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PULSED ELECTRON BEAM PRECHARGER

For the Period
September 1, 1989 -- May 31, 1992

Submitted by

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I. INTRODUCTION AND SUMMARY

A. The Aerosol Physics Program at FSU

The U.S. DOE - PETC contract entitled "Pulsed Electron Beam Precharger," #DE-FG22-89PC89768, covered the period September 1, 1989 - May 31, 1992. This is the fifth in a series of contracts and grants exploring the advanced particulate pollution control technology of electron beam precipitation. The Final Report covers work completed during the aforementioned time period, and also includes some work completed during the lapse period between the present and previous contracts (March - August, 1989).

The project currently under contract with the Pittsburgh Energy Technology Center, U.S. DOE, addresses the pressing problem of more efficiently controlling the emission of fine, high resistivity fly ash from low sulfur coal-burning power plants. As such, the project is an integral part of the DOE mission to advance technologies which provide for the safe and economically viable utilization of the nation's large but potentially polluting coal resources. Within the University Coal Research Program of the DOE, the objective of the project is also consistent with the goal of improving the performance of electrostatic precipitators and possibly fabric filters through the use of a first-stage electron beam particle precharger. Reducing the emission of particulate matter from coal fired boilers is in the national interest from a respiratory health standpoint, while improved power efficiency of the removal process serves the goals of lowered energy consumption. In addition, an earlier spinoff of the ongoing program at FSU was the invention of a new technology using pulsed streamer corona for SO₂ and NO_x removal, the pulse energized electron reactor (PEER) process. This development is also consistent with the DOE mission for the safe but productive utilization of coal, and with the focus

of the DOE on advanced technologies for the control of the acid rain precursors SO_2 and NO_x .

The specific objective of the Pulsed Electron Beam Precharger project is to further develop the technology of efficiently collecting high resistivity fly ash using a two-stage system composed of an electron beam precharger coupled with an electrostatic precipitator. High resistivity fly ash, produced by burning low sulfur coal in power plant and industrial boilers, limits the operating parameters of conventional electrostatic precipitators by initiating debilitating "back corona". If the particle charging and collecting functions are optimized separately in a two-stage configuration, higher removal efficiencies can be obtained and the back corona problem can largely be avoided.

The process of electron beam ionization of air molecules produces a bipolar plasma of ions and electrons in the precharger. One monopolar fraction (usually negative) is used to charge the dust particles to very high levels nearing the saturation limit. After precharging, the aerosol is removed in a downstream electrostatic collector operated in a back corona-free electrical condition. The superior charging performance of electron beam prechargers is due to the combined effects of space charge enhancement of the charging electric field, and a much superior particle charging by available free electrons.

Pulsed operation of the particle charging electric field is the subject of the present work. The advantage of pulsing the electric field lies in the fact that pulsed electric fields can be achieved which are much larger than the breakdown electric field for dc operation, provided that the pulse duration is sufficiently short (200 ns). The direct result is an increase in particle charge due to the increase in electric field during the pulse, and an enhancement of the charging field due to ionic space charge which would persist for some time after the pulse in the presence of a dc-bias.

The chief goal of the current contract was to develop to the proof-of-concept stage an electron beam precharger using a pulsed anode electric field. Contract tasks leading to the achievement of this goal are generally divided into two categories: tasks required to bring the Electron Beam Precipitator (EBP) test system up to an operational level for the contract work, and tasks concerning the actual experimental and analytical phase of the study. Not unexpectedly, the early portion of the contract duration was devoted to the commissioning of the EBP and its many subsystems, while the latter portion devoted itself to testing the new pulsed electron beam precharger.

During the previous contract, a number of important results concerning the E-beam precharging of particles were obtained. Collection efficiencies of up to 99.97% were achieved using fine, high resistivity polystyrene latex (PSL) particles at low concentrations. Improvement in collection efficiency due to the enhancement of particle charge by electron beam precharging is designated by the α -value (particle penetration with precharging/penetration with no precharging). Collection efficiency increases of up to a factor of almost 200 ($\alpha = 190$, efficiency of collector = 94.75%, efficiency of collector and precharger = 99.97%) were achieved in one case. In another case, an initial collector-only efficiency of 59.9% was improved to 99.55% with the addition of precharging.

A second series of experiments were run during the present contract to test electron beam precharging at much higher particle concentration levels. Hydrated alumina (Hydral) dust having a resistivity of about $10^{12} \Omega\text{-cm}$ was resuspended and injected into the EBP wind tunnel using a screw feeder/fluidized bed combination. These preliminary tests proved once again that E-beam precharging could significantly reduce the overall particle penetration, and α -values of as high as 40 were achieved under these much more difficult experimental conditions.

Electron beam precharging of fine particulate matter has been shown in these earlier studies to greatly improve the particle collection efficiency of a conventional electrostatic precipitator. Collection efficiency, according to the Deutsch-Anderson equation:

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

is dependent upon the collector plate area (A), the gas volume flowing through the precipitator (V), and the particle migration velocity (ω). For a given A/V, if the migration velocity in the collector can be increased, the collection efficiency should improve.

The theoretical migration velocity for field dependent charging is given as:

$$\omega = \frac{2 \epsilon_0 E_0 E_p a}{\eta_g}$$

where ω = theoretical migration velocity, ϵ_0 = permittivity of free space, E_0 = charging electric field, E_p = collecting electric field, a = particle radius, and η_g = gas viscosity. For a given particle radius and gas viscosity, the migration velocity varies with the charging and collecting electric fields E_0 and E_p , respectively. Setting aside the collecting electric field, if the charging field can be raised, the migration velocity and thus the collection efficiency should increase.

Later in the contract, even higher overall performance of the E-beam precharger/collector combination was found with pulsed operation. Pulsing the precharger anode to which a dc-bias voltage is also applied results in higher particle charge since the saturation particle charge for field charging is dependent upon the electric field. Levels of dc electric field which would cause

sparkover in the previous Mk. III precharging configuration were attained by using very short duration, fast rise time, high voltage pulses superimposed upon a small dc-bias voltage. In addition to higher electric field limits, other benefits which accrue with pulsed precharger operation include the avoidance of back corona, and the opportunity to take advantage of the copious supply of free electrons that are available from electron beam ionization of the test gas. Maximizing the particle collection efficiency of the EBP using high resistivity dust at moderate to high loadings was a major focus of the precharger developmental work.

In an earlier study conducted by the Aerosol Physics Group at FSU and sponsored by the U.S. DOE, positive pulsed streamer corona was used to promote the formation of free radicals (HO_2 , H , OH) in humid synthetic flue gas. These free radicals, in turn, reacted with the molecules SO_2 and NO_x forming aerosols which could be removed by conventional means from the gas stream. Since SO_2 and NO_x are the gas species principally responsible for the formation of acid rain, pulsed energized electron reactor (PEER) technology can be one component in reducing the emission of these harmful chemicals.

The power supply used in the pulse energized electron reactor experiments was modified for use in the present pulsed electron beam precharger work. Instead of being used to produce streamer corona which initiated a series of chemical reactions in the PEER device, the pulsed power supply was used here to provide a very high electric field for particle charging. The advantage in using a pulsed electric field instead of a dc field in the precharger lies in controlling the problem of back corona. When the precharger electrodes become coated with a layer of high resistivity dust, a voltage potential drop across the insulating dust later occurs. This potential drop causes a breakdown in the dust layer, ejecting both dust particles and positive ions back into the flue gas stream. Pulsing the precharger electrodes reduces or eliminates this problem because the initiation of back

corona is not possible within the time domain of the very fast, high frequency, high electric field pulses.

B. Project Summaries and Program History

1. Pulsed Electron Beam Precharger (EBP) Project

a. Electron Beam Precipitation

The primary motivation for the development of electron beam precharger technology continues to be the problem of efficiently collecting high resistivity fly ash using electrostatic precipitators. Electrostatic precipitators are expensive to purchase and maintain, and the possibility of reducing these costs has led to the investigation of a number of new technologies for the removal of particulate matter. A moderate increase in fly ash collection efficiency can mean a substantial reduction in the capital cost of the physical plant as well as reduced operating expenses. The prospect of more stringent emissions standards for respirable particulate matter adds further impetus to the development of new technologies for the removal of fly ash.

High resistivity fly ash, produced by burning low sulfur coal in power plant boilers, limits the operation of conventional electrostatic precipitators by initiating debilitating "back corona". If the charging and collecting functions separated into an optimized two-stage system (Figure 1) comprising an upstream particle precharger and a downstream electrostatic precipitator (operated at high electric field but low current), higher removal efficiencies can be obtained and the back corona problem can be largely avoided. Back corona does not exist in fabric filter collectors which, in part, accounts for the popularity of that technology in recent years. However, filtration in baghouses can also be made more efficient by first charging the particles; this has stimulated interest in two-stage systems involving prechargers and fabric filters.

TWO STAGE SYSTEMS FOR RESPIRABLE PARTICLE REMOVAL

Figure 1. Two-Stage Particle Removal Systems using an Electron Beam Precharger as the First Stage.

The physical reason for the use of an electron beam in a precharger is that copious ionization is produced by energetic electrons in a gas. The electron beam ionizes gas molecules within the precharger (Figure 2), forming a bipolar plasma of ions and electrons in a continuous process of creation and recombination. When a strong electric field is applied across the precharger duct through which the test aerosol passes, the plasma is separated into two monopolar fractions. The negative fraction, consisting of ions and electrons, is drawn across the duct by the electric field, charging the dust particles to very high levels nearing the saturation limit. After precharging, the aerosol is removed in a downstream collector resembling a conventional electrostatic precipitator operated in a back corona-free electrical condition. Because of the very large ion currents, space charge enhancement of the charging electric field is an advantageous possibility because of the dependence of particle charge on the electric field.

The superior particle charging performance of electron beam prechargers is due to the combined effects of space charge enhancement of the charging electric field caused by copious ionization currents, and much superior particle charging by available free electrons when compared to ionic charging. This was demonstrated in an offline bench-scale test in which the particle charge on high resistivity, one micron diameter test particles were as much as five times higher than the Pauthenier saturation field charging limit. A separate, well controlled study of free electron charging in model gas mixtures was undertaken to complement the work on electron beam precharging.

Promising results as indicated by high particle charging and collection efficiencies were obtained using model aerosol particles in a wind tunnel test system. Later tests proved that E-beam precharger technology can operate using more realistic concentrations of fine, high resistivity dust. The results obtained with the most recent precharger design (the Mk. III) confirm the impressive effectiveness of electron beam precharging,

MK III ELECTRON BEAM PRECHARGER

Figure 2. The Bipolar Ionization Zone and the Monopolar (Negative) Charging Zone within the Mk. III Electron Beam Precharger.

and have pointed out the need for further design modifications to achieve optimum performance.

b. Particle Charging and Collection

The earliest experiments at FSU demonstrated the copious ionization of electron beams in electrode geometries that are adaptable to electron beam prechargers. Based on these results, a laboratory scale, closed circuit, Electron Beam Precipitator (EBP) wind tunnel was constructed for testing electron beam prechargers in two-stage operation with an electrostatic precipitator (Figure 3). Various experimental precharging modules were followed downstream by a conventional electrostatic precipitator. The electrostatic precipitator can be operated either as a high current charging and collection device or in two-stage operation with the electron beam precharger. Experiments were initially carried out with light loadings of very fine, monodisperse polystyrene latex (PSL) particles in order to maximize experimental control.

Experiments have been carried out with several electron beam precharger designs (Mk I; Mk. II-A, B, C, D; Mk. III-A, B) using a 100 keV electron beam source. These experiments consisted of establishing the test aerosol baseline concentration, measuring the removal with the removal efficiency for the combined two-stage operation of the precharger and the electrostatic precipitator. Performance of the E-beam precharger was measured for various electron beam currents, average charging electric fields, and gas velocities.

In all cases, the particle collection efficiency for the two-stage EBP system comprising a dc electron beam precharger and an electrostatic precipitator was superior to the collection efficiency for the collector (electrostatic precipitator) operating alone. In one low aerosol concentration experiment, the collector-alone efficiency was 94.75% while the collection efficiency for the

F.S.U. ELECTRON BEAM PRECIPITATOR TEST SYSTEM

Figure 3. The FSU Two-Stage Electron Beam Precipitator (EBP) Wind Tunnel.

two-stage system was 99.97%. This is a reduction in particle penetration ($1 - \text{efficiency}$) of a factor of 190. In another experiment for which the collector-only efficiency was a modest 66%, the collection efficiency for two-stage operation was much greater at 99%. These results suggest that the electrostatic precipitator in a large scale, two-stage installation retrofitted with an electron beam precharger could be operated well below the threshold voltage for the onset of back corona, which is associated with high resistivity fly ash. At the same time, the electron beam precharger/electrostatic collector combination can maintain a high overall collection efficiency for the two-stage system.

The use of low concentrations of polystyrene latex spheres for early optimization studies led to higher loading experiments using hydrated alumina and fly ash. In one challenging set of particle collection efficiency experiments, an aerosol of fine, high resistivity hydrated alumina (Hydral) dust was removed at an efficiency of almost 40 greater than that using the collector-alone. This was accomplished despite the fact that the particle charge level as measured in several sets of experiments with Hydral and fly ash was lower than either the saturation or predicted charge levels. Further optimization of the relationships between the electron beam, electric field, and electrode geometry in the precharger can only be expected to improve upon these already successful results.

An economic analysis of the experimental program to date suggests that electron beam prechargers are superior to conventional electrostatic precipitators with regard to the ratio of total power vs. ionization power and the ratio of total power vs. charging power, but inferior with regard to the ratio of power vs. charging current. The clear advantage of electron beam prechargers lies with the power efficiency of the production of the ionized flux. Since superior charging power implies superior charging rate and saturation charge level, the Mk. III electron beam precharger holds a decided advantage over a conventional

electrostatic precipitator. One result of these experiments is that the present precharger design inefficiently utilizes the ionization flux. Precharger designs which avoid this difficulty are being analyzed, and improvements to the current design will be incorporated into the next generation of electron beam prechargers.

c. Pulsed Electron Beam Precharging

A successful electron beam precharger development program has been underway at Florida State University for a number of years, but until the present contract period, the prechargers had not been pulsed. Pulsed operation of the particle charging electric field is the principal research task of the present work. Synergistic advantage may accrue from pulsing both the charging electric field and the electron beam, but the accomplishment of the latter is beyond the guidelines of the present contract.

The advantage of pulsing the electric field lies in the fact that pulsed electric fields can be achieved which are much larger than the breakdown electric field for dc operation, provided that the pulse duration is sufficiently short. The direct result is two-fold: 1) an increase in particle charge due to the increase in electric field during the pulse, and 2) an enhancement of the charging field due to ionic space charge, which persists for some time after the pulse has ended when a dc-bias voltage is also present. Pulsed operation will momentarily draw larger monopolar currents from the ionization zone which will contribute to the ionic space charge. At the same time, the electron temperature during the pulse will be increased so that the attachment and retention of attachment are decreased resulting in the accrual of free electron charging.

A major benefit of pulsing the precharger is the superior charging by available free electrons, which will be less likely to attach or be retained once attached during the electric field pulse. An auxiliary benefit is the more even distribution of

negative ions due to the pulse-activated migration of free electrons before they ultimately attach. Evidence for these expectations has been discussed previously, but confirmation measurements of particle charge and removal efficiency in a system of known geometry were necessary to form the basis for modeling and optimization. It should again be mentioned that free electron charging is especially effective for fine respirable particles, and that the full-scale electron beam precipitator systems envisioned would have the potential for both new construction and retrofit applications.

The immediate objective of electric field pulsing is the rapid energization of electrons and the buildup of space charge during the pulse, followed by the prompt termination of the pulse before debilitating sparkover is initiated. Most of the equipment required to conduct the contracted research was previously available, although modifications were required to adapt this equipment for pulsed precharger research. The pulse was delivered to the precharger anode plate by a rotating spark gap pulsed power supply. This short pulse power supply has been used for other gas-phase pollution control studies, and it was modified and adapted for application to the electron beam precharger. Pulses of up to 80 kV energy having pulse widths of approximately 200 ns and rise times of as short as 20 ns can be produced. In addition, a dc-bias voltage of up to 20 kV can be supplied simultaneously to the precharger anode (Figure 4), insuring ion flux separation during the period when the pulse is off.

After determining the operational breakdown limits for various combinations of dc-bias and pulsed voltage, the research plan was to measure particle charge and particle removal efficiency in a two-stage system for monodisperse particles such as Hydral (hydrated alumina) dust. Charging and removal efficiency measurements with polydisperse particles including high resistivity fly ash followed after the basic systematics of pulsed precharger operation were established. The major result of pulsing the charging electric

(A) = Pulse-On Period
(B) = Pulse-Off Period
 V_p = Peak Pulse Voltage
 V_{dc} = DC-Bias Voltage

Figure 4. Voltage applied to the precharger anode during pulsed operation. The pulse repetition rate was 60 Hz.

field was that the presence of a dc-bias voltage was essential in order to produce an increase in particle charge and a concomitant improvement in the system particle collection efficiency. The knowledge gained from experiments in which the anode was pulsed with a dc-bias will serve as the basis for assessing the coordinated pulsing of both the charging electric field and the electron beam. This investigation of necessity will be deferred for a future project.

2. Free Electron Particle Charging (FEC) Project

In conventional electrostatic precipitators, fly ash particles are predominantly charged by negative ions, and the population of free electrons is small. In contrast, the population of free electrons in electron beam prechargers is markedly increased. The early reports by other workers of superior particle charging by free electrons as compared to particle charging by negative ions motivated a separate investigation of free electron charging. The superior charging of aerosol particles by free electrons has been confirmed at FSU, and an original theory has been developed to explain the experimental results.

A charging cell and gas handling apparatus was designed and constructed for the measurement of free electron charging of aerosol particles (Figure 5). The working gas was ultra-pure nitrogen since it is not electronegative and therefore will not attach electrons. Particular care was given to the exclusion of gases such as oxygen, since a trace of an electronegative gas can spuriously reduce the acquired particle charge by reducing the free electron temperature. To measure the acquired particle charge, a laser-illuminated oscillating ac field charge vs. radius (Q/A) measurement system based on a modified Millikan oil drop cell was constructed. A separate measurement of the size using the falling velocity yielded the particle charge. Particle charge was measured as a function of particle size, charging electric field and exposure parameter (Nt).

The enhanced particle charging by free electrons was extensively investigated in controlled experiments for non-electronegative gases such as ultra-pure nitrogen and argon. The results confirm that free electrons produce a higher particle charge than negative ions under the same set of conditions. For free electron charging, the particle charge varies linearly with particle radius, is a non-linear function of electric field, and is linear with $\ln(N_0t)$, in agreement with diffusion charging theory. For the two gases used

Figure 5. The Charging Cell and the Gas Flow Pathway of the Free Electron Charging (FEC) Experimental System. 19

in these experiments, particle charge appears to "saturate" as the electric field is increased.

A simulated flue gas containing typical percentages of N_2 , CO_2 , O_2 and H_2O was used in the last series of experiments. Particle charge values were again shown to be significantly higher than those predicted for ionic charging in air. All of the experiments were carried out at room temperature, although it was realized from the outset that elevated temperatures may be advantageous to free electron charging because of a decrease in the electron attachment probability and/or an increase in the electron detachment probability.

Free electron charging data obtained in the early experiments carried out elsewhere were not explained by conventional ionic charging theories, and this disagreement has been confirmed by the new, much more extensive body of data obtained in this project. A new free electron theory, the high electron temperature continuum-regime field-diffusion (HETFD) model, has been developed at FSU. The HETFD charging model was constructed using the field dependent electron temperature given by electron swarm data.

High electron temperature diffusion charging yields much higher particle charge than ionic diffusion charging, and is therefore the dominant free electron charging mechanism for particles in the normally field charging-dominated region of 0.1 - 3.0 μm particle diameter. The experimental data and the predictions of the HETFD model are in reasonable agreement; the difference between the theory and data may be due to both theoretical and experimental factors. A further experiment using argon as the carrier gas was carried out as an additional test of the theory. Within experimental errors, the data obtained with argon confirmed the new free electron charging theory.

3. Pulse Energized Electron Reactor (PEER) Project

A pulse-energized electron reactor (PEER) used for the combined removal of SO_2 , NO_x , and particles from power plant effluent gases (Figure 6) has been developed and patented by researchers at FSU. PEER uses a positive pulsed streamer corona (i.e., a high voltage ac electrical discharge) to energize electrons that will in turn promote gas phase chemical reactions, aerosol formation, and particle charging for the removal of contaminants from the gas. PEER is unique in that it uses a very short pulse width discharge (approximately 200 ns) which differs from a normal continuous discharge (dc corona) and a long pulse corona discharge. The brief duration of the pulse minimizes the power wasted on ionic migration because the mobility of ions is much less than that of electrons. Although there are other radiation-initiated SO_2 and NO_2 emission control technologies that use high energy electron beams, lasers, or microwave power to energize electrons, the advantages of PEER over these other processes include potential lower operating and capital costs, simultaneous removal of fly ash and air toxics, and, with the injection of ammonia, the production of salable fertilizer byproducts.

The use of positive pulsed streamer corona for effluent gas desulfurization was first developed at FSU in 1984. In the pulse energized electron reactor process, fast-rising, narrow, high voltage pulses superimposed on a dc-bias voltage and applied to a nonuniform electric field geometry to generate pulsed streamer corona. The pulsed streamer corona produces energetic free electrons, which dissociate gas molecules, forming radicals. These radicals cause chemical reactions that convert SO_2 and NO_2 into acid mists and/or solids, which can be removed from the gas stream by conventional means. The pulsed streamer corona also produces ions, and between pulses the ions charge the fly ash particles which are then collected by the dc-bias field.

Figure 6. Treatment Module and Gas Flow Apparatus of the Pulse Energized Electron Reactor (PEER) Test System.

In a number of pulse energized electron reactor performance tests on a humid air stream with an initial SO_2 and NO_x concentration of 1000 ppm and 400 ppm, respectively, more than 90 percent of the SO_2 and more than 60 percent of the NO_x was removed with an advantageously small power requirement. Combined treatment performance was demonstrated by introducing high resistivity fly ash into the gas stream. The fly ash collection efficiency of the pulse energized electron reactor was significantly better than that of a conventional dc wire-cylinder electrostatic precipitator when the electrodes of both were covered with a high resistivity layer. Most of the fly ash that escaped collection by the reactor was agglomerated, which facilitates subsequent collection by an electrostatic precipitator or fabric filter. Furthermore, the SO_2 removal efficiency was improved by the presence of fly ash. In addition, some of the SO_2 conversion products may lower the resistivity of the fly ash, thereby facilitating collection in an electrostatic precipitator by reducing back corona. The practical electrode configurations (wire-to-cylinder or wire-to-plate) and performance results of the reactor make it attractive for retrofit applications.

Proposed future research on the use of pulsed streamer corona for air toxics, SO_2/NO_x and particle removal by the PEER process is based on the results of preliminary experiments performed at Florida State University, and also on subsequent substantiating experimental work performed by Florida State University and others. As an example, mercury vapor removal from incinerator waste gas using high energy corona discharge has been demonstrated elsewhere. Although based on initial studies, the proposed project represents a substantial advancement in the strategy for investigating further aspects of PEER. The initial studies at FSU focused on SO_2/NO_x and particle removal, however the proposed study seeks, in addition, to consider the removal of heavy metals such as mercury.

The long term objective is to develop design, scale-up, and optimization methodologies for the industrial application of PEER.

Modeling efforts should include 1) simulation of the pulse corona discharge coupled with use of species continuity equations and the Poisson equation (for the electrical field) for the computation of the electron, negative ion, and radical formation, 2) accounting for the chemical reactions that produce gas phase acid species, and 3) introduction of aerosol formation, coagulation, condensation, and reactions, with heterogeneous reaction models and population balances. Experimental efforts should include variation of electric field parameters, electrode geometry, temperature, feed gas composition (including water vapor content, temperature, ammonia addition, mercury vapor content, and fly ash content), and reactor residence time. The experimental work would be closely coupled to the modeling efforts in order to develop a realistic description of the PEER process suitable for an eventual scale-up to pilot or larger plants.

4. Program Funding History

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

Government Support

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

- a. 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.
- b. 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.
- c. 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.
- d. 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.

- e. 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.
- f. Six-month funded extension of DOE-PETC Contract No. DE-AC22-86C91021, "Flue Gas Cleanup Technology Utilizing Energetic Electrons", September 6, 1988 - March 5, 1989.
Funding: Total = \$43,058, Direct = \$30,268, Indirect = \$12,790.
- g. 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

- a. 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.

- b. 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.

PROJECT OUTPUT

* PROJECT INCEPTION - September, 1976.

* EXTERNAL SUPPORT -

U. S. Department of Energy, Pittsburgh Energy Technology Center.

7 Contracts or Grants; September 1978 - August, 1991.

Industrial Support:

Combustion Engineering, Inc., Birmingham, AL.

F. L. Smidth Co., Copenhagen, Denmark.

Total Funding: Approximately 1.5 M including indirect costs.

