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PULSED ELECTRON BEAM PRECHARGER

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PULSED ELECTRON BEAM PRECHARGER
Technical Progress Report Number Six
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I. INTRODUCTION AND CURRENT STATUS OF THE PROJECT

Electron beam precharging of a high resistivity aerosol was successfully performed under a range of experimental conditions during Quarter Six of the contract. The initial E-beam particle precharging experiments completed this term were designed to extend the efficiency of particle charging and collection using a fine, monodisperse aerosol at relatively large loadings in the FSU Electron Beam Precipitator wind tunnel. There are several reasons for doing this: 1) to re-establish a baseline performance criterion for comparison to other runs, 2) to test several recently upgraded or repaired subsystems, and 3) to improve upon the collection efficiency of the electron beam precipitator when testing precharging effectiveness with a very high resistivity, moderate-to-high dust concentration. In addition, these shakedown runs were used to determine a set of suitable operational parameters for the wind tunnel, the electrostatic collecting sections, and the MINACC E-beam accelerator. These parameters will normally be held constant while the precharging parameters are varied to produce an optimum particle charge.

The electron beam precharging investigation performed during the period covered by Quarter Six used virtually the same experimental apparatus and procedures as in previous contract work, and these are described for review in this report. This investigation was part of an experimental effort which ran nearly continuously for nine months, encompassing work on the electrostatic collecting section, electron beam precharger, and particle charge-to-radius measuring apparatus. A summary of the work on dc electron beam precipitation is presented here.

Section II-A contains a review of the layout and operation of the entire FSU Electron Beam Precipitator (EBP) test system. The EBP is basically an instrumented wind tunnel in the form of a closed circuit loop of ductwork. Various functional modules are interspersed along the length of the wind tunnel, including specialized sections for aerosol generation, electron beam particle precharging, electrostatic dust collection, and gas and particle monitoring. Monodisperse (1.0 μm mean diameter) hydrated alumina "Hydral" dust or polydisperse fly ash aerosols are circulated in the wind tunnel using a high capacity blower; the particles are completely filtered out of the gas stream after passing through a large absolute filter.

Electron beam precipitation is a two-stage procedure, and, as such, different operational requirements are found in each of the two modules. The Mk. III electron beam precharger is located downstream from the aerosol entrainment module. It is composed of a length of insulated ductwork bounded on either side by a set of electrodes. A 100 keV electron accelerator produces a region of bipolar ionization within an annex adjacent to the precharger proper. DC or pulsed electric fields can be applied to the precharger electrodes, extracting a monopolar charge fraction from the ionization zone. Aerosols passing through the precharger are charged to very high levels, and then are transported downstream to the collector. The collecting section just downstream from the precharger is configured like a conventional electrostatic precipitator in order to test electron beam precharging in a "retrofit" situation. Together, the intense charging capability of the precharger and the high efficiency of the collector constitute an effective two-stage particle removal system.

Section II-B details the initial sequence of electron beam precharging experiments which were performed during Quarter Six. This portion of the Technical Progress Report contains subsections on recent upgrades to several important pieces of equipment, properties of the test aerosol, experimental methods, calculation of several comparative parameters, and an analysis of particle precharging and collection. In an effort to produce results which can be used as a basis for comparison to both previous dc electron beam precharging experiments and upcoming pulsed precharging experiments, great care was taken to insure the constancy and compatibility of all of the run parameters.

System modifications and upgrades to the EBP subsystems included installing a heated pressurization system for the AccuRate screw feeder which aided the feeding and deagglomeration process. Particle counting and sizing using the Climet multichannel analyzer and sensing unit (for dc-only runs) was improved by a long overdue overhaul. Data acquisition was made more reliable through the repair and recalibration of the MicroMac A/D signal converter and the aging but adequate microcomputer which links all of the electronic monitors.

Hydral (hydrated alumina) powder was chosen as the test dust to be resuspended in the wind tunnel because of its highly desirable properties for these experiments. It is monodisperse, having a mean diameter of $1.0 \mu\text{m}$, and, most importantly, it exhibits very high resistivity at ambient wind tunnel temperature. Hydral is fed into the EBP aerosol entrainment module ductwork at a concentration of approximately 0.01 gr/ft^3 . This dust concentration is lower than that found in conventional electrostatic precipitators primarily because of the limitations of the Climet optical particle counter. Later in the experimental

program, an absolute filter holder replaced the Climet as the primary particle monitoring device, allowing higher concentrations of aerosol to be tested.

Particle collection efficiency measurements were performed as a five-step procedure which determined the particle sample concentration with aerosol-only, with aerosol treated by the collector, and with aerosol treated by both the collector and the precharger. Comparison of the collector-only condition with the precharger-collector condition can be made using a computed collection efficiency improvement factor denoted as " α ". A series of these multi-step procedures was used to examine a number of precharger and collector parameters which were varied through an appropriate range. Values of aerosol penetration, particle collection efficiency, and the calculated α -value provided a quantitative indication of how well the system was performing at the optimum level of each tested parameter.

