC personnel installed nine bags. These bags represented nine of the twelve bags used for the first 100-hr pulse-jet test (PTC-BV-429) successfully completed for Subtask 3.3. Results from the 100-hr test (PTC-BV-429) showed NO_x reduction ranging from 73% to 92% for air-to-cloth ratios and ammonia-to-NO_x molar ratios of 2 to 6 ft/min and 0.7 to 0.96, respectively. Measured ammonia slip was <7.5% of the inlet NO_x concentration, which averaged 747 ppm. The average baghouse temperature was 655°F.

Completion of the 100-hr test and the resulting data established an excellent baseline from which to evaluate fabric performance and durability in the pulse-jet baghouse at the steam plant. Operation of the slipstream baghouse was initiated on July 16, 1992, and continued intermittently through December 3, 1993, at which time system operation was terminated because of funding limitations.

This section of the CFF final project report presents performance and durability results for the DE992 woven S2-glass catalyst-coated fabric used in a pilot-scale pulse-jet system. As of December 3, 1993, a total of 5136 hours of operating time had been accumulated resulting in 13,820 cleaning cycles. Data presented include coal analysis (Table 3-8), ash analysis (Table 3-9), a review of system operating conditions, results from particulate sampling, results from catalyst reactivity tests, and results from fabric strength tests (MIT flex and Mullen burst).

3.4.1 Coal Analysis

Collection of coal samples and coal analysis were not specifically planned for Subtask 3.4. Coal analyses routinely performed in support of UND steam plant operations were obtained and are presented in Table 3-8 for specific operating periods. Table 3-8 presents average values and standard deviations for coal moisture, ash, sulfur content, and higher heating value on an as-fired and moisture-free basis. These data represent 36 coal samples collected and analyzed from July 1992 through December 1993.

Data presented in Table 3-8 indicate that the coal moisture levels were high, generally 25%, typical for subbituminous coal. Coal sulfur content was low, ranging from 0.4% to 1.3% and averaging 0.54% to 0.79% on an as-fired basis. Ash content ranged from 5.6% to 11.3%, but was typically <10% on an as-fired basis. Higher heating values were

TABLE 3-8

Subtask 3.4 – Coal Analysis from UND Steam Plant[a]

Baghouse Operational Period	As-Fired				Moisture-Free		
	Moisture, wt%	Ash, wt%	Sulfur, wt%	Higher Heating Value, Btu/lb (kJ/kg)	Ash, wt%	Sulfur, wt%	Higher Heating Value, Btu/lb (kJ/kg)
July–August 1992	24.7 ± 1.4	8.2 ± 1.5	0.54 ± 0.11	8749 ± 193 (20,350 ± 448)	10.8 ± 1.8	0.72 ± 0.15	11,619 ± 341 (27,026 ± 794)
October–November 1992	25.1 ± 0.5	8.2 ± 1.2	0.75 ± 0.23	8729 ± 168 (20,303 ± 391)	10.9 ± 1.6	1.00 ± 0.31	11,651 ± 196 (27,100 ± 455)
April–May 1993	24.1 ± 1.3	8.5 ± 1.7	0.79 ± 0.16	8503 ± 303 (19,779 ± 704)	11.1 ± 2.1	1.04 ± 0.20	11,204 ± 564 (26,061 ± 1,311)
July–December 1993	24.9 ± 1.2	7.9 ± 1.5	0.61 ± 0.19	8823 ± 217 (20,521 ± 504)	10.6 ± 1.9	0.81 ± 0.26	11,758 ± 380 (27,349 ± 885)

[a] Coal fired in the UND stoker-fired boiler was a Montana subbituminous coal. The data represent 36 coal samples.

TABLE 3-9

XRF and LOI Analysis Results for Slipstream Baghouse Hopper Ash[a,b]

Oxide	August 1992	November 1992	May 1993	August 1993	October 1993	October 1993	November 1993
SiO_2	7.30	31.10	48.70	39.45	42.11	41.62	45.87
Al_2O_3	1.74	12.00	20.89	20.86	22.11	18.87	21.57
Fe_2O_3	0.45	1.54	12.74	2.20	1.82	9.45	15.82
TiO_2	0.04	0.81	1.25	1.12	1.21	0.88	0.81
P_2O_4	0.91	0.81	0.89	0.56	0.37	0.55	0.36
CaO	44.01	27.79	9.62	21.59	19.09	15.78	8.98
MgO	0.72	6.13	4.78	8.56	8.37	4.10	2.09
Na_2O	0.28	0.50	0.79	0.49	0.42	0.76	0.67
K_2O	0.20	0.30	0.34	0.34	0.33	1.18	1.19
SO_3	44.35	19.53	0.00	4.83	4.17	6.82	3.64
Loss on Ignition	NA	4.64	6.19	8.91	7.42	24.80	9.93

[a] Data are reported as wt% oxides on a normalized mass basis.

[b] Each data set represents an individual baghouse hopper ash sample collected for the month identified. Two samples were collected in October 1993: one the first week and one the last week of the month.

typically 8500 to 8800 Btu/lb (19,770 to 20,470 kJ/kg) and ranged from 8100 to 9100 Btu/lb (18,840 to 21,170 kJ/kg) on an as-fired basis.

3.4.2 Ash Analysis

Ash samples were collected from the baghouse hopper during Subtask 3.4. Sampling frequency was one sample per month of system operation. All baghouse hopper ash samples were characterized for carbon and major elemental content using LOI and XRF analysis, respectively. Particle-size distribution was determined for a few samples using sieve, Coulter counter, and a light-scattering particle-size analysis technique. Ash collected in the baghouse hopper represented ash entering the system from the stoker-fired boiler and supplemental ash injected into the slipstream baghouse system in order to maintain an adequate ash loading (>1.5 gr/scf or >3.4 g/m^3) to the baghouse.

The supplemental ash injected into the system dominated the characteristics of the ash entering the baghouse. Ash used for injection included ash from a pilot-scale pulse-jet baghouse operating in support of a circulating fluid-bed combustor (CFBC), ash collected in the pilot-scale reverse-gas and pulse-jet baghouses used during the 100- and 500-hour tests using the pilot-scale pc-fired combustor, and ash collected from a pulse-jet baghouse operating at the UND steam plant. The ash from the CFBC was collected during a series of tests involving the combustion of a petroleum coke and subbituminous coal. Ash from the pc-fired system resulted from the combustion of bituminous and subbituminous coal. Ash collected at the UND steam plant resulted from stoker-firing a subbituminous coal.

Table 3-9 summarizes the LOI and XRF analysis results. The carbon content of the ash collected in the slipstream baghouse hopper was typically <10 wt%. The exception was an ash sample collected in October 1993 which had an LOI value of 24.8 wt%. This high LOI value was a result of extremely poor combustion efficiency in the stoker-fired boiler because of high air velocities through the grate, resulting in the entrainment of unburned carbon particles in the flue gas. The carbon content of the supplemental ash injected in the slipstream baghouse was <1 wt% for the CFBC ash and subbituminous ash from pc-firing. Bituminous ash from pc-firing had a carbon content that was typically <5 wt%. Therefore, the carbon content of the ash collected in the slipstream baghouse hopper was primarily because of carbon carryover from the stoker fired boiler. XRF data in Table 3-9 summarize baghouse hopper ash chemical characteristics reported as wt% oxides on a normalized mass basis. The data indicate that the catalyst-coated bags were exposed to ash having a wide range of chemical characteristics. The ash sample collected in August 1992 contained very high levels of calcium and sulfur because of the high concentration of calcium sulfate present. This analysis is consistent with the injection of CFBC ash resulting from the combustion of petroleum coke using a limestone bed for sulfur control. The ash sample collected in November 1992 is representative of the ash from the stoker-fired boiler, but CFBC ash was also used on a limited basis, increasing the calcium sulfate concentration. Ash samples collected in May and November 1993 contained lower levels of alkali (Ca, Mg, and Na) and higher levels of silica, alumina, and iron, consistent with the mixing of bituminous ash from the pilot-scale pc-fired system and the subbituminous ash from the stoker-fired boiler. In August and October 1993, the XRF analysis results were typical of a subbituminous ash.

Sieve analysis was completed on two of the baghouse hopper ash samples. The data summarized in Table 3-10 represent two very different ash samples with respect to

TABLE 3-10

Sieve Analysis of Slipstream Baghouse Hopper Ash

Screen Mesh Size	November 1992, wt% Retained	May 1993, wt% Retained
30	0.33	–
60	5.78	–
80	5.63	–
100	6.51	4.95
140	–	3.12
200	50.22	3.02
230	–	2.11
270	–	1.04
325	14.35	0.19
Pan	17.01	84.93

particle-size distribution. The first sample, collected in November 1992, was nearly 82% <100 mesh (<147 microns) on a mass basis. As previously stated, this sample represents ash primarily generated in the stoker-fired boiler, although some supplemental ash from the baghouse of a pilot-scale CFBC was used. Figure 3-51 presents additional particle-size distribution data for the −325-mesh (−43-micron) material collected in the pan of the sieve analysis assembly. Analysis of that fraction, using a Malvern instrument employing a light-scattering technique, showed that 90 wt% of the −325-mesh (−43-micron) material had a volumetric particle size of <30 microns. Therefore, roughly 15 wt% of the bulk ash sample had a volumetric particle size of <30 microns.

The May 1993 ash sample had a significantly smaller particle size, nearly 85% <325 mesh (<43 microns) on a mass basis. As previously stated, this sample represented ash from a pc-fired pilot-scale system as well as ash from the stoker-fired boiler. In this case, the particle-size distribution of the baghouse hopper ash sample is more typical of an ash sample from a pc-fired system. Figure 3-51 presents additional particle-size distribution data for the −325-mesh (−43-micron) material collected in the pan of the sieve analysis assembly. Analysis of that fraction, using the Coulter counter technique, showed that roughly 90 wt% of the −325-mesh (−43-micron) material had a volumetric particle size of <40 microns. Therefore, roughly 76 wt% of the bulk ash sample had a volumetric particle size of <40 microns.

In general, the catalyst-coated bags were exposed to ash containing high concentrations of alkali (Ca, Mg, and Na) species, >20 wt%. The ash collected in the baghouse hopper typically took on the character of the supplemental ash injected upstream of the baghouse, with respect to chemical characteristics and particle-size distribution. Carbon content in the ash samples was primarily the result of carbon carryover in the ash from the stoker-fired boiler.

3.4.3 Baghouse Slipstream System Operation

The baghouse slipstream system operated quite well during the Subtask 3.4 evaluation of the catalyst-coated filter bags. All system shutdowns exceeding a few hours

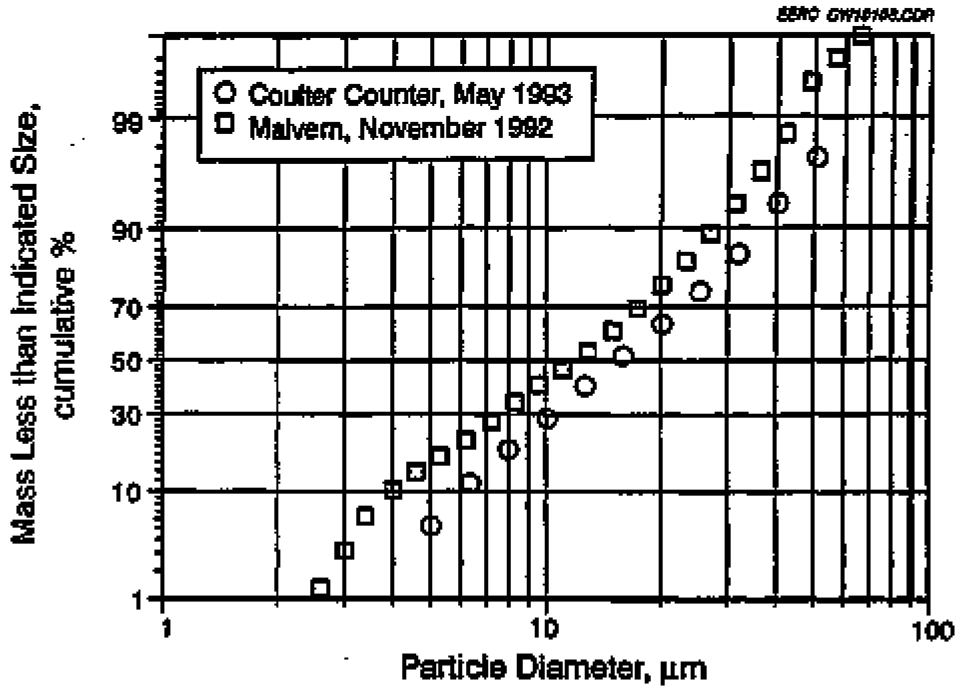

Figure 3-51. Particle-size distribution for two slipstream baghouse ash samples.

were a result of operational problems with the stoker-fired boiler or a planned boiler shutdown. Temporary shutdowns (2–4 hrs) were required periodically (once every 6 to 8 weeks) to clean ash deposits from the boiler flue gas extraction probe in order to maintain control over flue gas flow rates. Periodic replacement and maintenance of system instrumentation were also required. Typical replacement items included thermocouples and data logger components. Routine calibration of static and differential pressure transmitters was also required to assure data accuracy. Slipstream system piping was dismantled and thoroughly cleaned during extended system shutdowns. System instrumentation was covered with plastic to keep it clean and protected during periods of nonuse. Four electric resistance heaters were used to maintain the baghouse at temperatures >150°F during nonoperational periods to avoid moisture condensation on the catalyst-coated filter bags.

Subtask 3.4, Fabric Durability Testing/Pulse-Jet System, began in September 1991 in order to prepare the baghouse slipstream system at the UND steam plant for operation. During the week of July 6–10, 1992, nine catalyst-coated filter bags were installed in the slipstream baghouse. An initial dust cake was developed on the filter bags using dolomite. The purpose for developing the initial dust cake was to provide some moderate protection for the filter bags in the event unburned carbon particles from the stoker-fired boiler passed through the particle knockout device and entered the baghouse during the initial start-up phase. Carbon particle burnout on the surface of the catalyst-coated bags would have resulted in damage to the catalyst and S2-glass fibers and was actively avoided.

Table 3-11 summarizes baghouse operating conditions. Accumulated operating hours and cleaning cycles for Subtask 3.4 totaled 5136 and 13,820, respectively. Baghouse air-to-cloth ratio averaged 4 ft/min (1.2 m/min) with excursions as high as 5.3 ft/min (1.6 m/min) and as low as 2.8 ft/min (0.8 m/min). Baghouse mean temperature was typically 526°F (274°C) but ranged up to 700°F (371°C) and down to 350°F (177°C) as a result of boiler load settings. Average baghouse differential pressure was typically 3.5 in. W.C. (0.9 kPa) and ranged from 1 to 8 in. W.C. (0.2 to 2.0 kPa). Supplemental ash injection was used extensively during Subtask 3.4, and inlet particulate mass loading ranged from 1.5 to 17.7 gr/scf (3.4 to 40.5 g/m^3).

On July 16, 1992, operation of the baghouse slipstream system was initiated. Operation of the baghouse slipstream system was continuous for the last two weeks of July 1992 except for a 24-hr period on July 21 when the boiler was shut down for scheduled electrical maintenance. Operation of the baghouse continued through August 21, 1992, at which time baghouse operation was discontinued to permit inspection of the baghouse. Supplemental ash injection (CFBC ash) was used continuously during the July and August 1992 operating period.

TABLE 3-11

Summary of Subtask 3.4 Slipstream Baghouse Operating Data

Bag Material	Catalyst-coated woven fabric DE992, 22 oz/yd^2, S2-glass
Filter Temperature	526° ± 44°F (350°–700°F)
Filter Face Velocity	4.0 ± 0.5 ft/min (2.8–5.3 ft/min)
Operating ΔP	3.5 in. W.C. (1–8 in. W.C.)
Operating Hours Completed	5136
Filter Cleaning Cycles	13,820
Pulse-Air Reservoir Pressure	43 psig
Pulse Duration	0.10 sec
Pulse Volume	0.3 ft^3/bag
Inlet Dust Loading	4.2 gr/scf (1.5–17.7 gr/scf)
Filter Performance	
Outlet Dust Loading	0.0004 gr/scf (0.0001–0.0011 gr/scf)
Collection Efficiency	99.98% (99.96%–99.99%)

Inspection of the baghouse was necessary to determine the cause for a high level of particulate emissions measured at the outlet of the baghouse on August 20, 1992. Inspection of the baghouse revealed that one of the bags had failed and a second bag showed significant wear. The failure of one bag and the significant wear observed on a second bag were caused by the failure of a blank flange gasket in the top of the baghouse. This gasket was intended to seal off the top inlet to the baghouse. Failure of the blank flange gasket resulted in direct impaction of fly ash on the surface of one bag at high flue gas velocities, resulting in a 2- to 3-in.-diameter (5.0- to 7.6-cm) hole in both sides of the first bag and significant wear on the surface of the second bag.

The baghouse was cleaned up, and the damaged bags were replaced with spare bags in September 1992. The two catalyst-coated bags removed from the baghouse represented 840 hours of baghouse operation and were subsequently used to evaluate fabric strength and catalyst reactivity. Operation of the slipstream baghouse did not resume until October 1992 because of scheduled boiler maintenance which began August 25, 1992, and continued through mid-October. Baghouse operation resumed on October 20, 1992, and continued through November 22, 1992. Supplemental ash injection (circulating fluidized-bed combustion [CFBC] ash) was continuous in October but not in November 1992 because of limited ash availability.

Baghouse operation was discontinued on November 22, 1992, as a result of a boiler shutdown to permit the installation of a new flue gas duct on the steam plant boiler. Unfortunately, installation of the new flue gas duct required the relocation of the slipstream baghouse. It was only necessary to move the baghouse a few feet, but modifications to the inlet and outlet piping were required. In addition to the piping modifications, additional support steel and catwalks were required to provide for safe access to the top of the baghouse. Other activities included installation of new thermocouple leads and conduit, reinstalling power to the ID fan and panel board, verifying the data acquisition system, and precoating the bags with ash prior to initiating flue gas flow from the stoker-fired boiler. Except for a short period of time when the baghouse was actually being moved, the baghouse heaters were kept on to prevent moisture condensation in the baghouse.

Although the modifications to the slipstream baghouse system were completed by EERC personnel in a 6-week time frame, operation of the slipstream baghouse did not resume until April 1993. The holdup was because of contractor scheduling delays associated with installation of the new flue gas duct on the boiler, an unplanned steam line move, and the planned tie-in of a new stack.

Prior to system operation being resumed, the bags were removed, cleaned, inspected, reinstalled, and precoated with a lignite fly ash resulting from one of the 100-hr reverse-gas pilot-scale tests completed in 1992. One bag was removed and replaced with a spare bag to allow for determination of fabric strength and catalyst reactivity. The bag removed from the baghouse represented 1642 hours of baghouse operation. Operation of the baghouse slipstream system at the UND steam plant resumed on April 15, 1993. Operation of the baghouse was continuous through May 18, 1993. At that time, baghouse operation was discontinued as a result of scheduled boiler maintenance. Supplemental ash injection was continuous during this operating period. The ash used resulted from the combustion of lignite, subbituminous coal, and bituminous coal during pilot-scale 100- and 500-hr pc-fired tests completed in 1992.

It was anticipated that boiler operation would resume in late June 1993. However, a routine boiler inspection identified some unexpected grate damage that extended the boiler maintenance outage through late July 1993. Operation of the baghouse slipstream system resumed on July 29, 1993, and continued through October 13, 1993. The slipstream baghouse did not operate October 14–31, 1993, at the request of UND steam plant personnel due to boiler emissions testing at the steam plant. Operation of the baghouse slipstream system resumed again on November 1, 1993, and was ultimately terminated on December 3, 1993, because of project funding limitations. The baghouse also did not operate from November 25 through November 27, 1993, because of a forced shutdown as a result of a power failure at the UND steam plant. Supplemental ash injected into the system during the July through December 1993 time frame was a subbituminous ash collected from a conventional pulse-jet baghouse operating on one of the stoker-fired boilers for particulate emissions control.

One catalyst-coated bag was removed from the baghouse in December 1993, representing 5136 hours of baghouse operation. This bag was used to determine fabric strength and catalyst reactivity. Removal of the remaining bags was delayed until January 1994 in the hope that additional funding might become available to continue system operation. Ultimately, the remaining bags were removed from the baghouse in January 1994 and shipped to OCF for final storage and/or disposal. The slipstream baghouse system was cleaned and partially dismantled in January 1994 in preparation for long-term inactivity.

The accumulation of 5136 operating hours occurred as a result of four distinct operating periods from July 1992 through December 1993. As many as 2000 additional hours of operation may have been accumulated if relocation of the baghouse had not been required, had fewer start-ups and shutdowns been experienced, and if total system operation had been accomplished in a shorter time frame. Ultimately, project funding limitations determined the point at which system operation was terminated, preventing the accumulation of 12,000 hours of slipstream baghouse operation as planned in the original scope of work. Funding limitations occurred as a result of the entire $944,759 in planned commercial cost-share funding not being secured. A total of $219,702 of the planned commercial cost-share funding was not secured. This amount represented nearly all of the proposed funding for Subtask 3.4.

Figures 3-52, 3-53, and 3-54 present baghouse temperature, differential pressure, and filter face velocity, respectively, as a function of run time for the 5136 hours of operation completed. Baghouse temperature is reported as a mean baghouse temperature. This value was determined by averaging the values of four thermocouples located in the baghouse. During Subtask 3.4, baghouse temperature varied by as much as 20°F (11°C) from top to bottom. Fluctuations in baghouse temperature during Subtask 3.4 were primarily because of boiler load swings. More dramatic changes in baghouse temperature were the result of adjustments to flue gas flow rate and temporary system shutdowns for probe cleaning or instrument repairs. Data presented in Figure 3-52 show that baghouse mean temperature ranged from 350°F (177°C) to 700°F (371°C) and averaged 526°F (274°C).

Baghouse differential pressure data are presented as a function of run time in Figure 3-53. The figure indicates very clearly the time periods during which the cleaning cycle trigger point was set at 4 or 6 in. W.C. (1 or 1.5 kPa). Differential pressure spikes

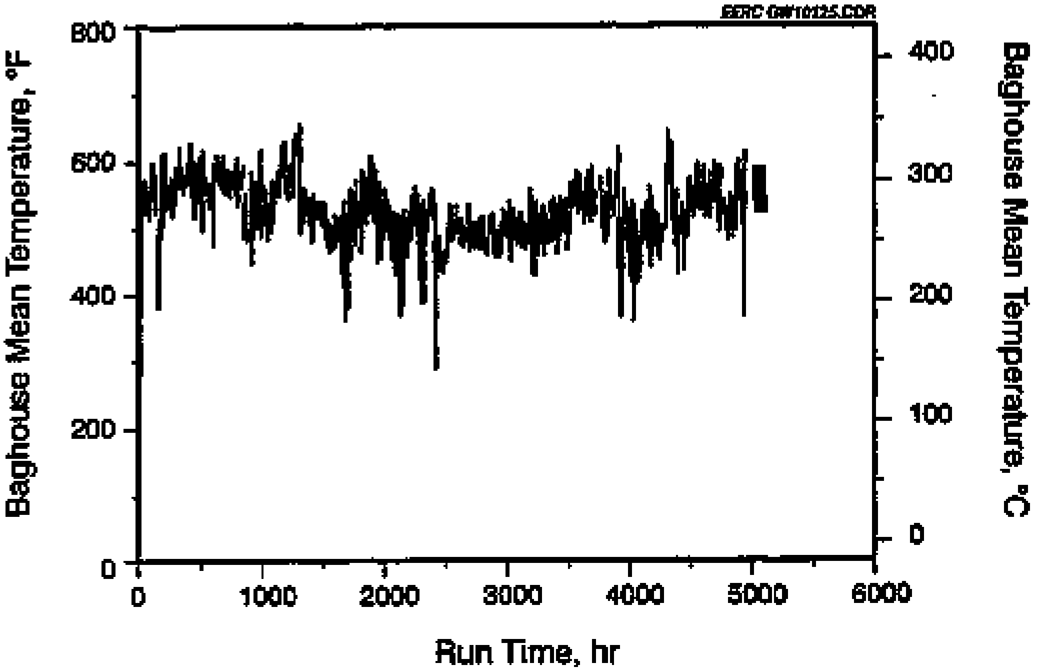

Figure 3-52. Slipstream baghouse mean temperature versus run time.

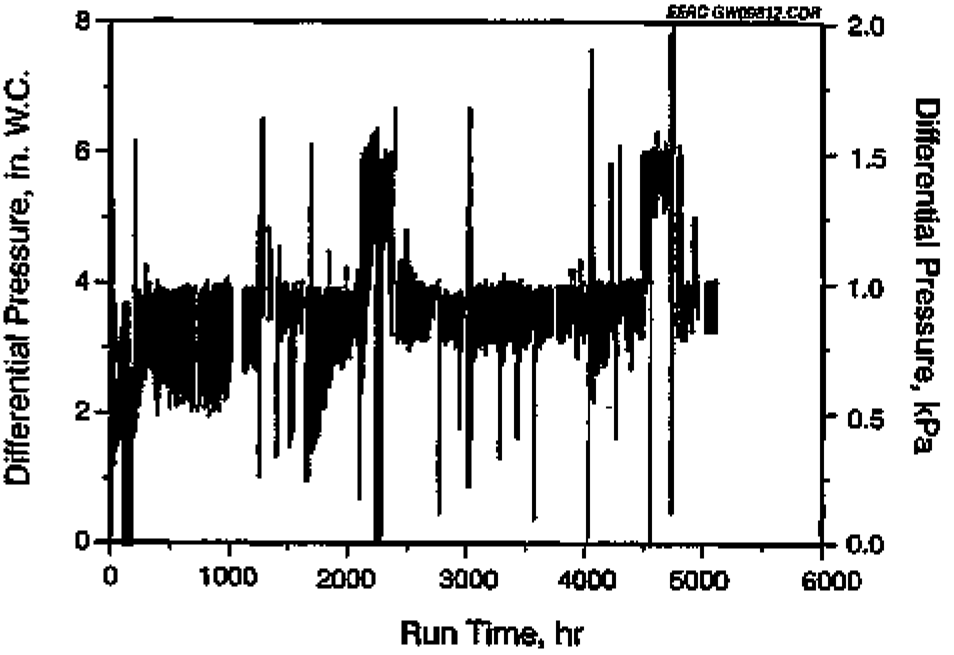

Figure 3-53. Slipstream baghouse differential pressure versus run time.

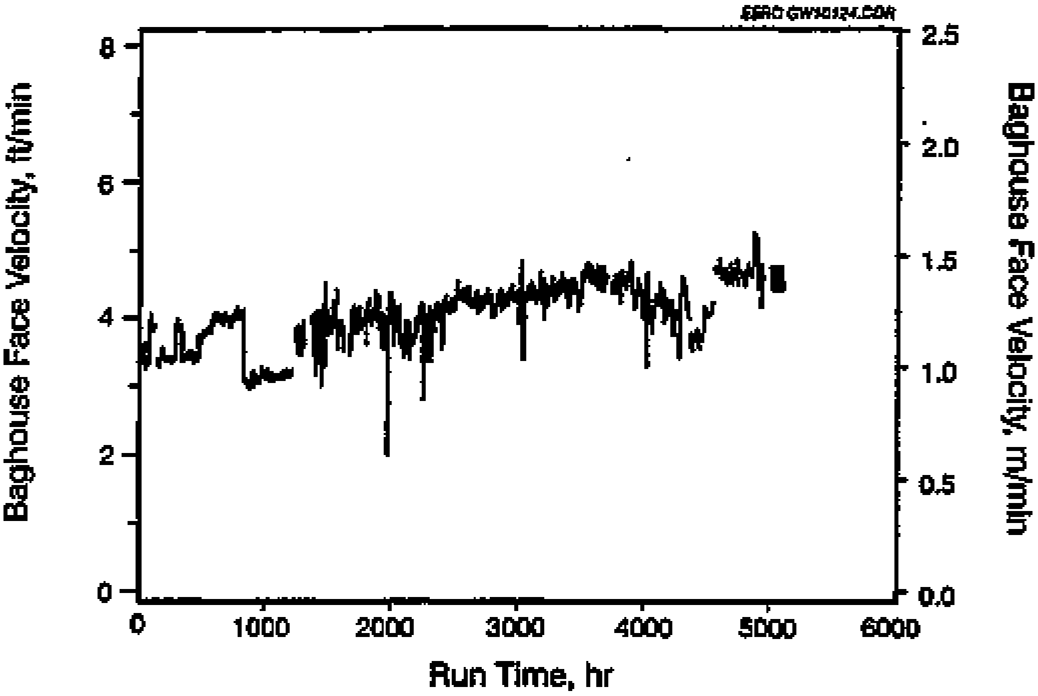

Figure 3-54. Slipstream baghouse face velocity versus run time.

were a result of either substantially reduced flue gas flow rates, temporary system shutdowns, or excursions because of an improperly set cleaning cycle trigger mechanism. The catalyst-coated filter bags experienced a total of 13,820 cleaning cycles during the 5136 hours of operating time, resulting in an average of one cleaning cycle every 22 minutes.

Figure 3-54 presents face velocity as a function of run time. Spikes toward lower face velocities resulted from temporary system shutdowns. Spikes toward higher face velocities were a result of overcorrection by the flow control valve. For the most part, flue gas flow rates through the system were stable, resulting in filter face velocities averaging 4 ft/min (1.2 m/min).

Flue gas analysis during the Subtask 3.4 filter bag durability test was limited. Data for oxygen and carbon monoxide content were collected periodically from steam plant instrumentation. SO_2 values were estimated based on the fuel sulfur content, and wet sulfur trioxide concentrations were measured using a selective condensation technique. Flue gas moisture content was determined as a function of particulate sampling activities. Table 3-12 summarizes data for flue gas analysis. Oxygen levels were 8%–13%. Carbon monoxide was not detected in the flue gas due to the high excess air levels. Sulfur dioxide values ranged from 130 to 780 ppm. Measured SO_3 concentrations were always <1 ppm because of the low fuel sulfur content and high alkali concentration in the fly ash. Flue gas moisture content was typically 4%–8%, relatively low for a subbituminous coal due to the high excess air levels.

TABLE 3-12

Flue Gas Analysis from Slipstream Baghouse System [a,b,c]

O_2	8%–13%
CO	Not detectable
SO_2	130–780 ppm
SO_3	<1 ppm
H_2O	4%–8%

[a] All values are reported on a volume %, moisture-free basis.

[b] Values for O_2 were obtained from steam plant instrumentation.

[c] Values for SO_2 were estimated based on fuel sulfur content, and SO_3 values were measured using a selective condensation technique.

3.4.4 Baghouse Particulate Collection Efficiency

Baghouse particulate collection efficiency during Subtask 3.4 was determined using a modified EPA Method 5 and multicyclone sampling. Results of the modified EPA Method 5 and multicyclone sampling are presented in Tables 3-13 and 3-14. Emissions from the baghouse were also measured in "real time" using an extractive aerodynamic particle sizer (TSI APS-33). The purpose of sampling at the baghouse outlet with the TSI APS-33 system was to supplement the modified EPA Method 5 results, generate emissions data before, during, and immediately after a cleaning cycle, and measure respirable mass emissions.

Particulate mass loading at the baghouse inlet because of boiler fly ash was generally <1 gr/scf (<2.3 g/m³). Therefore, with measured mass loadings typically ranging from 1.5 to 17.7 gr/scf (3.4 to 40.5 g/m³), the bulk of the particulate entering the baghouse was a result of supplemental ash injection. Variability observed for mass loading at the baghouse inlet was because of variability in the supplemental ash injection feed rate and swings in boiler load. Values for overall particulate collection efficiency ranged from 99.96% to 99.99% with an average value of 99.98%. The one value that was <99.9% corresponded to a sampling period during which fly ash emissions were very high because of a failed bag.

Particle-size distribution at the baghouse inlet was determined using a five-stage multicyclone sample train. Table 3-14 and Figure 3-55 summarize the multicyclone data for eleven sampling periods. The data show that during specific sampling periods, 74%–97% of the fly ash entering the slipstream baghouse had an aerodynamic diameter of >10 microns. Particulate mass having an aerodynamic diameter of <5 microns ranged from 1%–12%.

Seven sampling periods were completed with the TSI APS 33 sampling system. Figure 3-56 presents respirable mass emissions and baghouse pressure drop as a function of sampling time for a data set from October 30, 1992. The data set shows that respirable mass emissions were low, <0.002 gr/scf (<0.05 mg/m³), except during cleaning cycles. Emission spikes during cleaning cycles ranged from 0.0013 to 0.0131 gr/scf (0.3 to 3 mg/m³).

TABLE 3-13

Slipstream Baghouse Particulate Sampling Data[a,b]

Test Date	Inlet, gr/scf	Outlet, gr/scf	% H_2O	% Efficiency
07-16-92	1.5642	–	8.1	–
07-16-92	–	0.0001	6.4	99.992
07-16-92	2.5491[c]	–	7.1	–
08-20-92	1.7417	–	6.3	–
08-20-92	17.6786	–	7.3	–
08-20-92	–	2.5643	6.6	85.496[d]
08-20-92	14.9548[c]	–	6.1	–
10-29-92	4.0363	–	4.6	–
10-29-92	–	0.0006	5.2	99.986
10-29-92	–	0.0010	4.2	99.974
10-29-92	5.7311[c]	–	3.7	–
11-19-92	3.1900	–	6.7	–
11-19-92	–	0.0007	6.0	99.979
11-19-92	–	0.0011	5.5	99.965
11-19-92	2.6910[c]	–	4.8	–
04-27-93	1.6708[c]	–	5.0	–
04-27-93	–	0.0001	5.4	99.994[e]
04-27-93	–	0.0002	5.3	99.988[e]
05-14-93	2.2604[c]	–	6.2	–
05-14-93	–	0.0003	5.1	99.987[e]
05-14-93	–	0.0003	5.1	99.987[e]
08-04-93	2.2521[c]	–	5.4	–
08-04-93	–	0.0003	4.5	99.987[e]
08-04-93	–	0.0004	4.2	99.983[e]
09-10-93	1.7974[c]	–	3.4	–
09-10-93	1.9520	–	3.9	–
09-10-93	–	0.0002	5.2	99.988
09-10-93	–	0.0002	4.5	99.988
09-29-93	2.2451[c]	–	4.5	–
09-29-93	2.2124	–	7.4	–
09-29-93	–	0.0004	5.8	99.981
09-29-93	–	0.0005	5.5	99.979
10-28-93	2.5283[c]	–	3.4	–
10-28-93	2.6878	–	3.1	–
10-28-93	–	0.0003	4.5	99.989
10-28-93	–	0.0003	4.3	99.991

Continued . . .

TABLE 3-13 (continued)

Test Date	Inlet, gr/scf	Outlet, gr/scf	% H_2O	% Efficiency
11-23-93	4.0308[c]	–	4.6	–
11-23-93	5.7246	–	5.8	–
11-23-93	–	0.0003	5.0	99.995
11-23-93	–	0.0007	5.2	99.983

[a] Inlet EPA-5 sampling periods were 30–60 minutes in length, and outlet sampling periods were 2 hours in length. Multicyclone sampling periods at the baghouse inlet were typically 60 minutes.

[b] A selective condensation technique was used to determine flue gas SO_3 concentrations.

[c] Multicyclone sampling was used to determine the inlet mass loadings and particle-size distribution.

[d] The low particulate collection efficiency was due to the failure of a single bag.

[e] Overall efficiencies for particulate sampling on 4-27-93, 5-14-93, 8-4-93 were determined using the inlet loading value determined from multicyclone sampling.

Figure 3-57 presents mass emissions and baghouse pressure drop as a function of sampling time for a data set from November 23, 1993. The data set shows that total and respirable mass emissions were low, <0.0001 gr/scf (<0.03 mg/m^3), except during cleaning cycles. Emission spikes during cleaning cycles ranged from 0.0044 to 0.0131 gr/scf (1 to 3 mg/m^3). Emissions based on integrated averages ranged from 0.0003 to 0.0009 gr/scf (0.06 to 0.2 mg/m^3) for respirable mass and total mass emissions, respectively. In general, the APS data show that emission spikes due to cleaning cycles contribute significantly to the total mass emission rate. Also, the APS data support the modified EPA Method 5 data in concluding that the catalyst-coated DE992 fabric successfully controlled particulate emissions during the 5136 hours of baghouse operation. APS data not presented in this discussion are included in Appendix C.

3.4.5 Condition of Catalyst-Coated DE992 Filter Bags

During the Subtask 3.4 effort, four catalyst-coated DE992 bags were removed from the slipstream baghouse to determine fabric strength and catalyst reactivity as a function of flue gas exposure. Two bags were removed after 840 hours of exposure, one after 1642 hours, and another after 5136 hours. Figure 3-58 indicates the locations in the baghouse from which each of the four bags were removed. The first two filter bags were removed from Positions D and E as a result of the bag failure previously discussed. The third filter bag was removed from Position A prior to resuming baghouse operation in April 1993. A fourth bag was removed from Position I in December 1993. Selection of Positions A and I for removal of the third and fourth filter bags was a random selection.

Each time a filter bag was removed and at the conclusion of each operating period, the remaining catalyst-coated bags were visually inspected. With the exception of the one failed bag previously discussed, the tube sheet was found to be clean and the bags in good condition with no unusual dust cake formation or ash deposits. Upon removal from the baghouse, each bag was gently brushed/vacuumed clean. As a result, EERC personnel observed two distinct layers of ash on the surface of each of the nine bags installed at the beginning of the Subtask 3.4 operating period. The outer layer was gray in color and thicker than the inner layer. The nearly white inner layer was a thin, residual layer of

TABLE 3-14

Slipstream Baghouse Multicyclone Data[a]

07-16-92	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	9.24	6.07	3.27	2.23	0.93	-
Mass Collected, g	3.4958	0.3263	0.2812	0.1947	0.1327	0.0394
% Total Mass	78.21	7.30	6.29	4.35	2.97	0.88
Mass Less Than D_{50}, cumulative %	21.79	14.49	8.20	3.85	0.88	–

Total Mass Collected = 4.4700 g, Dust Loading = 2.5491 gr/scf, % Isokinetic = 99.0

08-20-92	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	8.67	5.49	2.93	2.01	0.84	-
Mass Collected, g	27.9474	0.4742	0.1699	0.0940	0.0730	0.0261
% Total Mass	97.09	1.65	0.59	0.33	0.25	0.09
Mass Less Than D_{50}, cumulative %	2.91	1.26	0.67	0.34	0.09	–

Total Mass Collected = 28.7845 g, Dust Loading = 14.9548 gr/scf, % Isokinetic = 100.9

10-29-92	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	10.27	7.09	3.88	2.61	1.08	–
Mass Collected, g	8.6404	0.0919	0.0397	0.0250	0.0278	0.0175
% Total Mass	97.72	1.04	0.45	0.28	0.31	0.20
Mass Less Than D_{50}, cumulative %	2.28	1.24	0.80	0.51	0.20	–

Total Mass Collected = 8.8424 g, Dust Loading = 5.7311 gr/scf, % Isokinetic = 90.6

Continued . . .

TABLE 3-14 (continued)

11-19-92	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	8.35	5.14	2.72	1.89	0.79	–
Mass Collected, g	5.2629	0.1398	0.0464	0.0182	0.0071	0.0156
% Total Mass	95.86	2.55	0.85	0.33	0.13	0.28
Mass Less Than D_{50}, cumulative %	4.14	1.59	0.75	0.41	0.28	–

Total Mass Collected = 5.4901 g, Dust Loading = 2.691 gr/scf, % Isokinetic = 100.0

04-27-93	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	8.50	5.17	2.73	1.91	0.80	–
Mass Collected, g	2.5941	0.2837	0.2670	0.1340	0.0817	0.0262
% Total Mass	76.60	8.38	7.88	3.96	2.41	0.77
Mass Less Than D_{50}, cumulative %	23.40	15.03	7.14	3.19	0.77	–

Total Mass Collected = 3.3867 g, Dust Loading = 1.6709 gr/scf, % Isokinetic = 102.9

05-14-93	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	7.38	4.21	2.20	1.55	0.64	–
Mass Collected, g	4.4662	0.7465	0.1675	0.0423	0.0236	0.0225
% Total Mass	81.67	13.65	3.06	0.77	0.43	0.41
Mass Less Than D_{50}, cumulative %	18.33	4.68	1.62	0.84	0.41	–

Total Mass Collected = 5.4685 g, Dust Loading = 2.260 gr/scf, % Isokinetic = 103.3

Continued . . .

TABLE 3-14 (continued)

08-04-93	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	6.77	3.85	2.00	1.40	0.56	–
Mass Collected, g	4.0157	1.7763	0.2531	0.1626	0.0536	0.0131
% Total Mass	64.00	28.31	4.03	2.59	0.85	0.21
Mass Less Than D_{50}, cumulative %	36.00	7.69	3.65	1.06	0.21	–

Total Mass Collected = 6.2744 g, Dust Loading = 2.2821 gr/scf, % Isokinetic = 103.2

09-10-93	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	9.51	6.32	3.42	2.32	0.96	–
Mass Collected, g	2.6665	0.1977	0.0847	0.0426	0.0503	0.0182
% Total Mass	87.14	6.46	2.77	1.39	1.64	0.60
Mass Less Than D_{50}, cumulative %	12.86	6.40	3.63	2.24	0.60	–

Total Mass Collected = 3.0600 g, Dust Loading = 1.7974 gr/scf, % Isokinetic = 100.6

09-29-93	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	9.22	6.05	3.26	2.22	0.92	–
Mass Collected, g	3.5055	0.2566	0.1211	0.575	0.0583	0.0222
% Total Mass	87.18	6.38	3.01	1.43	1.45	0.55
Mass Less Than D_{50}, cumulative %	12.82	6.44	3.43	2.00	0.55	–

Total Mass Collected = 4.0212 g, Dust Loading = 2.2451 gr/scf, % Isokinetic = 104.4

Continued . . .

TABLE 3-14 (continued)

10-28-93	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	10.90	7.87	4.38	2.90	1.19	–
Mass Collected, g	2.6305	0.4687	0.2252	0.0716	0.0683	0.0331
% Total Mass	75.21	13.40	6.44	2.05	1.95	0.95
Mass Less Than D_{50}, cumulative %	24.79	11.39	4.95	2.90	0.95	–

Total Mass Collected = 3.4974 g, Dust Loading = 2.5283 gr/scf, % Isokinetic = 99.90

11-23-93	CY1	CY2	CY3	CY4	CY5	Backup Filter
D_{50}, µm	10.09	6.97	3.81	2.56	1.06	–
Mass Collected, g	4.7901	0.9204	0.3537	0.1494	0.1008	0.0305
% Total Mass	75.50	14.51	5.57	2.35	1.59	0.48
Mass Less Than D_{50}, cumulative %	24.50	10.00	4.42	2.07	0.48	–

Total Mass Collected = 6.3447 g, Dust Loading = 4.0308 gr/scf, % Isokinetic = 97.5

[a] CY1 through CY5 refers to the first through the fifth cyclone stages in the multicyclone sampling system.

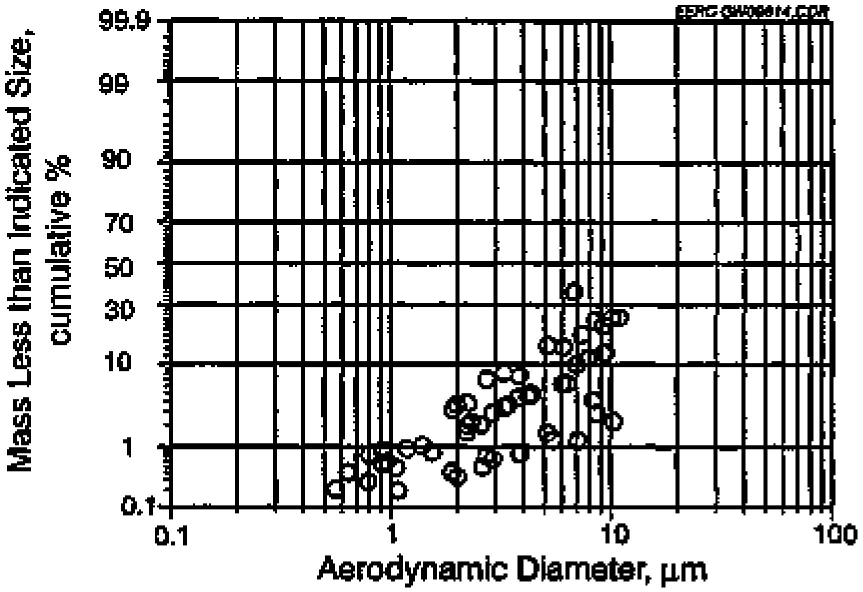

Figure 3-55. A summary of multicyclone data for ash collected in the slipstream baghouse.

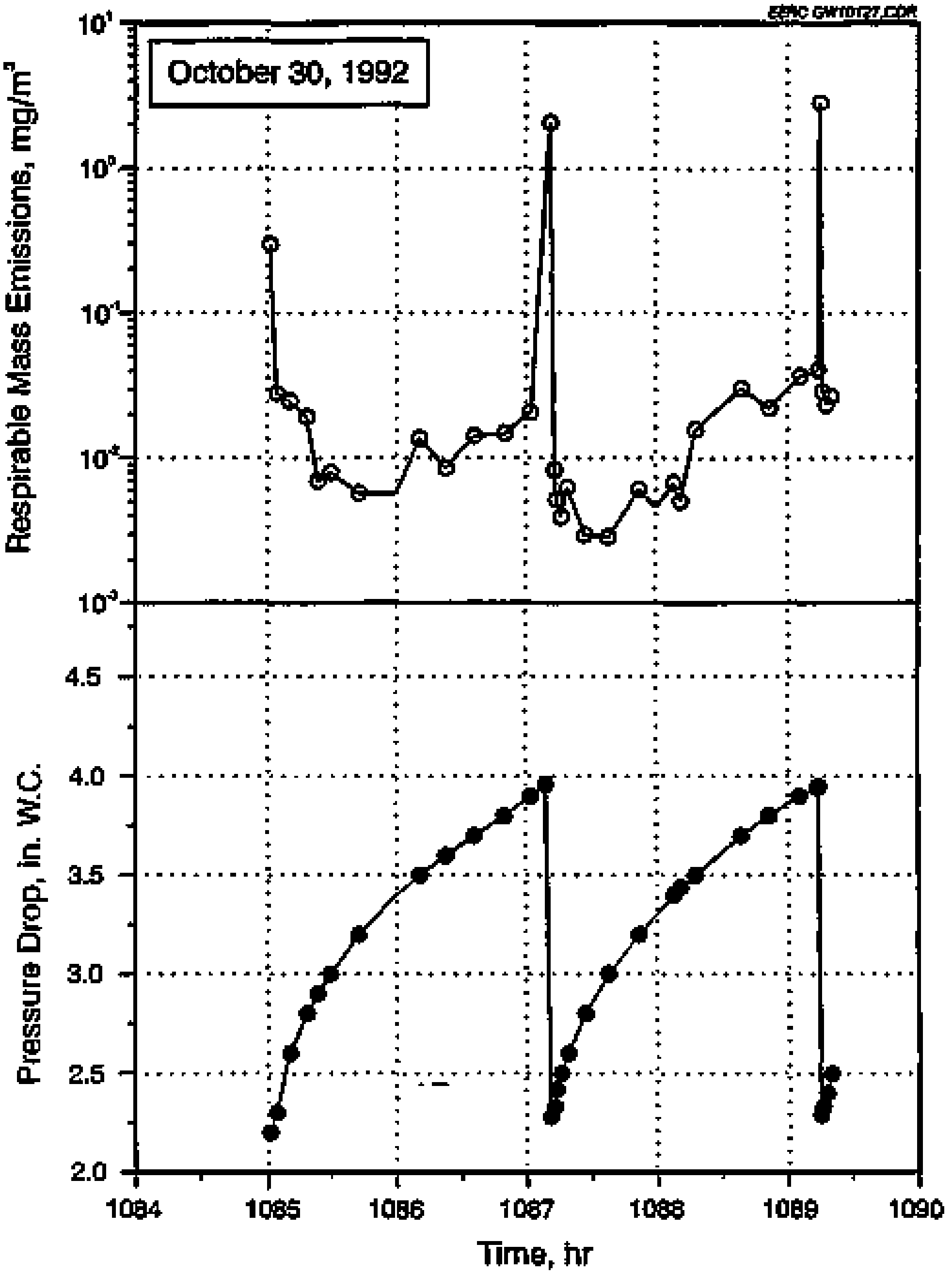

Figure 3-56. Respirable mass emissions and pressure drop as a function of time for the slipstream baghouse, October 30, 1992.

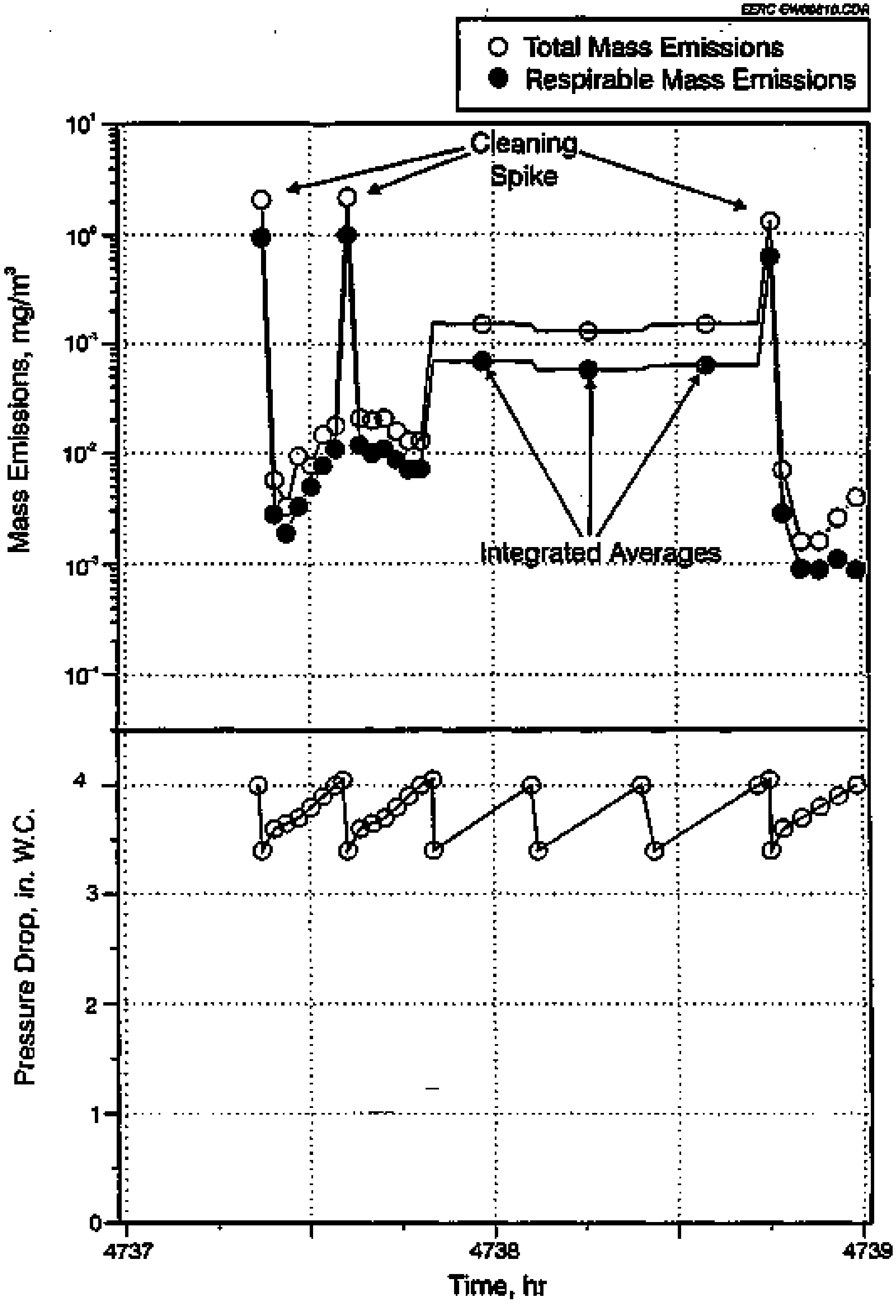

Figure 3-57. Mass emissions and pressure drop as a function of time for the slipstream baghouse, November 23, 1993.

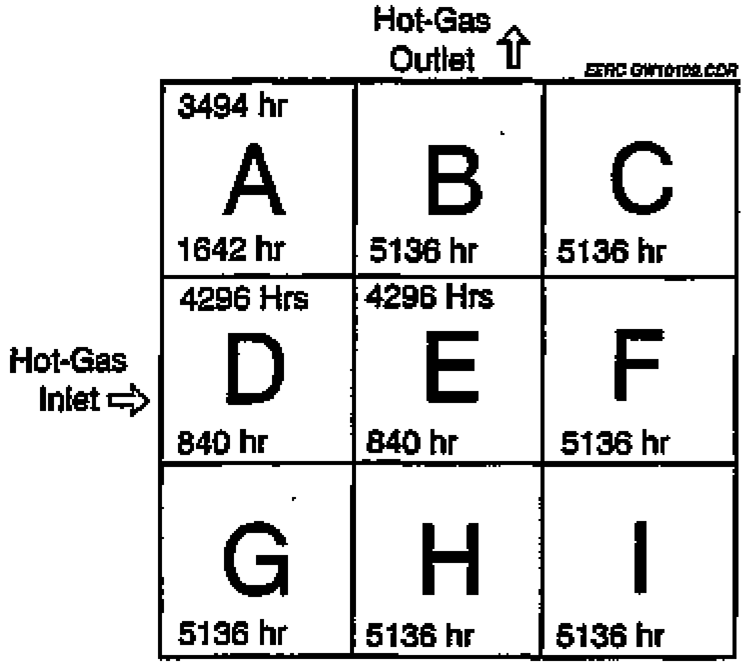

Figure 3-58. Perspective of individual bag location for the Subtask 3.4 durability test.

ash resulting from the bags being precoated with a pulverized dolomite material at the beginning of Subtask 3.4. These observations were made each time the baghouse was inspected and at the conclusion of the performance test.

Physical characterization of three bags removed from the baghouse at various times was completed by OCF personnel and focused on fabric strength and endurance. Fabric strength was measured using the Mullen burst test and data were compared for fabric samples from the three bags removed from the slipstream baghouse after 840, 1642, and 5136 hours of operation. Five samples of each bag were cut to size, 4 in. x 4 in. (102 mm x 102 mm), for testing. Figure 3-59 presents data for the Mullen burst test in a bar graph format. Each bar represents an average value (with standard deviation) for five fabric samples tested. The data actually indicate that fabric strength, as determined by the Mullen burst data, increased with exposure to flue gas. Average burst pressures for the fabric exposed to flue gas for 840, 1642, and 5136 hours were 618, 660, and 739 psig, respectively. Standard deviations ranged from 35 to 90 psig or ± 5.6% to ± 13.6% of the average values measured. No explanation has been found to explain the apparent increase in fabric strength as a function of flue gas exposure.

Fabric endurance was determined using the MIT Flex or folding endurance test. Five samples of each bag were tested, and the results are presented in Figure 3-59 in a bar graph format. Individual fabric samples were cut to size, 0.5 in. x 6 in. (13 mm x 152 mm), for testing. The sample folding rate was 175 ± 25 cycles per minute. Each bar represents an average value for five samples and indicates a standard deviation. The

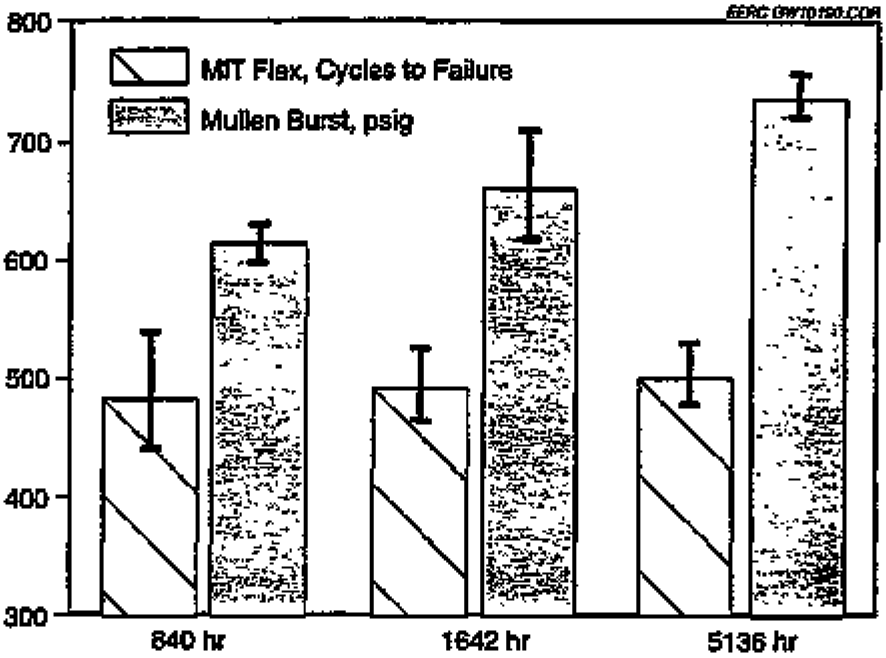

Figure 3-59. Mullen burst and MIT Flex test data for three catalyst-coated bags versus flue gas exposure times of 840, 1642, and 5136 hours.

data demonstrate that no change in fabric strength, as determined by the MIT Flex test, occurred with flue gas exposure. Average cycles to failure ranged from 488 to 505 with standard deviations of 55 to 100 cycles to failure or ± 10.9% to ± 20.5% of the average values measured.

The variability of the MIT Flex test data was greater than that of the Mullen burst data. Possible explanations for this difference may be the effect of air humidity and fabric cleanliness on the MIT Flex test results. Humidity can affect the results of a MIT Flex test on fabric samples. Under dry conditions (low absolute humidity), the number of cycles to failure will decrease. However, humidity was controlled during MIT Flex tests performed by OCF. Therefore, EERC personnel do not believe humidity contributed to the data variability.

The cleanliness of the individual fabric samples may have contributed to data variability. Although the surface of each bag was gently brushed/vacuumed clean before fabric samples were cut for testing, some fly ash was trapped in the fabric weave and not uniformly removed. Depending on the characteristics of the fly ash, its presence could have increased or decreased the number of cycles to failure observed during a MIT Flex test. If the fly ash particles were a hard, coarse material composed of alumina and silica, they could have acted as an abrasive, effectively reducing the number of cycles to failure. On the other hand, soft, powdery fly ash particles composed of alkali could have acted as a lubricant between the fabric fibers and increased the number of cycles to failure.

Catalyst-coated fabric samples (2-in. or 5-cm diameter) for bench-scale catalyst reactivity tests were cut from the bags removed from the slipstream baghouse representing 840, 1642, and 5136 hours of flue gas exposure. These tests were performed in the bench-scale system used for the catalyst deactivation tests previously discussed. The data from these tests are presented in Figure 3-60. Reactor temperature was 650°F, the filter face velocity was 4 ft/min, and the inlet NO_x concentration was 725 ppm. Each set of data points (NO_x reduction and ammonia slip) represents an arithmetic average of three individual experiments, one experiment for each of three fabric samples (top, middle, and bottom) removed from each bag tested. The results are presented in this manner because variability in the data for a single bag was typically less than 2% NO_x reduction and closure on the ammonia was typically 97%–103%.

Three observations can be made with respect to these bench-scale data. First, the fabric samples tested from the three bags removed from the slipstream baghouse at the UND steam plant demonstrated NO_x reduction and ammonia slip levels similar to those observed during the 500-hr test. These data imply that no decrease in catalyst reactivity was evident as a function of flue gas exposure for up to 5136 hours.

Second, all of the fabric samples that had been exposed to a flue gas stream in the pilot-scale pulse-jet baghouse during the 100- and 500-hr parametric tests showed equivalent performance in the bench-scale system. Therefore, all of the catalyst-coated bags used during the pilot-scale pulse-jet tests completed appear to have comparable catalyst reactivity after 100 hours of flue gas exposure.

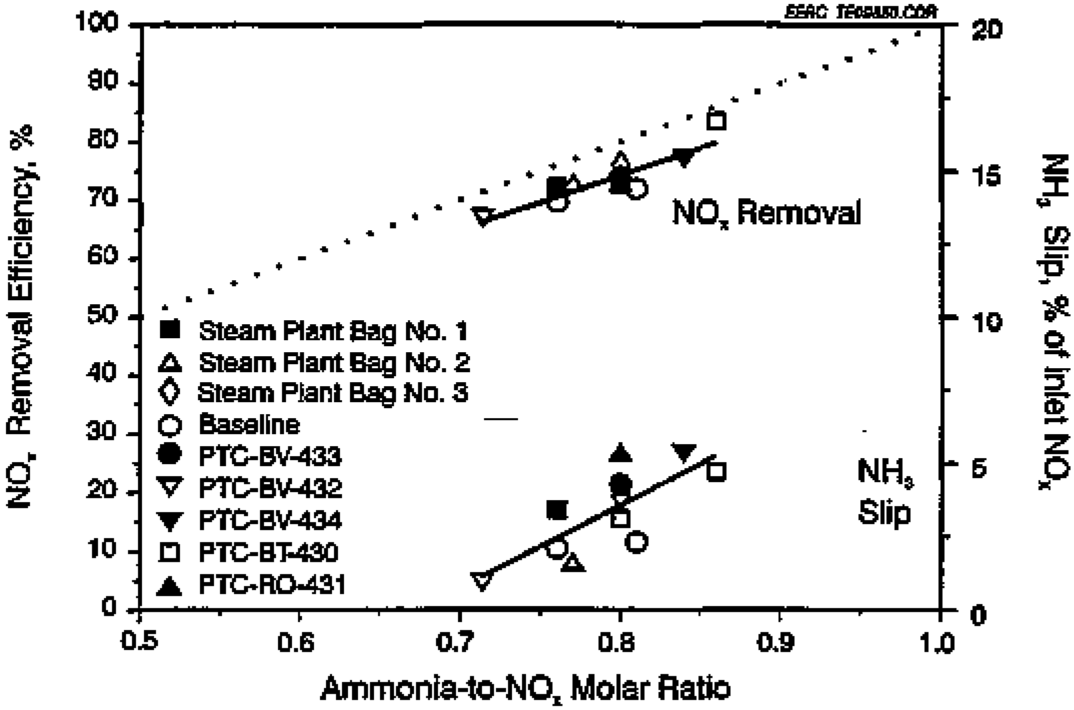

Figure 3-60. NO_x removal and ammonia slip versus ammonia-to-NO_x molar ratio for bench-scale fabric-screening tests.

Finally, the bench-scale ammonia slip levels observed are similar to those observed in the data set from the 100- and 500-hr pilot-scale experimental periods. The exception is one bench-scale baseline data set represented by a new heat-treated fabric sample. In this case, the ammonia slip was significantly lower in the bench-scale test, 2% versus 7% of the inlet NO_x concentration for the pilot-scale tests. One possible explanation for the difference is that the ammonia closure was only 91% for this particular baseline bench-scale test, indicating that the actual ammonia slip value was probably higher than the value measured.

The results of the fabric strength measurements performed indicate that the DE992 S2-glass woven fabric retained its strength for the 5136 hours of flue gas exposure to which the fabric was subjected. In addition, the bench-scale tests completed with fabric samples cut from the bags removed from the slipstream baghouse indicated that catalyst reactivity was not reduced with respect to NO_x reduction and ammonia slip. Therefore, the exposure of the DE992 catalyst-coated bags to flue gas in the slipstream baghouse at the UND steam plant had no detrimental effects on fabric strength or catalyst reactivity. Prior to commercialization, it will be necessary to demonstrate similar results for a minimum of 16,000 hours of flue gas exposure, representing over 90% availability for 2 years.

3.5 Task 4 – Conceptual Design and Economic Evaluation

Although the initial focus of a process development effort is to evaluate technical performance, successful technology commercialization is ultimately dependent on achieving technical performance goals at an economic advantage over competing technologies. One objective of the DOE/PETC Advanced NO_x Control program was to demonstrate that concepts selected for evaluation have application to both new and retrofit coal-fired systems and show the potential for a 50% cost savings when compared to a commercial SCR process capable of meeting the program objective of a 60-ppm (0.1 lb of NO_2/MMBtu) NO_x emission limit. A preliminary, unpublished evaluation of the CFF concept, based on bench-scale data, had indicated that the potential existed for the CFF concept to be 40% to 50% cheaper than a combination of conventional hot-side SCR and cold-side fabric filtration. However, the evaluation performed by RE&C for this project showed that the CFF concept only had a small economic advantage when compared to the SCR/PJFF alternative.

To determine the commercialization potential of the CFF concept, RE&C was asked to develop a conceptual design and prepare an economic evaluation of the CFF process to estimate capital, operating, maintenance, and levelized costs for two commercial pc-fired boiler applications: a new 500-MW plant and an older 250-MW plant. In both cases, the CFF concept was compared to conventional hot-side SCR for NO_x control and cold-side pulse-jet fabric filtration (PJFF) for particulate control. The economic analysis was prepared based on the EPRI TAG (30). Results from the Task 3 experimental activities were used as a basis for system design with respect to process conditions, such as CFF face velocity. In both cases, the evaluation assumed that NO_x concentrations exiting the boilers had been minimized as a result of low-NO_x burners or other combustion controls. The Task 4 effort was completed by RE&C under subcontract to the EERC. A report summarizing the Task 4 effort and results was prepared by RE&C and is presented in Appendix D.

3.5.1 New 500-MW Plant

Results of the evaluation for the new 500-MW plant case showed that the total, installed, plant investment for the CFF concept was 5% higher than that for the SCR/PJFF combination: \$145/kW versus \$138/kW. On a 30-year levelized cost basis, there was a 7.1% difference between the CFF and the SCR/PJFF concepts: 5.91 versus 6.33 mills/kWh, respectively.

The capital cost differential can be attributed to several factors. The single most significant factor was the ductwork requirements associated with installation of a hot-side baghouse. These requirements were extensive and more costly than first anticipated, representing 20% of the total, installed, equipment cost and nearly 64% more costly for the CFF than the SCR/PJFF.

Other elements contributing to the differential in total, installed, equipment costs included the baghouse, the air heater upgrade, the ammonia injection system, and the bag cages. The difference in baghouse and bag cage capital costs was due to the larger baghouse and number of bag cages required for the CFF hot-side baghouse to handle the larger flue gas volume. In addition, operation of the CFF at a gross filter face velocity of 3.44 versus 3.7 ft/min for the PJFF increased the CFF baghouse size and the number of bag cages required.

The cost of the individual catalyst-coated bags (DE992, 22 oz/yd^2 woven S2-glass, 6 in. in diameter x 20 ft in length) was estimated by OCF at \$250/bag. This estimate includes the cost for OCF to reprocess used catalyst-coated bags. However, it is uncertain whether the \$300/ft^3 SCR catalyst cost included a reprocessing component. When multiplied by the 25,000 bags required for CFF operation at a gross filter face velocity of 3.44 ft/min, the catalyst-coated bag cost represented 29% (\$42.0/kW) of the total installed CFF equipment cost. Equivalent costs for the SCR/PJFF include a combination of the SCR catalyst (\$300/ft^3) and the bags (\$85/bag) for the PJFF, representing 39% (\$53.8/kW) of the total, installed SCR/PJFF equipment cost.

Eliminating process and project contingencies reduces the total installed plant investment estimates for the CFF and SCR/PJFF concepts to \$113/kW and \$118/kW, respectively, which results in a 4.4% capital cost advantage for the CFF. The completed evaluation included the application of project and process contingencies for both the CFF and SCR/PJFF concepts as recommended by the EPRI TAG. Since the CFF concept has not been developed to the same extent as the SCR and PJFF concepts, the process contingency applied to the CFF was 17% versus 12% for the SCR/PJFF combination.

As previously stated, the 30-year levelized costs for the CFF and SCR/PJFF were 5.91 and 6.33 mills/kWh, respectively. The difference represents an annual savings of \$1,400,000 in capital, operating, and maintenance costs for the CFF compared to the SCR/PJFF. Levelized costs for the CFF are driven by catalyst-coated bag replacement costs. In this evaluation, the life of the catalyst-coated bags was assumed to be 2 years. Elements driving levelized costs for the SCR/PJFF included SCR catalyst replacement costs and the costs for additional ID fan power requirements to offset the combined pressure losses across the SCR reactors and the PJFF.

Cost sensitivity analysis for the CFF showed that the cost of the catalyst-coated bags has the strongest effect on overall economics, capital and levelized costs. Based on the assumptions used in the new plant evaluation, the individual bag cost would have to be reduced from $250 to $212/bag to achieve a capital cost break-even point for the CFF and SCR/PJFF.

3.5.2 Retrofit 250-MW Plant

Results of the evaluation for the 250-MW retrofit plant case showed that the total, installed, plant investment for the CFF concept was 3.8% less than that for the SCR/PJFF combination, $213/kW versus $221/kW. On a 15-year levelized cost basis, there was a smaller difference between the CFF and the SCR/PJFF concepts, 9.15 versus 10.07 mills/kWh, respectively.

As in the new plant case, the capital cost differential in the retrofit case was due to several factors. In this case, no single factor contributed significantly to the total, installed plant investment differential. Major factors contributing to the CFF total installed, plant investment cost included the baghouse, ductwork, and catalyst-coated bags. In the retrofit case, because of the equipment layout, the ductwork for the CFF was 9% less costly than that of the SCR/PJFF.

The difference in baghouse and bag cage capital costs were again due to the larger baghouse and number of bag cages required for the CFF hot-side baghouse necessary to handle the larger flue gas volume as well as the lower gross filter face velocity for the CFF, 3.44 versus 3.7 ft/min for the PJFF. Baghouse and bag cage capital costs for the CFF were more costly by 51% and 45%, respectively, than capital costs estimated for the SCR/PJFF.

As previously stated, the estimated cost of the individual catalyst-coated bags was $250/bag. When multiplied by the 12,600 bags required for CFF operation at a gross filter face velocity of 3.44 ft/min, the catalyst-coated bag cost represented 20% of the total installed CFF equipment cost for the 250-MW retrofit. Equivalent costs for the SCR/PJFF include a combination of the SCR catalyst and the bags for the PJFF. The SCR catalyst and PJFF bags represent 22% of the SCR/PJFF total installed equipment cost. Therefore the actual capital cost differential was roughly 14%, $42.6/kW versus $48.6/kW respectively, for these elements of the CFF and SCR/PJFF systems.