* PUBLICATIONS - 73 in Journals and Conference Proceedings

* PATENTS - 1

U. S. Patent No. 4,695,358, September 22, 1987.

Assignee: Florida State University.

"Method of Removing SO₂, NO_x, and Particles from Gas Mixtures using Streamer Corona"

C. Scientific and Technical Objectives

1. Overall Objectives

a. The primary motivation for the development of electron beam precharger technology is the goal of more efficiently collecting high resistivity fly ash using electrostatic precipitators. Fine, respirable dust in the 0.1 - 10 μm diameter range poses serious health risk to the population in general.

b. High resistivity fly ash, produced by burning low sulfur coal in power plant or industrial boilers, limits the operation of conventional electrostatic precipitators by initiating the phenomenon of reverse ionization or back corona. If the particle charging and collecting functions are separated into a two-stage system comprising an upstream electron beam precharger and a downstream collector similar to a conventional electrostatic precipitator which is operated at high electric field but low current, the back corona problem can be mitigated.

c. Electron beam prechargers are designed to create very high ion and electron current densities and large electric fields which produce the conditions necessary for superior particle charging performance. The increased particle charge derived from electron beam precharging is due to the combined effects of the space charge enhancement of the charging electric field and the availability of a copious supply of free electrons.

d. The ultimate goal of the project was to bring an electron beam precharger/electrostatic collector combination to the proof-of-concept stage. A large, laboratory scale wind tunnel was commissioned in order to test various concepts.

e. Electron beam precharging has been tested successfully using low and high dust concentrations with dc, pulsed, and pulsed

with dc-bias charging electric fields. This contract specifically concentrated on pulsing the charging electric field, with and without a superimposed dc-bias field. Pulsing the charging electric field in the presence of a dc-bias voltage resulted in even higher momentary electric field levels than with high dc voltage only, producing very high particle charge values.

2. Specific Task Objectives

- a. Task A: Modification of precharger for pulsed and dc energization of anode.

The electron beam precharger and precharging modules were designed and constructed for use with dc voltage-only applied to the anode. Successful results were previously obtained with the Mk. III precharger configuration using both low loadings of polystyrene latex test spheres and high loadings of high resistivity hydrated alumina and fly ash. Reconfiguration of the precharging module allowed both pulsed energization of the anode electrode and the application of a dc-bias voltage in order to achieve much higher charging electric fields. Upgrading of the electron beam precharger from the present dc Mk. III to the pulsed Mk. III version, as expected, produced a more uniform, higher intensity charging electric field which increased the charge on individual particles resulting in a higher overall system particle collection efficiency.

- b. Task B. Installation of the particle charge vs. radius (Q/A) measurement system.

An automated particle charge vs. radius (Q/A) measurement apparatus using a laser for particle illumination, an oscillating electric field for charge determination, and a microscope objective mated to a video camera as a recording system has been developed at FSU. This apparatus was used earlier in pioneering work on the

charging of aerosol particles with free electrons instead of ions in a controlled atmosphere with a low electronegative gas component. The Q/A apparatus was extensively rebuilt in order to allow its use in the measurement of charged particles exiting the electron beam precharger. The installation of fully remote operating controls with very fine control was a major part of this modification. After the above modifications were completed and the particle charge vs. radius device was installed adjacent to the EBP wind tunnel, studies of the relative effectiveness of electron beam particles precharging commenced.

- c. Task C. Modification and installation of pulsed power supply to provide both pulsed and dc energization of the precharger anode.

A rotating spark gap high voltage pulsed power supply was fabricated for use in another experimental project investigating the use of positive pulsed streamer corona for the formation of free radical species which react with the acid rain precursors SO_2 and NO_x . This power supply functioned satisfactorily for this work, and it proved to be a reliable source of pulsed high voltage within its design limitations. The rotating spark gap power supply was relocated to the proximity of the electron beam precharging module inside the wind tunnel boundary. Upgraded high voltage wiring, improved electrical insulation, and higher power capability resistors were installed. Provision for the use of a dc-bias voltage power supply, either separately or in conjunction with the pulsed power supply, was made possible by the design of a coupling capacitor network. Once the pulsed power supply modification and installation has been completed, the application to the precharger anode of dc-only, pulsed-only, and pulsed with dc-bias voltage regimes were compared.

- d. Task D. Measurement of the removal efficiency for monodisperse simulated fly ash particles for two energization frequencies and several pulse heights.

Using only dc voltage on the precharger anode, it was found previously that higher electric field values produced greater particle charge levels and thus higher collection efficiencies for the two-stage system. In other studies elsewhere, the application of pulsed voltage to corona wires in a conventional electrostatic precipitator has shown advantages over the more common dc energization. As earlier stated, the rotating spark gap pulsed power supply was upgraded to improve its performance. Pulse frequency was set to 60 Hz and the maximum peak pulsed voltage which could be delivered was about 80 kV, variable upward from an effective onset of about 30 kV. Monodisperse test dust (similar in properties to fly ash) in the form of high resistivity, 1.0 μm diameter hydrated alumina was resuspended in the EBP wind tunnel gas stream. The high voltage pulsed power supply was operated at between 60 kV and 77 kV peak pulse heights with a 60 Hz repetition rate. Particle collection efficiency was determined for single-stage operation using only the dc electrostatic collector, and then for two-stage operation using the pulsed electron beam precharger upstream from the collector. Dividing these two penetration figures (without and with the precharger operating) produced the α -value, a quantitative measure of the performance enhancement due to the action of precharging.

- e. Task E. Measurement of particle charge for monodisperse particles for dc-only and dc plus pulsed operation.

In earlier work, the charge on individual particles leaving the electron beam precharger was found using a unique, single particle charge vs. radius (Q/A) apparatus. High dc voltage-only was applied to the precharger anode in these experiments. Larger particle charge correlated directly with greater collection efficiency. Charge values of approximately 2.5×10^{17} C were

commonly found for precharger voltages of about 66 kV (4.5 kV/cm electric field). The upgraded Q/A measurement apparatus was installed adjacent to the wind tunnel and connected to sample the precharged gas stream. During this contract, shakedown runs initially commenced using dc-only voltage in the precharger in order to confirm and improve upon earlier results. Upon completion of all of the necessary EBP system modifications, a series of experimental runs began to determine the effect of dc-alone, pulsed-alone, and pulsed plus dc-bias voltage precharger operation. Fine, monodisperse, high resistivity Hydral dust was the subject aerosol. Individual particle charge values were compared with the associated collection efficiencies while other system parameters were varied through an appropriate range. An anode pulsed voltage of 66 kV superimposed on a dc-bias voltage of 20 kV produced the highest measured particle charge values to date, corresponding to the greatest collection efficiency.

- f. Task F. Optimization of pulse energization schedule for maximum removal efficiency of test aerosol particles.

In a separate investigation of positive pulsed streamer corona treatment of gas-phase SO_2 and NO_x , an optimum combination of pulse height, pulse width, pulse frequency, and dc-bias voltage was determined empirically. Maximizing the pulse height on top of a dc-bias voltage of approximately 10-20 kV gave the highest removal efficiency for the PEER configuration employed, and it was believed that the same voltage regime might also work for the purposes of particle precharging. Finding the proper coupling capacitance to allow both dc and pulsed voltage to be delivered to the precharger anode is one task which needed to be addressed immediately. Oscillograms of the pulsed voltage riding upon the dc bias provided a basis for adjusting the power supply parameters in order to produce the optimum particle charging electric field to the precharger. The highest particle charge was achieved at 66 kV pulsed voltage, 20 kV dc-bias voltage, with pulse characteristics of 20 ns rise time and 60 Hz frequency. Measurements in the two-

stage system of both particle collection efficiency and individual particle charge levels gave a clearer picture of the performance envelope of the pulsed electron beam precharger. Optimization should also encompass a power efficiency determination in order to find not only the best operating characteristics, but also the point at which input power is capitalized upon.

g. Task G: Practical assessment of results for monodisperse test particles.

Monodisperse test particles were originally injected into the electron beam precipitator wind tunnel at very low loadings under very well controlled conditions. Polystyrene latex spheres were resuspended within the system during the earliest characterization runs. Because a fine ($1.0\ \mu\text{m}$ mean diameter), high resistivity ($> 1 \times 10^{12}\ \Omega\text{-cm}$) aerosol is difficult for conventional electrostatic precipitators to collect, it represented a relatively conservative initial test of electron beam particle precharging. Low concentration of aerosol also allowed a wide variety of parameters to be varied with relative ease. During the present contract, a fine monodisperse dust at higher concentrations (hydrated alumina, or Hydral) had been used to assess the charging and collection efficiency of the electron beam precipitator. This dust is a much more difficult test of the system, but to date quite satisfactory results have been obtained for both dc and pulsed plus dc-bias particle precharging, which proves that electron beam precharger can improve the performance of a precipitator at more realistic, i.e., higher particle concentrations. The ultimate goal of the project is to develop a fully integrated precharger-collector combination, both matched to each other and to the particular application. For this reason, the use of high concentrations of monodisperse Hydral dust was continued. Controlling and optimizing the two-stage system's operating parameters will be critical to the assessment of the practical application of this technology to the pilot, demonstration, and ultimately, full scale. Any practical assessment must, of necessity, include economic considerations.

- h. Task H. Measurement of the removal efficiency for polydisperse test particles for two energization frequencies and several pulse heights.

Controlling the test particle size was of great importance during the initial contract precharging experiments. Monodisperse Hydral test dust suited the experimental conditions perfectly, and so no polydisperse aerosol was tried early in the program. Concurrent with the series of experiments using the monodisperse hydrated alumina dust was another investigation of electron beam particle precharging using a high resistivity, polydisperse fly ash. Particle size and number determinations were more difficult with the polydisperse dust due to limitations of the aerosol monitors in the lab. However, advantages include the possibility of determining fractional collection efficiencies for various particle diameters, and the obvious advantage of using "real" fly ash as the test subject. Although electrostatic precipitators have a difficult time collecting very fine, high resistivity dust, the final series of experiments under the present contract involved the resuspension and treatment of high resistivity fly ash. As stated above, fractional collection efficiencies should eventually be determined and compared to individual particle charge determinations for various sizes of particles. Within the scope of the present project, pulsed electron beam particle precharging has been brought to the proof-of-concept stage at the laboratory scale.

D. Resources, Facilities, and Capabilities

The Aerosol Physics Group in the Department of Physics at the Florida State University has considerable expertise in dealing with the applications of dc and pulsed corona discharges to remove solid, liquid, and gas-phase contaminants from various gas mixtures and air, and in the fundamentals of aerosol science. Extensive experimental work has been carried out on the treatment of flue gas for the removal particles of SO_2 , and NO_x using electron beam precipitators, pulse energized electron reactors, and free electron charging devices. Expertise has been developed in the areas of pulsed dc power supply design, electron beam ionization phenomena, single particle charge and mass measurement techniques, and the installation and operation of electronic particle and gas monitors and associated gas acquisition systems. The publications and presentations documenting this effort are given in Section VIII of this report. FSU also holds a patent on the application of pulsed streamer corona treatment for SO_2 and NO_x removal in a PEER reactor.

The existing experimental and computational facilities available were uniquely suited for the work on the application of pulsed electric field electron beam precharging of fine aerosol particles. The project through most of its duration involved one teaching faculty member, one research associate, and several student assistants. The following specific facilities were utilized during the course of the contract research program.

1. Aerosol Physics Laboratory at Florida State University

The aerosol physics laboratory includes an electron beam precipitator wind tunnel, pulsed streamer corona reactor test system and gas distribution manifold, other small reactor modules for gas and liquid studies, a high voltage pulsed power supply for pulsed corona energization of the precharger and reactors, a

variety of heavy duty ac and dc HV power supplies, low and high concentration aerosol generators, optical particle size monitors and cascade impactors for particle size measurements, a unique single particle charge vs. mass measurement device, a computer for on-line data acquisition and analysis, a 100 keV electron beam source, and a 3 MeV Van de Graff accelerator is available if needed. Within the Aerosol Physics lab, two facilities carried the bulk of the experimental work. These were:

a. Electron Beam Precharger Test Facility

The Electron Beam Precipitator Test Facility (EBP) is unique in the U.S., and is a flexible and well-instrumented test bed providing for performance tests of electron beam prechargers. Prechargers are installed in series with collectors similar to conventional electrostatic precipitators in order to improve the removal efficiency of fly ash. The system consists of a closed-circuit wind tunnel in a racetrack configuration in which a test gas of known particle concentration first passes through an electron beam precharger and then through a collecting section. Suitable particle size and concentration monitors measure the effectiveness of electron beam precharging. The electron beam precharger utilizes the copious ionization produced by energetic electrons by separating out one monopolar component of the ion flux for the charging of aerosol particles. Individual particle size and charge can be measured immediately downstream from the electron beam precharger. The test facility is located on the FSU campus in the Nuclear Research Building inside the target room of the 3 MeV Van de Graaff electron accelerator.

The following equipment was available for the electron beam precharger experiments:

1. Electron beam precharger test system for two-stage operation, including various prechargers and a conventional electrostatic precipitator.
2. A 100 kV electron beam source with power supply, vacuum station, vacuum gauges and gauge controller.
3. Low, medium, and high particle concentration aerosol generators.
4. Electronic particle size and concentration monitors.
5. Various heavy duty ac and dc power supplies and associated precipitator voltage and current meters.
6. A rotating spark gap pulsed power supply and coupling capacitor network.
7. Gas velocity, temperature, and humidity gauges.
8. An on-line microcomputer and a data acquisition analysis system.
9. Closed-circuit TV system for remote monitoring and recording.
10. Dust resistivity measurement system.
11. A laser/oscillating ac electric field single particle charge vs. radius (Q/A) measurement system.

b. Free Electron Charging Experimental System

The equipment for offline, bench-scale free electron charging experiments included the following:

1. Charging cell and bell jar used for the measurement of free electron charging of aerosol particles.
2. Gas purification and handling system.
3. Various test gases in compressed gas bottles.
4. Laser-illuminated particle charge vs. radius (Q/A) measurement system using an oscillating ac electric field and a closed circuit TV system mated to a microscope objective.

2. FSU Department of Physics

The Department of Physics has 50 faculty members. The experimental research programs include Molecular Beam Physics, Infrared Spectroscopy, Nuclear Physics, Computational Physics, High Energy Particle Physics, and Materials Sciences. The Physics department also has an Elemental Analysis Lab in which proton induced X-ray emission (PIXE) is used to analyze air pollution samples. Companion theoretical physics research programs exist in most these areas and a substantial increase in theoretical physics research has resulted from the installation of a supercomputer at Florida State University. Informal consultation on a variety of technical and scientific topics is readily available.

3. Shops - FSU Physics

The service of the Physics Electronic Shop is provided without charge to the contract as a part of the University contribution. The staff is capable of the design, construction and maintenance of experimental electronics and computer systems. The services of two instrument-making shops are also provided without charge as a part of the University contribution to the research. The staff of the shops assist in the design of the experimental apparatus in addition to the actual performance of the machine work.

4. FAMU/FSU College of Engineering, Department of Chemical Engineering

The Department of Chemical Engineering has five research laboratories in the areas of polymers, reactive mixing, biochemical engineering, thermodynamics, and materials processing. A sixth laboratory devoted to environmental engineering is shared with civil engineering. In addition to experimental research, the department performs mathematical modeling and computer based

investigations in the areas of fluid mechanics, particles, chemical kinetics, solvent extraction, and macromolecular transport phenomena in porous media. In the laboratory, the Department of Chemical Engineering has a Perkin Elmer UV Spectrophotometer and HPLC, an ozone generator, and various pH meters, conductivity meters, pumps and other miscellaneous equipment. All of these pieces of equipment are available on an as-needed basis to the corona project.

5. FSU Department of Chemistry

The Department of Chemistry at FSU is equipped with several laboratories that may prove to be useful for the research. This includes a laser spectroscopy laboratory, a magnetic resonance laboratory, a high resolution mass spectrometry laboratory, and an x-ray diffraction laboratory.

6. Computational Facilities

Florida State is home to the Supercomputer Computations Research Insitiute (SCRI). SCRI is a DOE funded national supercomputer research center housing a Cray Y-MP and a Thinking Machines Corporation CM-2 Connection Machine offering massive state of the art parallel architecture. In addition, a host of mainframe, mini- and microcomputer installations and readily available for data analysis.

7. Libraries

A reading room with current journals is maintained by the Department of Physics and a major collection of journals and books is housed in the University Science Library.

E. Contract Statement of Work and Schedule of Research Activities

1. Task A: Modification of precharger for pulsed and DC energization of anode.
September, 1989 - June 1990, (Quarters 1-3).
2. Task B: Installation of the Q/A measurement system.
December, 1988- June 1990, (Quarters 2-3)
3. Task C: Modification and installation of pulsed and dc energization of the precharger anode.
December, 1989 - November 1990, (Quarters 2-5)
4. Task D: Measurement of the removal efficiency for monodisperse simulated fly ash particles for two energization frequencies and several pulse heights.
September 1990 - August, 1991, (Quarters 5-8)
5. Task E: Measurement of particle charge for monodisperse particles for dc only and dc plus pulsed operation.
September 1990 - August 1991, (Quarters 5-8)
6. Task F: Optimization of pulse energization schedule for maximum removal efficiency of test aerosol particles.
December, 1990 - May, 1992, (Quarters 6-11)
7. Task G: Practical assessment of results for monodisperse test particles.
December, 1990 - November 1991, (Quarters 6-9)
8. Task H: Measurement of the removal efficiency for polydisperse test particles for two energization frequencies and several pulse heights.
June, 1991 - May, 1992, (Quarters 8-11)

F. Results, Accomplishments, and Future Work

1. Concise Summary of Accomplishments

a. Development was completed of a very high feed rate fluidized bed/screw feeder dust resuspension and delivery system which will produce realistically dense concentrations of test aerosol in the Electron Beam Precipitator wind tunnel.

b. Reconfiguration of the Mk. III electron beam precharging module allowed simultaneous pulsed and dc-bias energization of the precharger anode, thereby producing a more uniform, higher intensity particle charging electric field.

c. An automated particle charge vs. radius (Q/A) measurement apparatus using a laser for particle illumination, an oscillating electric field for charge determination, and a video recording system have been used to measure the mass and charge on individual particles exiting the electron beam precharger.

d. A rotating spark gap pulsed power supply has been modified extensively in order to deliver pulsed voltage to the electron beam precharger. Pulse characteristics are as follows: pulse voltage = 80 kV maximum, pulse frequency = 60 Hz, pulse duration = 200 ns, pulse rise time = 20 ns.

e. Using dc voltage-only on the electron beam precharger anode, system particle collection efficiency levels of up to 99.7% were achieved for a moderately high concentration of high resistivity hydrated alumina dust.

f. The α - value quantifies the improvement in collection efficiency due to the effect of the E-beam precharger over the effect of the collector alone; collection efficiency increases of up to a factor of 40 ($\alpha = 40$) have been achieved.

g. While precharger pulsed power alone does not increase system collection efficiency, the addition of a small dc-bias voltage to the precharger anode along with pulsed energization produces higher particle removal efficiencies than with large dc voltage-only.

h. Particle charge and mass measurements made on individual particles after passing through the pulsed electron beam precharger show that experimental particle charge falls below but is close to the charge predicted by the ionic saturation field charging theory.

i. Optimization of the pulse/dc-bias energized electron beam precharger has resulted in maximum performance at the following parameter levels: high precharger electric field, long aerosol residence time, and matched electron beam current with precharger electrode geometry.

j. Electron beam precharging of particles has now achieved the proof-of-concept stage. Prechargers using dc, pulsed, and pulsed plus dc-bias voltage have been shown to significantly improve the performance of electrostatic precipitators in removing fine, respirable, high resistivity dust from flue gas streams.

2. System Development

One major goal for any research program attempting to duplicate a fly ash-entrained gas stream in the laboratory has been the acquisition of a suitable dust feeder. In order to completely de-agglomerate and resuspend monodisperse hydrated alumina (Hydral) dust or polydisperse fly ash samples, a new aerosol generation system has been developed. Designed to replace an inadequate, commercially available device, the apparatus assembled at FSU consists of a flexible hopper screw feeder mated to a 3.5 inch diameter fluidized bed chamber. Dust from the screw feeder is fed into a violently agitating layer of glass beads suspended by a

warm, dry air stream forced up through a rigid, semi-porous screen baffle plate. The combined action of the gas flow and bed material action produces a fine, even, well-dispersed aerosol which is delivered to the Electron Beam Precipitator (EBP) wind tunnel. Development of this device represents a significant step forward in the search for a reliable dry powder generation system.

A dedicated vacuum station, the BG-2C, serves the 100 keV electron beam accelerator, both of which were designed and constructed at FSU. A major overhaul of the vacuum station was undertaken prior to and during current contract. A larger diffusion pump was installed in the BG-2C in order to achieve a higher pumping speed and a higher ultimate vacuum. The power consumption of this new pump, taken in total with the other mechanical pumps and the other station control electronics, was near the ac current limit of the existing 110 volt circuit being used. Therefore, the entire station, with the exception of the vacuum gauges and station controller, was rewired to accept 220 VAC power, increasing the operational headroom substantially.

The 100 keV MINACC electron beam source has served as a satisfactory source of energetic electrons for the E-beam precharger. Because it is a "homemade" device, a major overhaul of the accelerator is periodically warranted. The internal accelerating tubes were removed and cleaned while a new outer PVC pipe was fabricated to replace the badly ionized casing. A 0.0003 inch thick plastic Kapton window was installed, and a new, narrower filament serving as a hot cathode electron emitter was substituted for an older model. Electronics upgrades accompanying the mechanical changeovers included improvements to the ac filament voltage power supply and to the high voltage resistor column. The result of this refurbishment was a more intense, better focused electron beam creating less impingement of beam on the accelerator walls. Outgassing of the inside walls of the accelerator tube was also markedly decreased.

Installation and shielding of a rotating spark gap pulsed power supply adjacent to the electron beam precharging module was completed midway through the contract. This supply was used previously in a DOE-supported study of the removal of SO_2 and NO_x pollutants from a simulated flue gas stream using positive pulsed streamer corona (known as "PEER" gas treatment). Electrical connections within the power supply itself have been improved in order to reduce or eliminate unwanted spurious corona generation, and the precharger anode was tested under high pulsed and dc-bias voltage. Modifications to the dc coupling capacitor and to the tail resistor assembly used to truncate the pulse have improved power supply operation when dc-bias voltage is also used. Pulses of approximately 80 kV amplitude, 20 nsec rise time, 200 nsec pulse width, and 60 Hz frequency can be delivered to the precharger anode, either alone or with a 0 - 20 kV dc-bias.

A microprocessor-based analog-to-digital signal converter (the MicroMac), is used to receive analog voltage and current measurements from the precipitator collecting section. Analog data from the 12 collector plates is converted into a digital signal which is then transmitted to a microcomputer for storage and analysis. The MicroMac was out of service for a period of time due to failure of the circuits protecting the MicroMac from high voltage, high frequency spikes occurring when the collector sparks over. Extensive repairs included the replacement of one of the A-D converter IC's as well as modifications to the spark-protecting circuits. The MicroMac was returned to a normal operating mode for the bulk of the contract experimental period.

A unique, single particle charge vs. radius ratio measurement device has been developed at FSU. This Q/A apparatus was previously used in a comprehensive, bench-scale study of the charging of aerosol particles by free electrons instead of ions. In its new role, the Q/A measurement system was used to measure the charge and size of particles exiting the electron beam precharger. Relocation and installation of the apparatus to a position adjacent

to the EBP wind tunnel occurred during the first half of the contract. In order to improve the particle-laden gas flow through the Q/A charging cell, a redesigned gas flow pathway was installed. Electrical and mechanical modifications to the Q/A device will now allow complete remote operation from the accelerator control room. Remotely-controlled focusing of the closed circuit TV camera microscope objective lens was accomplished using a very low speed motor and associated electric and viewing circuitry. Laser illumination of the charging volume has been improved by realigning the precision 90° mirror, thus giving a better image of the charged particles through the video system. A rapid cleaning procedure for the charging cell which also improves resolution has been instituted. Data analysis and display techniques have also been updated with the adoption of a spreadsheet and computer graphics package. Although further automation of the Q/A device as it is presently configured is probable, the functional transfer of this unique device from the free electron charging apparatus to the EBP wind tunnel was completed.

The initial particle charge and collection efficiency experiments which were attempted using the pulsed power supply produced substantial RF interference to the Climet multichannel analyzer storing the particle counts, and to the MicroMac A-D converter reading the digital collector currents. Some particle charge data was obtained during these runs using the Q/A device, and an analysis was performed. Because of the RF interference problem, no collection efficiency data, and thus no calculated α -values, were able to be obtained from the Climet optical particle counter. Optical coupling of the signal lines and further isolation of the various grounding networks were two remedies which were addressed. In addition, an earth grounded Faraday Cage was assembled around the rotating spark gap pulsed power supply, which, in concert with the other alterations, allowed resumption of the experimental phase of the contract.

3. Experimental Results

A laboratory scale closed circuit wind tunnel has been constructed for the test of various experimental electron beam prechargers in two stage operation with an electrostatic precipitator. The electrostatic precipitator can be operated as a stand-alone high current charging and collecting device, or as a low current collector in two-stage operation with the electron beam precharger. Experiments were conducted with moderately high loadings of very fine, monodisperse hydrated alumina (Hydral) dust, and with high concentrations of actual polydisperse, high resistivity fly ash.