In one run example, Hydral dust was resuspended and circulated in the wind tunnel at 4.0 ft/sec precharger velocity. An initial count of 2,254,000 particles per count period dropped to 309,000 when the collector was energized at an electric field of 4.0 kV/cm. Precharging the aerosol with the collector still engaged lowered the count to 30,400 particles/count period at a precharger electric field of 4.4 kV/cm. A simple calculation for these experimental conditions results in a particle penetration through the system of 13.87% when only the collector is operating and a penetration of 1.339% when precharging is initiated. These figures correspond to collection efficiencies of 86.13% (collector-alone) and 98.66% (precharger and collector). Even higher efficiencies were attained at different parameter settings.

One method of quantifying the increase in overall system collection efficiency afforded by the precharger was selected for use in this study. The α -value represents this collection efficiency improvement in a dimensionless number which can be employed in a comparison between various runs having different precharger conditions. In previous work testing a very low concentration of synthetic aerosol, α -values of as high as 190 were found, meaning that the precharger was augmenting the efficiency of the collector by a factor of 190 times. The present work has produced more modest α -values of 10 in the currently discussed experiment; this level was eventually improved to a factor of 40 in later work this term.

The increased system collection efficiency attributed to electron beam precharging was determined to be the result of increased particle charge. It was found that as precharger electric field was raised, collection efficiency also increased. In sequence, saturation particle charge varies with the precharger electric field strength, migration velocity varies with the precharger and collector electric field, and collection efficiency varies with the migration velocity. Maximizing the system collection efficiency requires both a high charging electric field (provided by the E-beam precharger), and a high collecting electric field (provided by the collector wires and plates).

Section III is composed of a reprint of several sections of the "Peer Review Assessment of Research Programs in the Fossil Energy Advanced Research Programs" which was conducted by a review panel appointed by the U.S. DOE Office of Energy Research. The oral presentation to the panel in Bethesda, MD, in August, 1990, was preceded by a lengthy written submission designed to provide the panel with information on the Electron Beam Precipitator

Project. The sections of the written report presented here include the Project History, and the Publication Bibliography. Finally, Section IV lists the personnel currently affiliated with the project.

II. CONTRACT PROGRESS DURING QUARTER SIX

A. Electron Beam Precipitator - Review of Systems

Electron beam particle precharging experiments using a dc charging electric field were conducted using the FSU Electron Beam Precipitator wind tunnel, the Mk. III E-beam precharger, and a moderately high concentration of high resistivity Hydral test dust. Although the wind tunnel and associated subsystems have been described elsewhere in detail, a review of the experimental apparatus, the mechanics of precharging, and data acquisition and analysis procedures will be reviewed here.

Figure 1 shows the Electron Beam Precipitator (EBP) test system, a facility which is unique in the U.S. by virtue of combining the technologies of electron beam treatment, pulsed power energization, and electrostatic precipitation in a single unit. The closed-circuit or "racetrack" wind tunnel is composed of a continuous loop of square, stainless steel ductwork interspersed with a number of specialized modules. Some approximate dimensions of the system are: length - 19 ft, width - 7 ft, height - 3.5 ft, total path length - 45 ft, duct size - 1 ft x 1 ft. Opening module tops and sides as well as a number of sampling ports allow ready access to the interior of the wind tunnel.

A large squirrel cage blower controlled by an outlet damper circulates room temperature air at gas velocities and volumes of up to 33 ft and 2000 ACFM, respectively. Just upstream from the fan is a large H.E.P.A. high capacity filter capable of removing 99.97% of all particles larger than 0.3 μm diameter. A humidity control and monitoring device is located downstream from the fan. Relative humidity levels during the tests ranged from 30 - 50% but

F.S.U. ELECTRON BEAM PRECIPITATOR TEST SYSTEM

Figure 1. The Two-Stage, Laboratory Scale FSU Electron Beam Precipitator Wind Tunnel, showing the Aerosol Injection, E-Beam Precharger, and Collector Modules.

were generally very close to 40% RH. Dry air from a compressed air source can also be added to control humidity.

An aerosol of 1.0 μm median diameter hydrated alumina (Hydral) monodisperse test dust having a resistivity at room temperature of $> 10^{12} \Omega\text{-cm}$ was generated using the fluidized bed/screw feeder aerosol generator (Figure 2). The highly concentrated dust suspension was dispersed into the circulating gas stream at the particle injection module. Two 50% open area baffle screens downstream from the injection point insure that a completely distributed aerosol will be delivered to the precharger.

Since electron beam precipitation is a two-stage concept, particle charging and collecting occur as two separate functions. Particle charging is accomplished in the electron beam precharger upstream from the collecting stage. Figure 3 shows the precharging module and the associated electron beam source and vacuum station. The outer precharging module is the same cross sectional size (1 ft x 1 ft) as the wind tunnel ductwork although the actual precharger sub-duct is only one-quarter the size (6 in x 6 in). The smaller duct is suspended concentrically within the outer module and is constructed of an insulation material. Within the precharger are three parallel sets of metal plane electrodes across which the charging electric field is applied. The flow of test aerosol passes between two of these electrode sets which delineate the charging zone.