Eliminating process and project contingencies reduces the total, installed, plant investment estimates for the CFF and SCR/PJFF concepts to $168/kW and $187/kW, respectively, and increases the CFF cost advantage from to 3.8% to 11.3%. In the retrofit case, process contingencies for the CFF, SCR, and PJFF were 15%, 12%, and 9%, respectively, based on the EPRI TAG. As in the new plant case, further technical development of the CFF to a level comparable to the SCR/PJFF will reduce the total plant investment cost for the CFF concept.

The 15-year levelized costs for the CFF and SCR/PJFF were 9.15 and 10.07 mills/kWh, respectively. The difference represents an additional $1,300,000 that would be required on an annual basis to fully cover the capital, operating, and maintenance costs for the SCR/PJFF. Levelized costs for the CFF are driven by catalyst-coated bag replacement costs and an assumed catalyst-coated bag life of 2 years.

Elements driving levelized costs for the SCR/PJFF included SCR catalyst replacement costs and the additional ID fan power requirements to offset the combined pressure losses across the SCR reactors and the PJFF.

Cost sensitivity analysis for the CFF showed that the cost of the catalyst-coated bags has the strongest effect on overall economics, capital and levelized costs. However, it is unlikely that the cost of catalyst-coated bags can be significantly reduced. Therefore, cost reductions must be achieved as a result of increased catalyst reactivity and bag and catalyst life.

3.5.3 Potential for Improving CFF Economics

Further development of the CFF concept offers a number of options for reducing capital and levelized costs. First, if the current level of technical development of the CFF were comparable to that of the SCR/PJFF, there would be a reduction in the CFF capital and levelized costs estimated in this evaluation as a result of applying equivalent process contingencies. The effect on the new 500-MW plant case would be a decrease in the total, installed, equipment cost for the CFF, eliminating the advantage for the SCR/PJFF estimated in this evaluation and creating a 4% advantage for the CFF concept. An effective reduction in levelized costs would result in a larger economic advantage for the CFF concept. For the 250-MW retrofit case, the effect would result in a greater capital and levelized cost advantage for the CFF than that estimated in this evaluation.

The most direct approach to reducing the cost of the CFF would be to reduce the cost of the catalyst-coated bags. Based on current information, significant reductions in bag cost are unlikely. A decrease in CFF levelized costs could be realized if technical data supported an effective CFF bag life of 4 years rather than the 2 years assumed in this evaluation. For the new 500-MW plant, levelized costs would decrease from 5.91 to 5.22 mills/kWh for a 4-year bag life. The effect on the 250-MW retrofit plant would be a decrease from 9.15 to 8.5 mills/kWh. Another approach to reducing CFF costs would be to reduce the number of catalyst-coated bags required for a given application by improving the reactivity of the catalyst-coated bags, effectively permitting an increase in the gross air-to-cloth ratio.

Bench-scale catalyst-coated fabric-screening tests completed near the end of this project demonstrated the potential for higher levels of NO_x reduction and lower ammonia slip with a catalyst-coated fabric, prepared by OCF, using ten coats of catalyst rather than the seven coats used to prepare bags for the pilot-scale experimental work. Specific results for these bench-scale tests were reported in Section 3.1 of this report. Assuming these results are proven in future bench- and pilot-scale tests, the reduction in CFF costs could be significant.

Estimates by OCF indicate that the cost of the catalyst-coated bag may increase by 5% as a result of the three additional coating steps and increased catalyst usage. Assuming the reactivity of the catalyst-coated fabric permitted the operation of the CFF at a gross air-to-cloth ratio of 3.7 rather than 3.44, and the ammonia feed and slip values were identical to the SCR system, a significant reduction in CFF comparative costs would occur. The small increase in the catalyst-coated bag cost would be more than offset by increasing the gross air-to-cloth ratio from 3.44 to 3.7. Increasing the air-to-cloth ratio would reduce the size of the baghouse and number of catalyst-coated bags and bag cages by nearly 8%. In addition, the economic penalties incurred by the CFF for higher levels of ammonia slip would be eliminated. These adjustments would reduce the CFF total installed equipment cost for the new 500-MW plant from \$145/kW to \$132/kW, 4.5% less than the \$138/kW estimate for the SCR/PJFF system. The effect on CFF levelized costs would be a reduction of >8%, resulting in an overall economic advantage of >16% for the CFF for the new 500-MW plant.

Similar CFF cost reductions would be observed for the 250-MW retrofit plant. The CFF total, installed, equipment cost would decrease from \$213/kW to \$191/kW, resulting in a 15.7% cost advantage for the CFF compared to the \$221/kW value estimated for the SCR/PJFF. The effect on levelized costs would be to further increase the economic advantage estimated in this evaluation for the CFF for the 250-MW retrofit plant.

The conceptual design and economic evaluation completed by RE&C indicates that the CFF can be economically competitive with the SCR/PJFF. However, this objective can only be achieved if the CFF can be operated at air-to-cloth ratios equivalent to those used for cold-side PJFF and if the CFF can reduce NO_x emissions and control ammonia slip to levels consistent with conventional SCR performance. Key factors influencing CFF economics include bag cost, bag life, and air-to-cloth ratio. Therefore, future development efforts must focus on reducing the cost of catalyst-coated bags, by demonstrating a catalyst-coated bag life of greater than 2 years, and improving performance with respect to NO_x reduction and ammonia slip at air-to-cloth ratios equivalent to or higher than those used in this evaluation.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions drawn from the CFF experimental activities and the economic evaluation and resulting recommendations are summarized below.

4.1 Heat Treatment

- Catalyst-coated fabric must be heat-treated to remove a fugitive lubricant used in the bag-manufacturing process and complete catalyst curing. Bench-scale testing with three fabric types determined that 4 hours of exposure to a clean flue gas stream containing 2–4 vol% O_2 at 700°–725°F was adequate. This approach was effectively used to heat-treat catalyst-coated bags prior to pilot-scale tests.

- Heat treatment at flue gas temperatures exceeding 750°F resulted in a permanent loss of catalyst reactivity, and flue gas temperatures below 650°F were generally inadequate.

- Whether the catalyst-coated fabric could be effectively heat-treated with a dirty flue gas (SO_2 and fly ash) is unknown. Development of a heat treatment procedure for commercial use is necessary.

4.2 Catalyst Deactivation

- Strong acids (0.1 M HCl and H_2SO_4) and a strong base (0.1 M NaOH) were found to destroy catalyst reactivity on clean fabric samples. However, in the case of the acid-coated fabric, thoroughly washing the samples with water resulted in a complete recovery of catalyst reactivity. These results imply that the strong base chemically destroys catalyst reactivity, while the acid merely interferes with the catalyst site.

- Strong acids and a strong base were found to destroy catalyst reactivity on used fabric samples having a light residual ash layer. Although the degree of catalyst reactivity loss was greater for residual ashes containing greater concentrations of alkali, the end result in all cases was a significant decrease in catalyst reactivity, which would require catalyst-coated bag replacement.

- Exposure of clean catalyst-coated fabric to a severe moisture dew point showed little or no effect on catalyst reactivity. However, for used fabric samples having a light residual ash layer, catalyst reactivity was permanently reduced to a level requiring replacement of the catalyst-coated bags.

- Catalyst-coated fabric samples coated with any one of several chemical forms of alkali (Na, Ca, and K) and then exposed to a severe moisture dew point demonstrated a significant loss of catalyst reactivity. Independent of chemical form, sodium had a greater effect than calcium, and calcium a greater effect than potassium, consistent with the increasing Brønsted acidity of the ions.

4.3 Bench-Scale Screening Tests

- Bench-scale catalyst-coated fabric-screening tests with newly developed woven fabric samples prepared by OCF have shown the potential for improved catalyst reactivity when compared to catalyst-coated woven fabric used during the pilot-scale tests. In one case, a fabric sample prepared using ten coats of catalyst rather than seven increased NO_x reduction and reduced ammonia slip by over 60%. Assuming future bench- and pilot-scale tests substantiate the improved performance of the new catalyst-coated fabric, 80% NO_x reduction could be achieved with an ammonia slip of <10 ppm or 95% NO_x reduction could be achieved with an ammonia slip of <20 ppm.

4.4 Pilot-Scale Parametric Tests

- Pilot-scale 100-hr fabric-screening tests demonstrated that the 22-oz/yd^2 woven S2-glass fabric, prepared using seven coats of a vanadium–titanium catalyst and applied using an organic-based coating process, resulted in higher NO_x reduction and lower ammonia slip than the other four catalyst-coated fabric types tested. However, differences observed between the 14- and 22-oz/yd^2 fabric prepared using the same catalyst and organic-based coating process may be simply due to the greater catalyst concentration on the 22-oz/yd^2 fabric. Therefore, further development or testing of the catalyst-coating process would be appropriate to maximize the quantity of the catalyst that can be effectively applied to an S2-glass fabric.

- Although the aqueous-based catalyst-coating process did not perform nearly as well as the organic-based catalyst-coating process, the potential advantages of the aqueous-based process with respect to reduced costs and avoiding the handling and emissions issues inherent in the use of organic solvents warrant further developmental consideration.

- During 100-hr test periods using both the pulse-jet and reverse-gas baghouses, 90% NO_x reduction and <25-ppm ammonia slip were demonstrated. Air-to-cloth ratio had a significant effect on catalyst-coated fabric performance. An air-to-cloth ratio of <4 ft/min and a flue gas temperature of 650°–700°F were necessary to achieve 80% NO_x reduction and control ammonia slip adequately.

- Flue gas temperature also had an effect on catalyst-coated fabric performance. As flue gas temperatures were decreased from 650°F, ammonia slip increased and NO_x reduction decreased, while temperatures of >750°F are known to permanently deactivate the catalyst.

- The pilot-scale data from the 100-hr test periods indicate that fuel type (oil and coal) may have some effect on NO_x reduction and ammonia slip. However, the short duration of these tests and range of operating parameters experienced prevent the formulation of specific conclusions.

- In order to minimize the effect of fly ash characteristics on CFF performance, future development activities should evaluate a catalyst-coated S2-glass felt. The catalyst-coated felt would not be affected by pinholing to the degree a woven fabric is affected. Therefore, dust cake characteristics, such as pinholes, would have less effect on NO_x reduction and ammonia slip.

- Results from the 100-hr oil-fired test were similar to the 100-hr coal-fired tests. However, NO_x reduction was slightly lower and ammonia slip, as a percentage of inlet NO_x concentration, was slightly higher. Lower NO_x reduction and higher ammonia slip probably resulted from a very low fly ash loading entering the baghouse, resulting in very little dust cake development and a low operating differential pressure (<3 in. W.C.).

- Particulate collection efficiency was >99.5% for both the 14- and 22-oz/yd^2 woven S2-glass fabrics for all 100-hr coal-fired test periods when the ammonia was turned off. However, with the ammonia on, the calculated particulate collection efficiency for tests with high ammonia slip (>40 ppm) was lower because of ammonium sulfate or bisulfate formation on the particulate sampling filters artificially increasing measured outlet mass loadings.

- Baghouse differential pressure was controlled at reasonable levels, 4–8 in. W.C., during the 100-hr coal-fired test periods at all air-to-cloth ratios tested. Baghouse differential pressure was controlled using off-line cleaning during reverse-gas tests and on-line cleaning during pulse-jet tests. Pulse-cleaning frequency ranged from 10 to 60 minutes, depending on specific operating conditions.

- N_2O concentrations in the flue gas were measured at both the inlet and outlet of the CFF baghouse during several test periods to verify that nitric oxide and nitrogen dioxide were not being converted to N_2O. For all coals tested, N_2O concentrations were <10 ppm at the CFF baghouse inlet and outlet.

demonstrating that N_2O was not being formed as a result of flue gas exposure to the catalyst-coated bags.

- Based on the catalyst-coated fabric and baghouse hopper ash samples analyzed, no significant catalyst loss or erosion occurred that would affect performance with respect to NO_x reduction or ammonia slip or create concern with respect to fly ash disposal. This observation was made during the 100- and 500-hr pilot-scale parametric tests as well as the fabric durability test where catalyst-coated fabric was exposed to flue gas in a pilot-scale baghouse for 5136 hours. Therefore, the CFF concept meets the DOE–PETC Advanced NO_x Control objective concerning the production of a nonhazardous waste product. However, vendors of both the CFF concept and conventional SCR systems will need to address the recycle and/or disposal of spent catalyst in commercial applications.

- Measurements were made to determine SO_3 concentrations downstream of the CFF baghouse with the ammonia injection system turned off to avoid interference. Results from the 100- and 500-hr tests while various fuels were fired (oil, bituminous coal, subbituminous coal, and lignite) demonstrated that the CFF was not oxidizing SO_2 to SO_3.

- The 500-hr bituminous coal-fired tests demonstrated that the reactivity of the catalyst-coated fabric decreased slightly during the first 100 hours of operation. After 100 hours, performance was stable, demonstrating 80% NO_x reduction, with an ammonia slip of 7.5% of the inlet NO_x concentration at an air-to-cloth ratio of 3–3.5 ft/min. Assuming an inlet NO_x concentration of 300–400 ppm (0.5 to 0.7 lb of NO_2/MMBtu), which is greater than if not typical of pc-fired boilers with low NO_x burners, the resulting ammonia slip would be 20–30 ppm. These results demonstrate that the CFF can meet the DOE/PETC Advanced NO_x Control Program objective of reducing NO_x emissions to 60 ppm (0.1 lb of NO_2/MMBtu) or less and meet ammonia emission limits (9 to 30 ppm) currently enforced in some areas of the United States.

- Analysis of baghouse hopper ash collected during the 500-hr test showed that ammonia concentrations in the ash were <30 $\mu g/g$ when attempting to achieve 80% NO_x reduction. At this level, <30 $\mu g/g$, ammonia concentrations in the ash are not expected to interfere with ash disposal or utilization options.

- Particulate collection efficiency was typically $>99.9\%$ during the 500-hr tests, easily meeting the current New Source Performance Standard of 0.03 lb/MMBtu. Exceptions were observed when ammonia slip exceeded 40 ppm, resulting in the formation of sulfates or bisulfates. Baghouse differential pressure was easily controlled between 4 and 6 in. W.C. using on-line pulse cleaning.

4.5 Pilot-Scale Fabric Durability Test

- A single set of nine catalyst-coated DE992 bags was evaluated in a slipstream baghouse for 5136 hours, resulting in 13,820 cleaning cycles, while subbituminous coal was fired in a stoker-fired boiler at the UND steam plant. Supplemental ash injection was used to augment fly ash from the stoker-fired boiler. Baghouse operating conditions included flue gas temperatures of

500°–700°F, filter face velocities of 3–5 ft/min, and differential pressures of 2–6 in. W.C. No catalyst-coated fabric failures occurred as a result of the 5136 hours of normal baghouse operation. Because of project funding limitations and steam plant downtime, the project objective of demonstrating a bag/catalyst life of >1 year was not achieved. However, there were no data collected or observations made that would indicate a bag/catalyst life of <1 year.

- Particulate collection efficiency for the slipstream baghouse, as determined by a modified EPA Method 5, ranged from 99.96% to >99.99% for inlet mass loadings ranging from 1.5–5.7 gr/scf. An inlet mass loading of 3 gr/scf resulted in cleaning cycle frequencies of 20–30 minutes.

- Differential pressure across the slipstream baghouse was effectively controlled using on-line cleaning, a reservoir pulse pressure of 43 psig, and a pulse duration of 0.1 seconds. These pulse system conditions resulted in a pulse air volume of roughly 0.3 ft^3 per bag.

- Sampling at the outlet of the slipstream baghouse demonstrated that the catalyst-coated bags did not oxidize SO_2 to SO_3. Measured SO_3 concentrations were <1 ppm. These data are consistent with the results observed for the 100- and 500-hr pilot-scale parametric tests.

- Data from MIT Flex, Mullen burst, and bench-scale reactivity tests demonstrated that catalyst-coated fabric strength and reactivity did not degrade with time. Fabric samples tested represented 840, 1642, and 5136 hours of flue gas exposure.

4.6 Economic Evaluation

- The economic evaluation for the 500-MW new plant case showed that the total installed plant investment for the CFF concept was 5% higher than the total installed plant investment for the SCR/PJFF combination: $145/kW versus $138/kW. The capital cost differential was due to several factors, with the single most significant factor being the ductwork requirements associated with the installation of a hot-side baghouse. Other elements contributing to the differential in total installed equipment costs included the flange-to-flange baghouse and the catalyst-coated bags.

- On a 30-year levelized cost basis, there was a 7.1% difference between the CFF and the SCR/PJFF concepts, 5.91 versus 6.33 mills/kWh, respectively, for the new 500-MW plant. This represents an annual savings of $1,400,000 for the CFF. Levelized costs for the CFF are driven by catalyst-coated bag replacement costs. Elements driving levelized costs for the SCR/PJFF included SCR catalyst replacement costs and the additional ID fan power requirements to offset the combined pressure losses across the SCR reactors and the PJFF.

- Cost sensitivity analysis for the CFF showed that the cost of the catalyst-coated bags has the strongest effect on overall economics, capital and levelized costs, for the new 500-MW plant. Based on the assumptions used in the evaluation, the individual bag cost would have to be reduced from $250 to $212/bag in order to achieve a capital cost break-even point for the CFF versus the SCR/PJFF.

However, it is unlikely that the cost of catalyst-coated bags can be significantly reduced. Therefore, cost reductions must be achieved as a result of increased catalyst reactivity and bag and catalyst life.

- The economic evaluation for the 250-MW retrofit plant case showed that the total installed plant investment for the CFF concept was 3.8% less than the total installed plant investment for the SCR/PJFF combination: $213/kW versus $221/kW. In this case, no single factor contributed significantly to the differential. Major factors contributing to the CFF total installed plant investment cost included the baghouse, ductwork, and catalyst-coated bags.

- On a 15-year levelized cost basis, there was a 10% difference between the CFF and the SCR/PJFF concepts, 9.15 versus 10.07 mills/kWh, respectively, for the 250-MW retrofit. This represents an annual cost advantage of $1,300,000 for the CFF. Levelized costs for the CFF are driven by catalyst-coated bag replacement costs. Elements driving levelized costs for the SCR/PJFF included SCR catalyst replacement costs and the additional ID fan power requirements to offset the combined pressure losses across the SCR reactors and the PJFF.

- Cost sensitivity analysis for the CFF showed that the cost of the catalyst-coated bags has the strongest effect on overall economics, capital and levelized costs, for the 250-MW retrofit. However, it is unlikely that the cost of catalyst-coated bags can be significantly reduced. Therefore, cost reductions must be achieved as a result of increased catalyst reactivity and bag and catalyst life.

- Based on the economic evaluation, the CFF concept does not meet the Advanced NO_x Control Program objective of a 50% cost savings when compared to a commercial SCR process capable of meeting the 60-ppm (0.1 lb of NO_x/MMBtu) NO_x emission limit. However, this objective was developed in 1989, and estimated SCR costs have decreased significantly since then. In fact, shortly before the CFF economic evaluation was completed, the estimated cost of SCR catalyst decreased from $400/ft^3 to $300/ft^3. Therefore, the potential to develop a new, highly efficient NO_x control process that is 50% less costly than a conventional SCR system is diminishing as SCR costs become more competitive.

- The conceptual design and economic evaluation completed by RE&C indicates that the CFF can be economically competitive with the SCR/PJFF, but CFF costs must be reduced in order to compete commercially with the better developed technologies. Therefore, future CFF development efforts must focus on reducing the cost of catalyst-coated bags, demonstrating a bag and catalyst life of greater than 2 years, and improving performance with respect to NO_x reduction and ammonia slip at air-to-cloth ratios equivalent to or higher than those used in this evaluation.

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NOMENCLATURE

Al_2O_3	Aluminum Oxide	$NaCl$	Sodium Chloride
As_2O_3	Arsenic Trioxide	$NaOH$	Sodium Hydroxide
$CaCl_2$	Calcium Chloride	NH_2Cl	Chloramine
CaO	Calcium Oxide	NH_3	Ammonia
$CaSO_4$	Calcium Sulfate	NH_4Cl	Ammonium Chloride
CO	Carbon Monoxide	NO	Nitric Oxide
CO_2	Carbon Dioxide	NO_x	Nitrogen species
Cs_2O	Cesium Oxide	NO_2	Nitrogen Dioxide
Fe_2O_3	Ferric Oxide	O_2	Oxygen
H_2O	Water	P_2O_5	Phosphorus Pentoxide
H_2SO_4	Sulfuric Acid	PbO	Lead Oxide
HCl	Hydrogen Chloride	Rb_2O	Rubidium Oxide
K_2O	Potassium Oxide	SiO_2	Silicon Dioxide
K_2SO_4	Potassium Sulfate	SO_x	Sulfur Species
KCl	Potassium Chloride	SO_2	Sulfur Dioxide
Li_2O	Lithium Oxide	SO_3	Sulfur Trioxide
MgO	Magnesium Oxide	TiO_2	Titanium Oxide
N_2	Nitrogen	V–Ti	Vanadium–Titanium
N_2O	Nitrous Oxide	V_2O_5	Vanadium Pentoxide
Na_2O	Sodium Oxide	VCl_2	Vanadium Dichloride
Na_2SO_3	Sodium Sulfite	VCl_4	Vanadium Tetrachloride
Na_2SO_4	Sodium Sulfate		

Air-to-Cloth Rate	Gas Flow Rate (acfm)/Filter Surface Area (ft^2)
CY	Cyclone
Face Velocity	Gas Flow Rate (acfm)/Filter Surface Area (ft^2)
M	Molar
Space Velocity	Gas Flow Rate (acfm)/Catalyst Volume (ft^3)

APPENDIX A

CATALYTIC FABRIC FILTER TEST UNIT DESIGN

Back-up
Check

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CATALYTIC FABRIC FILTER TEST UNIT DESIGN
Contract No. DE-AC22-90PC90361

Catalytic Fabric Filtration for Simultaneous
NO_x and Particulate Control

for

U.S. Department of Energy
Pittsburgh Energy Technology Center
P.O. Box 10940
Pittsburgh, PA 15236-0940

DOE Contract Specialist: Debra Ball
DOE Contracting Officer's Representative: Felixa Eskey

by

Energy and Environmental Research Center
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Project Manager: Greg F. Weber
Research Engineers: Dennis L. Laudal
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October 1991

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CATALYTIC FABRIC FILTER TEST UNIT DESIGN

1.0 INTRODUCTION

The University of North Dakota Energy and Environmental Research Center (EERC), Owens-Corning Fiberglas Inc. (OCF), and Stearns-Roger, a division of United Engineers & Constructors (UE&C), have initiated a research project aimed at the development of a catalytic fabric filter for simultaneous NO_x and particulate control. The objective of the project is to reduce NO_x emissions by >90% (to achieve an NO_x emission of 60 ppm), reduce particulate emissions by >99.5%, and demonstrate a catalyst/bag life of greater than one year at a 50% cost savings when compared to a commercial selective catalytic reduction (SCR) process and conventional baghouse. The project is divided into five tasks as listed below:

Task 1 - Program Definition
Task 2 - Design and Construct Test Unit
Task 3 - Experimental Program and Data Reduction
Task 4 - Conceptual Design and Economic Evaluation
Task 5 - Test Unit Removal

Task 1, Program Definition, involved preparation of a Management Plan for the project. The Management Plan included a project work plan, schedule, budget, identification of key project personnel and their time commitments, and preparation of a Quality Assurance/Quality Control plan for the project. The Management Plan was submitted for approval in November 1990. Preliminary approval was obtained in December 1990, and final approval was received in January 1991.

Task 2, Design and Construct Test Unit, was initiated in January 1991. This task is divided into three subtasks. Subtasks 2.1 and 2.2 involved the detailed design of the test facility on which the experimental program will be performed, the construction of the test facility, and an operational shakedown of the system prior to initiating the experimental effort. Subtask 2.3 involves the preparation of the catalyst-coated fabric filters, by OCF, that will be evaluated in the experimental effort.

All experimental activities associated with the project will be performed using existing EERC or other University of North Dakota facilities. Therefore, it was not necessary to identify a host site or obtain a signed agreement for use of a site. Most of the equipment/facilities required to successfully complete the planned effort were already available at EERC. Specific Task 2 activities included upgrading existing equipment (flue gas instrumentation, the data acquisition system, and a reverse-gas baghouse) and constructing a new reverse-gas baghouse and a new pulse-jet baghouse.

This document presents the final "as-built" test unit design. An overall system flow diagram is presented along with detailed design information for the reverse-gas (Subtask 2.1) and pulse-jet baghouses (Subtask 2.2).

2.0 PARTICULATE TEST COMBUSTOR AND SUPPORT EQUIPMENT

The flue gas stream that will be used to evaluate the performance of the catalyst-coated fabric filters during the 100- and 500-hour test periods will be generated by firing pulverized coal in the EERC particulate test combustor (PTC). The PTC is a vertically oriented, pulverized coal-fired (pc-fired) combustor with a thermal firing rate of 550,000 Btu/hour. This corresponds to a coal feed rate of roughly 45 to 75 pounds/hour depending on the heating value of the coal. Figure 1 presents a simplified system flow diagram.

The combustor is oriented vertically to minimize wall deposits and was designed specifically to generate fly ash representative of that produced in a full-scale utility boiler. A refractory liner helps to ensure adequate flame temperature for complete combustion and prevents rapid quenching of the coalescing or condensing fly ash. The mean residence time of a particle in the combustor is approximately three seconds, based on the superficial gas velocity. Combustion efficiencies of +99%, based on loss on ignition of the fly ash and the CO concentration of the flue gas, are evidence that incomplete combustion is not a problem with this combustor. Figure 2 is a conceptual illustration of the PTC.

The coal nozzle of the PTC fires axially upward from the bottom of the combustor, and secondary air is introduced concentric to the primary air with turbulent mixing. In addition, tertiary air is supplied above the burner cone near the bottom of the combustor. Coal is introduced to the primary air stream via a screw feeder and ejector. An electric air preheater is used for precise control of the combustion air temperature. Combustion air temperature is selected and set based on the moisture content and swelling characteristics of the coal fired. A combination of water-jacketed heat exchangers, electrical resistance heat tape, and insulation provide flue gas temperature control at the inlet of either baghouse.

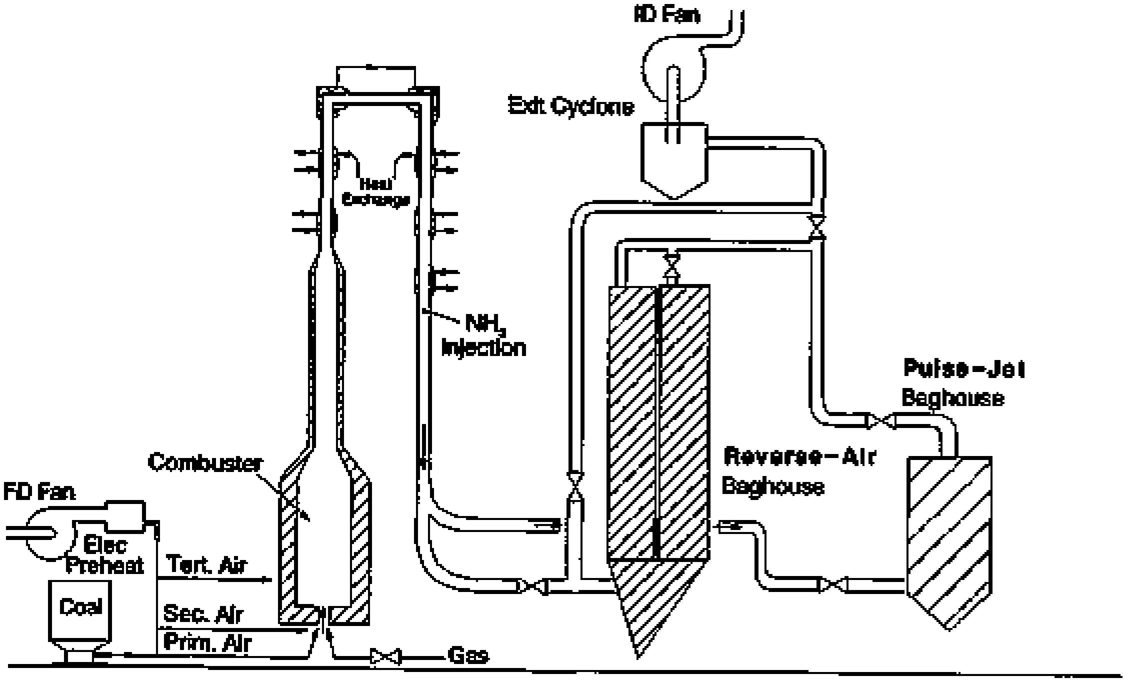


Figure 1. Simplified system flow diagram.

Instrumentation on the PTC permits system temperatures, pressures, flue gas flow rates and constituent concentrations, and baghouse-operating data to be monitored continuously and recorded on a Kaye data logger. The instrumentation includes two Beckman model 755 O_2 analyzers, two Thermo-Electron model 10 NO_x analyzers, two DuPont model 400 SO_2 analyzers, a Beckman model 865 CO_2 analyzer, and a Beckman model 880 CO analyzer. Flue gas sampling is routinely performed at three locations in the system: 1) the combustor exit, 2) the baghouse inlet, and 3) the baghouse outlet. Thermocouples are located at numerous points in the flue gas system to monitor key operating temperatures. System differential and static pressures are monitored with a combination of manometers, gauges, and pressure transducers.

Table 1 presents Kaye data logger numbers, the data source (thermocouple, pressure transducer, or flue gas analyzer), and a description of the location and operational limits established for the data source. Data points not recorded on the data logger are recorded continuously on circular chart recorders or manually on data sheets by operations personnel at specific time intervals. Data sheets completed by operations personnel are also used as backup to the circular chart recorders and data logger.

All of the data points from the data logger will be directly downloaded to an IBM compatible personal computer in order to create a complete spreadsheet and simplify data reduction. Although all of the data points will be continuously logged on the computer, only selected points will be critical to data reduction activities. These will include, but not be limited to, baghouse inlet and outlet temperature, NO_x concentration, O_2 concentration, NH_3 concentration, and baghouse differential pressure.

Flue gas flow rates will range from 110 to 150 scfm. This range of flue gas flow rates will be necessary in order to achieve the range of air-to-cloth ratios required for the reverse-gas (1.5, 2, 3, and 4 ft/min) and pulse-jet (2, 3, 4, and 6 ft/min) fabric filters. Recent modifications to the PTC permit continuous operation of the combustor for extended periods (up to 500 hours). Typical operating conditions for the PTC are listed in Table 2.

Modifications to the pilot-scale pc-fired combustor will not be required to complete the pc-fired experimental activities, but will be necessary to complete the oil-fired 100-hour test period. The modifications for the oil-fired test will include installation of a combustor bottom and nozzle/burner assembly used previously to fire coal-water slurries and possibly installation of a steam jacket on the fuel tank to ensure proper fluid flow. The coal-/water slurry burner assembly has adjustable secondary air swirl vanes. Figure 3 shows a cutaway of the combustion chamber and indicates the relative locations of primary, secondary, and tertiary air. The slurry is pumped from a continuously stirred storage tank through the burner gun to the atomizing nozzle, shown in Figure 4, where it mixes with atomizing air prior to entering the burner throat.

Heated primary air carries the atomized slurry out of the burner gun, while heated secondary air is introduced in an annular section surrounding the burner gun. Heated tertiary air is added through tangential ports located in the furnace wall about one foot above the burner cone. The percentages of the total air used as primary, secondary, and tertiary air are usually 10, 65, and 25%, respectively.

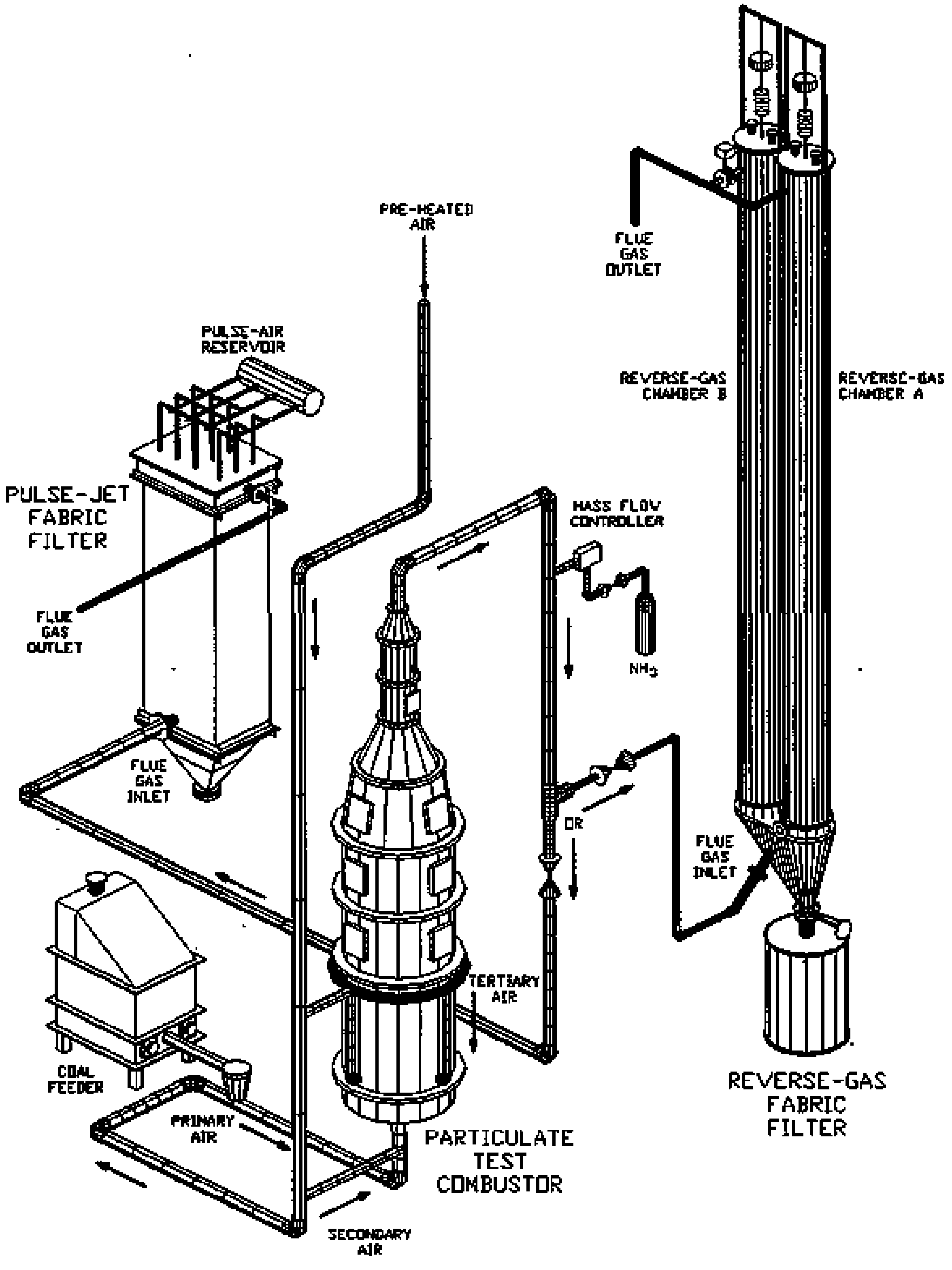


Figure 2. Particulate test combustor (PTC): pulverized coal- or gas-fired at 550,000 Btu/hr.

TABLE 1

Kaye Data Logger Data Channels

Kaye Data Logger No.	Data Source	Source Location	Typical Range
101	TC	Combustor Outlet	1800 ±50°F
102	TC	1st Transition Outlet	1575 ±25°F
103	TC	2nd Transition Outlet	1375 ±25°F
104	TC	HX #1 Flue Gas Outlet	1350 ±25°F
105	TC	HX #2 Flue Gas Outlet	1300 ±25°F
106	TC	HX #3 Flue Gas Outlet	1200 ±25°F
107	TC	HX #4 Flue Gas Outlet	925 ±10°F
108	TC	HX #5 Flue Gas Outlet	900 ±10°F
109	TC	HX #6 Flue Gas Outlet	830 ±10°F
110	TC	HX #7 Flue Gas Outlet	800 ±10°F
111	TC	Post Cyclone Flue Gas	225 ±10°F
112	TC	ID Fan Inlet	190 ±10°F
113	TC	ID Fan Outlet	210 ±10°F
114	TC	Air Preheater Temp.	200-800°F
115	TC	Combustion Air Temp.	300 ±25°F
116	TC	Particulate Sampling Elbow	700 ±10°F
201	TC	Annubar 2nd Level	350 ±10°F
202	TC	Cooling Water Inlet	50-60°F
203	TC	Combustor Cooling Water Out	150 -190°F
204	TC	HX #1 Cooling Water Out	150 -190°F
205	TC	HX #5 Cooling Water Out	150 -190°F
206	TC	ESP Flue Gas Inlet	250 -375°F
207	TC	ESP Chamber Temp.	250 -375°F
208	TC	ESP Flue Gas Outlet	250 -375°F
209	TC	Reverse-Gas Inlet	250 -750°F
210	TC	Reverse-Gas Outlet A	250 -750°F
211	TC	Reverse-Gas Outlet B	250 -750°F
212	TC	Pulse-Jet Inlet	250 -750°F
213	TC	Pulse-Jet Chamber	250 -750°F
214	TC	Pulse-Jet Outlet	250 -750°F
215	Pressure Transducer	R-G Differential Pressure A	0-10" W.C.
216	Pressure Transducer	R-G Differential Pressure B	0-10" W.C.
301	Pressure Transducer	R-G Static Pressure	0-20" W.C.
302	Pressure Transducer	P-J Differential Pressure	0-10" W.C.
303	Pressure Transducer	P-J Static Pressure	0-20" W.C.
304	Pressure Transducer	Orifice Differential Pressure	0-10" W.C.
305	Pressure Transducer	Annubar Differential Pressure	0-5" W.C.
306	Load Cell	Reverse-Gas Bag A	0-250 lbs
307	Load Cell	Reverse-Gas Bag B	0-250 lbs
308	NH_3 Analyzer	R G/P-J Inlet or Outlet	0-1000 ppm
309	SO_2-A Analyzer	Combustor Outlet/BH Inlet	0-5000 ppm
310	SO_2-B Analyzer	BH Inlet/BH Outlet	0-5000 ppm
311	O_2-A Analyzer	Combustor Outlet/BH Inlet	0-21 vol%
312	O_2-B Analyzer	BH Inlet/BH Outlet	0-21 vol%
313	CO_2 Analyzer	Combustor Outlet/BH Inlet	0-20 vol%
314	CO Analyzer	Combustor Outlet/BH Inlet	0-1 vol%
315	NO_x-A Analyzer	Combustor Outlet/BH Inlet	0-1000 ppm
316	NO_x-B Analyzer	BH Inlet/BH Outlet	0-1000 ppm

TABLE 2

Standard PTC Operating Conditions

Flue Gas Flow Rate	130 ±20 scfm
Coal Feed Rate	45 to 80 lbs/hour
Combustion Air Preheat	200 to 850°F
Combustor Exit Temperature	1750 to 1850°F
Flue Gas O_2	3 to 5 vol%
Flue Gas SO_2	300 to 3500 ppm
Flue Gas NO_x	400 to 800 ppm
Flue Gas CO_2	15 ± 5 vol%
Flue Gas H_2O	12 ± 5 vol%

Figure 5 illustrates the coal-water slurry feed system that will be used to fire fuel oil. The skid-mounted feed system includes a Moyno progressive cavity pump that is gravity fed from a tank or drum. The variable speed drive controls the slurry feed rate. Fuel flow rate is measured by a Micro-motion flowmeter with a digital indicator. An pneumatic operated mixer is available to continuously mix slurry fuels during a combustion test. Pressure gauges with diaphragms measure pump discharge and the fuel nozzle supply pressures.

EERC and Consolidated Edison personnel will discuss operational issues specific to the oil-fired test. Information concerning the heating value of the fuel oil, typical combustion air preheat temperature for oil firing, and requirements for preheating fuel oil to avoid storage and pumping problems will be addressed. Equipment funds in the amount of $2000 were originally specified and will be reserved for modification or acquisition needs.

3.0 SUBTASK 2.1, REVERSE-GAS SYSTEM

Subtask 2.1 involved the design and construction of a reverse-gas fabric filter device very similar to a device already in use at EERC. The existing reverse-gas chamber was specifically designed and constructed so that it can be operated in a manner that closely simulates bag behavior in full-scale baghouses. In order to achieve this goal, it was necessary to use a full-scale bag, tension the bag properly, and employ reverse-gas cleaning at a flow rate typical of full-scale operation.

The purpose for duplicating the existing device was to permit operation over the desired range of air-to-cloth ratios (1.5, 2, 3, and 4 ft/min) without having to slipstream a significant portion of the flue gas. This approach will minimize temperature and flue gas flow control problems.

The new and existing reverse-gas fabric filter chambers are illustrated in Figure 6. Each chamber is 27 feet tall, excluding the ash hopper, and will house a 12-inch-diameter bag roughly 26 feet long (25 linear feet of filtration area), providing 78.5 square feet of filtration area. When operated in parallel, the two chambers will provide a total reverse-gas filtration area of 157 square feet.

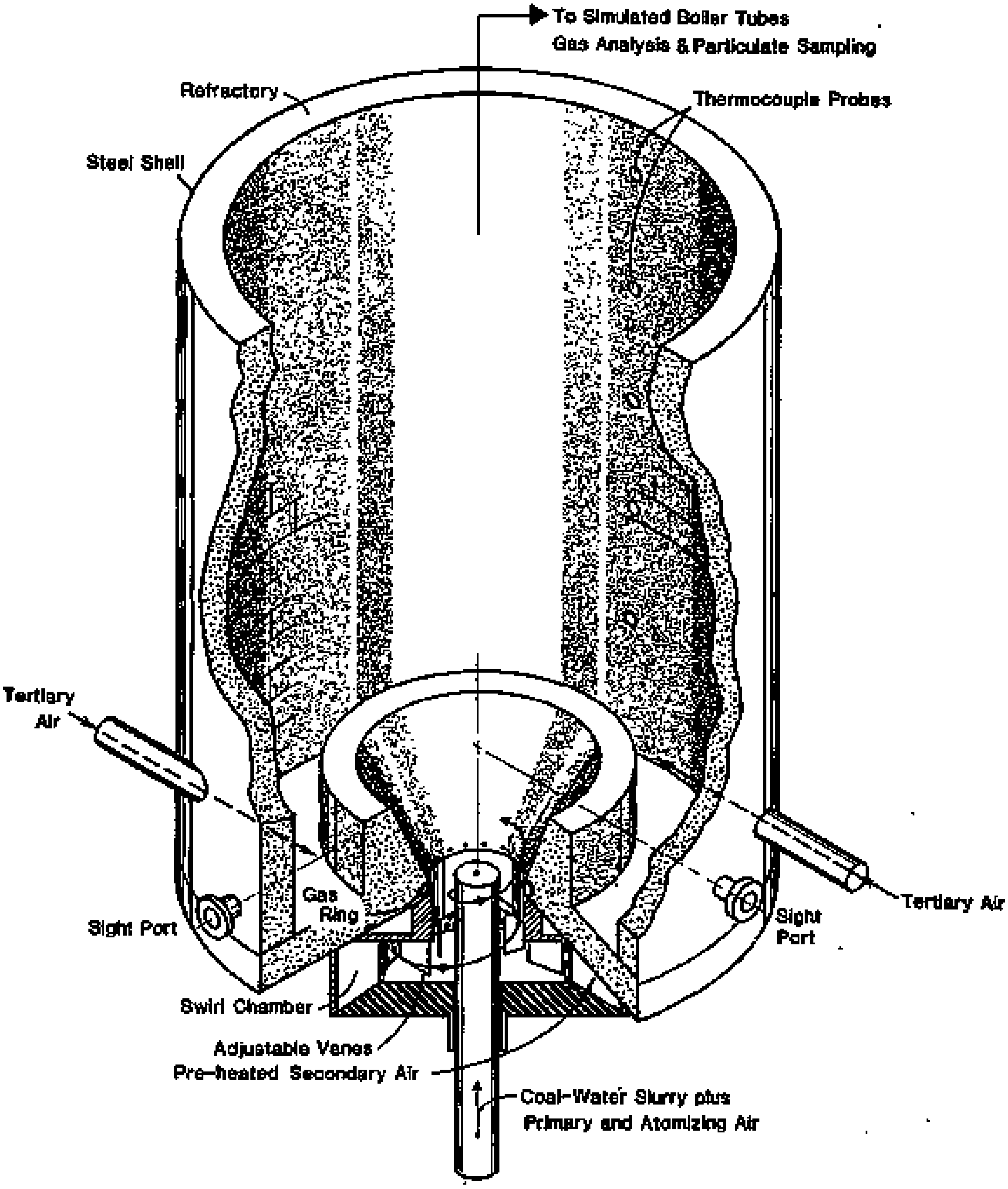


Figure 3. Combustion chamber configuration for oil-fired tests.

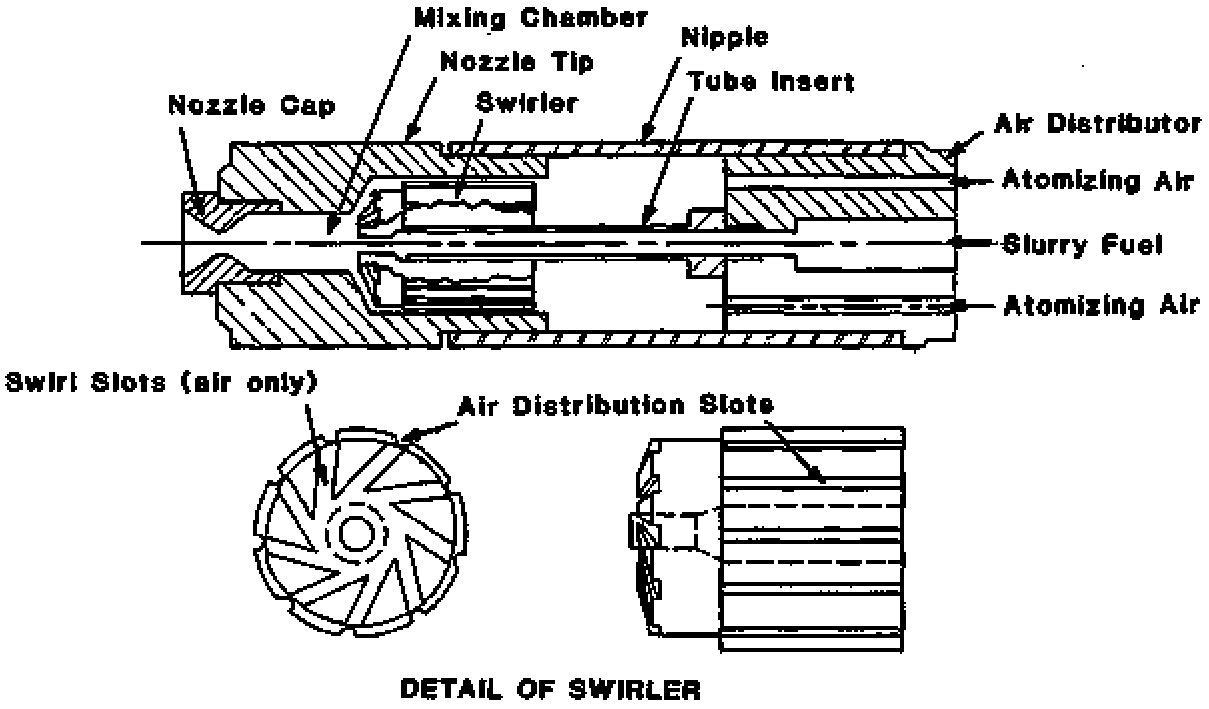


Figure 4. "B-II" slurry atomizing nozzle.

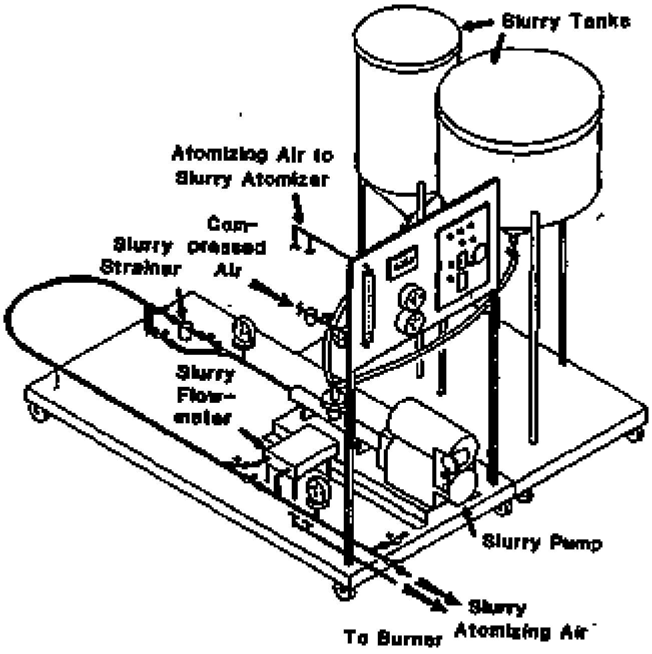


Figure 5. Coal-water slurry feed system.

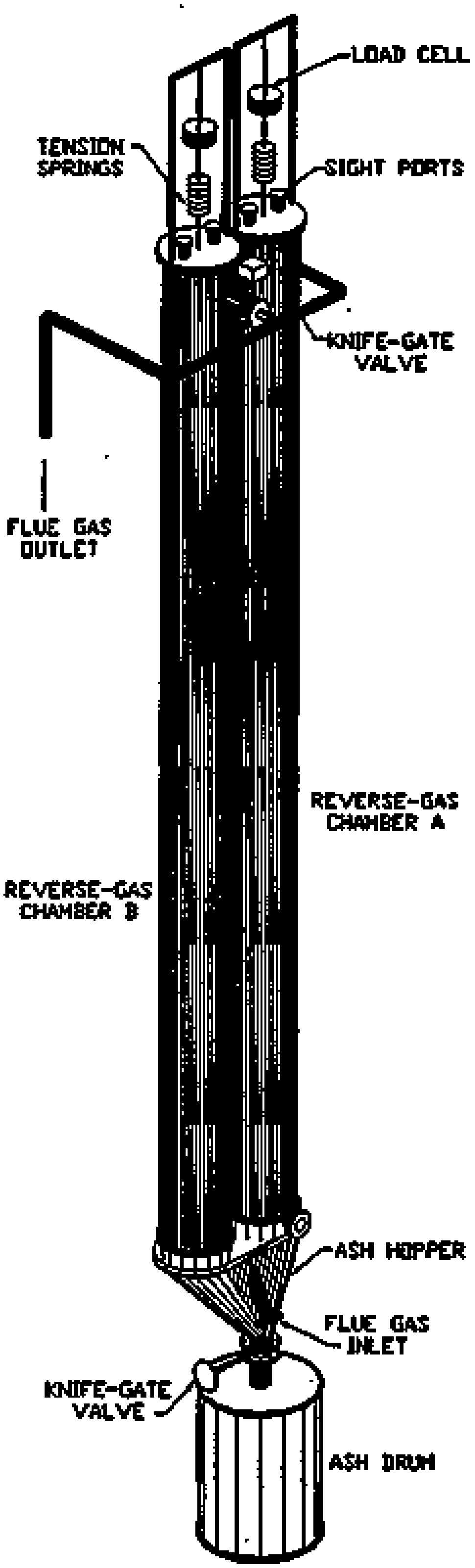


Figure 6. Reverse-gas fabric filter chambers.

A single filter bag will be used to achieve air-to-cloth ratios of 3 and 4 ft/min at flue gas flow rates of 236 acfm (111 scfm) and 314 acfm (147 scfm), respectively. Air-to-cloth ratios of 1.5 and 2 ft/min will require the use of two filter bags and total flue gas flow rates of 236 and 314 acfm (111 and 147 scfm), respectively. A knife-gate valve was installed at the outlet of the new reverse-gas chamber so that flue gas flow can be diverted through one or both chambers to control air-to-cloth ratio on-line. Flue gas piping was also valved so that both reverse-gas chambers can be completely bypassed.

The new reverse-gas chamber was constructed using nominal 20-inch, 304L schedule 5 stainless steel pipe (3/16-inch wall), the same material used to construct the first reverse-gas chamber. To simplify construction and assembly, the 27-foot chamber consists of three flanged/bolted sections, two 10 foot and one 7 foot. Each section was wrapped with low-watt density heat tape and insulated (3 inches) to provide the desired temperature control over the range of 500° to 750°F. Individual lengths of heat tape were wired in parallel so that the loss of one heat tape would not affect the operation of the remaining elements. Multiple controllers were used to assure adequate temperature control over the length of the reverse-gas chambers.

Access to each chamber is possible through the top as well as an access door near the bottom. This will be sufficient for filter bag installation and inspection before and after each 100- and 500-hour test period. Sight ports were installed in the chamber wall to permit visual determination of proper bag collapse during cleaning and dust bleed through to the outside (clean side) of the fabric during normal operation. A sight port was also located in the chamber top and bag cap to permit inspection of the inside (dirty side) of the filter bag.

A common ash hopper was constructed for the two chambers to simplify ash handling, provide a common flue gas inlet, and minimize space requirements. The ash hopper was constructed using 14-gauge stainless steel, wrapped with heat tape, and insulated to prevent moisture condensation and to control baghouse temperature. The flue gas inlet was located near the top of the hopper and centered between the two chamber inlets.

Clamps will be used to attach the reverse-gas filter bags to the thimbles at the bottom and caps at the top of each chamber. Each filter bag will be suspended using a tension spring and load cell so that bag tension can be set and bag weight can be continually monitored as a function of time and cleaning cycle. A load cell and tension spring were located above the top of each chamber with a suspension rod passing through a seal on top of each chamber. The rods are connected to the bag caps which support the top of each bag. This will allow the filter bags to be tensioned on-line and presents a less harsh environment for the load cell, facilitating more accurate determination of individual bag weight.

Thermocouples were installed at the inlet, outlet, and several locations along the length of each chamber. Differential pressure across each chamber and static pressure at the outlet of the two chambers will be monitored continuously with pressure transducers. Gauges will be used to visually monitor baghouse differential and static pressure at the main combustor control panel. Baghouse thermocouple and pressure transducer data will be automatically logged on the data logger. As a backup, all baghouse data will be recorded manually on data sheets.

Table 3 presents specifications and the cost of material and components that were purchased in order to construct the new reverse-gas chamber and modify the existing chamber. The total cost of these items was roughly $22,935, compared to the original proposal estimate of $40,000. Although payment for some minor equipment acquisitions is still anticipated, Table 3 summarizes all equipment items ordered/purchased as of September 30, 1991. Appendix A contains final construction drawings for the various components of the new reverse-gas chamber.

4.0 SUBTASK 2.2, PULSE-JET SYSTEM

Subtask 2.2 involved the design and construction of a pilot-scale pulse-jet fabric filter system for use in the experimental phase of Subtask 3.3, as well as for filtering the flue gas during off-line cleaning of the reverse-gas system. Construction of a new pulse-jet fabric filter system was necessary to achieve adequate temperature control over the range of interest (500° to 750°F) and to operate at the appropriate range of air-to-cloth ratios (2, 3, 4, and 6 ft/min), with minimal flue gas flow rate adjustments and slip-streaming. Due to the planned operating conditions, materials of construction are primarily stainless steel (14-gauge sheet metal and 2 x 2-, 3 x 3-, and 4 x 4-inch angle iron). Figure 7 illustrates the pilot-scale pulse-jet baghouse that was constructed.

The pulse-jet fabric filter houses twelve bags (arranged in a 4 x 3 array) 6 inches in diameter by roughly 8.25 feet long (8 linear feet of filtration area), providing a total filtration area of 151 square feet. Each filter bag is secured to the tube sheet using a snap band sewn into the top cuff. Stainless steel wire cages with 20 vertical wires and 6-inch ring spacing provide bag support. The pulse-jet system will be a single compartment capable of either on- or off-line cleaning. Flue gas enters the baghouse in an area just below the bottom of the cage-supported bags and above the ash hopper.

Access to the filter bags and stainless steel wire cages is gained by removing the clean air plenum at the top of the baghouse. A catwalk was built between the first deck of the PTC tower area and the pulse-jet baghouse at about the 14-foot level. A second catwalk extends around the perimeter of the baghouse to permit relatively easy access to the top of the pulse-jet baghouse for inspection, maintenance, and installation and removal of filter bags and cages.

Low-watt density heat tape made for conductive surfaces was used to preheat the baghouse to prevent moisture condensation during start-up and to control baghouse temperature over the range of interest (500° to 750°F). One-inch heat tape was run vertically on each of the four baghouse walls spaced on roughly 6-inch centers. The individual elements were wired in parallel to minimize the impact of single element failures. The baghouse ash hopper is heated in a similar manner. Five temperature controllers are used to adequately control electrical resistance heating on the pulse-jet baghouse.

TABLE 3
List of Equipment and Materials Procured/Fabricated for the Reverse-Gas Baghouse

Description	Vendor	Estimated Cost
Baghouse Shell: 24 feet of 20-inch 304L SS pipe, 20.25" OD with a 3/16-inch wall, Cut to lengths of 6, 7, 10, 0.5, and 0.5 feet	Crookston Welding	$ 3,050
8 carbon steel flanges, 2 inches by 5/8 inches, 16-5/8" oversized bolt holes, welded to sections of 20-inch pipe		
1 304 SS plate cap, 3/16" material, 16-5/8" oversized bolt holes		
Bolts/nuts/washers for assembly		
Electrical Heaters (Conductive surface heat tapes): 30-1" x 120" (208 V, 240 watts/in^2) 40-1" x 216" (208 V, 2 watts/in^2) 15-1/2" x 18' (208 V, 271 watt) (inlet/outlet pipe) 32-1" Hopper Heating Tapes	The Conrad Co.	$ 3,365
Temperature Controllers: 9 temperature controllers, 208 volts, 9 thermocouple converter boards, 9 45-ampere contactors	Border States	$ 2,400
Insulation: Fiberglas insulation, 350 TMZ, (2" thick, 850°F max.) 52 linear feet for steam pipe reroute	Scott Equipment	$ 840
140 linear feet for inlet/outlet pipe w/elbows 56 linear feet for 22-inch pipe	Applied Thermal Systems	$ 2,060
K-Wool high-temperature insulation, 10 rolls of 1" thick insulation, 24" wide by 25 feet long	Smith Sharpe	$ 875
Sight Ports: Sight glass, 2-10" dia. by 1/4", Sight glass, 4-3.5" dia. by 1/4"	Sci. Glass Engr.	$ 175
Stainless steel fittings, 4-inch, 4 each, fittings/ferrules/clamps/caps/gaskets,	Lincoln Supplies	$ 850

continued . . .

TABLE 3 (Continued)

Description	Vendor	Estimated Cost
Electrical Connectors/Misc.	Border States	$ 213
	Quest	$ 100
	Radio Shack	$ 25
Hopper Materials:		
4 by 5-foot 14GA 304 SS	Grand Forks Welding	$ 140
24 1/4" x 51 1/2" 3/16" 304 SS	Industrial Stainless	$ 455
48" x 96" 14GA 304 SS		
Load Cell System: 1 200-lb load cell, 2 rod end, 1 power supply, 24 volt DC 1 power supply, 10 volt	Omega	$ 775
1 250-lb dynamometer	McMaster Carr	$ 450
Pressure transducers: 2 differential pressure transducers, 2 0-10" W.C. and 1 0-5" W.C.	Simone	$ 1,730
Thermocouples and Wire: 12-8" Type K thermocouples, 6-4" Type K thermocouples, 1000 feet of Type K Wire	Simone	$ 600
DeZurik Valves: 1 pneumatic-actuated knife-gate, 3.5-inch pipe, 304 SS body and gate, Maximum temperature 1000°F Replacement packing	Plant Equipment	$ 765
Expansion Joints: 3-304 SS construction, 3.5-inch pipe with flow liner	Hyspan Prec. Prod.	$ 1,360
Miscellaneous Items:		
SS Fittings and Tubing, 1/4",	Quest Engr.	$ 170
1/4" Tygon tubing, 600 feet & ferrules	MN Valve & Fitting	$ 120
1/4" 304 SS tubing	Industrial Stainless	$ 77
3.5" 304 SS pipe, 60 feet	Advanced Fluids	$ 1,460
5 3.5" long radius 304 SS elbows		
1 3.5" 304 SS tee		
8 3.5" 304 SS, 150# flanges		
Structural Steel:	Grand Forks Welding	$ 695
Carbon steel safety plate,	Northern Plumbing	$ 70
channel iron, angle iron, floor plate, etc.	Linfoot	$ 115
Miscellaneous Items:		
Contingency:		$17,065
TOTAL		$40,000

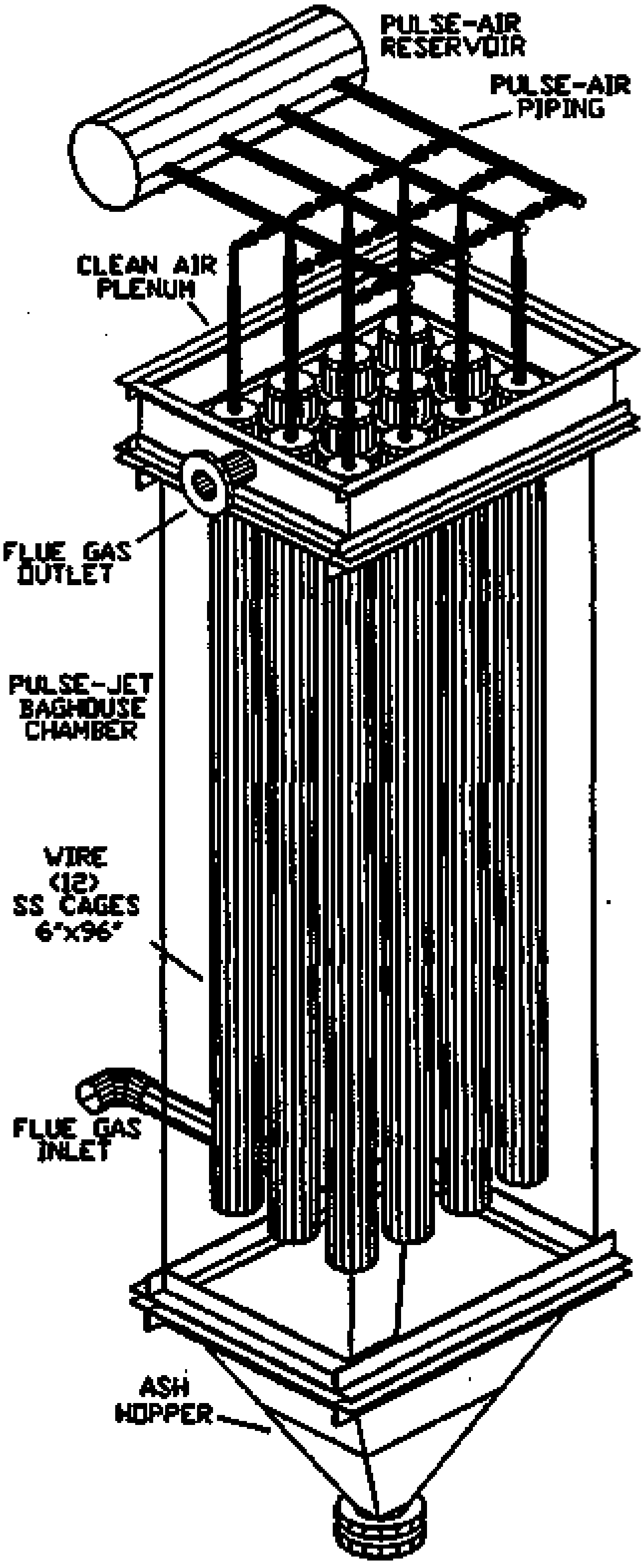


Figure 7. Pulse-jet fabric filter chamber.

Pulse-jet cleaning can be triggered as a function of baghouse differential pressure or as a function of time. The baghouse pulse-jet cleaning system is operated by a controller that permits adjustment of cleaning frequency and pulse duration. Timers are used to set pulse duration and off-time, while counters total baghouse operating time and test time in hours and total and test cleaning cycles. Filter bag cleaning occurs when the controller opens the solenoid-operated valves between the pulse-air reservoir and the four pulse-air manifold lines. Each manifold line provides pulse air to three filter bags. Three filter bags are cleaned simultaneously, with a short delay between each set of three filter bags to allow air pressure to recover in the pulse-air reservoir.

In response to a question raised by the commercial sponsors, the EERC Project Manager contacted Bob Carr of Electric Power Technologies, Inc. to obtain information on the pulse-air pressure and volume requirements for a low-pressure/high-volume system. Bob stated that during a recent pilot-scale test of low-pressure/high-volume cleaning at the Martin Drake station of Colorado Springs Department of Public Utilities, a pulse pressure of 12 psig was successfully used. Pulse volume was 2 ft^3 per pulse for 3 bags each having 25 ft^2 of filtering surface. This is roughly 0.67 ft^3 per bag or 0.03 ft^3/ft^2 of fabric surface. Based on the information provided by Bob Carr, the EERC has included high-pressure/low-volume and low-pressure/high-volume cleaning options in the final design of the pulse-air system for the pulse-jet baghouse.

In order to operate at a low-pressure/high-volume condition in the new pulse-jet baghouse, a pulse volume of 1.1 ft^3 would be required for each set of three bags. Figure 8 presents data from shakedown tests showing the relationship between pulse volume and pulse duration for a reservoir pressure of 12 psig. This data indicates that a pulse duration of roughly 0.33 seconds will be necessary to generate a pulse volume of 1.1 ft^3. Figures 9, 10, and 11 present similar data for reservoir pressures of 40, 50, and 60 psig, respectively. For the high-pressure/low-volume case, 0.01 to 0.02 ft^3/ft^2 of fabric surface is common. Therefore, a maximum pulse volume of 0.75 ft^3 will be required to clean one set of three bags. For a pulse pressure of 40 psig, a pulse duration of roughly 0.03 will be required. For reservoir pressures of 50 and 60 psig, the minimum pulse volume appears to be about 1 ft^3 for each set of three bags.

In order to control and operate the pulse-jet baghouse at air-to-cloth ratios of 2, 3, 4, and 6 ft/min, it will be necessary to stop gas flow through selected filter bags on-line. Table 4 lists the number of on-line filter bags that will be required in order to operate at the desired air-to-cloth ratios. A flue gas flow rate of 141 scfm (302 acfm) was chosen based on the typical operation of the pc-fired pilot-scale combustor. Figure 12 presents a more detailed illustration of the clean air plenum showing the intended approach to sealing off individual filter bags. Although a plug threaded into a pipe coupling may not be a perfect seal, it should be adequate to effect the flue gas flow control desired. When individual filter bags are sealed, at least one filter bag in each row of three will remain on-line to permit the cleaning mechanism to function properly. The geometric arrangement of the on-line filter bags will be selected to assure adequate flue gas distribution in the baghouse and avoid temperature gradients.

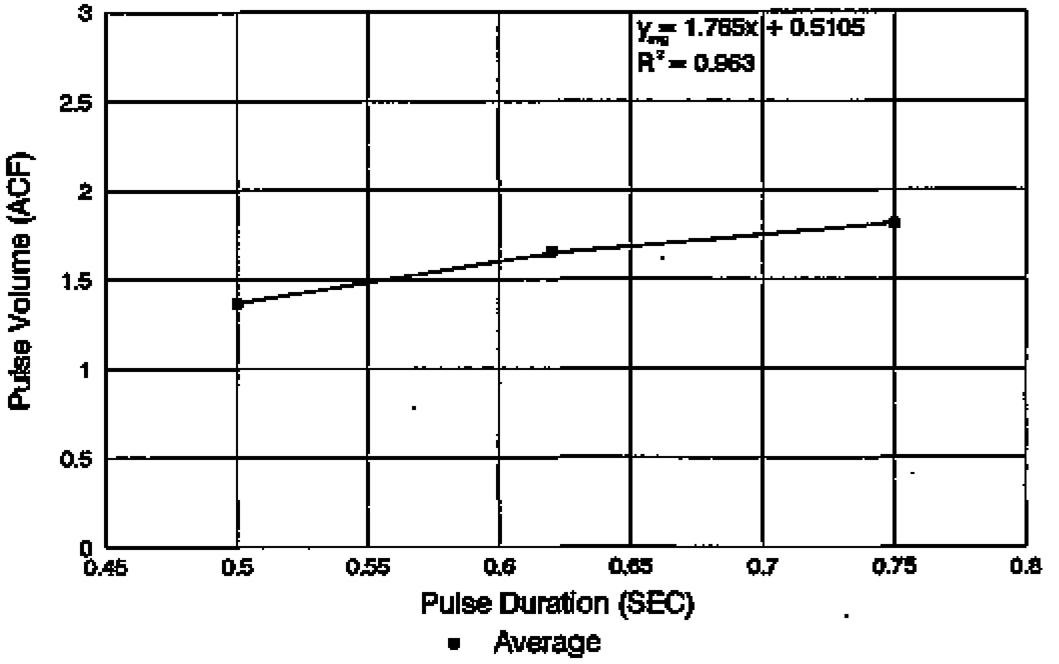


Figure 8. Pulse volume versus pulse duration at 12 psig.

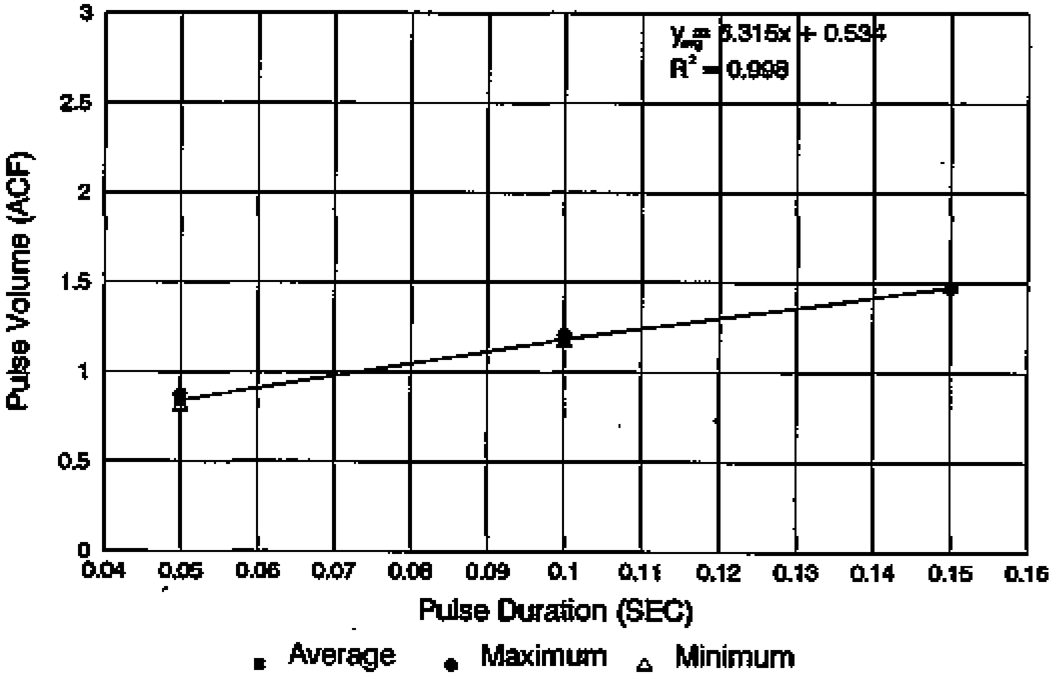


Figure 9. Pulse volume versus pulse duration at 40 psig.