A year-long experimental effort was designed to confirm and extend the envelope of electron beam precipitator performance achieved during the previous contract. Experiments were carried out using the most advanced electron beam precharger design to date, the Mk. III-B, along with the 100 keV electron beam source. These experiments consisted of establishing the test aerosol baseline concentration, measuring the removal with the electrostatic precipitator alone, and then measuring the removal efficiency while operating the combined two-stage E-beam precharger/electrostatic precipitator. Performance of the E-beam precharger was measured for various average charging electric fields, gas velocities, and energization schedules (dc-only, pulsed-only, and pulsed with a dc-bias). The charge and mass of individual particles exiting the electron beam precharger was measured using an FSU-developed laser illuminating/oscillating electric field charge vs. radius (Q/A) recording system.

In the first set of particle collection efficiency experiments performed this period, hydrated alumina (Hydral) dust at moderately high concentrations was injected into the EBP wind tunnel using the fluidized bed aerosol generator. The test aerosol was first charged using energetic electrons in the E-beam precharger, then removed in the downstream electrostatic collector. Particle size

and number information was recorded using a Climet optical particle counter. Experimental conditions were as follows: gas velocity = 4.0 ft/sec, collector electric field and current = 4.0 kV/cm and 0.1 mA, respectively, electron beam energy and current = 90 keV and 2.0 μ A, respectively, and precharger voltage and current = 70 kV dc and 43 μ A, respectively. Particle collection efficiencies of 86.04% (collector-alone) and 99.65% (precharger and collector) resulted in an χ - value (collector-alone penetration divided by precharger and collector penetration) of 40.21. In other words, the aerosol of fine, high resistivity hydrated alumina dust was removed at an efficiency of over 40 times greater than that using the collector-alone. This was accomplished despite the fact that the particle charge level as measure in several sets of experiments with hydrated alumina was lower than either the stauration or predicted charge levels. Optimization of the relationships between the electron beam, electric field, and electrode geometry in the precharger can only be expected to improve upon these already successful results.

For each of the above preliminary experimental runs, individual particle charge vs. radius measurements have been acquired using the Q/A device for comparison with the concurrent particle collection efficiency measurements. As expected, as the precharger electric field is raised while keeping all other parameters constant, the particle charge increases. For the example run mentioned earlier, the theoretical saturation charge for the particular electric field used (4.75 kV/cm) and the predicted particle charge for a residence time in the precharger of 250 msec (4 ft/sec gas velocity) were calculated. Both sets of calculated charge values are plotted vs. particle diameter, and a straight line is fitted to each of the sets of points. Experimental charge-to-radius data is plotted on the same set of axes and a line is fitted to the points. The experimental data falls below the predicted charge line, meaning that the test aerosol is not being charged up to potential levels. However, when compared with particle charge measurements taken earlier, this data

represents the best dc electron beam precharger performance yet achieved using Hydral dust. Further increases in charging and collection efficiency were expected with alterations to the precharger geometry and the use of pulsed voltage on the precharger anode.

The most recent series of E-beam precharging experiments concerned the application of pulsed power to the precharger anode. Electric field pulsing results in the rapid energization of electrons and space charge buildup during the pulse followed by the prompt termination of the pulse before debilitating sparkover can occur. Pulsed voltage was delivered to the precharger by a 60 Hz rotating spark gap pulsed power supply. This supply produces pulses of up to 80 kV with pulse widths and rise times of less than 200 ns and 20 ns, respectively. A dc-bias voltage of up to 20 kV can also be applied to the E-beam precharger in conjunction with pulsed power.

After determining the operational breakdown limits for various combinations of dc-bias and pulsed voltage, particle removal efficiency and individual particle charge was measured in the two-stage system for monodisperse hydrated alumina dust. In one experiment, the collector-alone removed 89.8% of the test aerosol which actually deteriorated to 57.8% removal efficiency when the precharger was operated with 70 kV pulsed power. However, when a 20 kV dc-bias was added to the 70 kV pulse, the system collection efficiency recovered and improved to 96.2%. Another experiment consisted of comparing the effectiveness of the electron beam precharger with equal levels of dc voltage, pulsed voltage, and pulsed plus dc-bias voltage. From a collector-alone particle collection efficiency of 93.2%, the application of 66 kV dc to the precharger increased the efficiency to 99.3%. As before, pulsing the precharger anode at 66 kV reduced the efficiency to 53.5%, but the imposition of a dc-bias while also pulsing at 66 kV caused an immediate jump in efficiency to 96.2% at 10 kV dc-bias and 99.5% at 20 kV dc-bias.

As evidenced by these experiments, the performance of the E-beam precharger when the anode is pulsed with no dc-bias is worse than the efficiency of the collector alone. This is probably because a continuous electric field across the charging zone is needed to separate the negative ion and electron fraction from the bipolar ionized plasma. The short duration of the period does not allow this to occur. Once a small dc-bias is present in the precharger, the maximum electric field (and thus particle charge) which can be achieved with pulsing is much greater than the dc breakdown limit; therein lies the advantage of using pulsed power instead of a high dc electric field.

Using the single particle charge vs. radius ratio apparatus, charge and mass data was obtained from particles sampled just downstream from the precharger. Following the collection efficiency trend, pulsed with dc-bias voltage produced greater individual particle charge than either pulsed voltage alone or dc voltage alone. Experimental particle charge levels were acceptably high, but they were found to be somewhat lower than the saturation charge predicted by ionic field charging theory. Optimization of the precharger electrical energization schedule should improve these already high particle charge levels.

The summary mechanism of electric field pulsing is the rapid energization of electrons and space charge buildup during the pulse followed by the prompt termination of the pulse before debilitating sparkover is initiated. Charging and removal efficiency measurements with polydisperse particles including high resistivity fly ash followed after the basic systematics of pulsed precharger operation were established, with similar results to those found for Hydral dust. The result of pulsing the charging electric field is an improvement in overall system particle collection efficiency. The performance with pulsing will serve as a basis for assessing the pulsing of both the charging field and the electron beam, the latter task being deferred for future work.

4. Near-Term Plans for Further Research

The particle collection efficiency experiments using monodisperse aerosol in the electron beam precipitator wind tunnel should be completed by testing the E-beam precharger at several higher energization frequencies and a wider range of pulse heights. Further investigation should be conducted into the roles of dc-bias on the charging and collection efficiency of the E-beam precharging process. The particle charge vs. radius (Q/A) measurements using the laser/oscillating field device should be continued for most of the pulsed precharging experiments. Optimum values for all of the electrical parameters affecting electron beam precharging including pulse voltage, frequency, width, risetime, and the dc-bias voltage should be determined. A more extensive series of measurements should be made of the particle collection efficiency and the charge vs. radius for polydisperse, high resistivity fly ash circulating through the E-beam precharger and collector.

Finally, a practical assessment of the results and data analysis from the entire body of pulsed electron beam precharging experiments should be formulated, including economic considerations and future directions for research.

II. ELECTRON BEAM PRECIPITATOR TEST SYSTEM

A. Components of the Electron Beam Precipitator Wind Tunnel

Electron beam particle precharging experiments using both dc and pulsed charging electric fields in the precharger were conducted using the FSU Electron Beam Precipitator wind tunnel coupled with the Mk. III E-beam precharger. Although the wind tunnel, precharger, and associated subsystems have been described in earlier reports in detail, a review of the experimental apparatus, the mechanics of precharging, and the data acquisition and analysis procedures will be presented here.

1. Ductwork and Aerosol Generation

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 gas 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, in order to provide

F.S.U. ELECTRON BEAM PRECIPITATOR TEST SYSTEM

a particle-free feed gas stream. 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.

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). Alternately, an aerosol of polydisperse, high resistivity fly ash originally collected from the hopper of a full-sized electrostatic precipitator was used. 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.

2. Precharging Module, Electron Beam Accelerator, and Vacuum Station

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 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.

Figure 2. The Fluidized Bed/Screw Feeder Aerosol Generator used for High Concentration Dust Resuspension.

Figure 3. The BG-2 Vacuum Station and the 100 keV Electron Beam Accelerator (MINACC) serving the Precharging Module.

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 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.

3. Ionization and Precharging

The mechanics of electron beam particle precharging have been described elsewhere, 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 plates 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 within the

Figure 4. Schematic Diagram of the 100 keV Electron Beam Accelerator (MINACC) used in Precharging Studies.

Figure 5. Top View of the M-1000 Electrometer Detector Designing and Manufacturing Division

Figure 6. Ionization of Air Molecules by Electron Beam Irradiation and Separation of Ion Flux into two Monopolar Fractions by an Electric Field.

charging zone, through which particle-laden gas is flowing. High levels of particle charge and rapid charging rates result from, respectively, the large electric fields and dense ion currents in the precharger.

4. Collecting Section

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 configured like a standard wire-plate precipitator design with two channels, one of which can be blocked off with a baffle plate thereby 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 that have a separation distance of 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., and blocking off one channel of the collector quartered the dimensionless SCA number from 1667 to 417. 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 electrostatic collecting section.

5. Monitoring and Data Acquisition Systems

Several monitoring locations are spaced throughout the wind tunnel, with the three main ones being 1) upstream from the precharger, 2) midway between the precharging and collecting modules, and 3) 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

Figure 7. Detail of the Collecting Module showing the six Corona Wire and Collector Plate Assemblies.

Dimensional Relationships of the EBP Wind Tunnel

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

determined. An 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. The FSU single particle charge vs. radius (Q/A) measurement device samples particles immediately downstream from the electron beam precharger. All of these monitors will be described in more detail in later sections of this report.

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 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.

6. Wind Tunnel Operating Characteristics

The design and construction of a laboratory-scale electrostatic precipitator which would be adaptable to a wide variety of experimental conditions was the principle task of a prior U.S. DOE/PETC contract. The EBP wind tunnel was subjected to a series of performance tests upon its completion. Among these tests were investigations of the air flow patterns through the system and a thorough examination of the racetrack electronic monitoring devices. These tests were generally successful although the monitoring systems, especially the Climet optical particle counters, were found to have larger errors than expected, which must be taken into account when using these devices for diagnostic purposes. The two Climet units always give somewhat different particle counts even when sampling the same gas stream, but initial

Figure 8. The Microcomputer-based Data Acquisition and Analysis System linking the EBP Wind Tunnel Monitors and Sensors.

difficulties obtaining quantitatively repeatable results have been largely overcome by internally adjusting the counting mechanisms.

The electron beam precipitator system represents a hostile environment in which to conduct experiments in two respects: ionizing radiation and high voltage energization. Shielding was provided to guard against radiation damage, but the need to operate under frequent high voltage sparking conditions uncovered a serious earth-ground problem which deleteriously affected the EBP sensors and digital equipment. Electrical damage to electronic sensors and the data acquisition system was repaired, and several preliminary grounding configurations were tried with increasing success. The problem was solved to a great extent by the installation of an extensive earth-ground network which effectively shunted the high voltage transients and prevented further instrument damage.

B. Aerosol Generation Systems

1. Overview

Aerosols of two basic types were resuspended in the aerosol entrainment module. The basic properties of electron beam precipitation (charging and collection efficiency, maximum field and current) were investigated using a monodisperse aerosol (hydrated alumina, or Hydral) at medium to high loadings. High loadings of polydisperse fly ash are needed to test the EBP under more realistic conditions. For either medium or high loading applications using bulk powders, a pressurized fluidized bed aerosol generator fed by a large capacity screw feeder was employed.

2. Redesign of the Fluidized Bed Distribution Plate

The main focus of attention on developing a suitable dust feeder for the Electron Beam Precipitator was centered on the completion of a redesigned fluidized bed aerosol generator (FBAG) system (Figure 9). As was reported in the Final Report to the U.S. Department of Energy for DOE Contract Number DE-AC22-86PC91021 (May 6, 1986 - March 5, 1989), there were several problems encountered with the original high concentration aerosol generation system used to supply test dust to the EBP wind tunnel. In these earlier experiments, the monodisperse Hydral dust, which is nominally 1 μm in diameter, was measured with a Climet optical particle counter to be as much as 2.5 μm in diameter. This discrepancy was attributed to the incomplete de-agglomeration of the raw Hydral dust in the fluidized bed aerosol generator, caused in part by a large accumulation of dust in the bed material.

A study was performed to determine the most effective way to correct this deficiency, which resulted in the conclusion that the

EBP Fluidized Bed Aerosol Generator

Florida State University

Figure 9. The FSU Fluidized Bed/Screw Feeder used to generate High Concentrations of Test Aerosol for the EBP.

sintered gas distribution plate and the semi-porous rigid screen needed to be modified and enlarged to allow a larger volume of gas flow at a lower pressure to pass. This action should maintain the integrity of the gas supply in the closed system while reducing the gas velocity through the bed material. A determination of the limits of the fluidized with regard to the volume of gas flow and the dimensions of the bed material and gas distribution plate was also needed.

The main concern was to reduce the amount of pressure and at the same time achieve a greater agitation of the glass beads. For this reason a revised gas distribution plate and a new cylinder with a small diameter were constructed, thereby decreasing the required pressure and increasing the agitation of the glass beads. A new gas distribution plate was designed in which a screen was sandwiched between two disk halves fabricated out of PVC. The top disk had a sloping edge as in an earlier model. The surface, however, was much smoother and steeper than that of the first sloped disk and was found to operate more efficiently than any of the previous designs.

3. Fluidized Bed Aerosol Generator - Current Layout

The Fluidized Bed Aerosol Generation (FBAG) system has been extensively modified in order to provide a more even, deagglomerated aerosol to the EBP wind tunnel. The FBAG was constructed out of a vertical plexiglass tube which is 4 inches in outside diameter and approximately 2 1/2 ft in length (Figure 9). Wall thickness of this tubing is 1/4 in, thereby making the inner diameter 3 1/2 in. The end caps of the fluidized bed tube were composed of two 4 in clean-out female fittings otherwise known as "grease traps". This fitting consists of a 4 in PVC pipe coupling on one side mated to a threaded female adaptor on the opposite side, into which a 4 in threaded PVC plug is inserted. A small adapter between the PVC pipe fitting and the tubing completed the

assembly; this machined adaptor was necessary in order to allow the pipe to properly seat against the tubing. The PVC plug was used to allow easy access to the fluidized bed interior while providing an airtight seal to allow the fluidized bed to function properly.

Feeding a steady stream of dust to the fluidized bed was an AccuRate series 300 dry material feeder. This dust feeder uses a flexible vinyl hopper and rotating screw gear type of delivery method. A variable speed motor connected to the screw shaft allows the AccuRate deliver between 0.000003 and 4.16 cubic feet of dry material per hour. The configuration of the screw feeder is such that the screw gear extends through the 1 in diameter PVC inlet pipe past the plexiglass tubing wall and into the interior of the fluidized bed where it directly deposits the dust into the glass bead bed material. Here, the dust is resuspended by a stream of compressed gas filtering up through the gas distribution plate, deagglomerated by the glass beads, and then carried out the top of the ported plexiglass tube and into the wind tunnel.

The bed material, which is composed of Potters Industries, Inc. Cat. # 2227, US Screen Number 100-200 solid glass spheres, is supported by a semi-porous, rigid gas distribution plate. An aluminum ring having an o-ring around its circumference was fitted snugly up against the inside of the plexiglass tube. Attached to the ring covering the open area was a woven wire screen composed of a patented product called Betamesh 30. Betamesh 30 is a Dutch weave wire cloth that is designed to allow higher gas flow rates, while retaining a larger portion of solids. This insures maximum air flow while preventing the bed material or dust from falling down through the screen. The gas distribution plate is located approximately 1.2 in below the dust inlet port.

After construction of the fluidized bed aerosol generation system and the screw feeder connection were completed, a test was performed to determine the flow rate needed to agitate the bed material and effectively resuspend hydrated alumina (Hydral) dust.

After careful consideration it was determined that a flow rate of 7 cu ft/min, which is approximately 12 % of the total volume of gas flow in the Electron Beam Precipitator wind tunnel, would provide maximum deagglomeration without excessive waste of the compressed gas supply.

Later in the contract period, an air preheater was added to the compressed gas inlet line supplying the lower chamber of the fluidized bed. Consisting of a strip heater mounted within an insulated stainless steel cylinder, the air preheater delivered a warm (50°C), dehumidified, compressed gas which aided the fluidization and deagglomeration processes. The test dust, namely hydrated alumina or "Hydral", is a very hygroscopic material which tends to form into clumps in both the screw feeder and the fluidized bed. Even though the heated air coursing up through the porous screen, glass beads, and dust layer broke down many of the clumps, compaction of the bulk Hydral in the screw feeder still remained a problem. Plans called for the installation of a positive pressure flow pathway which will force warm, humid, dehumidified air through the dust hopper to alleviate this difficulty.

C. Precharging Module and Precharger Components

1. Overview

Much of the recent work on ESP's has focused on precharging as a means of driving up the charge on particles to improve the collection efficiency of high resistivity fly ash. Electron beam precharging makes use of high ion current densities and electric fields to accomplish this goal. The FSU electron beam precharger is an ion current separation and collection device for charging particles passing through the precharging module of the EBP. It provides a large electric field to insure a high level of particle charge while allowing an unimpeded flow of particle-laden gas. High ion current density assures a rapid charging rate.

As described in earlier reports, a sub-duct or prosthesis was installed in the EBP racetrack to accept the prechargers transferred from the bench scale apparatus (Figure 10). The original stainless steel precharging module was rotated 90 degrees and reattached to the system, allowing a 3 ft long square PVC tube to be suspended in the center along the axis of flow. The cross section of the precharging module was reduced from 12 in² to 6 in² in order to satisfy the energy/geometry matching requirement for the laboratory-constructed 100 keV accelerator. While the lowest energy obtainable from the 3 MeV Van de Graaff machine was too high for a 12 in² precharger, a 6 in² geometry provides an appropriate match to an energy of 100 keV. The ideal energy for a 12 in² geometry is 200 to 400 keV, and future scale up will require the purchase of such an accelerator.

2. Ionization and Precharging Processes

The mechanics of electron beam particle precharging are as follows. Figure 11 shows the present internal electrode

Racetrack - Mounted Precharger (Top View)

Figure 10. Location of the Precharging Module within the Electron Beam Precipitator Wind Tunnel.

Figure 11. Top View of the Mk. III-B Electron Beam Precharging Module Showing the Ionization and Charging Zones.

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 electrodes which define the boundary of the charging zone (Figure 6). When an electric field (either dc or pulsed) is applied between the anode and cathode electrodes, the charge density is separated into two monopolar fractions. The negative fraction composed of ions and free electrons is drawn out into and maintained within 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.

D. MINACC Electron Beam Accelerator and Vacuum Station

1. Overview

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 (Figure 12). Within an evacuated, insulating PVC pipe are a hot filament cathode and a series of accelerating rings at successively lower electric potentials. 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 1×10^{-5} torr is a dedicated vacuum station, the BG-2 (Figure 13). 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.

2. Rewiring of BG-2 Vacuum Station

Previous equipment changes to the BG-2 vacuum station (Figure 13) dedicated to serving the 100 keV accelerator required the addition of a larger diffusion pump. However, it was found that the power consumption of this pump was approaching the ac current limit of the existing 110 volt circuit in the laboratory area. In addition, some of the wiring within the station itself was becoming excessively hot under the load. The solution to this problem was the conversion of the entire system to 220 VAC operation. This change required the electrical reconfiguration of the mechanical pump motors, the diffusion pump heaters, and minor changes in the control circuitry. The final result of this change in the station power supply reduced the current drawn by roughly half and thus relieved the heating in the vacuum station and associated wiring.

Figure 12. Schematic Diagram of the 100 keV maximum energy Electron Beam Accelerator, or the MINACC.

Figure 13. The BG-2 Vacuum Station, the MINACC Electron Beam Accelerator, and the E-Beam Precharging Module.

3. Mechanical Overhaul of Vacuum Station

At the beginning of this contract, one of the main objectives was to evaluate the BG-2 vacuum station and to restore it to a reasonably reliable state of operation. This station provides the necessary vacuum to the 100 keV MINACC electron beam accelerator utilized in the electron beam precharging experiments. As this vacuum system had not been run appreciably in approximately 6 months, getting it back its previous level of dependability to proved to be quite a task.

As a first step, the BG-2 was powered up and run through the normal start-up procedures. As a result, it was found that: 1) the fore pump connected to the outlet of the diffusion pump was leaking oil; 2) the "test valve" separating the inlet of the diffusion pump from the accelerator was sticking and would not open on its own; and 3) the ultimate vacuum attained after pumping on the accelerator for one day was on the order of 1×10^{-5} torr; which is the maximum pressure at which the electron beam source can operate effectively.

Upon examination of the fore pump, it was determined that it only needed a shaft seal. When a new seal was installed, the oil leak problem was solved. However, after much consultation with other vacuum technicians in the department, it was decided that a complete overhaul of the BG-2 vacuum station was in order. This entailed cleaning and changing the oil in the diffusion pump, overhauling the test valve, and replacing a four inch O-ring seal between the diffusion pump baffle and the test valve which had deteriorated.

When this work was completed, the vacuum station operated quite satisfactorily for approximately 6 weeks. Unfortunately, a cooling water leak soon developed in the upper cooling coils on the body of the diffusion pump. This particular leak was temporarily closed, but because the copper cooling coils were quite old and

eroded, other more serious leaks soon developed. The vacuum station was dismantled again, and the diffusion pump re-wrapped with new tubing. Although several of the major components are at least 20 years old, regular maintenance and periodic upgrading should keep the station functional for the pulsed electron beam precharger experiments.

4. Current Layout and Operation of BG-2c Vacuum Station

The BG-2c vacuum station is a dedicated system designed to maintain the 100 keV electron beam at sufficiently high vacuum for efficient operation. At its present state of development, the BG-2c consists of a 4 inch CVC diffusion pump with baffle, two Sargent Welch #1402 mechanical pumps, a CVC pneumatic test valve which isolates the diffusion pump from the accelerator cavity, a CVC GPT-450 vacuum gauge controller including two gauge sensing tubes, and a relay-based electronic logic system which controls the various valves in the system automatically. The system is built on the chassis of an old Veeco Mass Spectrometer Vacuum Leak Detector which earlier had been de-commissioned.

When the BG-2c vacuum station has been pumping on the 100 keV accelerator for at least one week, it can produce an ultimate vacuum in the accelerator cavity of approximately 3 μ torr (3×10^{-6} Torr). This is considered quite good for a system of this type without a liquid nitrogen cold-trap, and is sufficient for the production of a 90 keV beam of electrons with minimal beam scatter inside the accelerator.

In addition to a host of vacuum protection mechanisms already in place on the unit, an electrically actuated water flow switch which senses the loss of cooling water flow, and a thermostat which senses excessive temperature of the diffusion pump body were installed on the BG-2c station. Both of these devices turn off the

diffusion pump heaters to prevent damage to the housing and the fluid in the case of a cooling water or a fore pump failure.

Several setbacks in the realization of optimum vacuum system performance were encountered midway through the contract. Most of these problems stemmed from the failure of the recently installed water cutoff sensor. During an experimental run hiatus, the supply of water which cools the diffusion pump on the BG-2c vacuum station was interrupted because of a building outage. When the water supply to the station was cut off for a period of about 2 hours, the water flow sensor which switches off the diffusion pump heaters failed, resulting in a severe overheating of the silicone diffusion pump fluid. The only indication of this failure came long after cooling water was interrupted to the diffusion pump, when an unusual fluctuation in the pressure reading of the Penning Tube monitoring the accelerator cavity was noticed.

Later in the contract, another water interruption occurred, except that this time the building water system was down much longer due to campus construction. Once again, the water flow sensor which had been replaced after the last cooling water outage failed to turn off the heating elements. As a result, the diffusion pump had been overheated to the point that the cooling water lines wrapped around the pump had become detached, the solder attaching the copper cooling coils to the pump body had melted in places, and the diffusion pump fluid, of which only about 50% was left, had been scorched.

In investigating possible causes of this near catastrophe, some loose plastic of unknown composition originally in the chilled water supply was found to be lodged in the water flow sensor, blocking the switch from closing. In responding to these major vacuum station problems, three remedies were proposed and initiated. First, the water flow sensor was repaired and reinstalled in a more reliable location. Second, the diffusion pump was removed, thoroughly cleaned, sandblasted, and re-wrapped

with new copper tubing to try to upgrade the cooling coil arrangement. After reinstallation into the BG-2c support frame, new silicone diffusion pump fluid (Dow-Corning #704) was added. Third, a thermostat designed to shut off the diffusion pump cart heaters in the event of pump overheating was installed on the pump body as a backup to the water flow sensor.

The above listed repairs and improvements to the CVC diffusion pump prevented the loss of valuable accelerator run time. Currently, the BG-2c vacuum station has been fully recommissioned and is operating continuously at an optimum level. The vacuum in the accelerator was stable at about 4×10^{-6} Torr for most of the precharging runs. Furthermore, the modifications made should preclude most other foreseeable major problems in the future.