Ions and electrons for the particle charging process are provided by an electron beam source. The source itself is a 100 keV maximum energy electron accelerator constructed at FSU, dubbed the MINACC. Within an evacuated, insulating PVC pipe are a hot filament cathode and a series of accelerating rings at successively

EBP Fluidized Bed Aerosol Generator

Florida State University

Figure 2. Schematic Diagram of the Fluidized Bed / Screw Feeder Aerosol Generation System, which Deagglomerates and Resuspends Hydral and Fly Ash.

Figure 3. Top View of the BG/CP-2C Vacuum Station, The 100 keV Electron Beam Accelerator (MINACC), and the E-Beam Particle Precharging Module.

lower electric potentials (Figure 4). The electron beam passes down the pipe and through a thin plastic film "window" out into the precharger where the ionization process occurs.

Maintaining the MINACC at a pressure level of approximately 5×10^{-6} torr is a dedicated vacuum station, the BG-2 (Figure 3). Control over the pumping process is exercised by a CVC vacuum gauge controller and a series of solenoid-actuated valves. Protection for the diffusion pump is built into the station circuitry in case of an accelerator window blowout or other major vacuum leak.

The mechanics of electron beam particle precharging have been described elsewhere in detail, but the process will be briefly outlined again. Figure 5 shows the present internal electrode configuration of the Mk. III E-beam precharger. As the high energy electron beam passes from vacuum into air through the "window" on the end of the MINACC, the ionization process commences. Positive and negative ions and secondary electrons are created at a rate dependent upon the initial electron beam energy and current. This zone of ionization is contained within a recessed area out of the flow of aerosol in the precharger.

Along both side walls of the inner precharging module are a set of plate which define the boundary of the charging zone (Figure 5). When an electric field is applied between the anode and cathode electrodes, the charge density is separated into two monopolar fractions (Figure 6). The negative fraction composed of ions and free electrons is drawn out into and maintained in the charging zone, through which particle-laden gas is flowing. High levels of particle charge and fast charging rates result from, respectively, the large electric fields and dense ion currents in the precharger.

Figure 4. Side View Schematic Diagram of the 100 kV Electron Beam Accelerator (MINACC), showing the Accelerator Column, the thin Window, and the Dropping Resistors.

Figure 5. Top View of the Mk. III Electron Beam Precharging Module showing the E-Beam Accelerator, the Cathode and Anode Electrodes, and the Ionization and Charging Regions.

Figure 6. Representation of the process of Electron Beam Ionization of Air Molecules, showing the formation of Secondary Electrons by the Primary Beam, and the Separation of Charge using an intense dc Electric Field.

Highly charged particles pass out of the precharger, into an expansion section, and then into the collector. Baffle screens insure an even flow into and out of the collection module. The electrostatic collector (Figure 7) is of a standard wire-plate precipitator design with two channels, one of which can be blocked off with a baffle plate converting the collector to a higher velocity, lower SCA (Specific Collection Area) device. Each field is composed of two 2.5 ft wide by 4 ft high collecting plates separated by 6 in. Five 0.125 in thick wires spaced at 5 in hang between each set of plates. The gas velocity in the collector varied between 0.6 ft/sec and 2.35 ft/sec, changing the SCA from 833 to 1667 using only one collector channel. Voltage was generally set at either 26.7 kV (3.5 Kv/cm) or 30.5 kV (4.0 kv/cm). Table 1 shows the dimensional relationships between the precharging module, the racetrack ductwork, and the one and two channel collector configurations.

Several monitoring locations are spaced throughout the wind tunnel, with the three main ones being upstream from the precharger, midway between the precharging and collecting modules, and immediately downstream from the collector. The latter monitoring station was used for these experiments. It contains a Climet optical particle counter which measures particle size and number, from which the system collection efficiency can be determined. The previously described absolute filter holder bulk dust sampling device is also located here. A Kurz electronic air velocity probe and a General Eastern relative humidity and temperature sensor completed the array of aerosol monitors.

Figure 8 shows a schematic diagram of the microcomputer-based data acquisition system which ties the above mentioned monitors to a small computer. In addition to the inputs from the Climet

Figure 7. Top View of the Collecting Module within the EBP Wind Tunnel, showing detail of the Six Electric Field Regions composed of Parallel Collection Plates and Central Corona Wires.

Table 1.