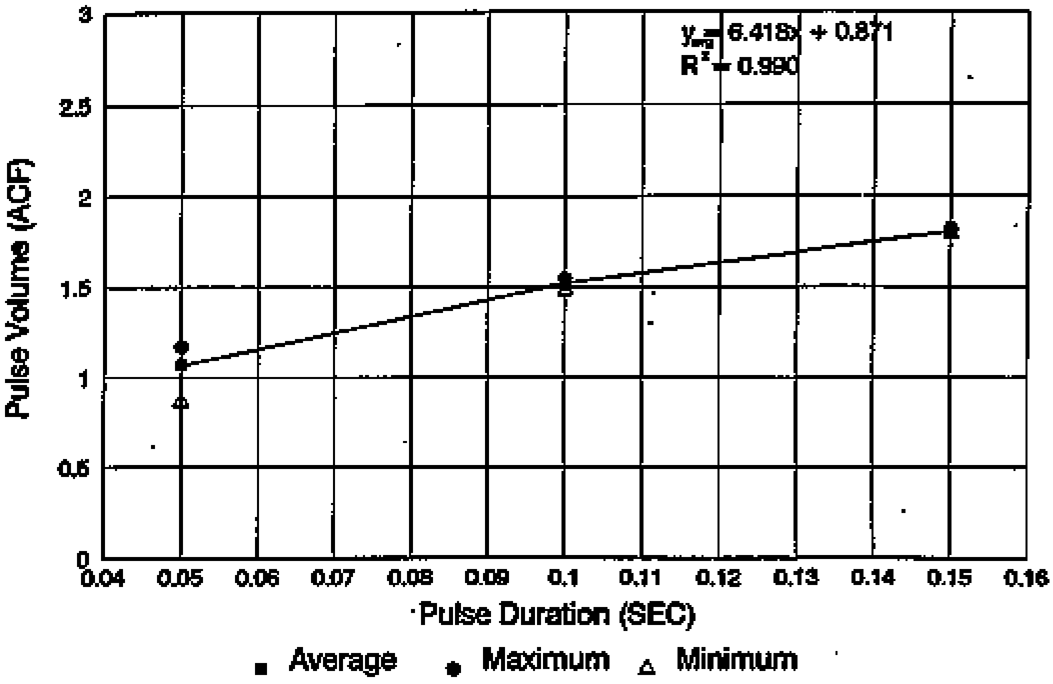


Figure 10. Pulse volume versus pulse duration at 50 psig.

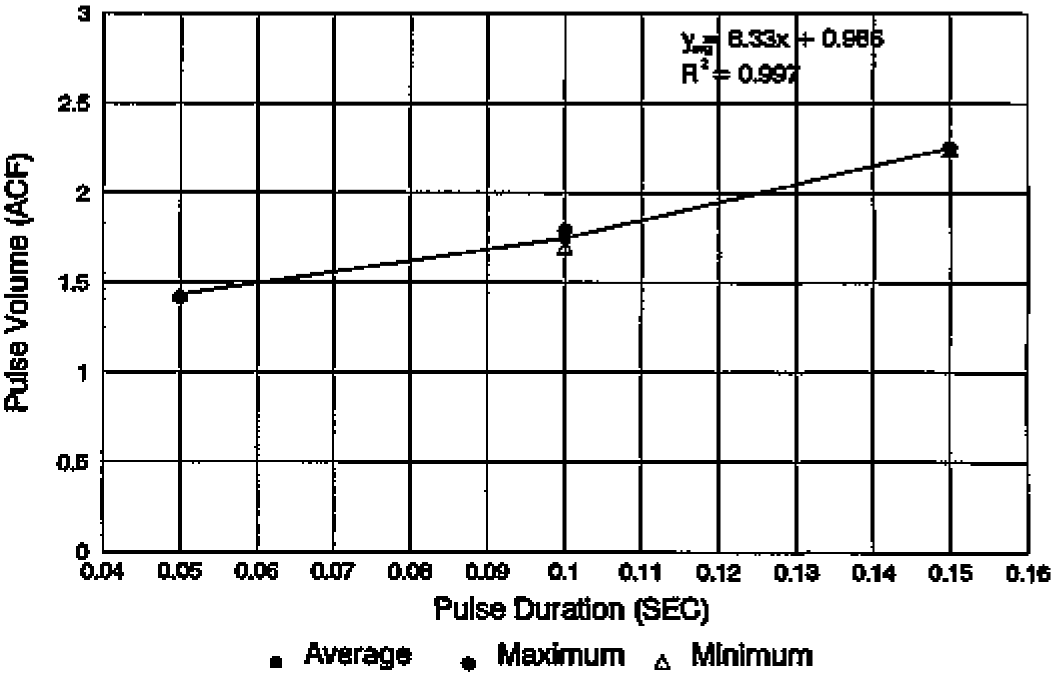


Figure 11. Pulse volume versus pulse duration at 60 psig.

TABLE 4

The Number of Filter Bags Required to Achieve the Range of Air-to-Cloth Ratios Desired in the Pulse-Jet Baghouse*

Number of Bags	Fabric Surface Area, ft^2	Air-to-Cloth Ratio, ft/min
4	50.3	6
6	75.4	4
8	100.6	3
12	150.8	2

* The flue gas flow rate for the pulse-jet baghouse tests will be 141 scfm (302 acfm).

Thermocouples were installed at the inlet and outlet, as well as at several locations along the length of the chamber. Differential pressure across the chamber and static pressure at the outlet of the chamber are monitored continuously with pressure transducers. Gauges are used to visually monitor baghouse differential and static pressure at the main combustor control panel. Baghouse thermocouple and pressure transducer data is automatically logged on the data logger. As a backup, baghouse data is recorded manually on data sheets.

Baghouse ash removal is accomplished by opening a 6-inch knife valve at the bottom of the hopper, allowing ash material to drain into a 5- to 10-gallon ash container. An ash container of this size facilitates ease in handling and is adequate for ash accumulation during relatively short test periods (up to 8 hours). Longer test periods will require a larger ash container or more frequent handling. This determination will be made as a result of completing several longer test periods and soliciting input from operations personnel.

Table 5 presents specifications and the cost of material and components that were purchased in order to construct the new pulse-jet baghouse. The total cost of these items was $25,672, compared to the original proposal estimate of $35,000. Although payment for some minor equipment acquisitions is still anticipated, Table 5 summarizes all equipment items ordered or purchased as of September 30, 1991. Appendix B contains final construction drawings for the various components of the new pulse-jet baghouse.

5.0 AMMONIA ANALYZER

A bid request for an on-line ammonia analyzer was prepared and mailed to prospective suppliers in January. Only two manufacturers responded to the bid request, ADA Technologies Inc. and Siemens Energy & Automation, Inc. After reviewing the specifications for an on-line ammonia analyzer submitted by the respective companies, EERC personnel felt that the analyzer proposed by Siemens Energy & Automation, Inc. was the best choice. This selection was based on cost and the fact that the Siemens instrument is currently being used commercially in Europe.

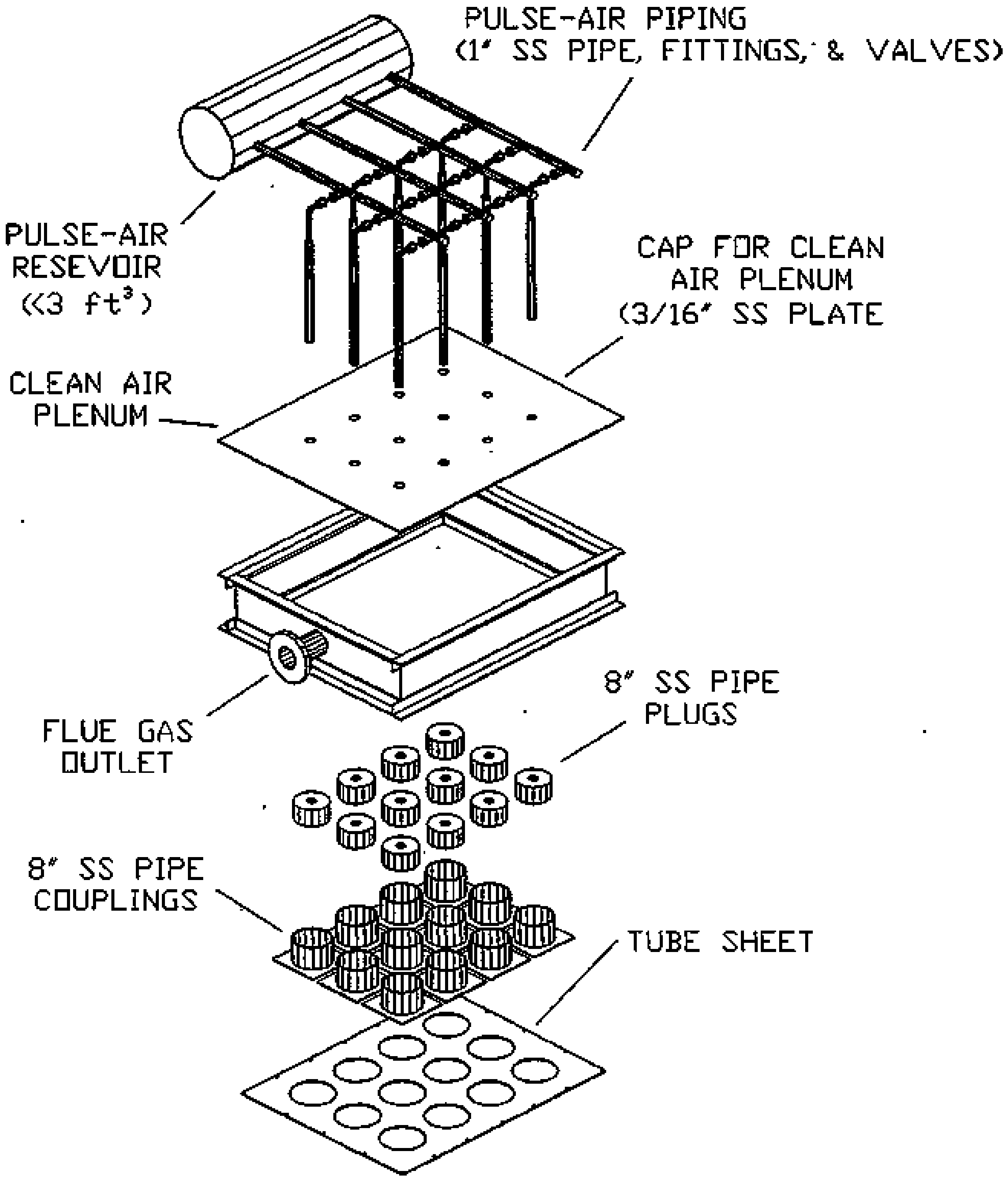


Figure 12. Pulse-jet clean air plenum.

TABLE 5

List of Equipment and Materials Procured/Fabricated for the Pulse-Jet Baghouse

Description	Vendor	Estimated Cost
Baghouse Shell:	Industrial SS	
2 sheets 14-gauge 304 SS, 4 by 10 ft		$ 360
3 3-ft by 10-ft sheet, 14GA 304 SS,		$ 410
2" x 2" x 1/4" SS angle, 100 feet		$ 290
3" x 3" x 1/4" SS angle, 40 feet		$ 445
4" x 4" x 1/4" SS angle, 20 feet		$ 320
50.75" x 40.75" (3/16" 304 SS) plate		$ 200
46" x 36" (3/16" 304 SS) plate		$ 165
2 48" x 120" (14GA 304 SS) plate		$ 360
3 36" x 120" (14GA 304 SS) plate		$ 410
Electrical Heaters (conductive surface heat tapes): 30 1-inch by 10-foot 208 volt, 2 watts/in^2 28 1" tapes for hopper	The Conrad Co.	$ 1,596
Temperature Controllers: 5 temperature controllers, 208 volts 5 thermocouple converter boards 5 heat sink 2 45-ampere contactors 5 solid-state relays	Border States	$ 1,330
Insulation:		
Fiberglas insulation, 350 TMZ (850°F max.) 10 pieces, 36" x 72" x 2"	Scott Equipment	$ 3,050
8 pieces 4' x 8' x 2"	Applied Thermal Systems	$ 1,010
K-Wool high-temperature insulation, 7 rolls of 1" thick insulation, 24" wide by 25 feet long	Smith Sharpe	$ 615
Sight Ports:		
Sight glass, 6-3.5" dia. by 1/4"	Sci. Glass Engr.	$ 40
Stainless steel fittings, 4-inch, 6 each, fittings/ferrules/clamps/caps/gaskets	Lincoln Supplies	$ 1,280
Pressure Transducers:		
1 Differential Pressure Transducers, 0-10" W.C.	Simone	$ 865
1 Static Pressure Transducer, 0-25" W.C.	Simone	$ 750
2 Power Supplies, 10 volt	Newark	$ 127

continued . . .

TABLE 5 (Continued)

Description	Vendor	Estimated Cost
Thermocouples and Wire:	Omega	$ 450
10-12" Type K thermocouples,		
2-4" Type K thermocouples,		
500 feet of Type K Wire		
14-6" thermocouple Type K	Simone	$ 155
Miscellaneous Electrical Supplies	Border States	$ 180
	Wesco	$ 83
2 Expansion Joints	Hyspan	$ 910
Pulse System:		
8" x 8" pipe nipples	Vincent Metals	$ 550
43" Sch5 12" (304 SS) Pipe	Industrial SS	$ 1,035
2-12" Pipecaps (304 SS)		
1" full pipe couplings (304 SS)		
1 1/2" female pipe couplings		
1 1/2" male pipe couplings x 3" long (304 SS)		
1" Sch40 pipe (304 SS)		
1" female pipe caps (304 SS)		
4-1" male threaded pipe couplings	Quest	$ 76
1-1/2" male threaded pipe couplings		
5 Solenoid valves	Goyen Valve	$ 200
12-12" overall length flexible hose (304 SS)	Ritchie Engr.	$ 475
Baghouse Controller:		
1 Dwyer 3010 photohelic,	Quest	$ 185
1 Redington counter (keyed) P32-1026-115AC,	Newark	$ 390
1 Redington counter (reset) P2-1006-115AC,		
1 Cramer nonreset clock 10053,		
1 Cramer resettable clock 10079,		
3 Crydon 115 volt solid-state relays,		
3 Assorted selector and start/stop switches,	Trask	$ 560
Magnehelic 0-10" WC, cabling	Quest	$ 415
Inlet/Outlet Piping:		
3 1/2" 304 SS pipe, 40 feet	Advanced Fluids	$ 1,100
9-3 1/2" long radius elbows		
4-3 1/2" 304 SS, 150# plate flanges		
8 3 1/2" 304 SS, 150# plate flanges	Industrial SS	$ 535
4-4" 304 SS, 150# plate flanges		$ 210
1" x 1/8" 304 Angle (304 SS)	Grand Forks Welding	$ 48
3' x 4' 3/16" 304 SS plate		$ 227
1" Sch40 304 SS pipe		$ 110
3/16" x 1" 304 SS strip		$ 75
Structural Steel:	Northern Plains Steel & Grand Forks Welding	$ 2,325
Carbon steel safety plate,		
6" channel,		
4" x 4" square tubing,		
3" x 3" angle		
Miscellaneous Construction Materials		

continued . . .

TABLE 5 (Continued)

Description	Vendor	Estimated Cost
1 Dezurik Valve	Dezurik Valve	$ 675
Filter Bag Cages: 13 pieces, 304 SS wire cage, 6" by 96", 20 vertical wires, C-channel top, welded bottom	Royal Wire	$ 1,080
Miscellaneous Items:		
Fuel Oil Firing		$ 2,000
Contingency:		$ 9,328
TOTAL		$37,000

The package proposed by Siemens included a sampling probe, an ammonia converter, and the Ultramat 5 nondispersive infrared analyzer. The purpose of the sampling probe is to remove dust and SO_2 from the sample gas stream. Dust removal is accomplished using a standard filter element. Sulfur dioxide is removed using a module containing a proprietary sorbent material. The sampling probe elements are all heated to 660°F (350°C) using electric furnace elements. This is necessary in order to avoid ammonium sulfate or bisulfate formation. Since the sampling probe proposed by Siemens is designed for use in a full-scale commercial application, it will not be appropriate for the 3.5-inch flue gas duct size on the PTC System. Therefore, EERC intends to build a heated sample probe more appropriate for this pilot-scale application. The sample probe will make use of a standard dust-loading filter to remove particulate from the gas stream and the Siemens proprietary commercial sorbent for SO_2 removal.

An ammonia converter will be required in order to generate an ammonia-free flue gas sample stream for the flow through the reference cell. To accomplish this, the flue gas sample stream is split, with half the flue gas sample stream entering a titanium dioxide ammonia converter and the second half entering the sample cell. The ammonia converter has an operating life of approximately 3 years and then can be regenerated in the field. The price quoted by Siemens for the ammonia converter was $5,778.

The Ultramat 5 is a nondispersive infrared analyzer. This is the same type of analyzer that EERC is currently using for measurement of nitrous oxide (N_2O), with the exception of the reference cell. The ammonia measurement technique in this case is sensitive to CO_2, SO_2, and water vapor. This sensitivity is mitigated by using the flow through reference cell and the SO_2 sorbent module. Ammonia measurement sensitivity to CO_2 and water vapor is eliminated as a result of both the reference and sample gas stream containing the same concentration of CO_2 and water vapor. Concerns with respect to ammonia/sulfur by-products are addressed, as previously stated, by removing the SO_2 from the sample gas stream prior to the analyzer. Table 6 presents additional specifications for the Ultramat 5 analyzer. The price quoted for the Siemens Ultramat 5 analyzer was $10,915.

At this time, EERC personnel estimate that the total cost for the on-line ammonia analysis system will be less than $30,000, well within the $50,000 originally included in the project budget. This cost includes the sample probe (to be designed and constructed by EERC), ammonia converter, and the Ultramat 5 analyzer. This is substantially cheaper than the roughly $60,000 quoted by ADA Technologies Inc., which also required design and construction of a sample probe to remove particulate and limit SO_2 concentration in the flue gas sample stream. In addition to cost, the fact that the Siemens instrument is currently being used commercially adds a degree of confidence to its potential performance in this pilot-scale application.

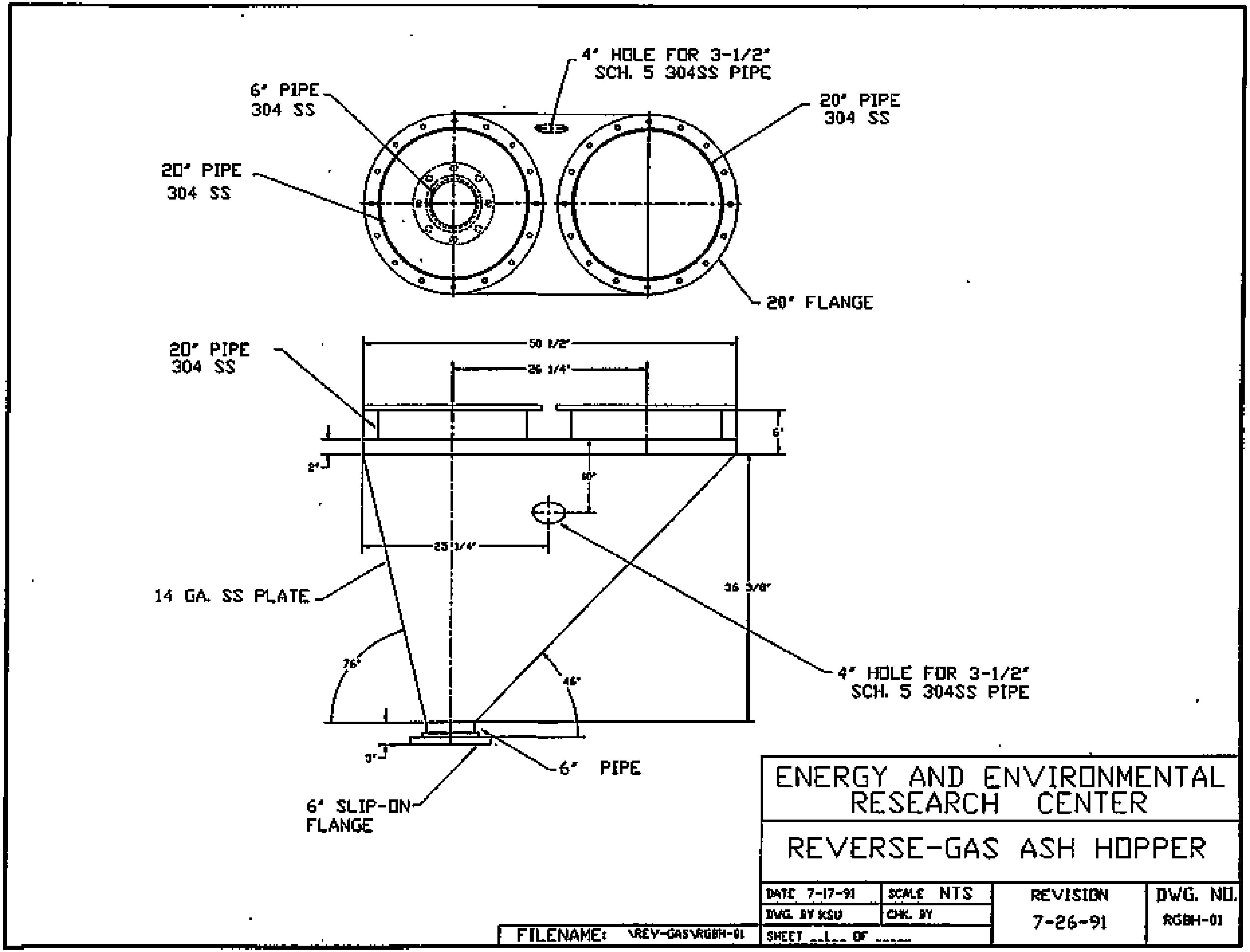
TABLE 6

Specifications for Siemens Ultramat 5 Nondispersive Infrared Analyzer

Output Signal:	Analog 0-20 mA, Digital RS 232C
Ammonia Measurement Ranges:	0-50 and 0-1000 ppm
Sample Cell Heated To:	75°C
Sample Gas Flow Rate:	2 liter/min
Resolution:	1.0% of full scale
Dimensions:	43.8 x 17.7 x 27 cm
Power Requirement:	110 volts AC
Materials of Construction for Sample Carrying Parts:	Stainless Steel

APPENDIX A

REVERSE-GAS AND PULSE-JET BAGHOUSE DRAWINGS



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REVERSE-GAS ASH HOPPER

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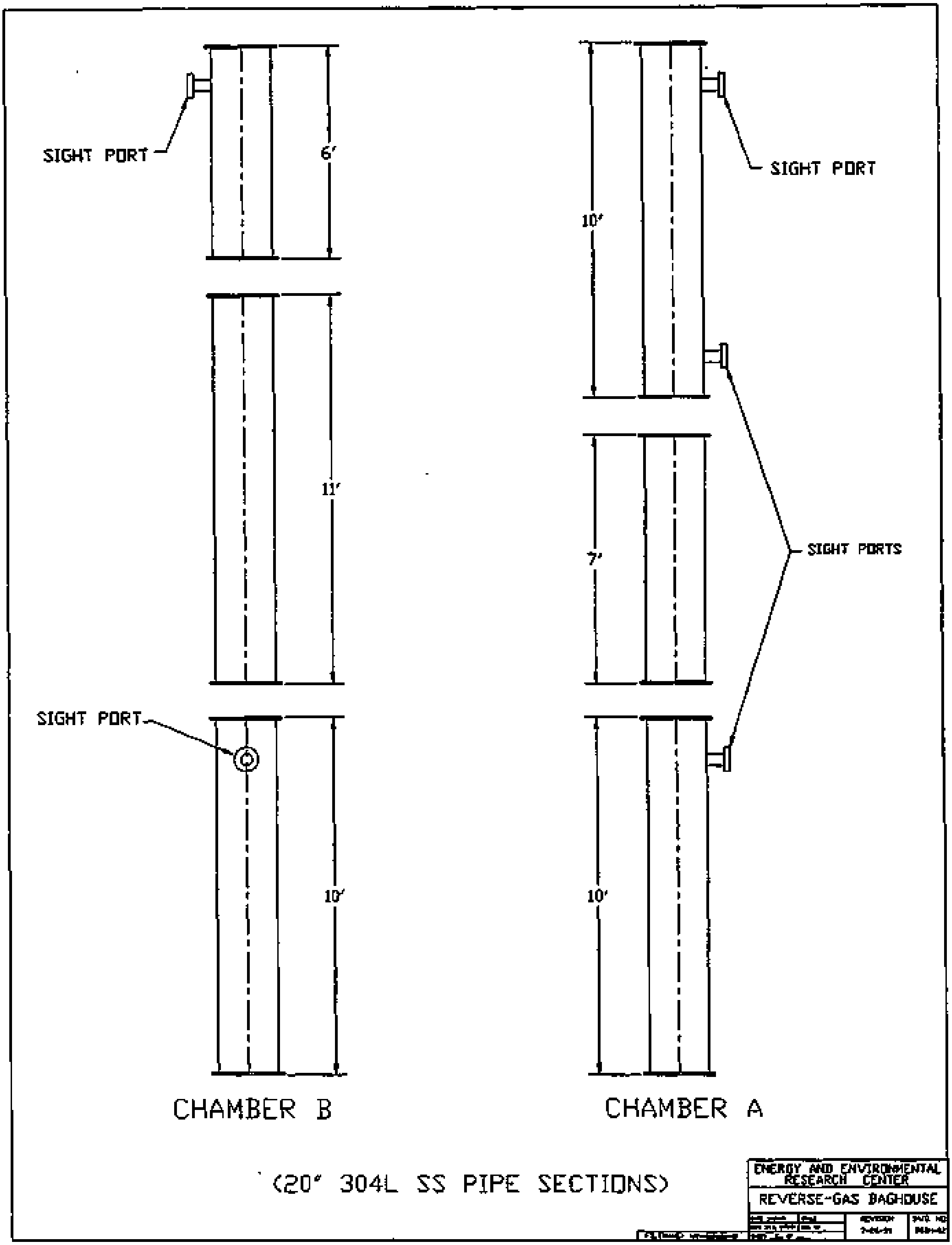
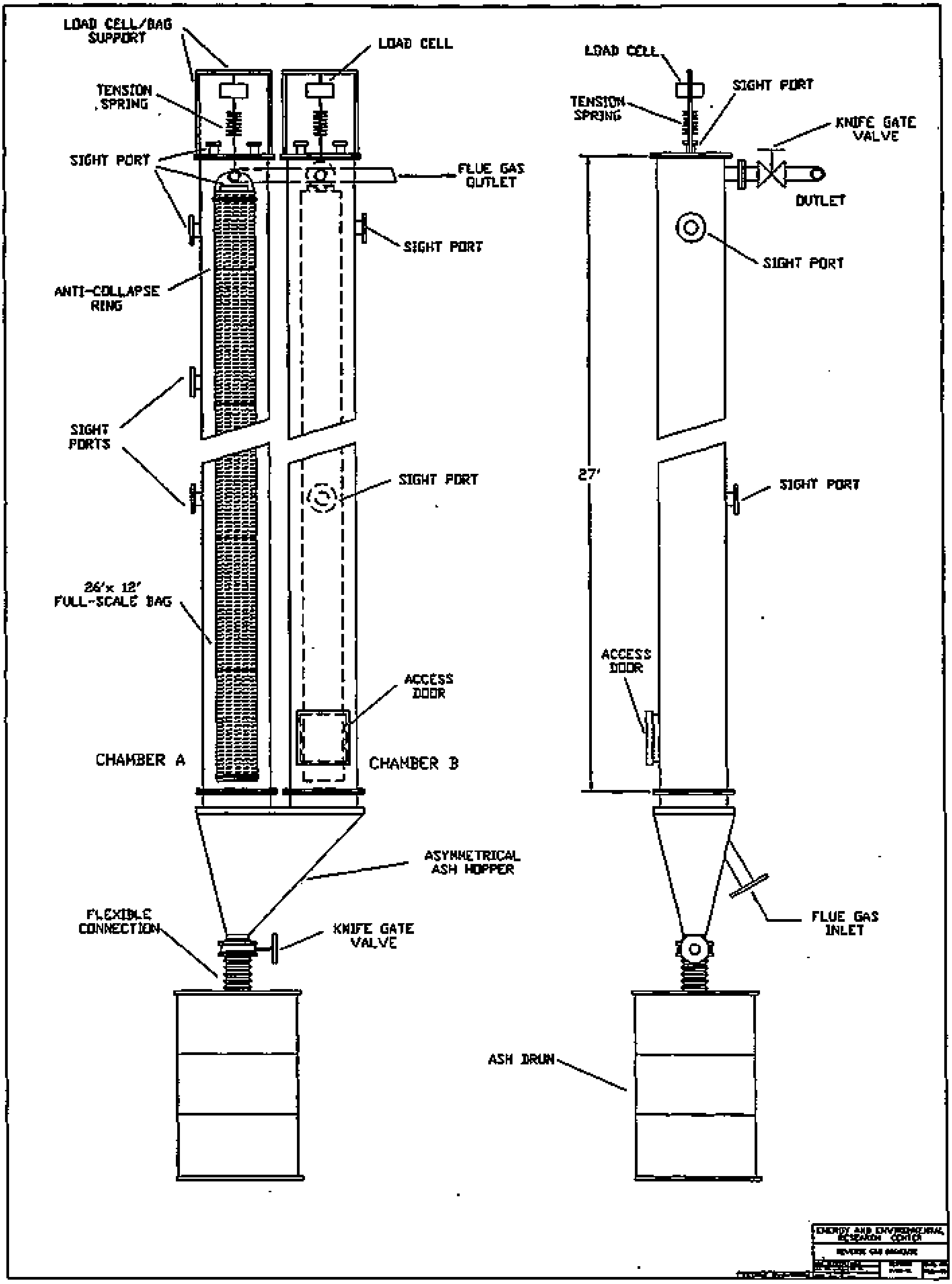
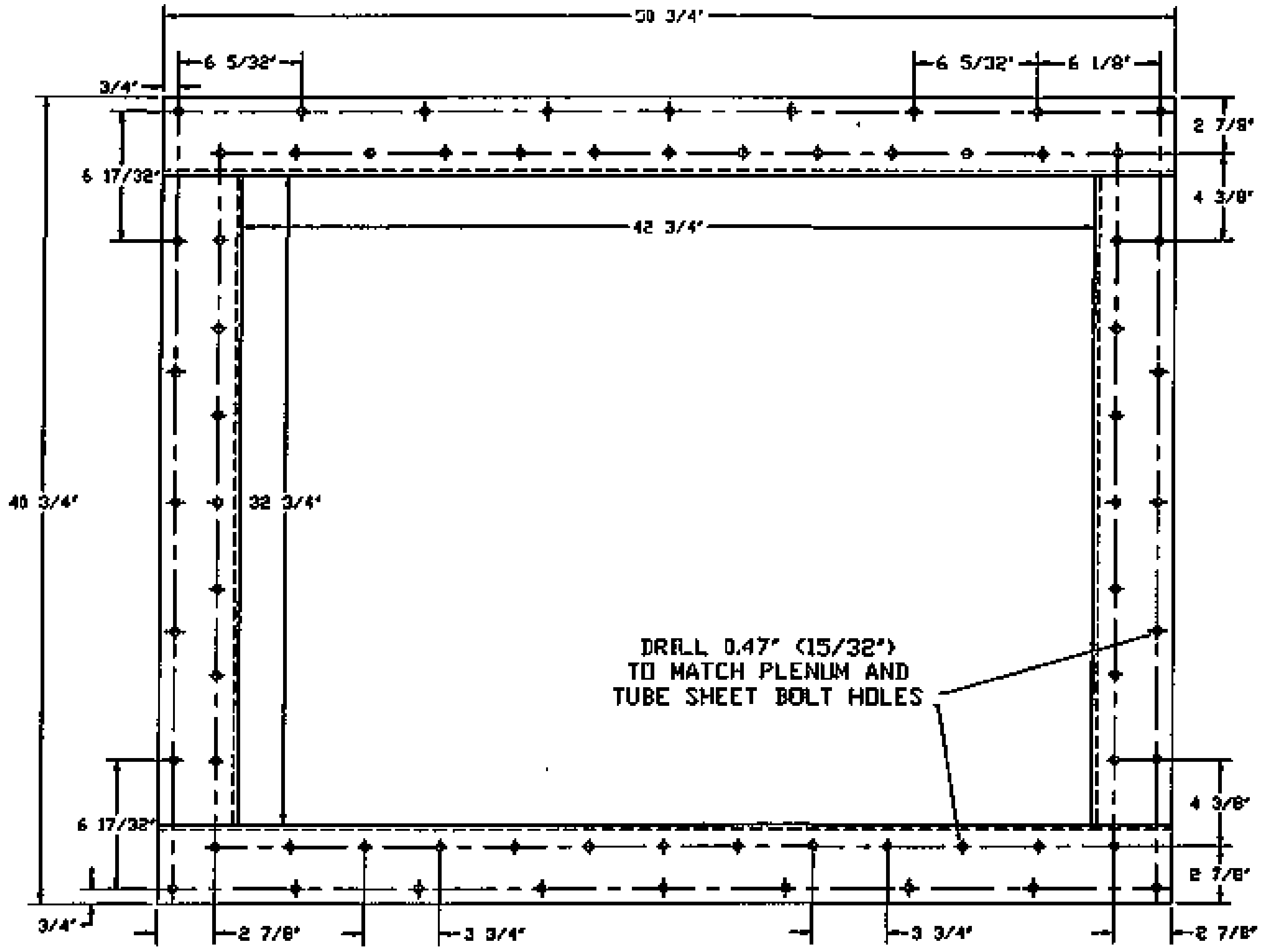

SIGHT PORT
6'
11'
SIGHT PORT
10'
SIGHT PORT
10'
SIGHT PORTS
7'
10'
CHAMBER B
CHAMBER A
(20" 304L SS PIPE SECTIONS)
ENERGY AND ENVIRONMENTAL RESEARCH CENTER
REVERSE-GAS BAGHOUSE


LOAD CELL/BAG SUPPORT
LOAD CELL
TENSION SPRING
SIGHT PORT
FLUE GAS OUTLET
SIGHT PORT
ANTI-COLLAPSE RING
SIGHT PORTS
SIGHT PORT
26'x 12' FULL-SCALE BAG
ACCESS DOOR
CHAMBER A
CHAMBER B
ASYMMETRICAL ASH HOPPER
FLEXIBLE CONNECTION
KNIFE GATE VALVE
LOAD CELL
TENSION SPRING
SIGHT PORT
KNIFE GATE VALVE
OUTLET
SIGHT PORT
27'
SIGHT PORT
ACCESS DOOR
FLUE GAS INLET
ASH DRUM
ENERGY AND ENVIRONMENTAL RESEARCH CENTER
REVERSE GAS BAGHOUSE



MATERIALS OF CONSTRUCTION:
4"x4"x1/4"304L SS ANGLE IRON

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PULSE-JET BAGHOUSE CHAMBER
TOP FLANGE

DATE 7-16-91	SCALE NTS	REVISION	DWG. NO.
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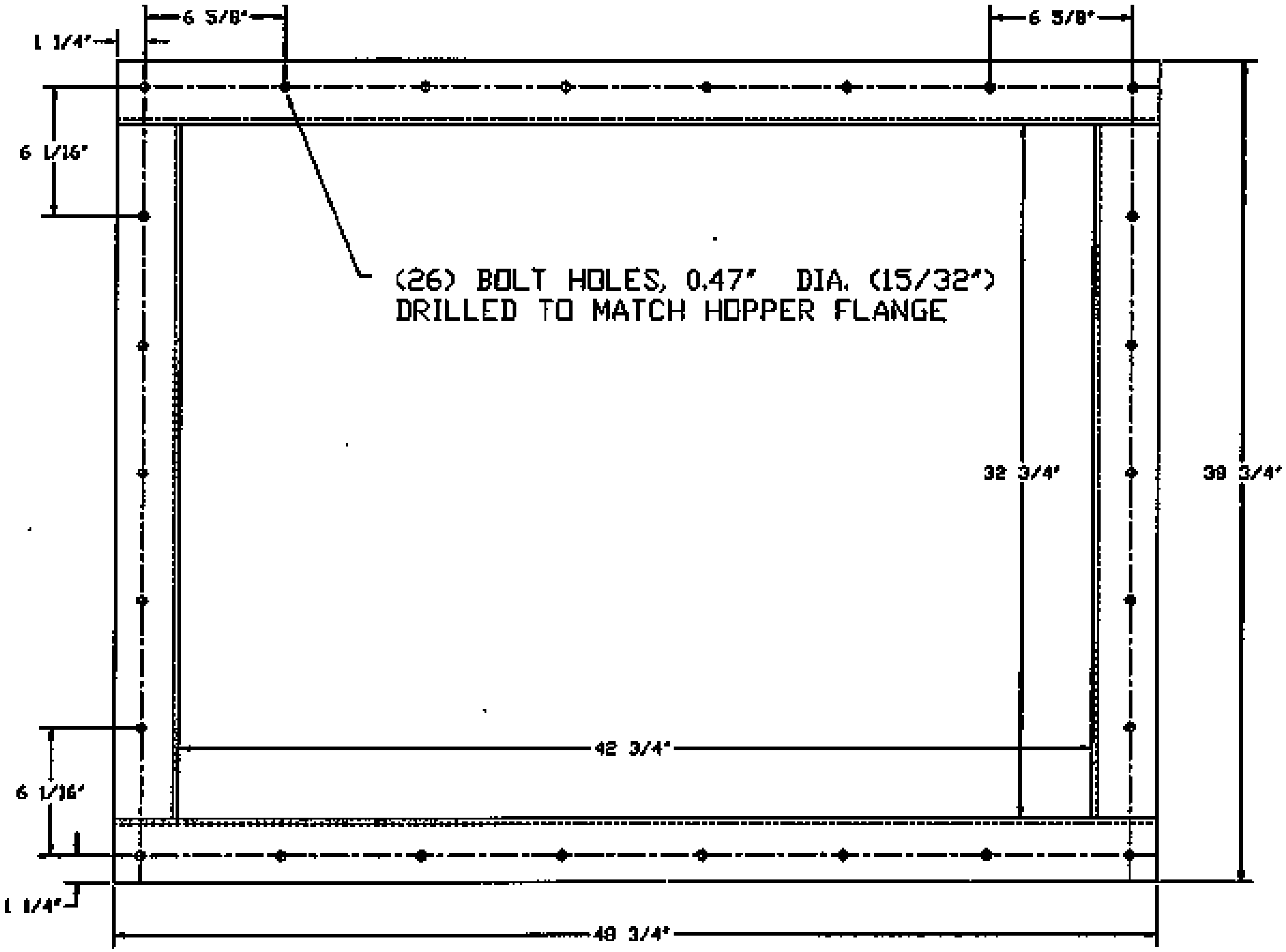
FILENAME: \PULSE\PJBH-01



MATERIAL OF CONSTRUCTION:
3"x3"x1/4" 304LSS ANGLE IRON

ENERGY AND ENVIRONMENTAL
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PULSE-JET BAGHOUSE CHAMBER
BOTTOM FLANGE

DATE
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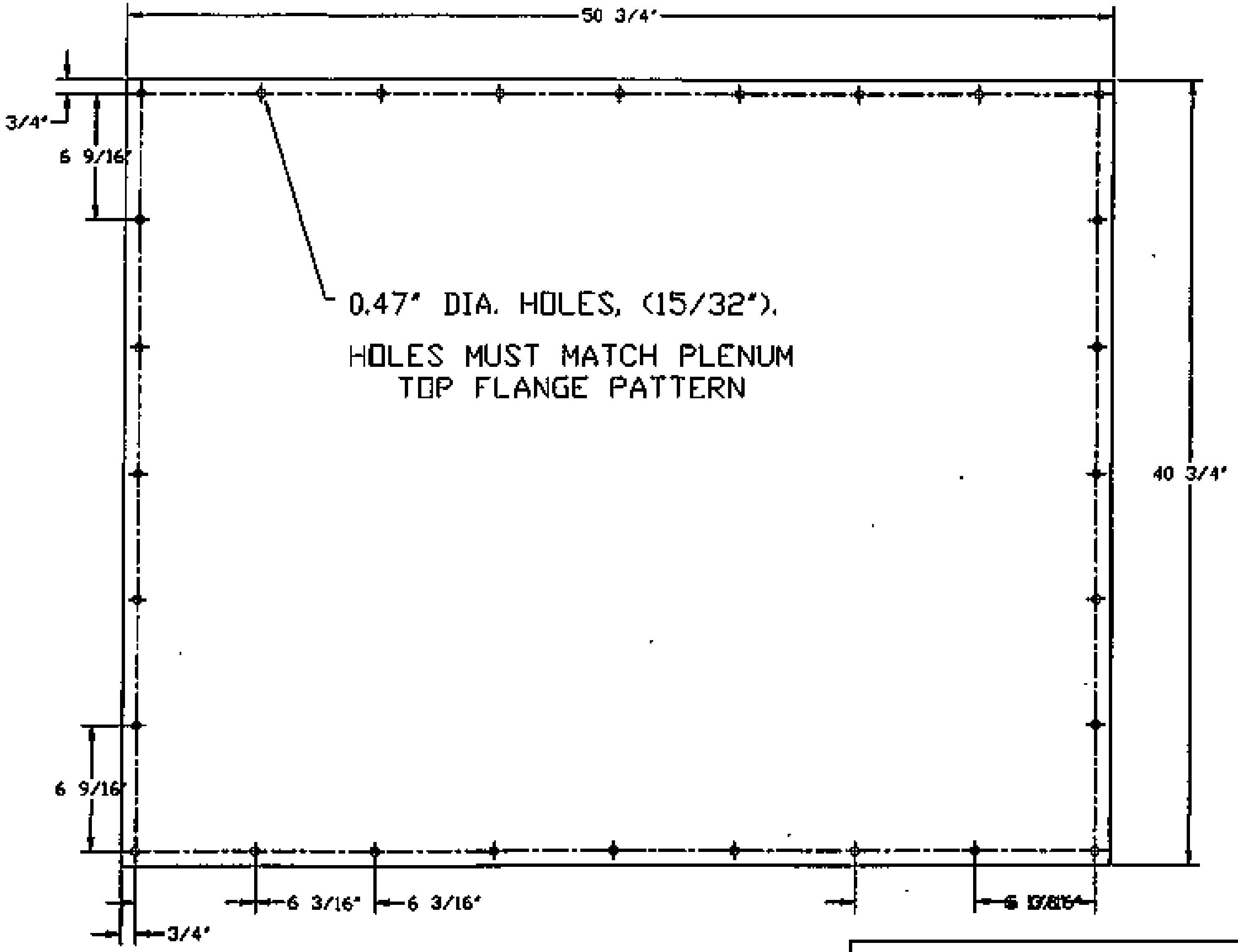

MATERIAL OF CONSTRUCTION:
3/16" 304L SS PLATE

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PULSE-JET BAGHOUSE
PLENUM TOP PLATE

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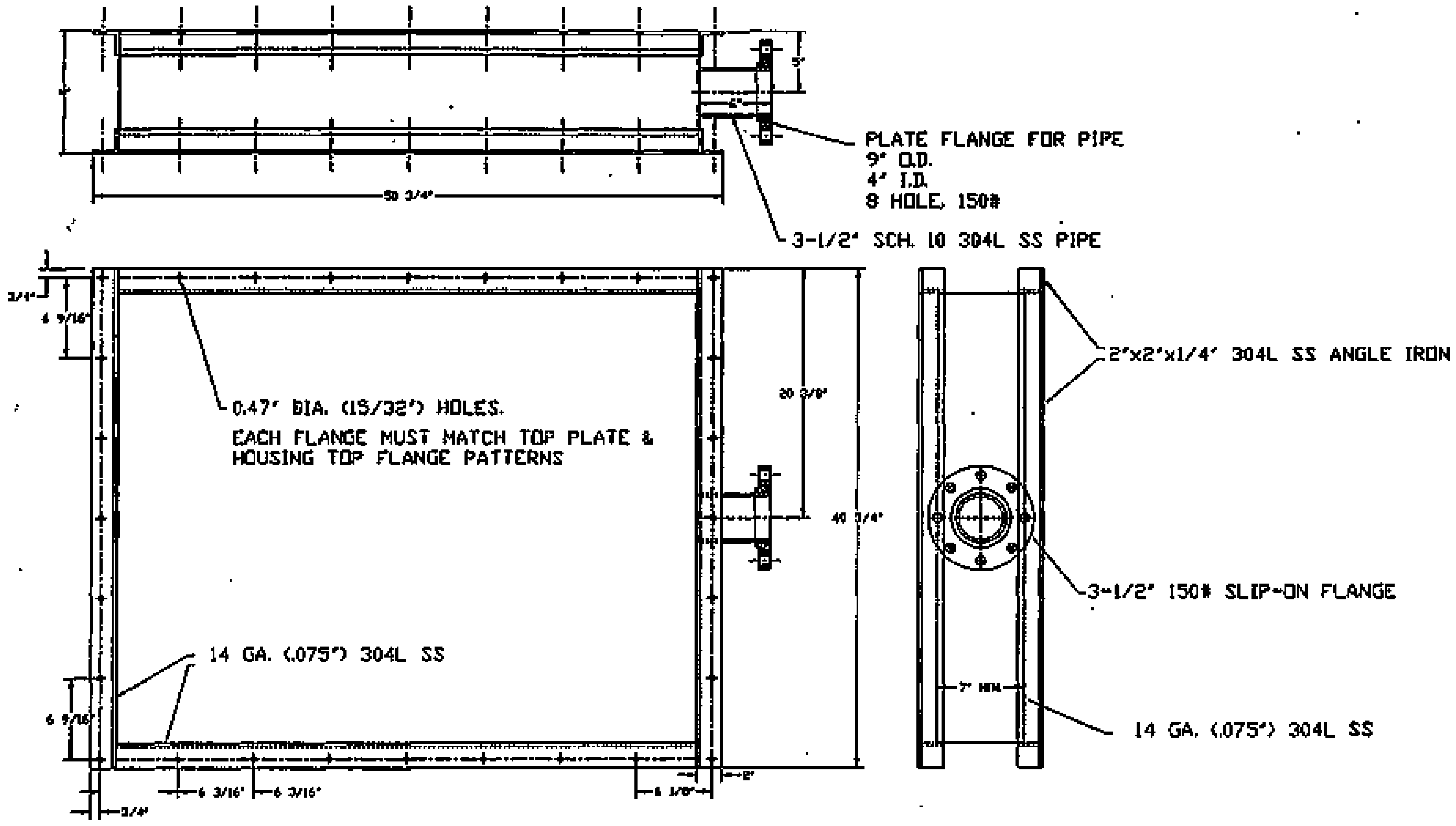

NOTES:

WELD AIR TIGHT

TOLERANCES ± 1/8"

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PULSE-JET BAGHOUSE
CLEAN AIR PLENUM

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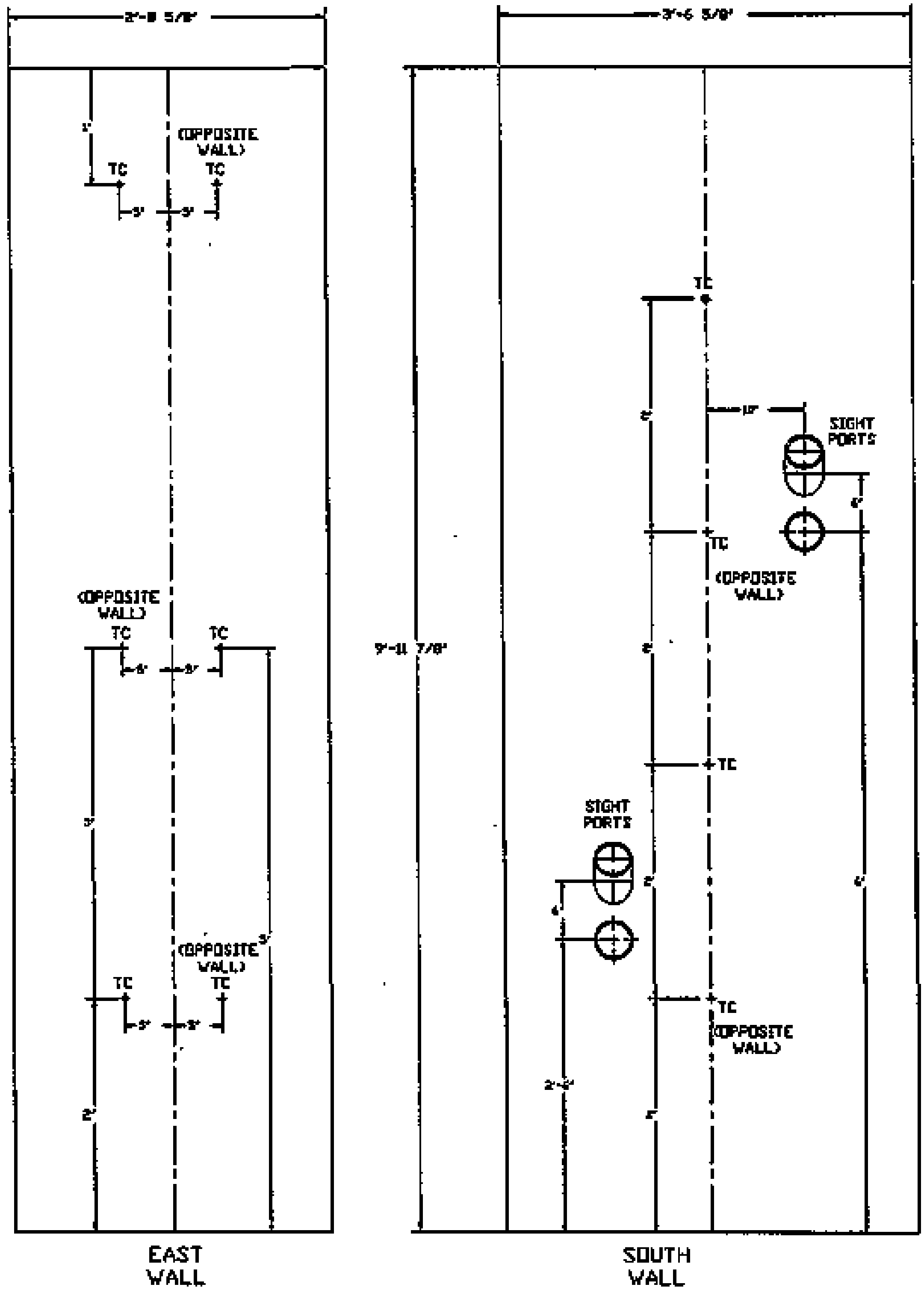

NOTES:

MATERIAL: 14 GA. 304L SS, (2) EACH

SIGHT PORTS ARE 4" O.D.

USE 1/4" SCH. 40 PIPE COUPLINGS
FOR THERMOCOUPLES (TC)

FILENAME: \PULSE\PJBH-05

ENERGY AND ENVIRONMENTAL
RESEARCH CENTER

PULSE-JET BAGHOUSE
CHAMBER WALLS

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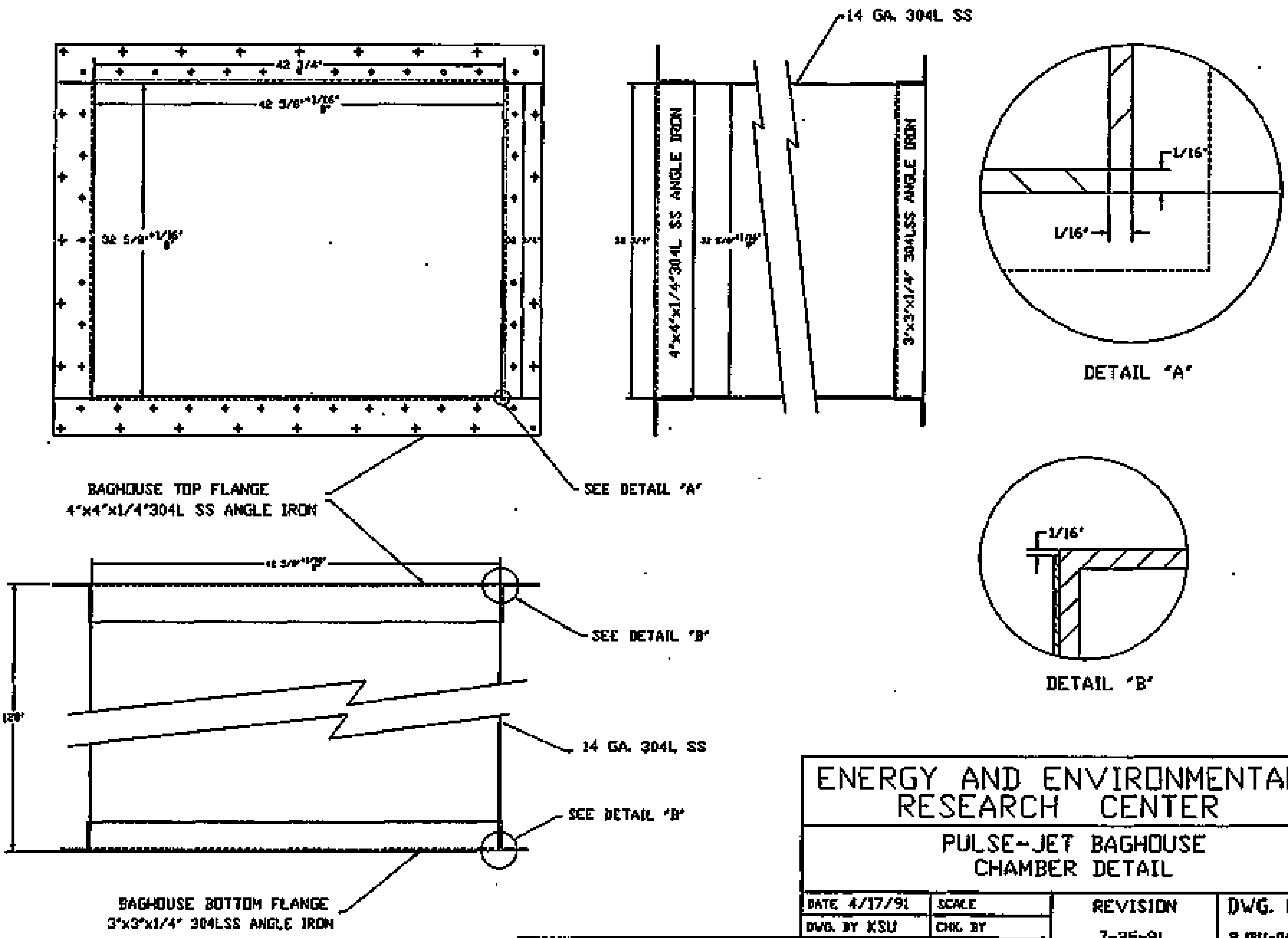

ENERGY AND ENVIRONMENTAL
RESEARCH CENTER

PULSE-JET BAGHOUSE
CHAMBER DETAIL

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SHEET 6 OF ___			

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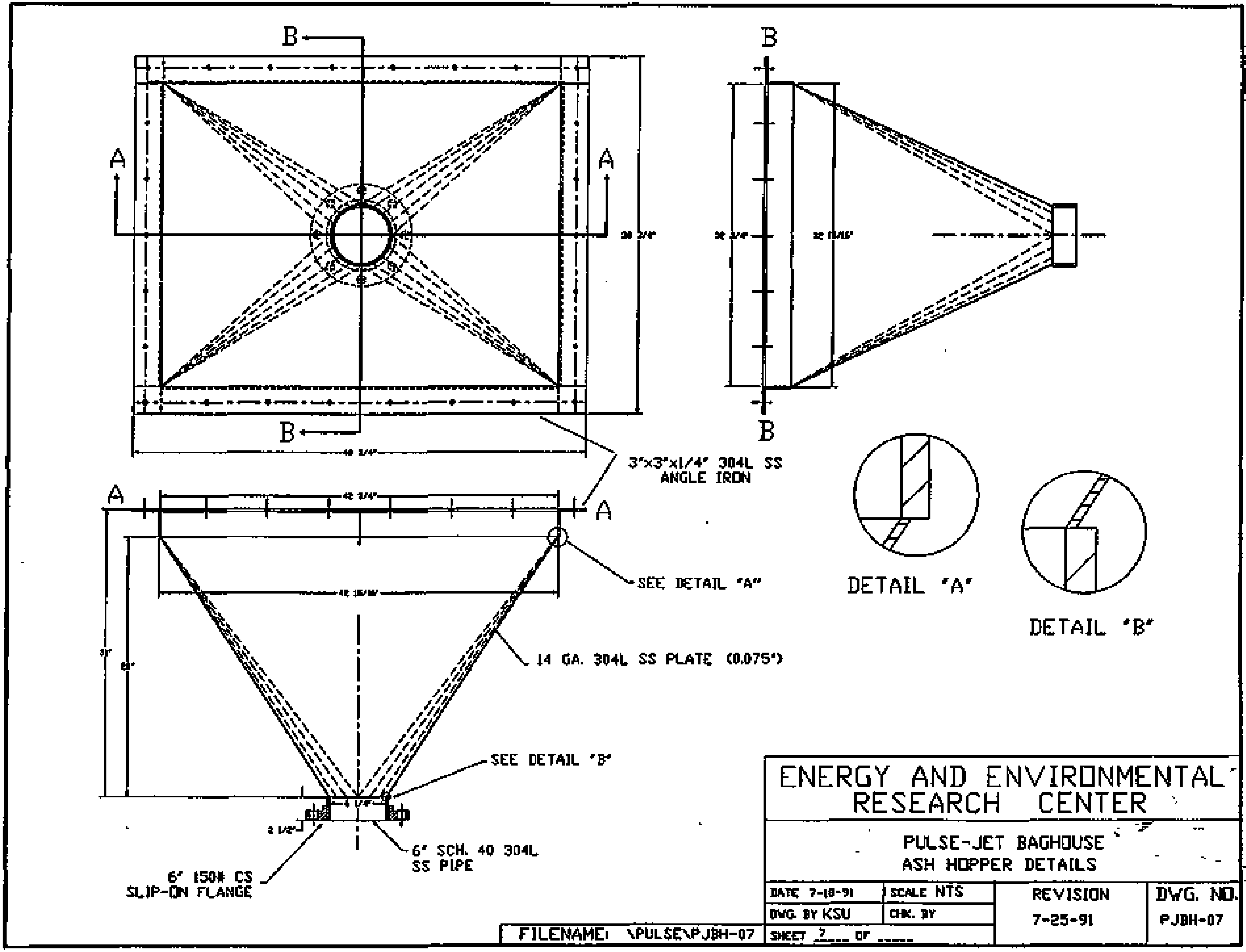

ENERGY AND ENVIRONMENTAL
RESEARCH CENTER

PULSE-JET BAGHOUSE
ASH HOPPER DETAILS

DATE 7-18-91	SCALE NTS	REVISION	DWG. NO.
DWG. BY KSU	CHK. BY	7-25-91	PJBH-07
SHEET 7 OF ____			

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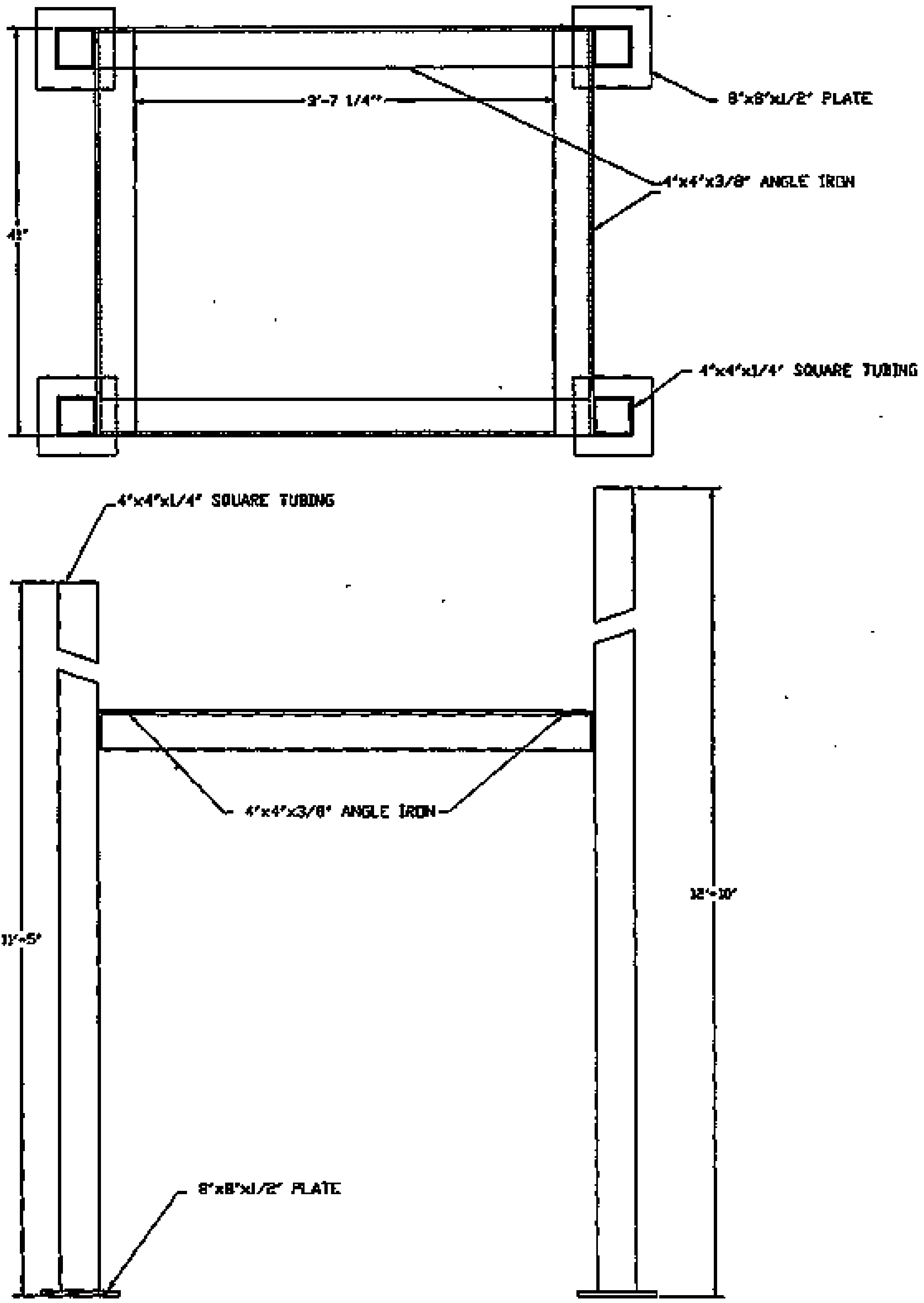

ENERGY AND ENVIRONMENTAL RESEARCH CENTER

PULSE-JET BAGHOUSE
SUPPORT STAND

DATE 7-[illegible]
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CHK. BY
SHEET 1 OF
REVISION 7-25-91
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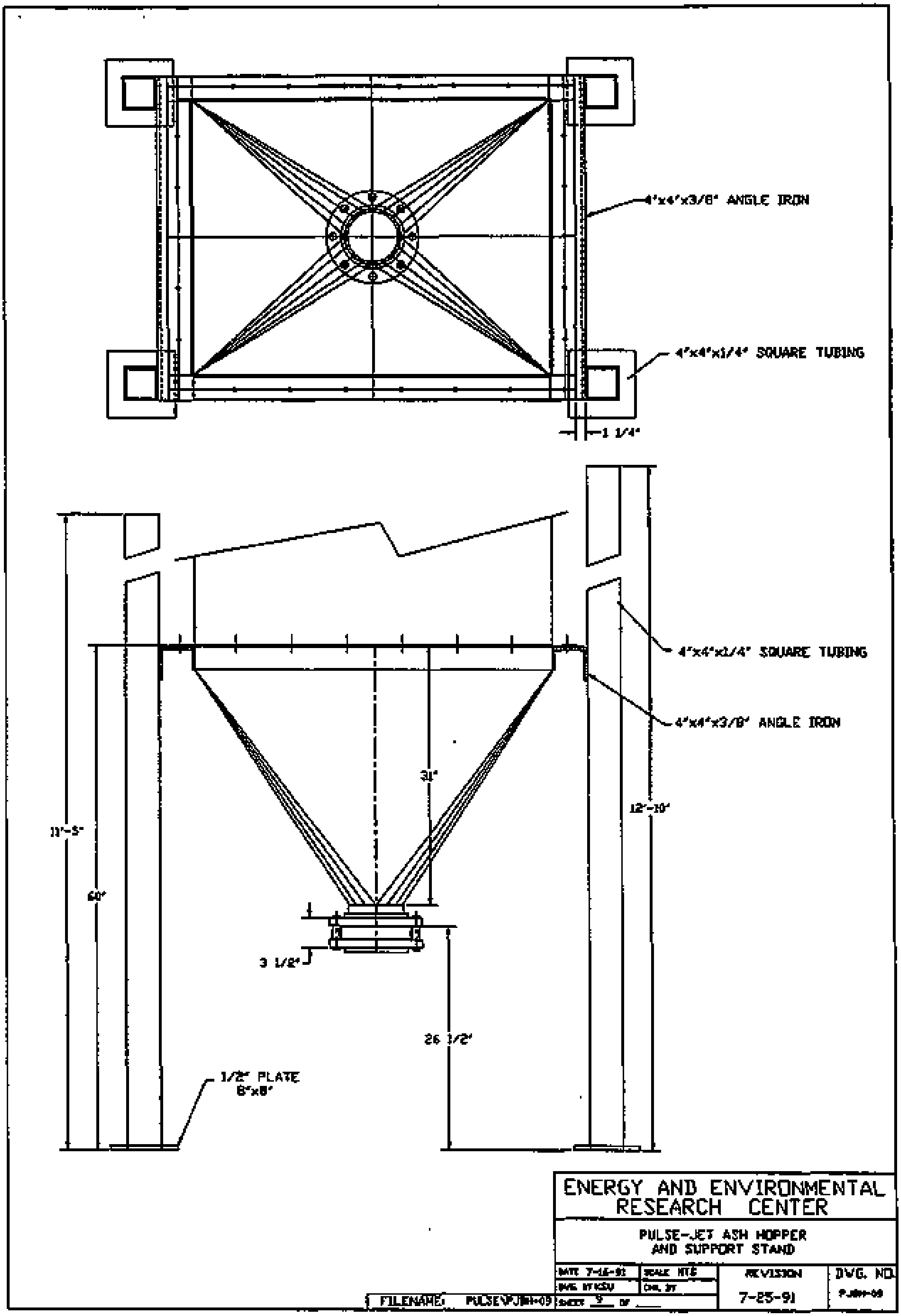
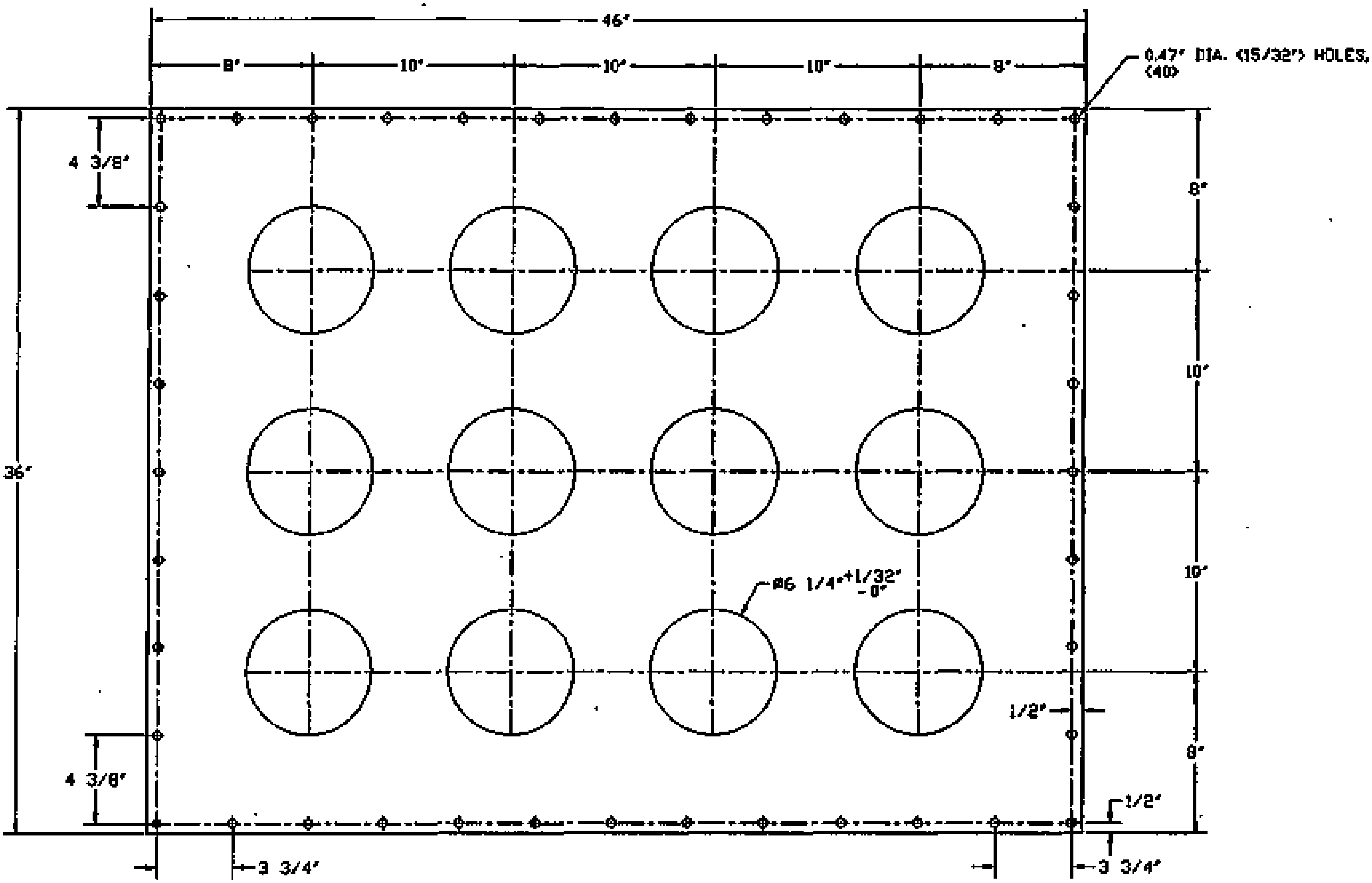

