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PULSED ELECTRON BEAM PRECHARGER

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Technical Progress Report Numbers Five and Six

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I. INTRODUCTION AND CURRENT STATUS OF THE PROJECT

Electron beam precharging of a high resistivity aerosol was successfully demonstrated during this reporting period (Quarters Five and Six). The initial E-beam particle precharging experiments completed this term were designed to confirm and extend some of the work performed under the previous contract. 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 concentration dust load. 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 generally be held constant while the precharging parameters are varied to produce an optimum particle charge.

The electron beam precharging investigations performed during the period covered by Quarter Five and Quarter Six use the same experimental apparatus and procedures and the work ran nearly continuously for six months. For this reason, this research will be reported in a single Technical Progress Report for Quarters 5 and 6 instead of two separate shorter reports containing unnecessarily repeated descriptions of the equipment and analytical methods. A summary of this work is presented in the following paragraphs.

Section II-A of TPR 5-6 contains a report on the continuing effort which was expended on the modification and upgrade of the pulsed power supply and the monitoring systems

prior to the initiation of the electron beam precharging experimental work. During earlier tests of the previously described rotating spark gap pulsed power supply, it was found that a large amount of electromagnetic noise was emitted from the pulsar spark gap. This RF emission interfered with the proper operation of the electronics of the optical particle counter and other on-line sensing equipment.

Despite numerous attempts to totally eliminate the emitted noise, only partial success in this endeavor was achieved. The optical particle counter was presently used in some of the tests using only dc energization of the precharger. For preliminary runs using pulsed power, however, the optical particle counter was abandoned in favor of a non-electronic filtering system for use in determining the wind tunnel particle concentration under high loading conditions. Shakedown runs with this filter holder proved its effectiveness in sampling the particle-laden gas passing through the E-beam precharger and collector.

One of the most important tasks of the present contract is to measure in-situ the charge and mass of individual particles exiting the electron beam precharger. Although this capability has been demonstrated during earlier experiments, there were recurring problems with the procedure which included the inability to remotely focus the microscope objective lens while running an experiment. Operation of the FSU-developed charge vs. radius (Q/A) apparatus was greatly improved with the addition of a synchronous motor and gear train which now allows very fine control of the particle image on the video screen.

Section II-B 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 ($1.0\ \mu\text{m}$ 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-C presents the results of a series of tests of the electrostatic collector section of the EBP wind tunnel. Normally, the collector forms the downstream half of the precharger/collector two-stage system, but no precharging was used in this particular investigation. The collector is usually operated in a low current mode in order to reduce the formation of back corona. These tests were designed to check the accuracy of the Micromac current measurement system, to ascertain the efficiency of the collector under high dust loading conditions, and to check the operation of the absolute filter holder bulk dust sampling system. This mechanical sampling device replaced the Climet optical particle counter in this study because of the aforementioned problems with electromagnetic interference from the pulsed power supply.

Collector electrode voltage was incrementally varied from 3.0 kV/cm to 5.0 kV/cm, and ion current was monitored by three methods. Particle collection efficiencies were high even at the corona onset point (approximately 3.0 kV/cm). At 4.5 kV/cm electric field, a large increase in ion current caused a jump in particle collection efficiency to a value of 97.4%. The operational limit of the collector was determined to be approximately 6.0 kV/cm at which point back corona begins to be evidenced. However, because of the high particle collection efficiencies that can be achieved at only moderate voltages, the collector can be run at electric fields of between 3 and 5 kV/cm. Furthermore, because particle charging duties are more effectively handled by the E-beam precharger, the collector can be run in a low current condition which provides energy savings as well as freedom from back corona.

Section II-D details the initial sequence of electron beam precharging experiments which were performed during Quarters Five and 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 $1.0\text{ }\mu\text{m}$, 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 II-E addresses an investigation of the electrical charge on individual particles exiting the precharger. As has already been stated, the magnitude of the electric field determines the theoretical saturation limit of the charge on a particle. However, the maximum potential charge on a particle depends upon, among other variables, the radius of the particle and the residence time of the particle in the charging electric field region.

Therefore, the calculated predicted particle charge level for a particular residence time will be lower than the theoretical saturation limit unless the residence time of the particle in question is infinite.

In addition to the computed charge values, the charge on individual particles was directly measured using the FSU-developed charge vs. radius ratio (Q/A) measurement system. This device samples particles from the EBP wind tunnel just downstream from the precharger and introduces them into a laser-illuminated chamber bounded by an oscillating electric field. Particle charge is derived from the magnitude of oscillation while radius and mass are determined by the falling velocity of the particle.