DIMENSIONAL RELATIONSHIPS OF THE EBP WIND TUNNEL (EBP)

FSU ELECTRON BEAM PRECIPITATOR

DUCT -- Stainless Steel, Closed Loop, 1 ft² Cross Sectional Area,
40 ft. Path Length

PRECHARGER -- Mk. III Version, Charging Zone
Length = 15 cm (0.5 ft)
Width = 14 cm (0.45 ft)

ELECTRICAL PARAMETERS -- Voltage = 0 - 77 kV dc
E - Field = 5.5 kV/cm
Ion Current = 0 - 40 μA_2
Current Density = 1.25 mA/m²

ELECTRON BEAM -- Energy = 90 keV
Current = 2 μA

COLLECTING SECTION -- Plate Area = 60 ft²
Width = 6 in
Wires = 0.109 in (15)

AEROSOLS AND GENERATORS -- PSL (Collision Nebulizer)
Hydrated Alumina, Fly Ash
(Fluidized Bed/Screw Feeder)

PARTICLE MONITORS -- Optical Particle Counter
Absolute Filter Holder

Figure 8. The Microprocessor-based Data Acquisition and Analysis System serving the Electron Beam Precipitator Monitors.

multichannel analyzer and the air velocity and humidity probes, a Micromac data acquisition device measures the precharger and collector voltages and currents and sends the digital data to the computer. A remote controlled, closed circuit TV system is used to visually monitor analog meters measuring the MINACC accelerator vacuum, the electron beam current, and the precharger and collector ion current levels.

B. DC Electron Beam Precharging and Collection of Particles

1. System Modifications and Upgrades

Since the last experiments using dc energization of the precharger were performed, a number of improvements have been made to the aerosol generator, the particle charge measurement device, and the data acquisition and analysis system. Most of these changes have been described in detail in earlier technical progress reports, but a short review will be provided here for completeness.

A smaller diameter screw and jacket were fitted to the AccuRate screw feeder (Figure 2), allowing a much faster motor speed and greater dust feeding accuracy. The screw feeder/fluidized bed combination was fitted with a positive pressure heated air network which aids the deagglomeration of the dust in the sealed hopper and the agitating glass bead bed. Remote focusing control was greatly improved on the single particle charge vs. radius (Q/A) apparatus (Figure 9) by installing a new one rpm motor and associated geartrain to the microscope objective focus knob.

Particle counting capability was increased by the addition of a dilution system to the Climet optical particle sensing unit. Repair and recalibration of the Climet multichannel analyzer (Figure 10) was required because of its age (ten years old) and the sensitivity of the unit to electromagnetic radiation. The MicroMac analog-to-digital converter (Figure 11) was completely overhauled, including the replacement of most of the semiconductor components in the circuit. This restored the ability of the MicroMac to automatically measure and record the ion current from each of the six collector plates presently in use. Many of the E-beam

F.S.U. Charge / Radius Measurement System

Figure 9. The FSU Particle Charge vs. Radius (Q/A) Monitoring Apparatus, showing the Laser Beam, the Video Recording System, and the Particle Charge Measurement Cell.

CI-225

FEATURES:

- ☐ 0.3 MICRON SENSITIVITY
- ☐ LONG DISTANCE DATA TRANSMISSION
- ☐ COMPACT DESIGN WITHOUT SACRIFICING VERSATILITY OR PERFORMANCE
- ☐ ELLIPTICAL MIRROR OPTICS

MODEL CI-225 OPTICAL SYSTEM:

The patented elliptical mirror light collection system is recognized as the finest in the world, gathering the greatest amount of scattered light for any given particle.

SPECIFICATIONS:

Power: 115/230 volt, 60/50 Hz.

Signals: (1) Digital Output, BNC Connector (J3)
(2) Analog Output for Particle Size Analysis, BNC Connector (J4)

Standard Particle Size Range: .3 to 10 microns and above

Flow Rate: .25 cubic feet per minute

Weight: 40 lbs.

Size: 9½" H, 11½" W, 19¾" L

CI-210 MULTI-CHANNEL ANALYZER

The Climet CI-210 Multi-Channel Analyzer is a micro-processor-controlled multiple pulse discriminator which receives pulses representing particle sizes from one to forty Climet Particle Sensors simultaneously. Pulses are continuously discriminated, accumulated, displayed, and recorded in the CI-210 according to the unit's ten internally stored programs. Most any number of sensors x size ranges per sensor combination $\leq$ forty can be specified. Alarms, data summaries, and computer interfaces are optional and available upon request.

Figure 10. The Climet Optical Particle Size/Number Measurement System, showing the CI-225 Counting Unit and the CI-210 Multichannel Analyzer.

Figure 11. Grounding Layout between the Microcomputer and Multichannel Analyzer (located in the control room), and the Particle Counter, MicroMac Current Converter, Pulsed Power Supply, and E-Beam Precipitator (located in the Accelerator Vault).

precipitator monitoring functions are coordinated by an old but still adequate microcomputer (Figure 8), which was also returned to its original state of operating capability through the replacement of several internal components and the changeout of the two floppy disk drives.

2. Properties and Concentration of the Test Aerosol

As called for in the contract Statement of Work, electron beam particle precharging was tested initially using hydrated alumina, or Hydral (Table 2). This Alcoa Aluminas product has the chemical formula $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ and its properties resemble common alumina in many respects. Hydral is composed of monodisperse particles of $1.0 \pm 0.5 \mu\text{m}$ diameter having a dielectric constant of 8.7. It has the physical form of a white, crystalline substance with a specific gravity of 2.40 g/cm^3 and a bulk density of $8\text{-}14 \text{ lb/ft}^3$, depending on packing. Hydral does not react chemically when exposed to air, water, heat, or strong oxidizers. Possibly most important in the present application is the fact that hydrated alumina exhibits high ($> 10^{12} \Omega\text{-cm}$) resistivity at room temperature, the temperature at which the EBP wind tunnel is currently operated.