5. Current Layout of MINACC Electron Beam Accelerator

The initial problems with the BG-2 vacuum station were eventually sorted out, and a program of testing and calibrating the 100 keV electron beam accelerator (Figure 12) began. After several successful test runs, accelerator window blowouts became an all too frequent occurrence. The accelerator window separates the interior components of the electron beam source (which must remain at high vacuum) from the particle-laden gas flowing through the precharger (which is at atmospheric pressure). Sudden loss of vacuum integrity in the accelerator generally causes a burnout of the hot cathode filament, resulting in a time-consuming disassembly of the E-beam source.

The window of the E-beam is a 0.0003 inch thick, 2.0 in diameter sheet of DuPont "Kapton" plastic film clamped between two halves of the ground potential electrode on the downstream end of the accelerator. The geometry of this electrode forms a 1.0 in diameter accelerator port through which the E-beam passes out into air. Kapton film of this thickness poses a negligible attenuation

to 90 keV electrons. In the past, the life of this window, when properly mounted and under sufficient vacuum, was found to be several months.

After much investigation and two more window replacements, it was determined that the abnormally frequent window blowouts were due to excessive oxidation of the interior surfaces of the accelerator housing, which were made out of polyvinyl chloride (PVC) pipe. The impingement of the electron beam on the inside of the beam tube led to the liberation of oxidized molecules into the accelerator, which caused excessive beam scattering. In addition, the liberated molecules themselves were accelerated down the beam tube by the potential voltage drop, finally impacting the Kapton window. After sufficient accelerator run time, these particles formed an attenuating film on the window which caused excessive window heating, finally resulting in failure of the window. Resolution of this problem necessitated constructing new PVC beam tube sections to replace the existing ones, cleaning the interior accelerating electrodes, and replacing both the window film and the hot cathode filament electron source.

These steps effectively ended the formation of any window deposits and have restored the accelerator to a reliable state of operation. The re-calibration and testing of the 100 keV MINACC electron beam accelerator was completed and was made ready for use in the pulsed E-beam particle precharging experiments.

6. MINACC Accelerator Upgrades and Beam Measurements

The 100 keV maximum energy electron beam accelerator (the MINACC) delivers an intense electron beam to the precharger for E-beam particle charging studies (Figure 12). This beam source was constructed at FSU using parts on-hand, and was disassembled and upgraded to improve its performance. Preliminary tests were run on the refurbished accelerator upon its completion. Beam current measurements were made of the total beam output through the thin

window ("probe current") the beam fraction lost to the cathode screen electrode ("screen current"), and the beam fraction lost to the window and the window frame ("window current"). The working electron beam energy was 90 keV, while the beam current output to the probe was found to be from 0.5 μA to 10 μA .

During these preliminary runs, problems with excessive window current readings were encountered while running the electron beam accelerator. The majority of the electron beam should, by design, pass through the window and out into the precharger without impacting upon the window housing. Approximately one-third of the total current was being lost to the window housing because of electron scattering within the accelerator. After thoroughly checking all of the accelerator wiring connections and beam current measurement leads, a slight modification was made to the internal electrode geometry in the vicinity of the cathode filament. The MINACC was then cleaned, reassembled, and reinstalled in the precharging module. This modification improved the focusing of the beam within the flight tube, and thus reduced the window current.

After this modification, the electron beam was tested extensively. In the course of this testing, data was tabulated relating the electron emitter current (produced by the hot filament cathode) to the filament voltage (Table 2), and also the filament current to the window, screen, and probe electron beam currents. This table was developed for future use in establishing the proper accelerator operating point for each experimental condition during precharger operation.

Figure 14 is a plot of filament current vs. filament voltage for the new cathode filament as well as an older version. The newer filament is physically smaller and better represents a point source of electrons, but it has a higher resistive value which requires greater voltage for the same current production.

TABLE 2.

Hot Cathode Filament Current and Voltage Measurements
for the new Electron Emitter Filament

Filament Current (mA)	Filament Voltage (VAC)
180	2.59
190	2.80
200	3.00
210	3.27
220	3.53
230	3.79
240	4.11
250	4.33
260	4.67
270	4.99
280	5.33
290	5.62
300	5.94
310	6.26
370	6.55

Figure 14. Plot of MINACC Electron Beam Cathode Filament Current vs. AC Filament Voltage for the new and old Electron Beam Emitter Filaments.

It should be noted that the probe which is used to measure the electron beam entering the precharger must be removed prior to precharger operation. The probe completely blocks the electron beam from entering the precharger, preventing the ionization process from occurring. Calibration curves are therefore necessary in order to relate window and screen current to probe current. Examples of these calibration curves are shown in Figures 15 and 16. In addition, the tests performed this term served to condition the accelerator housing by allowing sufficient time for outgassing, and also to familiarize the operator with the behavior of the electron beam and the MINACC itself.

Figure 15. Plot of MINACC Electron Beam Current vs. AC Filament Current for the Cathode Screen and the Window Assembly.

Figure 16. Plot of MINACC Electron Beam Current vs. AC Filament Current for the Cathode Screen and the Window Assembly.

E. Collecting Section

The collecting section downstream from the precharger (Figure 17) is the other major component of a two-stage precipitator. For the FSU E-beam precipitator, the collector was designed to model a down-sized conventional electrostatic precipitator (ESP). It is a typical wire-plate configuration and it can be operated at relatively low voltage to give high particle collection efficiencies. The reason for using a wire-plate design is two-fold: 1) to compare the collector operating at high current used as an ESP with the collector operating at a low current used as a second stage for a precharger, and 2) to realistically assess the performance of the E-beam precharger in a retrofit circumstance, i.e., upstream from a conventional wire-plate collector. A set of centrally located plates or large rods can replace the corona wires for investigation of a plate-plate collector if desired. Wide plate spacing can also be studied by completely removing the center plates and all corona wires.

Gas entering the collector is split into two channels, each of which has three sections for a total of six fields (Figure 17). Plexiglass top and bottom covers seal the module. Twelve stainless steel collector plates are mounted to standoff insulation and then to the collector frame. The six corona wire assemblies are each composed of six stainless steel corona wires suspended between aluminum buss rods which are insulated from the collector frame. Corona wires of practically any diameter can be substituted for the present 0.010 in diameter wires presently installed for testing. High voltage, high current dc power supplies are used to energize the collector. A 130 kV, 30 mA unit provides voltage to the collector wires. The collector fields can be sectionalized if necessary using another 130 kV supply. Either of the two channels may be blocked off by a baffle plate, thereby reducing the collection plate area by a factor of 2 and increasing the gas velocity in the open channel by a factor of 2. Blocking one

Figure 17. Detail of the Collecting Module Showing the six Corona Wire and Collector Plate Assemblies.

channel therefore results in a reduction in SCA of a factor of four.

The specifications of the collection module and its internal components are as follows:

1. Collector Module Dimensions = 7 1/2 ft long x 4 1/2 ft high x 1 1/4 ft wide.
2. Corona Wire Length = 48 in (122 cm).
3. Corona Wire Diameter = 0.109 in (2.8 mm).
4. Wire-to-Plate Spacing = 3 in (7.72 cm).
5. Single Plate Dimensions = 4 ft high x 2 ft 6 in wide.
6. Total Plate Area = 120 ft² (both channels).
7. Collector SCA (ft² per 1000 ACFM Gas Flow) = 200 at a Collector Velocity of 2.5 ft/sec.

Velocity changes within the racetrack must be carefully documented since the critical regions are of different sizes. Cross-sectional areas for the critical modules are as follows: precharger sub-duct = 0.25 ft²; wind tunnel ductwork, monitoring and aerosol entrainment modules = 1 ft²; collecting module = 4 ft². Therefore, gas passing through the working precharging-collection region experiences a 16:4:1 reduction passing from precharger to Q/A monitoring section to collector.

F. Particle and Gas Monitoring Systems

1. Overview

Characterizing the operating conditions of the gas stream and the particle charging and collection efficiency of the EBP required a comprehensive group of monitoring systems. These monitors must have remote controls and readouts located in the E-beam control room since the Electron Beam Precipitator (EBP) is located in the 3 MeV accelerator target vault. Monitoring modules are located upstream and downstream from the precipitator for the purpose of before and after measurement of a number of parameters.

Several monitoring systems measure gas stream conditions in the wind tunnel. A hot-wire type anemometer including a solid state temperature sensor is fastened to a side port of the monitoring modules. Electronic ion exchange relative humidity and solid state platinum thermometer probes are fastened to plexiglass tops at two points: on the return leg of the EBP downstream from the humidity control device and on the monitoring module adjacent to the collector.

Two types of particle samplers monitor the EBP: real-time and time-integrated. Optical particle counters give a real-time indication of the number and size of particles present in a continuously sampled gas stream. A multi-stage cascade impactor and an absolute filter holder sample the gas flow downstream from the collector in a time-integrated fashion.

2. Aerosol Dilution and Measurement System

In preparing various EBP wind tunnel subsystems for the particle precharging experiments, attention was directed toward the particle size and number measurement system. This entails having

a reliable and accurate method of monitoring the output of the fluidized bed/screw feeder aerosol generation system in order to insure that an even and consistent supply of resuspended Hydral dust is delivered to the EBP wind tunnel. The system used to fulfill that requirement consisted of a Climet CI-225 optical particle counter in cascade with a Climet CI-294 dilution system having a 100:1 air-to-aerosol ratio (Figure 18). Since no device currently available will measure the extremely high particle concentrations produced at the outlet of the fluidized bed, the aerosol was instead sampled from the EBP wind tunnel at the normal location just downstream from the collector.

The CI-294 dilution system extends the operating range of the CI-225, permitting it to operate on aerosol streams which are normally far too concentrated for the light scattering apparatus to handle ($> 10^7$ particles/min). Information in the form of particle size and number data integrated over a period of one second is sent to a Climet CI-210 multichannel analyzer and then to a microcomputer for storage and analysis. One of the design advantages of the Climet system is that it produces a "real-time" indication of particle concentration in the wind tunnel. This allows rapid diagnosis of the effects of electron beam precharging or other precipitator perturbations.

In order to ascertain the accuracy of the Climet optical particle counting system, an aerosol of a known size at very low concentration was fed directly into the CI-225, and the data output from the CI-210 was then verified. This test was accomplished using polystyrene latex (PSL) spheres of 1.32 and 1.5 μm in diameter. The plan to proceed with a test of the Climet units using an aerosol suspended in the EBP wind tunnel was delayed, however, because both of the CI-225 Particle counters were found to be operating defectively. One of the units would not calibrate properly, and the second unit could not be pressure-balanced.

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 18. The Climet Optical Particle Sizing and Counting System showing the CI-225 Sensing Unit and the CI-210 Multichannel Analyzer.

The process of electronic calibration involves adjusting a front panel potentiometer while in the "calibrate" mode which causes the various particle size ranges and count totals to coincide. Pressure-balancing of the apparatus is needed in order to insure that the CI-294 dilution system dilutes the sampled aerosol by a ratio of 100:1. Since the second machine could not be successfully pressure-balanced with the dilution system, the first machine, as advised by the manufacturer, was manually calibrated with 1.5 μm PSL, and then mated to one of the dilution systems. Effective sample dilution of a high concentration Hydral aerosol circulating in the wind tunnel could then be attempted. Tests subsequently conducted with the Climet optical counting system verified the functionality of this arrangement.

3. RFI Countermeasures - Climet Optical Particle Counter

In addressing the problem of inaccurate particle counting by the Climet optical particle monitoring system when the pulsed power supply was operating, two main options were considered. 1) Re-ground and electrically isolate all components of the Climet particle analysis system, supplying them with an isolated and filtered ac line power supply. Also, reroute the data transmission line to allow a much shorter length. 2) Design and install a fiber-optic data transmitter between the CI-225 particle counter and the CI-210 multichannel analyzer. This would allow electrical isolation of the units as well as a very low-noise signal transmission.

Although the second option was the preferred one, preliminary studies of the electronic hardware required to accomplish the task indicated that, due to the high system operating frequency necessary for accurate signal transmission (greater than 360 kHz), it would cost on the order of \$1000. Because of limited resources for troubleshooting this problem, the first option was pursued with

the hope that it would yield a sufficient improvement in noise rejection to facilitate accurate system operation.

In implementing the first option, the following was done:

- 1) The old data transmission line between the Climet-210 multichannel analyzer and Climet-225 optical particle counter was replaced by a new and much shorter length of 50 ohm coaxial cable.
- 2) The Climet-225 particle counter was electrically isolated from all other systems, which are grounded to earth in the accelerator vault containing the wind tunnel.
- 3) Filtered ac power was supplied from the control room, where the Climet unit is grounded through a heavy, low resistance ground strap. Figure 19 shows the basic system layout and grounding schematic.

Although the above modifications were completed, the Climet-210 multichannel analyzer subsequently developed microprocessor problems which have at this point not been repaired. Thus, there has not been an opportunity to establish the effectiveness of the latest round of modification to the input power and grounding systems.

4. Absolute Filter Holder Mechanical Particle Sampler

A rotating spark gap power supply was developed for the pulsed electron beam precharging experiments which were started midway through the contract period. During early tests of this pulser, it was found that a large amount of electromagnetic noise was produced by the rotating spark gap. Despite numerous attempts to totally eliminate the emitted noise, only partial success in this endeavor was achieved. A search was begun in order to locate a particle monitoring system which would not be affected by the operation of the pulsed power supply.

A new method to sample and count aerosol particles was commissioned because of the inability of the Climet to function in

Figure 19. The Grounding Layout between the Microcomputer and the Multichannel Analyzer (located in the control room), and the Particle Counter, MicroMac, Pulsed Power Supply, and EBP (located in the vault).

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 20) 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 20. The Absolute Filter Holder Aerosol Sampler, used for determining Bulk Particle Mass in E-Beam Experiments having High Concentrations of Hydral Dust or Fly Ash.

G. Charge vs. Radius (Q/A) Measurement Device

1. Overview

Particle charge versus mass measurement devices are used to quantify the effectiveness of the E-beam precharger prior to particle collection. A bulk charge vs. mass (Q/M) sampler based on a Faraday Cage-encased absolute filter can be used to measure total sample mass and total particle charge. A single particle charge vs. radius (Q/A) device developed at FSU was used to directly measure the size and charge of individual particles. The device operates by imposing an ac electric field on a chamber into which particles are introduced. A laser illuminates the oscillating particles, and a microscope lens and video camera display and record the event.

2. Detailed Description of Charge vs. Radius Apparatus

A device which had been used in earlier free electron particle charging studies, namely the charge vs. radius (Q/A) measurement system, has been applied to particle charging studies in the Electron Beam Precipitator wind tunnel. A sampling tube located just downstream from the end of the precharging module delivered a charged aerosol to the Q/A system. Experimentally determined particle charge levels were then compared with the theoretical values previously determined, and with values commonly found in corona wire ESPs.

The charge-to-radius measurement system (Figure 21) is a research apparatus originally invented in Japan and later fully developed at FSU. It is designed to determine the mass and charge of fine aerosol particles of the order of one micrometer diameter. This task is accomplished by observing the physical behavior of such particles in a controlled environment with known conditions.

F.S.U. Charge / Radius Measurement System

Figure 21. The FSU Charge-to-Radius (q/a) Measurement System; detail shows the Particle Charge Measurement Cell, the Laser and Mirror, and the Video Viewing/Recording System.

These conditions are:

1. A gaseous medium with minimal turbulence.
2. The action of gravity on a small particle of known density.
3. An oscillating uniform electric field with known frequency and voltage.

Since the behavior of a particle in such a well-defined environment can be predicted with well known physical laws and principles, it is also possible to reverse the process in order to determine information about the particle by applying those same physical laws to an unknown particle after monitoring its experimentally determined behavior.

The charge to radius measurement system consists of three subsystems: 1. the gas flow subsystem, 2. the electrical subsystem, and 3. the optical subsystem. Combining these three subsystems enables the desired measurement cell environment to be created and the particles' behavior within this environment to be monitored.

The gas flow subsystem transports aerosol particles from the wind tunnel into the particle measurement cell, isolates them there for observation, and then passes them out the exhaust. An input and an output tube connect the apparatus to the aerosol source and to the exhaust vent, respectively. Two solenoid valves, the Q/A measurement cell, and a small pump constitute the subsystem proper. The two solenoid valves are located in one flow line, one before and one after the measurement cell. With both valves open the aerosol can flow easily through the entire gas flow subsystem, allowing the old aerosol sample to be cleared from the measurement cell and a new sample to be brought in. Closing the valves seals the aerosol particles in the cell at that time, stopping the gas currents and turbulence within the measurement cell. The pump is provided to facilitate gas flow throughout the tubing and cell.

The electrical subsystem produces the required oscillating electric field within the particle measurement cell. Two opposing metal plate electrodes are mounted vertically to the insulated walls of the Q/A measurement cell on either side of a clear observation window. A variable frequency ac power supply is connected to the two electrodes between which test particles are allowed to either oscillate or free-fall. In practice, the voltage and frequency applied across the electrodes is set to a known constant value for the duration of the experiment.

The optical subsystem allows the behavior of the test aerosol particles within the particle measurement cell to be observed and recorded. A microscope objective in place of a normal lens is mounted on a high resolution closed circuit video camera. This objective lens is focused upon the center of the glass walled Q/A measurement cell through which the aerosol flows. Particles trapped in the measurement cell are illuminated from below through a window mounted on the bottom of the chamber. A 0.8 mW He-Ne laser provides a well-defined, intensely lighted region between the cell electrodes. Particle oscillation and free-fall behavior are videographed through the microscope objective and displayed on the TV monitor screen. The signal is simultaneously recorded for later detailed analysis using the video tape recorder.

The raw data produced from these charge vs. radius experiments consists of a tape recording of a number of small white dumbbell-shaped "lines" falling downward. These lines are produced by the reflected laser light bouncing off the rapidly oscillating particles within the measurement cell. By measuring the length of these lines and the distance they fall in a given number of video frames of known duration, it is possible to determine the charge and the radius of the particle. Calculations of charge-to-radius (Q/A) ratios were done on either a microcomputer based spreadsheet program, or a BASIC computer program written specifically for this purpose.

3. Initial EBP Tests of the Charge vs. Radius Apparatus

Near the beginning of the contract, the single particle charge vs. radius (Q/A) measurement system (Figure 21) was removed from the Free Electron Charging Experimental Apparatus used in the previous contract and prepared for its new role. The Q/A device will be used to measure the charge and size of particles sampled from the electron beam precharger, as stipulated by the current contract tasks. This new application of the Q/A system required a number of modifications, which consisted of the redesign of the gas flow system into and out of the measurement cell to allow connection to the wind tunnel, and those changes necessary to operate the unit remotely so as to satisfy radiation safety requirements. Modifications for remote operation included the lengthening of the video, solenoid valve, pump, and power cables, and the mounting of a remotely controlled low speed motor to the focus control of the Q/A optical subsystem. This motor allows the operator (who is in a different location from the Q/A apparatus) to "chase" desired particles as they change viewing depth within the Q/A measurement cell.

Once the Q/A system was successfully connected to the racetrack downstream from the precharger, several high loading precharging test runs using Hydral and fly ash test dust were completed. Both collection efficiencies and particle charge of selected samples were measured and recorded for different precharger conditions. The raw particle charge and radius data was recorded on videotape for later analysis.

Though good data was obtained using the modified Q/A system in its new role, some deficiencies were noted. The most troublesome was the slow buildup of an opaque particle film on the observation window of the measurement cell. This film obscured the suspended particles in the cell from view, eventually making charge and fall-rate measurements impossible and forcing an end to such measurements until the cell could be disassembled and cleaned. This

problem is almost certainly due to the extremely high concentration of particles produced for the high loading experiment.

4. Design Alternatives for the Q/A Measurement System

Following the initial tests of the charge vs. radius device using high loadings of Hydral dust, the entire Q/A system was disassembled and the components of each subsystem were cleaned and refurbished in order to prepare for future experiments. Of special importance was the disassembly and cleaning of the Q/A measurement cell which had accumulated a thin film deposit on the observation window during the earlier high loading experiments. As was noted previously, this dust deposit was one of several deficiencies with the Q/A system in its prior design incarnation. These problems were:

1) Poor particle illumination due to the small diameter of the laser beam relative to the cell width. Only those particles exactly within the beam boundary were illuminated sufficiently for measurement, but the beam diameter was too small to illuminate the entire measurement cell interior. Consequently, particles under study did not remain within the beam long enough to be easily measured.

2) Instability of the 90° laser mirror. The mirror's rotating stand was too easily jarred by outside forces, resulting in the laser beam becoming misaligned with the cell if the optics bench was disturbed.

3) The build-up of a particle film on all four sides of the measurement cell, especially on the front observation window, although the ac electric field plates are also affected. This coating severely restricted or prevented observation of particle behavior in the cell. The effect of the film on the ac field

plates is unknown. This condition was a problem primarily in the high particle loading runs.

4) Inadequate coupling of the focusing motor to the microscope focusing knob. The original method of attaching the low speed motor to the focusing knob of the Q/A microscope by the use of set screws worked for only a short while before the set screws began to strip the threads of their mounting holes, thus slipping on the focusing knob. Eventually the set screws failed completely; a new method of attachment was needed.

Two of the above problems were solved fairly easily. The instability problem with the laser mirror was easily solved by disassembling it and greasing the rotating mechanism with silicone vacuum grease. This mucilaginous substance prevented the slippage caused by the pump and solenoid valve vibration. The motor was taken off of its mount and a new mount constructed for greater stability. The motor-focus knob coupler has yet to be reattached, but it was believed that a few dabs of silicone rubber cement between the coupler and the knob will provide the needed connection and yet still be removable if necessary.

The particle film deposit and the laser illumination problems proved to be far more intractable. The film deposit can be removed by disconnecting the gas input line and inserting a cotton swab into the cell and wiping the front observation window. Unfortunately, this solution required a break in the experimental run and is not conducive to remote operation. The possibility of using an air jet to blast the window clean was considered. The laser illumination problem is a difficult one which requires a re-analysis of the fundamental design of the Q/A measurement cell.

Other preparations for the electron beam particle precharging experiments involved the relocation of the gas flow control system which samples and measures a test aerosol stream to allow easier operation by the Q/A technician. Previously, the position of the

gas flow control switch required the assistance of another researcher to activate. Extending the control cable consisted of splicing in an additional 10 feet of cable and installing a second control switch. Another change which was needed was a new video signal cable. The previously used cable was required for another research project and had to be disconnected. Consequently, another cable was routed and assigned to the Q/A system, and then fitted with the appropriate connectors.

5. Revised Remote Focus for Q/A Apparatus

Operation of the charge vs. radius device was tested under normal experimental conditions in several runs during the middle of the contract. The experimental Q/A data was compared to the predicted and saturation theoretical particle charge values for a given electric field. The system performed satisfactorily; the test particles were well illuminated and their oscillations and fall rates were visible on the video monitor. However, a few needed system improvements became evident when the recorded data were further analyzed. The main problem with the data acquisition process was that the sample particles within the observation cell, as shown on the video monitor, lost focus after only a few tape frames and were difficult to analyze. This was mainly due to inadequacies in the motorized microscope objective focusing system.

Problems with the present focusing system are: 1) Motor torque is too low at initial motor engagement, causing a slow startup focus speed and not allowing a quick change from forward to reverse focus. 2) Overshooting of the focus, i.e., the motor continues to turn after the focus control buttons have been released. 3) Camera cannot be focused manually because the automatic focus assembly is permanently attached to the focus knob. It was decided that a new remote focusing system should be designed and built which would solve the above problems and, in addition, add the ability to vary the focusing speed.

Designs for the new remote focus apparatus began to take shape during the middle and latter parts of this reporting period. The first task at hand was to obtain a suitable focusing motor that would solve some of the aforementioned difficulties with inadequate torque and overshoot. After researching this topic, conducting focusing speed and torque tests, and consulting with manufacturers' representatives, an ac synchronous stepping motor was decided upon. An order was placed, and during the intervening period, a workable design for a variable speed gear train which will be mated to the motor shaft and the focusing knob was developed. The arrangement incorporates a number of gears, one of which can be changed out to other sizes when an increase or decrease in the output focusing speed is desired for different run conditions. A suitable supplier was then contacted and the gears were ordered. Work on the design of a framework for the gear train was also begun this term.

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.

H. Data Acquisition Computer and MicroMac A/D Converter

1. Overview

A microprocessor-based data acquisition and analysis system (Figure 22) was developed to coordinate most of the data outputs of the Electron Beam Precipitator. It was used to accumulate, condition, process, and store all signals from the energized sections of the precharger and collector and from the EBP electronic monitors. Interfaced to the computer are a number of monitor signal inputs. These include: voltage and ion current signals from the precipitator through the MicroMac data conditioning system, the velocity and temperature sensors, and the optical particle counters and humidity/temperature probes through the multichannel analyzer. Data analysis subsequent to acquisition was performed using Basic and Fortran languages. In addition, a closed-circuit TV system was used to remotely monitor precharger and collector ion current meters on the high voltage side of the circuit.