4"x4"x3/8" ANGLE IRON
4"x4"x1/4" SQUARE TUBING
1 1/4"
4"x4"x1/4" SQUARE TUBING
4"x4"x3/8" ANGLE IRON
31"
12'-10"
11'-5"
60"
3 1/2"
26 1/2"
1/2" PLATE
8"x8"
ENERGY AND ENVIRONMENTAL
RESEARCH CENTER
PULSE-JET ASH HOPPER
AND SUPPORT STAND
DATE 7-16-91
SCALE NTS
DWG. BY KSU
CHK. BY
SHEET 9 OF
REVISION
7-25-91
DWG. NO.
PJBH-09
FILENAME: PULSE\PJBH-09



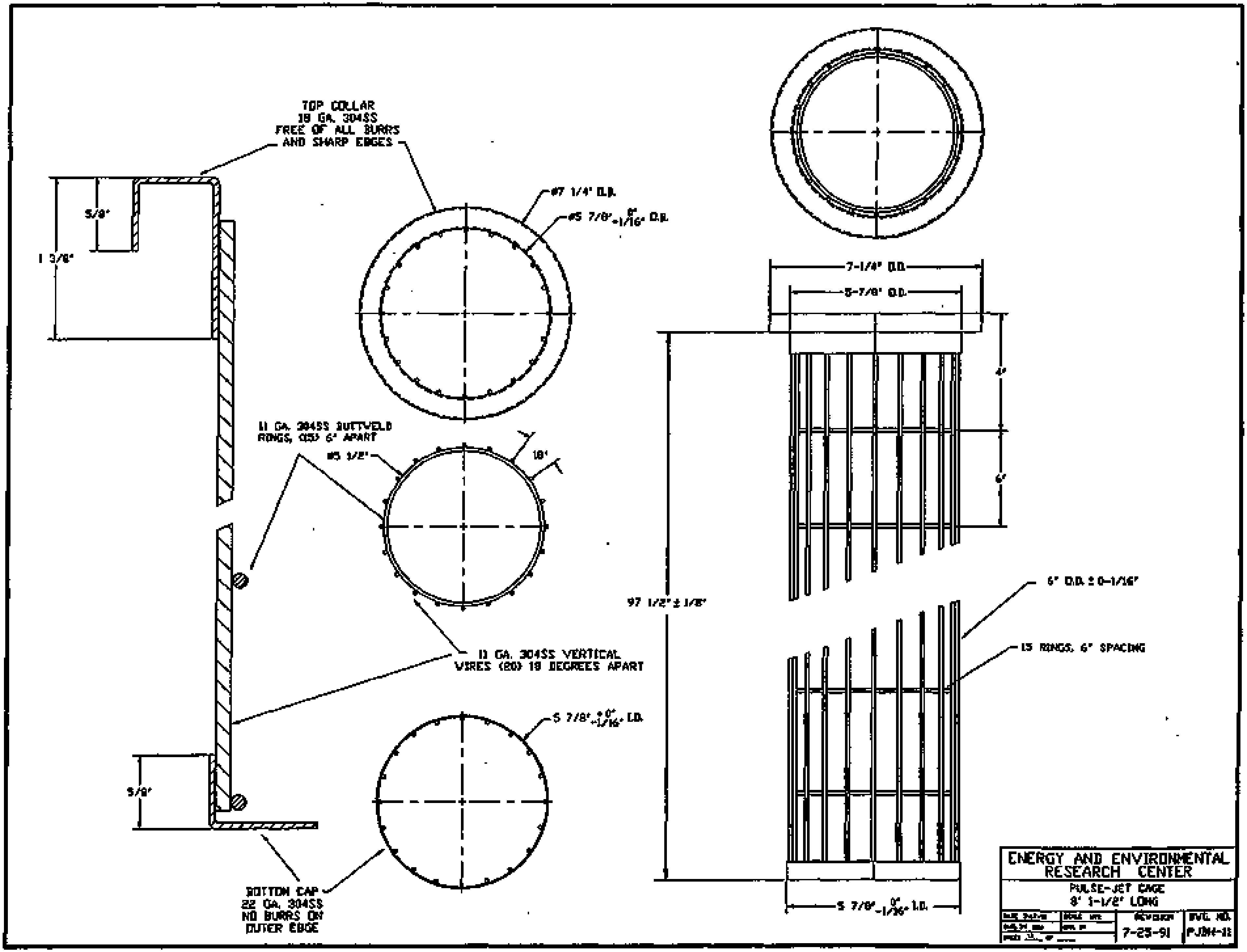
MATERIALS OF CONSTRUCTION:
3/16" 304L SS PLATE

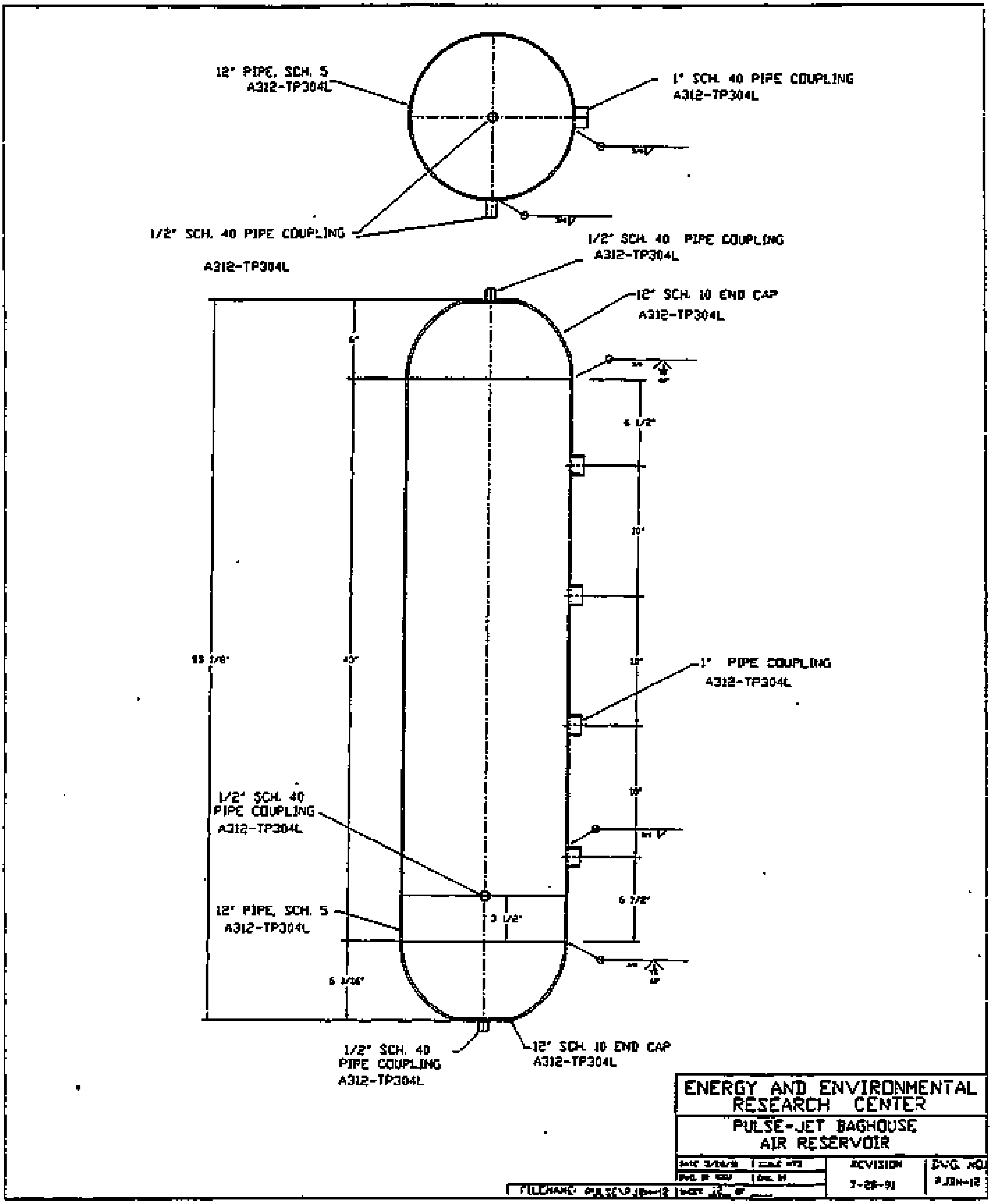
ENERGY AND ENVIRONMENTAL
RESEARCH CENTER

PULSE-JET BAGHOUSE
TUBE SHEET

DATE 7-16-91	SCALE NTS	REVISION	DWG. NO.
DWG. BY KSU	CHK. BY	7-25-91	PJBH-10
SHEET 10 OF ____			

FILENAME: \PULSE\PJBH-10


TOP COLLAR
18 GA. 304SS
FREE OF ALL BURRS
AND SHARP EDGES
5/8"
1 3/8"
#7 1/4" O.D.
#5 7/8" +0" -1/16" O.D.
11 GA. 304SS BUTTWELD
RINGS, (15) 6" APART
#5 1/2"
18°
11 GA. 304SS VERTICAL
WIRES (20) 18 DEGREES APART
5 7/8" +0" -1/16" I.D.
5/8"
BOTTOM CAP
22 GA. 304SS
NO BURRS ON
OUTER EDGE
7-1/4" O.D.
5-7/8" O.D.
4"
6"
97 1/2" ± 1/8"
6" O.D. ± 0-1/16"
15 RINGS, 6" SPACING
5 7/8" -0" -1/16" I.D.
ENERGY AND ENVIRONMENTAL
RESEARCH CENTER
PULSE-JET CAGE
8' 1-1/2" LONG
REVISION
7-25-91
DWG. NO.
PJBH-13



ENERGY AND ENVIRONMENTAL
RESEARCH CENTER

PULSE-JET BAGHOUSE
AIR RESERVOIR

REVISION
7-28-91

DWG. NO.
PJBH-12

FILENAME: PULSE\PJBH-12

APPENDIX B

DESCRIPTION OF BAGHOUSE SLIPSTREAM SYSTEM AND PROCEDURES

B-i No folio

DESCRIPTION OF BAGHOUSE SLIPSTREAM SYSTEM AND PROCEDURES

The baghouse slipstream system consists of the following eight major components: 1) UND steam plant Boiler No. 7, 2) a particle knockout device, 3) a pneumatic ash injection system, 4) a baghouse, 5) catalyst-coated filter bags, 6) four water-cooled heat exchangers, 7) an induced-draft (ID) fan, and 8) system instrumentation. Individual component design and operating characteristics are described in the following paragraphs, as well as particulate sampling and analytical procedures used during the bag durability test. Figure B-1 is a conceptual illustration of the baghouse slipstream system.

UND STEAM PLANT BOILER

The UND steam plant boiler (Boiler No. 7) is a spreader-stoker boiler designed to produce 72,750 lb/hr (33,000 kg/hr) of steam at 355°F (180°C) and 140 psig (896 kPa). This boiler was designed and built by Zurn Industries, Inc., in 1978. Typical operation of this boiler results in load swings from 20,000 to 100,000 lb/hr (9080 to 45,400 kg/hr) of steam to support the University's heating and cooling systems. This boiler typically operates from October 1 to May 15 of each year.

A western subbituminous coal was fired in the UND steam plant boilers. Fly ash produced in the boiler is mechanically collected at the ID fan inlet by a multicyclone. Fly ash from 20% of the flue gas is also collected in a conventional pulse-jet fabric filter. The minimal instrumentation on the boiler consists of devices to measure system static and differential pressures, flue gas temperatures at various locations, and steam-side temperatures, pressures, and flow rates.

PARTICLE KNOCKOUT DEVICE

A particle knockout device was installed upstream of the slipstream pulse-jet baghouse to remove +100-mesh (+147-μm) ash and uncombusted carbon particles from the flue gas stream. Previous particulate sampling at the location in Boiler No. 7 from which the flue gas slipstream was to be removed indicated that 40–45 wt% of the +100-mesh (+147-μm) particles was carbon. Removal of these particles upstream of the baghouse was deemed necessary to minimize the potential for carbon burnout in the hot-side baghouse. Installation of the particle knockout device reduced the carbon content of the fly ash entering the baghouse from about 25%–30% to <15% by weight. The particle knockout device is illustrated in Figure B-2.

The design is relatively simple and minimizes additional system pressure drop. Flue gas velocity is decreased by increasing the cross-sectional area of the flow path from 0.10 to 0.38 ft^2 (0.009 to 0.035 m^2). This increase in flow path area results in a decrease in flue gas velocity from roughly 75 to 20 ft/sec (23 to 6 m/sec). Reducing the flue gas velocity allows the +100-mesh (+147-μm) particles to settle out of the flow path, impact the downstream wall, and settle into the hopper. As a contingency, an adjustable deflector plate was installed in the particle knockout device to divert the flue gas flow path, increasing particulate impaction on the walls of the device and resulting in increased particulate fallout. Opposing sight ports were installed near the outlet of the particle

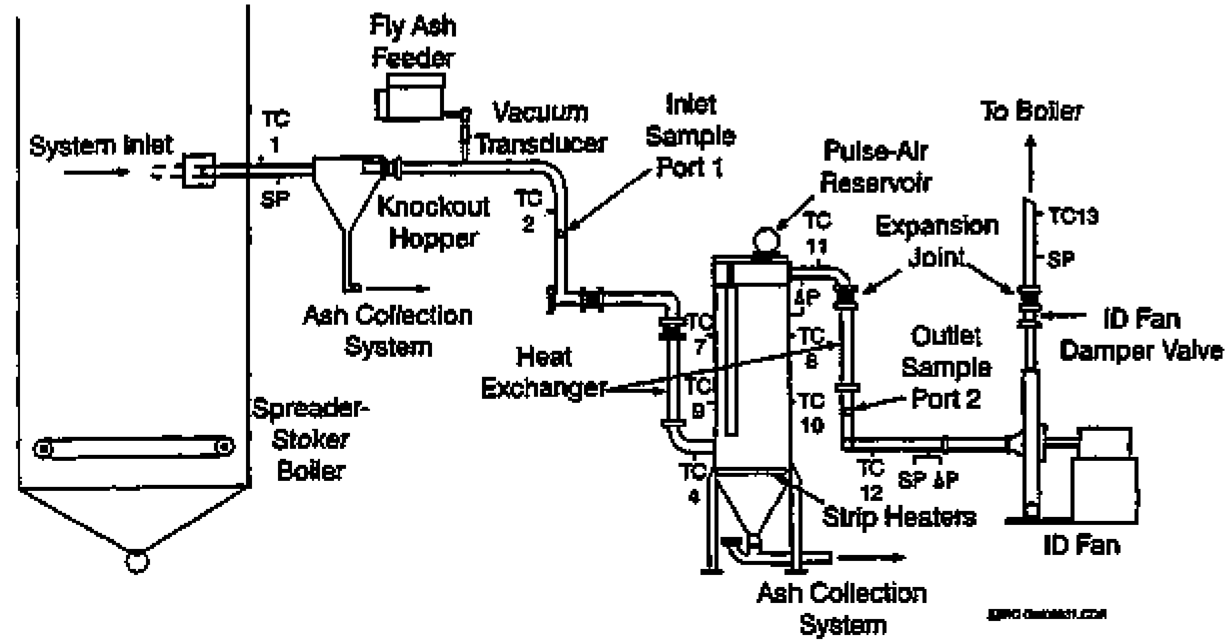


Figure B-1. Baghouse slipstream system.

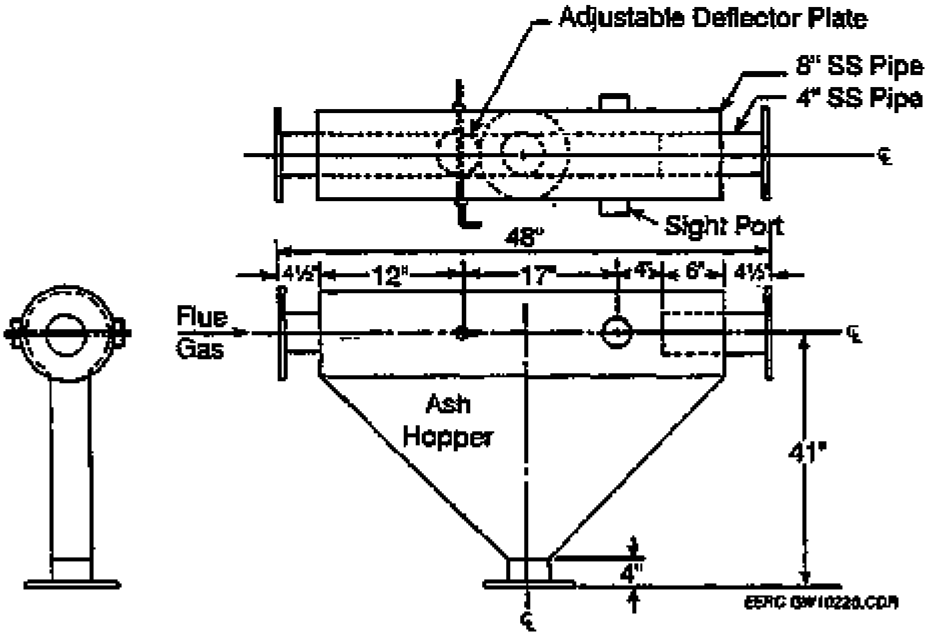


Figure B-2. Particle knockout device.

knockout device so that burning particulate entrained in the flue gas leaving the device could be visually monitored. The ash hopper of the particle knockout device was piped into the boiler's pneumatic ash-handling system, minimizing operator time required for ash dumping and eliminating direct ash handling. The operating temperature of the particle knockout device is about 1300°F (~705°C), requiring stainless steel construction and insulation of all exposed surfaces with the exception of flanges.

PNEUMATIC ASH INJECTION SYSTEM

The pneumatic ash injection system used to introduce supplemental ash into the flue gas slipstream consisted of two primary components: the volumetric feeder and the air-operated vacuum pump. Figure B-3 illustrates the basic system components. Ash was injected into the flue gas slipstream immediately downstream of the particulate knockout device. An Acrison Inc. Model 105 volumetric feeder was used. The feeder was electrically driven using a 50:1 gear ratio and a 0.73-in. (18.5-cm) solid-core screw. Based on an ash density of 100 lb/ft^3 (1603 kg/m^3), feed rate capacity ranged from 1.6 to 81.0 lb/hr (0.7 to 36.8 kg/hr). The volumetric feeder hopper was modified to increase its capacity from 1.8 to 5.7 ft^3 (0.05 to 0.16 m^3) to minimize refilling requirements.

An air-operated vacuum pump, Model TDHR 880M manufactured by AIR-VAC Inc., was used to disperse fly ash particles into the flue gas slipstream. The air-operated vacuum pump employed compressed air entering through an annular orifice, which resulted in a straight-through vacuum passage and permitted solids to pass directly through the pump with no directional change or reduction of vacuum flow. Figure B-3 illustrates this specific vacuum pump design.

Solids were discharged from the vacuum pump into a 0.5-in. (1.3-cm) stainless tube through which the solids were injected concurrently into the flue gas slipstream. Total exhaust air from the vacuum pump amounted to about 8 scfm (0.2 m^3/min).

BAGHOUSE

The baghouse for the slipstream was designed and built by Donaldson Company, Inc., and is illustrated in Figure B-4. Materials of construction are primarily stainless steel because of baghouse operating conditions. Baghouse design permits operation at temperatures of up to 1000°F (538°C) and flue gas flow rates of 680 acfm (19.2 m^3/min). The baghouse is a single compartment housing nine bags, each 0.5 ft (0.15 m) in diameter by 8 ft (2.4 m) long. Total bag filtration area is 113 ft^2 (10.5 m^2).

The bags and stainless steel cages are accessed through a 2.3- x 8.7-ft (0.70- x 2.65-m) door in one wall or by removing the clean air plenum at the top of the baghouse. Electric heaters are located just above the baghouse ash hopper to prevent moisture condensation during start-up and nonoperational periods.

Pulse-jet cleaning can be triggered as a function of baghouse differential pressure (ΔP) or time. During Subtask 3.4, filter bag cleaning was performed as a function of baghouse ΔP. The baghouse pulse-jet cleaning system is operated by a programmable controller that controls cleaning frequency and pulse duration. Clocks and counters in the

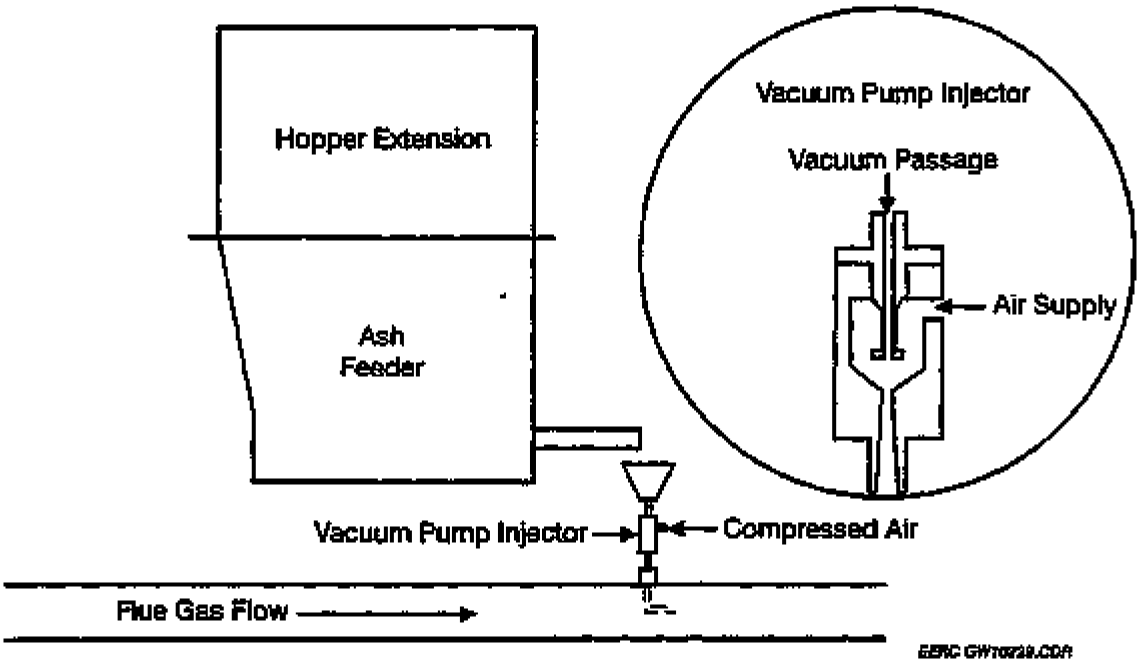


Figure B-3. Illustration of ash injection system.

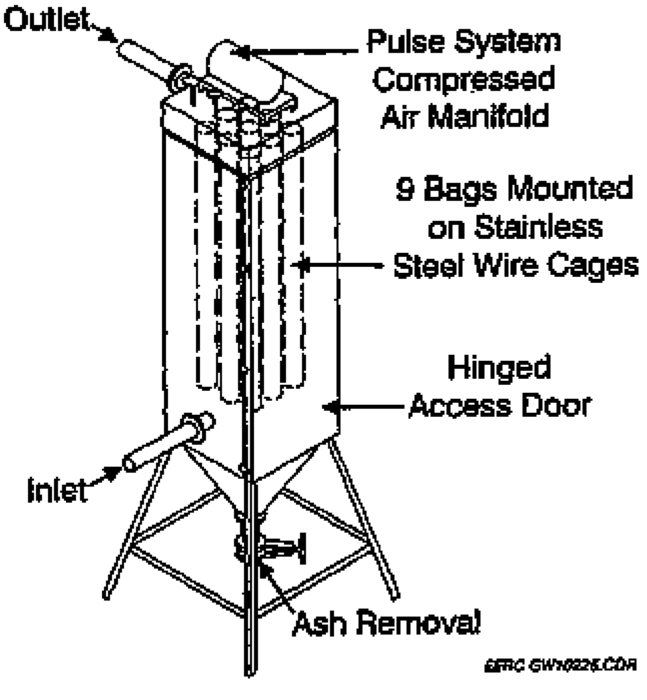


Figure B-4. High-temperature pulse-jet baghouse.

controller display total system operating time and test time in hours, total cleaning cycles, and test cleaning cycles. Filter bag cleaning occurs when the programmable controller opens solenoid-operated valves between the pulse-air manifold and the three filter bag blowpipes. Each blowpipe contains three pulse-air orifices, one located over each individual bag. Figure B-5 illustrates the pulse-jet component configuration for the baghouse. Three filter bags are cleaned simultaneously with a short delay between each set of three filter bags to allow air pressure to recover in the pulse-air manifold. Air pressure in the manifold was nominally 43 psig (297 kPa). Manifold pressures of as much as 100 psig (690 kPa) are possible. At a nominal pulse-air manifold pressure of 43 psig (297 kPa), a pulse-air volume of approximately 0.91 scf (0.03 m^3) is discharged to each set of three bags during a cleaning cycle. Actual pulse pressures are quite low, ~3 psig (21 kPa), because of a large pressure loss across the solenoid-operated valves. Pulse pressure and volume at each pulse-air orifice appear to be uniform.

Baghouse ash removal is accomplished by opening a 0.5-ft (0.15-m) knife valve at the bottom of the hopper to allow pneumatic transfer via Boiler No. 7's ash-handling system. Access to the pneumatic transfer line below the baghouse ash hopper is possible, facilitating collection of ash samples.

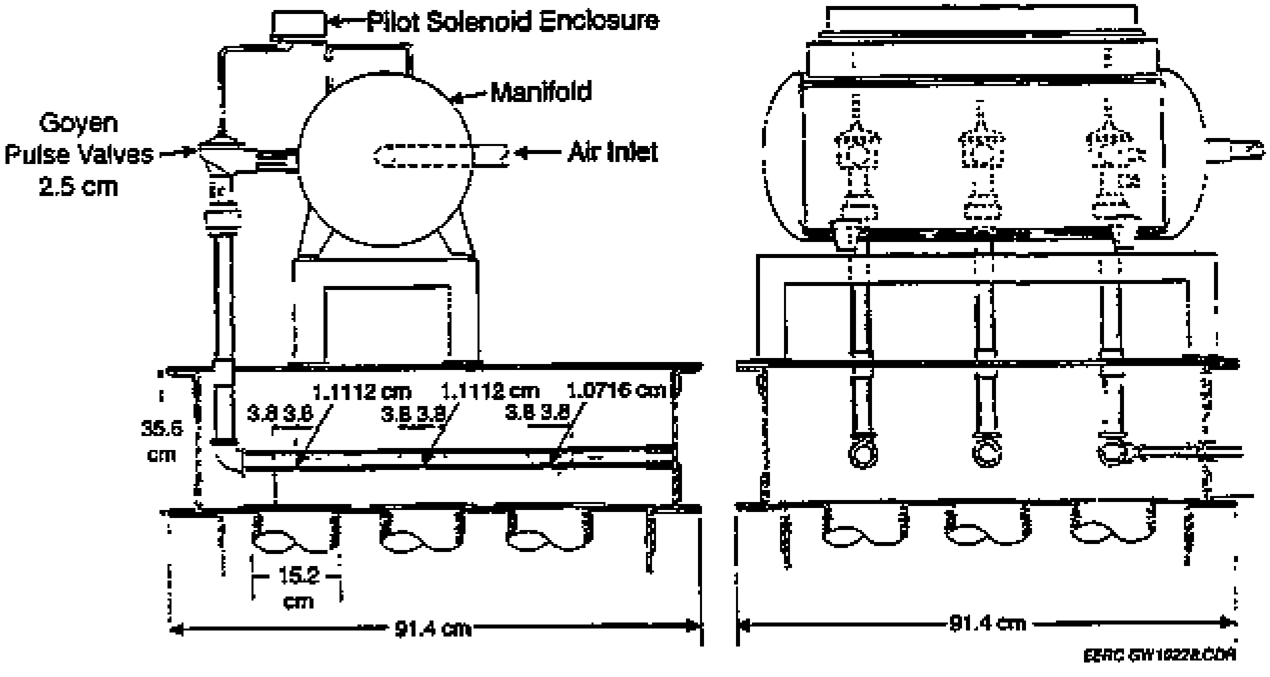


Figure B-5. Baghouse pulse-jet component configuration.

CATALYST-COATED FILTER BAGS

The catalyst-coated bags installed in the slipstream baghouse had been previously used during a 100-hr pilot-scale pulse-jet test (PTC-BV-429) in support of Subtask 3.3. Nine of the twelve bags used during the 100-hr test were installed in the slipstream baghouse, with the remaining three bags available as spares for periodic bag replacement. The bags installed were 0.5 ft (0.15 m) in diameter and roughly 8.25-ft (2.51-m) long. These filter bags were prepared using a high-temperature woven glass (S2-glass) composed of DE-fibers (6.5 micron) having a fabric weight of 22 oz/yd^2 (746 g/m^2) (DE992 fabric). Seven coats of a vanadium–titanium catalyst were applied to the fabric using an organic-based process, corresponding to Fabrics 17 and 106B in previous bench-scale tests. Each bag was constructed using a sewn vertical seam and sewn cuffs on the top and bottom. The rolled, top cuff was 2.5 in. (6.35 cm) wide and contained a snap-band for securing the bag to the tube sheet. The bottom cuff was also 2.5 in. (6.35 cm) wide and provided a disc closure on the bottom of the bag and a cage wear strip.

Filter bag installation was accomplished using a standard snap-band closure that secured each bag to the tube sheet. The bags were supported by stainless steel wire cages. Each cage was constructed using 20 vertical wires and a ring spacing of roughly 6 in. (15.24 cm). The top collar was a rolled channel which protected the top of the bag cuff and supported the cage on the tube sheet. A solid cap secured the bottom of each cage, and all cage components were welded.

WATER-COOLED HEAT EXCHANGERS

Flue gas cooling prior to the ID fan was necessary to maintain control of overall system flue gas flow rates and to prevent overheating of the ID fan. Maximum operating temperature for the ID fan is 600°F (316°C), as specified by the manufacturer. Therefore, flue gas temperature is reduced 150°–400°F (83°–222°C), depending on flue gas flow rates and baghouse temperature, prior to entering the ID fan. Four water-cooled annular heat exchangers are situated upstream of the ID fan at the following locations: 1) the particle knockout device exit, 2) the baghouse inlet, 3) the baghouse exit, and 4) the ID fan inlet.

As a result of this arrangement, flue gas must pass through two heat exchangers prior to its entering the baghouse and two additional heat exchangers prior to entering the ID fan whether the baghouse is on-line or has been bypassed. The water flow rate through each heat exchanger is typically <1.0 gpm (<3.8 L/min). Heat-exchanger surface area totals 32.9 ft^2 (3.0 m^2). Of the total heat-exchanger area, 6.7 ft^2 (0.7 m^2) was added upstream of the baghouse to provide more flue gas cooling prior to initiating Subtask 3.4.

INDUCED-DRAFT FAN

The ID fan on the baghouse slipstream system is a Chicago Blower centrifugal fan. Fan capacity is 560 ft^3/min at 600°F and 48.5-in. W.C. (15.8 m^3/min at 316°C and 12.2 kPa). The fan is powered by a direct-drive 7.5-hp (5.6-kW) motor operating at 3500 rpm. Flue gas flow rate through the fan is controlled by a 4-in. (10.2-cm) butterfly valve located downstream of the fan. Flue gas from the baghouse slipstream system is then dumped back into the Boiler No. 7 flue gas ducts upstream of the Boiler No. 7 multicyclone and ID fan.

INSTRUMENTATION

Instrumentation on the baghouse slipstream system is limited to that necessary to monitor and record temperatures, static and differential pressures, cooling water flow rates, ID fan vibration, and ID fan amperage. Thermocouples (TCs) are located at sixteen points in the baghouse slipstream system. Eleven TCs monitor flue gas temperature and five monitor water temperature in the cooling system. Of the eleven flue gas TCs, four are located upstream of the baghouse, four are located in the baghouse, and three are located downstream of the baghouse. The baghouse TCs penetrate the walls of the baghouse and are placed vertically and horizontally in such a way as to produce a baghouse temperature profile on the dirty-gas side. All TC values are automatically logged on an incremental time basis. Table B-1 presents Kaye data logger numbers for each TC, a description of TC locations, and operational limits established for each.

Three static and two differential pressures are measured continuously on the baghouse slipstream system. Static pressures are measured at the inlet to the baghouse slipstream system, at the clean-gas side of the baghouse, and at the location where the annubar differential pressure is measured. Differential pressure is measured at the baghouse and downstream of the baghouse with an annubar. The annubar differential and static pressures and the flue gas temperature downstream of the baghouse are used to calculate flue gas flow rates. Flue gas flow rate is controlled by maintaining a constant annubar differential pressure using a motorized butterfly valve located downstream of the ID fan. Manual adjustments are made to the controller set point only when significant changes in boiler steam load (±10,000 lb/hr or 4540 kg/hr) occur. Table B-1 presents Kaye Data Logger numbers, a description of location and operational limits established for annubar and baghouse differential pressures, and baghouse and slipstream system static pressures.

A vibration monitor and an ammeter are used to monitor the operation of the ID fan. The vibration monitor measures displacement, activating an audible alarm at the first limit (0.002 in. or 0.006 cm) and shutting down the ID fan at the second limit (0.003 in. or 0.007 cm) to prevent equipment damage and potential injury to personnel.

PARTICULATE SAMPLING PROCEDURES

Three types of particulate sampling methods were employed during Subtask 3.4, a modified EPA Method 5, multicyclone, and real-time sampling with the TSI APS-33 system. A modified EPA Method 5 was the primary sampling technique used for determining baghouse efficiency and required sampling at both the baghouse inlet and outlet. Inlet particulate sampling with a modified EPA Method 5 sample train used a 30- to 60-min sampling period. Particulate sampling at the baghouse outlet generally consisted of a 2-hr sampling period. Wet SO_3 measurements were periodically conducted using a selective condensation technique.

TABLE B-1

Kaye Data Logger Channels

Kaye Data Logger No.	Data Source	Source Location	Maximum Limit
101	TC	Slipstream System Inlet	1700°F (927°C)
102	TC	Inlet EPA-5 Sample Port	1300°F (705°C)
103	TC	Baghouse Inlet Heat Exchanger Flue Gas Inlet	1100°F (594°C)
104	TC	Baghouse Flue Gas Inlet	750°F (399°C)
105	TC	Baghouse Inlet Heat Exchanger Cooling-Water Outlet	190°F (88°C)
106	TC	System Inlet Heat Exchanger Cooling-Water Outlet	190°F (88°C)
107	TC	Baghouse South Side, Top	725°F (385°C)
108	TC	Baghouse North Side, Top	725°F (385°C)
109	TC	Baghouse South Side, Bottom	725°F (385°C)
110	TC	Baghouse North Side, Bottom	725°F (385°C)
111	TC	Baghouse Flue Gas Outlet	725°F (385°C)
112	TC	ID Fan Flue Gas Inlet	575°F (302°C)
113	TC	ID Fan Flue Gas Outlet	550°F (288°C)
114	TC	Cooling-Water Inlet	Variable
115	TC	Baghouse Outlet Heat Exchanger Cooling-Water Outlet	190°F (88°C)
116	TC	Baghouse Bypass Heat Exchanger Cooling-Water Outlet	190°F (88°C)
201	Pressure Transducer	Annubar Differential Pressure	2.5 in. W.C. (0.6 kPa)
202	Pressure Transducer	Baghouse Differential Pressure	10 in. W.C. (2.5 kPa)
203	Pressure Transducer	Baghouse Static Pressure	20 in. W.C. (5.0 kPa)
204	Pressure Transducer	Slipstream System Inlet Static Pressure	20 in. W.C. (5.0 kPa)
205	Vibration Monitor	ID Fan Vibration	0.003 in. (0.007 cm)

Multicyclone sampling was conducted at the baghouse inlet to determine fly ash particle-size distribution. Particulate concentration at the baghouse outlet was too low to warrant multicyclone sampling. A five-stage Southern Research Institute (SoRI) multicyclone was used to collect size-fractionated samples to determine particle-size distributions. The SoRI multicyclone was used extractively; the sampling probe was heated, and the entire multicyclone was contained in an oven to prevent moisture condensation.

Real-time sampling with the TSI APS-33 sampling system was performed to generate emissions data before, during, and immediately after a cleaning cycle. The APS-33 laser particle sizer, manufactured by TSI Inc., can count and size particles in the 0.5–30-µm range. The primary advantages of this system are the high spatial resolution and the short sampling time. In the APS, particle-laden air is passed through a thin-walled orifice with the particles lagging behind the gas because of their higher inertia. The velocity lag is related to the aerodynamic diameter of the particles allowing the determination of the aerodynamic diameter of a particle by measuring the velocity of a particle as it exits from the orifice.

To measure the particle velocity, the APS employs a laser beam split into two beams and refocused onto two rectangular planes a certain distance apart in front of the orifice. The light scattered by a particle passing through these beams is collected and focused onto a photomultiplier tube which emits two pulses separated by the time taken for the particle to cross the distance between the two planes. This time interval is measured electronically and used to calculate the particle's aerodynamic diameter. The APS consists of two main components: the sensor and the microcomputer system. The sensor module consists of an accelerating orifice and laser velocimeter. The sensor is schematically shown in Figure B-6.

ANALYTICAL PROCEDURES

Fly ash samples were collected from the baghouse hopper and analyzed for loss on ignition (LOI), particle-size distribution, and major mineral oxides. LOI was performed using ASTM Method C618-72. Particle-size distributions were determined by Coulter counter and a dry sieve technique. Concentrations of major mineral oxides (Al, Si, Na, Mg, Ca, P, K, Fe, Ti, and S) were determined by x-ray fluorescence.

Catalyst-coated fabric durability was also measured as a function of fabric strength and folding endurance. Catalyst-coated fabric samples removed from the baghouse during Subtask 3.4 were evaluated for strength using the Mullen burst test, OCF Test Method S-13Ab, and for folding endurance using a modified MIT Flex test, OCF Test Method S-10Ga. The Mullen burst test was performed on five fabric samples from each of three bags removed from the slipstream baghouse. The bags represented 840, 1642, and 5136 hours of baghouse operation. The OCF Test Method S-13Ab is a modified version of ASTM D751-73, "Standard Method of Testing Coated Fabrics." The method is applied to textile materials with a thickness of <0.25 in. having a burst range of 50 to 2250 psig (Mullen points). The aperture burst area is 1.25 in. with a uniform pumping rate of 170 ± 15 mL/min. Fabric samples are cut to a size of 4 in. x 4 in. and conditioned for a minimum of 24 hours at a temperature of 70°F ± 2°F and a relative humidity of 65% ± 2% prior to testing. Burst pressure is increased at a uniform rate for each fabric sample until the sample ruptures. The data are reported to three significant figures as net bursting strength in psig.

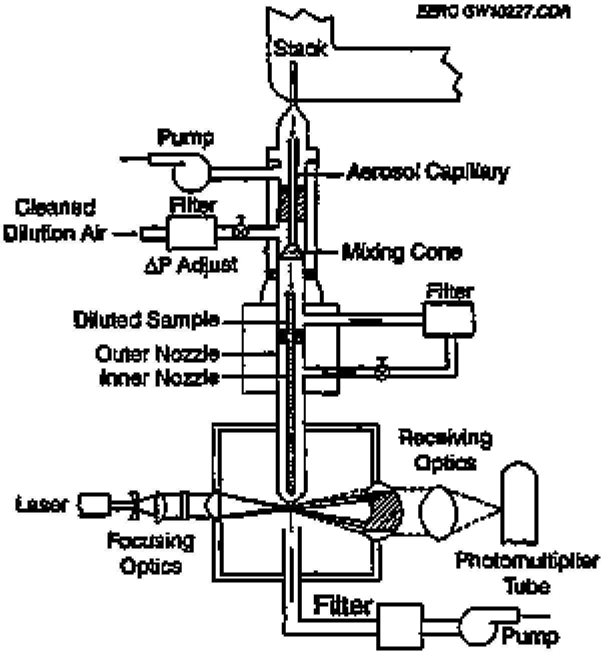


Figure B-6. APS-33 flow scheme and optics.

A modified folding endurance test was also performed on five fabric samples from each bag. The OCF Test Method S-10Ga is a modified version of ASTM Method D2176-69. This folding endurance method is applied to woven, nonwoven, and mat Fiberglas® products. Fabric samples are cut to a size of 0.5 in. x 6 in. and conditioned for a minimum of 24 hours at a temperature of 70°F ± 2°F and a relative humidity of 65% ± 2% prior to testing. Each fabric sample was repeatedly folded through an angle of 180° with a 4-lb tensional force applied at a uniform rate of 175 ± 25 cycles per minute. The test was concluded when the fabric sample failed and data reported as cycles to failure.

APPENDIX C

SUPPORTING EXPERIMENTAL DATA

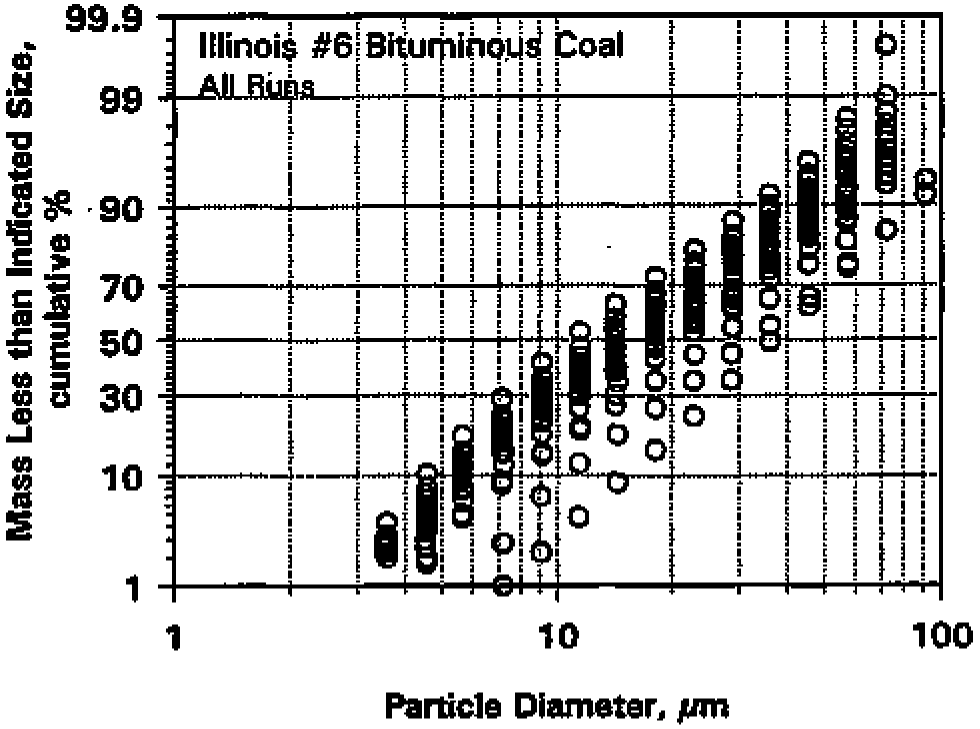


Figure C-1. Coulter counter data for baghouse hopper ash when Illinois No. 6 bituminous coal was fired, 100-hr tests.

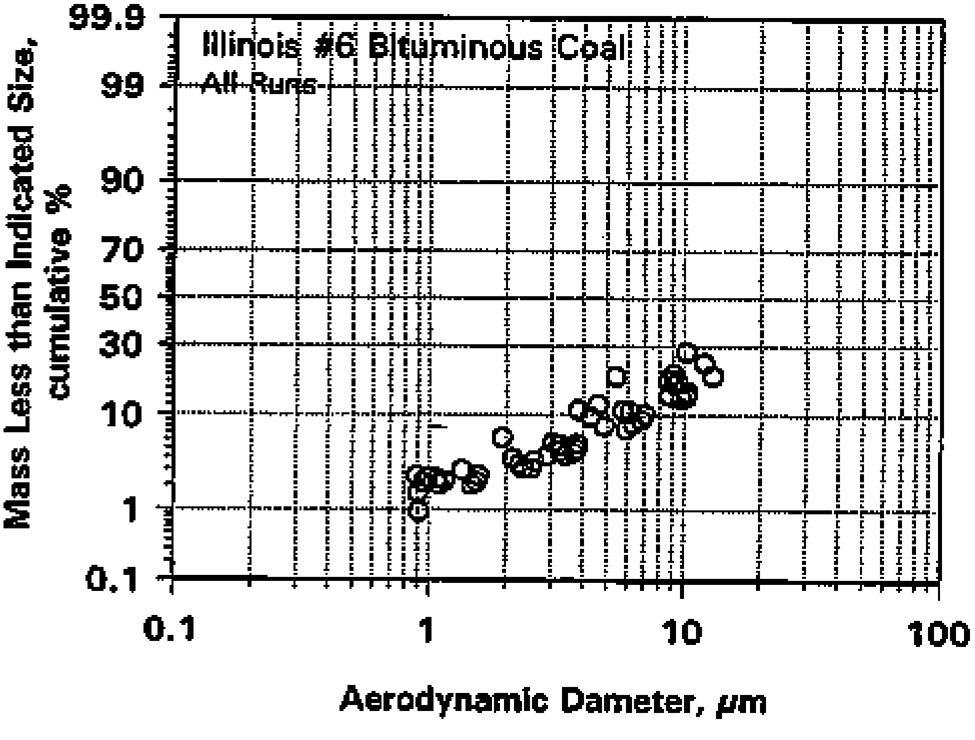


Figure C-2. Multicyclone data for Illinois No. 6 bituminous coal fly ash, 100-hr tests.

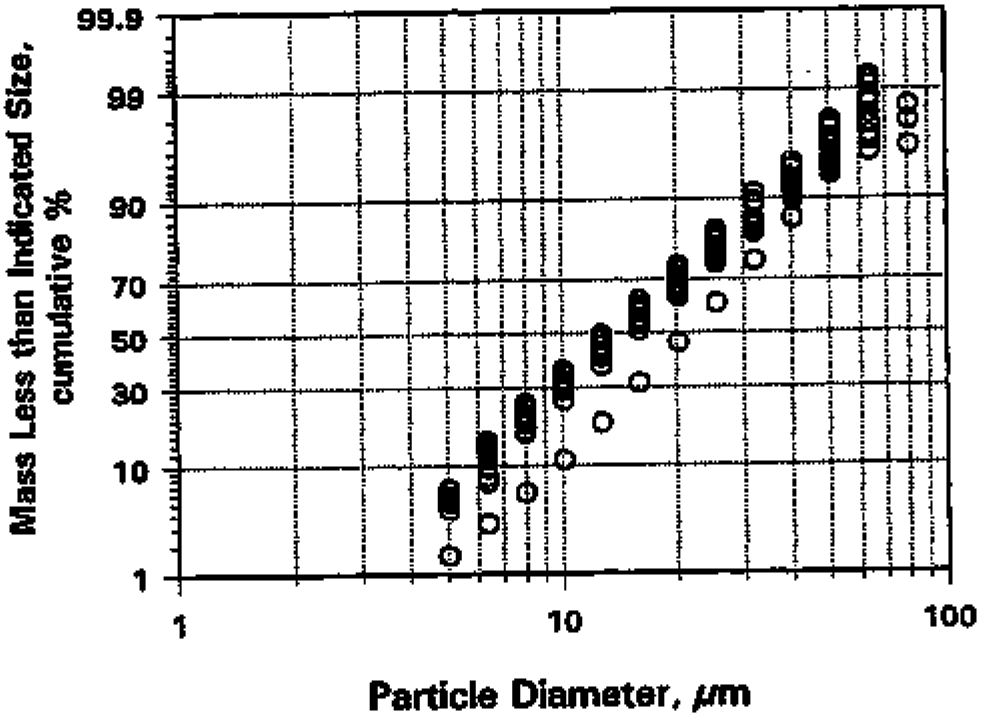


Figure C-3. Coulter counter data for baghouse hopper ash when Blacksville bituminous coal was fired, 100-hr test.

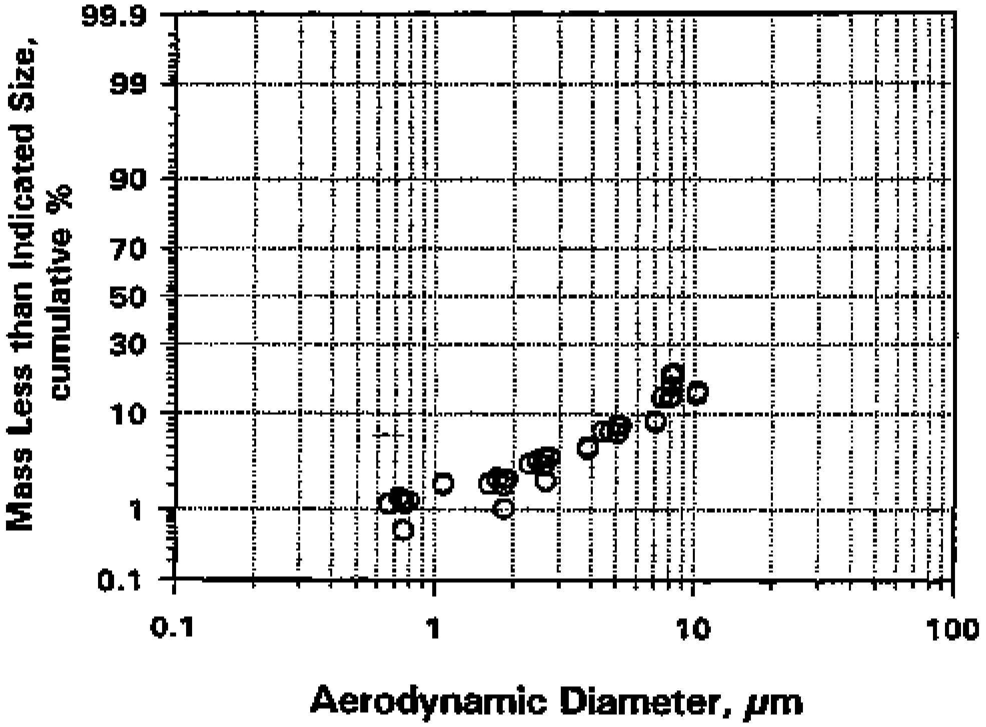


Figure C-4. Multicyclone data for Blacksville bituminous coal fly ash, 100-hr test.

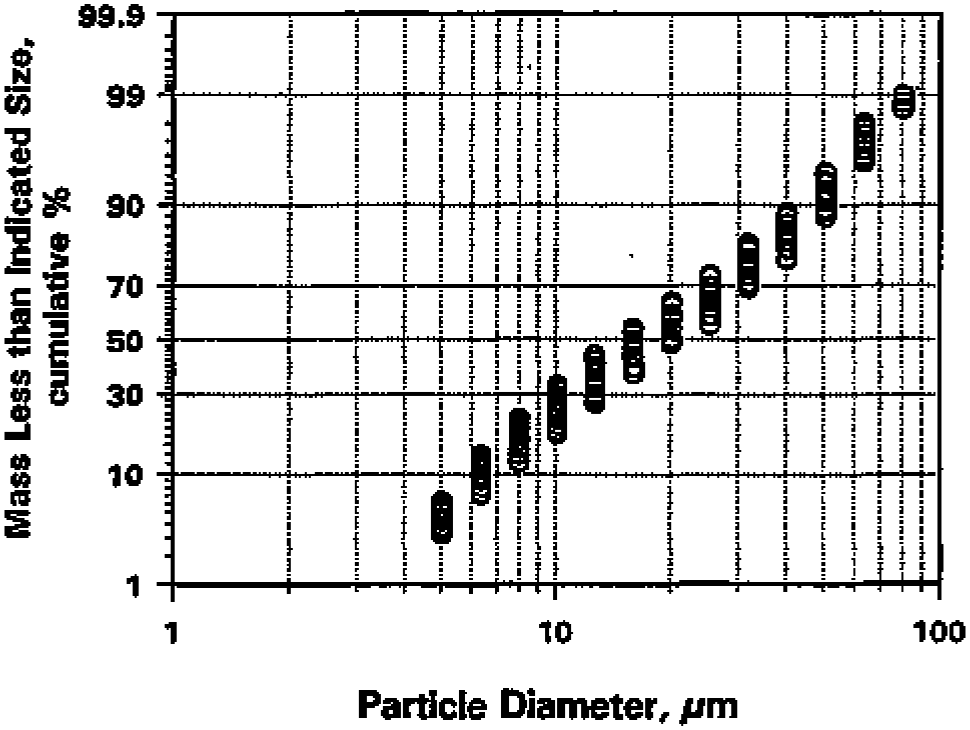


Figure C-5. Coulter counter data for baghouse hopper ash when Black Thunder subbituminous coal was fired, 100-hr test.

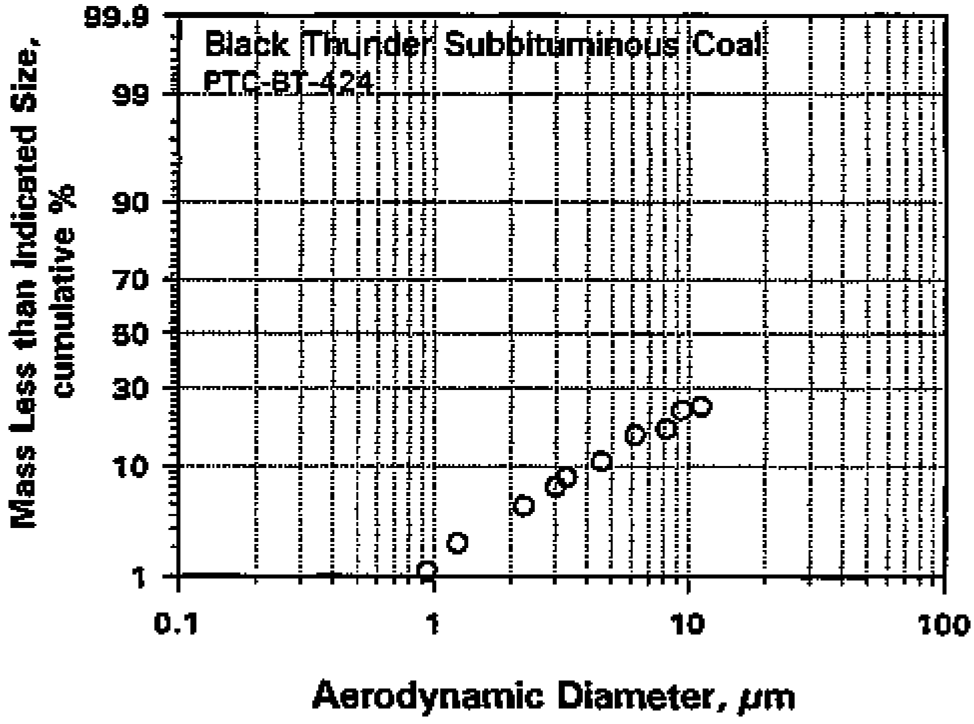


Figure C-6. Multicyclone data for Black Thunder subbituminous coal fly ash, 100-hr test.

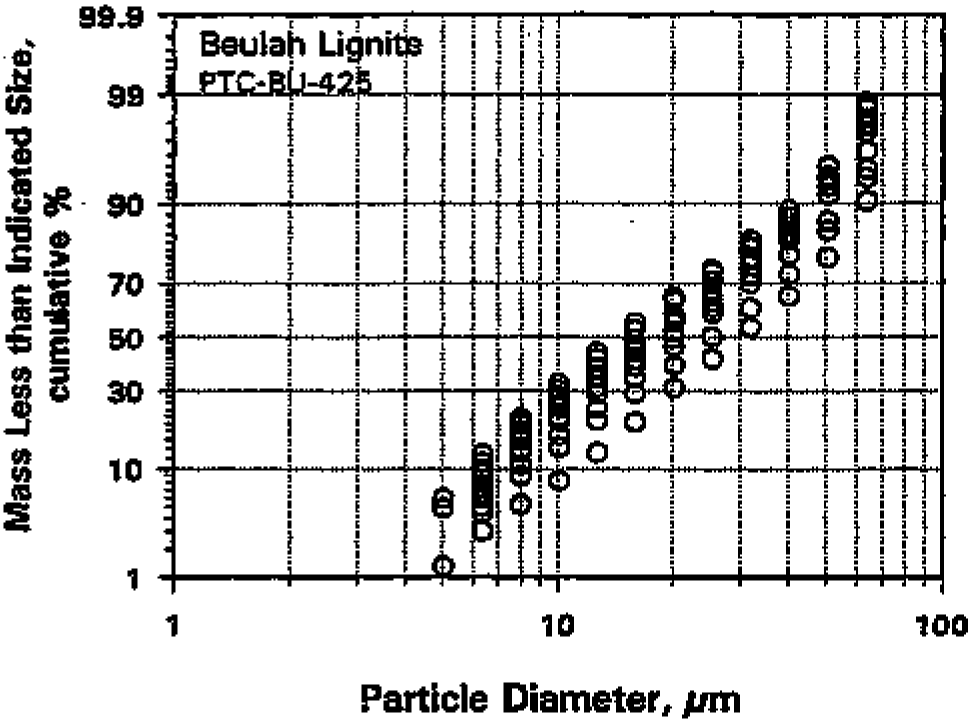


Figure C-7. Coulter counter data for baghouse hopper ash when North Dakota Beulah lignite was fired, 100-hr test.

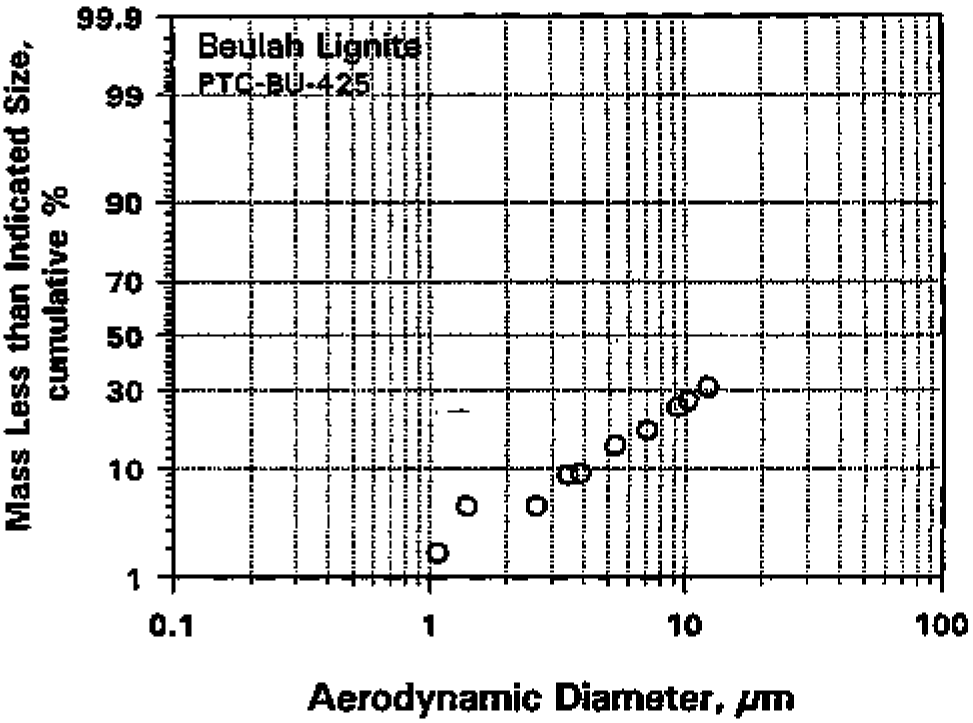


Figure C-8. Multicyclone data for North Dakota Beulah lignite fly ash, 100-hr test.

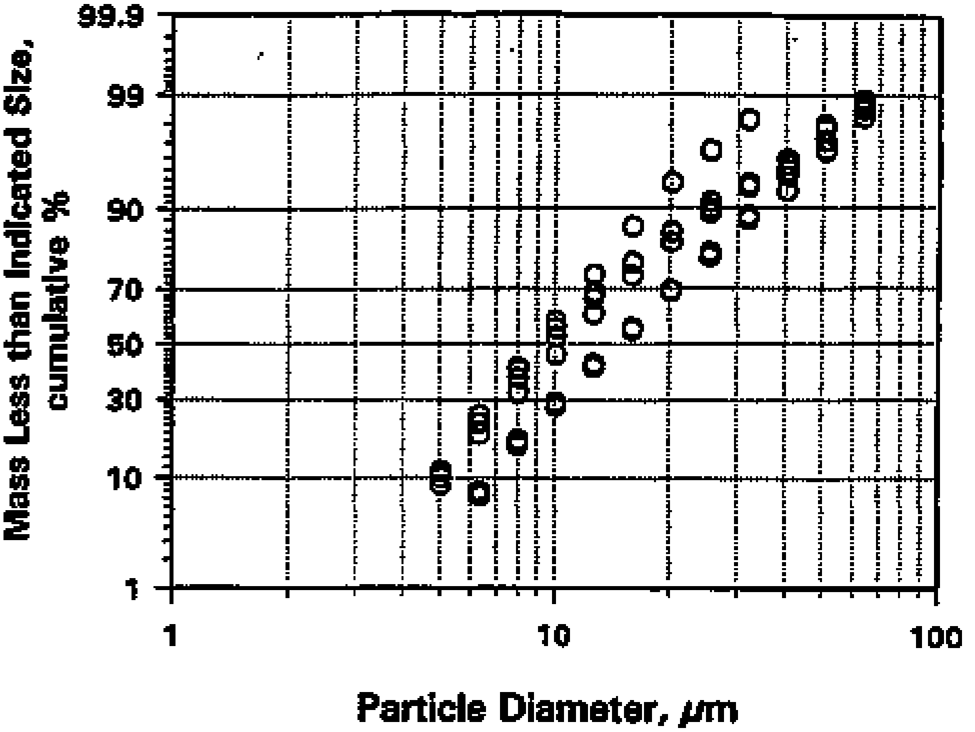


Figure C-9. Coulter counter data for baghouse hopper ash when Blacksville bituminous coal was fired, 500-hr test.

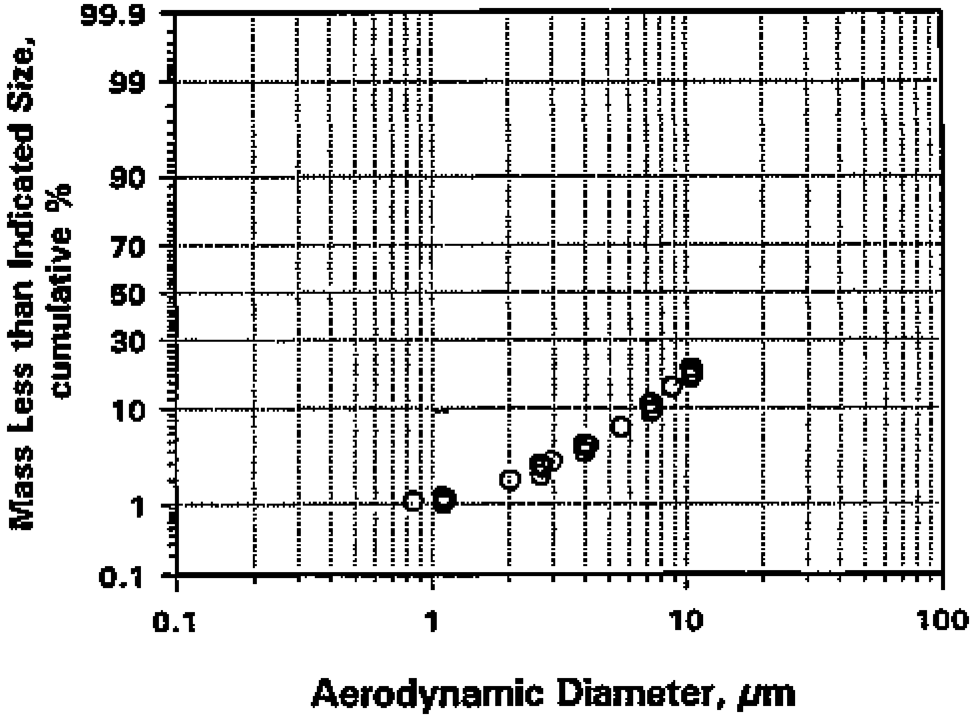


Figure C-10. Multicyclone data for Blacksville bituminous coal fly ash, 500-hr test.

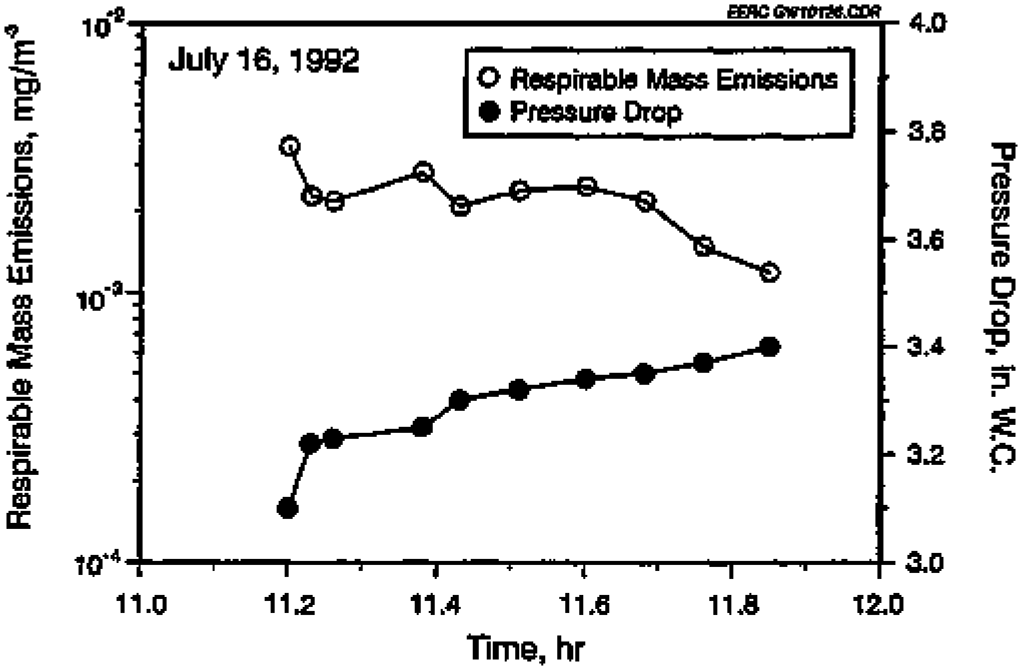


Figure C-11. Respirable mass emissions and pressure drop as a function of time for the slipstream baghouse, July 16, 1992.

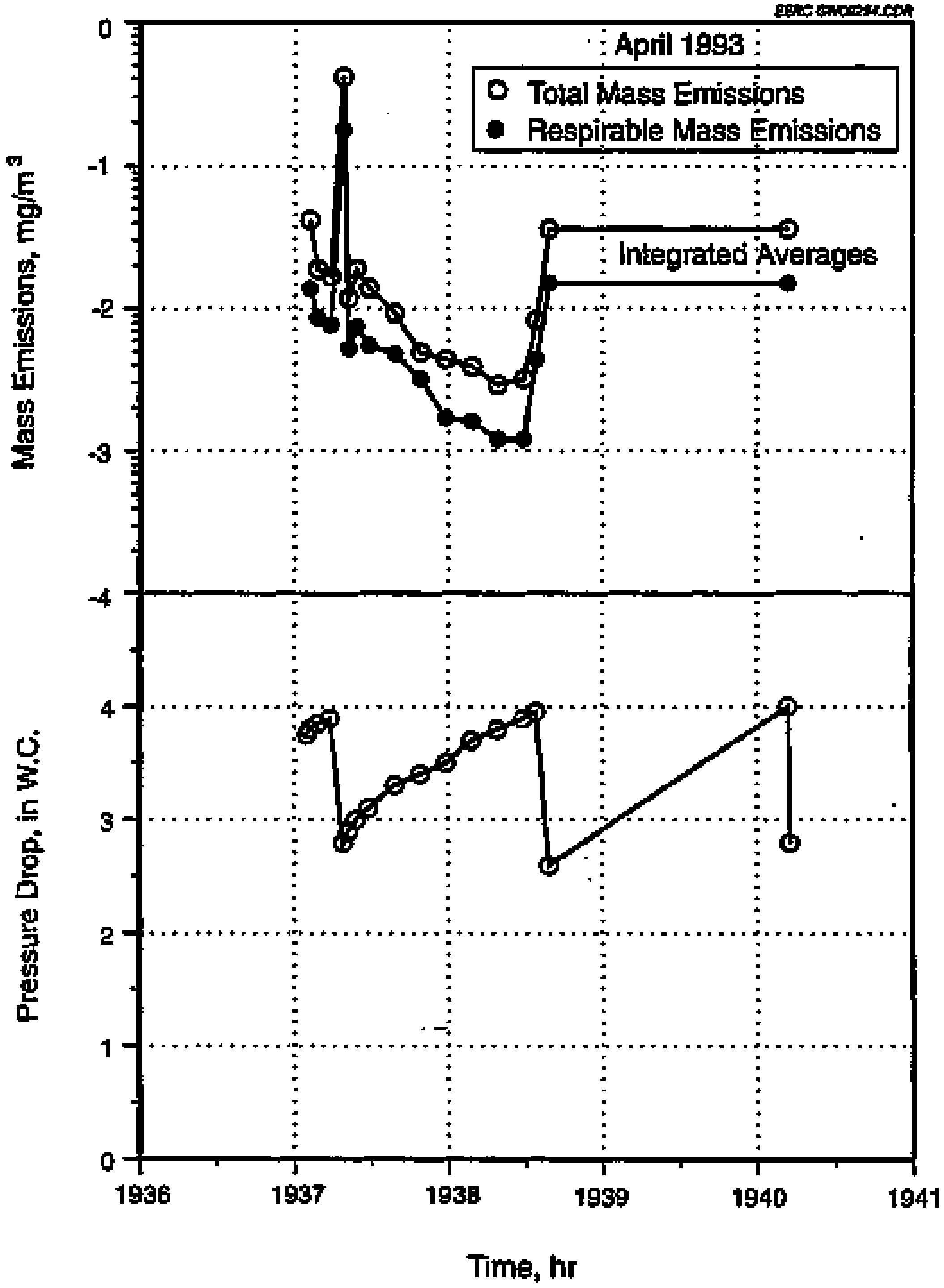


Figure C-12. Mass emissions and pressure drop as a function of time for the slipstream baghouse, April 1993.