Conventional electrostatic precipitators typically operate with duct dust concentrations on the order of 1 grain/ft^3 , which corresponds to a particle concentration of $2.7 \times 10^{10} \text{ particles/ft}^3$. Since the particle counting capability of the Climet CI-225 optical particle counter with outboard dilution system is only $5.4 \times 10^8 \text{ particles/ft}^3$, or a factor of 50 lower, the maximum dust loading that can be tested in the EBP wind tunnel is 0.02 grain/ft^3 . Actual dust concentration was somewhat lower. For the three experiments presented in this report, the highest particle concentration that was generated was 113,525,000 particles per 84

Table 2.

Chemical, Physical, and Size Distribution Properties of "Hydral"Typical Chemical Analysis

<u>Chemical</u>	<u>Formula</u>	<u>Percent (%)</u>
Aluminum Oxide	Al_2O_3	64.7
Silica	SiO_2	0.04
Ferric Oxide	Fe_2O_3	0.01
Sodium Oxide	Na_2O	0.45
Sodium Oxide (soluble)	Na_2O	less than 0.25
Moisture	H_2O	less than 1

Typical Physical Properties

Specific Gravity, g/cm ³	2.40
Tapped Density, lbs/cu ft.	26 - 34
Loose Density, lbs/cu ft.	8 - 14
Lbs./Solid Gallon	19.99
One Lb. Bulks, Gallons	0.0500
Passage Through 325 mesh, %	99.85
Dielectric Constant	~8.7

Typical Particle Size Distribution

<u>Microns</u>	<u>% less than</u>
2	100
1	85
0.5	28

second count period, which translates to a moderately high loading of 307,286,000 particles/ft³. In the measurement units more commonly used in electrostatic precipitator terminology, this experimental particle loading is equivalent to 0.0114 grain/ft³. The original target goal of 1 grain/ft³ was unattainable in the present experiments due to particle monitor limitations. However, the dust concentration resuspended into the wind tunnel for the three experiments presented here is almost three times higher than the dust concentration in any previous experiment.

3. Experimental Procedures

The experimental methods used in the previous high aerosol concentration electron beam precharging runs were for the most part repeated in the present set of experiments. Air at room temperature and 40% relative humidity was circulated in the FSU Electron Beam Precipitator wind tunnel (Figure 1) at a gas volume of 3.2 ft/sec. A particle-free source of test gas was insured by a high capacity absolute filter located upstream from the aerosol entrainment module. The screw feeder/fluidized bed aerosol generator produced a moderately high concentration of resuspended dust which was then injected into the circulating gas stream. Four porous baffle screens along the flow path separating the aerosol entrainment module and the E-beam precharger mixed the dust laden gas thoroughly.

Charging of the particles in the test aerosol takes place in the Mk. III-B electron beam precharger (Figure 5), approximately 12 feet downstream from the point of dust injection. Layout and function of the precharger, the 100 keV MINACC E-beam accelerator, and the dedicated BG-2 vacuum station have already been described in Section II.A. After precharging, the airborne particles are

removed from the gas stream in the collecting section. A monitoring section just downstream from the collector houses a gas temperature and velocity sensor and a sampling take leading to the Climet optical particle counter and dilution system. Electronic signals from all of the monitoring devices were subsequently sent to a microcomputer-based data acquisition system for on-line analysis and eventual storage.

Procedures for making a complete experimental run are as follows. Normally one parameter is varied while the others are held constant. The experiment itself consists of several steps which compare the EBP system collection efficiency with just the collector operating to that with both the precharger and collector operating. Each count period lasted 84 seconds (1.4 minutes) corresponding to a preset cycle in the Climet multichannel analyzer. Particle count information is recorded for the five-step process: 1) aerosol alone, 2) aerosol treated by collector only, 3) aerosol treated by precharger and collector, 4) repeat Step 2, and 5) repeat Step 1. Data from Steps 1 and 5 and also Steps 2 and 4 were averaged in order to offset any small changes in aerosol concentration over time. Runs were performed using Hydral test dust at moderately high concentrations with a dc electric field only (no pulsed power) applied to the electron beam precharger.

In addition to the particle count data, charge vs. radius (Q/A) measurements were made during most of the experiments to correlate particle charge with particle collection efficiency; these will be discussed separately in Technical Progress Report 7. Theoretical saturation charge and predicted charge calculations were also performed to compare to the experimental particle charge data.

4. Calculation of Collection Efficiency and Improvement Factor " α " -- An Example

The first electron beam precharging experiment which was completed this term will be used to illustrate the procedures used to analyze a run. Hydral dust of $1.0 \mu m$ mean diameter was resuspended in the circulating gas stream at $25^{\circ}C$ and 40% RH. Duct gas velocity was 1.0 ft/sec while precharger gas velocity was 4.0 ft/sec. Particle count periods for each run condition were monitored until the data stabilized, at which time a count total was recorded.