2. MicroMac Analog/Digital Converter and Electronics

The Analog Devices, Inc., MicroMac (μ -Mac) is an independent, microcomputer data measurement system (see Figure 22) that can be connected to either a terminal or a host computer. It is used mainly in the collection and transmission of data acquired from the Electron Beam Precipitator (EBP) wind tunnel. An on-board microcomputer measures and stores input data in random access memory which is continuously updated at a rate of 15 readings per second. Several analog to digital converters as well as a main processing unit that receives and executes commands comprise the architecture of the device. The MicroMac has twelve channels of input, or four channels per A/D converter, and each A/D converter

MICROCOMPUTER DATA ACQUISITION SYSTEM

Figure 22. The Microprocessor-based Data Acquisition and Analysis System showing inputs from the EBP Wind Tunnel, and Computer Peripherals.

unit can be configured to measure either voltage, current or temperature.

In the present application, the MicroMac is used to measure the voltage drops across precision resistors connected to each of the electrode plates in the particle collecting section of the EBP. This information is then sent to the host computer for analysis and storage on magnetic media. A separate program which converts the voltage reading to current is run on the host computer (an old Z-80 microprocessor). Commands from this program are sent to the MicroMac, thus automating the system to read data at different intervals of time.

Originally installed in 1982, the MicroMac and the host computer have functioned satisfactorily for a wide range of collector operating conditions. An extensive network of spark protection devices and heavy grounding strips were installed in order to minimize the effect of infrequent but periodic collector wire-plate sparkover. An electrically shielded bunker housed the MicroMac and the precision resistors to reduce the possibility of damage. Occasionally, however, during particularly energetic episodes of collector flashover, some unavoidable circuit failures would occur.

During a hiatus in the experimental run schedule, a problem developed with the MicroMac. Four of the channels serving the collector read a constant zero on the host computer. The MicroMac was tested and it was found that one of the three on-board analog to digital converters had malfunctioned. Since the converters are not repairable on-site, an order for a replacement part was sent and the new A/D converter circuit arrived from Analog Devices after five weeks. After the A/D converter was replaced, tests using a terminal only were carried out to ascertain that the system was operating normally. The MicroMac was then configured to operate with the host computer and the system was tested again. A few problems determined by this configuration resulted in a time delay

before the repaired system produced adequate results. These problems were related to the spark protection devices that act on the input signal before it is sent to the Micromac.

A schematic of the wiring layout of the MicroMac, the host computer, and the collector electrodes are shown in Figure 23. The inputs from the collector electrode plates go through a series of two spark protection circuits that are designed to shunt a high voltage pulse to ground in the event that an arc is sustained between a high voltage wire and an electrode plate in the collector. Data is then sent to the MicroMac which is directly hooked up to a host computer situated in a remote location away from the collector. The communication line between the MicroMac and the host computer consists of a 20 mA current loop instead of an RS232C interface. The reason for this is that a considerable distance (75 ft.) separates the MicroMac and host computer, and signal attenuation would occur through such a long communications line. The RS232C interface is recommended only for distances up to 50 ft.

3. RFI Countermeasures - MicroMac Current Measurement System

Currently, the MicroMac measures voltages across precision resistors (24.9Ω) that are connected in series between the electrode plates of the collector and ground potential. It samples these voltage levels at its inputs 15 times every second and constantly updates its onboard memory. The voltages are then transmitted to the host computer which converts them into current values and stores them on a disk file. The host computer is controlled by an independent program that "handshakes" with the MicroMac and requests transmission of the collected data at intervals of 5 seconds.

Previously, the MicroMac underwent repairs to replace an analog to digital converter. After reinstalling the repaired

MicroMac, adequate results were obtained while operating the collector with a high dc potential. However, when the MicroMac was operated while the precharger pulsed power supply was engaged, the RF noise generated by the pulsed power supply caused the MicroMac to temporarily fail.

The problem with the proper operation of the MicroMac collector current measuring system was attacked on several fronts. Because the prohibitive cost of a fiber optic solution was established earlier when working on the Climet system, a similar strategy of equipment grounding and power supply isolation was pursued. However, in this case, the communication lines are 20 mA optically coupled current loops. This communication link allows complete electrical isolation between the MicroMac and the host computer, but still requires long cable runs which are vulnerable to RFI interference. In addition, the MicroMac was originally located in very close proximity to the pulsed power supply.

To improve this situation, the MicroMac is currently being mounted in a completely sealed metal cabinet which will have external fittings for the power supply and communications cables. In addition, the MicroMac will be relocated to the vicinity of the downstream end of the collector. This arrangement will both greatly decrease the length of communications cables required and position the unit itself on the opposite side of the wind tunnel from the pulsed power supply. Although this work was not completed during this term, we feel that these modifications will significantly improve the overall RF rejection of the system. In addition, because the MicroMac will be in a small, thoroughly shielded, and mobile package, this should increase the general flexibility of the collector current monitoring system.

Figure 23. Circuit Layout of the MicroMac Analog-to-Digital Converter showing the connections to the Collector Plate Electrodes and the Microcomputer.

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I. Pulsed Power Supply

1. Overview

The pulsed power supply used in the Pulsed Electron Beam Precharger study was transferred from the previously described PEER project and then modified for use with the electron beam precharger. Designed and assembled at FSU, the rotating spark gap power supply shown in Figure 24 can produce pulses of approximately 80 kV amplitude, 200 ns pulse width, 20 ns rise time, and variable duration at either 120 or 60 cycles per second. It consists of an ac high voltage power supply input, current limiting resistors, high voltage rectifier network, high voltage capacitor bank, rotating spark-gap, and a duration limiting resistor which is housed in a cooling tower (Figure 25). This power supply, with minor modifications, was used to drive the pulsed streamer corona reactor for the removal of SO_2 and NO_x , where it has performed quite well in the past.

After the pulsed power supply was completed and installed, a coupling capacitor bank and current limiting resistor were mounted on the outside of the precharger near the pulsed power supply. These two devices were added to isolate the high voltage dc input from the pulsed power supply, and vice-versa, when both are driving the precharger together. This configuration is necessary in order desired to produce a pulsed voltage with a dc-bias at the anode of the precharger. Specifically, the coupling capacitor bank will serve to isolate the "tail" resistor of the pulsed power supply from the large dc offset or bias voltage, while the current limiting resistor will protect the dc power supply in the event of a short at the precharger and will also isolate it to some degree from the pulses produced by the pulsed power supply. These changes will allow the precharger to be driven by essentially three different voltage waveforms, those being 1) dc, 2) pulsed, and 3) pulsed with dc-bias.

PULSED POWER SUPPLY SCHEMATIC

Figure 24. Schematic Diagram of the Circuit Layout of the Rotating Spark Gap Pulsed Power Supply.

Pulsed Power Supply

Figure 25. Functional Diagram of the FSU Rotating Spark Gap Pulsed Power Supply.

2. Modification and Installation of Pulsed Power Supply

A test run of the electron beam precharger was attempted using the pulsed power supply instead of a dc power supply. The outcome of this initial dry run was that it exposed a potentially serious problem with the ability of the data collection systems to function properly when the rotating spark gap is operating. Systems affected by the rotating spark gap include, principally, the MicroMac analog-digital converter, the Climet CI-225 optical particle counter and CI-210 multichannel analyzer, and the microcomputer and peripherals.

The pulsed power supply produces pulses with a width of approximately 200 nsec and a rise-time of approximately 20 ns. The fast rise-time of this pulse is achieved by using a motorized double pole mechanical spark gap (Figure 25), rotating at 60 Hz, which produces an inordinate amount of RFI. Initially, the operation of this power supply at a normal voltage level of 60 kV rms caused a temporary failure of the entire data acquisition system due to induced noise generated in the signal lines. As the magnitude of this electrical noise grossly exceeded the noise tolerance level of the computer, it began to behave in an unpredictable and random manner. This behavior rendered the possibility of acquiring any meaningful data from the particle size analyzer or the precipitator current meters useless.

After meticulously separating the grounding networks of the pulsed power supply from the data acquisition system and adding EMI/RFI filtering to all of the AC power inputs, normal continuous operation of the computer was restored. However, a significant amount of ambient noise which was generated by the rotating spark gap was still causing erroneous readings from the Climet CI-225 optical particle counter to be sent to the CI-210 multichannel analyzer. The particle counter located in the accelerator vault is connected to the multichannel analyzer in the control room via a long run (60 ft) of 50 ohm impedance transmission cable. It is

this coaxial transmission line that remains the root of the problem since it acts as an antenna for the high frequency noise emanating from the pulsed power supply.

3. Faraday Cage Installation and Testing

To mitigate the effects of emitted RF noise on the Climet and MicroMac systems, it was decided that the most effective course of action would be to erect a Faraday cage around the noise source - the mechanical spark gap used to produce the pulse delivered to the precharger anode. Due to the limited space available around the power supply and the high voltages present, the size and placement of the cage was given much consideration. After consulting personnel from the Physics department's technical staff, a simple enclosure of dimensions 2 ft x 2 ft x 1 ft constructed of aluminum L-angle braces and stainless steel screen was designed and built (Figure 26). The cage completely surrounded the spark gap and was connected to earth ground with a heavy copper braid. Ceramic lead-through tubes prevented any arcing that might occur between the grounded cage and the high voltage cables leading into and away from the pulsed power supply. After installation of the cage around the spark gap, the pulsed power supply was reassembled and tested, and the computer system ground connections were checked and improved where necessary.

Testing of the system consisted of raising the potential of the pulsed power supply to 30 kV (nominally the voltage for a steady discharge across the spark gap), and checking the system for undesirable corona -- especially around and inside the cage. The pulsed supply voltage was then increased in increments of 10 kV and the system rechecked until 60 kV was attained. After safe power supply operation at 60 kV had been established, the data acquisition system was powered up and the operation of its various subsystems was checked.

Figure 26. Side View Schematic of the Rotating Spark Gap portion of the Pulsed Power Supply (top), and the Grounded Faraday Cage (bottom).

During this inspection, the following improvements were noted:

- 1) The bands of "snow" which had been observed on the CRT of the computer terminal during the preliminary tests had been eliminated;
- 2) the accurate operation of the computer was restored, and it performed operations at random as during the previous tests. In spite of these improvements, however, the Climet optical particle counter was still malfunctioning. Because of the noise induced into the data transmission line interconnecting the counting unit and the multichannel analyzer, the system "counted" particles that did not exist. To compound these difficulties, the MicroMac collector current monitoring system was still non-operational. All systems immediately returned to a normal functioning capability after the pulsed power supply was shut down.

To reduce emission production from the power supply itself, the Faraday cage surrounding the rotating spark gap 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. radiation problems, most of which stem from the relatively long cable runs between pulser components.

A great deal has been learned about the behavior of pulsed power supplies from working with the present system. With this increased understanding, it became apparent that the only permanent, long term solution to the noise problem was a complete redesign of the pulsed power supply. However, for the pulsed precharging experiments accomplished during this contract period, the previously described absolute filter holder worked very well as the chief particle concentration monitor in the presence of high voltage pulsing.

III. HIGH AEROSOL CONCENTRATION DC E-BEAM PRECHARGING EXPERIMENTS

A. Introduction and Overview

Electron beam precharging of a high resistivity aerosol was successfully performed under a range of experimental conditions during the contract. The initial E-beam particle precharging experiments completed 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 the current contract 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.

The initial sequence of electron beam precharging experiments which were performed during the contract are detailed in the following sections. This portion of the Final Report contains subsections on 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.

B. Electron Beam Precipitator - Review of Systems

The Electron Beam Precipitator (EBP) is basically an instrumented wind tunnel in the form of a closed circuit loop of ductwork (Figure 1). 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 ($1.0\text{ }\mu\text{m}$ 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 (Figure 2) 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.

F.S.U. ELECTRON BEAM PRECIPITATOR TEST SYSTEM

Figure 2. Top View of the Mk. III-B Electron Beam Precharging Module showing the Ionization and Charging Zones.

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 3) 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

Figure 3. Detail of the Collecting Module showing the six Corona Wire and Collector Plate Assemblies.

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 diam.
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 1. 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. 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

Table 1.

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	-	-

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. Electron Beam Precharging Experiments Using DC Power

1. 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 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 $0.0114 \text{ grain/ft}^3$. The original target goal of 1 grain/ft^3 was unattainable in the present experiments due to particle monitor limitations. However, the dust concentration resuspended into the wind tunnel for the

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

three experiments presented here is almost three times higher than the dust concentration in any previous experiment.

2. 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 velocity 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 2), 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. 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 Section IV. Theoretical saturation charge and predicted charge calculations were also performed to compare to the experimental particle charge data.

3. Calculation of Collection Efficiency and α -Value

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 0.8 ft/sec while precharger gas velocity was 3.2 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

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	-	-	-	-	-	-

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 μ A beam current) and the precharger anode was energized (55 kV voltage, 3.7 kV/cm electric field, 40 μ A 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 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 -

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.

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 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 .

4. 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 -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:

$$\omega = \frac{2 \epsilon_0 E_0 E_p a}{\eta_g}$$

where:

ω	=	theoretical migration velocity
ϵ	=	permittivity of free space
E_0	=	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.

5. 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 (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.

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

6. Summary of DC E-Beam 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 contract period. These results will be presented in Section V.

IV. PARTICLE CHARGE VS. RADIUS RATIO (Q/A) -- THEORY AND EXPERIMENTS (DC PRECHARGER)

A. Introduction and Overview

The previous report section demonstrated that the charging and removal of a fine, high resistivity aerosol using the advanced technology of electron beam precipitation has been successfully accomplished. Precharging a dust stream circulating through the EBP wind tunnel produced collection efficiency figures of up to 40 times greater than with corona charging and collection alone. 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 became greater. In sequence, saturation particle charge varies with the precharger electric field strength, particle 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).

Because increased particle collection efficiency is directly attributable to higher particle charge, during the middle part of the contract period the focus of research was shifted to learning more about the actual charge magnitude on the aerosol particles. Charge determinations in precipitators have traditionally been made on bulk dust samples collected from the flue gas stream, which gives an overall charge vs. mass (Q/M) ratio measurement. More recently, techniques have been developed which allow the measurement of the charge on individual particles in a rapid and

repeatable fashion. One such advanced technique has been developed at FSU for use in characterizing the electron beam precharger.

The FSU particle charge vs. radius (Q/A) apparatus is based in principal on the old Millikan oil drop physics experiment in which the charge of an electron is found using fine particles suspended in an electric field. This unique device has the advantage of being able to directly measure the charge on many individual particles in a short period of time. The Q/A apparatus was frequently operated in conjunction with the particle collection efficiency experiments, and the particle charge data was compared with theoretical values in order to assess the charging effectiveness of the electron beam precharger.

A detailed summary of the particle charge vs. radius investigations is presented in the following sections. Included is a description of the general experimental methods, chemical and physical properties of the test aerosol, the Q/A ratio measurement device, 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 the pulsed precharging experiments, great care was taken to insure the constancy and compatibility of all of the run parameters.

B. Experimental Apparatus

1. EBP Test System

The experimental apparatus and methods used in the previous high aerosol concentration electron beam precharging runs described in Section III were repeated for the particle charge vs. radius experiments. Air at room temperature and 40% relative humidity was circulated in the FSU Electron Beam Precipitator (EBP) wind tunnel (Figure 1) at a gas volume of $1.0 \text{ ft}^3/\text{s}$ (velocity = 4.0 ft/s). 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. Electron beam particle precharging was tested initially using hydrated alumina, or Hydral (Table 1). This $1.0 \text{ }\mu\text{m}$ diameter monodisperse dust has chemical and physical properties similar to common alumina powder. 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 2), 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. The sampling nozzle for the particle charge vs. radius apparatus is located immediately downstream from the precharger outlet. 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 two sampling tubes, one leading to the Climet optical particle counter and dilution system, and the other to the bulk dust absolute filter holder. Electronic signals

F.S.U. ELECTRON BEAM PRECIPITATOR TEST SYSTEM

Figure 1. The FSU Two-Stage Electron Beam Precipitator (EBP) Wind Tunnel.

Table 1.

Mk. III ELECTRON BEAM PRECHARGER HIGH CONCENTRATION EXPERIMENTS

Hydral (Hydrated Alumina)

1. Chemical Formula	:	$\text{Al}_2\text{O}_3 \cdot 3 \text{H}_2\text{O}$
2. Density	:	2.40 g/cm^3
3. Resistivity	:	$> 10^{12} \Omega\text{-cm}$

4. Particle Size Distribution

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

Fly Ash

1. Chemical Composition	:	Al_2O_3 , SiO_2 , principally
2. Density	:	$\sim 2.5 \text{ g/cm}^3$
3. Resistivity	:	$\sim 10^{11} \Omega\text{-cm}$
4. Particle Size Distribution	:	Polydisperse

Aerosol Concentration

0.01 - 0.1 gr/ft³

Figure 2. Top View of the Mk. III-B Electron Beam Precharging Module Showing the Ionization and Charging Zones.

from all of the monitoring devices were subsequently sent to a microcomputer-based data acquisition system for on-line analysis and eventual storage.

The Climet optical particle counter was used in some of the earlier tests using dc-only energization of the precharger electrodes (see Section III). For the present experimental runs focusing on the determination of particle charge vs. radius, and for the future runs using pulsed power, however, the optical particle counter was abandoned in favor of a non-electronic, bulk dust filtering system (Figure 3) 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.

2. Charge vs. Radius Ratio Measurement Device

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 should be collected with greater efficiency. Particle charge vs. radius (Q/A) measurements were made using the unique laser-oscillating field Q/A apparatus which was developed several years ago at FSU. The principles of design and operation of this unique device are described in the following paragraphs.

The charge vs. radius measurement apparatus (Figure 4) is based on a highly modified Millikan Oil Drop apparatus used to measure particle size and charge in an airborne medium. In operation, a precharged aerosol sample is drawn from the wind tunnel using a nozzle and then introduced into the Q/A device. Particle charge and radius measurements are made possible by making video recordings of the laser-illuminated particles as they are

Figure 3. The Absolute Filter Holder Bulk Dust Aerosol Sampler used to monitor Aerosol Concentration when the Pulsed Power Supply is operating.

F.S.U. Charge / Radius Measurement System

Figure 4. The FSU Charge-to-Radius (q/a) Measurement System; detail shows the Particle Charge Measurement Cell, the Laser and Mirror, and the Video Viewing/Recording System.

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. Using the magnitude of particle oscillation and also the rate of fall of the particles in a series of 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.

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 introduced into the Q/A cell and then individual particles were tested for charge and mass. Approximately five repeat cell samples were measured at each different parametric condition. The data was analyzed and is presented as a series of particles having varying radii and charge levels.

C. General Experimental Procedures

Experimental procedures for making a complete particle charge and collection efficiency run are as follows. Normally one parameter was varied while the others were held constant. Each run consisted of several steps which compared the EBP system collection efficiency with just the collector operating to the collection efficiency with both the precharger and collector operating. For each step, a sampling period using the absolute filter holder and pumping train lasted 900 seconds (15 minutes). Particle mass information was 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.

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. In addition to the individual particle charge vs. radius determinations, a concurrent measurement of the total particle mass for each sampling period provided a quantitative indication of how well the system was performing at the optimum level of each tested parameter.

Runs were performed using Hydral test dust at moderately high concentrations with a dc electric field only (no pulsed power) applied to the precharger electrodes, while the electron beam itself was also operated in the dc continuous mode. Periodic samples were withdrawn from the wind tunnel just downstream from the precharger, and charge vs. radius (Q/A) measurements were made to correlate particle charge with particle collection efficiency. Theoretical saturation charge and predicted charge calculations were also performed to compare to the experimental particle charge data.

General run conditions were as follows:

1. Gas Composition : Air
2. Gas Temperature & Humidity: 25°C, 40% RH
3. Prech. Volume & Velocity : 1.0 ft³/s, 4.0 ft/s
4. Test Dust Type and Size : Hydral, 1.0 µm mean diameter
5. Fluidized Bed Flow : 0.12 ft³/s
6. Screw Feeder Setting : 100
7. Filter Sampler Flow : 3.75 SCFH = isokinetic
8. Sample Time : 15 minutes (900 seconds) .

D. Computation of Saturation and Predicted Particle Charge

Concurrent with the experimental work on particle Q/A ratios, calculations were made of the theoretical charge on 1.0 μm diameter Hydral particles for several electron beam precharger electric field values (Table 2). The parameters employed in the theoretical calculations corresponded to conditions used in actual experimental runs. During preliminary runs, parameter values were chosen which were found 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 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 2, 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 Pauthenier 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 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 limit. When the precharger gas velocity is increased above zero, less time is available for a particle to be charged to the maximum level. The relation of saturation charge and time is governed by the charging time constant equation:

$$q(t) = q(\infty) \frac{t/\tau}{1 + t/\tau}$$

where:

$q(t)$	=	particle charge at time t
$q(\infty)$	=	saturation particle charge
t	=	residence time in the charging zone
τ	=	charging time constant.

According to the above relation, as residence time approaches infinity, particle charge will asymptotically approach the saturation limit.

Table 2.

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

For the present example, a gas velocity of 4.0 ft/s corresponded to a particle residence time in the precharger of 250 ms. The predicted charge on a particle passing through the charging zone for this time interval was calculated and compared to the saturation charge at infinite residence time. The average ion current density (J) was held constant at 1.25 mA/m^2 . Predicted particle charge varied from $2.55 \times 10^{-17} \text{ C}$ (159 electronic charges) to $3.51 \times 10^{-17} \text{ C}$ (219 e) as the electric field was increased from 3.93 kV/cm to 5.50 kV/cm. These charge values are close to the theoretical saturation charge levels for infinite residence time, ranging from 95.5 % of the saturation charge limit at 55 kV anode voltage, to 94.4 % of the limit at 77 kV voltage.

From earlier studies using low concentrations of $1.0 \text{ }\mu\text{m}$ diameter polystyrene latex spheres, charging particles to within 5 % of the saturation charge limit for a given current density results in very high particle collection 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 would then be a significantly degraded system particle collection efficiency.

E. 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 $1.0\text{ }\mu\text{m}$ mean diameter Hydral dust was generated and re-dispersed at moderately high density into the EBP wind tunnel. Gas velocity was 1.0 ft/s in the wind tunnel duct and 4.0 ft/s in the precharging module. The MINACC electron beam source was operated at a beam energy and current of 90 keV and $2\text{ }\mu\text{A}$, 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 $40\text{ }\mu\text{A}$, or 1.25 mA/m^2 .

Figures 5 and 6 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 ($1.0\text{ }\mu\text{m}$ diameter, $\pm$ approximately $0.5\text{ }\mu\text{m}$), most of the data should fall near the $1.0\text{ }\mu\text{m}$ 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. The test aerosol being generated and circulated through the precharging module is not perfectly monodisperse. This causes measured "particles" of up to almost $2\text{ }\mu\text{m}$ diameter to show up in the experimental data. Each

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

Figure 5. Plot 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 6. Plot of Particle Charge in Number of Electronic Charges vs. Particle Diameter in Micrometers for Hydral Aerosol at a Precharger Voltage of 77 kV.

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 5), 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 μm nominal diameter (+ 0.5 μm - 0.25 μm) 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 charging performance for the particular conditions.

Particle charging efficiency deteriorated when the precharger voltage was raised to 77 kV (5.5 kV/cm electric field). Figure 6 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, reduced monopolar particle charging is occurring in the precharger. The 16 % 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 when operated 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 amount of positive charge overcomes and degrades 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 Section VI.

F. Summary of DC Particle Charge vs. Radius Investigation

A thorough investigation has been made of the charge vs. radius ratio of particles exiting the electron beam precharger. Particle samples were withdrawn from the EBP wind tunnel operating at conditions similar to those found in the particle collection efficiency experiments reported in Section III. 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 fluidized bed portion of the dust feeder apparatus. As earlier described, for these experiments an absolute filter holder replaced the Climet as the primary particle monitoring device, allowing higher than previous concentrations of aerosol to be tested.

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 limit 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. Theoretical saturation and predicted particle charge levels were calculated for a number of parametric conditions corresponding to many of the experiments run both previously and specifically for this study.

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 in the enclosed chamber.

Experimental and theoretical particle charge values were determined for precharger gas velocities of zero (infinite residence time) and 4.0 ft/s (250 ms residence time) at various precharger anode voltages. The predicted charge at 4.0 ft/s is approximately 95% of the saturation charge limit, meaning that at realistic duct gas velocities, particles passing through the precharger should have the potential 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 spurious positive ions in the charging zone (which normally should be completely negatively monopolar).

V. PULSED ANODE ELECTRON BEAM PARTICLE PRECHARGING

A. Introduction and Summary

The latter half of the contract research effort was principally devoted to the operation of the E-beam precharger in the pulsed anode mode. We shall first briefly review the motivation for carrying out this phase of the electron beam precharging project and the experimental approach used.

The combustion of low sulfur coal for the purpose of generating electric energy in power plants results in the production of a flue gas containing very high resistivity fly ash. This fly ash is not easily collected by conventional electrostatic precipitators due to the large electric potential difference which develops across the layer of fly ash on the collector plate. If this layer of collected material is allowed to reach a thickness as great as is normally desirable before "rapping" the plates, then the collected fly ash is subject to re-entrainment into the flue gas stream due to back-corona. The re-entrainment problem which results from the presence of back-corona can be eliminated through the reduction of the voltage applied across the high voltage wires and the grounded plates of the electrostatic precipitator. This is not a good solution to the problem since the charging capability and collection efficiency of the precipitator system are both greatly reduced at the low voltages required to avoid the back-corona problem. The mechanics of back-corona are described more fully in the next section of this report.