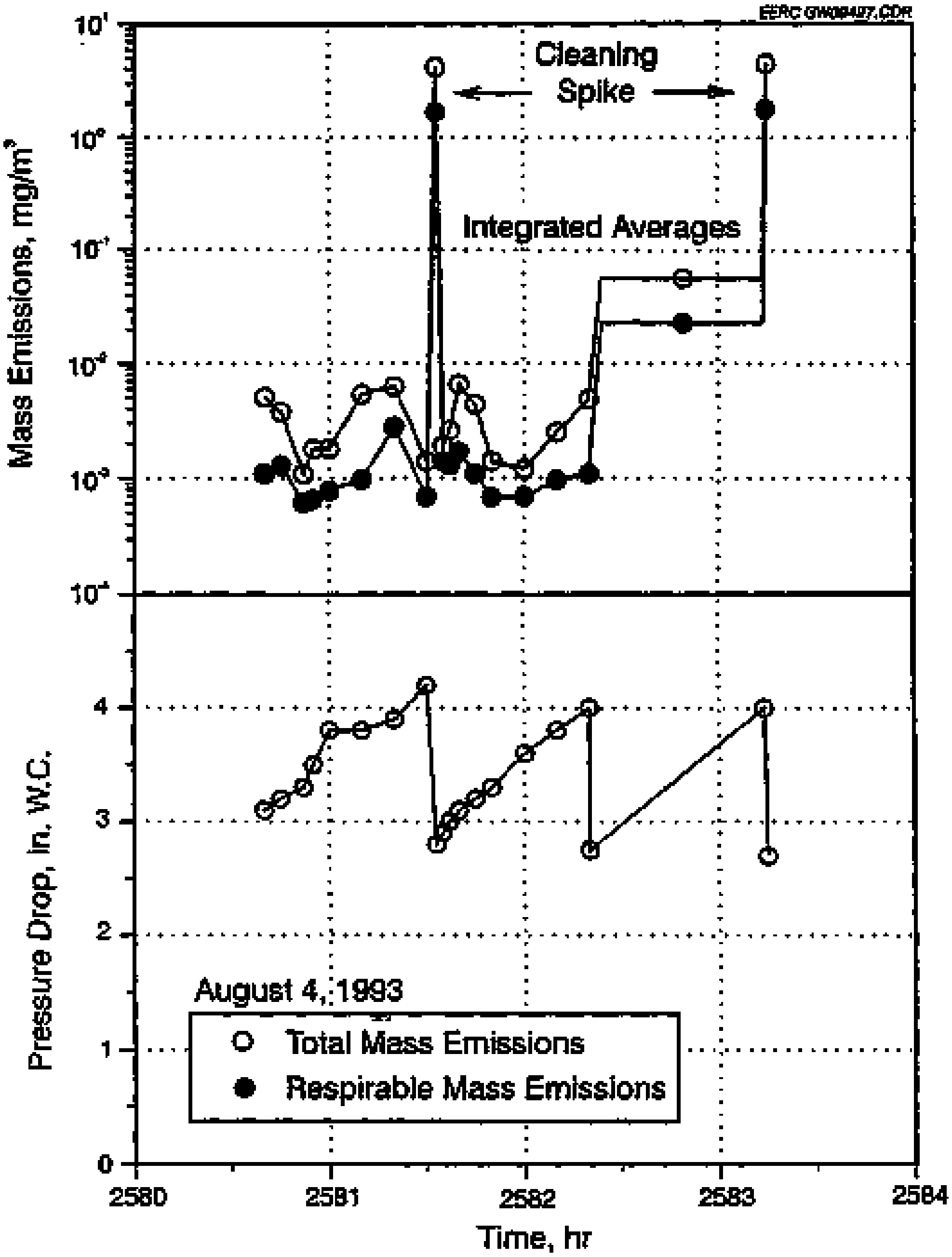


Figure C-13. Mass emissions and pressure drop as a function of time for the slipstream baghouse, August 4, 1993.

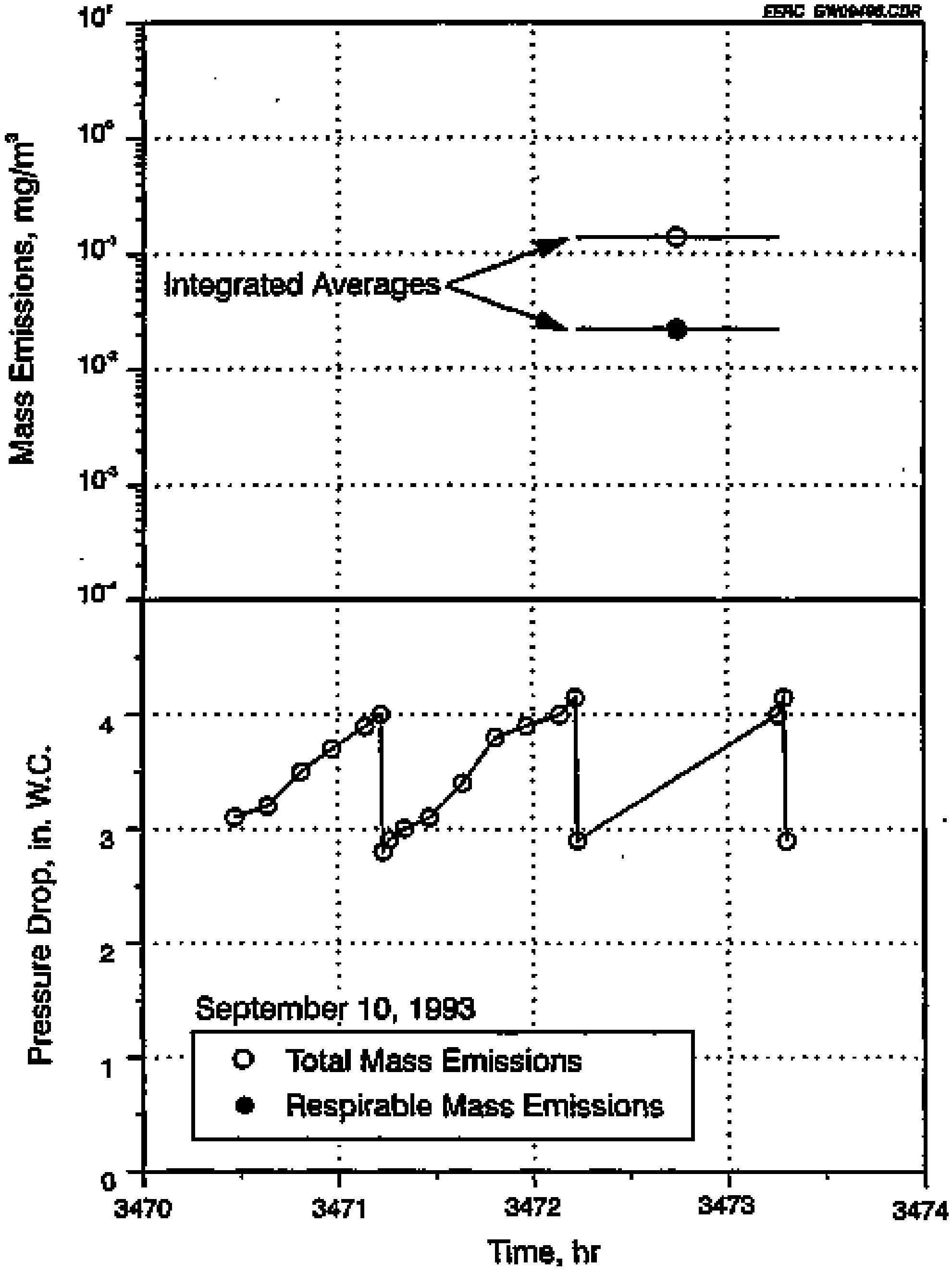


Figure C-14. Mass emissions and pressure drop as a function of time for the slipstream baghouse, September 10, 1993.

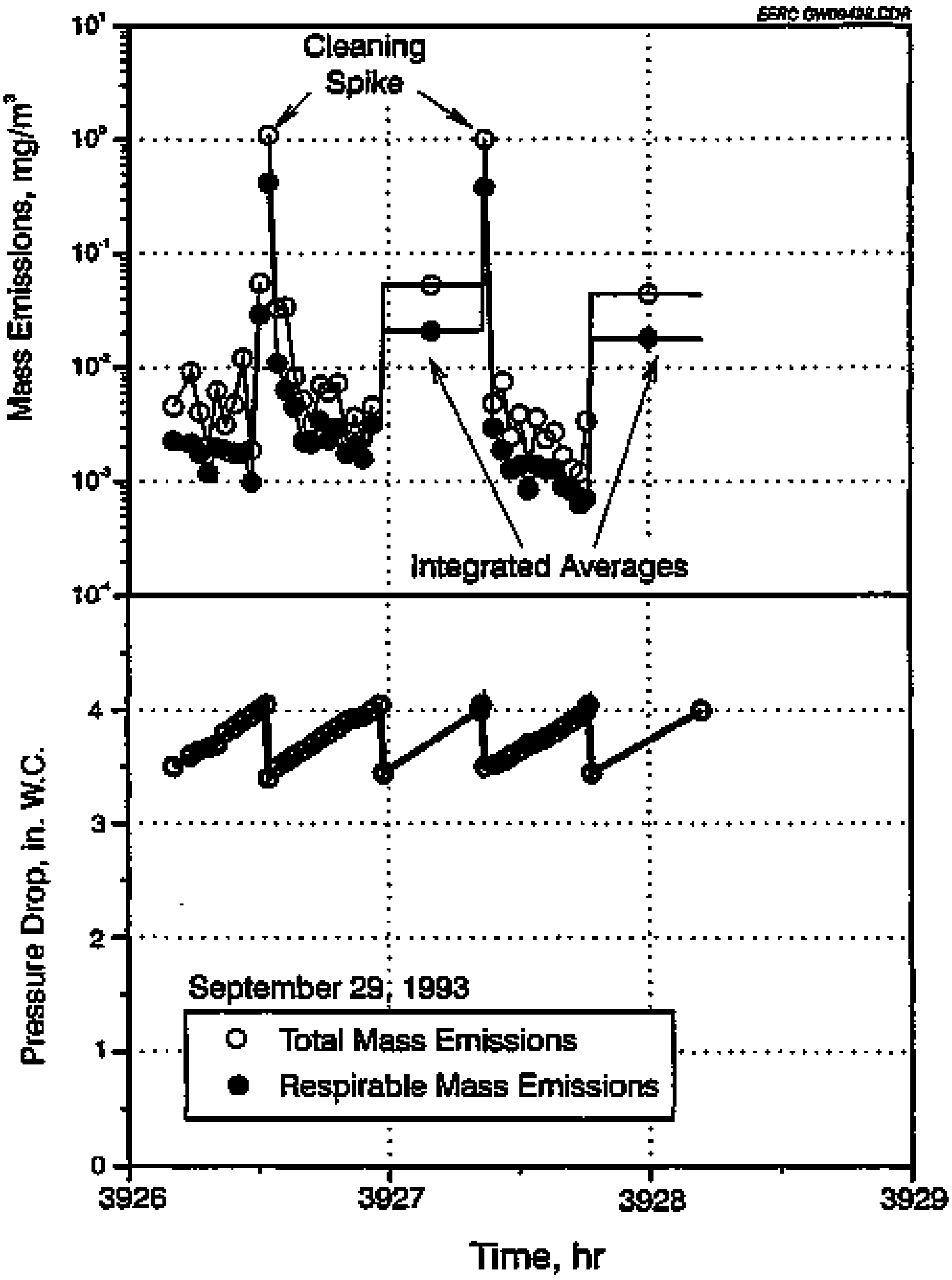


Figure C-15. Mass emissions and pressure drop as a function of time for the slipstream baghouse, September 29, 1993.

APPENDIX D

TASK 4
CONCEPTUAL DESIGN AND ECONOMIC EVALUATION

Netsko

Catalytic Fabric Filter Technology

for the Simultaneous Control of NO_x and Particulate Emissions from Coal–Fired Boilers

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

Task 4
Conceptual Engineering and Economic Evaluation

Prepared for

Energy & Environmental Research Center

Prepared by

Raytheon
Engineers & Constructors

May 1994
Revision 1

Catalytic Fabric Filter Technology
for the Simultaneous Control of NO_x and Particulate Emissions from Coal Fired Boilers

(U.S. DOE CONTRACT NO. DE-AC22-90PC90361)

TASK 4
CONCEPTUAL ENGINEERING AND ECONOMIC EVALUATION
FINAL REPORT

Prepared For
Energy & Environmental Research Center
University of North Dakota
Grand Forks, North Dakota

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Raytheon Project 6224.001

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Revision 1

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ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The Catalytic Fabric Filter (CFF) is a technology under development by the U.S. Department of Energy (DOE) for the simultaneous control of Nitric Oxide (NO_x) and particulate emissions from coal fired boilers.

The commercial viability of Catalytic Fabric Filter technology depends upon its cost effectiveness compared to other particulate and NO_x control technologies. CFF technology is intended for both new and retrofit plant applications and is intended to be an alternative to combining conventional hot-side Selective Catalytic Reduction (SCR) with a cold-side pulse jet fabric filter (PJFF).

Raytheon Engineers & Constructors under sub-contract to the University of North Dakota Energy and Environmental Research Center (EERC) conducted an economic evaluation of the CFF process to determine capital, operating, and levelized costs for commercial PC Boiler applications. Evaluations were conducted for both a new 500 MW grass roots power plant installation and for retrofit to an older 250 MW plant with typical arrangement constraints. For both new and retrofit cases, CFF costs were compared to those of conventional hot-side SCR for NO_x reduction in combination with a pulse jet fabric filter for particulate control.

CFF technology is expected to achieve commercial status in the mid-to-late 1990's. Both new and retrofit applications evaluated in this study are on boilers which have minimized NO_x production through combustion controls.

Fabric Filter (CFF and PJFF) costs were developed from vendor quotes using empirical cost models[3], with CFF bag costs provided by Owens-Corning Fiberglas Corporation. SCR costs were derived using empirical cost models and SCR economic evaluations developed by EPRI.[2] The economic factors and contingency fees were developed using the EPRI Technical Assessment Guide.[1] CFF process parameters were developed from the results of EERC's laboratory and Pilot Plant Testing conducted under this DOE program.[5]

Results from the economic evaluation indicated that although slightly higher in capital cost, on a levelized cost basis CFF technology can be competitive with an SCR/PJFF combination. Figure ES-1 compares the capital costs of a CFF with that of an SCR/PJFF combination for a new 500 MW plant installation. The CFF cost is approximately 5% greater than that of the SCR/PJFF. Several factors have a strong influence on CFF costs. Figure ES-2 shows that ductwork and filter bags represent major components of the capital equipment costs. The CFF, because of its position upstream of the air heater, requires extensive ductwork. The special catalyst coated filter bags are very expensive and over 25,000 bags are required for a 500 MW plant. Figure ES-3 compares the CFF versus the SCR/PJFF in terms of levelized costs (mills/kWh). CFF levelized costs are approximately 7% less than those of the SCR/PJFF. Catalyst coated bag replacement (a two year bag life was used) had the strongest influence on the CFF levelized costs.

The retrofit scenario was selected which represented a site favorable to a CFF installation; 250 MW plant with a small under-performing electrostatic precipitator must comply with stringent NO_x and particulate emissions requirements. Available space for new equipment is limited. Figure ES-4 shows that for this case, the CFF capital cost is approximately 4% less than that of the SCR/PJFF. Figure ES-5 is a breakdown of these costs. The breakdown is similar to that of a new plant, except that ID booster fans required to accommodate the additional pressure drop of the SCR/PJFF are added to the scope. Figure ES-6 presents a levelized cost (mills/kWh) comparison of the CFF and the SCR/PJFF which indicate a 9% cost advantage for the CFF.

FIGURE ES-1

CFF vs SCR/CONVENTIONAL BAGHOUSE TOTAL PLANT INVESTMENT - NEW 500 MW PLANT

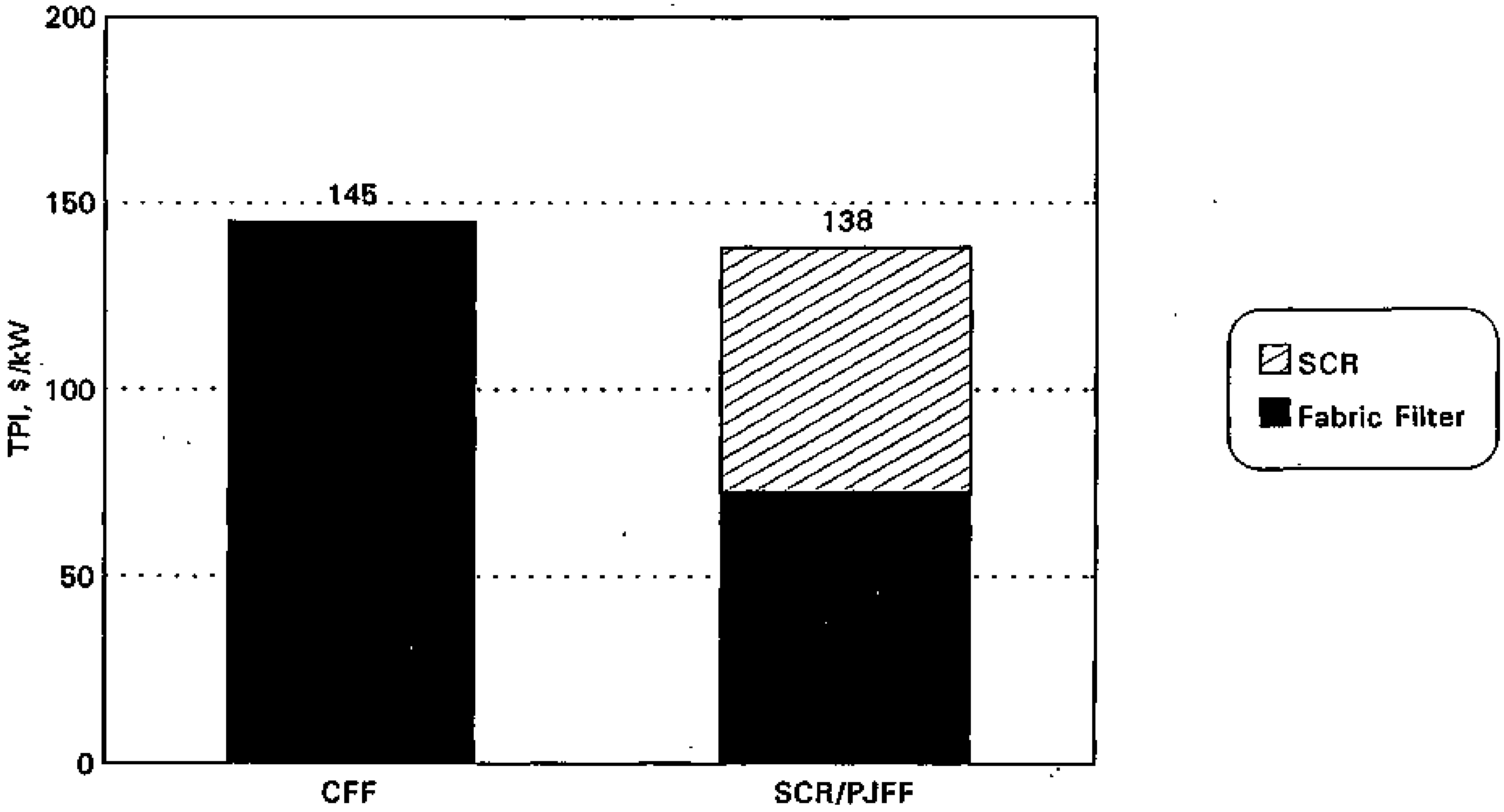


FIGURE ES-2

CFF CAPITAL COST

TOTAL INSTALLED EQUIPMENT COST BREAKDOWN - NEW 500 MW PLANT

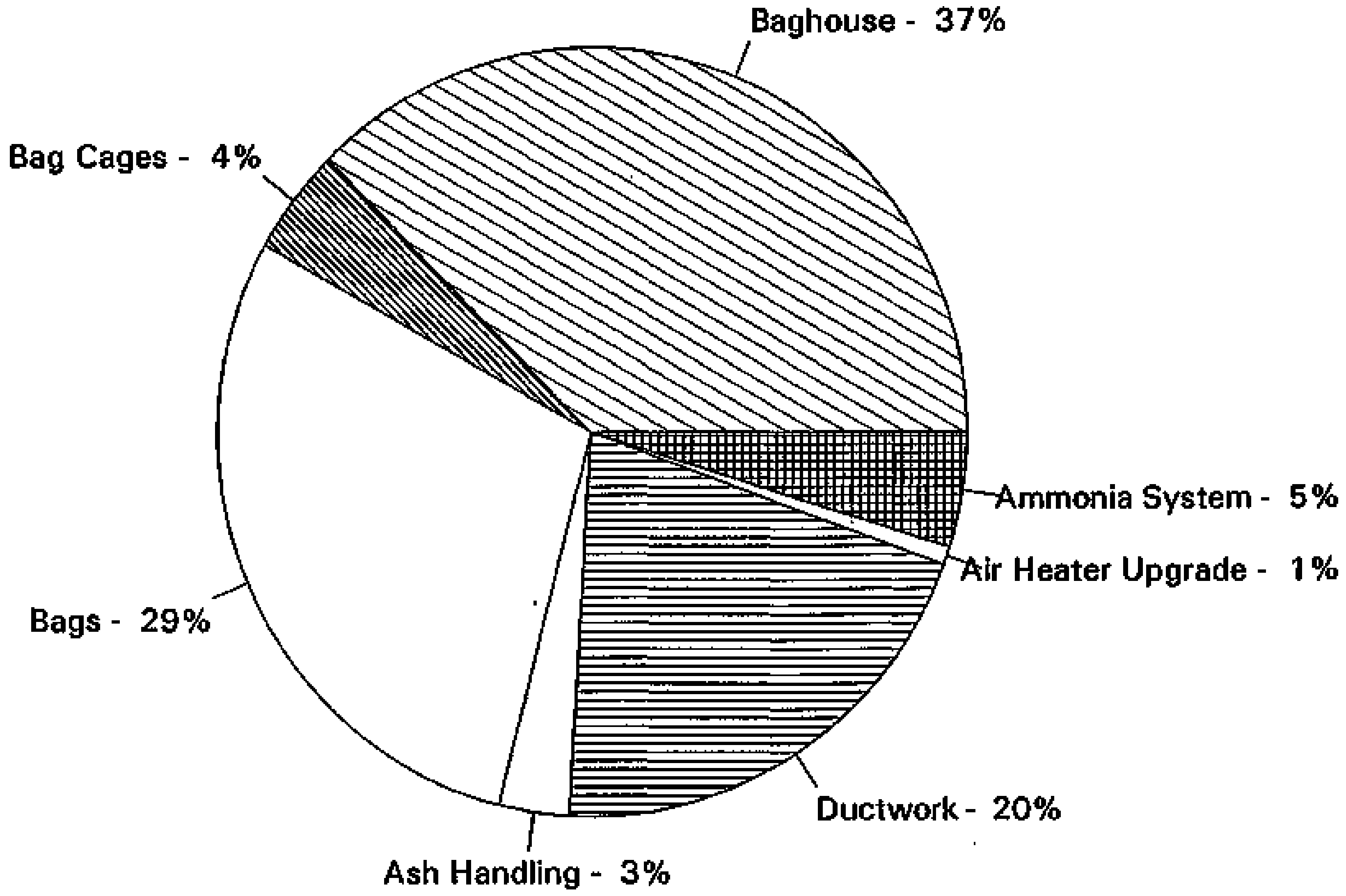
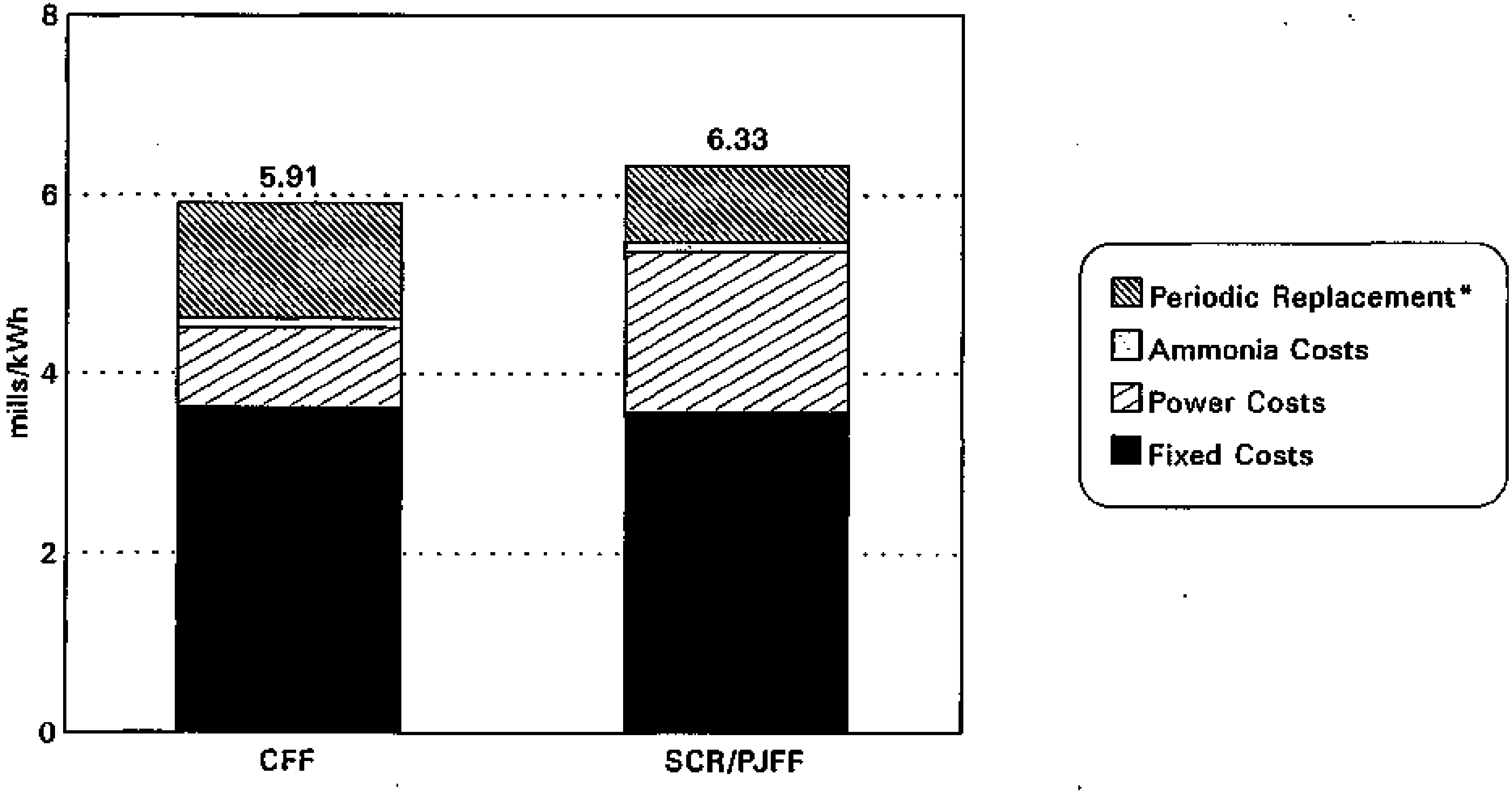


FIGURE ES-3

CFF vs SCR/CONVENTIONAL BAGHOUSE LEVELIZED COST BREAKDOWN - NEW 500 MW PLANT



* Filter Bags, Cages, and SCR Catalyst

FIGURE ES-4

CFF vs SCR/CONVENTIONAL BAGHOUSE
TOTAL PLANT INVESTMENT - RETROFIT 250 MW PLANT

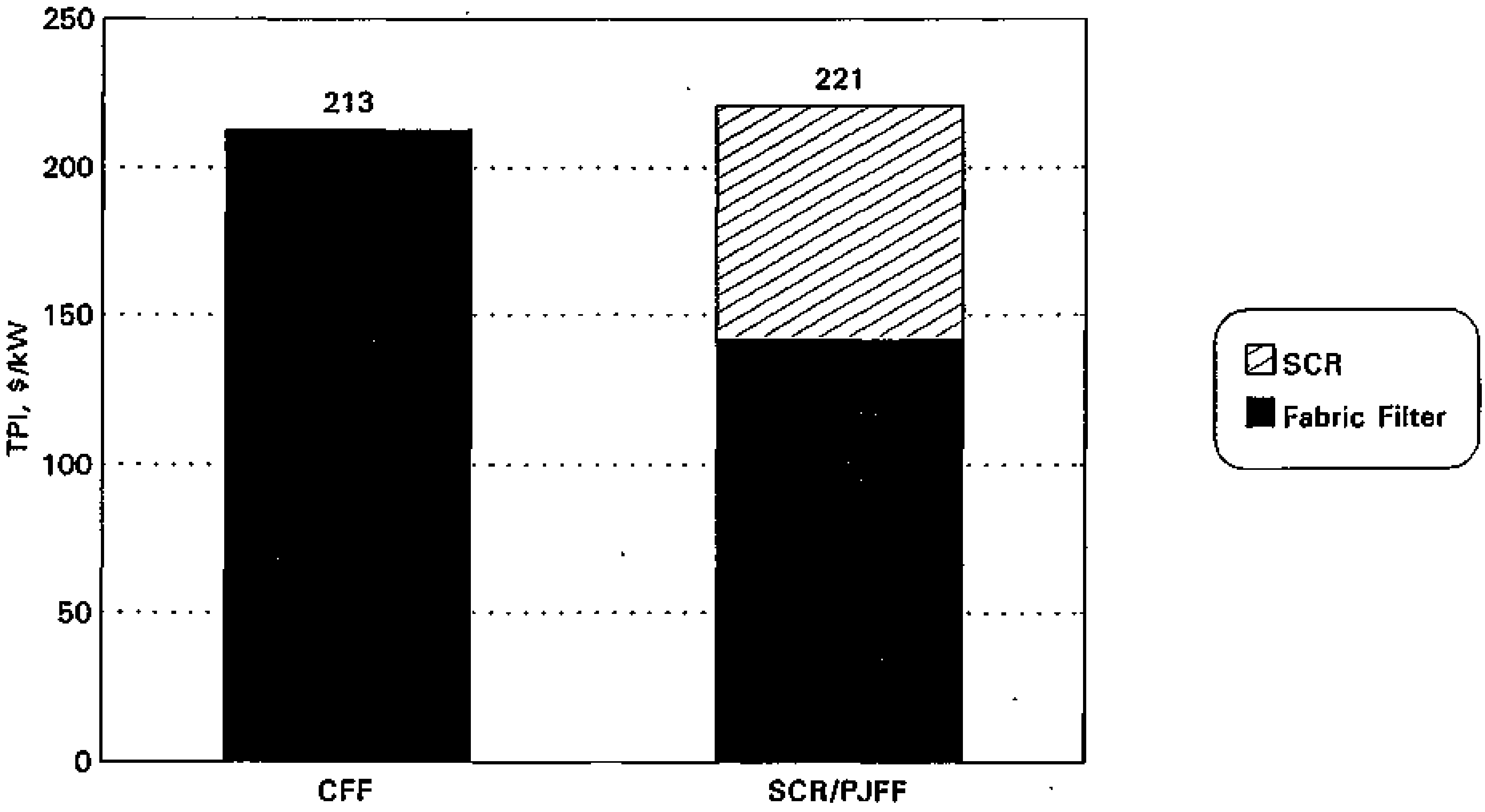


FIGURE ES-5

CFF CAPITAL COST

TOTAL INSTALLED EQUIPMENT COST BREAKDOWN - RETROFIT 250 MW PLANT

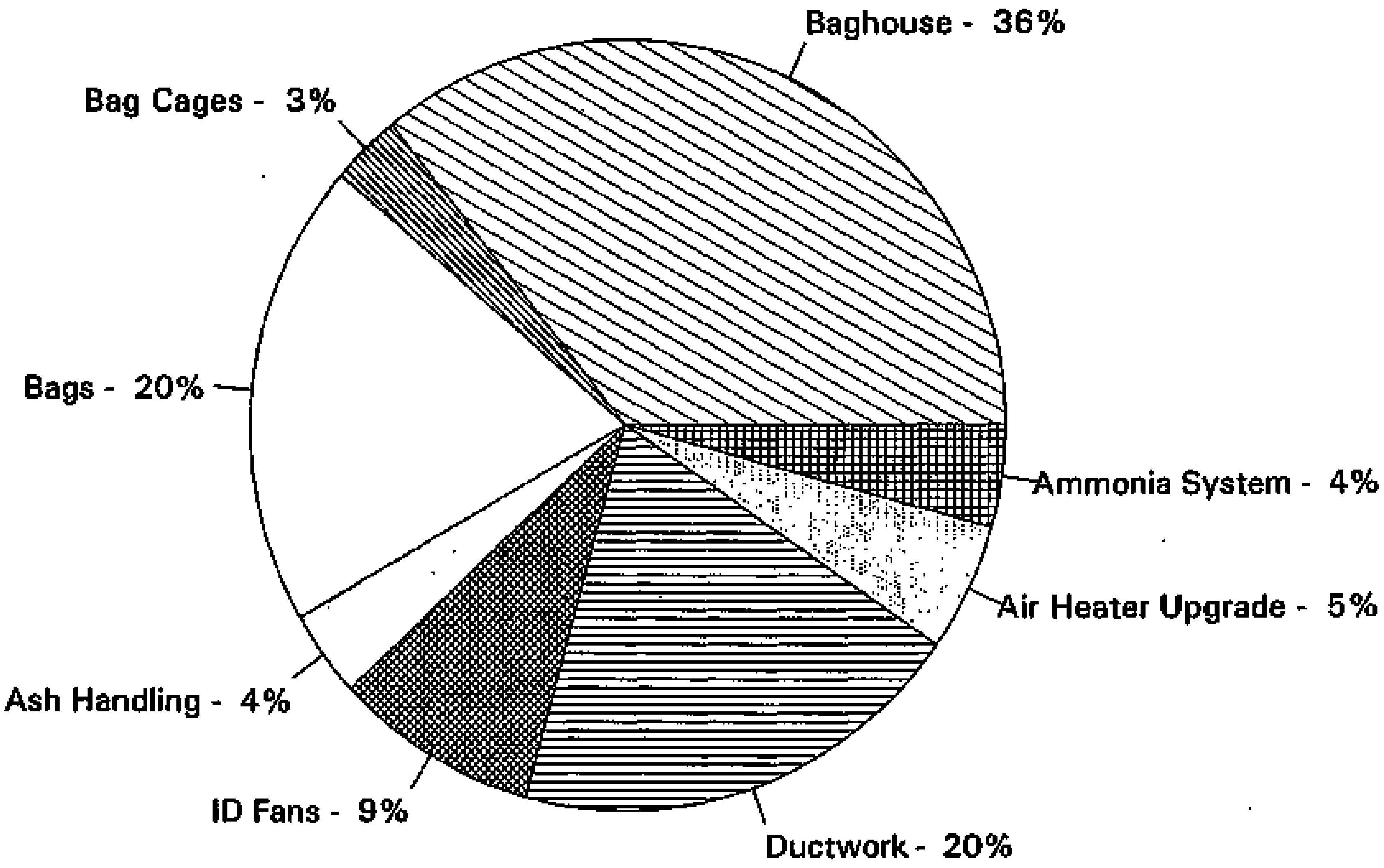
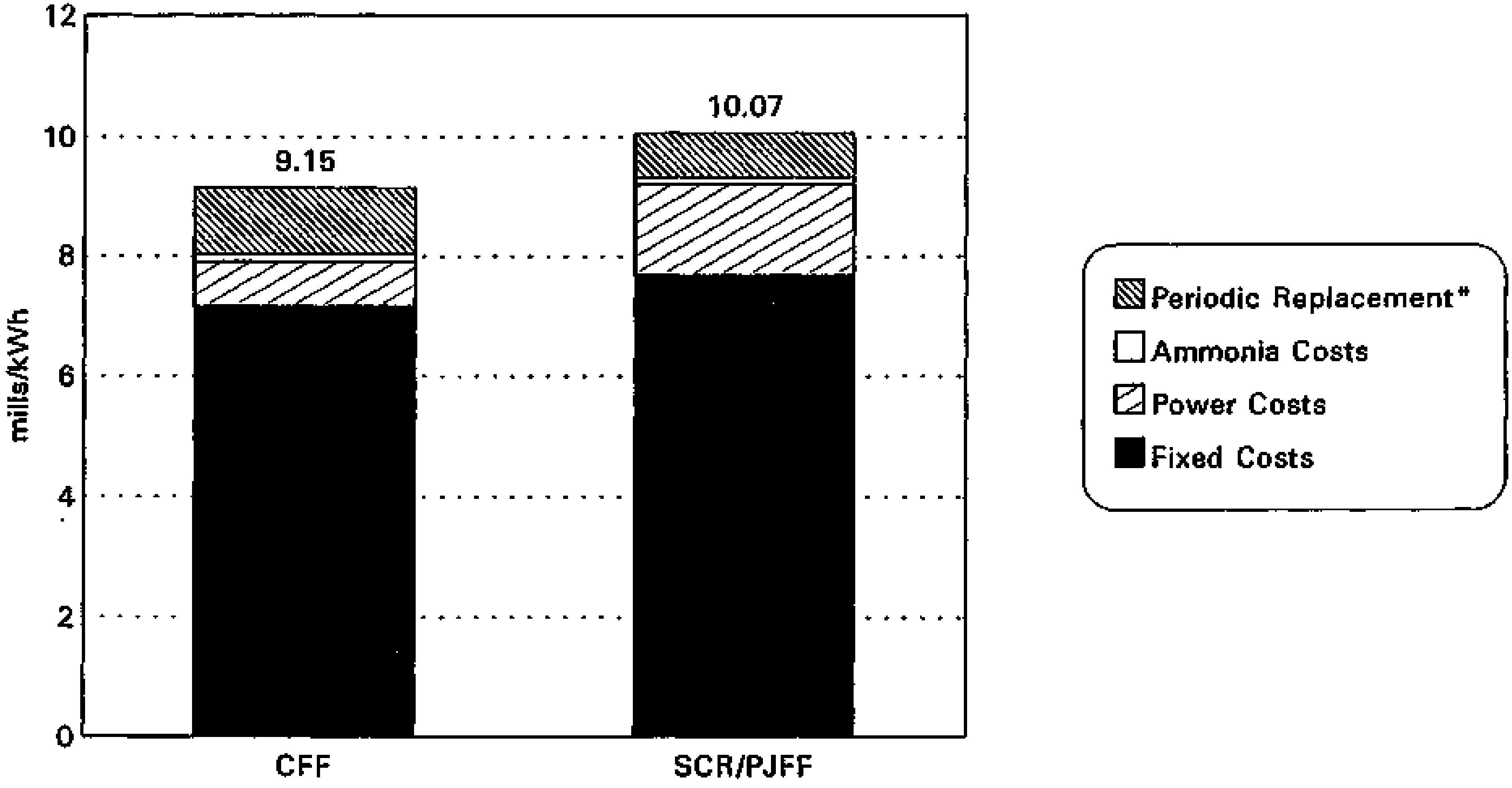


FIGURE ES-6

CFF vs SCR/CONVENTIONAL BAGHOUSE
LEVELIZED COST BREAKDOWN - RETROFIT 250 MW PLANT



* Filter Bags, Cages, and SCR Catalyst

The major findings of this investigation are:

1. CFF technology can be economically competitive with an SCR/PJFF for both new plant and retrofit applications, but must reduce costs in order to compete commercially with these established technologies.

2. The complex ductwork requirements associated with hot-side equipment location are a major cost component of any CFF or SCR/PJFF installation.

3. Bag cost, bag life, and air to cloth ratio are the parameters which have the strongest influence on CFF economics. Improvements in one or more of these areas will enhance the commercial viability of this technology.

4. Plant arrangement constraints and other site-specific issues will determine the feasibility and cost of a CFF retrofit.

5. The impact of ammonia carryover from the CFF process on the plant air heater(s) is unknown, and will affect both feasibility and costs.

6. The major retrofit issues which will impact CFF costs include:

    - Equipment arrangement and ductwork routing.
    - Time required to tie into existing plant ductwork.
    - Re-use of existing equipment.
    - Existing ID fan capacity - need for new fans
    - Draft controls and furnace reinforcements
    - Ash removal system - reuse of components
    - Modification to control deposition of ammonia-sulfur compounds in the air heater

7. Future research and development efforts required to improve the commercial viability of Catalytic Fabric Filter Technology should include:

   - Reducing the cost of the catalyst coated filter bags.
   - Increasing the service life of the bags.
   - Demonstrating the CFF process with longer pulse jet filter bags.
   - Maintaining the current performance (NO_x and Particulate Control) while operating at higher air to cloth ratios. This will reduce CFF baghouse size and cost.
   - Reducing the ammonia slip.
   - Determining impacts of the CFF process on air-heater equipment.

CATALYTIC FABRIC FILTER TECHNOLOGY FOR THE SIMULTANEOUS CONTROL OF NO_x AND PARTICULATE EMISSIONS FROM COAL FIRED BOILERS

TASK 4 - CONCEPTUAL ENGINEERING AND ECONOMIC ANALYSIS

TABLE OF CONTENTS

1.0 INTRODUCTION

Raytheon Engineers & Constructors (Raytheon) participated as a subcontractor to the University of North Dakota Energy and Environmental Research Center (EERC) in a U.S. Department of Energy (DOE) research project (DOE Contract No. DE-AC22-90PC90361) to develop a catalytic fabric filter. Raytheon's activities fell under Task 4 - Conceptual Design and Economic Evaluation. This report describes the activities and results of Task 4.

The Catalytic Fabric Filter (CFF) is a developing post-combustion technology that provides simultaneous NO_x reduction and particulate removal. NO_x reduction comparable to Selective Catalytic Reduction (SCR) process technology and particulate removal efficiencies comparable to a conventional fabric filter in the cold-side (downstream of the air heater) location are reported.

The CFF consists of a hot-side (upstream of the air heaters) baghouse where a catalyst has been applied to the bags to catalytically reduce NO_x in the presence of ammonia at temperatures of 625-750°F. The catalyst is an amorphous vanadium catalyst applied to the woven glass substrate. The active catalyst and refractory oxides are bound chemically to the glass fibers, minimizing mechanical removal of the catalyst from the bag surface.

The commercial viability of Catalytic Fabric Filter (CFF) technology depends upon its cost effectiveness compared to other particulate and NO_x control technologies.

An economic evaluation (+/- 25%) of the CFF process was conducted to determine capital, operating, and levelized costs for commercial utility applications. Evaluations were conducted for both a new grass roots power plant installation and for retrofit to an older plant with typical arrangement constraints. For both new and retrofit cases, CFF costs were compared to those of conventional hot-side Selective Catalytic Reduction (SCR) for NO_x reduction in combination with a Pulse Jet Fabric Filter (PJFF) for particulate control.

The location for both cases is Western Pennsylvania. Since the CFF technology will not reach commercial status before the middle to late 1990's, both new and retrofit plants are assumed to be operating at the lowest achievable NO_x emissions through combustion controls. The new grassroots plant will be designed with integral state of the art low NO_x Burner (LNB) and overfire air (OFA) resulting in a furnace exit NO_x concentration of 0.30 lbs/MMBtu. The retrofit case plant, after LNB and OFA conversion, operates at a furnace exit NO_x concentration of 0.40 Lbs/MMBtu.

Technical and process criteria for the CFF were developed from the results of Laboratory and Pilot Plant testing conducted by EERC.

2.0 ECONOMIC BASIS

The economic factors used in evaluating costs for the catalytic fabric filter, SCR, and pulse jet baghouse were developed using EPRI Technical Assessment Guide (TAG) guidelines[1]. SCR costs were derived from cost data developed by EPRI[2] and baghouse costs were developed from vendor quotes and empirical cost models[3]. The CFF bag cost was provided by Owens-Corning Fiberglas Corporation. Table 2-1 lists the economic parameters used in these evaluations. The overall project contingencies for the new and retrofit CFF's are 11% of the Total Erected Cost. The project contingencies for the PJFF baghouses and the SCR are 12% and 6%, respectively. A 17% process contingency is assessed against the new plant CFF baghouse casing(s) and filter bags because of the "hot-side" placement of the baghouse and uncertainty associated with scaling the NO_x removal process from pilot plant data. The CFF retrofit plant process contingency is 15%. An 8% process contingency is assessed against the SCR process due to the limited commercial experience on medium sulfur coal applications. A 10% process contingency was assessed against the new plant pulse jet fabric filter, and a 9% process contingency against the retrofit plant, because although there have been no commercial utility installations in the U.S., there has been extensive worldwide experience with this technology.

2.1 CAPITAL AND LEVELIZED COST COMPONENTS

The capital and levelized costs are two primary factors in selecting a flue gas cleanup process. The Total Plant Investment (TPI) is the total capital required for purchase, construction, and start-up. The TPI can be broken down into four components:

- Total Direct Cost
- Total Plant Cost
- Total Cash Expended
- Allowance for Funds During Construction

TABLE 2-1
ECONOMIC PARAMETERS

GENERAL	NEW PLANT	RETROFIT PLANT
UNIT CAPACITY, MW	500	250
Year of Cost Calculations	1993	1993
Reference State	Pennsylvania	Pennsylvania
State Multiplier	1.10	1.10
Power Cost, mils/kW	50	50
Ammonia Cost, $/ton	145	145
CFF Bag Cost, $/bag	250	250
PJFF Bag Cost $/Bag	85	85
Cage Cost $/Cage	40	40
SCR Catalyst Replacement Cost, $/ft^3	300	300
Uninstalled Insulated Ductwork, $/ft^2	81	81
Capacity Factor, %	75	65
ECONOMIC FACTORS		
Capital Escalation During Construction, %	5.0	5.0
Construction Period, years	2	2
Annual Inflation, %	5.0	5.0
Discount Rate (MAR), %	11.50	11.50
AFUDC Rate, %	11.50	11.50
Levelized Fixed Charge Rate (FCR), %	16.50	19.20
Service Life, years	30	15
Real Escalation Rates*		
Consumables (O&M), %	0	0
Fuel, %	0	0
Power, %	0.3	0.3
Nominal Escalation Rates**		
Consumables (O&M), %	5.00	5.00
Fuel, %	5.00	5.00
Power, %	5.32	5.32
CFF Project Contingency, % of Total Erected Cost	11	11
CFF Process Contingency, % of Total Erected Cost	17	15
PJFF Project Contingency, % of Total Erected Cost	12	12
PJFF Process Contingency, % of Total Erected Cost	10	9
SCR Project Contingency, % of Total Erected Cost	6	6
SCR Process Contingency, % of Total Erected Cost	8	8

* Constant dollar analysis

** Current dollar analysis

Total Direct Cost (TDC) - The TDC includes all equipment and installation costs. The equipment costs include the uninstalled equipment, instruments and controls, taxes, and freight charges. The installation cost includes earthwork, foundations and supports, equipment erection, electrical, piping, insulation, and painting.

Total Plant Investment (TPI) - The TPI includes the TDC and all indirect charges such as engineering and supervision, construction and field expenses, construction fees, startup costs, and performance tests. The TDC and the indirect costs are summed to get the total erected cost. The TPI also includes any project and process contingency fees assessed against the process. These fees are calculated from the total erected cost.

Total Cash Expended (TCE) - The TCE is the estimate of the total cash expended during the construction period of the project.

Allowance for Funds Used During Construction (AFUDC) - The AFUDC is the estimate of the allowance for interest expenses incurred during the construction period and is calculated from the TPI.

Levelized costs account for fixed capital and fixed and variable operating costs. Levelized costs are used to determine average annual expenditures and are used to compare processes with differing capital and operating costs.

3.0 NEW PLANT

3.1 GENERAL PLANT DESIGN CRITERIA

The net generating capacity for the new plant is 500 MW. This new plant is located in Western Pennsylvania with no constraints to limit equipment arrangement or construction. The pulverized coal boiler is equipped with low NO_x burners and over-fire air to minimize boiler NO_x production. For both CFF and SCR cases, the regenerative air heaters are sized and designed with high open surface, Corten construction, soot blowers and a integral washing system to control the deposition of ammonia-sulfur products. A high efficiency wet scrubber flue gas desulfurization system (FGD) is used for SO_2 removal. Table 3-1 summarizes the new plant general design criteria.

Table 3-2 provides the coal and ash analyses used in this evaluation. The fuel selected for this evaluation is a 2.27 percent sulfur Eastern Bituminous coal. The boiler heat input rate is 4861 MMBtu/hr and the boiler output NO_x concentration is 0.30 lb NO_x/MMBtu.

TABLE 3-1

NEW PLANT GENERAL DESIGN CRITERIA

Design Criteria	Design Value
Unit Size	500 MW
Gas Flow Exiting Economizer	2,536,000 ACFM @ 650°F
NO_x Concentration Exiting Economizer - ppmv dry @ 3% O_2 - lbs/MMBtu	 341 0.30
Particulate Concentration Exiting Economizer	5.02 lbs/MMBtu 2.82 gr/dscf
Boiler Heat Input Rate	4,861 MMBtu/hr
Boiler Efficiency	88%
Excess Air	20%
Air Heater In-leakage	15%
Flue Gas Temperature - Exiting Economizer - Exiting Air Heater	 650°F 277°F

TABLE 3-2

COAL AND ASH ANALYSIS

EASTERN BITUMINOUS COAL USED IN CFF ECONOMIC ANALYSES

Proximate Analysis, wt%	
Moisture	1.70
Volatile Matter	41.24
Fixed Carbon	49.02
Ash	8.03
Ultimate Analysis, wt%	
Hydrogen	5.05
Carbon	74.86
Nitrogen	1.27
Sulfur	2.27
Oxygen	8.52
Ash	8.03
Heating Value, Btu/lb	13,401
Ash Analysis, wt%	
SiO_2	40.19
Al_2O_3	18.82
Fe_2O_3	23.63
TiO_2	0.78
P_2O_5	0.73
CaO	7.28
MgO	0.68
Na_2O	1.13
K_2O	1.11
SO_3	5.44

3.2 CATALYTIC FABRIC FILTER DESIGN

Table 3-3 summarizes the CFF New Plant Design Criteria. CFF Process Criteria were developed from the results of the CFF laboratory and pilot plant tests conducted by EERC for this DOE project.[5] A 2 year life is assumed for the catalyst coated bags; however, this value had not been confirmed by long term fabric durability testing at the time of this report. Flue gas exiting the economizer is split into two 50% trains, each supplying one 14 compartment Catalytic Fabric Filter (CFF) casing. The CFFs are designed as intermediate pressure, intermediate volume pulse jet fabric filters with special amorphous vanadium catalyst-coated woven S2-glass bags. These 20 foot long, by 6 inch diameter bags are designed to simultaneously capture the particulate matter (fly ash) and catalytically convert the nitric oxide in the flue gas to nitrogen and water vapor with the aid of ammonia injection upstream of the baghouses. To maintain NO_x, particulate and ammonia emissions within the design ranges, the fabric filters are sized based on a gross air-to-cloth ratio of 3.44 fpm. Cleaning is conducted on-line. The air-to-cloth ratio with one 900 bag compartment (in each casing) out of service is 3.7 fpm.

The ammonia injection system is designed to provide 7 days storage of anhydrous ammonia. The anhydrous ammonia is stored in a horizontal pressure vessel and is vaporized using steam-heat. The vaporized ammonia is metered to a dilution blower skid assembly and then injected through a distribution grid located in the duct upstream of the baghouses.

Control of the CFF NO_x reduction process utilizes a feed-forward/feedback system. Proper mole ratios of ammonia to NO_x are maintained by regulating the flow of ammonia to the dilution air skid on the basis of

TABLE 3-3

CATALYTIC FABRIC FILTER

NEW 500 MW PLANT DESIGN CRITERIA

Design Criteria	Design Value
Total Gas Volume	2,536,000 ACFM
Gas Temperature	650°F
Inlet Grain Loading	5.02 lbs/MMBtu (2.82 gr/dscf)
Inlet NO_x	0.30 lbs/MMBtu (341 ppmv*)
Air to Cloth Ratio	
Net-1	3.70 fpm
Gross	3.44 fpm
Flange-Flange delta P	
Design	8" w.c.
Operating	6" w.c.
Bag Length	20′
Bag Diameter	6"
Bag Type	Catalyst Coated S2-glass
Bag Life	2 years
Number of Baghouses	2
Number of Bags/Compartment	900
Number Compartments/Baghouse	14
NH_3/NO_x Ratio	0.85 mol NH_3/mol NO_x inlet
NH_3 Feed Rate	481 lbs/hr
NH_3 Storage Capacity	7 days
Ammonia Slip	25 ppmv*
NO_x Emissions	0.06 lbs/MMBtu (68 ppmv*)
Particulate Emissions	0.02 lbs/MMBtu (.011 gr/dscf)

* ppmv is dry at 3% O_2

feed-forward signals from boiler load and the CFF inlet NO_x analyzer. Feedback from the CFF outlet NO_x analyzer is used to adjust the molar ratio. Outlet ammonia concentration is monitored (pending commercial availability of a continuous NH_3 analyzer) and will override the outlet NO_x concentration signal at the maximum ammonia slip limit.

During startup, the control system does not permit the injection of ammonia until CFF temperature is above the minimum catalyst temperature (600°F). These controls also interrupt ammonia flow should reactor temperature fall below the critical minimum.

During shutdown, controls interrupt ammonia flow when reactor temperatures fall below approximately 600°F; however, the dilution air blower continues to operate to purge the system and is shut down with the I.D. and F.D. fans. If an emergency shutdown is required, ammonia flow would be interrupted by the master fuel trip interlock signal, but the dilution air blower would continue to operate on auxiliary power to purge the system.

The CFFs are designed for a particulate emissions rate of 0.02 lbs/MMBtu or, 0.011 gr/dscf. The ammonia injection system is designed for 80% NO_x reduction across the CFF resulting in a maximum design NO_x emissions rate of 0.06 lbs/MMBtu or 68 ppmv. The ammonia is injected at a rate of 0.85 mol NH_3/mol NO_x inlet to the fabric filter. The maximum ammonia slip is 25 ppmv.

3.3 SCR/CONVENTIONAL BAGHOUSE DESIGN

Conventional Hot-Side Selective Catalytic Reduction (SCR) to control NO_x, combined with a pulse jet fabric filter downstream of the air heater to control particulate, was selected as a basis for economic comparison and feasibility of a full-scale CFF unit.

3.3.1 Selective Catalytic Reduction (SCR)

Each of the two 50 percent flue gas trains exit the economizer and enter an SCR reactor. The SCR reactors are designed as vertical gas flow units with rectifying grids at the reactor inlets to promote even gas flow distribution. The reactors are also designed with sufficient volume to add a spare catalyst layer per reactor, if required. The SCR unit is designed for 80% NO_x reduction at an ammonia to NO_x ratio of 0.8, resulting in a NO_x emission rate of 0.06 lbs/MMBTU or 68 ppmv. The ammonia slip is 5 ppmv. Table 3-4 summarizes the SCR design criteria.

The ammonia injection system is designed to provide 7 days storage of anhydrous ammonia. The anhydrous ammonia is stored in a horizontal pressure vessel and is vaporized using steam-heat. The vaporized ammonia is metered to a dilution blower skid assembly and then injected through a distribution grid located in the duct upstream of the SCR reactors.

3.3.2 Pulse Jet Fabric Filter (PJFF)

The PJFF is an intermediate pressure-intermediate volume design using 20 foot long x 6 inch diameter Ryton felt bags. Two 50 percent capacity baghouses are required. Each PJFF casing houses 10 compartments with 800 bags per compartment. The PJFF is sized based on a gross air to cloth ratio of 3.7 fpm which is typical of utility scale PJFF installations utilizing felted ryton

TABLE 3-4

SELECTIVE CATALYTIC REDUCTION
NEW 500 MW PLANT DESIGN CRITERIA

Design Criteria	Design Value
Gas Temperature	650°F
Total Gas Volume	2,536,000 ACFM
Flange-Flange delta P	
Design	11" w.c.
Operating	8" w.c.
NO_x Entering SCR	0.30 lbs/MMBtu (341 ppmv*)
NO_x Removal	80%
NH_3/NO_x Ratio	0.8 mol NH_3/mol NO_x
NH_3 Feed Rate	453 lbs/hr
Ammonia Slip	5 ppmv*
NH_3 Storage Capacity	7 days
Number of Reactors	2
Catalyst Space Velocity	3,200 NCF/ft^3/hr
Catalyst Life	4 years
Number of Catalyst Layers/Reactor	4
NO_x Emissions	0.06 lbs/MMBtu (68 ppmv*)

* ppmv is dry at 3% O_2

bags.[6] Compartments are cleaned on line. The air to cloth ratio with one compartment out of service is 4.0 fpm. Table 3-5 summarizes the PJFF design criteria.

3.4 DUCTWORK AND EQUIPMENT ARRANGEMENT

The arrangement of the CFF equipment has a strong influence on process economics due to the large amount of flue gas ductwork required. Two general arrangements for the new plant case were evaluated, differing primarily in the location of the air heaters and forced draft (FD) fans.

In the first arrangement, the air heaters and FD fans are located along with the ID fans behind the catalytic fabric filters. A hot air return duct provides primary and secondary air back to the boiler house. This arrangement has been used in several hot-side ESP installations.

In the second arrangement, the air heaters and FD fans are in more conventional locations within the boiler house.

Arrangement 1-Air Heaters and FD Fans Located Behind the CFF

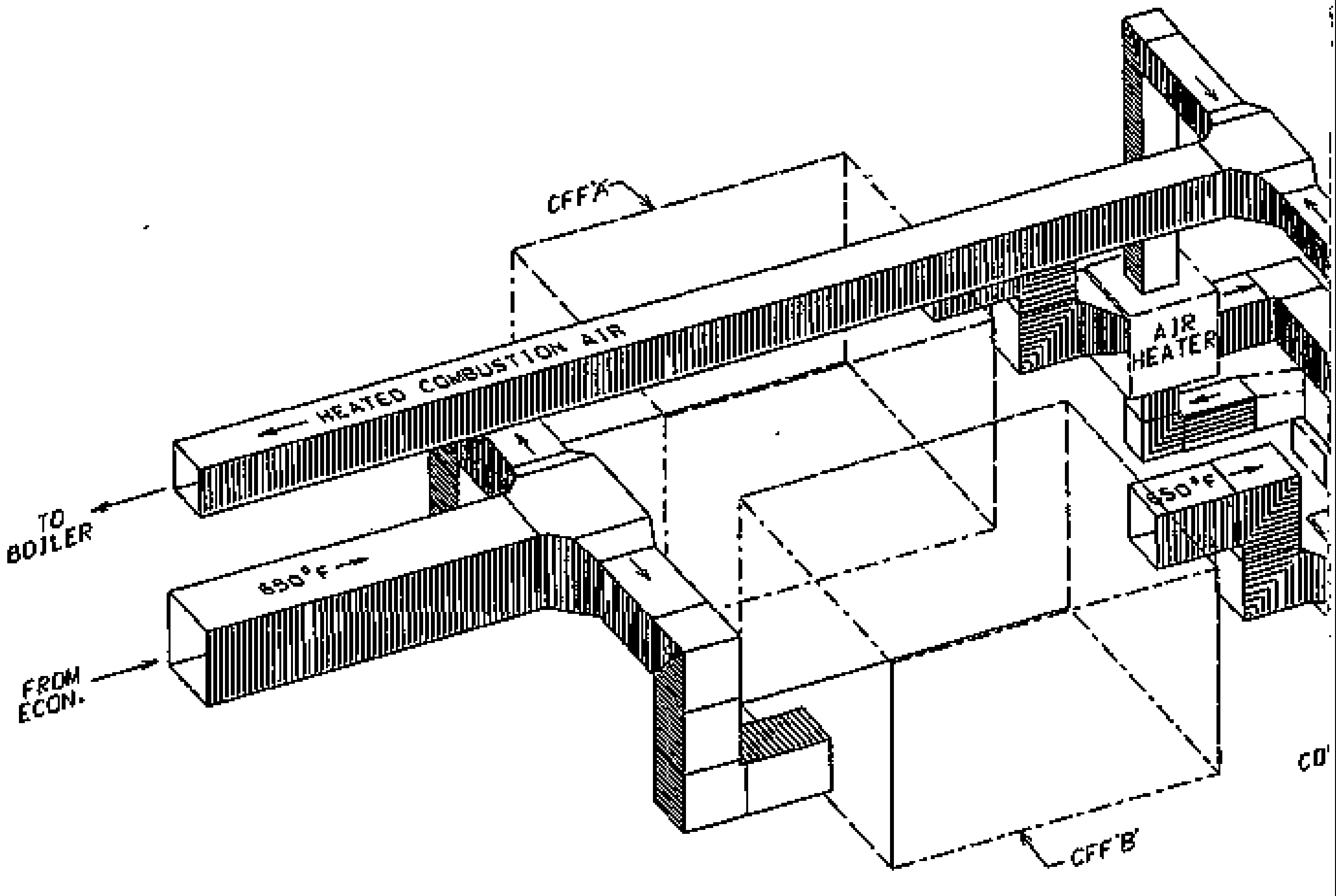
Hot flue gas (650°F) exits the economizer, splits into two 50% trains, and enters two 50% CFF casings. The clean gas exits the CFF from the opposite end of the casings and into the air heaters. The flue gas leaves the air heaters through two 50% ID fans, then is combined into a common duct leading to the FGD system inlet. Heated air exits the air heaters, then is combined into a common duct which runs back (past the CFF and inlet ductwork) into the boiler house. Figure 3-1 is a conceptual sketch of this arrangement illustrating the complexity of the ductwork.

TABLE 3-5

PULSE JET FABRIC FILTER

NEW 500 MW PLANT DESIGN CRITERIA

Design Criteria	Design Value
Total Gas Volume	1,732,000 ACFM
Gas Temperature	277 °F
Inlet Grain Loading	5.02 lbs/MMBtu (2.45 gr/dscf)
Air to Cloth Ratio	
Net-1	4.0 fpm
Gross	3.70 fpm
Flange-Flange delta P	
Design	8" w.c.
Operating	6" w.c.
Bag Length	20 ft
Bag Diameter	6 in
Bag Type	Ryton Felt
Bag Life	3 years
Number of Baghouses	2
Number Bags/Compartment	800
Number Compartments/Baghouse	10
Particulate Emissions	0.02 lbs/MMBtu (.011 gr/dscf)



ISOMETRIC VIEW

VCHR	ADV NO	DATE	REVISIONS	DSGN	CHKD

REVISION APPROVAL RECORD

REV

DISCIPLINE	REVIEWED	DATE	DISCIPLINE	REVIEWED	DATE
CIVIL			PIPING		
STRUCTURAL			ELECTRICAL		
HVAC			ARCHITECTURAL		
MECHANICAL			INST & CONTROL		
PROCESS			ENVIRONMENTAL		
NUCLEAR			SEAL ANNUAL		

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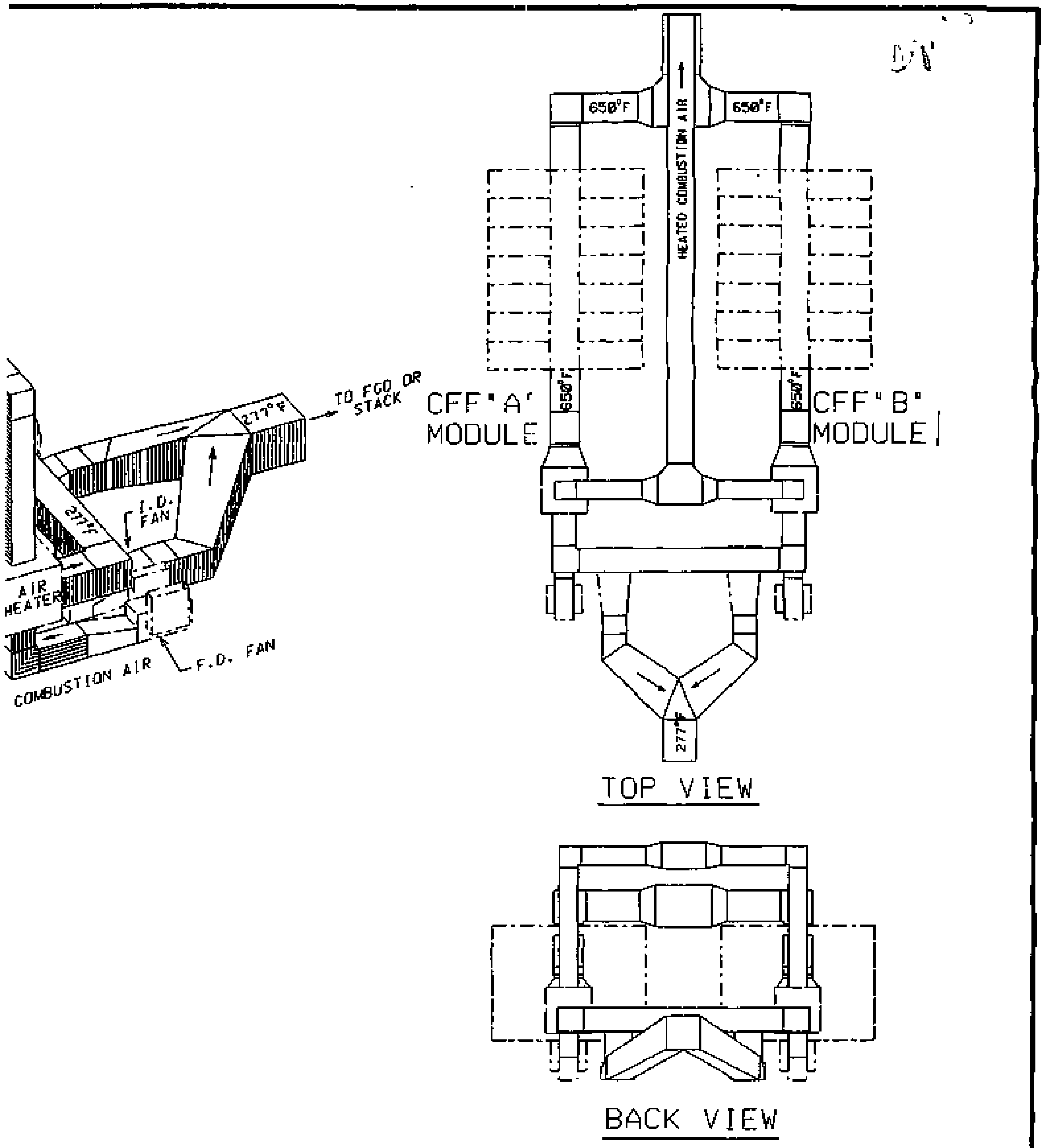
CHECKER
CADD
TYPE: NS

CENTIMETERS
INCHES



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		FIELD						
CONDUCT.		VEND. CO.						

DRAWING STATUS				
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REVISED & APPROVED FOR CONSTRUCTION				

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GENERAL ARRANGEMENT

NEW PLANT CFF DUCT CONFIGURATION
AIR HEATER AND FANS BEHIND CFF

SCALE: NONE

U.S. DEPARTMENT OF ENERGY
CATALYTIC FABRIC FILTRATION FOR
SIMULTANEOUS NOx AND PARTICULATE CONTROL

Raytheon
Engineers & Constructors

DWG. NO. FIGURE 3-1

ORDER NO. 6224.001

This sketch is not to scale. The spacial relationships among the various ducts in this figure are for clarity, and do not necessarily represent an actual installation. The total (combined, all duct sizes) square feet of ductwork steel plate required for a 500 MW installation was estimated a 102,396 FT^2.