Table 3 shows the results of the sample Mk. III E-beam precharger run. The initial particle count total was 2,254,000 (Run 430.3) corresponding to a dust concentration of approximately 0.01 grain/ft³. When the collector was energized at 30.5 kV dc (4.0 kV/cm electric field), the particle count dropped to 309,000 particles/count period (Run 430.8). With the collector still operating, the electron beam was engaged (90 keV energy, 2.0 μA beam current) and the precharger anode was energized (55 kV voltage, 3.7 kV/cm electric field, 40 μA ion current). The particle count for this set of conditions was 38,200 (Run 431.2), falling further to 30,400 (Run 431.4) when the precharger anode voltage was increased to 66 kV or 4.4 kV/cm electric field. Slightly different but nevertheless similar particle count readings were obtained when repeating the collector-only run (No. 432.8, count = 321,000) and the aerosol-only run (No. 433.1, count = 2,287,000).

Data from this and subsequent runs were analyzed using the series of calculations shown in Table 4. Part A of the table details the sequence followed to obtain the particle collection

Table 3.

Experimental Run of the Mk. III Electron Beam Precharger
Hydral (Hydrated Alumina) Test Dust, 1.0 μm Mean Diameter

Run Number	Particle Count	Collector E-Field (kV/cm)	Collector Current (mA)	E-Beam Energy (keV)	E-Beam Current (μA)	Precharger E-Field (kV/cm)	Precharger Current (μA)
430.3	2,254,000	-	-	-	-	-	-
430.8	309,000	4.0	0.2	-	-	-	-
431.2	38,200	4.0	0.2	90	2.0	3.7	40
431.4	30,400	4.0	0.2	90	2.0	4.4	41
432.8	321,000	4.0	0.2	-	-	-	-
433.1	2,287,000	-	-	-	-	-	-

efficiency for each case. The two aerosol-only runs and the two collector-only runs were averaged to obtain the values in the table. Recorded counts for the two experimental precharger voltages (55 and 66 kV) are also shown. Particle penetration through the system with only the collector operating was found by dividing this particle count (315,000) by the particle count with aerosol-only (2,270,000). The resulting penetration (collector only) of 13.87% yields a particle collection efficiency of 86.13% since penetration and efficiency are described by the relation $\eta = 1 - P$, where η is the efficiency and P is the penetration. Penetration and collection efficiency values for the condition when both the E-beam precharger and collector were operating were found in a similar manner. Individual calculations for precharger voltages of 55 and 66 kV are shown in the table.

Part B of Table 4 contains the calculation of the precharger efficiency improvement factor " α ". Dividing the collector-only penetration by the precharger-collector penetration gives a ratio which can be used to compare the two penetration figures. The α -value represents a quantitative measure of the increase in system collection efficiency due solely to the contribution of electron beam precharging. This factor will always be greater than unity if the precharger is augmenting the latent particle charge.

As shown in the example in Table 4, for a precharger voltage of 55 kV the penetration for the collector-only condition is 13.87%, while the penetration for the precharger-collector condition is 1.682%. The calculated α -value therefore is 8.246, indicating a significant (8-fold) improvement in precipitator performance directly due to the effect of electron beam particle precharging. In general, the collector is run at a relatively low electric field level (4.0 kV/cm) to prevent back corona from

Table 4.

A. Collection Efficiency Calculation

Hydral Dust Only.....Average Count = 2,270,500

Hydral, Collector On.....Average Count = 315,000
(Precharger Off)

Particles, Collector On

Precharger = 55 kV.....Recorded Count = 38,200

Precharger = 66 kV.....Recorded Count = 30,400

Collector-Alone Penetration = 13.87%

Collector-Alone Efficiency = 86.13%

Precharger-Collector Penetration

Precharger = 55 kV = 1.682 %

Precharger = 66 kV = 1.339 %

Precharger-Collector Efficiency

Precharger = 55 kV = 98.32 %

Precharger = 66 kV = 98.66 %

B. Precharger Efficiency Improvement Factor (α)

$$\alpha = \frac{\text{Collector Penetration}}{\text{Precharger - Collector Penetration}}$$

For Precharger at 55 kV,

$$\alpha = \frac{13.87\%}{1.682\%} = 8.246$$

For Precharger at 66 kV,

$$\alpha = \frac{13.87\%}{1.339\%} = 10.36$$

Therefore, at 66 kV precharger voltage, the Electron Beam Precharger generates more than a 10-fold increase in overall system collection efficiency.

occurring. This allows ample opportunity for E-beam precharging to greatly increase the overall system particle collection efficiency, as revealed by the efficiency improvement factor α .

5. Analysis of E-Beam Precharging Run

The example cited in the previous section of this report constituted the initial electron beam precharging experiment of this contract. In continuing the analysis of this first run, reference will be made to Tables 3 and 4 from the last section. Two dc electric field levels were tested in the precharger: 3.7 kV/cm (55 kV anode voltage) and 4.4 kV/cm (66 kV anode voltage). Table 3 shows that there is a substantial reduction in particle count while using E-beam precharging with either field compared to the count when only the collector is operating. However, only a modest quantitative difference in the number of particles counted by the optical particle counter for these two anode electric fields is noted.