Another approach to solving the problems inherent in collecting high resistivity fly ash in electrostatic precipitators is to decouple the charging and collecting functions. At FSU, an electron beam precharger is employed directly before (upstream in

the flue gas pathway) the precipitator collecting section. This precharger can be optimized for the charging function while the downstream collector can be optimized for removal of the high-resistivity fly ash. The characteristics of the Mk. III electron beam precharger have been investigated in a prior phase of this research (see Sections III and IV). In this previous work, electrons from an ionization zone created by the electron beam accelerator were drawn out into a charging zone across the flue gas stream by the application of a constant high potential. The maximum voltage was limited by the onset of sparking or the production of opposite sign ions in the precharger.

Numerous studies using a dc electric potential on the anode have shown that the precharger approach was an excellent solution to the back-corona problem. The results of this research suggested that even better results should be obtainable provided that the precharger anode potential could be raised above the sparking potential limit. Since it has long been known that short duration electric potentials exceeding the onset of sparking can be applied to gaseous mediums without the initiation of spark production, the present research with pulsed anode potentials of short duration (ca. 200 ns) was undertaken. The present research using pulsed anode potentials has been highly successful, and we believe that this success is due to the formation of streamers in the gas stream during the high voltage potential pulse.

Although the present research has not been concerned with the removal of sulfur dioxide from the flue gas stream, it is likely that the streamers created in the pulsed electron beam precharging process would convert this gas phase pollutant to sulfides in a condensible vapor form. These condensible products would tend to collect on the fly ash particles and be removed concurrently with the fly ash in the collecting section. The deposited sulfides would reduce the resistivity of the fly ash layer on the collector plates, thereby further reducing the back-corona problem. Sulfur dioxide removal efficiency of the pulsed electron beam precharger

has not be investigated in the present research, but should certainly be addressed in a future research program. We are very excited about the possibilities inherent in such an investigation.

B. Advantages of Precharging with Pulsed Electric Fields

Pulsing the charging electric field will raise the electric field charging limit in the electron beam precharger. The maximum electric field obtainable through pulsing can be substantially greater than the dc breakdown electric field if the pulse duration is sufficiently short (less than approximately 1 μ sec). In producing a higher electric field, pulsing increases the theoretical saturation particle charge limit for the ionic field charging regime. Particle charge varies with the electric field for a given particle radius and dielectric constant. Concurrently, the electron temperature during the pulse will be greater so that electron attachment and retention of attachment are decreased. This results in the major benefit of free electron charging, which, added to the already improved ionic charging potential, makes pulsed electric field particle charging an even greater advantage.

An increase in the ionic space charge is also expected, which will further increase the electric field. Space charge enhancement of the charging electric field occurs in conventional precipitators, but this effect will be magnified in the electron beam precharger because of the much larger population of charge species in both the ionization and charging zones. The presence of a dc-bias voltage in the presence of a pulsed electric field will sustain this space charge enhancement. The end result of pulsing the charging electric field and increasing the particle charge will be a greater collection efficiency for the two-stage precharger/electrostatic precipitator combination.

To summarize, a pulsed electric field has distinct advantages over a dc-only electric field for the purpose of particle charging in an electron beam precharger. These include 1) a higher charging electric field, 2) an increased ionic space charge and greater space charge enhanced electric field, 3) the added component of free electron charging which is superior to ionic charging, 4) a

more even distribution of the charging ion species in the presence of a dc-bias electric field, and 5) avoidance of back corona in the precharger, since the very short pulses are terminated before back corona can set in. The present work concentrating on pulsing the charging electric field will serve as a basis for assessing the possibility of pulsing the electron beam itself. Coordinated pulsing of both the anode electric field and the E-beam may produce the ultimate in precharging performance.

C. Rotating Spark Gap Pulsed Power Supply

The main objective of this contract is to test the particle collection efficiency of the existing precharger and precipitator system with a pulsed rather than a dc voltage applied to the precharger. One of the first steps taken toward the initiation of this work was the modification of the existing precharger setup so that it can be driven not only by its existing dc power supply, but by a pulsed power supply as well.

To install the pulsed power supply, a 3 x 4 foot platform was constructed in the middle of the precipitator test loop. This location was chosen because of its close proximity to the precharger, its safety, and its convenience. Bracing was first installed by adding iron cross-members to the ductwork structure across one end of the wind tunnel. These new cross-members support a table top of 1/2 inch thick plywood covered with 3/8 inch thick PVC sheet acting as an insulator.

The pulsed power supply installed on the platform was transferred from the previously described PEER project and then modified for use with the electron beam precharger. Designed and assembled at FSU, the rotating spark gap power supply shown in Figure 1 can produce pulses of approximately 80 kV peak amplitude, 200 ns pulse width, 20 ns rise time, and variable duration at either 120 or 60 cycles per second. It consists of a current limiting resistor, high voltage rectifier network, high voltage capacitor bank, rotating spark-gap, and a duration limiting resistor which is housed in a cooling tower (Figure 2). This power supply, with minor modifications, was used to drive the pulsed streamer corona reactor for the removal of SO₂ and NO_x, where it has performed quite well in the past.

After the pulsed power supply was completed and installed, a coupling capacitor bank and current limiting resistor were mounted

PULSED POWER SUPPLY SCHEMATIC

Figure 1. Schematic Circuit Diagram of the Pulsed Power Supply, showing Resistors (R), Capacitors (C), and Diodes (D).

Pulsed Power Supply

Figure 2. Functional Layout of the Rotating Spark Gap Pulsed Power Supply.

on the outside of the precharger near the pulsed power supply. These two devices were added to isolate the high voltage dc input from the pulsed power supply, and vice-versa, when both are driving the precharger together. This configuration is necessary in order desired to produce a pulsed voltage with a dc-bias at the anode of the precharger. Specifically, the coupling capacitor bank will serve to isolate the "tail" resistor of the pulsed power supply from the large dc offset or bias voltage, while the current limiting resistor will protect the dc power supply in the event of a short at the precharger and will also isolate it to some degree from the pulsed produced by the pulsed power supply. These changes will allow the precharger to be driven by essentially three different voltage waveforms, those being 1) dc, 2) pulsed, and 3) pulsed with dc- bias.

D. Experimental Rationale and Procedures

The present phase of the Electron Beam Precharger Project is devoted to determining whether any advantage accrues to pulsing the positive anode potential of the precharger, and the motivation for undertaking such an experimental study of anode pulsing has been previously discussed. In proposing this study it was anticipated that the anode voltage could be increased above the dc sparking potential for a short time (200 ns or so), but that in order to gain an advantage over dc operation of the anode it would be necessary to provide many pulses per second. For this reason, it was originally proposed to run the pulsed precharger at several frequencies provided we had the time and resources to do this at the end of the project.

Pulsed anode operation of the precharger was found to be much more effective than was originally anticipated in the proposal. Therefore, it turned out not to be necessary to operate the pulsed anode at a frequency higher than that available from the normal ac utility line (60 Hz). A duty cycle of the anode pulses (fraction of the time the anode was 'on' during each second) of only 0.0012% was determined to be adequate (200 ns pulse width, 60 Hz frequency). It was also found that pulsing the anode was ineffective in the absence of a small dc-bias voltage, however. These matters are discussed further, below.

Before the anode pulsing experiments were undertaken, several improvements were made to the pulsed power supply, precharging module, and associated equipment. These upgrades have been discussed in detail in Section II. Some experiments with the new precharging configuration where the anode was operated at a dc electric potential were carried out during this contract in connection with these improvements, and these results are also been presented in Section III.

One serious problem was immediately encountered when particle charge and collection efficiency measurements using pulsed power on the precharger anode were attempted. The rotating spark gap pulsed power supply (Figure 2) was found to produce a great deal of radio frequency electromagnetic emissions which interfered with the data acquisition and analysis system electronics. A great deal of effort was made over a considerable period of time to electrically shield the pulsed power supply and provide an optimum network of earth grounds between the various electronic devices of the data accumulation system. It was possible to operate the apparatus which performed the charge vs. radius measurements after the shielding and grounding modifications were made. However, the Climet optical particle counter could not be operated even after all the grounding and shielding precautions had been taken.

An alternative method was implemented whereby a nozzle was inserted into the ductwork at the exit of the collector, and an aerosol sample was drawn into an absolute filter holder containing a paper filter. A series of filters was weighed before, during, and after a run to determine the aerosol transmission through the precharger-collector system. This new method of determining the aerosol concentration was checked by comparing the results obtained in this way with results obtained under the same experimental conditions using the Climet optical particle counter. Good agreement was obtained.

A description of the Electron Beam Precipitator wind tunnel (Figure 3) and the in-depth experimental procedures used to execute a precharging test run will not be repeated here. Please refer to Sections II and III-B for details of the general arrangement and modifications made to the experimental apparatus in order to carry out the pulsed electron beam precharging experiments described here. Sections II-G and IV-B contain information regarding the charge vs. radius device and its operation.

F.S.U. ELECTRON BEAM PRECIPITATOR TEST SYSTEM

Figure 3. The FSU Two-Stage Electron Beam Precipitator (EBP) Wind Tunnel.

The experimental results obtained using pulsed anode power are discussed in the following subsections. First, the pulsed power measurements of the collection efficiency and improvement factor are described in Section E, and a description of the corresponding charge vs. radius experiments follows in Section F. A summary statement and the conclusions are presented in Section G.

E. Particle Collection Efficiency Measurements Using Pulsed Anode

A comparison has been made of several pulsed precharger anode runs (with and without a dc-bias) with runs during which the anode was maintained at a constant potential. The experimental results presented in Table 1 serve as representative examples of a larger body of data investigating pulsed electron beam precharging of fine, high resistivity aerosol powders. The constants at the top of the table are the experimental parameters common to all of the experiments in Table 1.

First, consider the results with the precharger turned off and the collector (electrostatic precipitator) operated at 4 kV/cm (please refer to the top entry of each run listed in Table 1). This electric field strength is appropriate for collecting high resistivity fly ash while producing a minimum of back-corona. In this case the only charging of the particles before passing into the collector is due to incidental frictional charging in the fluidized bed and gas stream ductwork. Collection efficiencies of approximately 90% were obtained. The efficiencies vary somewhat between the four different runs which were carried out on different days, with the values varying from 86.1% to 93.2%. These differences are attributed to the fact that 1) there is always some uncontrolled variation in the frictional charging (see Section F) in the gas stream prior to its entry into the collector, and 2) there is turbulent mixing of the aerosol in the ductwork. The frictional charging is uncontrolled insofar as we do not fully understand the details of its origin.

Looking next at the pulsed anode results with no dc-bias voltage applied (Table 1, Runs B-30, B-60 and B-100) which carry the label "pp" in the precharger voltage column to indicate pulsed power, one can see that the particle collection efficiencies are much less than those in which the precharger is not energized at all (top entry with no label). This trend holds for both Hydral

Table 1. Results from experimental runs measuring the collection efficiency and precharger efficiency improvement factor. The improvement factor is listed in the last column and is designated by the symbol α . The first row for each run in the table gives the collection efficiency obtained when the precharger was not energized. The constants listed immediately below apply to all the experiments except that the electron beam current and electron beam voltage were zero for the first row of each run. The data listed are those obtained in the dc, pulsed, and pulsed-with-dc-bias modes of operation of the precharger. References in the text to runs listed in this table are made using a subrun suffix. For example, run B-100-5 refers to the fifth subrun (row) of run B-100, which is 66 kV pulses superimposed on a 20 kV dc bias.

Constants:

Gas Velocity	3.2 ft/s
Collector Electric Field	4.0 kV/cm
Collector Ion Current	30 μ A
Electron Beam Voltage	90 keV
Electron Beam Current	2.0 μ A

Run Number	Comparison (Test Dust)	Precharger Voltage (kV)	Precharger E-Field (kV/cm)	Precharger Ion Current (μ A)	Collection Efficiency (%)	α -Value (Collector + Precharger)
A-430	dc-only (Hydral)	--	--	--	86.1	--
		55 dc	3.9	40	98.3	8.2
		66 dc	4.7	41	98.7	10.4
B-30	Pulse Voltage (Hydral)	--	--	--	89.8	--
		60 pp	4.3	3 rms	48.8	< 1
		70 pp	5.0	4 rms	57.8	< 1
		70 pp, 20 dc	6.4	21 rms	96.2	2.7
B-60	dc vs. Pulsed (Hydral)	--	--	--	93.2	--
		66 dc	4.7	30	99.3	9.7
		66 pp	4.7	4 rms	53.5	< 1
		66 pp, 10 dc	5.5	6 rms	96.2	1.8
		66 pp, 20 dc	6.2	8 rms	99.5	14.0
B-100	dc vs. Pulsed (Fly Ash)	--	--	--	88.2	--
		66 dc	4.7	20	97.8	5.5
		66 pp	4.7	4	61.4	< 1
		66 pp, 10 dc	5.5	6	97.4	4.5
		66 pp, 20 dc	6.3	8	99.4	21.1

and fly ash test aerosols. The collection efficiencies are only about 50% to 60% in the pulsed-only situation, compared with an efficiency of about 90% for the precharger-off condition. Aerosol particles are being charged in the E-beam precharger in the pulsed voltage-only situation (see Section F), but it is believed that about equal numbers of particles are being given positive and negative charges. Obviously, positively charged aerosol particles are highly unlikely to be collected in the negatively-biased electrostatic precipitator, and therefore the collection efficiency falls off drastically with the application of pulsed-only precharger voltage.

Now addressing the results for operation of the precharger anode at a dc-only electric potential, which are indicated with the label "dc" in the precharger voltage column of Table 1, it can be seen that the results are comparable with the results given in the final report of the previous project (DOE Contract Number DE-AC22-86PC91021) entitled "Flue Gas Cleanup Technology Using Energetic Electrons". The precharger, collector, and wind tunnel system used for the present dc E-beam precharging experiments is nearly identical to the apparatus in those earlier experiments. The only minor differences between the two complements of experimental apparatus are slight modifications to the electrode configuration, and the fact that the Climet particle counter which was used in the earlier experiments is not used here due to the presence of RF interference during anode pulsing. The replacement time-averaged filter weighing technique used here to determine the collection efficiency is subject to greater random error than the Climet optical particle counter real-time technique, and this accounts for the slight discrepancy between the present results and the results reported earlier. The run-to-run reproducibility of measurements reported here is not quite as good here as it was in the earlier experiments for the same reason (see, e.g., the collection efficiency for the 66 kV dc condition during runs A-430 and B-60 in Table 1, each of which were made on different days).

Consider next the E-beam precharger runs made with a positive dc-bias voltage applied simultaneously with a pulsed voltage to the anode. These measurements were made using a small dc-bias of only 10 kV or 20 kV along with positive anode pulses of 66 to 70 kV. Runs B-60 and B-100 (Table 1) for Hydral dust and fly ash, respectively, show that the particle collection efficiencies obtained using 66 kV peak pulses superimposed upon a 20 kV dc-bias are better than those obtained using 66 kV dc-alone. This is an impressive result in view of the fact that full voltage is applied to the anode only 0.0012% of the time, and only when in the pulsed mode. Power consumption in the precharger is thereby reduced by approximately a factor of three in the pulsed mode as compared to the dc mode.

Section VI, Discussion and Analysis, of this contract Final Report will be devoted to a discussion of possible microscopic (i.e., atomic and molecular) processes which could explain these experimental results for the experimental case of the pulsed anode with a dc-bias. It is clear that particle charging is so rapid in this situation that the standard theoretical model previously used to interpret the dc-only precharging data is inadequate.

F. Pulsed Voltage Particle Charge vs. Radius (Q/A) Experiments

In order to ascertain the underlying reason for the high particle collection efficiencies attributed to the pulsed with dc-bias voltage condition in the precharger, particle charge vs. radius measurements were again made concurrently with the pulsed precharger collection efficiency runs. Experimental apparatus and run conditions were identical to those outlined in Section V for the case of the dc precharger. As before, the empirically determined charge vs. radius ratios obtained during pulsed E-beam precharging were compared with the theoretical saturation particle charge level and the predicted charge level for the same set of experimental conditions.

Table 2 lists seven representative pulsed anode charge vs. radius runs and the corresponding experimental conditions. This table also lists the number of the figure which exhibits the data in graphical form for each run. In these cases, particle diameter is displayed on the abscissa of the graphs instead of radius. The aerosol samples for the charge vs. radius measurements in all of the following cases were taken directly from the gas stream exiting the precharger. The collector is also energized at an electric field of 4.0 kV/cm in all cases except the first.

Table 2.

Listing of dc and pulsed voltage charge vs. diameter experimental runs.

Run No.	Collector Voltage (kV/cm)	Precharger dc-Bias Voltage (kV)	Precharger Pulsed Voltage (kV)	Figure No.
1	0	0	0	1
2	4	66	0	2
3	4	0	60	3
4	4	0	66	4
5	4	0	70	5
6	4	10	66	6
7	4	20	66	7

Figure 4 shows the charge vs. particle diameter measurements for the case of the precharger not in operation, i.e., both the electron beam and anode potential are turned off (as stated earlier, the collector is also off in this example). The fine, high resistivity test aerosol is incidentally frictionally charged in the fluidized bed dust feeder and the wind tunnel. The Hydral particles are monodisperse, that is to say all the particles have approximately the same diameter ($1.0 \pm 0.5 \mu\text{m}$). The fact that particles of various diameters were measured in the dust samples (which shows up as a wider spread on the graph abscissa) results from the situation where two or more Hydral particles clump together to form a composite particle of a greater effective diameter. Note that these diameters are "quantized" as a result of clumping, that is to say particles are found only at certain distinct effective diameters.

Figure 4. Charge-vs-diameter measurements for the case of both the precharger electron beam and precharger electric field turned off. The measured charge observed results from frictional charging in the fluidized bed particle feeder and in the gas stream. The closed circles are data points for composite hydal particles. Although the particles are monodisperse with a diameter of approximately 1μ , composite particles are formed in the gas stream due to clumping. The straight line is a best fit for the data, and serves mainly as a guide to the eye. In this figure and the those that follow, the scatter in the data points is not due to experimental error, but is due to the statistical nature of the charging process. Averaging the charge of the particles found at each diameter eliminates much of the scatter, but the present form is preferred because it exhibits the maximum amount of information.

Figure 5 gives the charge vs. particle diameter measurements for the case of the precharger operated at 66 kV dc and the collector energized at a standard 4.0 kV/cm. This is the situation which was found to produce the most efficient dc precharging in the earlier contract research, and the present results are consistent with those obtained in that previous work.

Figures 6, 7, and 8 give the charge vs. particle diameter measurements for purely pulsed operation of the precharger anode with no applied dc-bias; the peak voltages of the pulses are 60 kV, 66 kV and 70 kV, respectively. Comparing the 66 kV pulsed run of Figure 7 with the 66 kV dc run of Figure 5 shows that particle charging in the pulsed case is only slightly greater than one-half that obtained in the dc case. This may seem strange in light of the collection efficiency data listed in Table 1 for the collection of Hydral in the two cases. The collection efficiency for the anode operated at 66 kV dc is 99.3% while for a 66 kV pulsed anode it is only 53.5%. The difference in collection efficiency is much greater than that which should be expected from the above comparison of the the charging data.

There is a simple explanation for this seeming incongruity, however: the charge vs. radius apparatus does not measure the sign of the charge on the aerosol particles. Since the electrostatic collector is operated in a polarity appropriate to the collection of negatively charged particles, it can be immediately seen that purely pulsed operation of the precharger is not producing monopolar charging of the aerosol particles. A collector electrical configuration that is appropriate to the collection of particles having mixed charge polarities would be one with parallel plates oppositely charged. Given this type of collector also having a small ion current for particle retention, it may be true that pure pulsing of the anode is a useful way to operate the precharger. Only the wire-to-plate geometry has been used in the present electrostatic collector (plates "positively" charged), and it was found that pure pulsing (with no dc-bias) is not a useful

Figure 5. Charge-vs-diameter measurements for the case of the precharger operating with a potential of 66 kV dc applied between the anode and cathode. The solid points are the experimental points for individual composite Hydral particles. See the caption of Figure 1 for an explanation of the scatter. The time required for an element of the gas stream to be transported through the precharger is 156 ms. The reason the experimental values fall below the theoretical curve is probably due to the fact that the theoretical model fails to take into account the reduction of electric field in the charging region due to space charge. The straight line fitted to the data is intended only as a guide to the eye.

Figure 6. Charge-vs-diameter measurements for the case of the precharger operating with 60 kV positive pulses applied between the anode and cathode. The temporal length of each pulse is approximately 200 ns. The closed circles are the experimental points. See the caption of Figure 1 for an explanation of the scatter. The straight line fitted to the data is intended only as a guide to the eye. The theoretical curves shown do not apply to the pulsed case but are rather for dc charging; they are shown merely for reference.. A theory of the pulsed case has not yet been formulated.

Figure 7. Same as Figure 3 except that 66 kV anode pulses are employed.

Figure 8. Same as Figure 3 except that 70 kV anode pulses are employed.

mode in which to operate the electron beam precharger in conjunction with a collector of this type.

Figures 9 and 10 give the charge vs. diameter measurements in the case of a pulsed anode with a dc-bias. Figure 9 shows the data for the situation of a 10 kV dc anode bias while Figure 10 gives the data for a 20 kV dc anode bias. The pulsed voltage is 66 kV in each case. When allowance is made for the different scales of the ordinates on the plots, it is seen that 66 kV dc operation of the anode (Figure 5) gives approximately the same charging as is obtained with a 20 kV dc-bias along with 66 kV pulsing (Figure 10) on the anode. However, much lower power consumption results from using 66 kV pulsed power with a 20 kV dc-bias compared to 66 kV dc, for the same approximate collection efficiency. As stated earlier, the pulse is only "on" for a very small fraction of the time, resulting in a great improvement in electrical consumption. Pulsing the precharger anode therefore gives an economic advantage over normal dc precharging. Reduction of the dc-bias to 10 kV gives reduced charging (Figure 9) and thus lower collection efficiency (Table 1).

It should be emphasized again that the best collection efficiency results to date for the electron beam precharger/electrostatic collector combination were obtained with 66 kV pulsed power along with 20 kV dc-bias on the anode, and it should be pointed out that the power consumption is greatly reduced in comparison with the use of pure dc power in the precharger. Operation of the precharger with only 20 kV dc-bias eliminates the chance of back-corona and sparking, and makes for a more stable operation. These matters will be discussed further in Section VI, Discussion and Analysis.

Figure 9. Charge-vs-diameter measurements for the case of the precharger operating with 66 kV positive pulses and 10 kV positive dc bias applied between the precharger anode and cathode. The duration of each pulse was approximately 200 ns, and the repetition rate was 60-Hz. The closed circles are the experimental points. See the caption of Figure 1 for an explanation of the scatter. The straight line fitted to the data is intended only as a guide to the eye. The theoretical curves shown (squares and triangles) do not apply to the pulsed-plus-dc-bias case but are rather for dc charging; they are shown merely for reference. A detailed microscopic theory of the pulsed-plus-dc-bias case at overvoltage has not yet been formulated.

Figure 10. Same as Figure 6 except that the dc bias is 20 kV.

G. Summary Statement and Conclusion

Pulsing the anode electrode of an electron beam precharger gives excellent particle collection efficiency results provided that a small dc-bias of approximately 20 kV is maintained on the anode. Some dc-bias voltage is needed to maintain the separation of ionic and electronic charge species into two predominantly monopolar fractions during the time between pulses. Without this continual charge separation insured by the dc-bias, the precharger will produce charges of both positive and negative polarity, resulting in poor particle collection efficiency. Since the pulsed voltage is on for only a short period of time, power consumption is reduced and a more stable operation is obtained in this mode. Anodic pulsing without a dc-bias is not a useful mode in which to operate the precharger while using a collector with the present unipolar wire-plate geometry collector. Please refer to Table 3 which summarizes these and other results of the pulsed anode electron beam precharging experiments to date.

Table 3.

SUMMARY OF TRENDS PULSED ELECTRON BEAM PRECHARGER EXPERIMENTS

HIGHEST VALUES:

- * Collection Efficiency, Collection = 88.2%
- * Collection Efficiency, Pulsed PC and Coll. = 99.4%
- * Efficiency Improvement Factor (α) = 21

GENERAL TRENDS --

- * Pulsed + dc > dc-Only > Collector > Pulsed-Only
- * Pulsed-Only Not Effective -
 1. Pulses too short to Separate Ionization
 2. dc-Bias necessary for Monopolar Charging
 3. Possible Positive Streamer Formation
- * Use Highest dc-Bias below Corona Onset
- * Longer Pulses, Higher Frequency may Improve Performance

CHARGE VS. RADIUS RATIOS (Q/A) --

- * Predicted Charge ($t = 156 \text{ ms}$) 90% of Saturation Charge ($t = \infty$).
- * Electron Beam Precharging Increases Particle Charge Significantly (Pulsed with dc-Bias, dc-Only)
- * Experimental Data falls below Predicted Charge Line because of Incomplete Charging.