Experimental and theoretical particle charge values were determined for precharger gas velocities of zero (infinite residence time) and 4.0 ft/sec at various precharger anode voltages. The predicted charge at 4.0 ft/sec is approximately 95% of the saturation charge limit, meaning that at realistic duct gas velocities, particles passing through the precharger should have the opportunity to closely approach the maximum possible charge. Saturation and predicted charge levels for the experimental conditions examined this term ranged from 2.55 to 3.73×10^{-17} C, or 159 to 232 electronic charges. Individual particle charge as measured by the Q/A device at the same conditions was only about 80% of the predicted charge for a particular particle radius. This may be due to imperfect gas flow through the precharger or to the presence of positive ions in the charging zone (which normally should be completely negatively monopolar).

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.

Section IV of this TPR reports on the visit of Dr. Kanko Janka, who represented the Tampella Company, Finland. The Tampella Company is a very large, diversified organization involved in a wide variety of activities including power generation and the pulp and paper industry, and Dr. Janka visited the Aerosol Physics Group at FSU with the purpose of learning more about the electron beam precipitator and the PEER pulsed streamer corona treatment method of treating SO_2 and NO_x gases. One of our group (Finney) accepted an invitation to present the departmental colloquium in the Department of Chemical Engineering at FSU in order to apprise new faculty members of the work being carried out by the Aerosol Physics Group. Finally, Section V lists the personnel currently affiliated with the project.

II. CONTRACT PROGRESS DURING QUARTERS FIVE AND SIX — DEMONSTRATION OF ELECTRON BEAM PARTICLE PRECHARGING

A. Modification of Power Supply and Monitoring Apparatus

1. Pulsed Power Supply - Electromagnetic Noise Reduction

The main objective of the project during this reporting period was to begin running electron beam precharging experiments. However, due to the electromagnetic noise emitted by the pulsed power supply, and problems with the Climet multi-channel analyzer, this seemingly simple objective became difficult to attain without substantial electronic and mechanical modifications. To mitigate and hopefully overcome the problems associated with the noise generated by the pulsed power supply (Figure 1), the group worked on basically two fronts: 1) reduce noise emissions from the pulser itself, and 2) improve the shielding and grounding around the affected monitoring systems in order to enhance their noise immunity.

To reduce emission production from the power supply itself, the Faraday cage surrounding the rotating spark gap (Figure 2) was regrounded using a 6 inch wide copper strip rather than a heavy braid. This was done because the copper strip has a much higher surface area and a much lower surge impedance than the braid. In addition, the pulser grounding connections and interconnections were inspected and similarly improved wherever possible. Even after the completion of the new grounding system, the pulsed power supply was still saddled with E.M. noise radiation problems, most of which stem from the relatively long cable runs between pulser components. At this point we have learned a great deal about the behavior of pulsed power supplies from working with the

Pulsed Power Supply

Figure 1. Top View of the High Voltage Pulsed Power Supply, showing the Rectifier Network, the Capacitor Bank, the Rotating Spark Gap, and other components.

FINNEY 003 MP

Figure 2. Side View Schematic of the Rotating Spark Gap portion of the Pulsed Power Supply showing the support framework (top), and the Grounded Faraday Cage (bottom).

present system. With this increased understanding, it is becoming apparent that the only permanent, long term solution to the noise problem is a complete redesign of the pulsed power supply.

To improve the noise immunity of the affected computer and monitoring systems, we first constructed a tightly shielded case for the MicroMac analog/digital data collection system (Figure 3). This measure allowed the operation of the MicroMac at low pulsed voltages of around 30 kV. However, fatal MicroMac system errors still occurred, and periodically they occurred with greater frequency as the pulse voltage was increased above 30 kV.

Next, we turned our attention yet again to the Climet optical particle sampling and counting system (Figure 4). Various grounding schemes utilizing the sampling unit, the dilution system, and the multichannel analyzer were tried with no success. The possibility of buying or constructing a balanced data transmission system was even investigated. Finally, E and H-field probes were acquired from the department technical staff. These probes, along with expertise from outside of our group, showed that the magnitude of the noise being emitted from the pulsed power supply was such that the operation of any electronically-based data collection system in the vicinity of the pulsed power supply would be nearly impossible without resorting to expensive and exotic shielding methods.