Table 3 presents these results in the form of penetration reduction, efficiency increase, and efficiency improvement factor. Penetration of dust through the precharger-collector system with the precharger anode set at 55 kV was 1.68%, or an efficiency of 98.32%. Corresponding penetration and efficiency values for a precharger anode voltage of 66 kV are, respectively, 1.34% and 98.66%. The α -value relates the collector-alone penetration to the precharger-collector penetration in a single number, which should be greater than one if using precharging improves the overall collection efficiency. At 55 kV precharger voltage, the computed α -value is 8.25, which improves to 10.36 for a precharger voltage of 66 kV.

The higher α -value for 66 kV reflects the fact that higher precharger electric field levels yield higher particle charge. According to the ionic field charging relation, particle charge is directly proportional to the charging electric field. Further, the

Deutsch-Anderson particle collection efficiency equation:

$$\eta = 1 - \exp \left(\frac{-A}{V} \omega \right)$$

where:

- η = particle collection efficiency
- A = collector plate area
- V = gas flow volume through precipitator
- ω = empirical particle migration velocity

holds that for a given constant specific collection plate area, the particle migration velocity " ω " will ultimately determine the collection efficiency. If the migration velocity can be increased in the collector, the efficiency should improve. The theoretical migration velocity equation for field dependent charging is given as:

$$\omega = \frac{2 \epsilon_0 E_o E_p a}{\eta_g}$$

where:

- ω = theoretical migration velocity
- ϵ = permittivity of free space
- E_o = charging electric field
- E_p = collecting electric field
- a = particle radius
- η_g = gas viscosity .

From the above two equations, it can be seen that as the charging electric field (in this case, the field in the electron beam precharger) is raised, the particle migration velocity will increase, leading to an improvement in the system collection

efficiency. Indeed, raising the electric field 20% from 3.7 kV/cm to 4.4 kV/cm results in an approximate 25% increase in system collection efficiency for this particular example. Greater precharger anode voltage levels could yield even higher collection efficiencies.

6. Maximizing System Collection Efficiency and α -Value

Another experiment designed to attempt to attain higher collection efficiencies under dense particle loading conditions was performed during this contract period. Experimental conditions and parameters for this run were similar to the previously described run. Table 5 shows the run conditions along with the results of the Mk. III-B electron beam precharger treating a high concentration Hydral aerosol. Once again, particle number was registered by a Climet optical particle counter, and two precharger electric field values and their corresponding ion currents were used during the experiment.

An initial particle count of 80,575,000 per 84 second count period was generated from the screw feeder/fluidized bed aerosol generator (Table 5). When the collecting section was energized at an electric field of 4.0 kV/cm, the particle count dropped to 11,250,000, resulting in a penetration of 14.0% that of the original concentration. Precharging upstream from the collector with a charging electric field of 4.7 kV/cm reduces the particle penetration further to a level of 1,070,000 (1.33% penetration).

The α -value provides a quantitative measure of the improvement in precharger efficiency and is defined as (penetration of collector) $\div$ (penetration of precharger and collector). This increase in efficiency from 86.0% to 98.7% gives an α -value of 10.5

Table 5.

High Particle Loading Collection Efficiency Runs -
Mk. III-B E-Beam Precharger using 1.0 μm Hydral

Experimental Conditions - Run # 450

Test Aerosol	:	Hydral, 1.0 μm diameter
Particle Count Period	:	84 sec.
Climet Dilution Ratio	:	50:1
Precharger Gas Velocity	:	3.2 ft.sec
Collector Electric Field	:	4.0 kV/cm
Collector Ion Current	:	100 μA
Electron Beam Energy	:	90 keV
Electron Beam Current	:	2.0 μA
Precharger Voltage	:	66, 70 kV
Precharger Electric Field	:	4.7, 5.0 kV/cm
Precharger Ion Current	:	41, 43 μA

	Particle Count	Penetration %	Efficiency %	α -Value	Electric Field
<u>Run #305</u>					
Particles Only	80,575,000				
Particles, Coll.	11,250,000	14.0	86.0		
Part., Coll., Prech.	1,070,000	1.33	98.7	10.5	4.7 kV/cm
Part., Coll., Prech.	279,250	0.35	99.7	40.2	5.0 kV/cm

(a ten-fold improvement due solely to E-beam precharging). Raising the voltage from 66 to 70 kV increases the charging electric field to 5.0 kV/cm, which in turn improves the system collection efficiency to an even higher value of 99.7%. This level of efficiency and the resulting α -value of 40.2 represent the best electron beam precipitator performance to date when operating with a high density, high resistivity test aerosol.