VI. DISCUSSION AND ANALYSIS -- PULSED E-BEAM PRECHARGING

A. Introduction

This section of the Final Report for the Pulsed Electron Beam Precharger project will be principally devoted to reviewing and interpreting the experimental results obtained during the past eleven quarters of the project. The experimental apparatus and experimental results have been presented in great detail in previous sections of the report. The experimental apparatus was modified for pulsed operation during the periods covered by Technical Progress Reports 1 through 4. Quarter 5 was devoted to a shakedown of the wind tunnel and collecting section. Technical Progress Report Numbers 6 and 7 detailed the results of experiments performed using the dc anode electron beam precharger, with TPR-6 reporting on the particle collection efficiency measurements and TPR-7 addressing the particle charging aspect of this study. Technical Progress Report 8 discussed the experimental data taken under pulsed anode conditions and compares this data with that taken under the condition of dc operation of the anode. We are concerned here mainly with progress made during the latter stages of the contract period (Quarters 9, 10, 11) which was focussed on the understanding and interpretation of the experimental results previously presented.

B. Motivation and Analysis of DC Electron Beam Precharging

The Pulsed Electron Beam Precharger Project addresses the problem of removing particulate matter from flue gases produced by the combustion of low sulfur coal. The fly ash produced by the combustion of this fuel has a very high resistivity, which leads to a "back-corona" problem in electrostatic precipitators used to collect the fly ash particles. The back-corona condition results in the production and injection of positive ions into the flue gas stream. Re-entrainment of the fly ash from the precipitator collector plates also occurs due to localized, explosion-like electrical breakdown across the layer of fly ash on the collector plate. These breakdown phenomena are caused by the high electric field and resulting voltage drop which develops across the high resistivity fly ash layer. The breakdown can be eliminated by reducing the voltage applied between the corona wires and the collector plates of the precipitator, but this is not a practical solution to the problem since the reduced voltage does not normally produce enough corona current or a high enough electric field to adequately charge the particles. In the absence of sufficient electric charge, the particles cannot be collected on the plates of the precipitator.

Previous results of research on the Electron Beam Precipitator test system developed at Florida State University have shown that fine, high-resistivity fly ash particles can be successfully precharged by exposing the gas stream to an energetic electron beam. Most of the free electrons produced by the E-beam are attached to electronegative atoms in the gas stream to form negative ions. The negative ions and the small remaining number of free electrons are drawn across the gas stream from the cathode (near the end of the accelerator) to the anode of the precharger, the latter being operated at a positive electric potential of 40 to 70 kV dc (3 - 5 kV/cm electric field strength). The electrode geometry is designed so that the positive ions produced by the

ionizing electron beam are drawn back to the cathode and not allowed to enter the gas stream. Spurious positive ions would deleteriously discharge the dust particles previously charged by negative ions and electrons. The negatively charged dust particles are carried downstream where they are collected by a conventional precipitator operating at a sufficiently low corona current and electric field (4.0 kV/cm) so that back corona does not occur.

A collection efficiency of 99.3% was attained in the dc precharger using an anode to cathode voltage difference of 66 kV dc (4.7 kV/cm electric field). The collection efficiency was found to improve as the anode-cathode voltage was increased, but a limit on the latter was reached due to onset of sparking between the two electrode sets within the precharger.

C. Motivation and Analysis of Pulsed Anode E-Beam Precharging

Since the electron current density (and hence volume charge density) in the active volume of the dc precharger is limited by the maximum anode-cathode voltage at the onset of electrical sparking, it was desired to find a way to eliminate the sparking problem. Sparks develop across a gaseous medium between anode and cathode electrodes by a series of rather complicated events, finally producing a highly conducting filament bridging the electrodes through the gaseous medium. This complicated train of events requires an appreciable amount of time to transpire, so that a spark does not immediately occur when an overvoltage (a voltage in excess of the sparking threshold) is applied across the electrodes.

The present pulsed precharger design makes use of the spark-free time interval during which a large overvoltage may be applied, and the resultant discharge is found to produce very rapid charging of the particles. The rapidity of this charging can be appreciated by noting that the application of a 20 kilovolt overvoltage (above sparking threshold) for only an additional 1.9 microseconds greatly increases fly ash particle charging compared to the application of a voltage just below the sparking threshold applied for 156 ms (dc operation of anode). This can be seen by comparing fly ash runs B-100-2 (dc run) and B-100-5 (pulsed run) of Table 1. The alpha values are 5.5 and 21, respectively, so that the dust particle penetration through the system was four times less ($21/5.5$) for pulsed operation (the alpha value is defined as ratio of the penetration with only the collector in operation divided by the penetration with both collector and precharger in operation). If only the small 20 kV dc-bias is applied without the added pulses for the situation of fly ash run B-100-5, the alpha value is approximately unity.

Table 1. Results from experimental runs measuring the collection efficiency and precharger efficiency improvement factor. The improvement factor is listed in the last column and is designated by the symbol α . The first row for each run in the table gives the collection efficiency obtained when the precharger was not energized. The constants listed immediately below apply to all the experiments except that the electron beam current and voltage were zero for the first row of each run. The data listed are representative of those obtained in the DC, pulsed, and pulsed-with-DC-bias modes of operation of the precharger.

Constants:

Gas Velocity	3.2 ft/s
Collector Electric Field	4.0 kV/cm
Collector Ion Current	30 μ A
Electron Beam Voltage	90 keV
Electron Beam Current	2.0 μ A

Run Number	Comparison (Test Dust)	Precharger Voltage (kV)	Precharger E-Field (kV/cm)	Precharger Ion Current (μ A)	Collection Efficiency (%)	α -Value (Collector + Precharger)
A-430	dc-only (Hydral)	--	--	--	86.1	--
		55 dc	3.9	40	98.3	8.2
		66 dc	4.7	41	98.7	10.4
B-30	Pulse Voltage (Hydral)	--	--	--	89.8	--
		60 pp	4.3	3 rms	48.8	< 1
		70 pp	5.0	4 rms	57.8	< 1
		70 pp, 20 dc	6.4	21 rms	96.2	2.7
B-60	dc vs. Pulsed (Hydral)	--	--	--	93.2	--
		66 dc	4.7	30	99.3	9.7
		66 pp	4.7	4 rms	53.5	< 1
		66 pp, 10 dc	5.5	6 rms	96.2	1.8
		66 pp, 20 dc	6.2	8 rms	99.5	14.0
B-100	dc vs. Pulsed (Fly Ash)	--	--	--	88.2	--
		66 dc	4.7	20	97.8	5.5
		66 pp	4.7	4	61.4	< 1
		66 pp, 10 dc	5.5	6	97.4	4.5
		66 pp, 20 dc	6.3	8	99.4	21.1

The 1.9 microseconds of overvoltage application is obtained as follows. There are 60 pulses of 200 nanoseconds pulse width each during each second, for a total 'on' time of 12 microseconds per second (0.0012% duty cycle). But in passing through the precharger, an element of flue gas volume remains in the active region of the precharger for only 156 ms. Hence any particle within the flue gas is exposed to the overvoltage for only 1.9 microseconds.

D. Particle Charge Levels in the Pulsed Anode Precharger

A look at the theoretical particle charge vs. time relation shows that particle charging using short pulses above the sparking voltage is not correctly predicted by the ionic charging theory, because according to this theory, only a tiny amount of charging should result from the 1.9 microseconds of exposure of the particles to the precharger field. The relation of ionic charge on the aerosol particle and time is governed by the charging equation:

$$q(t) = q(\infty) \frac{t/\tau}{1 + t/\tau} \quad (1)$$

where:

$q(t)$	=	particle charge at time t
$q(\infty)$	=	saturation particle charge
t	=	residence time in charging zone
τ	=	charging time constant.

For times that are short compared to the charging time constant τ , this equation takes the approximate form:

$$q(t) \approx q(\infty) t/\tau. \quad (2)$$

The saturation charge $q(\infty)$ is approximately $260e$ at 86 kV and the ionic charging time constant is approximately 12 ms. During the $1.9 \mu s$ exposure to the pulses, the charge collected by the aerosol particle should be only $0.04e$ according to the ionic charging equation shown above. Hence the overvoltage is applied for such a short time during passage of the gas through the precharger that the theory yields a negligible increase in charge due to the pulses. Only the dc-bias should produce charging according to the theory, and the amount predicted is small. The

saturation charge predicted by Equation (1) for 20 kV dc is only 60e. Experimental runs at 20 kV dc (1.4 kV/cm) have given alpha values of near unity, in agreement with theory.

E. Streamer Production and Particle Charging

What new phenomenon is occurring in the gas in the voltage regime beyond the sparking potential which causes the observed extremely rapid particle charging to take place? It is well known that beyond the sparking potential electron avalanches occur in the gas, and these lead to the production of streamers. Given excessive time to act, streamers would produce the highly conducting filaments (bridging the precharger electrodes) which lead to sparks.

The results obtained in the pulsed electron beam precharger developed at FSU are attributed to the production of streamers. Streamers are still poorly understood, but it is known that within a streamer the electric field strength is much greater than that predicted by just considering the voltage applied across the anode-cathode spacing. In some cases, the electric field strength at the tip of a streamer can be as much as 100 kV/cm for an applied anode-cathode pulsed/dc electric field of 8 kV/cm. In addition, the electron velocities and densities are much greater than those envisioned by uniform drift theories assuming a homogenous medium. The streamer could be described as a strong, localized, space-charge inhomogeneity propagating through the gaseous medium while gathering energy from a strong potential gradient. The conditions within the streamer are exactly those which lead to rapid particle charging, i.e., high current density and large electric fields. To the best of the knowledge of the present investigators, no theory of streamer charging of particulates has been formulated, nor are we aware of any experimental work in this field other than that contained in the present work.

Even though the interior of a streamer is clearly a good place in which to effect the charging of particles, it does not logically follow that particles will be appreciably charged in a flue gas sample in which streamers are present. Conditions must also be

such that a particle will be exposed to one or more streamers while passing through the precharger electric field, so that a high density of streamers is an additional requirement. Again, there seems to be no literature on the density of streamers induced in overvoltaged gases -- most of the work is on the formation, propagation, and decay of individual streamers as a function of the gaseous medium and imposed electric field. The fact that an adequate number of streamers exists in our device can be inferred only from the resultant particle charging measurements. Basic research on the characteristics of streamers is needed; modern supercomputers could be employed on this task to great advantage.

It is known that a free electron is needed in order to trigger the electron avalanche leading to the formation of a streamer. In the electron beam precharger, these free electrons are supplied by the electron beam accelerator in the manner discussed previously, and are drawn into the gas stream by the small dc-bias voltage maintained between the anode and cathode of the precharger (Figure 1). The data in this report taken with only pulsed overvoltage (no dc-bias voltage) do not show useful charging of the particles (see Table 1, fly ash run B-100-3), and this is because there are almost no free electrons in the gaseous medium under conditions of no applied bias voltage. The increase in particle charging observed with a larger bias voltage is attributed to a greater number of streamers produced and/or an increase in the strength of individual streamers. At least one free electron is required to produce an electron avalanche, which can then lead to the formation of a streamer.

Another concern might be why the positive ions in the streamer would not neutralize the negative ions and electrons already attached to the dust particle. After all, charge is conserved and as many (positive ions) as (electrons & negative ions) must be produced in the streamer. The answer is that the pulse is so rapid that all ions are essentially frozen in position during the pulse due to their large masses. The mobility of ions is approximately

(A) = Pulse-On Period
(B) = Pulse-Off Period
 V_p = Peak Pulse Voltage
 V_{dc} = DC-Bias Voltage

Figure 1. Voltage applied to the precharger anode during pulsed operation. The pulse repetition rate was 60 Hz.

1000 times less than that of electrons. After the pulse is over, the excess free electrons recombine with the positive ions before these relatively slowly moving ions can be collected by the dust particles.

F. Power Efficiency of DC Versus Pulsed Anode Precharging

What are the relative merits of dc operation of the precharger versus pulsed operation with a small dc-bias? A particle collection efficiency of about 99.4% (fly ash) to 99.5% (Hydral) was obtained using a pulsed voltage of 66 kV and a dc-bias voltage of 20 kV dc, while the corresponding poorer values using 66 kV dc alone were 97.8% (fly ash) and 99.3% (Hydral). Note that the system penetration using fly ash is reduced by a factor of approximately 4 when going from dc to pulsed operation.

The power consumption is greatly reduced in the case of pulsed operation versus dc operation of the precharger, since full voltage is applied between the anode and cathode for only about 0.0012% of the time, and the 20 kV dc-bias draws only a small current. Pulsed anode precharging should prove to be a more economical, power efficient means for particle charging, especially when combined with a redesigned high electric field, low current collector.

G. Directions for Further Research

It is believed that the greatest advantage of pulsed precharger operation will be found in a study using actual flue gas produced by the combustion of low sulfur coal and subsequently passed through the electron beam precharger. The present device demonstrates the practicality of streamer charging of particulate matter (in particular, fly ash) entrained in a gas stream.

Previously, workers at this laboratory had demonstrated (and patented) a similar device which used streamers to convert SO_2 and NO_x to condensible sulfides and nitrides -- the pulse energized electron reactor (PEER) device. The triggering electrons in the PEER device were produced by a pulsed corona. This corona was generated in the vicinity of a wire or rod electrode, surrounded by a concentric grounded pipe electrode. Streamers completely filled the active volume of the reactor, producing very high sulfur dioxide and nitrogen dioxide removal efficiencies. The triggering electrons in the present particle precharger device are introduced externally via an electron beam rather than being generated from a pulsed corona wire. The initiation of electron avalanches and the resultant streamers depends upon the application of sufficient overvoltage, and it is not specific to a particular electrode geometry.

The SO_2/NO_x conversion aspect of streamer processing of flue gas has not been demonstrated in the present precharger device, but there is every reason to expect that it is present. We have simply not had the funds needed to acquire the equipment needed to make SO_2/NO_x conversion measurements in the present experimental apparatus. The electrode geometry of the present precharger device does differ from that used in the original PEER device, but it is the existence of streamers in each of these systems which makes them both similar and effective, and it is not due to the details of electrode geometry.

Fly ash produced from low sulfur coal which normally has high resistivity is expected to show a reduction in resistivity after being passed through the pulsed E-beam precharger. Sulfides will be produced in the gas phase by the streamers, and SO_3 will be subsequently condensed on the particle surfaces. This should make streamer-processed low sulfur coal fly ash have a resistivity more like that of high sulfur coal fly ash. Under these circumstances back corona would be less of a problem, and the collector voltage could be increased so that it no longer would serve simply as a collector, but could contribute to additional charging of the particles and give an even lower penetration. It is well known that high sulfur coal fly ash collected on the precipitator plates does not exhibit the catastrophic voltage drop leading to back corona formation. Concurrent removal of sulfur in addition to fly ash from the flue gas would be an added benefit.

H. Conclusion

This research has resulted in the discovery of an important new way to charge aerosol particles in a gas stream.

Previous electrostatic precipitators and electron beam prechargers for flue gases have been based on the concept of a monopolar charging medium -- this medium normally consisting of negative ions and a few free electrons. Great care has been taken in those devices to preclude the existence of ions of opposite charge (positive, in this case) in the medium, since the presence of only a few of these opposite-sign ions can produce a serious discharge of the aerosol particles.

The experimental results lead us to believe that there is an intermittent bipolar medium in the precharger during the very short time span of the positive anode pulses, and that this bipolar medium results from the production of streamers in the overvoltaged gas. Positive ions serve a useful function in this medium, since they shield the electrons from mutual Coulomb repulsion, and thus permit a high density of free electrons for aerosol charging. The pulse duration is so short that the relatively massive ions cannot attach to the aerosol particles during the pulse. After the pulse drops off, the positive ions are rapidly eliminated by recombination with the free electrons. The important factors here are 1) the mass difference between ions and electrons, and 2) the short pulse time interval employed.

Experimental results from the pulsed electron beam precharging phase of the project illustrate the superiority of this method over dc precharging, regardless of whether our hypothesis about the mechanism invoked above to explain our results does or does not prove correct.

VII. RELATED PROJECTS WITHIN THE AEROSOL PHYSICS PROGRAM

A. Free Electron Charging of Aerosol Particles (FECAP) Project

Within the framework of the FSU Department of Physics' Aerosol Physics Program, there are two other major research efforts which paralleled the Electron Beam Precipitator Project during the decade of the 1980's. The first of these is the Free Electron Charging (FECAP) Project, in which an in-depth study was made of the superior charging of fine aerosol particles by free electrons instead of ions. An extensive series of experiments involving charging particles in ultrapure, non-electronegative gas atmospheres produced an empirical framework for the development of a new particle charging theory. This improved theory quantifies this unexpectedly high particle charging by electrons for both the field and diffusion particle size ranges. A model constructed to describe the data has been dubbed the "high electron temperature continuum-regime field/diffusion (HETFD) charging model.

Both the supporting experimental data and the theoretical model are presented in the paper entitled "Aerosol Particle Charging by Free Electrons", authored by D. B. O'Hara, J. S. Clements, W. C. Finney, and R. H. Davis. This paper appeared during the early part of the current contract in the Journal of Aerosol Science, Volume 20, Number 3, pp. 313-330, 1989, and because it is such an important topic, it is reprinted in its entirety here.

Aerosol Particle Charging by Free Electrons

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ABSTRACT

The strong dependence of electrostatic precipitator efficiency on particle charge has motivated a number of investigations of charge enhancement techniques. Measurements of free electron charging of aerosol particles reported here for nitrogen and argon confirm the earlier evidence (Dubard, 1983) that free electron charging in nitrogen produced substantially higher particle charge than charging by ions. The measured particle charge was 2 – 10 times larger for free electron charging than for ionic charging depending upon the experimental conditions. The dependence of free electron charging upon the gas, electric field, particle radius, and the charging parameter $N_e t$ has been measured. Previously available charging theories do not predict the observed dependence of free electron charging on the various parameters. The importance of electric-field-enhanced electron temperatures is recognized for diffusion charging, and a new high electron temperature continuum-regime field-diffusion charging model is presented which utilizes the Boltzman relation as an approximate solution for the electron densities near the particle. The predictions of this model are dependent upon the boundary conditions utilized at the particle surface, but are in satisfactory agreement with the data (considering the possible sensitivity of electron charging to gas impurities).

INTRODUCTION

An electrostatic precipitator is a particle removal system for the control of fly ash emissions at many coal-burning power plants. Since fly ash particles are removed by the action of an electric field on the particle charge, one of the most important parameters governing removal efficiency is the electric charge which the particles acquire. During the last twenty years, a number of investigators reported evidence for the existence of free electrons in electrostatic precipitators. More importantly, there is evidence that free electron charging produces an enhanced charge on aerosol particles. The paucity of data and the absence of an explanation of the available data led to the work reported here.

Experiments have been performed which confirm the superiority of free electron charging over ionic charging. In order to analyze the data, high electron temperature diffusion charging has been quantified and a new high electron temperature continuum-regime field-diffusion (HETFD) model has been introduced. The predictions of this model are dependent upon the boundary conditions utilized at the particle surface, but are in satisfactory agreement with the data (considering the approximations required for analytical solution and the possible sensitivity of electron charging to gas impurities).

Some free electrons exist in conventional electrostatic precipitators, but the conditions are such that most of the working charges available for charging particles are negative oxygen ions. Consequently, a contribution to particle charge by free electron charging is not typically regarded as important. Since the number of free electrons increases as the temperature or the electric field is increased, free electron charging can be significant under extreme conditions. The superior charging of particles by free electrons is of immediate importance to electron beam prechargers since the population of free electrons in these devices is larger than that in a conventional precipitator.

An electron beam precharger which utilizes the copious ionization from energetic electrons is

being developed at the Florida State University. Preliminary tests of one precharger configuration already suggest that free electron charging is important. An understanding of the charging mechanism is useful if not essential to optimizing the design of a practical device. No satisfactory model for atmospheric-pressure free electron charging existed before the present work (although there have been attempts to construct one). A high electron temperature field-diffusion model (HETFD) has been formulated and the predictions of this model provide the best representation of the data to date.

A number of authors have reported evidence for the anomalous charging of aerosol particles by free electrons. Penny and Lynch (1957) measured the charge imparted to $0.15\text{ }\mu\text{m}$ diameter particles by both positive and negative corona discharges. They reported that the imparted charge was 50% higher for negative corona than was the case for positive corona under experimental conditions which were otherwise the same. They suggested that the small population of free electrons in the charging region was largely responsible for the enhanced particle charge. Evidence for the existence of free electrons in negative corona at elevated temperatures was reported by C.C Shale (1967). He measured corona currents at various temperatures for both positive and negative corona discharges. At elevated temperatures the negative corona current was much greater than expected, and this increase in corona current was thought to be caused by free, unattached electrons. MacDonald, et al. (1980) made measurements of the electric charge on particles exiting a laboratory precipitator in the temperature range of $37 - 343^{\circ}\text{C}$ for both positive and negative corona. The charge acquired by $1 - 2\text{ }\mu\text{m}$ particles was a factor of two higher with negative corona than the charge acquired from positive corona at the higher temperatures. The charge enhancement was again attributed to free, unattached electrons.

DuBard and collaborators (1983) made the first quantitative measurements of particle charging by free electrons in 1982. Using di(2-ethylhexyl) sebacate oil (DES) particles (radius = $0.5 - 1.5$

μm) in a gas with no affinity for electron attachment (ultra-pure nitrogen), they found that free electron charging produced a particle charge which was much higher than that produced by ionic field charging. Their data exhibited a linear dependence of particle charge on radius and a "saturation" of particle charge with increasing electric field. The observed dependence of charge on particle size and electric field is not consistent with that predicted by the conventional field charging model normally used in this size range. This disagreement was demonstrated by a comparison of the data with the results of the field charging model modified to incorporate electron mobility.

More recently Clements, et al. (1984) made measurements of the charge acquired by PSL particles in an electron beam precharger. The measured particle charge was as much as a factor of two times larger than that predicted by ionic charging. Again, the enhanced charge was attributed in part to free, unattached electrons. The present research was initiated to (1) experimentally confirm enhanced particle charging by free electrons, (2) measure the dependence of charge on various parameters, (3) construct a model which describes free electron charging, and (4) assess the practical application of free electron charging in electron beam prechargers.

IONIC PARTICLE CHARGING

There are two distinct mechanisms for the ionic charging of particles: field charging and diffusion charging. The theory for field charging was developed by Rohmann (1923). Pauthenier and Moreau-Hanot (1932) rederived the charging equation in a different form. A more recent analysis of field charging has been given by both White (1963) and by Oglesby and Nichols (1978). For particles which are spherical, independent of one another, and in a region of uniform electric field, a convenient equation for field charging is

$$q(t) = q_s \frac{1}{(1 + \tau/t)}. \quad (1)$$

Here q_s is the saturation charge which is approached as $t \rightarrow \infty$,

$$q_s = 12\pi a^2 \frac{k}{k+2} \epsilon_o E \quad (2)$$

and τ is the characteristic charging time

$$\tau = \frac{4\epsilon_o}{eN_o b} \quad (3)$$

or

$$\tau = 4\epsilon_o \frac{E}{J} \quad (4)$$

with the definitions:

$q(t)$ = particle charge

q_s = saturation charge of particle

a = particle radius

ϵ_o = permittivity of free space

k = relative dielectric constant of particle

E = electric field

N_o = ion density

t = exposure time of particle to charging current

e = electronic charge

b = ion mobility

J = ion current density.

For field charging, the saturation charge varies with the radius squared and is linear with the electric field. The particle charge reaches some percentage of the saturation value depending upon the charging rate (Eqs. 3 and 4) and the exposure time.

The diffusion charging mechanism depends upon the thermal motion of the ions which surround the aerosol particle. The ions transfer charge by collisions with the particles, and the charge is held on the particle by image forces. As the particle gains charge, only those ions which have enough energy to overcome the Coulomb potential barrier can reach the particle. Since the number of ions in the thermal energy distribution asymptotically approaches zero as the energy is increased, there are a few ions with sufficient energy to overcome any barrier. Consequently, a charge limit is not inherent in diffusion charging, but the charging rate becomes progressively smaller as the charge increases.

Arendt and Kallmann (1926) published the first analysis of ionic diffusion charging. White (1963) used a simpler derivation to obtain an analytic expression for field-free ionic diffusion charging which is similar to that obtained by Arendt and Kallmann. White's analysis is reproduced by Oglesby and Nichols (1978). White's formula is strictly applicable to only the free molecular regime (i.e., $K_N \gg 1$, where $K_N = \lambda/a$, λ = ionic mean free path, and a = particle radius), which for ions occurs when $a < 0.03 \mu\text{m}$. However, the White formula often gives good results for the continuum regime ($a > 0.03 \mu\text{m}$) as well. A complete theory for ionic diffusion charging in the presence of an electric field was developed for the free molecular regime by Brock and Wu (1973), but numerical solution was required.