The conclusion of the effort to reduce the E.M. noise emanating from the pulsed power supply was that all electronically-based instrumentation systems would be temporarily abandoned in favor of using mechanically-based aerosol sampling systems. Until such time as adequate resources and expertise can be made available for the task of properly shielding the monitors and pulser, other methods will be used to collect

Figure 3. 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).

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 ≤ forty can be specified. Alarms, data summaries, and computer interfaces are optional and available upon request.

Figure 4. The Climet Optical Particle Size/Number Measurement System, showing the CI-225 Counting Unit and the CI-210 Multichannel Analyzer.

particle size and number data from the electron beam precipitator when pulsed power is used. Consultation with other groups employing pulsed power in close proximity with electronic monitors has revealed that our problem is far from uncommon, but nevertheless resolvable.

2. Particle Charge vs. Radius Apparatus

The charge vs. radius (Q/A) measurement apparatus (Figure 5), which has been detailed in TPR No. 2, is a highly modified Millikan Oil Drop apparatus which is used to measure particle size and charge in an airborne medium. These measurements are made possible by making video recordings of the laser-illuminated particles as they are passed into an airtight cell. The cell chamber contains a set of parallel plates which generate an ac electric field, causing particles in the field to oscillate in a known and calculable manner. By using the magnitude of particle oscillation and the rate of fall of the particles in computer spreadsheet and graphing programs, a Q/A ratio can be obtained. Thus, for each experimental run, the particle charge provided by electron beam precharging can be compared with the particle collection efficiency of the system in order to establish a cause and effect relationship.

The main goal of this reporting period was to complete the upgrade of the Q/A focusing system. As parts for the upgrade began to arrive from orders placed during Quarter 4, a completely dimensioned draft sketch was made of the exact system design. A synchronous ac stepping motor and an adjustable gear train assembly was developed in order to provide for finer control of the optical components and to allow the focusing speeds to be changed as desired.

F.S.U. Charge / Radius Measurement System

Figure 5. The FSU Particle Charge vs. Radius (Q/A) Monitoring Apparatus, showing the Laser Beam, the Video Recording System, and the Particle Charge Measurement Cell.

The first task of constructing the focus system frame proved to be a labor-intensive job due to the fact that many of the pieces necessary for assembly had to be machined by hand. Another step consisted of wiring the motor control switching circuitry into a grounded metal box with standard AC input line. Additional time was allocated for rewiring the external focus control system to be compatible with the new motor and, in addition, replacing the control pushbuttons with a single toggle switch.

The final Q/A focusing system design consisted of a V-shaped apparatus with slots milled in either side. These slots were used to secure the motor and gear train, and allowed the assembly to be moved to accommodate different gear ratios. Changing gear ratios adjusts focusing speed and torque of the apparatus as deemed necessary for various experimental conditions. The gear train consists of four gears, three of which are fixed ratio gears, and a removable fourth gear which provides providing the output speed. Any gear out of a set of variable sized gears (current set includes three) can act as the fourth gear, thereby changing the gear train ratio and speed. Input to output ratios range from 1:24 to 1:12 to 1:8, giving output speeds of 3, 6, and 9 RPM (as reduced from the fixed motor speed of 72 RPM). This fourth gear is attached to a shaft which runs to the focus control knob; this knob moves the lens focus carriage located on the structural beam forward or in reverse. In addition, a set of safety microswitches was installed on the carriage and wired to the motor control lines. The microswitches prevent the focus control from overshooting the carriage stops by turning off the motor when the carriage reaches a certain point. Without this safety failure, the gears could possibly "strip" if the focusing system locked up.

Operation and setup of the new camera focus system is similar to the previous focusing system. The motor control circuitry is connected to a control line which runs inside the accelerator vault to an external panel switch in the control room. The motor is then easily controlled from outside the vault. Moving the switch up or down moves the focus lens in or out; when the switch is placed in the middle position, the motor is almost instantaneously stopped with no noticeable backlash which was a major problem in the previous setup.

In final testing of the completed focus system it was concluded that the new design was more versatile and was extremely effective in solving the problems with the earlier design. The motor control started and stopped with almost no delay while being, fully reversible, and the new system was also easily removable from the Q/A bench as well. An added feature of speed control over the system was also an important benefit, which may prove to be very useful in experiments to come.