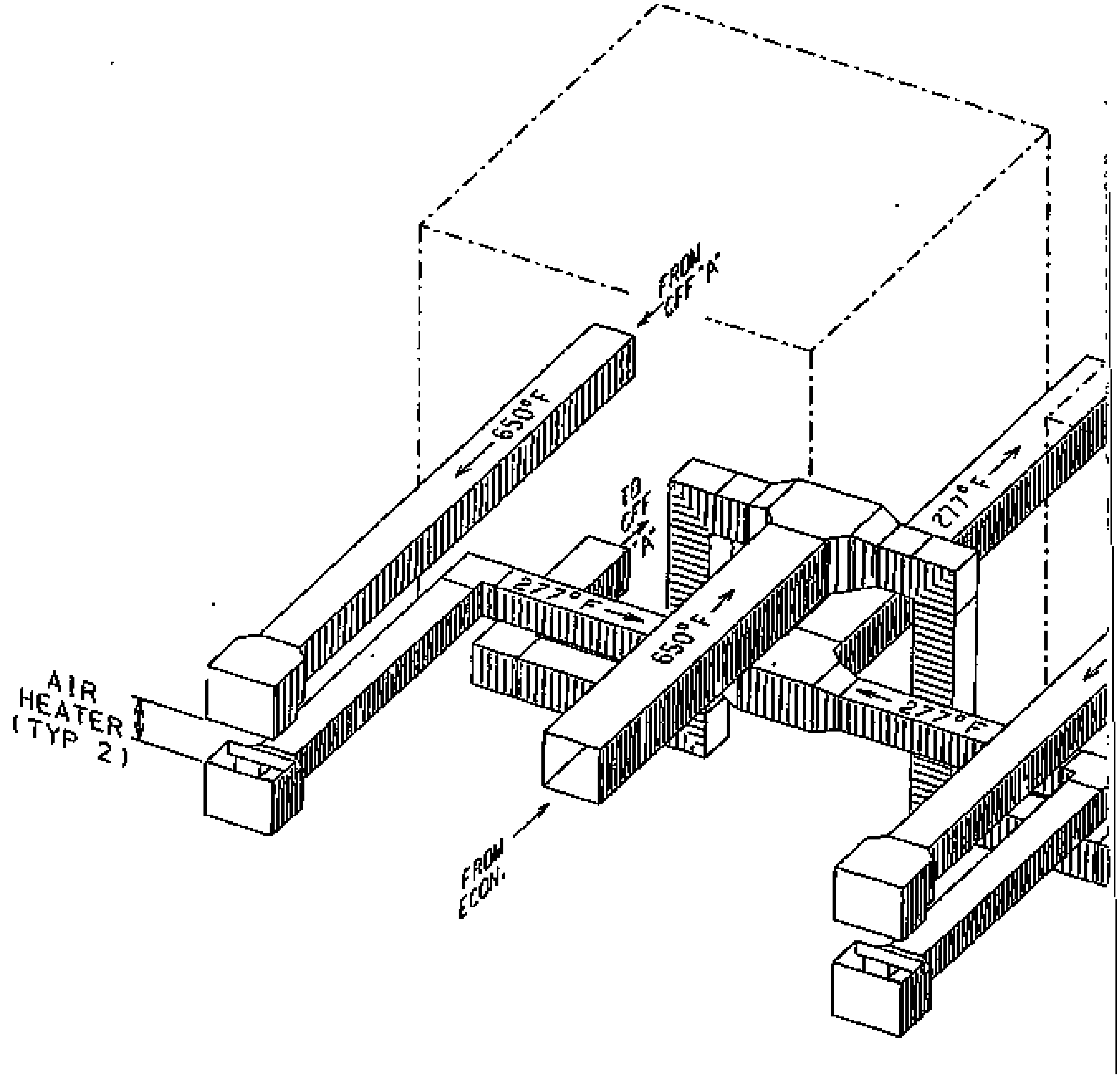
Arrangement 2 - Air Heaters and FD Fans in Conventional Location

Hot flue gas (650°F) exits the economizer, splits into two 50% trains and enters two 50% CFF casings. The clean gas exits the CFF from the same end through return ducts back into the two air heaters. Flue gas leaves the air heaters then combines into a common duct which runs past the CFFs into the FGD inlet. Figure 3-2 is a conceptual sketch of this arrangement illustrating the complexity of the ductwork. This sketch is not to scale. The spacial relationships among the various ducts in this figure are for clarity, and do not necessarily represent an actual installation. The total (combined, all duct sizes) square feet of ductwork steel plate required for a 500 MW installation was estimated at 83,496 FT^2.

The total ductwork requirements for each arrangement were estimated for a new 500 MW plant with no space or arrangement restrictions. Arrangement 2 with the air heaters and FD fans located behind the CFF's required twenty three (23) percent less ductwork steel and supports, than Arrangement 1 and therefore Arrangement 2 was selected as the base arrangement for this economic evaluation.

SCR/Conventional Baghouse Arrangement

As with the CFF arrangement, the air heaters and FD fans are in the conventional boiler house location. The arrangement brings the gas exiting the economizers into the top of the SCR units. The gas exits the



ISOMETRIC VIEW

MICRO	FLT NO	DATE	REVISIONS	DSGN	CHKD

REVISION APPROVAL RECORD

REV

DISCIPLINE	REVIEWED	DATE	DISCIPLINE	REVIEWED	DATE
CIVIL			PIPING		
STRUCTURAL			ELECTRICAL		
HVAC			ARCHITECTURAL		
MECHANICAL			INST & CONTROL		
PROCESS			ENVIRONMENTAL		
NUCLEAR			GEN. ARRANG.		

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CENTIMETERS

INCHES

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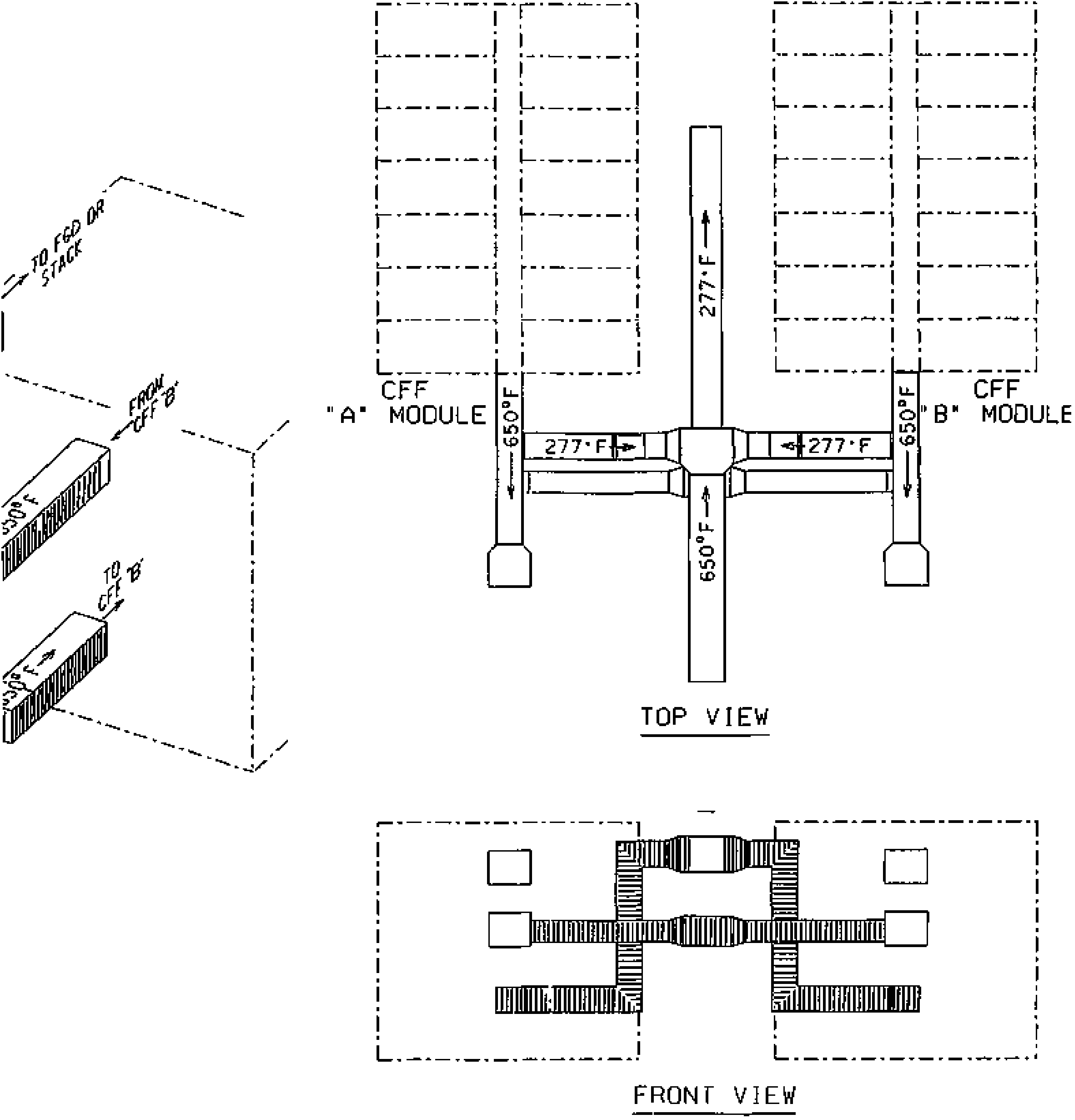

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GENERAL ARRANGEMENT

NEW PLANT CFF DUCT CONFIGURATION
CONVENTIONAL AIR HEATER LOCATION

SCALE: NONE	U.S. DEPARTMENT OF ENERGY CATALYTIC FABRIC FILTRATION FOR SIMULTANEOUS NOx AND PARTICULATE CONTROL

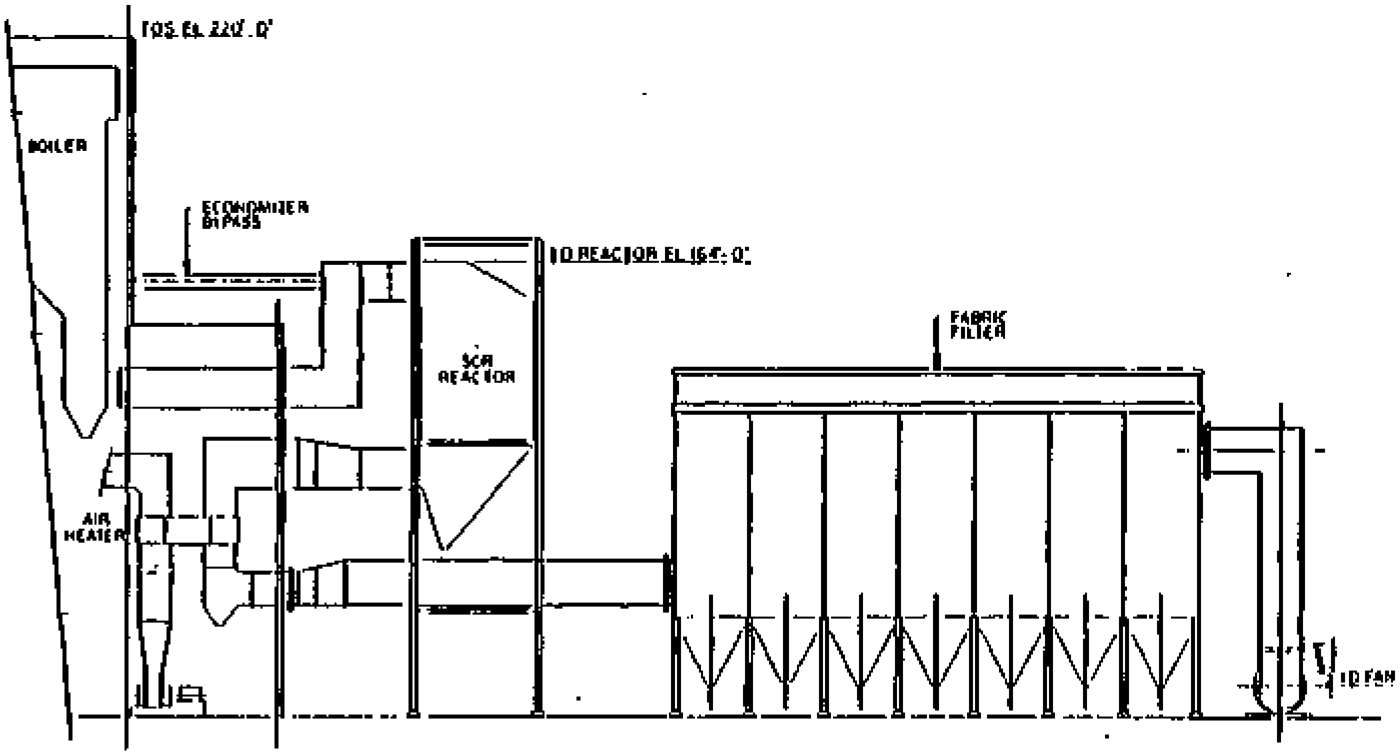
Raytheon Engineers & Constructors	DWG. NO.	FIGURE 3-2	
	ORDER NO.	6224.001	REV P

bottom of the SCR units through the return ducts back to the air heaters. The ductwork connecting the air heater outlet to the PJFF runs beneath the elevated SCR reactors. Flue gas exits the PJFF from the opposite end into the ID fans and FGD inlet. Figure 3-3 shows a typical hot side SCR equipment arrangement. The total (combined, all duct sizes) square feet of ductwork steel plate required for a 500 MW installation was estimated at 55,020 FT^2.

3.5 RESULTS

3.5.1 Equipment Costs

Figure 3-4 shows a breakdown of the installed equipment costs for the CFF. The ductwork cost reflects the cost for Arrangement 2, as described in Section 3.4 of this report. Figure 3-4 shows that the capital cost of the ductwork is a major cost component. With the ductwork cost being such a large portion of the capital costs, optimizing the ductwork arrangement is critical to the economic viability of the CFF. The initial complement of filter bags also represents a significant portion of the overall CFF capital costs. Reductions in filter bag costs will reduce both capital and levelized costs of CFF technology. Figure 3-5 presents the breakdown of SCR-PJFF capital costs. A computer printout of the complete breakdown of the equipment costs and associated installation and indirect charges is in Appendix A. The new plant CFF equipment list is included in Appendix B.



ELEVATION

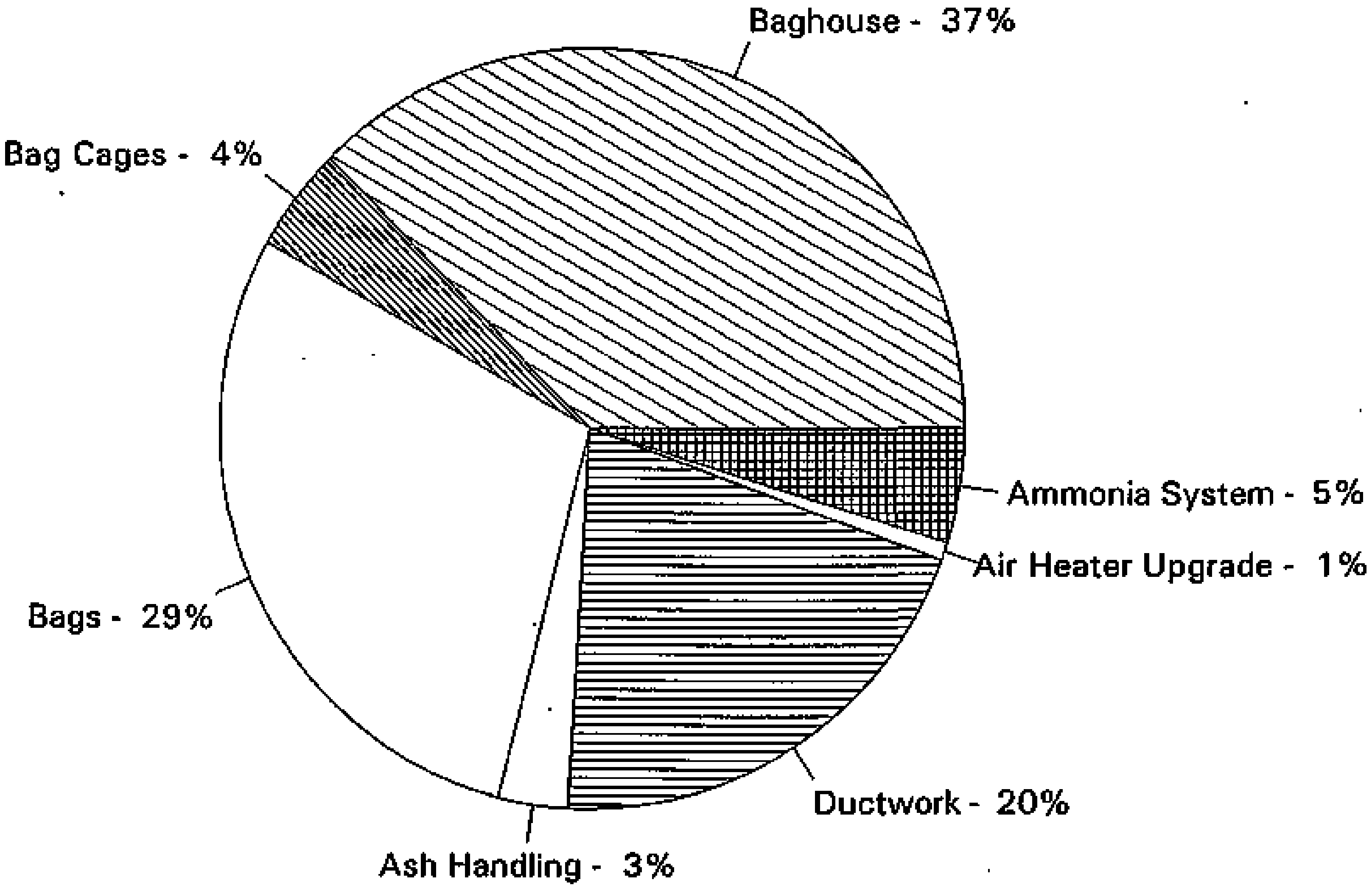
Figure 3-3
SCR General Arrangement: Elevation View

Reference: "Technical Feasibility and Cost of Selective Catalytic Reduction (SCR) NOx Control," EPRI Report No. GS-7266, May 1991.

FIGURE 3-4

CFF CAPITAL COST*

TOTAL INSTALLED EQUIPMENT COST BREAKDOWN - NEW 500 MW PLANT

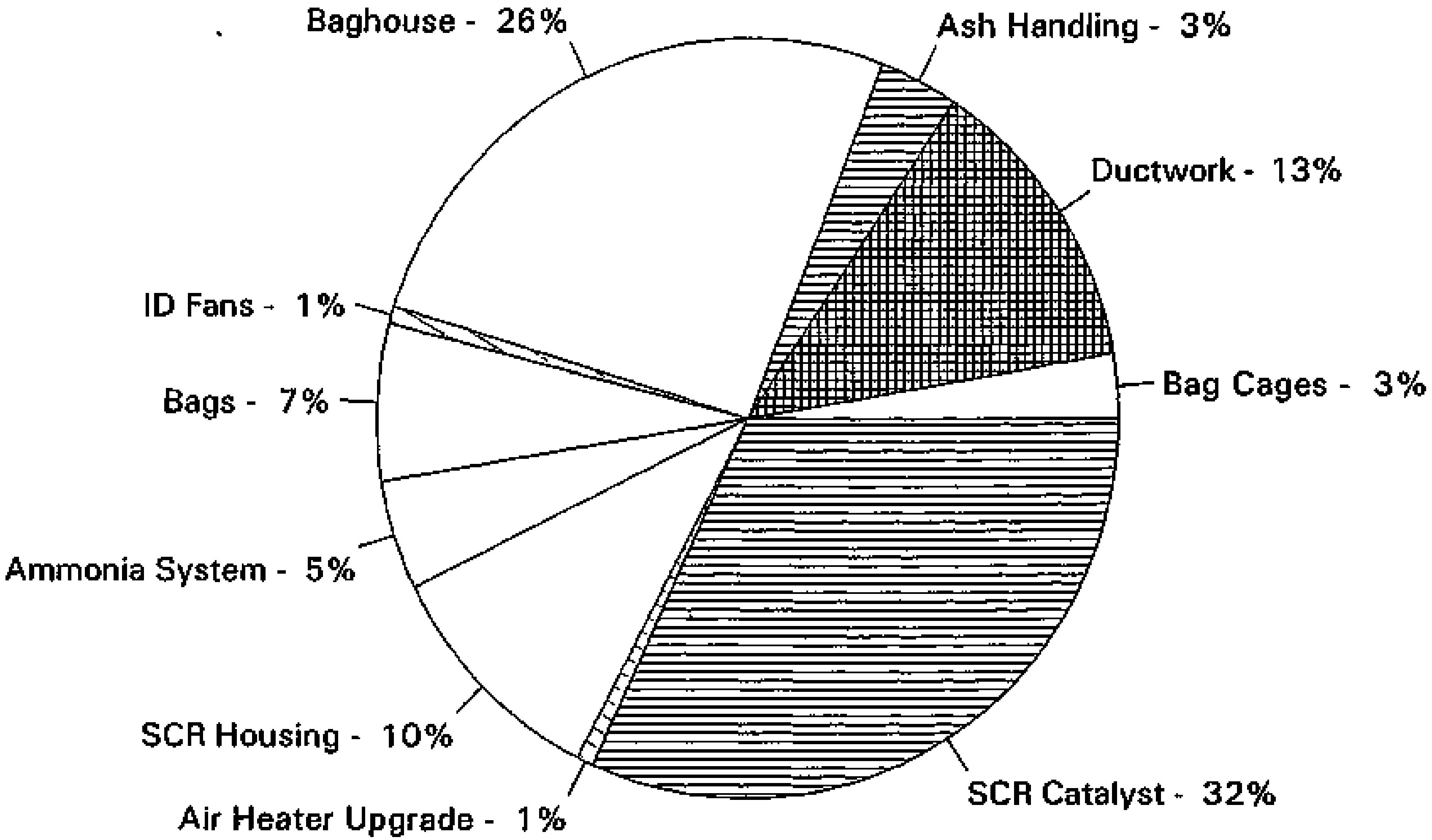


* TOTAL DOLLARS = K$54,782

FIGURE 3-5

SCR/PJFF CAPITAL COST*

TOTAL INSTALLED EQUIPMENT COST BREAKDOWN - NEW 500 MW PLANT



* TOTAL DOLLARS = K$56,905

3.5.2 Capital and Levelized Costs

Capital and levelized costs were developed for the CFF, SCR, and pulse jet baghouse. Figure 3-6 shows the Total Plant Investment (TPI) requirements for a Catalytic Fabric Filter system compared to a combined SCR and pulse jet fabric filter (SCR/PJFF) system. The TPI for the new CFF system is $145/kW. The TPI for the new SCR unit is $65/kW. The TPI for the new PJFF unit is $73/kW. The total TPI for the SCR/PJFF system is $138/kW, or 5% less than that of the CFF. Ductwork is broken out separately since plant arrangements can vary. Without ductwork, the TPI for the CFF is $117/kW, while the SCR/PJFF TPI is $119/kW excluding ductwork. The TPI for the CFF includes a seventeen (17) percent process contingency assessed against the CFF baghouse casing and filter bags (as recommended by EPRI TAG guidelines for unproven technologies) versus an eight (8) percent contingency for the SCR and PJFF processes. With these contingency costs removed, as illustrated in Figure 3-7, CFF capital requirements are 4% less than those of the SCR/PJFF.

Figure 3-8 shows the total current dollar (includes inflation) levelized costs in terms of mills/kWh. The SCR/PJFF system levelized cost is almost identical to that of the CFF.

The CFF system levelized costs are driven by the catalyst coated S2-glass bag replacement cost. The SCR system levelized costs are driven by SCR catalyst replacement and the difference in I.D. fan power required to overcome the pressure losses across both the SCR reactors and the PJFF.

FIGURE 3-6

CFF vs SCR/CONVENTIONAL BAGHOUSE
TOTAL PLANT INVESTMENT - NEW 500 MW PLANT

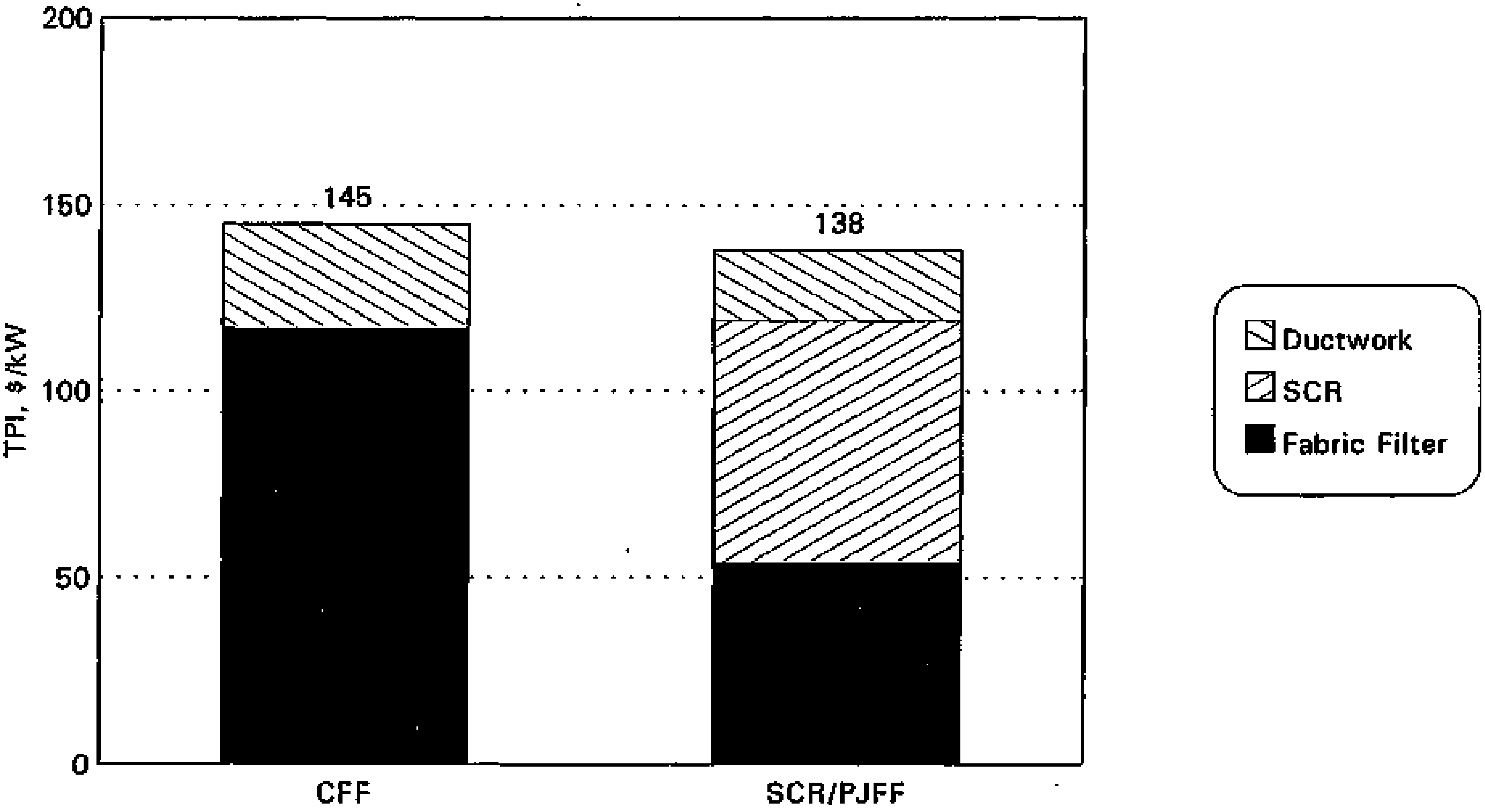


FIGURE 3-7

CFF vs SCR/CONVENTIONAL BAGHOUSE
TOTAL PLANT INVESTMENT - NEW 500 MW PLANT

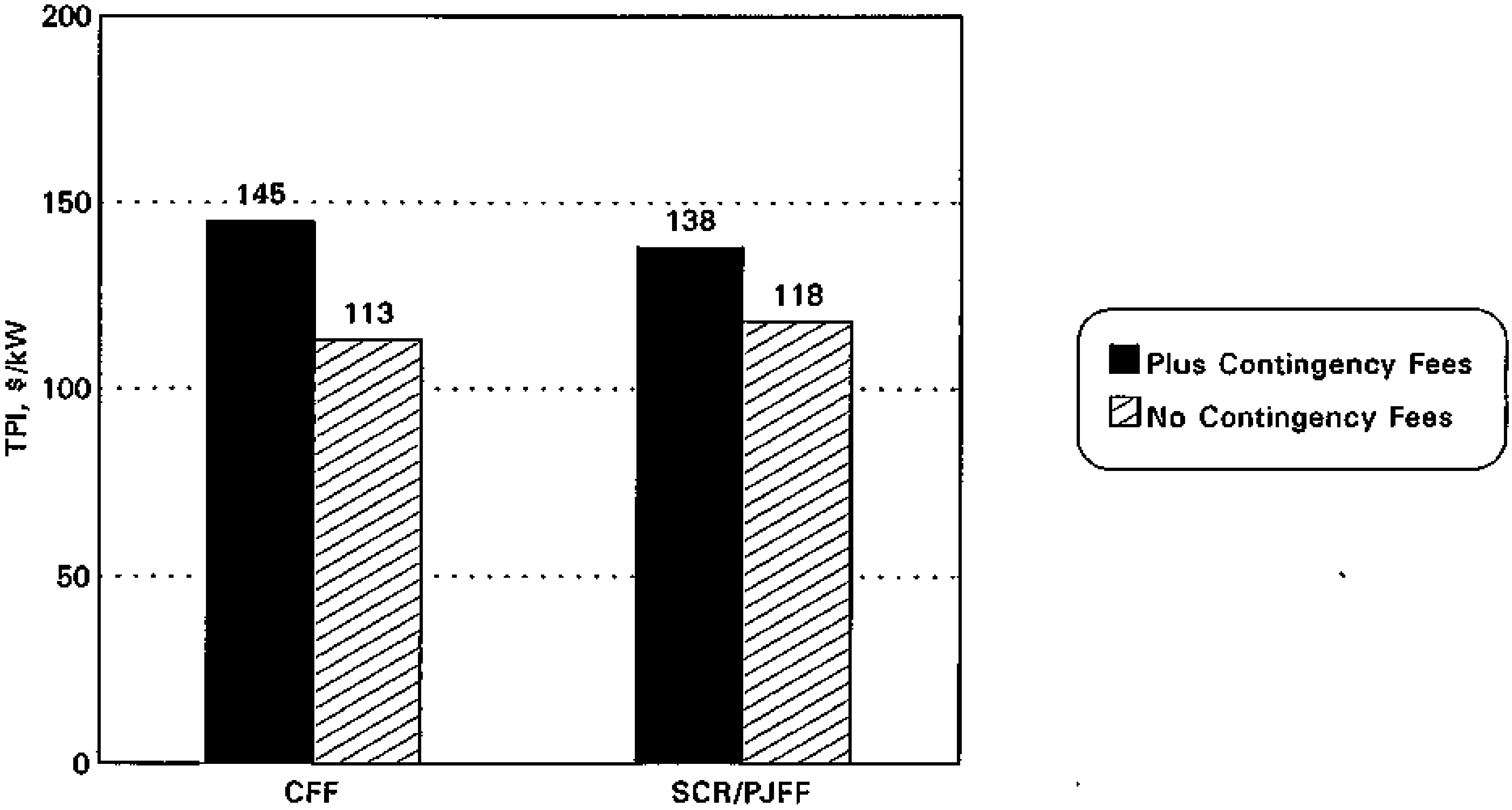


FIGURE 3-8

CFF vs SCR/CONVENTIONAL BAGHOUSE LEVELIZED COSTS - NEW 500 MW PLANT

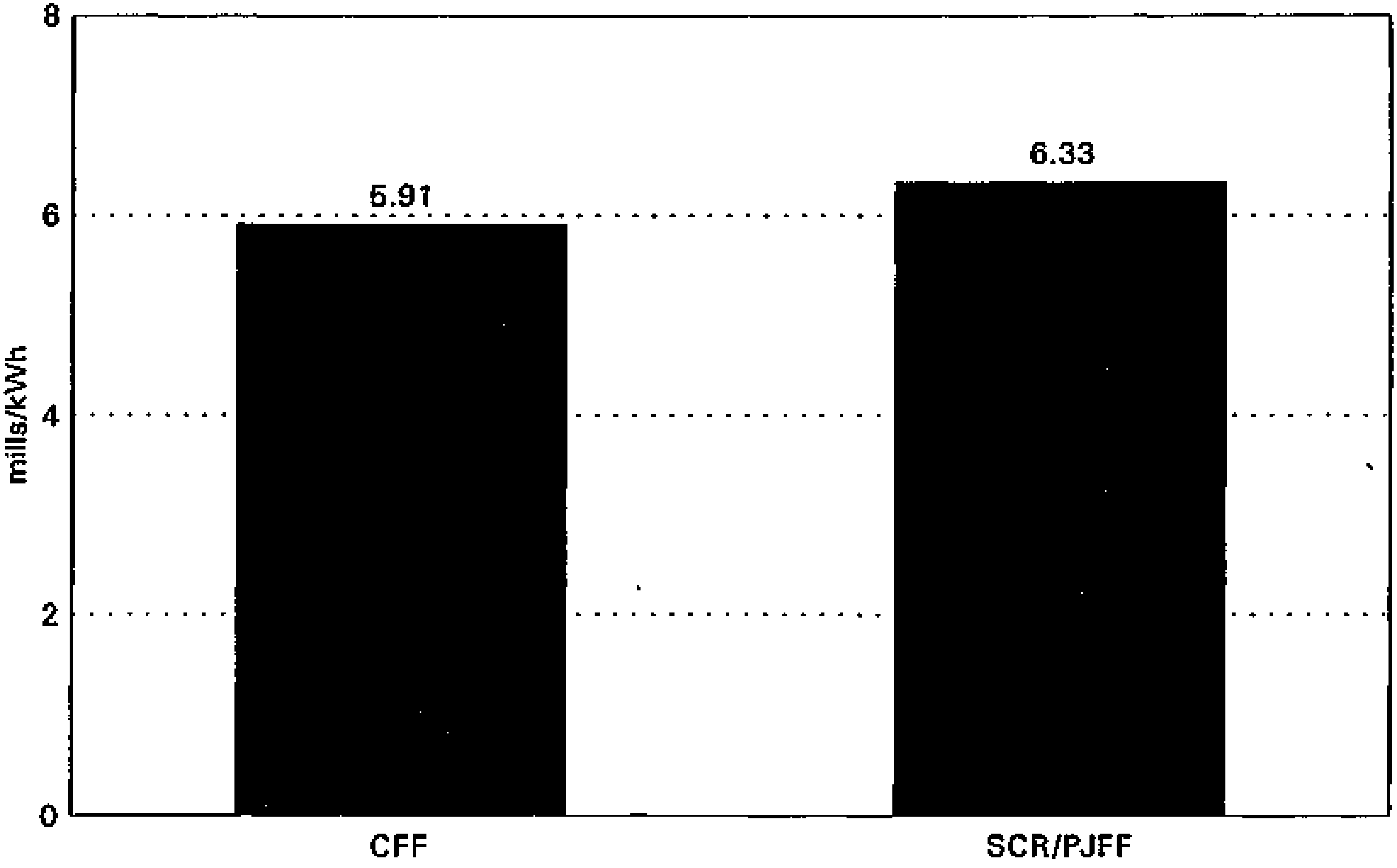


Figure 3-9 shows a partial breakdown of the levelized cost components in terms of mills/kWh. Figure 3-10 presents the costs compared in terms of levelized $/year. This levelized cost represents the amount of money which would be required each year to fully cover both the capital and operating/maintenance costs of that technology. For this 500 MW new plant case study, the CFF requires $1,400,000 less than the SCR/PJFF.

3.5.3 CFF Cost Sensitivity Analyses

Several cost sensitivity analyses were performed on the CFF base case to determine critical design and economic parameters. The sensitivity parameters examined are listed below and are presented in Figures 3-11 through 3-16 in order of decreasing sensitivity. The cost of the catalyst coated bags has the strongest influence on CFF economics and is shown in Figures 3-11 and 3-12. The SCR-PJFF base case cost is indicated on Figures 3-11 through 3-14 as a point of comparison.

- Bag Cost
- Bag Life
- A/C Ratio
- Plant Size, MW
- Inlet NO_x Concentration

Figure 3-11 shows a steady increase in levelized costs with increasing bag cost. Figure 3-12 shows the CFF bag cost sensitivity relative to capital cost. The figure shows that the capital cost breakeven point for the CFF and SCR/PJFF is approximately $212/bag. Figure 3-13 shows the decrease in levelized costs is most dramatic for a 1 to 2 year life but, the slope steadily decreases with increasing bag life. Figure 3-14 shows an expected reduction in costs due to higher air-to-cloth ratios.

FIGURE 3-9

CFF vs SCR/CONVENTIONAL BAGHOUSE
LEVELIZED COST BREAKDOWN - NEW 500 MW PLANT

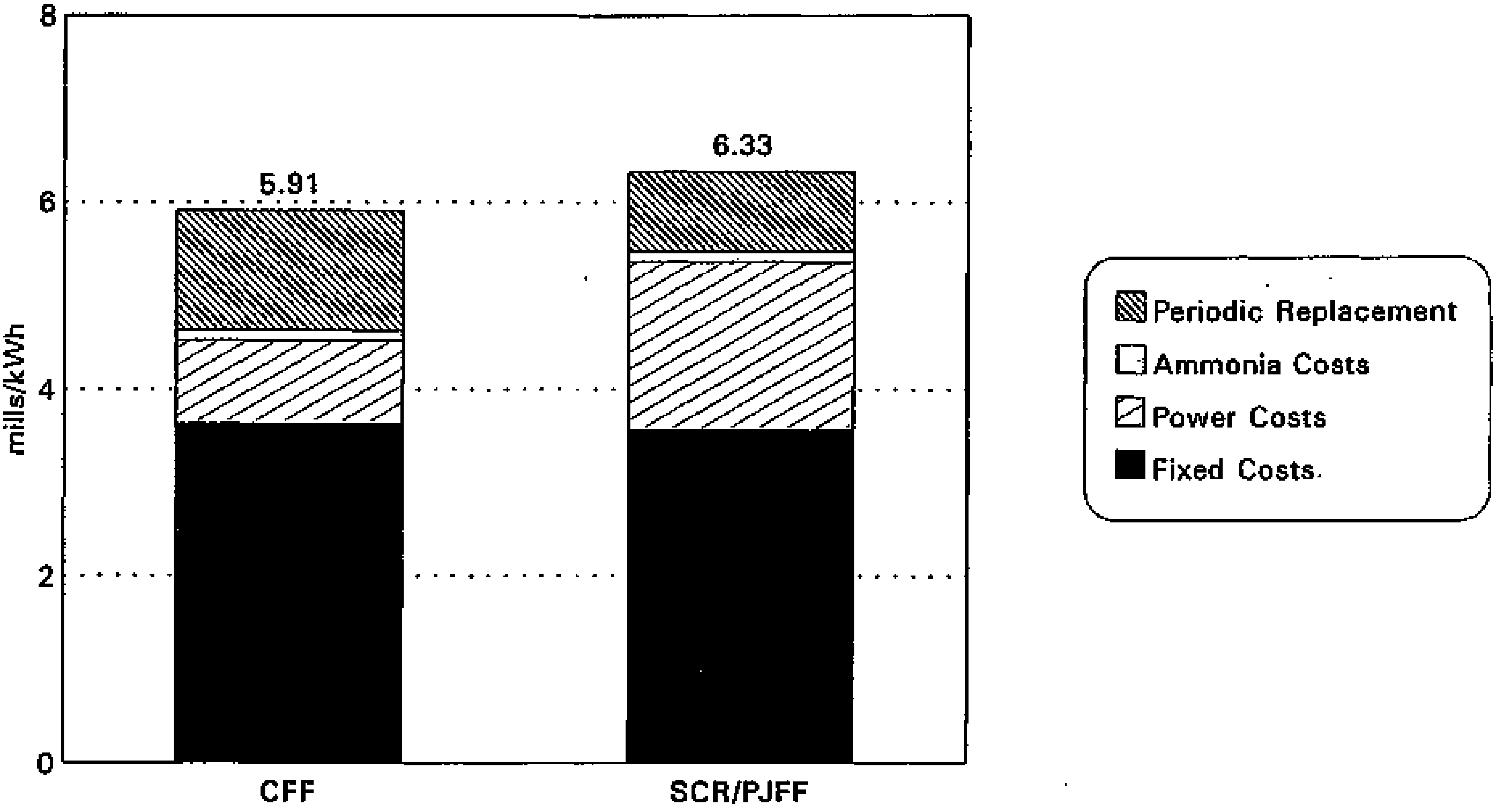
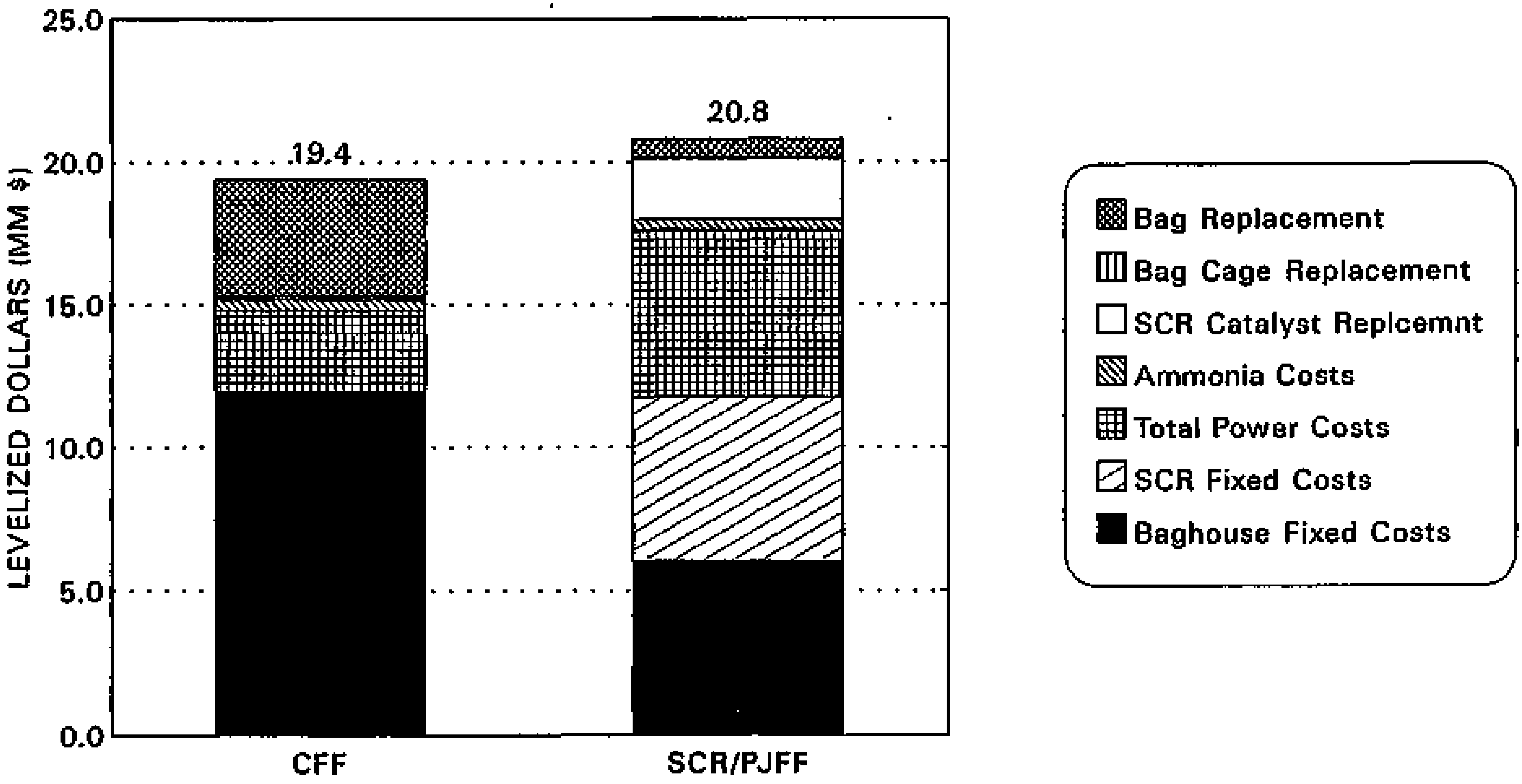


FIGURE 3-10

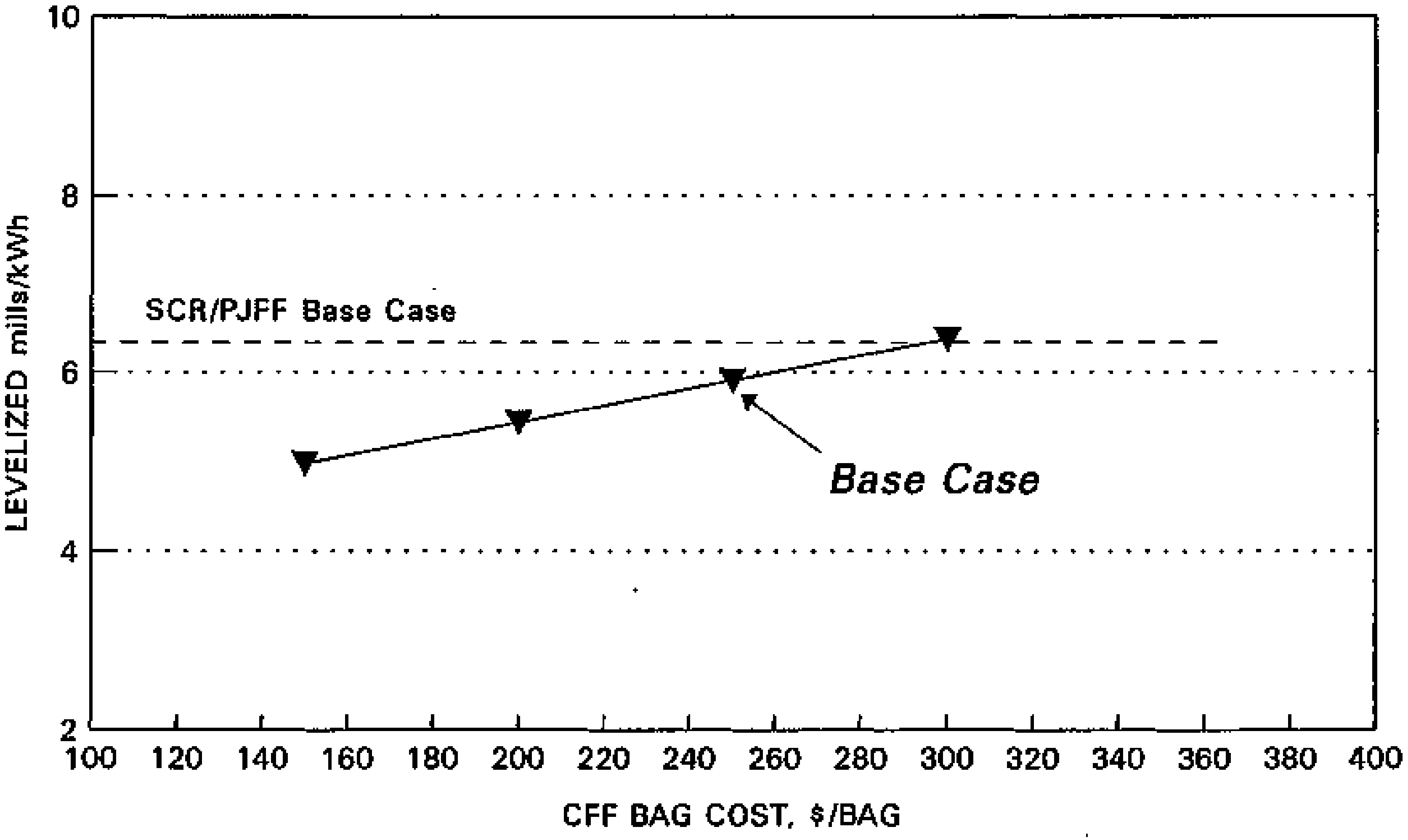
CFF vs SCR/CONVENTIONAL BAGHOUSE
LEVELIZED COST BREAKDOWN - NEW 500 MW PLANT*



*Levelized Annual Revenue Requirement

FIGURE 3-11

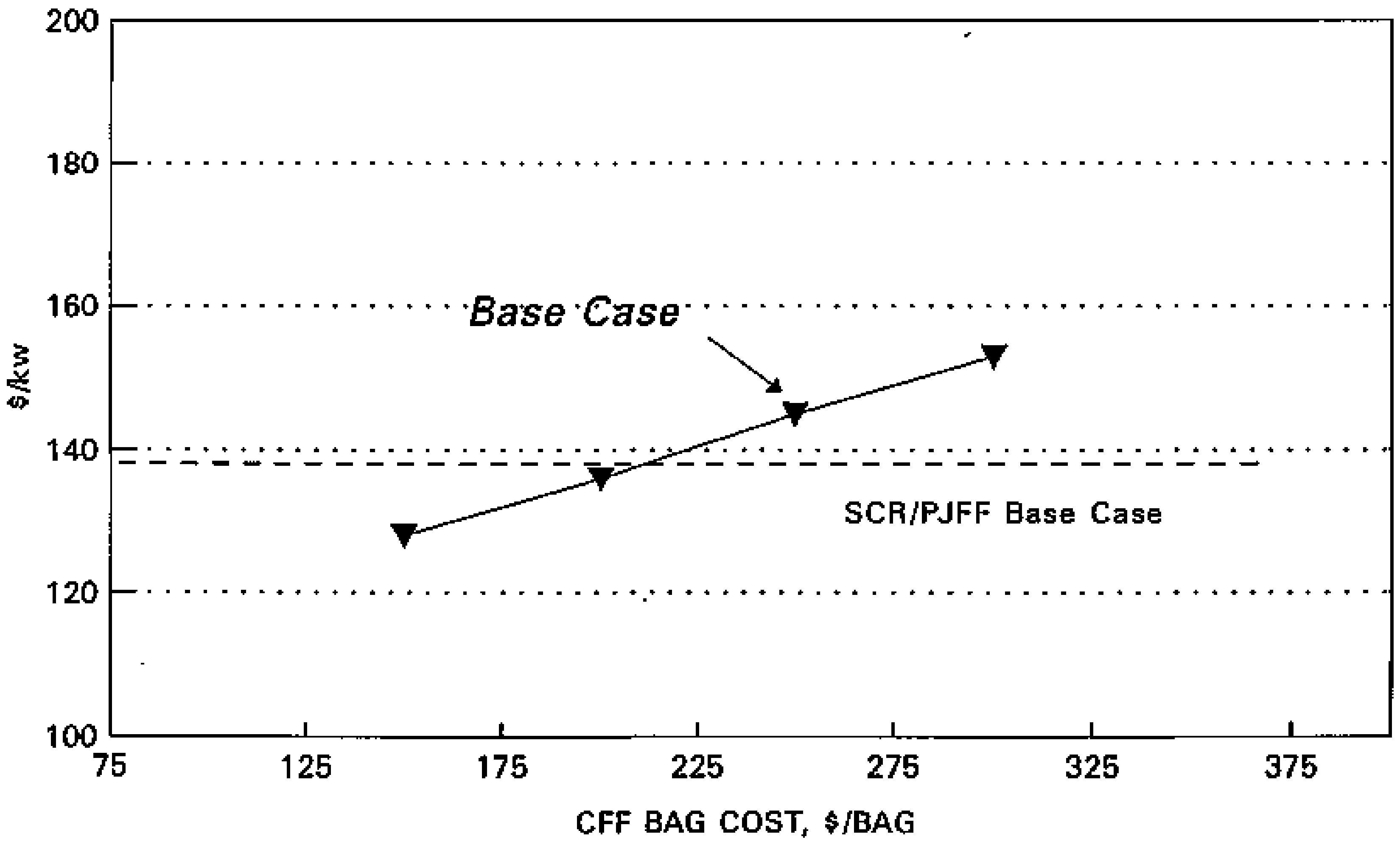
CFF SENSITIVITY PARAMETERS
BAG COST - NEW 500 MW PLANT*



*25,200 Total Bags, 2 Yr Bag Life

FIGURE 3-12

CFF SENSITIVITY PARAMETERS
BAG COST - NEW 500 MW PLANT*



*25,200 Total Bags, 2 Yr Bag Life

FIGURE 3-13

CFF SENSITIVITY PARAMETERS
BAG LIFE - NEW 500 MW PLANT

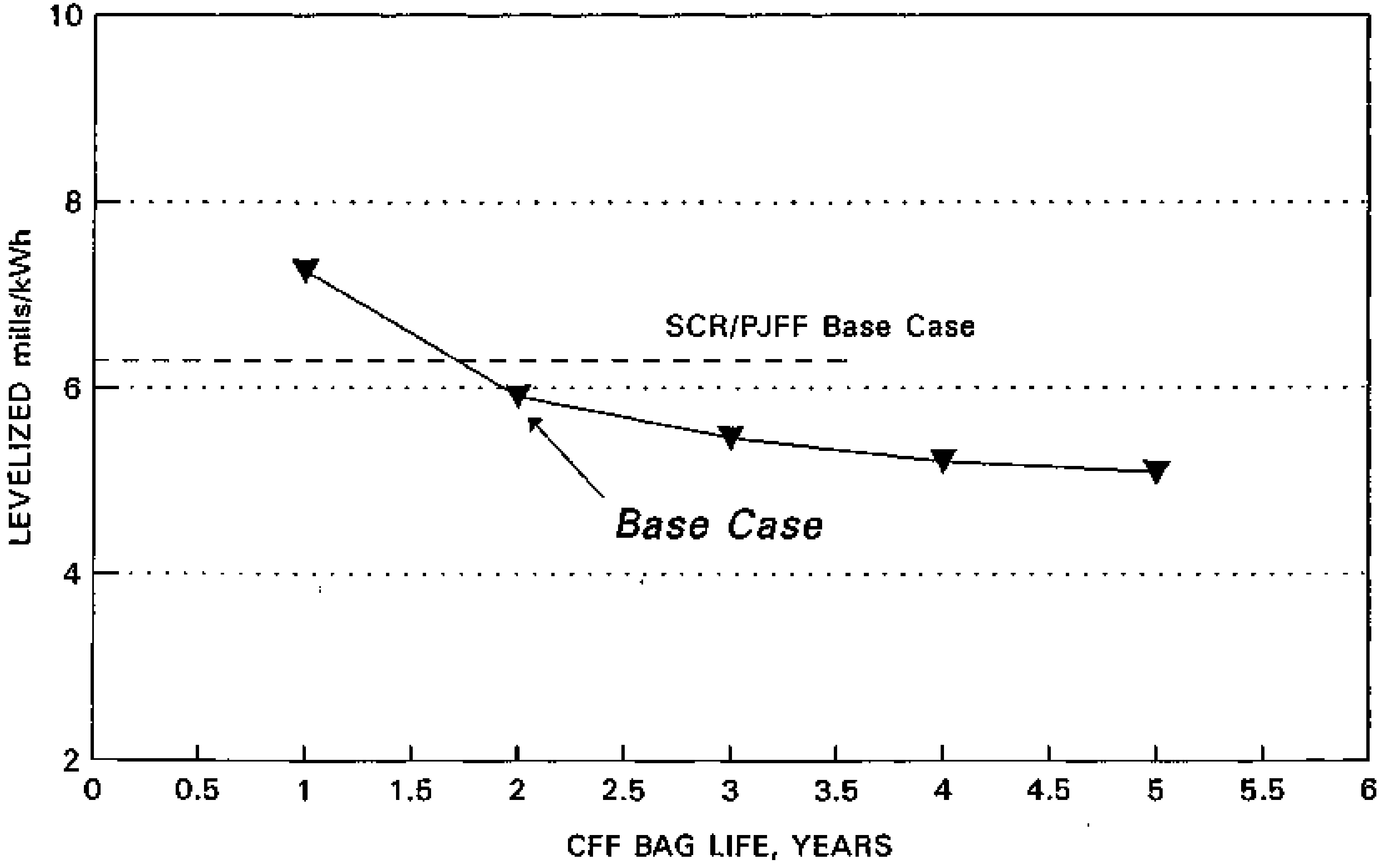


FIGURE 3-14

CFF SENSITIVITY PARAMETERS
AIR TO CLOTH RATIO - NEW 500 MW PLANT

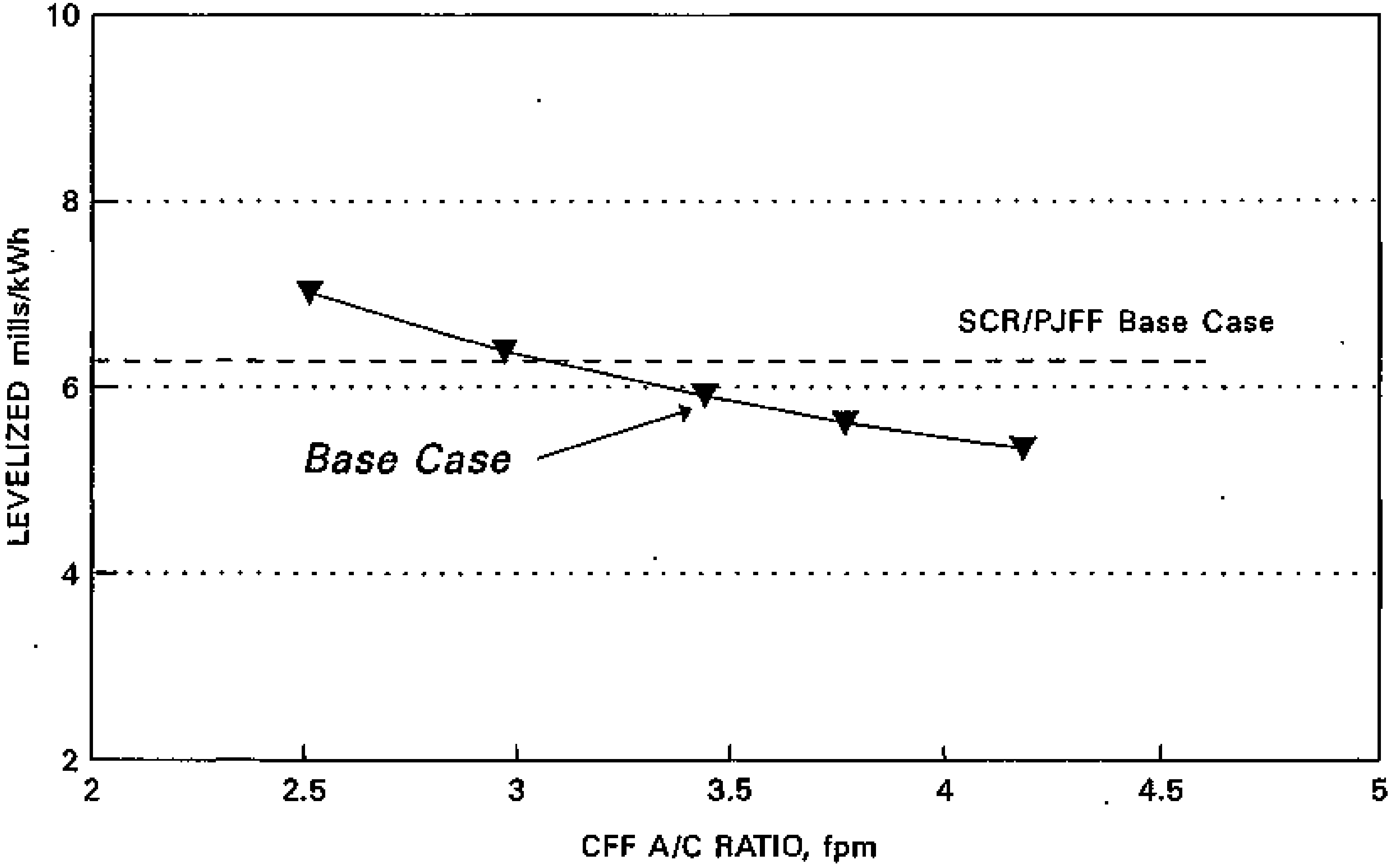
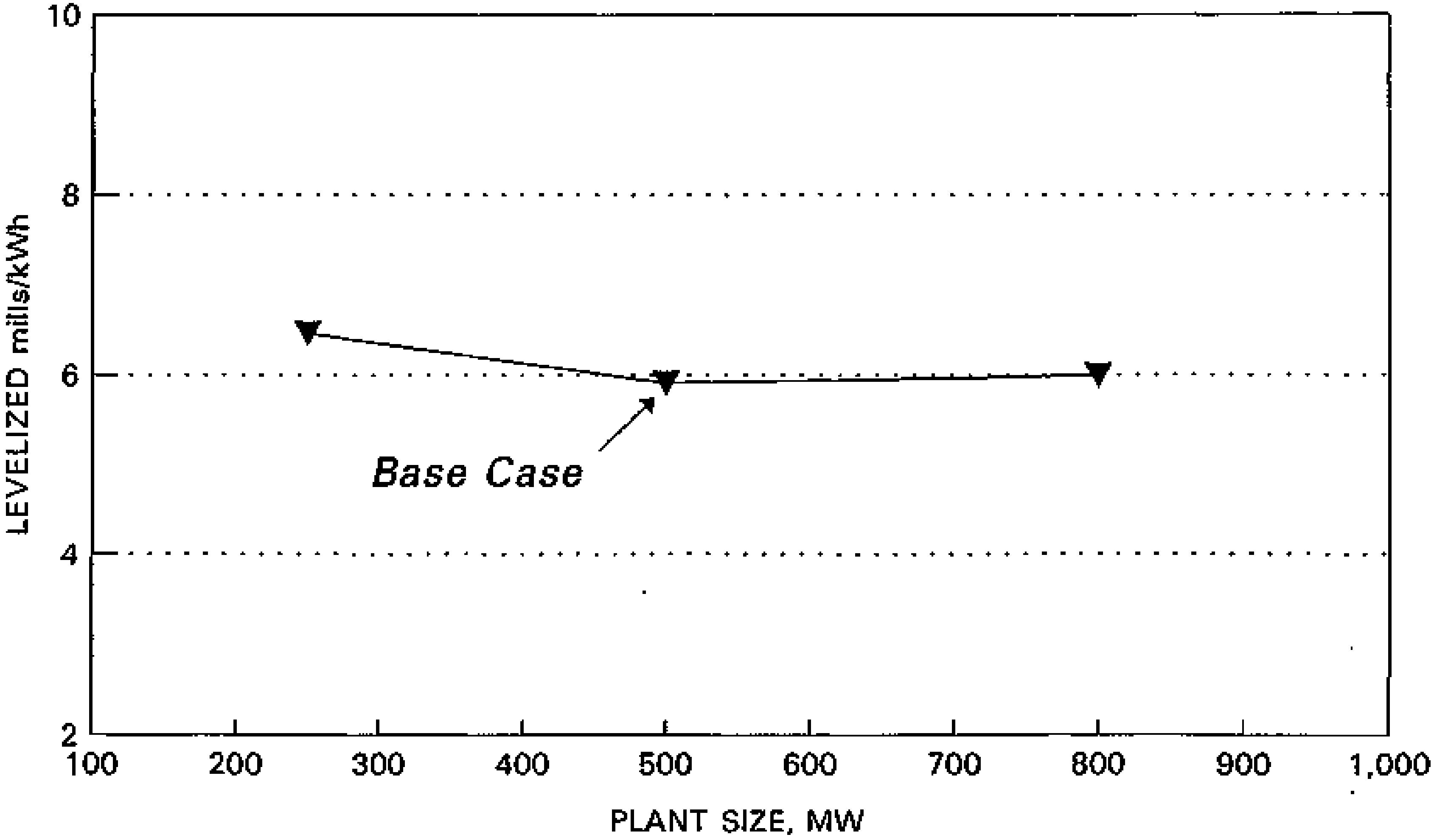


FIGURE 3-15

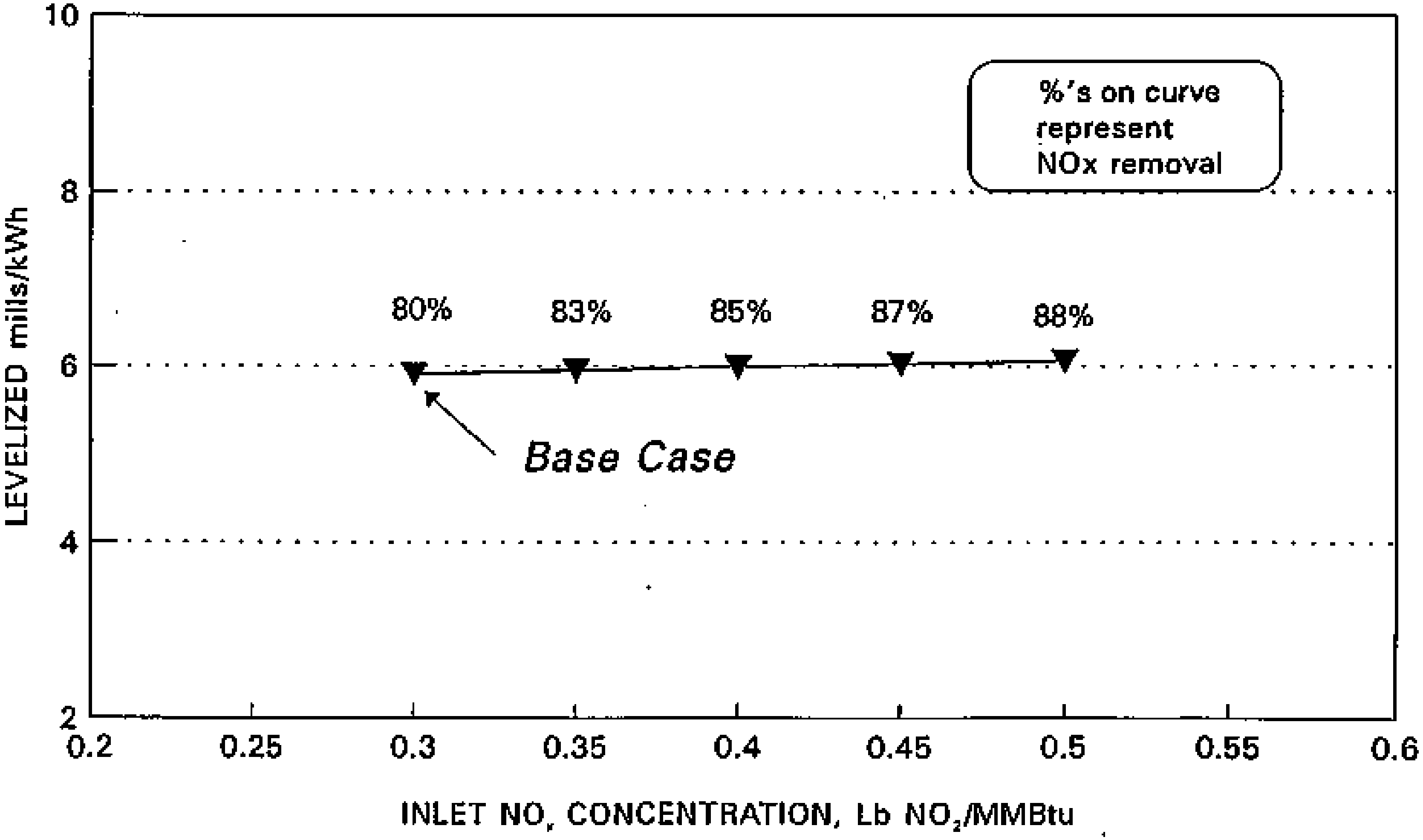
CFF SENSITIVITY PARAMETERS
PLANT SIZE, MW - NEW 500 MW PLANT*



*1 CFF Required for 250 MW, 2 Required for 500 MW, 3 Required for 800 MW

FIGURE 3-16

CFF SENSITIVITY PARAMETERS
INLET NO_x CONCENTRATION - NEW 500 MW PLANT*



* 0.06 Lb NO_x/MMBtu NO_x Emission Rate

Figure 3-15 shows a slight increase in levelized costs for units greater than 500 MW. The increase in levelized cost for units greater than 500 MW is due to the need for additional baghouses and ductwork required to accommodate the increased gas flow. The maximum practical size for an individual baghouse casing is 14 compartments (for acceptable gas flow distribution) and a maximum of 1000 bags/compartment which is equivalent to approximately 260 MW based on typical 650°F flue gas flow. The least sensitive parameter is the inlet NO_x concentration. The inlet NO_x concentration sensitivity was developed based on a 0.06 lb NO_x/MMBtu outlet emission rate for all inlet NO_x concentrations. NO_x removal ranges from 80% to 88% for the chosen inlet concentrations. Figure 3-16 shows the levelized mills/kWh cost increases slightly with increasing inlet NO_x concentration but the overall impact on the cost is negligible.

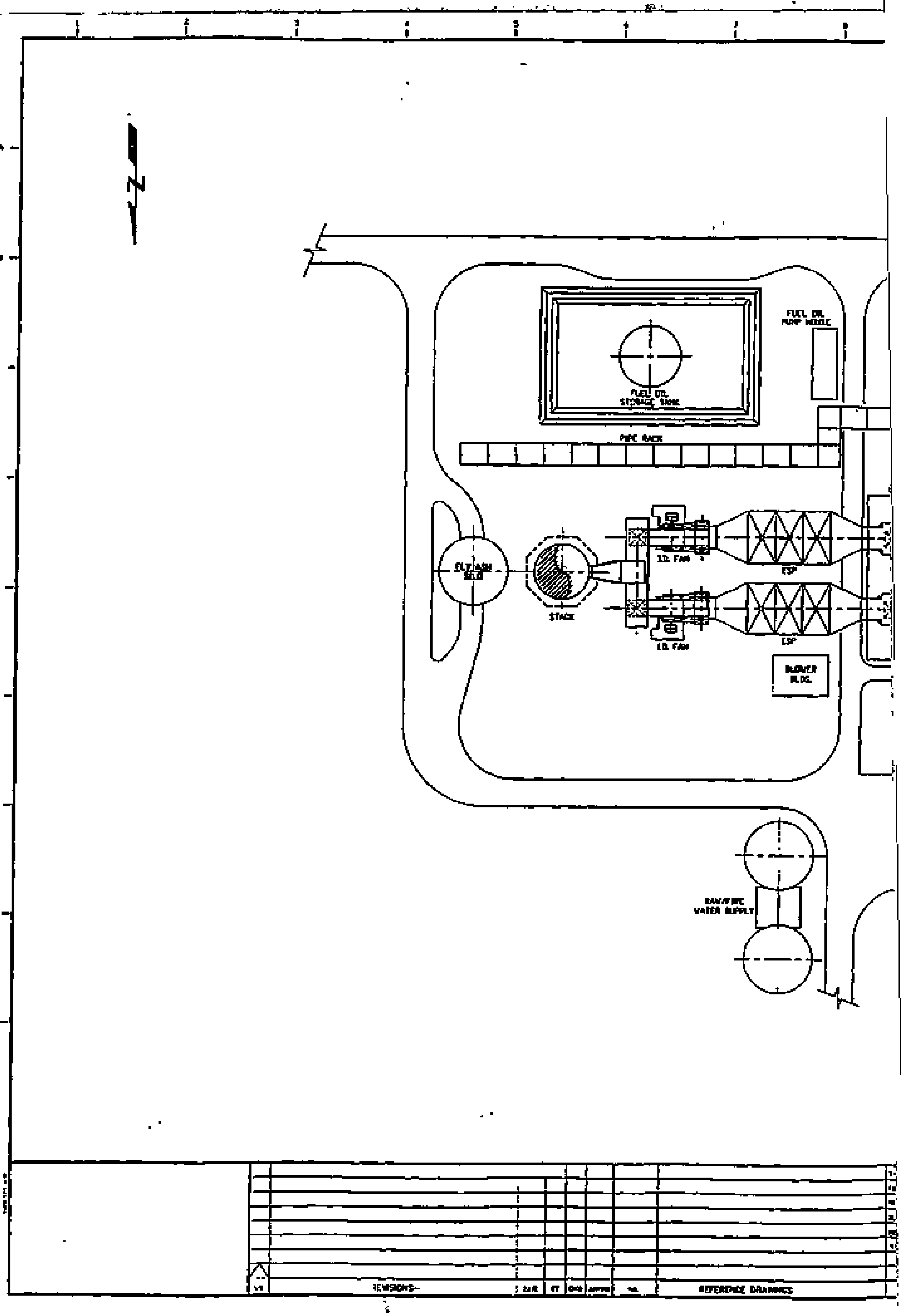
4.0 RETROFIT PLANT

Catalytic Fabric Filter Technology was also evaluated for retrofit applications. The site constraints at each plant will determine the feasibility and costs of retrofitting new plant equipment. For this study, a site was selected which represents a favorable scenario for a CFF retrofit. This site has limited available space for new equipment and is equipped with an undersized, underperforming electrostatic precipitator. The plant must reduce NO_x emissions to 0.08 lbs/MMBtu, and particulate emissions to 0.02 lbs/MMBtu.