7. Summary of High Aerosol Concentration Precharging Experiments

Precipitator collection efficiency depends upon particle migration velocity, which, in turn, depends upon the charging and collecting electric fields. In a two stage system such as the E-Beam precharger/collector arrangement, the charging electric field is measured in the precharger. Pauthenier's ionic field charging equation describes the saturation charge on a spherical particle in a electric field. For a given particle radius and dielectric constant, the level of saturation charge varies with the charging electric field. Restated, a higher voltage on the precharger electrodes will theoretically result in a greater particle charge and, ultimately, increased collection efficiency.

The results of these experiments conducted using a dc charging electric field confirmed expectations. Electron beam particle precharging works successfully when operated upstream from a wire-plate collector which is run at a voltage just above the corona onset point and at low current. Overall system collection efficiencies are much higher when using precharging than when using the collector alone as evidenced by the calculated α -values, all of which are much greater than one. Precharging boosts the charge level on the test particles flowing through the E-beam precharger

above that which they could obtain from corona charging in the collecting section. This elevated particle charge translates directly to a greater migration velocity in the collector, leading to more efficient removal.

Although the improvement in collection efficiency due to precharging (as represented by the α -value) was not as dramatic here as in the low aerosol concentration experiments detailed in the Final Report of the previous contract, a very significant increase of up to a factor of $\alpha = 40$ was still obtained. High resistivity hydrated alumina dust resuspended in the wind tunnel at dense concentrations is much more difficult to remove than light concentrations of polystyrene latex spheres. This observation holds true for either case of 1) operating the collector alone as a conventional electrostatic precipitator, or 2) using both precharger and collector in two-stage operation. Nevertheless, removal efficiencies of as high as 99.7% have been achieved in these preliminary experiments.

Further enhancements of particle charging and collection are expected with the addition of pulsing to the charging electric field. The first pulsed electron beam precharger experiments were begun during the latter part of the present reporting period. These results will be presented in a future Technical Progress Report.

III. PEER REVIEW ASSESSMENT OF PULSED ELECTRON BEAM PRECHARGER PROJECT

A. Project History

Contract Number, Title, Dates, Funding (including direct research funding and overhead).

U.S. Department of Energy, Morgantown Energy Technology Center (Contract No. 1), Pittsburgh Energy Technology Center (Contract Nos. 2-7).

1. DOE-METC Contract No. DE-AS21-78ET-11316
"Electron Beam Ionization for Coal Fly Ash Precipitators".
July 14, 1978 - December 1, 1980.
Funding: Total = \$163,695, Direct = \$97,562,
Indirect = \$66,133.
2. DOE-PETC Contract No. DE-AC21-81MC16229
"Configurational Testing of Electron Beam Ionization for Coal Fly Ash Precipitators"
December 2, 1980 - December 1, 1982.
Funding: Total = \$268,861, Direct = \$204,301,
Indirect = \$64,560.
3. Eight-month funded extension of DOE-PETC Contract No. DE-AC21-81MC16229
"Configurational Testing of Electron Beam Ionization for Coal Fly Ash Precipitators"
December 2, 1982 - August 4, 1983.
Funding: Total = \$101,195, Direct = \$79,319,
Indirect = \$21,876.
4. DOE-PETC Contract No. DE-AC22-83PC60266
"Configurational Testing of Electron Beam Ionization for Coal Fly Ash Precipitators"
August 5, 1983 - August 4, 1985
Funding: Total = \$399,637, Direct = \$282,079,
Indirect = \$117,558.
5. DOE-PETC Contract No. DE-AC22-86PC91021
"Flue Gas Cleanup Technology Utilizing Energetic Electrons"
May 6, 1986 - September 5, 1988
Funding: Total = \$337,206, Direct = \$236,298,
Indirect = \$100,908.

6. Six-month funded extension of DOE-PETC Contract No. DE-AC22-86PC91021
"Flue Gas Cleanup Technology Utilizing Energetic Electrons"
September 6, 1988 - March 5, 1989
Funding: Total = \$43,058, Direct = \$30,268,
Indirect = \$12,790.
7. DOE-PETC Contract No. DE-FG22-89PC89768
"Pulsed Electron Beam Precharger"
September 1, 1989 - August 31, 1991
Funding: Total = \$137,958, Direct = \$96,537,
Indirect = \$41,421.

Industrial Support

1. Combustion Engineering, Inc., Birmingham, AL.
"Design and Test of a PEER Module for a Pilot System"
February 10, 1988 - December 14, 1988
Funding: Total = \$30,000, Direct = \$30,000,
Indirect = \$ -0- .
* In addition, an approximate total of \$50,000 in equipment and supplies was donated to FSU for use in the contracted research program.
2. F.L. Smidth Co., Copenhagen, Denmark.
"Operation of the FSU PEER Bench System on SO₂ and NO_x Gases"
April 15, 1989 - July 15, 1989
Funding: Total = \$3500, Direct = \$3500, Indirect = \$ -0- .
* In addition, approximately \$25,000 was committed to the work at FSU to support one senior researcher and to provide for equipment and supplies.

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4. R.H. Davis and W.C. Finney. Application of Electron Beam Ionization in Electrostatic Precipitators. IEEE Transactions on Nuclear Science, Volume NS-26, No. 1, pp. 1490-1492, 1979.
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