3. Absolute Filter Holder Aerosol Sampler

A new method to sample and count aerosol particles was commissioned this term because of the inability of the Climet to function in concert with the pulsed power supply. When an oscilloscope was connected to the communication cable of the Climet, it was found that a voltage with a peak value of as high as 50 volts was induced on the cable by the pulsed power supply. This noise resulted in a distortion of the data transmitted from the sensing unit to the multichannel analyzer, usually causing the entire network to "lock up".

The new particle monitoring protocol involved attaching an "absolute filter holder" (Figure 6) on the side of the monitoring module downstream from the collecting section. Monodisperse aerosol in the wind tunnel was sampled using a nozzle attached to the body of the filter holder which was, in turn, attached to a vacuum pump. The vacuum pump was calibrated to sample the air isokinetically; this isokinetic rate was found to be 3.75 SCFH. Contained within the filter holder was a paper filter which removed 99.9% of all particles of 0.1 μm diameter or greater. The number of individual Hydral particles could then be calculated by weighing the filter paper before and after the sampling period.

A number of test samples of fifteen minutes duration were taken to determine the constancy of this method. The filter paper was weighed before and after an electron beam precharging run, and a change in weight was determined. The change in the filter paper weight was small, within the range of 0.3 mg. This, however, represents a difference of approximately 12,500 particles when using 1.0 μm diameter hydrated alumina dust as the test aerosol. From early indications, the absolute filter holder method of monitoring particle concentration, while not "real time", represents the best available technique which is also immune to noise emitted from the pulsed power supply.

Figure 6. The Absolute Filter Holder Aerosol Sampler, used for determining bulk particle mass in E-Beam experiments having high concentrations of Hydral Dust.

B. Electron Beam Precipitator - Review of Systems

As a prelude to beginning the electron beam particle precharging experiments using a pulsed charging electric field, several shakedown runs using dc power in the precharger were completed this term. Experiments were conducted using the FSU Electron Beam Precipitator wind tunnel, the Mk. III E-beam precharger, and a moderately high concentration of 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 7 shows the Electron Beam Precipitator (EBP) test system. 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 were generally very close to 40% RH. Dry air from a compressed air source can also be added to control humidity.

F.S.U. ELECTRON BEAM PRECIPITATOR TEST SYSTEM

Figure 7. The Two-Stage, Laboratory Scale FSU Electron Beam Precipitator Wind Tunnel, showing the Aerosol Injection, E-Beam Precharger, and Collector Modules.

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 8). 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 9 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 lower electric potentials (Figure 10). 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

Figure 8. Schematic Diagram of the Fluidized Bed / Screw Feeder Aerosol Generation System, which Deagglomerates and Resuspends Hydral and Fly Ash.

Figure 9. Top View of the BG/CP-2C Vacuum Station, The 100 keV Electron Beam Accelerator (MINACC), and the E-Beam Particle Precharging Module.

Figure 10. Side View Schematic Diagram of the 100 keV Electron Beam Accelerator (MINACC), showing the Accelerator Column, the thin Window, and the Dropping Resistors.

dedicated vacuum station, the BG-2 (Figure 9). 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 11 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 11). When an electric field is applied between the anode and cathode electrodes, the charge density is separated into two monopolar fractions (Figure 12). 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.

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 13) is of a standard wire-plate precipitator design with two channels, one of which can be blocked off with a baffle plate converting

Figure 11. 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 12. 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.

Figure 13. 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.

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 14 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 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.

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 μ A₂
Current Density = 1.25 mA/m²

ELECTRON BEAM -- Energy = 90 keV
Current = 2 μ A

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

MICROCOMPUTER DATA ACQUISITION SYSTEM

Figure 14. The Microprocessor-based Data Acquisition and Analysis System serving the Electron Beam Precipitator Monitors.

C. Experimental Run of Electrostatic Collector

Prior to testing electron beam precharging in conjunction with the low current collecting section, an experiment was run on the collector while operating in a high voltage, high current mode. The collector in the EBP wind tunnel (Figure 13) is configured like a conventional electrostatic precipitator, with two 6 inch wide channels each bisected with a row of centrally located tensioned discharge wires. Wire length and diameter are 4 feet and 0.109 inch, respectively, and plate dimensions for each of the six total fields are 4 feet high and 2.5 feet wide. Only one channel, or three fields in-line, were used in the present experiment in order to raise the gas velocity in the collector without also increasing the total gas volume.