4.1 GENERAL PLANT DESIGN CRITERIA

The retrofit plant design is based on a hypothetical medium capacity single boiler unit with a small underperforming ESP. The boiler has been retrofit with Low NO_x Burners (LNB) and Over Fire Air (OFA). Table 4-1 summarizes the critical boiler design parameters. The generating capacity of this unit is 250 MW net. The retrofit plant is located in western Pennsylvania and is assumed to be a moderately difficult retrofit situation. Figures 4-1 and 4-2 show the layout and elevation view of the existing plant equipment before the retrofit. The downtime required for construction and duct tie-in must be minimized to avoid excessive replacement power costs.

The selected fuel is a 2.27 percent sulfur Blacksville Bituminous coal (see Table 4-2). The boiler heat input rate is 2430 MMBtu/hr and the boiler output NO_x concentration is 0.40 lb NO_x/MMBtu.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FUEL OIL PUMP MODULE
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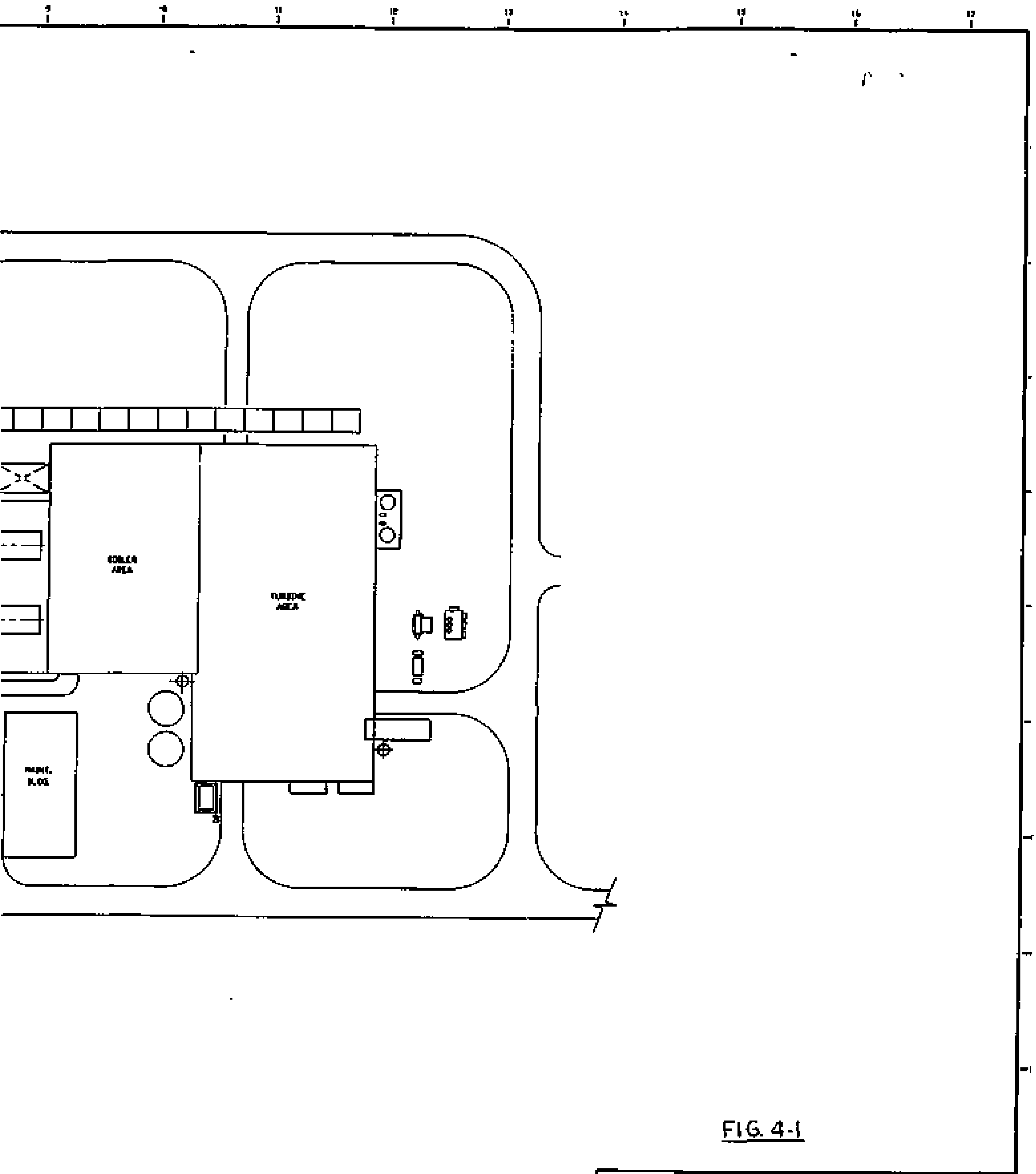

FIG. 4-1

250 MW POWER PLANT

GENERAL ARRANGEMENT
GROUND FLOOR PLAN
PRE-RETROFIT PLANT CONFIGURATION

U.S. DEPARTMENT OF ENERGY
CATALYTIC FABRIC FILTRATION FOR
SIMULTANEOUS NO_x AND PARTICULATE CONTROL

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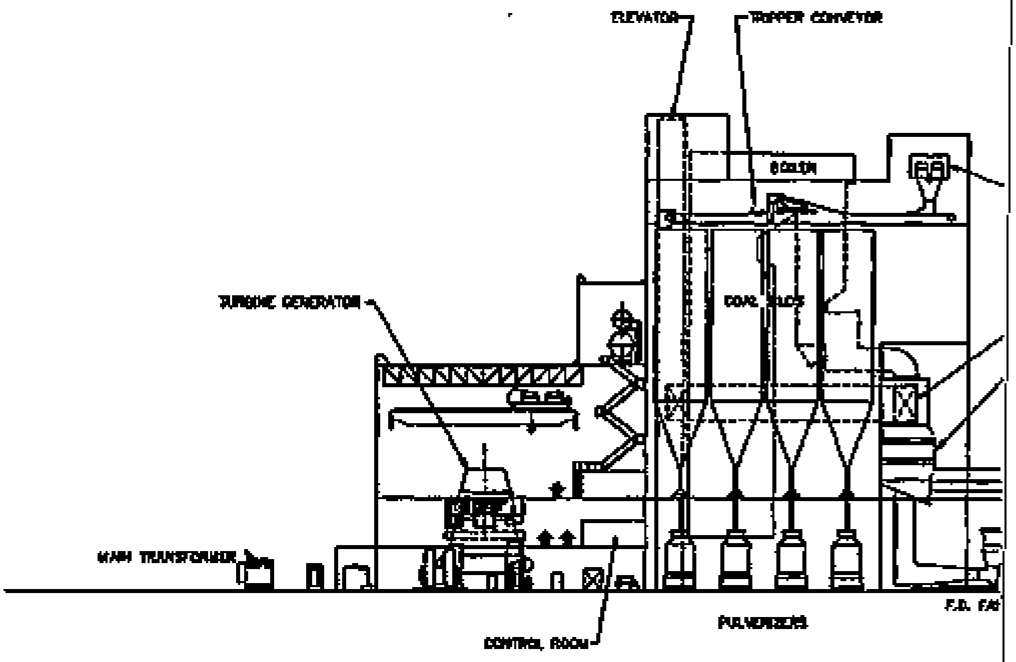

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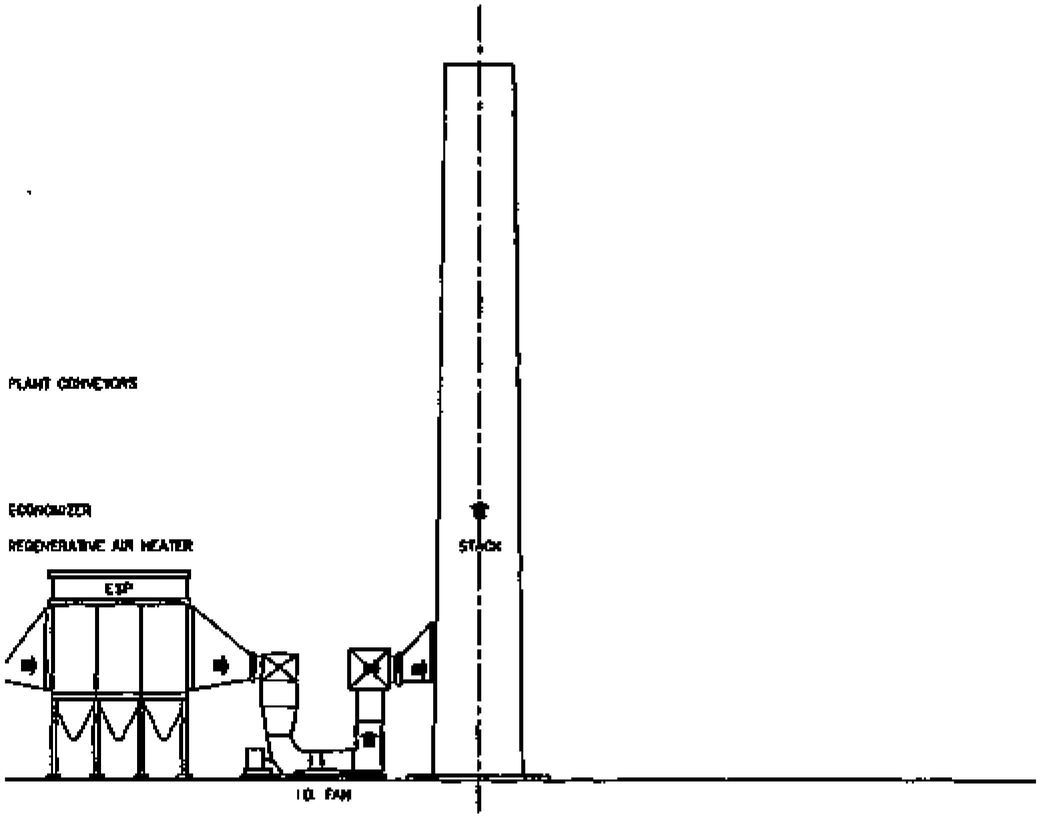
REFERENCE DRAWINGS



CTION "A"

FIG. 4-2

250 MW POWER PLANT

GENERAL ARRANGEMENT

SECTION

PRE-RETROFIT PLANT CONFIGURATION

U.S. DEPARTMENT OF ENERGY
CATALYTIC FABRIC FILTRATION FOR
SIMULTANEOUS NOx AND PARTICULATE CONTROL

6224.001

1"=40'

11-01-02-002

ENG. RECORD

DRAWING STATUS

PRINT RECORD

TABLE 4-1

RETROFIT PLANT GENERAL DESIGN CRITERIA

Design Criteria	Design Value
Unit Size	250 MW
Gas Flow Exiting Economizer	1,268,000 ACFM @ 650°F
NO_x Concentration Exiting Economizer - ppmv dry @ 3% O_2 - lbs/MMBtu	 455 0.40
Particulate Concentration Exiting Economizer	5.02 lbs/MMBtu 2.82 gr/dscf
Boiler Heat Input Rate	2,430 MMBtu/hr
Boiler Efficiency	88%
Excess Air	20%
Air Heater In-leakage	15%
Flue Gas Temperature - Exiting Economizer - Exiting Air Heater	 650°F 277°F

TABLE 4-2

COAL AND ASH ANALYSIS

EASTERN BITUMINOUS COAL USED IN CFF ECONOMIC ANALYSES

Proximate Analysis, wt%	
Moisture	1.70
Volatile Matter	41.24
Fixed Carbon	49.02
Ash	8.03
Ultimate Analysis, wt%	
Hydrogen	5.05
Carbon	74.86
Nitrogen	1.27
Sulfur	2.27
Oxygen	8.52
Ash	8.03
Heating Value, Btu/lb	13,401
Ash Analysis, wt%	
SiO_2	40.19
Al_2O_3	18.82
Fe_2O_3	23.63
TiO_2	0.78
P_2O_5	0.73
CaO	7.28
MgO	0.68
Na_2O	1.13
K_2O	1.11
SO_3	5.44

CRITICAL PLANT RETROFIT ISSUES

The retrofit of new pollution control equipment to an established plant site will require a variety of modifications to the existing plant equipment. For the purpose of this study, not all of these site specific items will be addressed in detail. In the comparison evaluation of the CFF and the SCR/PJFF, many of these modifications and plant upgrades are assumed equivalent. These include:

- Modifications to the plant Distributed Control System
- Modifications to the plant Power Distribution System and associated electrical equipment
- Modifications to the compressed air system (excluding pulse air systems)
- Miscellaneous plant utility interfaces
- Below grade modification/relocation
- Reinforcements to the boiler and back pass to accommodate increased draft requirements

These site specific costs can be substantial and must be carefully evaluated in the process selection and cost estimation of a prospective project.

The major plant equipment retrofit items which are addressed in this economic evaluation are:

- All interconnecting ductwork
- New induced draft (ID) fans to overcome additional pressure losses across the new pollution control devices and ductwork, and air heater deposition

- New fly ash piping to all pick-up points and associated valves. Existing blowers, silos and controls will be re-used.
- Air heater modifications to control deposition of ammonia sulfur compounds. New Corten baskets in cold end section, soot blowers and a washing system are included.

4.2 CATALYTIC FABRIC FILTER DESIGN

Table 4-3 summarizes the CFF Retrofit Plant Design Criteria. Catalytic Fabric Filter (CFF) process design criteria were developed from the results of the CFF laboratory and pilot plant tests conducted by EERC for this DOE project.[5] A 2 year life was assumed for the catalyst coated bags, but had not been confirmed by long term testing at the time of this report. A single flue duct leaves the economizer and enters the CFF. The 14 compartment CFF is designed as an intermediate pressure, intermediate volume pulse jet fabric filter. The 20 foot by 6 inch diameter bags used in the filter are an amorphous vanadium catalyst-coated woven S2-glass designed to simultaneously remove particulate matter (fly ash) and reduce the NO_x content of the flue gas, with the aid of ammonia injection upstream of the baghouse. To maintain NO_x particulate and ammonia emissions within design ranges, the fabric filter is sized based on a gross air to cloth ratio of 3.44 fpm. Cleaning is on-line. The air-to-cloth ratio with one 900 bag compartment out of service is 3.7 fpm.

The ammonia injection system is designed to provide 7 days storage of anhydrous ammonia. The anhydrous ammonia is stored in a horizontal pressure vessel and is vaporized using steam heat. The vaporized ammonia is metered to a dilution blower skid assembly and then injected through a distribution grid located in the duct upstream of the baghouse.

TABLE 4-3

CATALYTIC FABRIC FILTER 250 MW RETROFIT PLANT DESIGN CRITERIA

Design Criteria	Design Value
Total Gas Volume	1,268,000 ACFM
Gas Temperature	650°F
Inlet grain loading	5.02 lbs/MMBtu (2.82 gr/dscf)
Inlet NO_x	0.40 lbs/MMBtu (455 ppmv*)
Air to Cloth Ratio	
Net-1	3.70 fpm
Gross	3.44 fpm
Flange-Flange delta P	
Design	8" W.C.
Operating	6" W.C.
Bag Length	20′
Bag Diameter	6"
Bag Type	Catalyst Coated S2-glass
Bag Life	2 years
Number of Baghouses	1
Number of Bags/Compartment	900
Number Compartments/Baghouse	14
NH_3/NO_x Ratio	0.85 mol NH_3/mol NO_x inlet
NH_3 Feed Rate	321 lbs/hr
NH_3 Storage Capacity	7 days
Ammonia Slip	34 ppmv*
Particulate Emissions	0.02 lbs/MMBtu
NO_x Emissions	0.08 lbs/MMBtu (91 ppmv*)

* ppmv is dry @ 3% O_2

Control of the CFF NO_x reduction process utilizes a feed-forward/feedback system. Proper mole ratios of ammonia to NO_x are maintained by regulating the flow of ammonia to the dilution air skid on the basis of feed-forward signals from boiler load and the inlet NO_x analyzer. Feedback from the CFF outlet NO_x analyzer is used to adjust the molar ratio. Outlet ammonia concentration is monitored (pending commercial availability of a continuous NH_3 analyzer) and will override the outlet NO_x concentration signal at the maximum ammonia slip limit.

During startup, the control system does not permit the injection of ammonia until the CFF temperature is above the minimum (600°F) catalyst temperature. These controls also interrupt ammonia flow should reactor temperature fall below the critical minimum.

During shutdown, controls interrupt ammonia flow when reactor temperatures fall below approximately 600°F; however, the dilution air blower continues to operate to purge the system and is shut down with the I.D. and F.D. fans. If an emergency shutdown is required, ammonia flow would be interrupted by the master fuel trip interlock signal, but the dilution air blower would continue to operate on auxiliary power to purge the system.

The CFF is designed for a particulate emissions rate of 0.02 lbs/MMBtu or, 0.011 gr/dscf. The ammonia injection system is designed for 80% NO_x reduction across the CFF. The ammonia is injected at a rate of 0.85 mol NH_3/mol NO_x entering the fabric filter. The maximum ammonia slip is 34 ppmv.

4.3 SCR/CONVENTIONAL BAGHOUSE DESIGN

Hot side Selective Catalytic Reduction (SCR) to control NO_x, in combination with a cold side pulse jet fabric filter (PJFF) design to control particulate emissions, was selected as a basis for economic comparison and feasibility of a full-scale CFF unit.

4.3.1 Selective Catalytic Reduction (SCR)

Flue gas leaves the economizer and enters a single SCR reactor before returning to the air heater. The SCR reactor is designed as a vertical gas flow unit with a rectifying grid at the reactor inlet to promote even gas flow distribution. The reactor is also designed with sufficient volume to add a spare catalyst layer, if required. The SCR unit is designed for 80% NO_x reduction at an ammonia to NO_x ratio of 0.8. Resulting is a NO_x emission rate of 0.08 lbs/MMBtu or 91 ppmv. The ammonia slip is 5 ppm. Table 4-4 summarizes the SCR design criteria.

The ammonia injection system is designed to provide 7 days storage of anhydrous ammonia. The anhydrous ammonia is stored in a horizontal pressure vessel and is vaporized using steam-heat. The vaporized ammonia is metered to a dilution blower skid assembly and then injected through a distribution grid located in the duct upstream of the SCR reactor.

TABLE 4-4

SELECTIVE CATALYTIC REDUCTION
250 MW RETROFIT PLANT DESIGN CRITERIA

Design Criteria	Design Value
Gas Temperature	650°F
Total Gas Volume	1,268,000 ACFM
Flange-Flange delta P	
Design	11" w.c.
Operating	8" w.c.
NO_x Entering SCR	0.4 lbs/MMBtu (455 ppmv*)
NO_x Removal	80%
NH_3/NO_x Ratio	0.8 mol NH_3/mol NO_x
NH_3 Feed Rate	302 lbs/hr
NH_3 Storage Capacity	7 days
Ammonia Slip	5 ppmv
Number of Reactors	1
Catalyst Space Velocity	3,200 NCF/ft^3/hr
Catalyst Life	4 years
Number of Catalyst Layers/Reactor	4
NO_x Emissions	0.08 lbs/MMBtu (91 ppmv*)

* ppmv is dry at 3% O_2

4.3.2 Pulse Jet Fabric Filter (PJFF)

Flue gas from the air heater is ducted to a single 10 compartment Pulse Jet Fabric Filter (PJFF). The PJFF is an intermediate pressure, intermediate volume design sized for an air to cloth ratio of 4.0 ft/min with one 800 bag compartment off-line for maintenance. The air-to-cloth ratio is typical of utility scale pulse-jet fabric filters with felted Ryton bags.[6] The Ryton filter bags measure 20 feet long by 6 inches diameter. Table 4-5 presents the PJFF design criteria.

4.4 DUCTWORK AND EQUIPMENT ARRANGEMENT

Locating the catalytic fabric filter to minimize ductwork requirements is critical to the project costs since the hot gas exiting the CFF must return to the air heaters before going to the stack. The situation is further complicated in retrofits since most of the construction must be done around existing plant equipment while the plant is operating. A relatively brief (6 to 8 weeks) outage is assumed for ductwork tie-ins and various interfaces.

Catalytic Fabric Filter Arrangement

Figure 4-3 shows the general arrangement of the CFF equipment. The CFF is erected to the north of the existing ID fans and stack. The CFF inlet and outlet ductwork is tied into the economizer outlet and air heater inlet, respectively. The existing air heater outlet ductwork, ESPs and ESP outlet duct are re-used in this arrangement. Because the CFF removes nearly all of the particulate from the flue gas, the existing ESPs are deenergized and the fly ash removal system is removed from service. Costs to remove ESP internals and fly ash piping are not included.

TABLE 4-5

CONVENTIONAL PULSE JET FABRIC FILTER RETROFIT PLANT DESIGN CRITERIA

Design Criteria	Design Value
Total Gas Volume	866,000 ACFM
Gas Temperature	277°F
Inlet Grain Loading	5.02 lbs/MMBtu (2.45 gr/dscf)
Air to Cloth Ratio	
Net-1	4.0 fpm
Gross	3.70 fpm
Flange-Flange delta P	
Design	8" W.C.
Operating	6" W.C.
Bag Length	20 ft
Bag Diameter	6 in
Bag Type	Ryton Felt
Bag Life	3 years
Number of Baghouses	1
Number Bags/Compartment	800
Number Compartments/Baghouse	10
Particulate Emissions	0.02 lbs/MMBtu (0.011 gr/dscf)

Because the CFF and new ductwork add approximately 10 inches w.c. (design) of pressure loss, additional induced draft fan capacity is required. The existing ID fans at the retrofit plant like many older plants, are assumed to operate near capacity at full load. A series ID booster fan was installed adjacent to the existing fans and ducted back into the existing stack breaching.

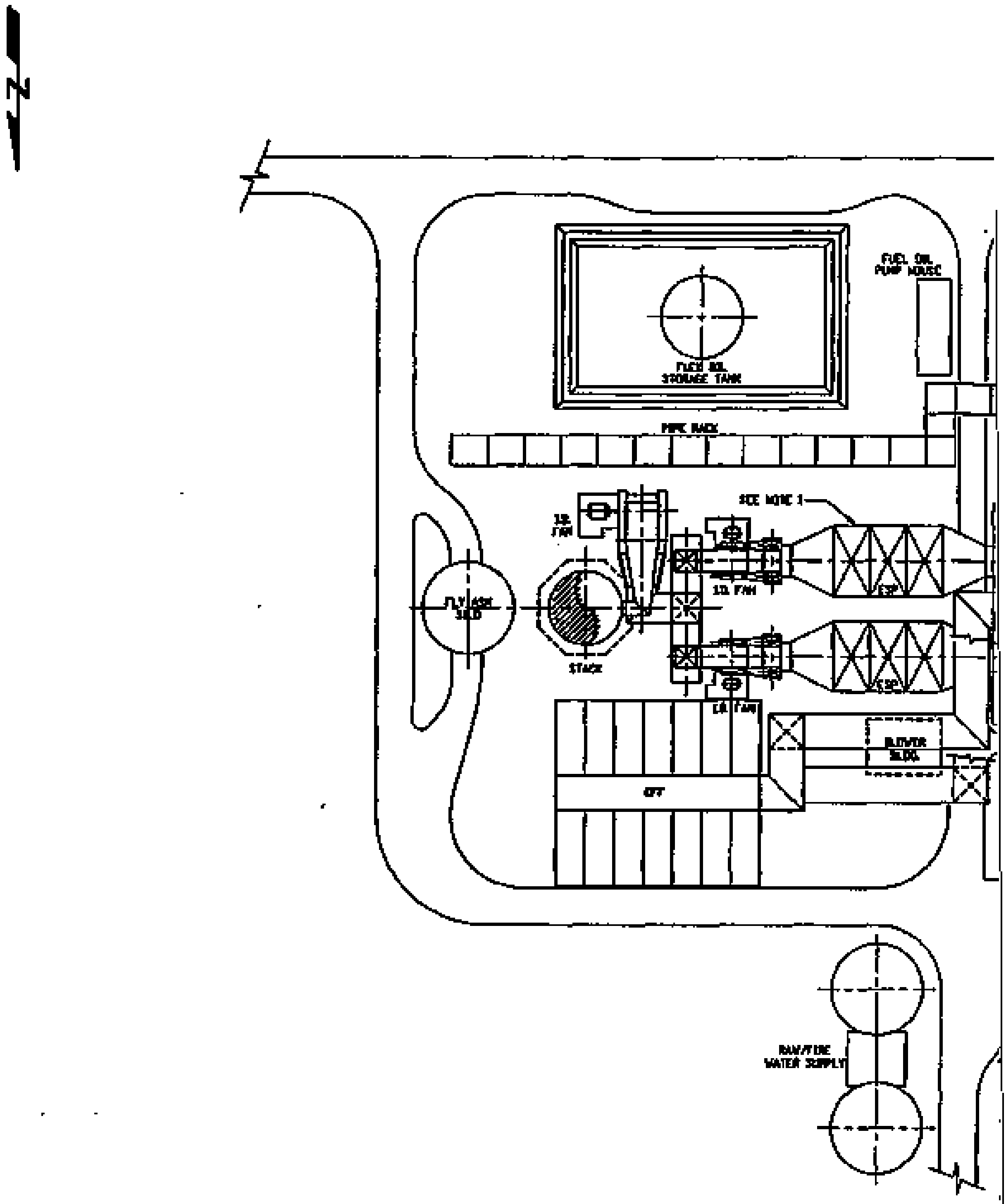
SCR-PJFF Arrangement

Figure 4-4 shows the general arrangement of the hot side SCR reactor, cold-side pulse jet fabric filter and all associated ductwork. The SCR inlet and outlet ductwork is tied into the economizer outlet and air heater inlet, respectively. New ductwork runs along the north side of the existing ESPs to the PJFF. A new full capacity ID fan is required, since it is not practical to duct back into the existing equipment. The existing ESP ductwork and ash piping are abandoned in place. A new duct connects the ID fan to the existing stack breaching. Costs to demolish and remove the abandoned ESP, ductwork, and ash piping are not included.

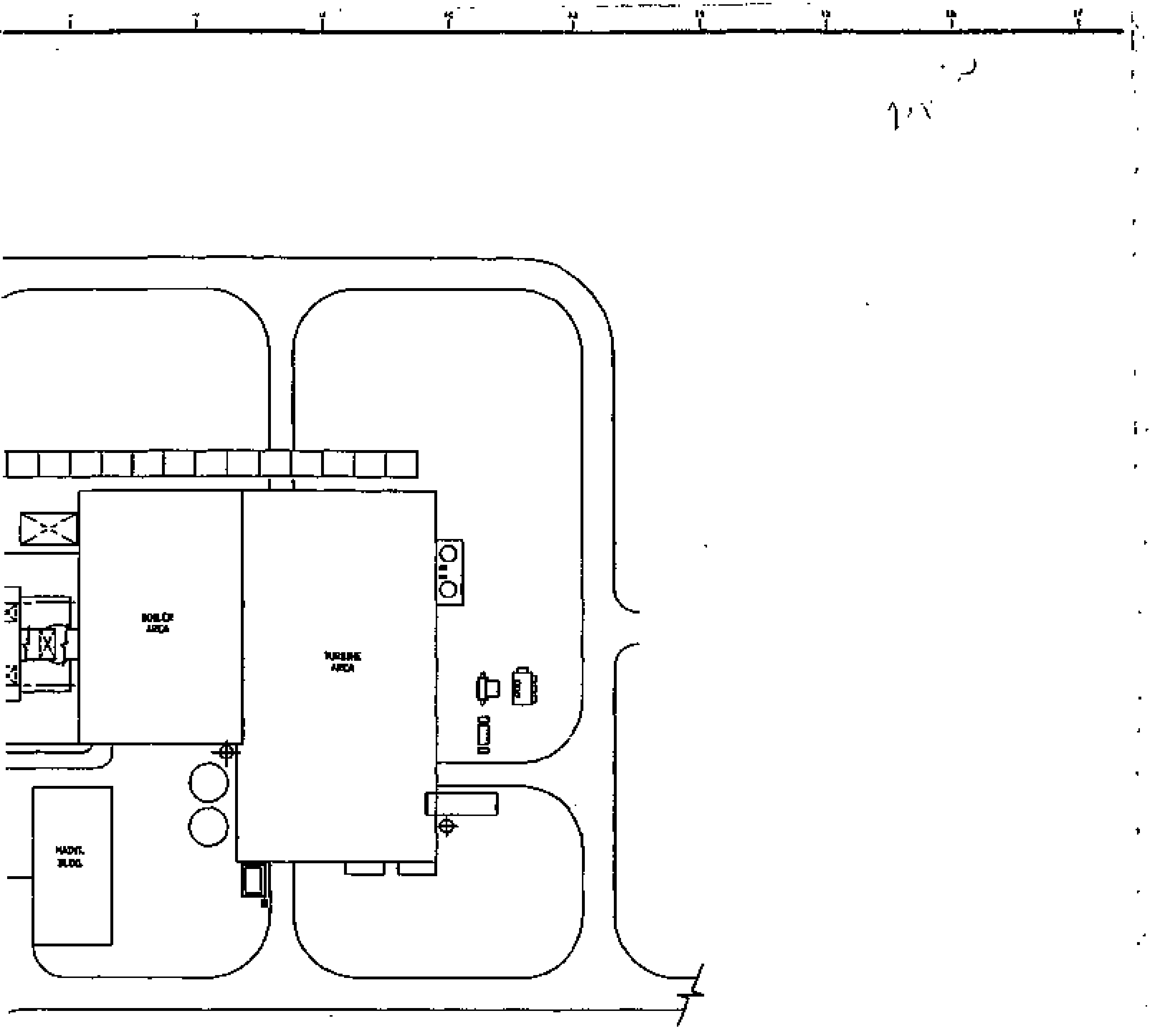
4.5 RESULTS

4.5.1 Equipment Costs

Figure 4-5 shows a breakdown of the installed equipment costs for the CFF. Figure 4-5 shows that the capital cost of the ductwork is nearly 80% of the cost of the flange to flange CFF. With the ductwork cost being such a large portion of the capital costs, optimizing the ductwork arrangement is critical to the economic viability of the CFF.



NO.	REVISIONS	DATE	BY	CHK	APPVD	NO.	REFERENCE DRAWINGS
△							



NOTES:
1. EXISTING ESP'S ARE DE-ENERGIZED AND USED AS DUCTWORK

FIG. 4-3

250 MW POWER PLANT

GENERAL ARRANGEMENT
GROUND FLOOR PLAN
CFF-RETROFIT PLANT CONFIGURATION

U.S. DEPARTMENT OF ENERGY
CATALYTIC FABRIC FILTRATION FOR
SIMULTANEOUS NOx AND PARTICULATE CONTROL

JOB NO.	SCALE		DWG. NO.	REV
6224.004	1"=40'	Raytheon Engineers & Constructors	11-01-02-004	A

DATE									
FOR									
ISSUED									
CUSTOMER									
FIELD									
[illegible]									

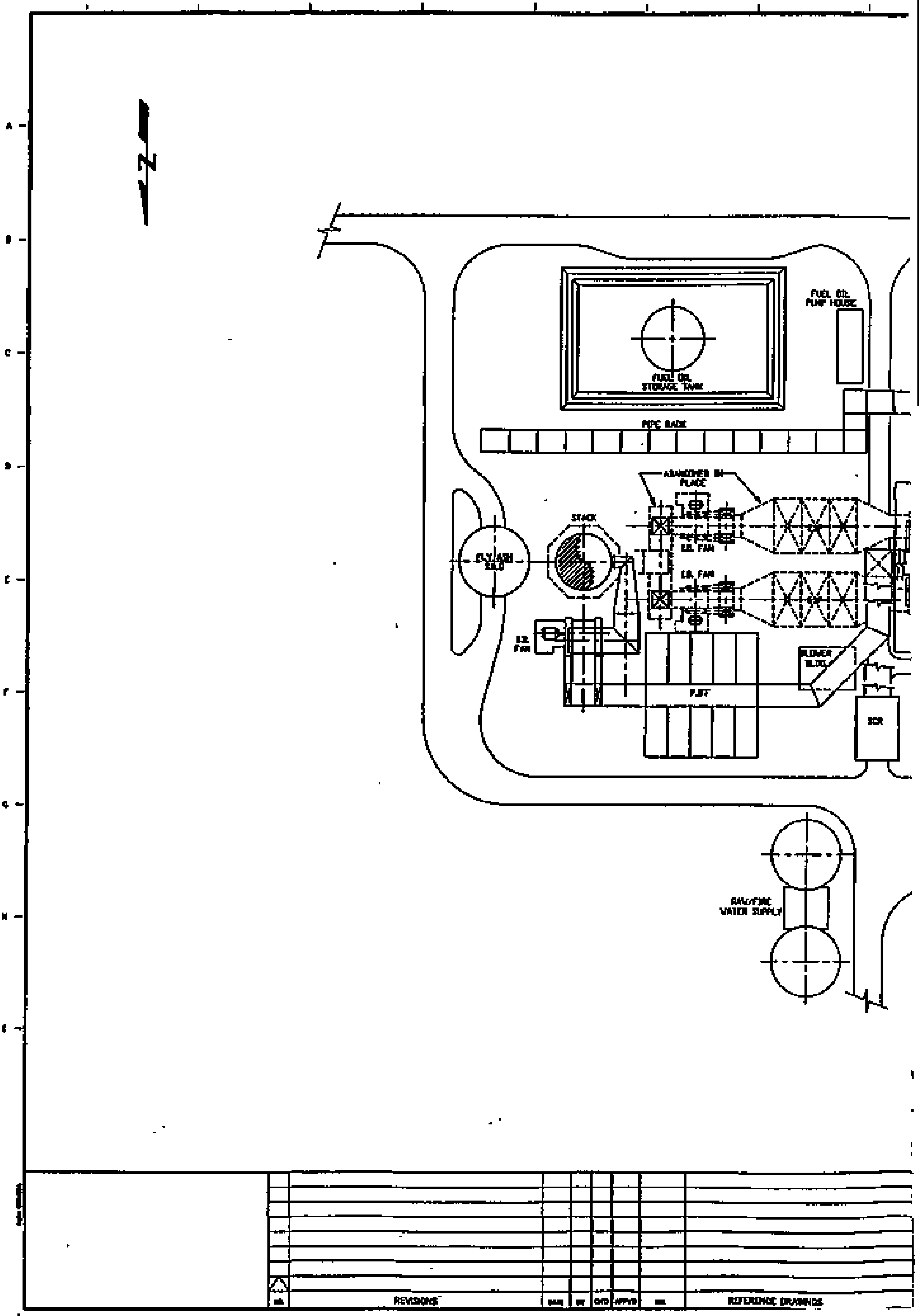
PRINT RECORD

DWG. RECORD

DRAWN		
CHECKED		
MECHANICAL		
STRUCTURAL		
ELECTRICAL		
CIVIL		
CONTROL SYSTEMS		
[illegible]		
[illegible]		

DRAWING STATUS

STATUS	DATE
PRELIMINARY FOR COMMENTS AND/OR APPROVAL ISSUED APPROVED FOR CONSTRUCTION	
ISSUED APPROVED FOR CONSTRUCTION	

A
B
C
D
E
F
G
H
I
N
FUEL OIL PUMP HOUSE
FUEL OIL STORAGE TANK
PIPE RACK
ABANDONED IN PLACE
STACK
I.D. FAN
I.D. FAN
FLY ASH SILO
I.D. FAN
BLOWER BLDG.
PJFF
SCR
RAW/FIRE WATER SUPPLY
REVISIONS
REFERENCE DRAWINGS

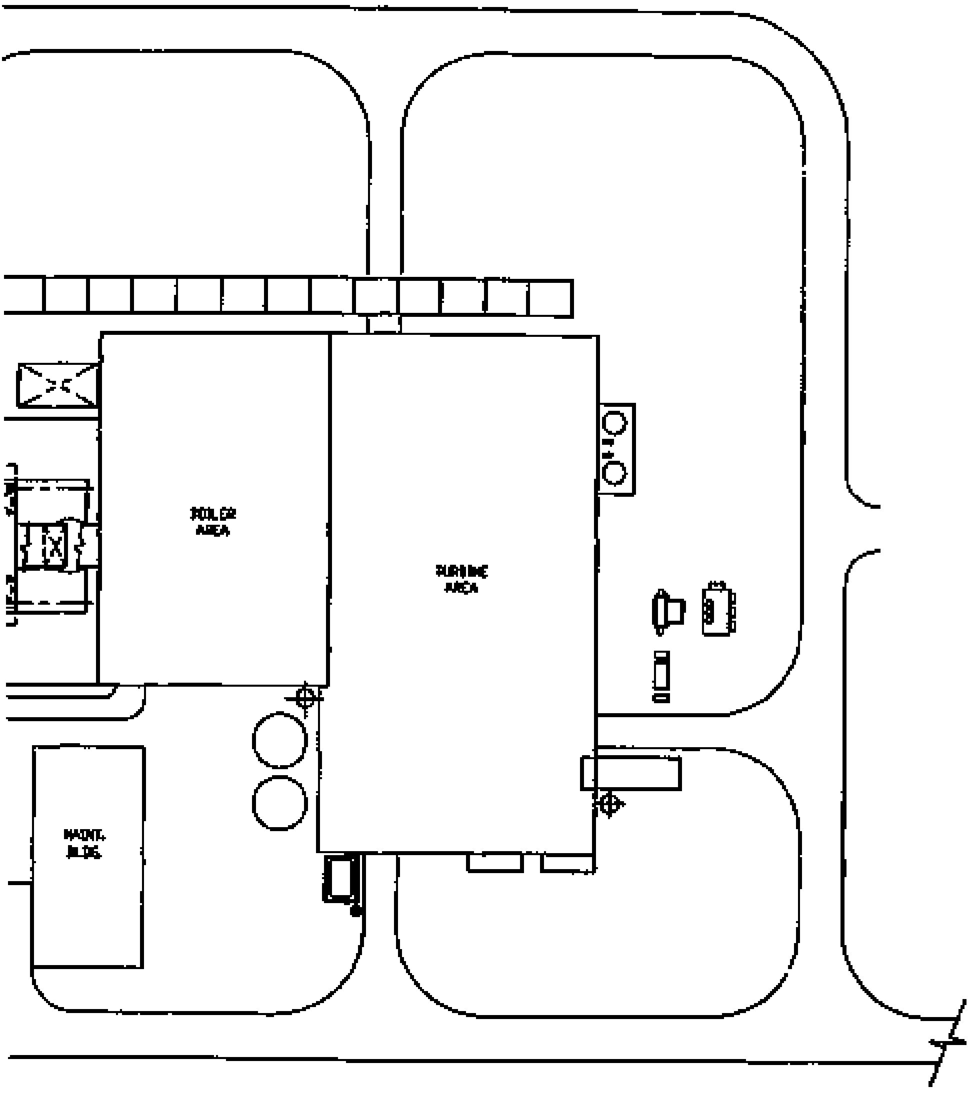


FIG. 4-4

250 MW POWER PLANT

GENERAL ARRANGEMENT
GROUND FLOOR PLAN
SCR/PJFF-RETROFIT PLANT CONFIG.

U.S. DEPARTMENT OF ENERGY
CATALYTIC FABRIC FILTRATION FOR
SIMULTANEOUS NOx AND PARTICULATE CONTROL

Raytheon

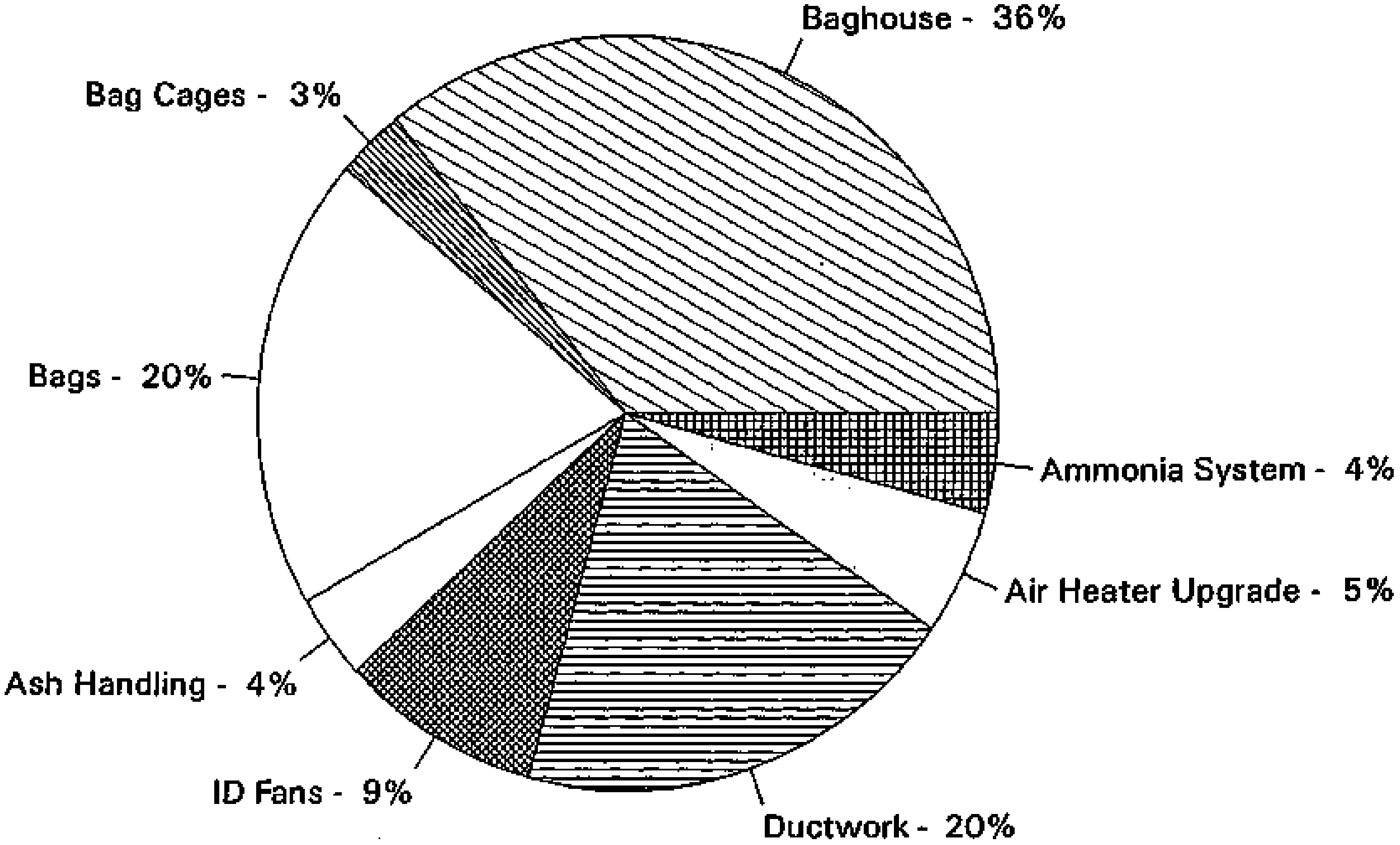
ENG. RECORD

DRAWING STATUS

PRINT RECORD

FIGURE 4-5

CFF CAPITAL COST
TOTAL INSTALLED EQUIPMENT COST BREAKDOWN - RETROFIT 250 MW PLANT*



* TOTAL DOLLARS = K$40,713

The cost of the catalyst coated filter bags are a second major component of the overall CFF capital costs. Reduction in bag, costs will also improve the CFF economics. Figure 4-6 shows the breakdown of the SCR/PJFF equipment costs.

A computer printout of the complete breakdown of the equipment costs and associated installation and indirect charges is presented in Appendix A. The retrofit CFF equipment list is included in Appendix B.

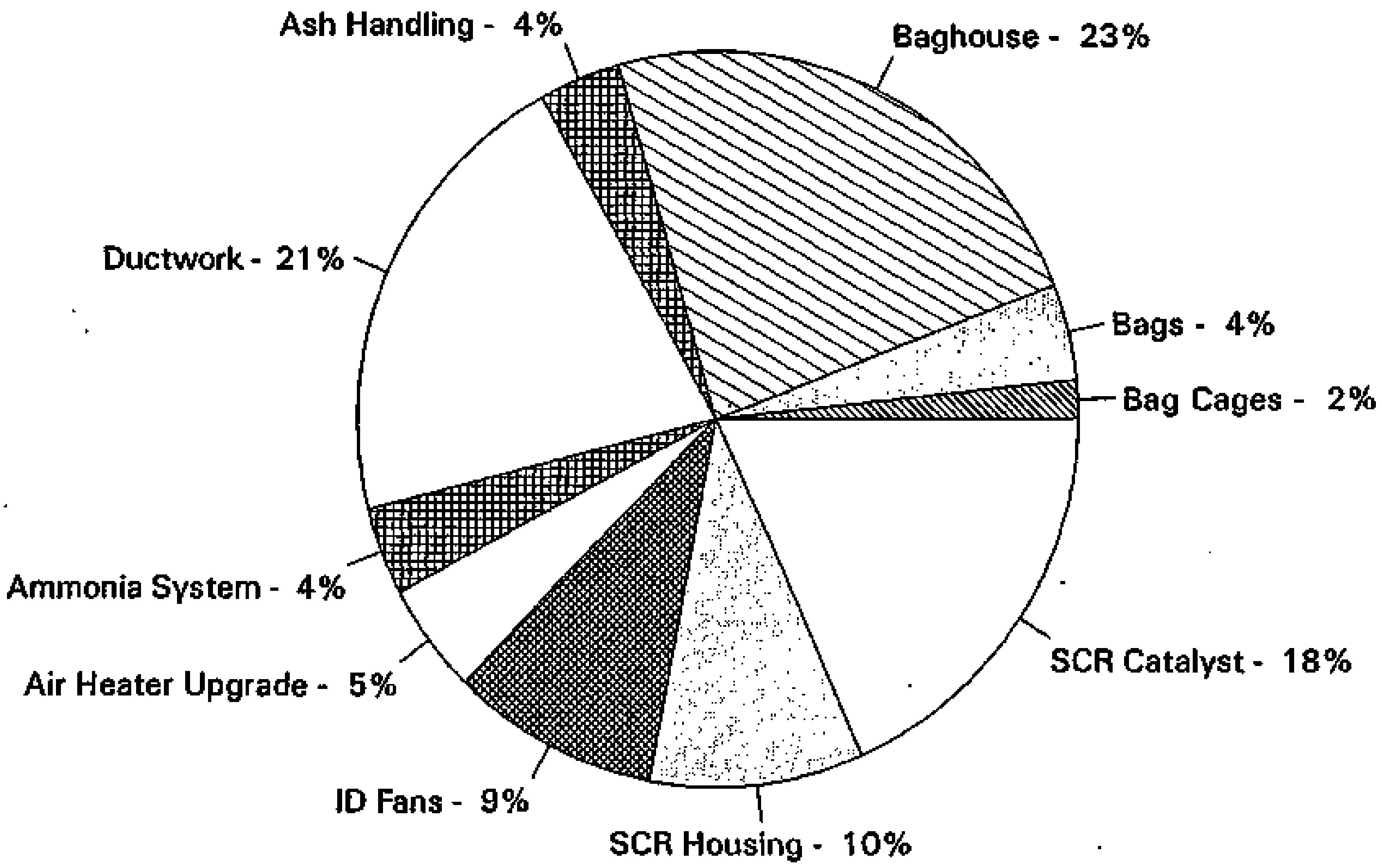
4.5.2 Capital and Levelized Costs

Capital and levelized costs were developed for the CFF, SCR, and pulse jet baghouse. Figure 4-7 compares breakdowns of the Total Plant Investment (TPI) requirements for a catalytic fabric filter system to those of the SCR/PJFF combination. The TPI for the retrofit CFF system is $213/kW. The TPI for the retrofit SCR unit is $79/kW and $142/kW is required for the PJFF, making the TPI for the total SCR/PJFF retrofit system $221/kW, or 4% more than that of the CFF. The CFF system requires a similar capital investment to the SCR/PJFF system, due to the high cost of the fabric filter bags. The ductwork and I.D. fans are broken out separately since these vary dramatically with retrofit scenarios. When the ductwork and I.D. fan costs are excluded, the TPI for the CFF case and the SCR/PJFF case are $155/kW and $152/kW, respectively.

FIGURE 4-6

SCR/PJFF CAPITAL COST*

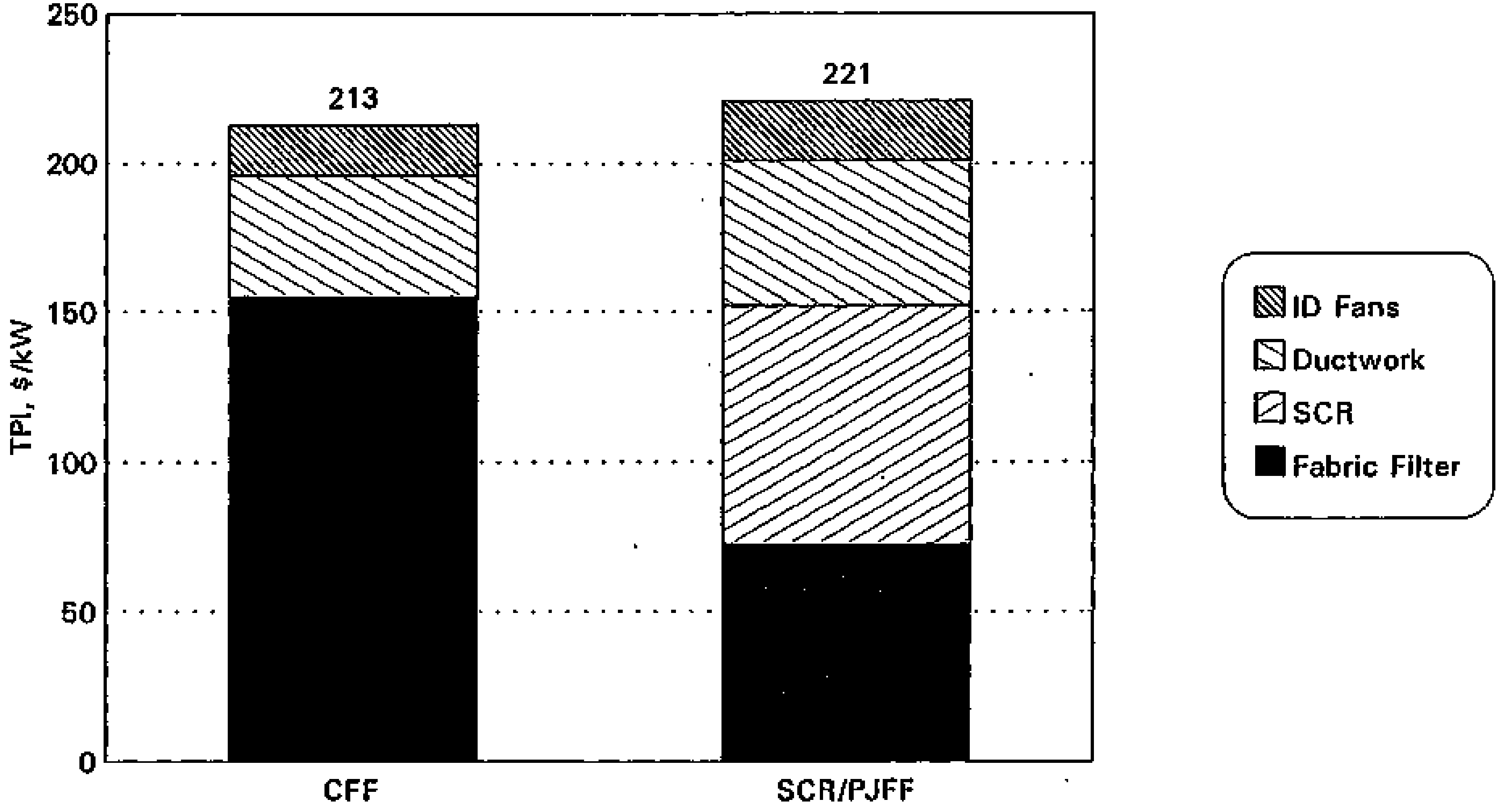
TOTAL INSTALLED EQUIPMENT COST BREAKDOWN - RETROFIT 250 MW PLANT



* TOTAL DOLLARS = K$40,388

FIGURE 4-7

CFF vs SCR/CONVENTIONAL BAGHOUSE
TOTAL PLANT INVESTMENT - RETROFIT 250 MW PLANT



The CFF costs include a fifteen (15) percent process contingency (as recommended by EPRI TAG Guidelines for developing processes) assessed against the CFF baghouse casing and filter bag components. Because SCR and PJFF technologies have been demonstrated commercially, their process contingencies are eight (8) and nine (9) percent, respectively. Figure 4-8 provides the TPI comparisons without these contingency costs, and indicates an 11% advantage for the CFF.

Figure 4-9 shows the total current dollar (includes inflation) levelized cost in terms of mills/kWh. The levelized cost for the CFF retrofit is 9.15 mills/kWh, and the cost for the SCR/PJFF retrofit is 10.07 mills/kWh, or 10 percent greater.

The CFF system levelized costs are driven by the catalyst coated S2-glass bag replacement cost. The SCR/PJFF system levelized costs are driven by the catalyst replacement costs along with the fan power requirement to overcome both SCR and PJFF pressure drop.

Figure 4-10 is a breakdown of the levelized cost components in terms of mills/kWh. Figure 4-11 presents the costs compared in terms of levelized dollars/year. This levelized cost represents the amount of many which would be required each year to fully cover both the capital and operating/maintenance costs of that technology. In this 250 MW retrofit plant case study, the CFF requires $1,300,000 less per year (15 years) than the SCR/PJFF.

FIGURE 4-8

CFF vs SCR/CONVENTIONAL BAGHOUSE
TOTAL PLANT INVESTMENT - RETROFIT 250 MW PLANT

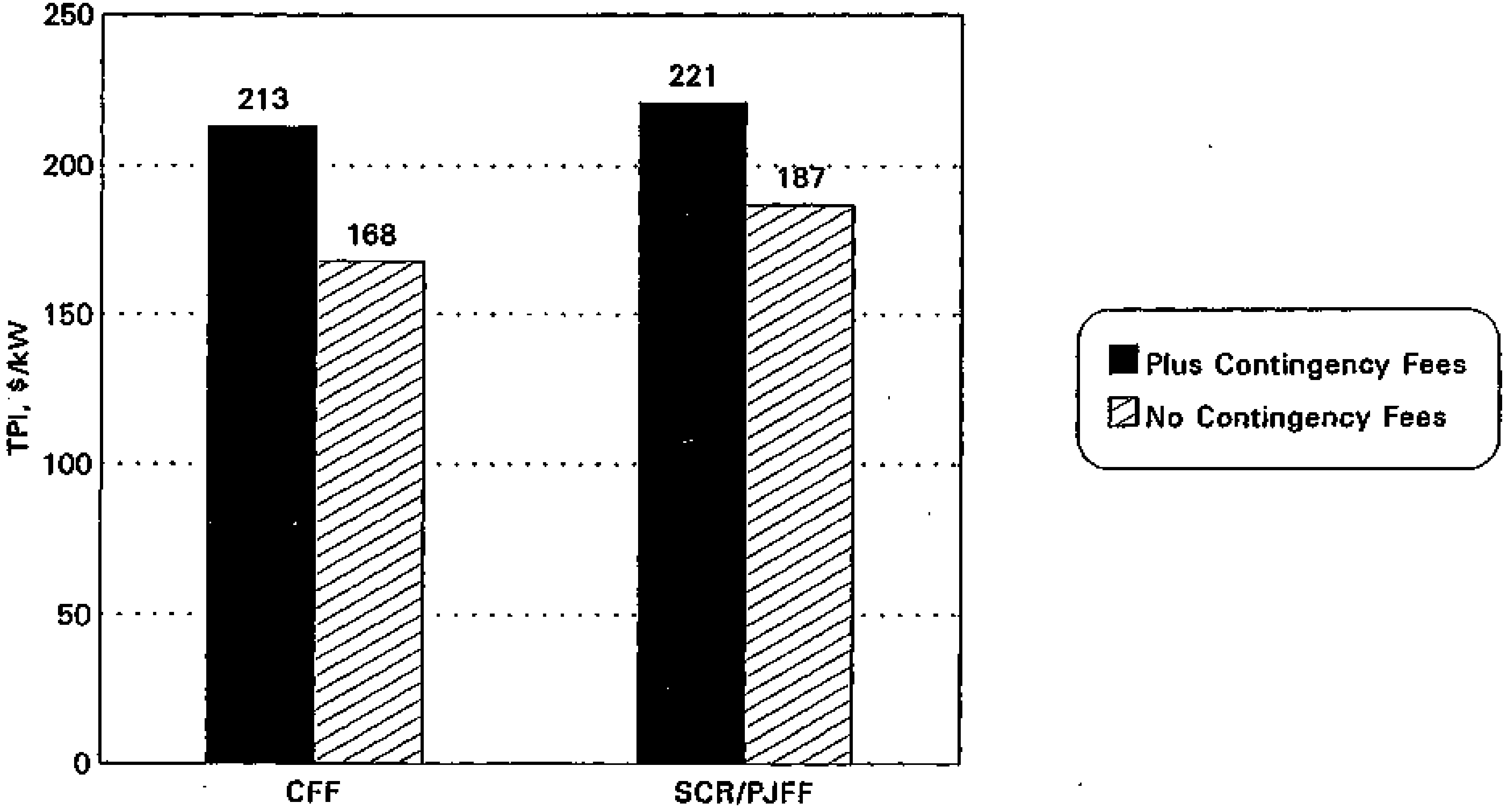


FIGURE 4-9

CFF vs SCR/CONVENTIONAL BAGHOUSE LEVELIZED COSTS - RETROFIT 250 MW PLANT

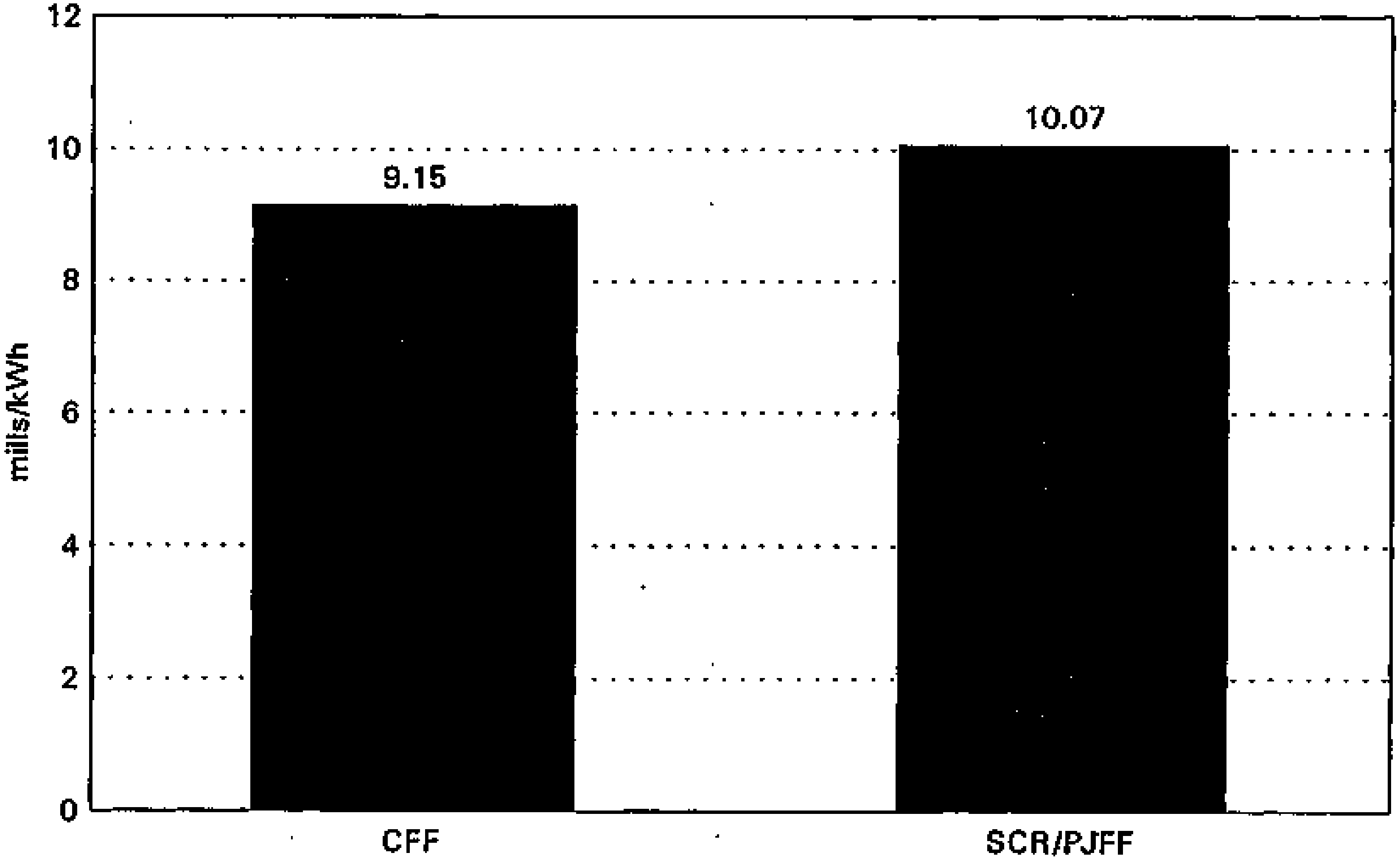


FIGURE 4-10

CFF vs SCR/CONVENTIONAL BAGHOUSE
LEVELIZED COST BREAKDOWN - RETROFIT 250 MW PLANT

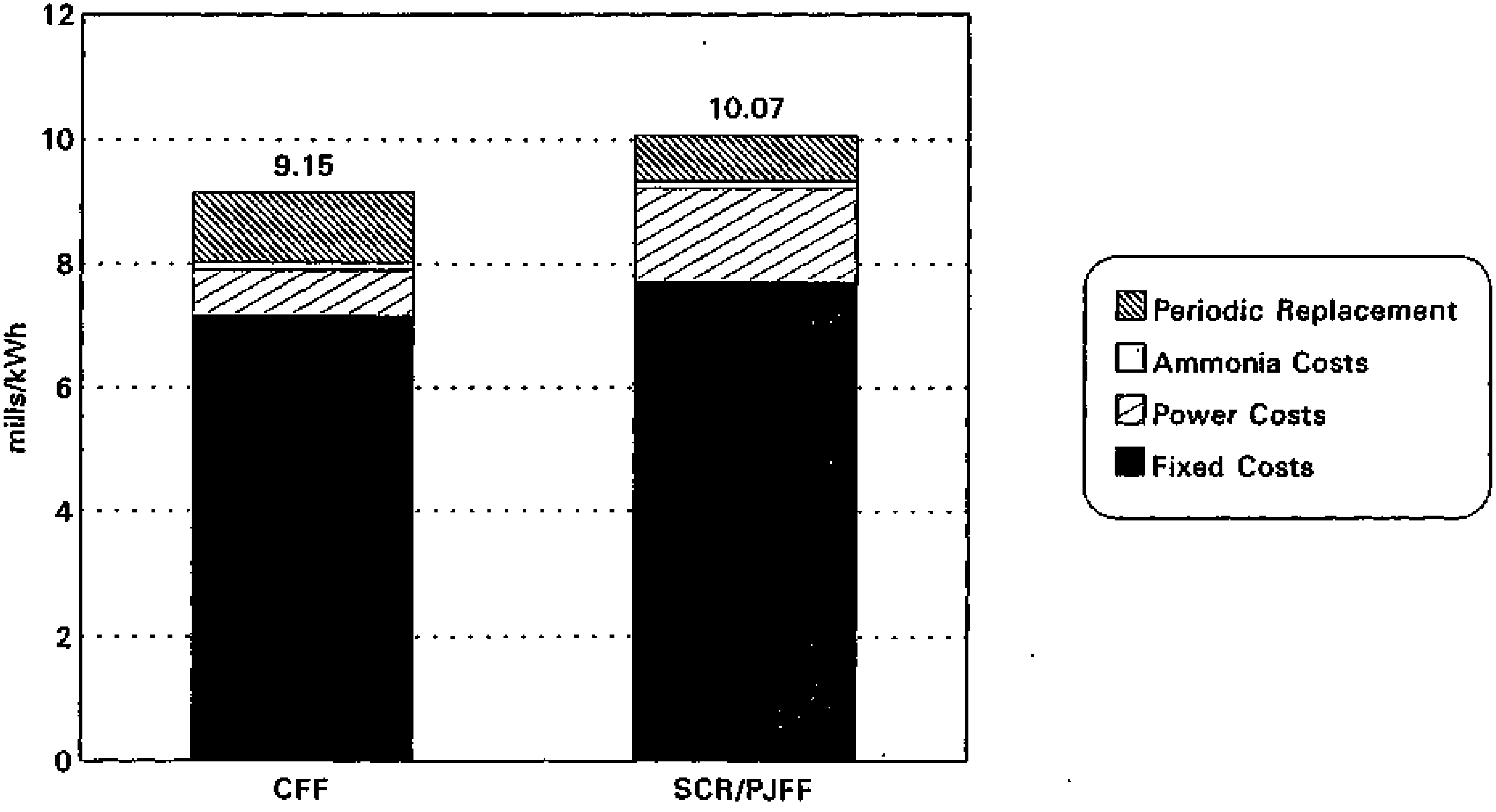
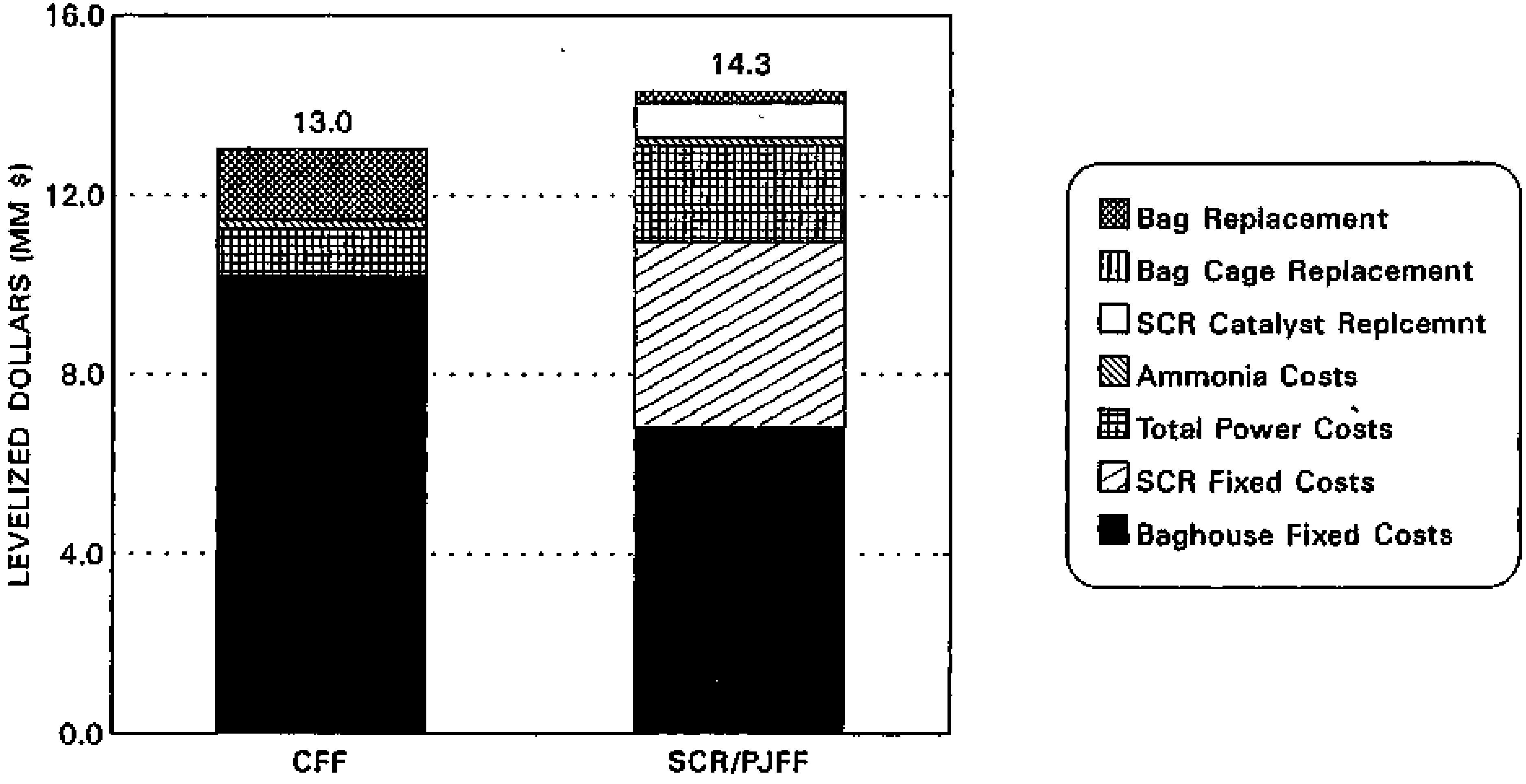


FIGURE 4-11

CFF vs SCR/CONVENTIONAL BAGHOUSE
LEVELIZED COST BREAKDOWN - RETROFIT 250 MW PLANT*



*Levelized Annual Revenue Requirement

4.5.3 CFF Cost Sensitivity Analyses

Several cost sensitivity analyses were performed on the CFF base case to determine critical design and economic parameters. The sensitivity parameters examined are listed below and are presented in Figures 4-12 through 4-17 in order of decreasing sensitivity. The cost of the catalyst coated bags has the strongest influence on CFF economics and is shown in Figures 4-12 and 4-13.