The purpose of this experiment was three-fold. First, a comparison was made between a) the collector ion current reading as recorded by the MicroMac A/D converter and b) the currents obtained from the analog meters in the high voltage input line supplying the discharge wires and in the power supply control circuit. Second, the newly instituted method of taking bulk dust samples with an absolute filter holder which was described earlier was tested under realistic experimental conditions. Third, the dust penetration and collection efficiency was determined for various electric field levels in order to ascertain a suitable collector voltage for the pulsed electron beam precharging experiments. Fine, high resistivity ($> 10^{12} \Omega\text{-cm}$) Hydral dust was used for a conservative test of the system.

Procedures for characterizing the collecting section began with obtaining a baseline particle count consisting of a filter sample taken with the absolute filter holder from the EBP wind tunnel while the collector was off. Next, a series of five filter samples were

obtained with the collector operating at electric field values of between 3.0 and 5.0 kV/cm. Finally, another baseline sample similar to the first run was taken after the collector was de-energized. Each of the filter samples were weighed before and after each run, yielding a net sample weight. The first and last samples with the collector off were averaged to offset any change in particle concentration which occurred over the two hour duration of the experiment. Run conditions were as follows:

1. Gas Composition : Air
2. Gas Temperature & Humidity : 75°C, 40% RH
3. Gas Volume & Velocity : 1.0 ft³/sec, 0.5 ft/sec
4. Test Dust Type and Size : Hydral, 1.0 μ m mean diameter
5. Fluidized Bed Flow : 0.12 ft³/sec
6. Screw Feeder Setting : 100
7. Filter Sampler Flow : 3.75 SCFH = isokinetic
8. Sample Time : 10 min (900 sec)

The results of the collector particle removal efficiency experiment are shown in Table 2. An initial voltage level of 23 kV (3.0 kV/cm) was selected because corona onset occurs near this point. Ion current was measured by three methods: 1) the MicroMac A/D converter on the ground side of the precipitator collection plates, 2) an analog milliammeter in the high voltage line leading to the discharge wires, and 3) the output current meter on the front panel of the HV power supply. At corona onset, the measured ion current is very small, only approximately 100 μ A for the total of all six collector plates.

Table 2.

Particle Collection Efficiency of Hydral Dust (Collector Only)

Run #	Voltage (kV)	Electric Field (kV/cm)	MicroMac Current (mA)	Analog Current (mA)	Power Supply Current (mA)	Sample Weight (mg)	Particle Penetration (%)	Collection Efficiency (%)
1	0	0	0	0	0	0.36	-	-
2	23	3.0	>0.01	0.02	>0.01	0.05	12.99	87.01
3	26.5	3.5	0.01	0.02	0.02	0.04	10.39	89.61
4	30.5	4.0	0.03	0.035	0.05	0.04	10.39	89.61
5	34.0	4.5	0.42	0.45	0.44	0.01	2.60	97.40
6	37.5	5.0	1.65	>2.0	1.72	>0.005	<1.30	98.70
7	0	0	0	0	0	0.41	-	-

However, the particle penetration was only 12.99%, meaning that even relatively low electric field and current levels produce a rather high collection efficiency of 87%.

As the voltage (and thus electric field) level is raised above the corona onset point at about 23 kV, ion current increases slowly at first and then undergoes a sharp rise when 34 kV (4.5 kV/cm electric field) is reached. Concurrently, the decrease in particle penetration with increasing electric field is small (several percent) until a voltage of 34 kV causes a significant decrease in penetration. The jump from 89.6% particle collection efficiency to 97.4% with only a 3.5 kV increase in collector voltage (from 30.5 kV to 34 kV) is heralded by a much larger corona charging current. At 5.0 kV/cm electric field, very little Hydral dust was collected on the filter representing high efficiency for the single channel collector.

Sparkover between the corona wires and the collector plates occurs at between 6 and 8 kV/cm electric field, depending upon the thickness and composition of the high resistivity ash layer coating the plates. With only a moderate dust coating, back corona sets in soon after 6.0 kV/cm is reached, causing particle discharging and dust reentrainment among other ills. As higher, more realistic dust loadings are achieved, the collector will regress into a back corona condition at even lower voltages. In the upcoming experiments, a pulsed electron beam precharger will be used to charge particles to very high levels upstream from the collector. Therefore, the collector will not be required to operate at a high voltage and ion current which induces debilitating back corona. The collector can be run at a relatively low voltage and current while still providing a sufficient electric field strength for collecting the previously precharged particles.

D. 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 8), 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 5) 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 4) was required because of its age (10 years old) and the sensitivity of the unit to electromagnetic radiation. The MicroMac analog-to-digital converter (Figure 3) 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 precipitator monitoring functions are coordinated by an old but still adequate microcomputer (Figure 14) 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. 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 a monodisperse, $1.0 \pm 0.5 \mu\text{m}$ diameter powder 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 8-14 lb/ft³, 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/ft³, which corresponds to a particle concentration of 2.7×10^{10} particles/ft³. Since the particle counting capability of the Climet CI-225 optical particle counter with outboard dilution system is only 5.4×10^8 particles/ft³, or a factor of 50 lower, the maximum dust loading that can be tested in the EBP wind tunnel is 0.02 grain/ft³. 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 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 7) 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 11), 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-B. 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 tube 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 Section II-E. 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 μm mean diameter was resuspended in the circulating gas stream at 25°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 efficiency. 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

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	-	-	-	-	-	-

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.

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 $\eta = 1 - P$. 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 the table, 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 because 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 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 4 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 -factor 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:

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

where:

n = 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

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

efficiency from 86.0% to 98.7% gives an α -value of 10.5 (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 included in a more extensive writeup which will be presented in the next Technical Progress Report.

E. Particle Charge vs. Radius Ratio Determination

1. Experimental Procedures for Q/A Runs

Particle collection efficiency measurements are one way to assess the effectiveness of E-beam precharging on overall system performance. Another way is through the direct measurement of the charge on individual particles exiting the precharger; more highly charged particles will be collected with greater efficiency. Particle charge vs. radius (Q/A) measurements were made using the laser-oscillating field Q/A apparatus which was developed at FSU and is shown in Figure 5. A probe was inserted into the wind tunnel duct immediately downstream from the precharger in order to sample the highly charged particles as close to the source as possible. The charge vs. radius unit was positioned adjacent to the wind tunnel to minimize tubing length. During an experiment, a number of aerosol samples were tested for charge and mass in the Q/A cell for each different condition. The data is presented and analyzed as a series of particles having varying radii and charge levels.

2. Computation of Saturation and Predicted Particle Charge

Calculations of the theoretical charge on 1.0 μm diameter Hydral particles for several electron beam precharging electric field values is shown in Table 6. The experiment was run at conditions which were found during preliminary runs to be optimal for efficient particle charging. Precharger anode voltage was varied in 11 kV steps from 55 to 77 kV, corresponding to electric field values of from 3.93 to 5.50 kV/cm. Particle charge determinations were made using a computer program which calculated the theoretical field charge limit on Hydral particles having a dielectric constant of 8.7. Two charge

Table 6.

Theoretical Particle Charge for Several
Precharger Electric Field Values

Run Conditions

Particle Type : Hydrated Alumina, "Hydral"
 Particle Diameter : 1.0 μm monodisperse
 Dielectric Constant : 8.7
 Anode Ion Current : 40 μA
 Average Current Density : 1.25 mA/m^2
 Precharging Path Length : 30.5 cm (1.0 ft)
 Electrode Separation : 14 cm (0.46 ft)

Anode Voltage (kV)	Electric Field (kV/cm)	Precharger Gas Velocity (ft/sec)	Residence Time (msec)	Particle Charge ($\times 10^{-17}$ C)	Electronic Charge (#e ⁻)
55	3.93	0	∞	2.67	166e
"	"	4.0	250	2.55	159e
66	4.71	0	∞	3.20	199e
"	"	4.0	250	3.04	189e
77	5.50	0	∞	3.73	232e
"	"	4.0	250	3.51	219e

values were generated for each voltage setting: one for infinite residence time (precharger gas velocity = 0), and one for a residence time of the aerosol in the charging zone of 250 ms (precharger gas velocity = 4.0 ft/s).

From Table 6, the theoretical saturation field charge on particles increased as the precharger electric field was raised from 3.93 to 5.5 kV/cm. The fact that the charge saturation limit varies with electric field is given by the well known Panthenier ionic field charging equation:

$$q(\infty) = \frac{12\pi\epsilon_0\epsilon_s a^2 E}{(\epsilon_s + 2)}$$

where:

$q(\infty)$ = saturation field charge of particle

ϵ_0 = permittivity of free space

ϵ_s = specific dielectric permittivity

a = radius of particle

E = charging electric field

and by more recent improvements to the theory. From these calculations, saturation particle charge for an infinite residence time ranges from 2.67×10^{-17} C (166 electronic charges) to 3.73×10^{-17} C (232 e) for the precharger anode voltages of from 55 to 77 kV.