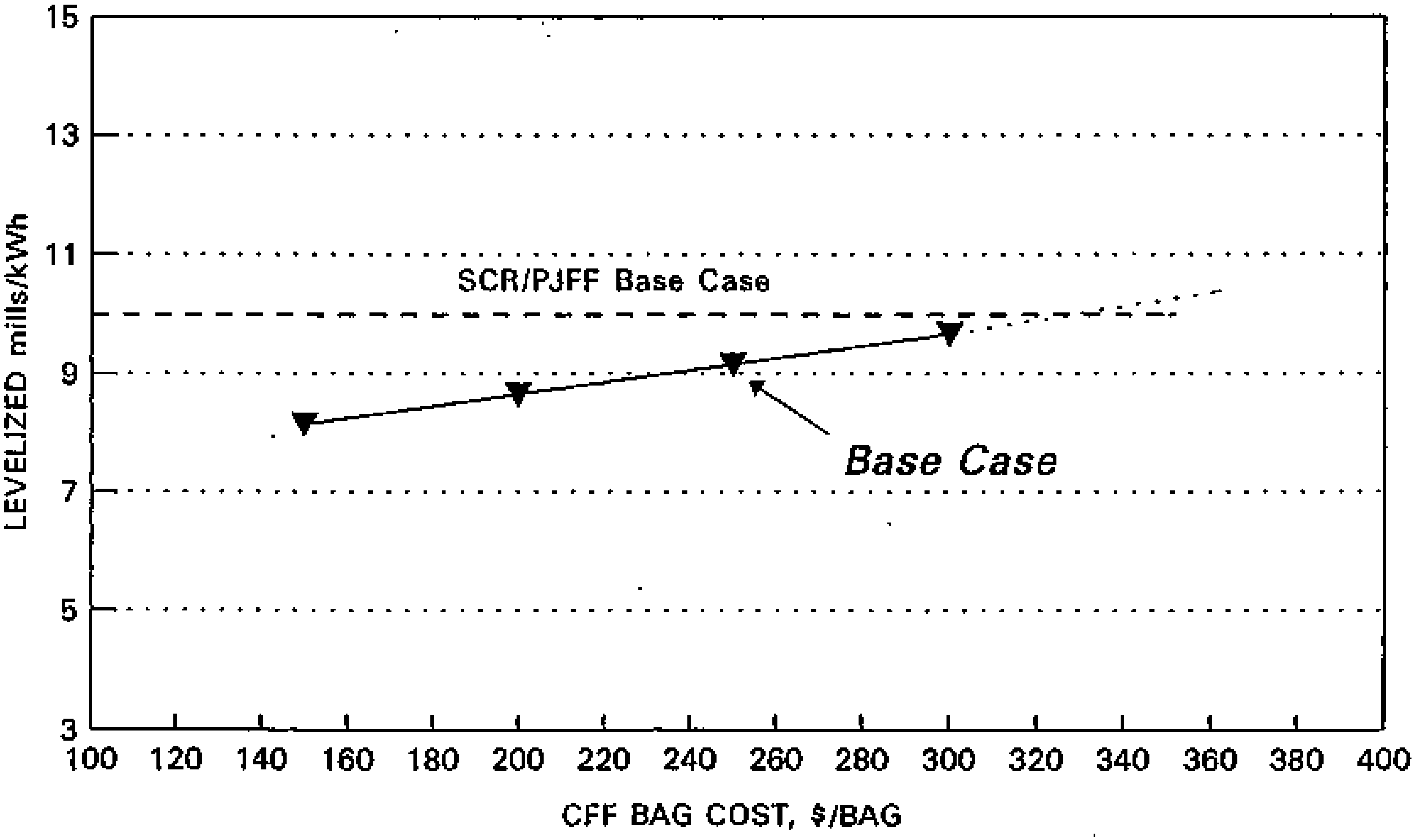
- Bag Cost
- Bag Life
- A/C Ratio
- Plant Size, MW
- Inlet NO_x Concentration

Figure 4-12 shows a steady increase in levelized costs with increasing bag cost. Figure 4-13 shows the CFF bag cost sensitivity relative to capital cost. The figure shows that the capital cost breakeven point for the CFF and SCR/PJFF is approximately $300/bag. Figure 4-14 shows the decrease in levelized $/ton is most dramatic for a 1 to 2 year life, but the slope steadily decreases with increasing bag life. Figure 4-15 shows an expected decline in costs due to higher air-to-cloth ratios.

Figure 4-16 shows a steady decrease in levelized costs for units with increasing MW capacity. The maximum practical size considered for a CFF baghouse casing is approximately 260 MW based on 14 compartments (for acceptable gas flow distribution) and a maximum of 1000 bags/ compartment. Units larger than 260 MW will likely require multiple casings and associated

FIGURE 4-12

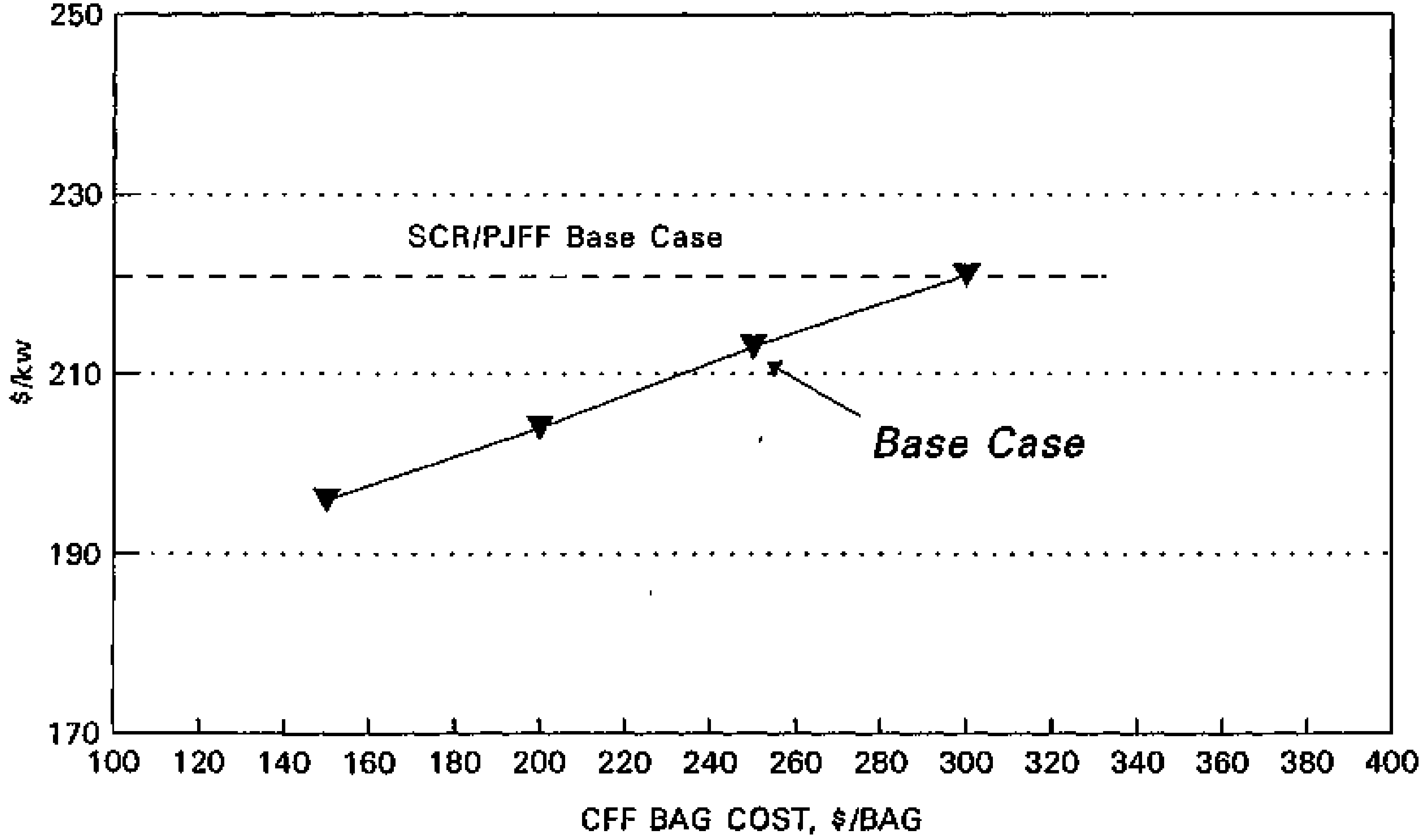
CFF SENSITIVITY PARAMETERS
BAG COST - RETROFIT 250 MW PLANT*



*12,600 Total Bags, 2 Yr Bag Life

FIGURE 4-13

CFF SENSITIVITY PARAMETERS
BAG COST - RETROFIT 250 MW PLANT*



*12,600 Total Bags, 2 Yr Bag Life

FIGURE 4-14

CFF SENSITIVITY PARAMETERS
BAG LIFE - RETROFIT 250 MW PLANT

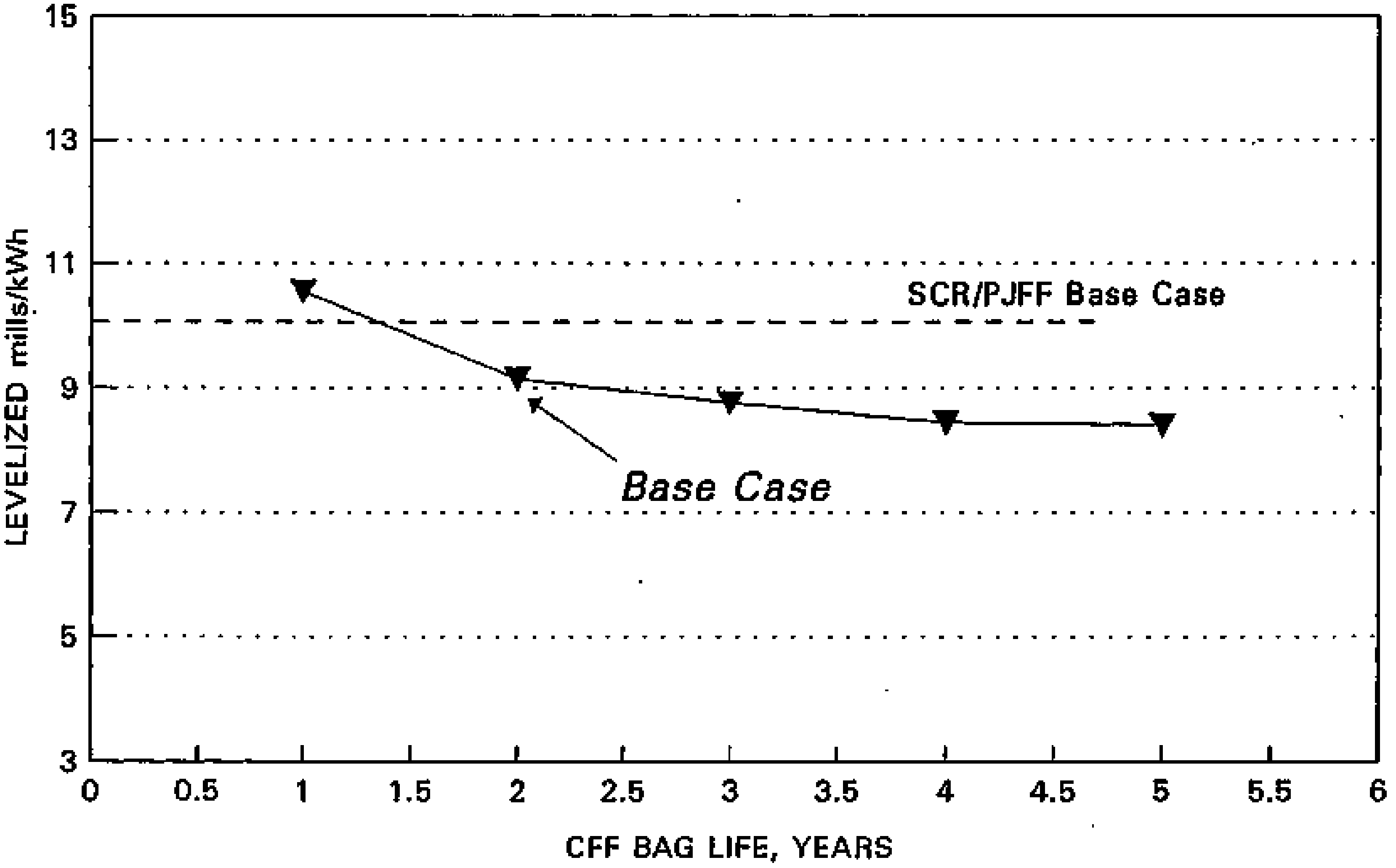


FIGURE 4-15

CFF SENSITIVITY PARAMETERS
AIR TO CLOTH RATIO - RETROFIT 250 MW PLANT

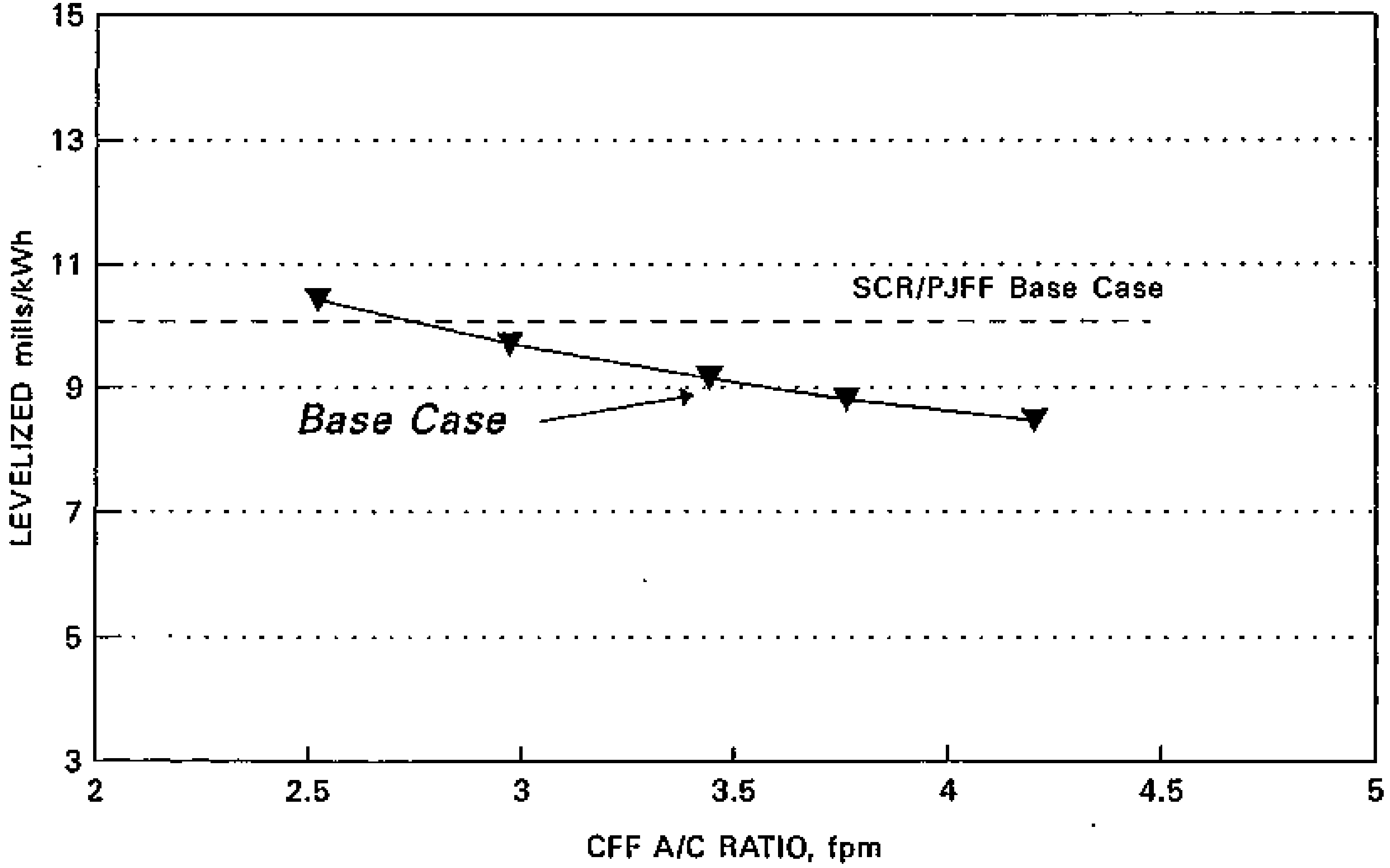
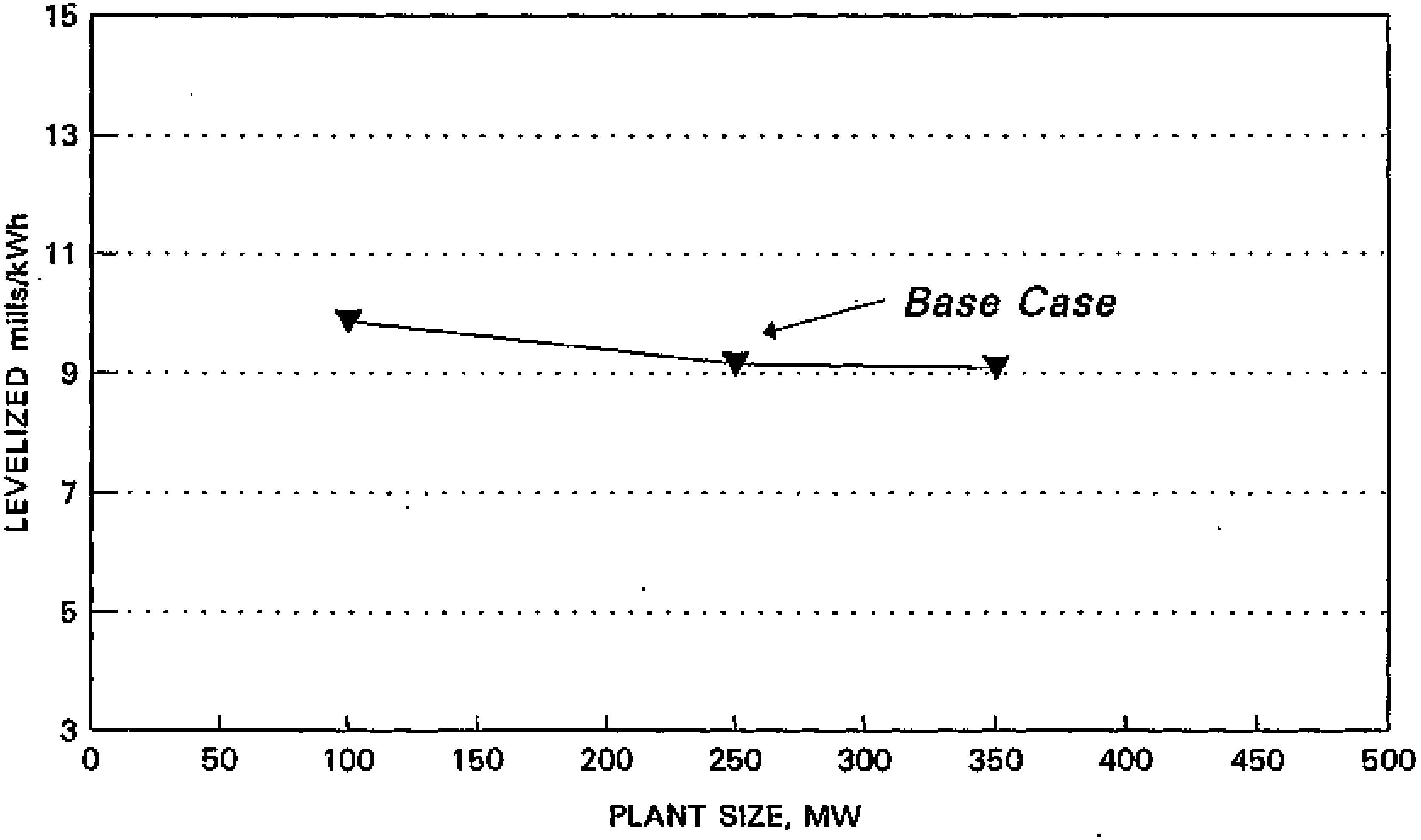


FIGURE 4-16

CFF SENSITIVITY PARAMETERS
PLANT SIZE, MW - RETROFIT 250 MW PLANT*

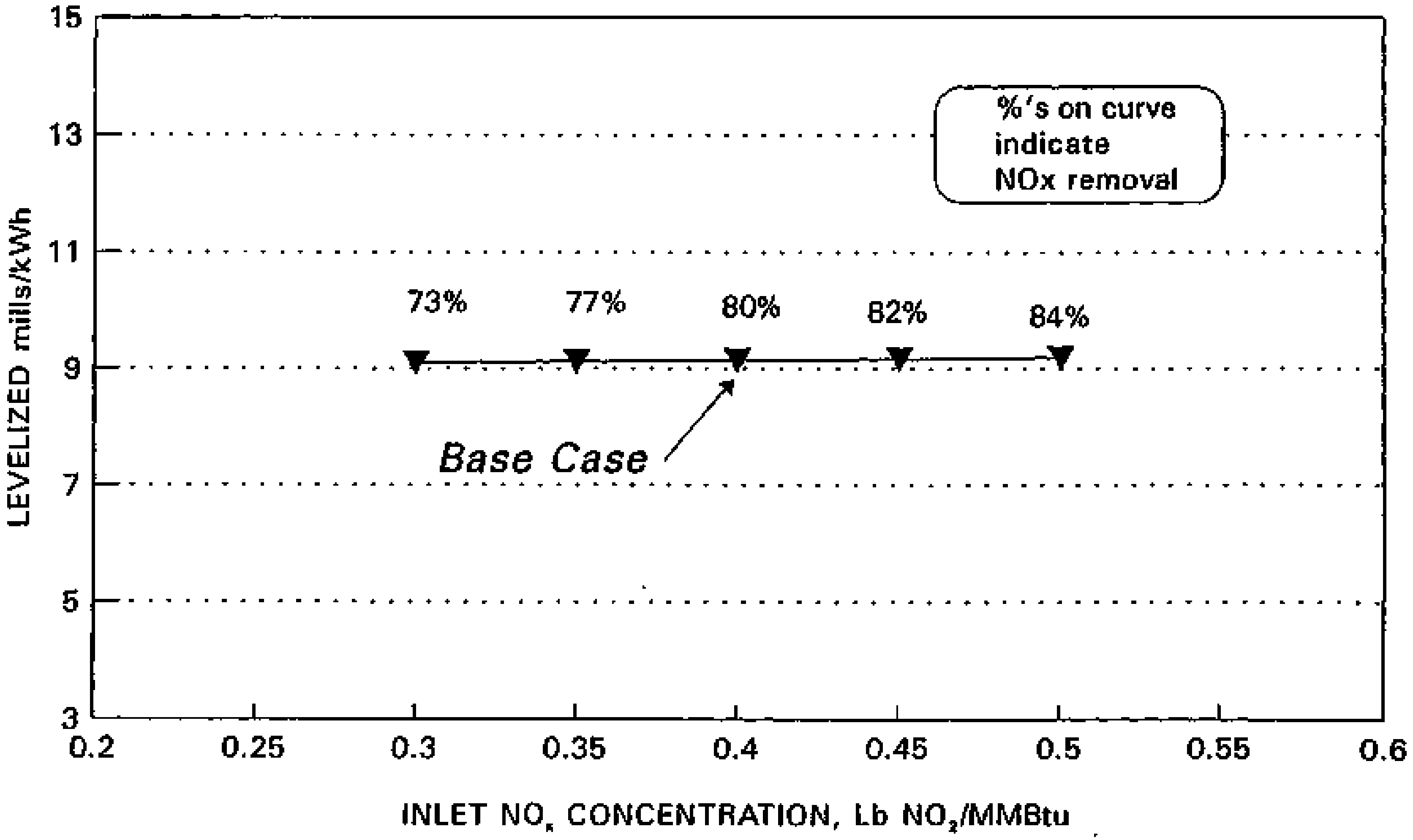


*1 CFF Required for 100 and 250 MW, 2 Required for 350

FIGURE 4-17

CFF SENSITIVITY PARAMETERS

INLET NO_x CONCENTRATION - RETROFIT 250 MW PLANT*



* 0.08 Lb NO_x/MMBtu NO_x Emission Rate

ductwork which will drive up costs accordingly. The least sensitive parameter is the inlet NO_x concentration. The inlet NO_x concentration sensitivity was developed based on a 0.08 lb NO_x/MMBtu outlet emission rate for all inlet NO_x concentrations. NO_x removal ranges from 73% to 84% for the chosen inlet concentrations. Figure 4-17 shows the levelized mills/kWh cost decreases slightly with increasing inlet NO_x concentration but the overall impact on the cost is negligible.

5.0 OTHER FACTORS AFFECTING THE DESIGN AND COST OF CFF TECHNOLOGY

5.1 AMMONIA SLIP

At the time of this report, pilot plant test data[5] indicate that to achieve 80% NO_x reduction, 25 ppmv slips through the CFF unreacted, compared to 5 ppmv or less ammonia slip from an SCR under the same condition. Ammonia slip can impact the design and cost of the CFF process in two ways:

- Air Heater Impacts
- Ammonia Stack Emissions

Since the CFF pilot plant did not include an air heater, there is no operating experience to predict the impact of the ammonia sulfur reactions on downstream equipment. Little fly ash is present in the flue gas, but deposition of ammonia-sulfur reaction products could still cause pluggage and corrosion problems in the cold end baskets of the air heater. This could potentially affect the heat transfer characteristics of the air heater, the pressure drop and I.D. fan power requirements, as well as requiring periodic replacement of corroded air heater elements. Flue gas temperature, ammonia concentration, SO_2/SO_3 concentration and moisture affect the formation of these products. Provisions should be included to control the deposition of these materials on air heater surfaces. Options include using baskets with greater open area, higher grade materials, additional air heater soot blower capacity, and an air heater wash system.

The emission of ammonia to the atmosphere may be unacceptable in some regulatory areas. If a wet scrubber is used downstream of the air heater for SO_2 control, virtually all of the ammonia leaving the air heater will be captured in the absorber. If the scrubber is designed for wallboard grade gypsum, additional water treatment may be required.

If no scrubber or other downstream SO_2 control is used, the CFF process parameters may have to be adjusted. The two major CFF process parameters affecting ammonia slip are the ammonia to NO_x stoichiometric ratio and the CFF air to cloth ratio. Reducing the NH_3:NO_x ratio would result in lower NO_x removal efficiencies, while lower air to cloth ratios increase the size of the baghouse and number of filter bags required. CFF capital and levelized costs would increase accordingly.

Because of these concerns, reducing the ammonia slip from the CFF process should be a major objective of future CFF research and development efforts.

5.2 FLY ASH UTILIZATION/SALES

The presence of ammonia-sulfur compounds and/or ammonia adsorption on fly ash particles may affect the potential for some fly ash utilization options, such as for use as a cement admixture. Fly ash specifications should be reviewed to determine if the CFF will affect a plant's current or future fly ash sales.

6.0 CONCLUSIONS/RECOMMENDATIONS

6.1 CONCLUSIONS

1. The CFF can be economically competitive with an SCR/PJFF combination for the control of NO_x and particle emissions from a new power plant installation.

2. Costs to retrofit CFF equipment to an existing plant are very dependent upon site specific constraints. Sites with limited available space may favor the CFF over an SCR/PJFF combination since less equipment and ductwork are required.

3. Bag life, bag cost, and air to cloth ratio have the strongest influence on CFF economics. Continued optimization in these areas can further reduce the costs of this technology.

4. Because ductwork is a major capital cost component of CFF technology, the equipment arrangement can determine the feasibility and cost effectiveness of both new and retrofit CFF applications.

5. The CFF requires less additional fan power than a SCR/PJFF combination due to lower pressure drop requirements.

6. Economy of scale is limited by the maximum CFF baghouse size. As additional baghouse casings and associated ductwork are required, step function increases in costs occur.

7. The costs of CFF technology must be significantly reduced in order to be commercially competitive with more established technologies, such as SCR/PJFF combinations.

6.2 RECOMMENDATIONS

Future research and development efforts required to improve the commercial viability of Catalytic Fabric Filter Technology should include:

1. Reducing the cost of the catalyst coated filter bags.
2. Increasing the service life of the bags.
3. Maintaining the current or better performance (NO_x and Particulate Control, Ammonia Slip) while operating at higher air to cloth ratios. This will reduce CFF baghouse size.
4. Demonstrating the CFF process with longer pulse jet filter bags. Conventional felted pulse jet bags of 23' to 26' in length have been demonstrated on cold-side applications.
5. Reducing the ammonia slip.
6. Determining impacts of the CFF process on air heater equipment.

7.0 REFERENCES

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3. W. W. Hoskins and J. K. Terrill, "Model for Predicting Fabric Filter and ESP Costs," American Power Conference, Chicago, IL, 1992.

4. "Economic Evaluation of FGD Systems," EPRI Report No. GS-7193, Volume 1 (February 1991).

5. G. F. Weber, G. E. Dunham, and D. L. Laudal, "Pilot-Scale Evaluation of a Catalyst Coated Fabric Filter for Simultaneous NO_x and Particulate Control in a Pulse-Jet Baghouse," presented at the EPRI-EPA Joint Symposium on Stationary NO_x Control, Bal Harbour, Fla, 1993.

6. V. H. Belba, T. Grubb, R. Chang, "A Worldwide Survey of Pulse-Jet Baghouse Performance on Coal Fired Boilers", presented at the Ninth EPRI Particulate Control Symposium, Williamsburg, VA, 1991.

APPENDIX

APPENDIX A

Baghouse and SCR

Computer Spreadsheet

Printouts

FABRIC FILTER/SCR COST SUMMARY

	NEW PLANT				RETROFIT PLANT			
	Catalytic Fabric Filter	SCR Plus Conventional Pulse Jet Fabric Filter	Conventional Pulse Jet Fabric Filter	Selective Catalytic Reduction	Catalytic Fabric Filter	SCR Plus Conventional Pulse Jet Fabric Filter	Conventional Pulse Jet Fabric Filter	Selective Catalytic Reduction
EQUIPMENT COSTS - 1/1/1993 - 1000's $								
Total Direct Cost	$42,912	$44,057	$22,770	$21,288	$31,917	$34,800	$21,917	$12,883
Total Plant Cost	$70,181	$66,912	$35,562	$31,350	$51,599	$53,314	$34,472	$18,842
Total Cash Expended	$68,510	$65,477	$34,715	$30,762	$50,370	$52,115	$33,651	$18,464
AFUDC	$3,843	$3,357	$1,947	$1,410	$2,826	$2,793	$1,888	$905
Total Plant Investment	$72,353	$68,835	$36,663	$32,172	$53,196	$54,908	$35,539	$19,369
$/kW	146	138	73	66	213	221	142	79
TOTAL LEVELIZED ANNUAL COSTS ($000, EOY)								
Fixed Costs	$11,938	$11,762	$6,049	$6,713	$10,214	$10,967	$6,823	$4,144
Operating Costs (Power)	$2,878	$5,892	$1,946	$3,946	$1,051	$2,145	$710	$1,436
Operating Costs (Ammonia)	$370	$349	$0	$348	$181	$171	$0	$171
Periodic Replacement Items	$4,224	$2,806	$899	$2,106	$1,583	$1,041	$261	$780
Total Levelized Annual Cost	$19,410	$20,807	$8,894	$12,113	$13,030	$14,324	$7,794	$6,530
TOTAL LEVELIZED ANNUAL COSTS ($/Ton NOx/Particulate Remo			$/ton Part.	$/ton NOx			$/ton Part.	$/ton NOx
Fixed Costs	146.07	142.93	75.67	2,226.38	283.69	304.62	197.66	2,795.00
Operating Costs (Power)	34.97	71.69	24.40	1,537.77	29.19	59.67	20.56	967.69
Operating Costs (Ammonia)	4.49	4.23	0.00	135.62	5.04	4.74	0.00	115.20
Bag Cage Replacement	1.47	0.94	0.97	0.00	1.01	0.67	0.67	0.00
Bag Replacement	48.86	7.56	7.81	0.00	42.98	6.90	6.90	0.00
SCR Catalyst Replacement	0.00	25.59	0.00	820.72	0.00	21.34	0.00	526.10
Total Levelized Annual Cost	235.68	252.84	109.05	4,720.48	361.91	397.65	225.79	4,404.19
TOTAL LEVELIZED ANNUAL COSTS (mills/kWh, EOY)								
Fixed Costs	3.63	3.56	1.84	1.74	7.17	7.70	4.79	2.81
Operating Costs (Power)	0.88	1.79	0.59	1.20	0.74	1.51	0.60	1.01
Operating Costs (Ammonia)	0.11	0.11	0.00	0.11	0.13	0.12	0.00	0.12
Bag Cage Replacement	0.04	0.02	0.02	0.00	0.03	0.02	0.02	0.00
Bag Replacement	1.25	0.19	0.19	0.00	1.09	0.17	0.17	0.00
SCR Catalyst Replacement	0.00	0.64	0.00	0.64	0.00	0.55	0.00	0.56
Total Levelized Annual Cost	5.91	6.33	2.65	3.69	9.15	10.07	5.48	4.69

TECHNICAL INPUTS SUMMARY

	NEW PLANT		RETROFIT PLANT	
	CFF	PJFF	CFF	PJFF
ACFM	2,535,000	1,731,000	1,268,000	866,000
A/C Ratio (Max Velocity,fpm)	4.00	4.00	4.00	4.00
Bag Diameter, In	6.00	6.00	6.00	6.00
Bag Reach	21	21	21	21
Type Cleaning: 1 - RG, 2 - SD, 3 - PJ	3	3	3	3
Duct Design Velocity, FPM	3,500	3,500	3,500	3,500
Hot Duct Length, Ft	773	625	655	940
Cold Duct Length, Ft	0	0	0	0
Is This New Plant or Retrofit?	0	0	1	1
(New = 0 or Retrofit = 1)				
If Retrofit, Replace ID Fan?	1	1	0	0
(Yes = 0 or No = 1)				
Replace Existing Stack?	1	1	1	1
(Yes = 0 or No = 1)				
Retrofit Difficulty?	0	0	2	2
New = 0, Lo = 1, Med = 2, Hi = 3, Very Hi = 4				
Bag Material	5	3	5	3
Fiberglas = 1, Acrylic = 2, (Dralon T), Ryton = 3, Gortex = 4, Catalytic FF = 5				
Bag Life, Years	2	3	2	3
Bag Cage Life, Years	8	8	8	8
Flange-Flange Pressure Drop, in H2O	8	6	6.0	6.0
Total System Pressure Drop, in H2O (Retrofit Only)			26.0	34.0
Construction Period, Yrs	2	2	2.0	2.0
Number of New Fans (Retrofit Only)			1.0	1.0
Project Contingency @	15%	15%	15.0%	15.0%
Process Contingency @	20%	0%	20.0%	0.0%
NOx CONTROL PARAMETERS				
Heat Input, MMBtu/hr	4881	4881	2430.5	2430.5
Boiler NOx Rate, Lb NO2/MMBtu	0.3	0.3	0.4	0.4
Percent NOx Removal, %	80%	80%	80%	80%
NH3 Feed Rate, Mol NH3/Mol NOx inlet	0.85	0.85	0.85	0.85
Particulate Emissions Rate, Lb/MMBtu	0.02	0.02	0.02	0.02
A. GENERAL				
Date of Cost (Ref Yr - 1991)	1993	1993	1993	1993
Selected State	Pennsylvania	Pennsylvania	Pennsylvania	Pennsylvania
State Multiplier	1.10	1.10	1.10	1.10
Power Cost, Cents/kWh	5.00	5.00	5.00	5.00
Ammonia Cost, $/ton	145.00	145.00	145.00	145.00
Ammonia System, $1000	956.00	956.00	661.73	526.41
Capacity Factor, %	75%	75%	65.0%	65.0%
B. ECONOMIC INPUTS				
Capital Esc During Construction	5.0%	5.0%	5.0%	5.0%
Construction Years	2	2	2.0	2.0
Annual Inflation	5.0%	5.0%	5.0%	5.0%
Discount Rate, % (MAR) =	11.50%	11.50%	11.50%	11.50%
AFUDC Rate	11.50%	11.50%	11.50%	11.50%
Lev Fixed Charge Rate (FCR) =	16.50%	16.50%	19.20%	19.20%
Service Life (years) =	30	30	15	15
Real Escalation Rates :				
Consumables (O & M) =	0	0	0	0
Fuel =	0	0	0	0
Power =	0.3	0.3	0.3	0.3
Nominal Escalation Rates :				
Consumables (O & M) =	5.00%	5.00%	5.00%	5.00%
Fuel =	5.00%	5.00%	5.00%	5.00%
Power =	5.32%	5.32%	5.32%	5.32%

FABRIC FILTER SIZING SUMMARY

	NEW PLANT		RETROFIT PLANT	
	CFF	PJFF	CFF	PJFF
Type of Fabric Filter	Pulse Jet	Pulse Jet	Pulse Jet	Pulse Jet
Flue Gas Flow, ACFM	2,535,000	1,731,000	1,268,000	866,000
Air-to-Cloth Ratio, fpm	3.44	3.70	3.44	3.70
Number of Baghouses	2	2	1	1
Bag Length, Ft	20.00	20.00	20.00	20.00
Square Ft/Bag	29.27	29.27	29.27	29.27
Cubic Ft/ Bag	117.09	117.09	117.09	117.09
Initial # Bags	21,649	14,783	10,828	7,396
Final # of Bags, Total	25,200	16,000	12,600	8,000
Number of Bags/Compart	900	800	900	800
Bag Spacing, In	7.5	7.5	7.5	7.5
Number of Compart	28	20	14	10
Bags Wide	20	20	20	20
Bags Deep	45	40	45	40
Number of Aisles	0	0	0	0
Compartment Dimension, Ft				
Width	16	16	16	16
Length	41	36	41	36
Hopper Height, Ft	22.61	20.60	22.61	20.60
Single Hopper Volume, Ft ³	1,725	1,327	1,725	1,327
Hopper Volume, Total Ft ³	48,293	26,544	24,146	13,272
Total Dimensions of Fabric Filters, Ft				
Length	112	80	112	80
Width	212	186	101	88
Height	57	55	57	55
Dimensions of Each Fabric Filter, Ft				
Length	112	80	112	80
Width (Incl. Width of Center Duct)	101	88	101	88
Height	57	55	57	55
Height/Width of Center Duct	19	16	19	16
Grating/Clearance Between FFs	10	10	10	10
Square Ft Cloth, Total	737,695	468,376	368,846	234,188
Duct Cross-Section, Ft ²	724.29	494.57	362.29	247.43
Duct Dimensions, Ft				
Width	27	22	19	16
Height	27	22	19	16
Equivalent Length - Hot Duct	773	626	655	940
Equivalent Length - Cold Duct	0	0	0	0
Total Ash Flow, TPH	12.2	12.2	6.1	6.1
Inlet NOx Rate, Lb NOx/hr	976.43	976.43	651.0	651.0
Total NOx Removed, kpph	0.78	0.78	0.5	0.5
Total NOx Removed, tpy	3,421.40	3,421.40	2280.9	2280.9
Total NOx Removed, tpy (incl. cap factor)	2,566.05	2,566.05	1482.6	1482.6
Ammonia Required, tpy (incl. cap factor)	1,560.09	1,560.09	912.9	912.9
Particulate Removed, tpy (incl. cap factor)	79,726.16	79,726.16	34520.5	34520.5
FABRIC FILTER OPERATING PARAMETERS				
Power Required Excluding ID Fan, kW	1,082	708	551	359
ID Fan Power For FF Delta P, kW	3,413	2,331	1,707	1,166
Total Power, kW	4,495	3,039	2,258	1,525
Annual Power Cost (EOY), $	$1,724,946	$1,168,161	$750,918	$607,136

DETAILED FABRIC FILTER COST SUMMARY

	NEW PLANT		RETROFIT PLANT	
	CFF	PJFF	CFF	PJFF
Flow Rate, ACFM	2,535,000	1,731,000	1,258,000	866,000
A/C Ratio, Ft/Min	3.44	3.70	3.44	3.70
Type Cleaning	Pulse Jet	Pulse Jet	Pulse Jet	Pulse Jet
Plant Location	Pennsylvania	Pennsylvania	Pennsylvania	Pennsylvania
DIRECT COSTS, 1/1/1993, 1000s $	(Grass Roots)	(Grass Roots)	(Retrofit)	(Retrofit)
Equipment				
Fabric Filter	$8,508	$6,146	$6,028	$4,400
Bag Cages	$1,008	$640	$504	$320
Bags	$6,615	$1,575	$3,308	$787
Ash Handling (Excl. Storage)	$694	$694	$609	$608
ID Fan(s)	$0	$0	$1,484	$1,755
Ductwork (Hot & Cold)	$7,803	$5,213	$5,611	$6,655
Stack	$0	$0	$0	$0
Air Heater Modifications	$175	$0	$904	$0
Ammonia System	$1,107	$0	$730	$0
"D" Equipment Subtotal (A)	$25,909	$14,268	$19,178	$14,528
Instruments & Controls	$362	$181	$271	$157
Taxes	$1,086	$643	$814	$472
Freight	$906	$463	$678	$394
Purchased Equipment Subtotal (B)	$28,263	$15,446	$20,941	$15,549
Installation				
Earthwork	$1,023	$512	$767	$445
Foundations & Supports	$1,432	$716	$1,073	$623
Erection	$10,147	$5,074	$7,603	$4,411
Electrical	$818	$409	$613	$356
Piping	$205	$102	$153	$89
Insulation	$818	$409	$613	$356
Painting	$205	$102	$153	$89
Total Direct Cost	$42,912	$22,770	$31,918	$21,917
INDIRECT COSTS				
Engineering & Supervision	$2,828	$1,544	$2,094	$1,555
Construction & Field Expenses	$5,653	$3,089	$4,188	$3,110
Construction Fees	$2,828	$1,544	$2,094	$1,555
Startup Costs	$283	$154	$209	$155
Performance Tests	$283	$154	$209	$155
Total Indirect Cost	$11,871	$6,487	$8,795	$6,531
Total Erected Cost	$54,782	$29,257	$40,713	$28,448
Project Contingency	$6,250	$3,380	$4,631	$3,391
Process Contingency	$9,149	$2,926	$6,254	$2,633
TOTAL PLANT COST	$70,181	$35,562	$51,598	$34,472
Market Demand (MD)	$0	$0	$0	$0
Total Plant Cost With MD	$70,181	$35,562	$51,596	$34,472
Total Cash Expended	$68,510	$34,715	$50,370	$33,651
AFUDC	$3,843	$1,947	$2,828	$1,888
Total Plant Investment With MD	$72,353	$36,663	$53,198	$35,539
LEVELIZED ANNUAL FABRIC FILTER COSTS ($000, EOY)				
Fixed Costs	$11,938	$6,049	$10,214	$6,823
Operating Costs (Power)	$2,878	$1,946	$1,051	$710
Operating Costs (Ammonia)	$370	$0	$181	$0
Periodic Replacement Items	$4,224	$689	$1,584	$261
Total Levelized Annual Cost	$19,410	$8,684	$13,030	$7,794
LEVELIZED ANNUAL FABRIC FILTER COSTS ($/Ton NOx/Particulate Removed, EOY)				
Fixed Costs	145.07	75.87	283.69	197.66
Operating Costs (Power)	34.97	24.40	28.19	20.56
Operating Costs (Ammonia)	4.49	0.00	5.04	0.00
Periodic Replacement Items	51.33	8.77	43.89	7.57
Total Levelized Annual Cost	235.86	109.06	361.81	225.79

SCR Input Parameters and Cost Results

1	DESCRIPTION AND TECHNICAL PARAMETERS		New Plant	Retrofit Plant
2				
3	Description	*	CFF Base Case	CFF Base Case
4	NOTE: The * in Column 3 denotes an input;			
5	no * denotes a calculated number.			
6				
7				
8	New or Retrofit	*	New	Retrofit
9	Fuel Type	*	Eastern Bituminous	Eastern Bituminous
10				
11	Generation Inputs			
12	Net Capacity (MW)	*	500.00	250.00
13	Capacity Factor	*	75.0%	65.0%
14	Plant Downtime Factor		14.5%	25.0%
15	Average NOx Generation Factor		75.0%	65.0%
16	KWH per year		3.2850E+09	1.4235E+09
17	Heat Input, MM Btu/hr @ MCR		4,861.0	2,430.5
18	Power Cost Inputs			
19	House Power Cost ($/kWh)	*	0.050	0.050
20	Downtime Costs During Construction			
21	Replacement Power Cost ($/kWh)	*	0.060	0.060
22	Fuel/O&M House Power Savings ($/kWh)	*	0.030	0.030
23	Delta Cost ($/kWh)		0.030	0.030
24				
25	Construction Inputs			
26	SCR Construction Period (months)		18	18
27	Months of Downtime During Construction	*	0	0
28				
29	Environmental Inputs			
30	Boiler NOx Rate, lb NO2/MM Btu	*	0.30	0.40
31	SNCR NOx Reduction, %	*	0.0%	0.0%
32	SCR Inlet NOx Rate, lb NO2/MM Btu		0.3	0.4
33	SCR NOx Reduction	*	80.0%	80.0%
34	SCR Inlet NOx (lbs NOx/hr)	*	978	651
35	NOx Removed (tons NOx/yr)		2,568	1,483
36	NH3 Slip (ppmvd @ 3% O2)	*	5.0	5.0
37				
38	Catalyst Inputs			
39	Catalyst Retrofit Factor	*	1.00	1.00
40	Sales Tax	*	1.060	1.060
41	Catalyst Installation Labor (hrs/layer)	*	1050.0	1050.0
42	Number of active catalyst layers	*	4.0	4.0
43	Catalyst Labor Retrofit Factor	*	1.00	1.00
44	Base Reactor Housing Cost for Cost Scaling	*	2,443	2,443
45	Base Catalyst Volume (ft3) for Scaling	*	33,769	33,769
46	Scale Factor for Reactor Housing	*	0.4	0.4
47				
48	ECONOMIC FACTORS			
49				
50	MAR	*	11.50%	11.50%
51	Levelized Carrying Charge Rate	*	0.1650	0.1970
52	Economic Life	*	30	15
53	P/A Factor		8.36371	6.99671
54	A/P Factor		0.11956	0.14292
55	Capital Cost Escalation Rate	*	5.0%	5.0%
56	O&M, Catalyst Escalation Rate	*	5.0%	5.0%
57	Fuel Escalation Rate	*	5.0%	5.0%
58	Power and Steam Cost Escalation Rate	*	5.3%	5.3%
59	P/AE Factor (fuel, ammonia)		13.48877	9.59251
60	P/AE Factor (O&M, catalyst)		13.48877	9.59251

61	P/AE Factor (power)		13.98171	9.79669
62	Retrofit Factor		1.00	1.20
63	State Cost		1.0121	1.0121
64	CAPITAL COSTS ($1000, December 1992)			
65	Catalyst Parameters			
66	Vendor Quote: Equivalent Catalyst Cost ($/ft3)	*	440	440
67	Vendor Scope Installation Cost ($/ft3)	*	151	151
68	NCFM Flue Gas (@ 32 degrees F)	*	1,160,000	580,000
69	Space Velocity (NCF/ft3-hr)	*	3,200.00	3,200.00
70	Catalyst Volume (ft3)		21,750.0	10,875.0
71	Replacement Catalyst Cost, ($/ft3)	*	300.00	300.00
72	Total Process Capital			
73	Reactor Housing		2,048.8	1,552.7
74	SCR Vendor Scope/Catalyst		11,660.7	5,344.1
75	Subtotal Reactor Housing & Catalyst		13,709.5	6,896.8
76	NH3 Storage	*	1,106.9	730.5
77	Ductwork	*	0.0	0.0
78	Structural Support	*	0.0	0.0
79	Air Heater Modifications	*	176.0	904.3
80	Economizer Modifications	*	0.0	0.0
81				
82	ID Fan Modifications	*	180.2	0.0
83	Ash Handling Addition	*	116.5	78.2
84	Water Treatment Addition	*	0.0	0.0
85	Instrumentation & Control	*	291.5	192.3
86				
87	Subtotal Process Capital Cost		15,581.6	8,802.0
88	Flow Modeling	*	100.0	66.0
89	Total Process Capital Cost (TPCC)		15,681.6	8,868.0
90	Taxes		940.9	532.1
91	Freight		784.1	443.4
92	Purchased Equipment Subtotal		17,406.5	9,843.5
93	Installation			
94	Earthwork		287.3	225.0
95	Foundations		402.2	315.0
96	Erection		2,616.9	2,049.2
97	Electrical		229.8	180.0
98	Piping		57.5	45.0
99	Insulation		229.8	180.0
100	Painting		57.5	45.0
101				
102	Total Direct Cost (TPCC + Installation)		21,287.5	12,882.6
103	Project Contingency Factors			
104	Reactor Housing	*	10.0%	10.0%
105	Catalyst	*	10.0%	10.0%
106	NH3 Storage	*	15.0%	15.0%
107	Ductwork	*	15.0%	15.0%
108	Structural Support	*	15.0%	15.0%
109	Air Heater Modifications	*	10.0%	10.0%
110	Economizer Modifications	*	0.0%	0.0%
111				
112	ID Fan Modifications	*	10.0%	10.0%
113	Ash Handling Addition	*	15.0%	15.0%
114	Water Treatment Addition	*	15.0%	15.0%
115	Instrumentation & Control	*	0.0%	0.0%
116	Process Contingency Factors			
117	Reactor Housing	*	10.0%	10.0%
118	Catalyst	*	15.0%	15.0%
119	NH3 Storage	*	10.0%	10.0%
120	Ductwork	*	10.0%	10.0%

121	Structural Support	*	10.0%	10.0%
122	Air Heater Modifications	*	15.0%	15.0%
123	Economizer Modifications	*	0.0%	0.0%
124				
125	ID Fan Modifications	*	5.0%	5.0%
126	Ash Handling Addition	*	10.0%	20.0%
127	Water Treatment Addition	*	0.0%	15.0%
128	Instrumentation & Control	*	0.0%	0.0%
129	Total Plant Cost			
130	Total Process Capital Cost (TPCC)-Catalyst Cost		4,020.9	4,228.7
131	General Facilities Factor	*	10.0%	10.0%
132	General Facilities Cost		402.1	422.9
133				
134	Total Direct Cost		21,287.5	12,882.6
135	Eng & Home Office Factor	*	10.0%	10.0%
136	Eng & Home Office Cost		2,128.8	1,288.3
137	Construction		3,481.31	1,968.70
138	Startup Costs		174.07	98.43
139	Performance Tests		174.07	98.43
140				
141	Project Contingency		1,590.3	901.4
142	Process Contingency		2,111.9	1,181.2
143	Total Plant Cost (TPC)		31,349.9	18,841.9
144				
145	Allowance for Funds During Construction			
146	Monthly Cash Flows (% TPC, "overnight costs")	1	0.3%	0.3%
147		2	0.3%	0.3%
148	--Based on "typical" cash flow curve	3	0.3%	0.3%
149	--Catalyst cost installed in last month	4	0.5%	0.5%
150		5	0.8%	0.9%
151		6	1.5%	1.6%
152		7	2.4%	2.6%
153		8	3.9%	4.1%
154		9	5.9%	6.3%
155		10	8.5%	9.0%
156		11	11.8%	12.6%
157		12	8.8%	9.4%
158		13	7.9%	8.4%
159		14	7.6%	8.1%
160		15	5.9%	6.3%
161		16	3.8%	4.0%
162		17	2.6%	2.7%
163		18	27.3%	22.3%
164				
165	Subtotal		100.00%	100.00%
166				
167	Monthly Interest Rate		0.96%	0.96%
168	Monthly Escalation Rate		0.41%	0.41%
169				
170	Total Cash Expended (TCE), as % of TPC		98.12%	98.00%
171	Total Cash Expended (TCE), $1000		30,762	18,464
172				
173	AFDC (or interest during construction)			
174	as % of TPC		4.50%	4.81%
175	$1000		1,410	905
176				
177	Total Plant Investment (TPI), (TCE + AFDC)		32,171.4	19,369.6
178				
179	Total Capital Requirement			
180	Preproduction Costs (no coal consumption costs)		518.9	315.4
181	Inventory Capital (.5% of TPCC - catalyst cost)		67.4	52.7
182	Initial Catalyst and Chemicals (included with TPC)		0.0	0.0
183	Prepaid Royalties (included with TPC)		0.0	0.0
184	Total Capital Requirement (TCR, $ 1000)		32,757.6	19,737.7
185	($/kW)		65.5	79.0
186				
187	OPERATING COSTS ($1000/yr, Dec. 1993)			
188				

189	ID Fan HP			
190	ACFM1 without SCR	*	2,535,000	1,268,000
191	ACFM2 with SCR	*	2,608,000	1,304,000
192				
193	Delta P1 w/o SCR	*	19.0	19.0
194	Delta P2 w/ SCR	*	30.0	30.0
195				
196	HP increase		6,760	3,378
197	KW Increase		5,043	2,520
198	Power Cost ($1000/yr)		1,858.5	717.4
199				
200	FD Fan HP			
201	NH3 Rate (lb/hr)		452.7	301.8
202	Temperature Ambient, (°F)	*	60.0	60.0
203	Pressure Ambient (PSIA)	*	14.6	14.6
204	Delta P. in w.c.	*	23.0	23.0
205	Air Htr Leakage Rate w/o SCR	*	0.11	0.11
206	Air Htr Leakage Rate w/SCR	*	0.13	0.13
207	Air Htr Leakage w/ SCR (lbs/hr)	*	751,649	375,825
208	M (Air Htr Leakage delta)		127,202	63,601
209	MDA (dilution air, lb/hr)		14,588	9,726
210	HP increase		14.9	7.7
211	KW Increase		11.1	5.7
212	Power Cost ($1000/yr)		3.6	1.5
213				
214	ESP Power Consumption Increase			
215	Rel Total Power Consumption increase (KW)	*	0	0
216	Rel Useful Power Consmp Rate (watts/1000 ACFM)	*	0	0
217	Volume Increase	*	0.0%	0.0%
218	Actual Useful Power Consmp Rate (watts/1000 ACFM)	*	0	0
219	ESP Power Increase		0	0
220	Power Cost ($1000/yr)		0.0	0.0
221				
222	Downtime Replacement Power Cost			
223	Months of Downtime During Construction		0	0
224	Delta Replacement Power Cost		0.030	0.030
225	Power Cost ($1000/yr)		0	0
226				
227	Ammonia Cost			
228	Ammonia Cost ($/ton)	*	145	145
229	NH3 Rate (lb/hr)		452.7	301.8
230	Cost ($1000/yr)		215.8	124.6
231				
232	Steam Consumption			
233	Cost for 50 PSIG ($/1000lb)	*	2.85	2.85
234	Cost for 200 PSIG ($/1000lb)	*	3.50	3.50
235	Cost for 250 PSIG ($/1000lb)	*	5.30	5.30
236				
237	Air Heater Delta			
238	Cycle Time (min)	*	35	35
239	Size (CE/APH Model)	*	28	28
240	Sootblow Rate (lb/min)	*	81	81
241	Delta Cycles per Shift	*	0	0
242	No. of Air Heaters	*	1	1
243	Cost ($1000/yr)		0.0	0.0
244				
245	SCR			
246	Steam Use Factor (lb atm/hr-sq ft)	*	2.73%	2.73%
247	Catalyst Face Area (sq ft)	*	19,740	9,870
248	Cost ($1000/yr)		21.4	9.4
249				
250	NH3 Vaporization (50 psig steam), (lb/hr)		297.2	198.1
251	Cost ($1000/yr)		3.6	2.0
252				
253	Total Steam Cost ($1000/yr)		24.9	11.4
254				
255	Fly Ash Marketability			
256	Trigger (0=No, 1=Yes)		0.0	0.0
257	Tons/hr	*	0.0	0.0

258	Differential Ash Cost ($/ton)	*	9.0	9.0
259	Total Differential Ash Cost ($1000/yr)		0.0	0.0
260				
261	Flue Gas Heat Loss			
262	Mass Flow Rate (lb/hr)	*	4,734,200	2,367,100
263	Flue Gas Temperature Increase (°F)	*	20.0	20.0
264	Heat Capacity (Btu/lb-°F)	*	0.2632	0.2632
265	Turbine Cycle Heat Rate (Btu/kWh)	*	9,318	9,318
266	Boiler Efficiency	*	0.7727	0.7727
267	KW Increase		2,067	1,033
268	Power Cost ($1000/yr)		676.9	294.2
269				
270	Catalyst Replacement Cost			
271	Replacement Life (yrs)	*	4	4
272	Catalyst Replacement Cost ($1000/yr)		6,525	3,263
273	Catalyst Replacement Labor Cost ($1000/yr)		84	84
274	Total Replacement Cost ($1000/yr)		6,609	3,347
275	Replacement Fraction/yr		25.0%	25.0%
276	Replacement Cost/yr ($1000/yr)		1,652.3	836.8
277	Catalyst Replacement Labor, MH's/layer	*	1050	1050
278	Water Treatment Chemical Cost			
279	Methanol Cost ($/gal)	*	0.60	0.60
280	NH3 Bleed Rate (lb/hr)	*	16.90	16.90
281	NH3 Capture Rate	*	0.0%	0.0%
282	Methanol Requirement (gal)		0	0
283	Methanol Cost ($1000/yr)		0.0	0.0
284				
285	SCR Catalyst Disposal Cost			
286	Trigger (0=no, 1=yes)	*	0	0
287	Catalyst Weight (lbs/cu ft)	*	46	46
288	Tons/year		125.1	62.5
289	Disposal Cost Rate ($/ton)	*	500.0	500.0
290	Disposal Cost ($1000/year)		0.0	0.0
291				
292	FGD Reheat Penalty			
293	Trigger (0=no, 1=yes)	*	0	0
294	Reheat (°F)	*	0.0	0.0
295	Average Heat Capacity (Btu/lb-°F)	*	0.293	0.293
296	Mass Flow Differential (lb-hr)	*	159,000	159,000
297	200 psig Steam Enthalpy (Btu/lb)	*	1,043.0	1,043.0
298	Efficiency	*	90.0%	90.0%
299	Steam Consumption (1000 lb)		0	0
300	Cost ($1000/yr)		0.0	0.0
301				
302	Water Consumption Increase			
303	FGD Water Evap Increase (gpm)	*	0	0
304	Water Cost ($/1000 gal)	*	0.000	0.000
305	($1000/year)		0.0	0.0
306				
307				
308	FIRST YEAR COSTS ($1000/YR, December 1993)			
309	-			
310	Fixed Operating Costs			
311	Labor Rate ($/hr)	*	20.00	20.00
312	Operating Labor (8 hrs/day)		58	58
313	Maintenance Labor (8 hrs/day)		58	58
314	Maintenance Mater		38	35
315	Admin/Support		35	35
316	Subtotal		191	186
317				
318				
319	Variable Operating Cost Summary			
320	ID Fan HP		1,657	717
321	FD Fan HP		4	2
322	ESP Power Increase		0	0
323	Downtime Replacement Power Cost		0	0
324	Ammonia Cost		216	125
325	Steam Consumption		26	11
326	Ash Cost		0	0

327	Flue Gas Heat Loss		679	294
328	Catalyst Replacement		0	0
329	SCR Catalyst Disposal Cost		0	0
330	FGD Reheat Penalty		0	0
331	Water Consumption Increase		0	0
332	Water Treatment Chemical Cost		0	0
333	Subtotal		2,590	1,149
334				
335	Levelized Fixed Charges		5,405	3,888
336				
337	Total		8,176	5,224
338				
339				
340				
341	LEVELIZED COSTS (mills/kWh, end-of-year, beginning 1993)			
342				
343	Fixed Operating Costs			
344	Operating Labor (4 hrs/day)		0.03	0.06
345	Maintenance Labor (8 hrs/day)		0.03	0.06
346	Maintenance Mater		0.02	0.03
347	Admin/Support		0.02	0.03
348	Subtotal		0.09	0.18
349				
350	Variable Operating Costs			
351	ID Fan HP		0.84	0.71
352	FD Fan HP		0.00	0.00
353	ESP Power Increase		0.00	0.00
354	Downtime Replacement Power Cost		0.00	0.00
355	Ammonia Cost		0.11	0.12
356	Steam Consumption		0.01	0.01
357	Ash Cost		0.00	0.00
358	Flue Gas Heat Loss		0.34	0.29
359	Catalyst Replacement (levelized)		0.64	0.55
360	SCR Catalyst Disposal Cost		0.00	0.00
361	FGD Reheat Penalty		0.00	0.00
362	Water Consumption Increase		0.00	0.00
363	Water Treatment Chemical Cost		0.00	0.00
364	Subtotal		1.95	1.68
365				
366	Fixed Charges		1.65	2.73
367				
368	Total		3.69	4.59

FIRST YEAR AND LEVELIZED COST SUMMARY FOR ==> NEW PLANT

	FIRST YEAR (January, 1993 U.S. dollars)					LEVELIZED FOR (end-of-year values) 30 Years			
	$1000	$/KW-YR	MILS/KWH	NOx Removed $/ton	%	$/KW-YR	MILS/KWH	NOx Removed $/ton	%
FIXED O&M COSTS									
Operating Labor	58	0.12	0.02	23	0.7%	0.19	0.03	37	0.8%
Maintenance Labor	58	0.12	0.02	23	0.7%	0.19	0.03	37	0.8%
Maintenance Material	39	0.08	0.01	15	0.5%	0.13	0.02	25	0.5%
Administration/Support Labor	35	0.07	0.01	14	0.4%	0.11	0.02	22	0.5%
Subtotal	191	0.38	0.06	74	2.3%	0.62	0.09	120	2.6%
VARIABLE OPERATING COSTS									
ID Fan HP	1,657	3.31	0.50	646	20.3%	5.53	0.84	1,078	22.8%
FD Fan HP	4	0.01	0.00	1	0.0%	0.01	0.00	2	0.1%
ESP Power Increase	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Downtime Replacement Power Cost	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Ammonia Cost	216	0.43	0.07	84	2.6%	0.70	0.11	136	2.9%
Steam Consumption	25	0.05	0.01	10	0.3%	0.08	0.01	16	0.3%
Ash Cost	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Flue Gas Heat Loss	679	1.36	0.21	265	8.3%	2.27	0.34	442	9.4%
Catalyst Replacement	0	0.00	0.00	0	0.0%	4.21	0.64	821	17.4%
SCR Catalyst Disposal Cost	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
FGD Reheat Penalty	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Water Consumption Increase	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Water Treatment Chemical Cost	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Subtotal	2,580	5.16	0.79	1005	31.6%	12.80	1.95	2,494	52.8%
FIXED CHARGES	5,405	10.81	1.65	2,108	66.1%	10.81	1.65	2,108	44.6%
TOTAL	8,176	16.35	2.49	3,188	100.0%	24.23	3.69	4,720	100.0%

FIRST YEAR AND LEVELIZED COST SUMMARY FOR ==> RETROFIT PLANT

	FIRST YEAR (January, 1993 U.S. dollars)					LEVELIZED FOR (end-of-year values) 15 Years			
	$1000	$/KW-YR	MILS/KWH	NOx Removed $/ton	%	$/KW-YR	MILS/KWH	NOx Removed $/ton	%
FIXED O&M COSTS									
Operating Labor	58	0.23	0.04	39	1.1%	0.32	0.06	54	1.2%
Maintenance Labor	58	0.23	0.04	39	1.1%	0.32	0.06	54	1.2%
Maintenance Material	35	0.14	0.02	23	0.7%	0.19	0.03	32	0.7%
Administration/Support Labor	35	0.14	0.02	24	0.7%	0.19	0.03	32	0.7%
Subtotal	186	0.75	0.13	126	3.6%	1.02	0.18	172	3.9%
VARIABLE OPERATING COSTS									
ID Fan HP	717	2.87	0.50	484	13.7%	4.02	0.71	677	15.4%
FD Fan HP	2	0.01	0.00	1	0.0%	0.01	0.00	2	0.0%
ESP Power Increase	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Downtime Replacement Power Cost	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Ammonia Cost	125	0.50	0.09	84	2.4%	0.68	0.12	115	2.6%
Steam Consumption	11	0.05	0.01	8	0.2%	0.06	0.01	11	0.2%
Ash Cost	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Flue Gas Heat Loss	294	1.18	0.21	198	5.6%	1.65	0.29	278	6.3%
Catalyst Replacement	0	0.00	0.00	0	0.0%	3.12	0.55	526	11.9%
SCR Catalyst Disposal Cost	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
FGD Reheat Penalty	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Water Consumption Increase	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Water Treatment Chemical Cost	0	0.00	0.00	0	0.0%	0.00	0.00	0	0.0%
Subtotal	1,149	4.60	0.81	775	22.0%	9.54	1.68	1609	36.5%
FIXED CHARGES	3,888	15.55	2.73	2,623	74.4%	15.55	2.73	2,623	59.6%
TOTAL	5,224	20.90	3.67	3,523	100.0%	26.12	4.59	4,404	100.0%

Levelized $ (1000 $)

Case No.	New Plant	Retrofit
Total Fixed	5713	4144
Var. Op. - Cat Repl-Ammonia	3946	1435
Catalyst Replacement	2106	780
Ammonia	348	171

APPENDIX B

New and Retrofit CFF

Plant Equipment Lists

CATALYTIC FABRIC FILTER SYSTEM EQUIPMENT LIST
(For One 500 MW Unit - 2,536,000 ACFM @ 650°F)

New Plant

EQUIPMENT ITEM AND DESCRIPTION		QUANTITY	TOTAL COST
AREA 10 - COLLECTORS AND HOPPERS			
Fabric Filter		1 lot	$16,131,000
Type:	Pulse Jet	(2 baghouses)	
A/C Ratio (Gross):	3.44		
Number of Compartments:	28 (14 per baghouse)		
Material of Construction:	1/4" steel plate, welded		
Bags/Compartment:	900		
Bag Dimensions:	6" dia. x 20' long		
Total Cloth Area:	737,700 ft² (368,850 per baghouse)		
Bag Material:	Vanadium/Titanium Catalyst-Coated Glass		
Compressors:	3 x 50% pulse air compressors with dryers and filters		
Includes:	Design, delivery, and erection of all support steel, structural components and insulation; hopper heaters, cleaning system		
Total Power Required:	1,080 kW		
AREA 20 - FLY ASH HANDLING SYSTEM			
Includes:	Pneumatic Conveyor Piping and Valves, Ash Hopper Valves, Control Panel, Pneumatic Conveyor Blower, Hopper Level Indicators	1 lot	$694,000
AREA 30 - FLUE GAS HANDLING			
Ductwork			$7,803,000
Includes:	Inlet/Outlet duct tie-ins for baghouse		
AREA 40 - AMMONIA SYSTEM			
Ammonia Unloading and Storage		1 lot	$1,107,000
Includes:	Includes Horizontal Bullet C.S. storage vessel (9.5' I.D. x 28.5' T-T Long, 7 days storage at MCR), truck unloading station (2 x 50% vapor recovery compressors, water deluge system, transfer piping).		
Ammonia Vaporizer and Injection Grid		1 lot	Included
Includes:	1 x 100% Ammonia Vaporizer (carbon steel tank with heated water bath and ammonia coil); Ammonia/Dilution Air Mixer (static in-line mixer); Ammonia Injection Grid (co-current flow injection nozzles with ammonia injection pipe adjusting valves); dilution air ductwork and dampers.		

CATALYTIC FABRIC FILTER SYSTEM EQUIPMENT LIST
(For One 500 MW Unit - 2,536,000 ACFM @ 650°F)

New Plant

EQUIPMENT ITEM AND DESCRIPTION	QUANTITY	TOTAL COST
AREA 50 - SYSTEM INSTALLATION		
Includes: A. Earthwork B. Foundations & Supports C. Erection D. Electrical E. Piping F. Insulation G. Painting		$14,649,000

CATALYTIC FABRIC FILTER SYSTEM EQUIPMENT LIST
(For One 250 MW Unit - 1,268,000 ACFM @ 650°F)

Retrofit Plant

EQUIPMENT ITEM AND DESCRIPTION		QUANTITY	TOTAL COST
AREA 10 - COLLECTORS AND HOPPERS			
Fabric Filter		1 lot	$9,840,000
Type:	Pulse Jet	(1 baghouse)	
A/C Ratio (Gross):	3.44		
Number of Compartments:	14		
Material of Construction:	1/4" steel plate, welded		
Bags/Compartment:	900		
Bag Dimensions:	6" dia. x 20' long		
Total Cloth Area:	368,850 ft^2		
Bag Material:	Vanadium/Titanium Catalyst-Coated Glass		
Includes:	Design, delivery, and erection of all support steel, structural components and insulation; hopper heaters, cleaning system		
Total Power Required:	550 kW		
AREA 20 - FLY ASH HANDLING SYSTEM			
Includes:	Pneumatic Conveyor Piping and Valves, Ash Hopper Valves, Control Panel, Pneumatic Conveyor Blower, Hopper Level Indicators	1 lot	$608,000
AREA 30 - FLUE GAS HANDLING			
I.D. Booster Fans - CFF System		1 op.	$1,484,000
Type:	Centrifugal		
Operating Conditions:	886,000 ACFM @ 25" w.c. and 277°F		
Operating Hp:	4,260 Hp (total)		
Brake Hp:	7,000 Hp (total)		
I.D. Booster Fans - PJFF System		1 op.	$1,755,000
Type:	Centrifugal		
Operating Conditions:	886,000 ACFM @ 34" w.c. and 277°F		
Operating Hp:	5,790 Hp (total)		
Brake Hp:	9,000 Hp (total)		
Ductwork			$5,611,000
Includes:	Inlet/Outlet duct tie-ins for baghouse		

CATALYTIC FABRIC FILTER SYSTEM EQUIPMENT LIST
(For One 250 MW Unit - 1,268,000 ACFM @ 650°F)

Retrofit Plant

EQUIPMENT ITEM AND DESCRIPTION		QUANTITY	TOTAL COST
AREA 40 - AMMONIA SYSTEM			
Ammonia Unloading and Storage		1 lot	$730,000
Includes:	Includes Horizontal Bullet C.S. storage vessel (8.5' I.D. x 25.5' T-T Long, 7 days storage at MCR), truck unloading station (2 x 50% vapor recovery compressors, water deluge system, transfer piping).		
Ammonia Vaporizer and Injection Grid		1 lot	Included
Includes:	1 x 100% Ammonia Vaporizer (carbon steel tank with heated water bath and ammonia coil); Ammonia/Dilution Air Mixer (static in-line mixer); Ammonia Injection Grid (co-current flow injection nozzles with ammonia injection pipe adjusting valves); dilution air ductwork and dampers.		
AREA 50 - SYSTEM INSTALLATION			
Includes: A. Earthwork B. Foundations & Supports C. Erection D. Electrical E. Piping F. Insulation G. Painting		1 lot	$10,875,000