Nearing or achieving saturation charge assumes that a particle will have a sufficiently long residence time in the precharger. If the precharger gas velocity is zero, residence time is infinite and the charge on a particle will eventually reach the saturation efficiencies. However, if the precharger gas velocity is increased and the residence time

is thereby reduced, other calculations show that the predicted particle charge falls off dramatically. The result should be a significantly degraded system particle collection efficiency.

3. Charge vs. Radius Ratios - Measured Values

To compare actual particle charge levels with calculated theoretical saturation charge levels, a series of experimental runs measuring the charge vs. radius ratio of particles exiting the precharger was performed. An aerosol composed of 1.0 μm mean diameter Hydral dust was generated and re-dispersed at moderately high density into the EBP wind tunnel. Gas velocity was 1.0 ft/sec in the wind tunnel duct and 4.0 ft/sec in the precharging module. The MINACC electron beam source was operated at a beam energy and current of 90 keV and 2 μA , respectively. Two successively higher electric potentials (66 kV and 77 kV) were applied across the 14 cm wide charging zone gap in the Mk. III-B electron beam precharger. Average ion current and current density produced under these conditions was measured at 40 μA , or 1.25 mA/m².

Figures 15 and 16 illustrate the results of the particle charge vs. radius measurement experiment. Plots of particle charge (in number of electronic charges) vs. particle diameter (in micrometers) was fit by a straight line using a least-squares simple regression. An equation of the straight line is included at the lower right corner of each of the two figures along with the correlation coefficient "R". Second degree polynomial fits of the theoretical maximum saturation charge and the predicted charge level of a particle with 250 ms residence time in the precharger are also plotted on the figures.

Since Hydral dust is nominally monodisperse (1.0 μm diameter, $\pm$ approximately 0.5

Charge vs. Diameter: Hydral Run #17, 66 kV, S=14 cm

Figure 15. Graph of Particle Charge in Number of Electronic Charges vs. Particle Diameter in Micrometers for Hydral Aerosol at a Precharger Voltage of 66 kV.

Charge vs. Diameter: Hydral Run #17, 77kV, S=14 cm

Figure 16. Graph of Particle Charge in Number of Electronic Charges vs. Particle Diameter in Micrometers for Hydral Aerosol at a Precharger Voltage of 77 kV.

μm), most of the data should fall near the $1.0 \mu\text{m}$ diameter point on the abscissa. However, due to incomplete de-agglomeration of the bulk Hydral by the fluidized bed, clumping of two or more particles is apparently occurring. A test aerosol which is not perfectly monodisperse is being generated and circulated through the precharging module. This causes measured "particles" of up to almost $2 \mu\text{m}$ diameter to show up in the experimental data. Each individual particle represented by a data point, regardless of size, is measured separately to determine the charge and mass. Therefore, the data accurately represent the results of E-beam precharging even though particle clumping may be occurring.

At 66 kV precharger voltage, or 4.71 kV/cm electric field (Figure 15), plotted lines representing a) the theoretical maximum saturation particle charge for infinite residence time, and b) the predicted saturation particle charge at 250 ms residence time, fall very close to each other. As calculated earlier, the predicted charge line falls just slightly below the maximum saturation charge line because, under ideal conditions, 250 ms is sufficient time for a particle of $1.0 \mu\text{m}$ nominal diameter ($+ 0.5 \mu\text{m} - 0.25 \mu\text{m}$) to achieve about 95% of the infinite residence time charge. The experimental data and fitted line for 66 kV precharger voltage fell somewhat lower than the 250 ms predicted charge line. Nevertheless, at 66 kV voltage, the precharger demonstrates its charging effectiveness by yielding data which approach the predicted charge line which, of course, represents ideal conditions.

Particle charging efficiency deteriorated when the precharger voltage was raised to 77 kV (5.5 kV/cm electric field). Figure 16 shows that particle charge remains approximately the same regardless of particle size. The nearly horizontal line fit of the

data diverges substantially from the calculated particle charge lines at infinite residence time and at 250 ms residence time. These results exhibit behavior which suggest that at 77 kV anode voltage, very little monopolar particle charging is occurring in the precharger. Only a small increase in precharger anode voltage from 66 kV to 77 kV dramatically decreases electron beam particle precharging.

Several reasons for the disparity in the predicted and actual particle charge levels at 77 kV can be postulated. The first concerns the fact that at excessive precharger electric fields, free electrons in the charging zone may become accelerated to an energy level high enough to produce bipolar secondary ionization. Secondly, very high anode voltage levels may attract the leading edge of the primary electron beam out into the charging zone, producing another source of unwanted bipolar ionization. A third source of ions opposite in sign to the negative working ions may result from the emission of positive corona from the anode electrode at high precharger electric fields.

Each of the above phenomena introduce positive ions into the charging zone, effectively negating the proper monopolar operation of the precharger. Even a small positive charge overcomes the dense negative ion and electron flux which normally predominates throughout the charging zone. For a particular precharger geometry (dimensions, electrode arrangement, E-beam placement), care must be taken not to exceed a precharger anode voltage which will initiate any of the aforementioned undesirable conditions. A more in-depth analysis of the mechanics of electron beam energy/precharger geometry/anode voltage matching 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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73. R.H. Davis, W.C. Finney, and J.S. Clements. Electron Beam Ionization in Combustion Aerosol Control Technology. In preparation for submission to Aerosol, Science, and Technology. 1990.

IV. PUBLICATIONS AND PRESENTATIONS

A. Visit of Dr. Kanko Janka, Tampella Company, Finland.

The Aerosol Physics Laboratory was visited this term by Dr. Kanko Janka, Project Manager, Power Industry Division, Tampella Corporation Ltd., Tampere, Finland. The Tampella Corporation is a large, diversified, multinational company involved in the areas of forest products, packaging materials, mining and rock excavation, pulp and paper manufacturing, and, most applicable to FSU, power industries. The Power Industry Division is concentrated in the fields of energy generation, chemical recovery, hydroelectric construction, and air pollution control technology. Specifically, Tampella is interested in advanced techniques for fly ash removal and flue gas desulfurization in coal fired boilers.

An all-day meeting between members of the Aerosol Physics Group (APG) and Dr. Janka took place on Monday, May 7, 1990. Topics of discussion centered on the progress made by the APG in the areas of electron beam aerosol precipitation, free electron particle charging, and pulsed streamer corona treatment of SO_2 and NO_x . Dr. Janka's interest in these technologies was directed towards the possible utilization of the E-beam precharger and the pulse energized electron reactor (PEER) on several Tampella Co. power plant boilers. The APG will keep in contact with Tampella in order to foster the industrial acceptance of these advanced pollution control systems invented at FSU.

B. Department of Chemical Engineering Colloquium, Florida State University - "Air Pollution Control Technology using Energetic Electrons for Coal Fired Power Plants".

During the period covered by this Technical Progress Report (Quarters Five and Six), one of the authors was invited to give the departmental colloquium to the Department of Chemical Engineering, Florida A & M/Florida State University College of Engineering. Professors Bruce R. Locke and Pedro Z. Arce hosted W. C. Finney who presented a talk entitled "Air Pollution Control Technology using Energetic Electrons for Coal Fired Power Plants" on Wednesday, October 17, 1990, in the Central Engineering Building at the Innovation Park Campus of FSU.

Topics which were discussed in depth during the colloquium included: two-stage electron beam precipitation of aerosols; dc and pulsed E-beam particle precharging, advanced collector designs; monitoring systems, free electron charging of aerosol particles; high energy electron beam irradiation of SO_x and NO_x gas-phase pollutants; and pulsed streamer corona (PEER) treatment of SO_2 , NO_x , and fly ash (RO_x). Recent experimental results from the Pulsed Electron Beam Precharger project were especially emphasized.

The colloquium presentation and subsequent meetings have led to the establishment of an ongoing, mutually beneficial working relationship between personnel from the Aerosol Physics Group and the Chemical Engineering department. Many research subjects of common interest in the fields of air pollution control technology will be pursued jointly by these two groups.

V. PERSONNEL

A. Scientific Investigators

1. Dr. W. Neil Shelton   Principle Investigator
2. Mr. Wright C. Finney   Associate in Research

B. Graduate Student Assistants

1. TBA

C. Undergraduate Student Assistants

1. Chris Oswald
2. Milsho Sarwar
3. John Blair

D. Part-Time Secretaries

1. Nancy Lochner
2. Amy Maxey
3. Natalie Duguid

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