White's ionic diffusion charging model describes the diffusion charging mechanism in terms of kinetic gas theory (White, 1963; Oglesby and Nichols, 1978). The specific density of gas ions N at radius r from the center of a suspended particle of radius a is given by Boltzman's relation

$$N(r) = N_o \exp(-U/KT) \quad (5)$$

where

N_o = average density of ions at large r

U = potential energy of the particle - ion system

K = Boltzmann's constant

T = absolute temperature of ions = T_{gas} .

The potential energy U is expressed as

$$U = \Phi(r)e = \frac{-ne}{4\pi\epsilon_o r}e = \frac{-ne^2}{4\pi\epsilon_o r} \quad (6)$$

where

$\Phi(r)$ = electric potential near particle

n = the number of charges on the particle

r = distance from center of particle.

The density of ions at a distance r from the center of the particle becomes

$$N(r) = N_o \exp(-ne^2/4\pi\epsilon_o rKT) \quad (7)$$

and at the surface of the particle

$$N(a) = N_o \exp(-ne^2/4\pi\epsilon_o aKT). \quad (8)$$

The number of ions which strike the particle surface per second is, from kinetic theory

$$\frac{dn}{dt} = \frac{N(a)\bar{C}}{4}(4\pi a^2) = \pi a^2 N(a)\bar{C} \quad (9)$$

where $\bar{C}$ is the root-mean-square velocity of the ions. Combining Eqs. 8 and 9 yields the differential equation for the charging rate

$$\frac{dn}{dt} = \pi a^2 \bar{C} N_o \exp(-ne^2/4\pi\epsilon_o aKT). \quad (10)$$

The solution is

$$n = \frac{4\pi\epsilon_o aKT}{e^2} \ln \left[1 + \frac{e^2 \bar{C} N_o t}{4\epsilon_o KT} \right]. \quad (11)$$

Complete ionic charging theories which incorporate both field and diffusion charging are necessary for the size range where the mechanisms are comparable; i.e., approximately 0.1 to 1.0 μm radius, depending on the electric field strength (White, 1963; Oglesby and Nichols, 1978; Liu and Kapadia, 1978; Fjeld et al., 1983). For ionic charging, field charging dominates above this range and diffusion charging below. The derivation of a formula for continuum-regime ionic diffusion charging in the presence of an applied electric field results in a partial differential equation which must be solved numerically using a high speed computer. Oglesby and Nichols (1978) review the results of several such analyses where approximations were used to simplify the equations. More exact

analyses are those by Liu and Kapadia (1978) for unipolar charging and by Fjeld et. al. (1983) for bipolar charging.

APPARATUS

A charging cell and the associated gas handling and charge measurement system were constructed for the purpose of confirming or denying the enhancement of particle charge by free electrons. If confirmed, a further purpose was the measurement of sufficient data to guide the development of a model for free electron charging. The system is based on a design by DuBard of Southern Research Institute (1983) and construction was initiated by Stout at FSU (1983).

A simplified schematic of the cell electrodes and circuit is shown schematically in Fig. 1. Negative high voltage is applied to the corona needle. Resistance R_1 is used for spark suppression, and capacitance C_1 and resistance R_2 are used to smooth low frequency variations in the corona current. Screen S_1 provides electrical control and can be used to limit current through a second screen S_2 which is grounded to attract corona current from the corona needle. The cell anode is made from a flat aluminum plate with rounded edges. Resting on the aluminum plate is a block of plexiglass which has a channel cut into it to allow for the passage of gas and particles. Just above the plexiglass is the grounded screen S_2 . Screen S_2 is covered with a piece of aluminum foil having a 2 cm diameter opening in the center. The opening allows the passage of corona current and defines the charging region. A positive voltage is applied to the flat plate anode, and the geometry is such that a uniform field is maintained in the charging region between S_2 and the anode. The current control screen S_1 mounted above screen S_2 can be positively or negatively biased. The corona needle is fastened to an aluminum plate which will allow variable needle spacing between it and S_1 . The electrode apparatus is mounted in a plexiglass tube with appropriate gas inlets and outlets.

The entire charging cell is placed under a bell jar which allows ambient air to be evacuated and replaced with dry air or other gases. A comprehensive gas handling system allows the bell

jar and cell to be back filled after evacuation (Fig. 2). Particles were suspended using a Collison nebulizer. The Collison nebulizer generates an aerosol from di(2-ethylhexyl) sebacate oil (DES) and delivers it into the charging cell. To measure particle charge (q) and radius (a), a q/a measurement system developed by Mizuno and Otuka (1982) was used (Fig. 3). This method involves trajectory measurements of oscillating charged particles within a region bounded by an AC electric field. Particles are illuminated by a laser beam and the oscillation amplitude and falling velocity are monitored using a microscope lens mated to a video camera and recording system. Using the q/a device, particle size is determined from particle free fall velocity, while particle charge is found from its oscillation amplitude in the alternating (AC) electric field.

EXPERIMENTAL TECHNIQUE AND RESULTS

As a system performance check and as a test of experimental technique, the first experiments were run using ionic charging since ionic charging is well understood both experimentally and theoretically. Polydisperse DES particles were generated by the Collison nebulizer, suspended in dry air, and charged in the corona cell. The theoretical values for ionic charging were obtained by the generally accepted practice of adding the theoretical field charging and diffusion charging values together (Gaunt, 1984). This analytical theory agrees quite well with the complex continuum-regime field-diffusion theory of Liu and Kapadia (1978), although it usually slightly underpredicts the particle charge values. In Fig. 4 it can be seen that the data is in fairly good agreement with the field plus diffusion ionic field charging theory. This agreement with well established ionic charging theory confirmed the capability of the equipment and the validity of the measurement technique.

To measure free electron charging without interference from ionic charging, the carrier gas must not be electronegative. Ultra-high purity (UHP) nitrogen or argon (< 1 ppm O_2) was used as the carrier gas since electrons do not readily attach to N_2 or Ar molecules. The bell jar and charging cell were pumped down to 50 millitorr for twelve hours. Both the bell jar and the Collison nebulizer

were then back filled with UHP nitrogen or argon for two hours. The charging parameter N_0t was varied by changing the gas flow rate and by controlling the current through the charging region.

Runs were made at values of electric field between 208 V/cm and 6.6 kV/cm with various N_0t parameters. Examples of data for these runs can be seen in Figs. 5 – 7. Calculated values for ionic field plus diffusion charging (with the same N_0t value) are also shown for comparison. In every case the free electron charging values are substantially higher than those predicted by ionic charging theory. The data also shows that the measured charge is approximately proportional to the radius, rather than to the radius squared as predicted by field charging theory. This is consistent with the results of DuBard, et al. (1983). The systematics suggest that for a sufficiently large radius the field charging curve will overtake and intercept the empirical linear dependence on radius. Unfortunately, it was difficult to measure sufficiently large particles to confirm an intercept.

The dependence of particle charge on electric field was measured. The value of N_0t was held constant by adjusting the exposure time of the particles in the charging region. Electric field levels were varied to determine the experimental relationship between particle charge and electric field. Space charge distortion of the charging field was estimated to be small and was neglected in this work. Figure 8 shows the data and the calculated curve for ionic field plus diffusion charging. The relationship between charge and electric field is non-linear. The particle charge increases as the charging electric field increases, but the charge increment for a given field increment diminishes as the field is increased. This is also consistent with DuBard's data.

Another experiment was designed to determine the empirical dependence of charge on the exposure parameter N_0t . The electric field was set at 2.5 kV/cm and N_0t was varied between 2×10^9 and $2 \times 10^{12} \text{ e}^- - \text{sec}/\text{m}^3$. It can be seen in Fig. 9 that charge seems to vary linearly with $\ln(N_0t)$.

Two electron charging experiments were run using argon and the data are shown in Figs. 10

and 11. The measured particle charge is much higher than that for nitrogen. The charge deposited on the particles in argon was so high that almost all of the particles were precipitated in the charging cell. For this reason it was difficult to get much data for argon, especially for larger particles and high electric field strengths.

If free electron charging is analogous to ionic charging, the dominant charging mechanism for the particle size region $a > 1.0 \mu\text{m}$ at moderately high fields should be field charging ($q \propto a^2$). However, not only does free electron charging provide a much higher charge than that predicted by ionic field theory, but the charge is proportional to a , not to a^2 (see Figs. 5 – 7). Furthermore, the charge is a non-linear function of electric field.

FREE ELECTRON CHARGING MODELS

A. Electron Field Charging

DuBard and co-workers (1983) endeavored to explain enhanced free electron charging of ~ 0.5 to $1.5 \mu\text{m}$ radius particles with a modified ionic field charging theory (see Eqs. 1 – 4). Ionic particle charging in this size range is normally dominated by field charging for moderately high values of electric field. For the mobility value in the theory, the “mobility” of electrons (about 300 times that of ions for their experimental conditions) was used. For field charging, the theoretical saturation charge is charge specie independent and should be the same for ionic or electronic charging (Eq. 2). However, the charging rate is dependent on the mobility of the specie, and therefore should be faster for electrons if $N_o t$ is the same (see Eq. 3). It should be noted that, unlike ion mobility, electron “mobility” varies with the electric field; therefore the product of “mobility” and field (velocity) is often used instead. If the same ratio of E/J (Eq. 4) is used for both ionic and free electron charging, then the charging rates should be equal since N_o will be smaller for electrons due to their high mobility. In the Dubard et al work, $N_o t$ was held constant, therefore the higher electron mobility would have increased the charging rate. However, this electron field charging model greatly

underpredicted the particle charge, and also did not agree with the observed linear dependence of charge on particle radius.

B. High Electron Temperature Diffusion Charging

The linearity of charge as a function of radius for free electron charging suggests diffusion charging (Eq. 11) even though these 0.5 to 1.5 μm radius particles are normally too large for diffusion charging to dominate (at moderate field values). To apply the ionic diffusion theory to electrons, the mean ion velocity $\bar{C}$ in Eq. 11 should be replaced by the much larger mean electron velocity $\bar{c}_e$. This difference between the thermal velocities of the ions and electrons increases the charging rate in the existing diffusion charging theory, but still does not account for the large final particle charge observed for free electron charging.

A new and promising extension of the electron diffusion model is based on a suggestion by Clements (1985). It was noted that in a gas with an applied electric field, the mean electron temperature is significantly higher than that for ions. In other words, the electron energy is increased whereas the ions remain in thermal equilibrium with the gas molecules. The incorporation of the elevated electron temperature into the diffusion charging equation (Eq. 11) immediately yields a higher particle charge than is the case for thermal electrons (at the temperature of the gas molecules and ions). This enlarges the particle size domain for which electron diffusion charging is significant as compared to electron field charging.

The mean electron energy ($1/2 m\bar{c}_e^2$) and temperature (T_e) depend on the electric field strength and are related to those of the carrier gas by the so-called Townsend energy factor (k) given by Townsend (1921, and p. 336 in Huxley, 1962):

$$\frac{1}{2}m\bar{c}_e^2 = \frac{3}{2}KT_e = k\frac{3}{2}KT = k\frac{1}{2}M\bar{C}^2 \quad (12)$$

and

$$T_e = kT \quad (13)$$

where

k = the ratio of the mean energy of the electrons to that of the gas atoms

at $15^\circ C$ ($288^\circ K$)

K = Boltzmann's constant

$\bar{c}_e$ = electron thermal velocity (root mean square)

$\bar{C}$ = ion thermal velocity (root mean square)

m = electron mass

M = gas molecule mass

T_e = mean electron temperature

T = gas temperature.

For ions in a gas with an applied electric field, the measurable quantities of electric field, drift velocity, and diffusion coefficient are related by the Einstein relation (Huxley, p. 336, 1962):

$$W/D = \frac{eE}{KT} \quad (14)$$

where

K = Boltzmann's constant

W = ion drift velocity

D = ion diffusion coefficient

T = gas temperature

E = electric field

e = electronic charge.

The Einstein relation is modified for electrons due to the fact that the mean electron temperature is raised above that of the gas (Eq. 13) and also due to the electron energy distribution function not necessarily being Maxwellian. The modified Einstein relation (p.352 in Huxley, 1962, p. 631 in Dutton, 1975) is

$$W/D_T = \frac{eE}{Kk_1T} \quad (15)$$

with

$$k_1 = \frac{3k}{2F} \quad (16)$$

where D_T is the electron diffusion coefficient transverse to the field direction, k_1 is the apparent electron temperature enhancement factor, and F is a dimensionless quantity that depends on the type of distribution function that the electrons follow (Loeb, 1961). If the energy distribution of the electrons is Maxwellian (electrons in thermal equilibrium with the carrier gas), then $F = 3/2$. In this case $k_1 = k$ (Eq. 16) and the Einstein relation for electrons (Eq. 15) is the same as that for ions (Eq. 14), since $T_e = kT$ and $k = 1$. However, in general the Einstein relation for electrons

differs from that for ions due to the presence of the electron energy distribution parameter F and because $T_e = kT$.

As the mean electron temperature is raised above that of the gas, k becomes greater than one and the electron energy distribution becomes less Maxwellian. At large k , a closer approximation to the actual electron energy distribution is the Druyvesteyn distribution which assumes: (1) low electron density, (2) the electrons lose a small fraction of their energy upon impact with gas molecules, (3) there are no inelastic collisions, and (4) the electron mean free path is independent of electron energy (Loeb, 1961). Since in general the mean free path varies with energy (the Ramsauer – Townsend effect), the actual electron distribution may be distorted from the Druyvesteyn. The value of F will vary from 1.0 for monoenergetic electrons to 1.5 for Maxwellian distributions (Loeb, 1961; Dutton, 1975), with $F = 1.312$ for Druyvesteyn distributions.

Using $W = \mu E$ where μ = “mobility” of electrons, and substituting (16), equation (15) becomes

$$kT = \left(\frac{D_T}{\mu} \right) e \left(\frac{2}{3} \frac{F}{K} \right). \quad (17)$$

Using $T_e = kT$ yields

$$T_e = \left(\frac{D_T}{\mu} \right) e \left(\frac{2}{3} \frac{F}{K} \right). \quad (18)$$

The quantity D_T/μ has been tabulated by Dutton (1975) for electrons in various gases as a function of the ratio of electric field to gas density (E/N_g); so that for a given set of conditions, the mean electron temperature T_e is determined if F is known.

White’s formula for diffusion charging (White, 1963) is strictly applicable only in the free molecular regime (i.e. $K_n \gg 1$, where $K_n = \lambda/a$, λ = ionic mean free path.), which for ions

at N.T.P. occurs when $a < 0.03 \mu\text{m}$. At atmospheric pressure, the mean free path of a single ion in air is the order of $0.1 \mu\text{m}$, but in practice ions usually consist of a cluster of ~ 100 atoms with a mean free path of $\sim 0.03 \mu\text{m}$. The mean free path of electrons in gases is determined by complicated quantum mechanical effects (e.g., the Ramsauer-Townsend effect) which occur during collisions between electrons and gas molecules. Therefore the mean free path of electrons depends strongly on the species of the gas molecule and on the electron temperature, in addition to the usual parameter of gas density. Particles in this experiment range in size from $0.1 \mu\text{m}$ to $3.0 \mu\text{m}$ radius so that even though the mean free path of electrons can be several times that of ions, the Knudsen number is usually equal to or less than 1.

C. Continuum-regime field-diffusion electron charging

When $K_n < 1$, continuum-regime particle charging theories are normally used, with the charging flux described by macroscopic fluid-flow equations. The region with $1 < K_n < 10$ is a transitional regime where both macroscopic and free molecular equations are used; typically the macroscopic fluid-flow equations are applied with the region near the particle being described using boundary conditions determined by free molecular kinetic theory. In this paper we use the continuum-regime flux equation to describe electron charging with the reservation that for cases where K_n approaches 1, the boundary conditions near the particle become more approximate. Therefore, two different boundary conditions are used in the flux equation and the results from both are shown. In addition, the very significant effect of electric-field enhancement of the mean electron temperature is included in the theory.

Both field and diffusion ionic charging are simultaneously described by the continuum ion flux equation, (Liu & Kapadia, 1978; Fjeld, 1983):

$$\bar{\Gamma} = \pm \mu N_i(r) E - D \nabla N_i(r) \quad (19)$$

where

$\bar{\Gamma}$ = ion flux density to particle

μ = ion mobility

D = ion diffusion coefficient

$N_i(r)$ = ion density at a distance r from center of particle

E = total electric field.

Normally, equation (19) is solved using the finite-difference method (with appropriate boundary conditions) to obtain $N_i(r)$. Unfortunately, this requires a very lengthy numerical solution for each experimental condition. In the present work, the Boltzmann relation is used to obtain an approximate analytical expression for $N(r)$. The Boltzmann relation is valid for steady state conditions with a Boltzmann energy distribution, and for the continuum regime can be derived from equation (19) when $\bar{\Gamma}$ is zero (see the Appendix). Therefore this approximate solution for $N(r)$ becomes more accurate as the particle is charged (because $\bar{\Gamma}$ decreases to a small value as the particle becomes charged).

When the charge carriers are electrons instead of ions, equation (19) becomes

$$\bar{\Gamma} = -\mu N_e(r)E - D\nabla N_e(r) \quad (20)$$

where

$\bar{\Gamma}$ = electron flux density

μ = electron "mobility"

D = electron diffusion coefficient.

The product μE is the electron drift velocity W , so that (20) becomes

$$\bar{\Gamma} = -W N_e(r) - D \nabla N_e(r). \quad (21)$$

Both W and D are functions of the electric field. This theory assumes that, due to the extremely high thermal conductivity of electrons (Chen, 1984), the drift velocity W , the diffusion coefficient D , and the mean electron temperature T_e are determined by the electric field far from the particle (E_o). When $\bar{\Gamma}$ is small, the Boltzmann relation can also be used to obtain an approximate solution for the electron density $N_e(r)$. However, this solution becomes less accurate at large E/N_g values (N_g = density of gas molecules) because the electron energy distribution becomes less Maxwellian at high E/N_g (see the Appendix). The general Boltzmann relation (Eq. 5) is

$$N(r) = N_o \exp\left(\frac{-U}{KT}\right) \quad (22)$$

which for electrons can be written

$$N_e(r) = N_{eo} \exp\left[\frac{e\Phi(r)}{KT_e}\right] \quad (23)$$

where

r = distance from center of particle

N_{eo} = electron density at $r = \infty$

$\Phi(r)$ = electric potential

K = Boltzmann's constant

T_e = mean electron temperature

e = electronic charge.

For this charging theory, the potential in equation (23) is the Coulomb potential due to the charge on the particle, plus the potential due to the applied field:

$$\Phi(r) = \frac{-ne}{4\pi\epsilon_0 r} - \left[r/a - \left(\frac{k-1}{k+2} \right) \frac{a^2}{r^2} \right] E_o a \cos \theta \quad (24)$$

where

n = number of charges on the particle

a = particle radius

k = relative dielectric constant of particle

E_o = applied field

ϵ_o = permittivity of free space.

Image forces are usually neglected in the continuum regime because the image potential varies as $1/r^2$ whereas the Coulomb potential varies as $1/r$. Also, if the image force is used, the Boltzmann relation (23) cannot be applied at the particle surface.

The boundary condition which is normally used in continuum regime particle charging theory is that the density of free charges at the particle surface is zero ($N_e|_{r=a} = 0$). Using this boundary condition in the flux equation (21) yields

$$\bar{\Gamma}|_{r=a} = -D \nabla N_e(r)|_{r=a}. \quad (25)$$

Substituting the Boltzmann relation (23) for $N_e(r)$ and expression (24) for the potential, the electron flux at the particle surface is then

$$\bar{\Gamma}|_{r=a} = \frac{-DN_o e}{KT_e} \exp \left[\frac{e\Phi(a)}{KT_e} \right] \nabla \Phi(r, \theta)|_{r=a} \quad (26)$$

$$= \left(\frac{-DN_o e}{KT_e} \right) \exp \left[\frac{e\Phi(a)}{KT_e} \right] \frac{d\Phi(r)}{dr} |_{r=a} \quad (27)$$

$$\bar{\Gamma}(a) = \frac{-DN_o e}{KT_e} \exp \left\{ \frac{e}{KT_e} \left[\frac{-ne}{4\pi\epsilon_o a} - \left(1 - \frac{k-1}{k+2} \right) E_o a \cos \theta \right] \right\} \left\{ \frac{ne}{4\pi\epsilon_o a^2} - \frac{3k}{k+2} E_o \cos \theta \right\}. \quad (28)$$

Only the radial component of the gradient is needed (Eq. 27) because the charging rate is given by

$$\frac{dn}{dt} = - \int_{\theta} \int_{\phi} \bar{\Gamma} \cdot \bar{da} = -2\pi a^2 \int_{\theta=0}^{\pi} \bar{\Gamma}(a) \sin \theta d\theta. \quad (29)$$

This surface integral yields

$$\frac{dn}{dt} = \left\{ \left(\frac{-ne^2 DN_o}{2\epsilon_o KT_e} \right) \left(\frac{e^{-\alpha} - e^{\alpha}}{\alpha} \right) + \frac{2\pi a Dek N_o}{\alpha} [(\alpha + 1)e^{-\alpha} + (\alpha - 1)e^{\alpha}] \right\} \exp \left(\frac{-ne^2}{4\pi\epsilon_o a KT_e} \right) \quad (30)$$

where

$$\alpha = \frac{-3eE_0a}{(k+2)KT_e}$$

Another possible boundary condition is that $\nabla N_e(r) = 0$ at or near $r = a$ ($\nabla N_e|_{r=a} = 0$). The flux equation (21) then becomes

$$\bar{\Gamma}|_{r=a} = -W N_e(r)|_{r=a}. \quad (31)$$

Again substituting Eqs. 23 and 24 for $N_e(r)$ yields

$$\bar{\Gamma}|_{r=a} = -W N_o \exp \left[\frac{-ne^2}{4\pi\epsilon_0 a K T_e} - \left(\frac{3}{k+2} \right) \frac{eE_0 a \cos \theta}{K T_e} \right]. \quad (32)$$

Integrating over the surface of the particle yields

$$\frac{dn}{dt} = 2\pi a^2 W N_o \exp \left(\frac{-ne^2}{4\pi\epsilon_0 a K T_e} \right) \frac{e^\alpha - e^{-\alpha}}{\alpha} \quad (33)$$

where

$$\alpha = \frac{-3eE_0a}{(k+2)KT_e}$$

In these calculations we use $D = D_T$ (in Eq. 30), with D_T being the electron diffusion coefficient transverse to the electric field direction. The value of D_T can be obtained using

$$D_T = \left(\frac{D_T}{\mu} \right) \left(\frac{W}{E} \right). \quad (34)$$

The mean electron temperature T_e is estimated using Eq. (18). The parameters W and D_T/μ are tabulated in Dutton (1975) as a function of E/N_g for various gases. The value of D_T/μ (which determines the electron temperature) has some uncertainty because there may be polyatomic impurities in the carrier gas (from residual gas, the DES particles, the oil in the vacuum pump, etc.) which would decrease the actual electron temperature. In argon, molecular impurities in concentrations as low as several ppm are sufficient to drastically alter electron energy distributions (Ogawa, 1984). Consequently, the experimental particle charges may be lower than those predicted for an absolutely pure gas. Another error in determining T_e results from the difficulty in choosing the correct value for F in Eq. (18). For a pure gas with low to moderate E/N_g values, $F = 1.312$ (Druyvesteyn) is a reasonable value to use. However, since the actual T_e was probably lowered due to impurities in the experimental gas, a value of $F = 1$ is used in these calculations (this gives a slightly lower T_e than using $F = 1.312$). These values of W , D_T , and T_e are substituted into Eqs. (30) and (33). The charging rate equation for $N_e|_{r=a} = 0$ (Eq. 30) can be easily integrated numerically to yield particle charge as a function of particle radius, electric field and $N_o t$. Predicted curves along with actual data are shown in Figs. 5 – 7 and 10 – 11. In every case this theory predicts a charge higher than the data.

Equation (33), the semi-empirical theory based upon the boundary condition $\nabla N_e|_{r=a} = 0$, can be integrated analytically to yield particle charge versus time:

$$n = \frac{4\pi\epsilon_o a K T_e}{e^2} \ln \left[1 + \frac{W N_o t e^2 a}{2\epsilon_o K T_e} \left(\frac{e^\alpha - e^{-\alpha}}{\alpha} \right) \right]. \quad (35)$$

Equation (35) bears a strong resemblance to high electron temperature diffusion charging (White's

equation 11 with the ion mean velocity and temperature replaced by those for electrons). Predicted values obtained using the $\nabla N_e|_{r=a} = 0$ boundary condition are shown in Figs. 5 – 11. The use of this boundary condition results in better agreement with the data than using the boundary condition $N_e|_{r=a} = 0$. However, one should not rule out the $N_e|_{r=a} = 0$ boundary condition because of the possibility that the experimental particle charge may have been lowered due to the gas impurity problem having been more severe than anticipated.

DISCUSSION AND SUMMARY

The charging of aerosol particles in ultrapure nitrogen has been measured in the particle radius range of approximately $0.1 \leq a \leq 3 \mu\text{m}$ for electric field values from 0.21 to 6.6 kV/cm. The particle charge acquired using free electron charging was considerably higher – as much as ten times higher – than that by ionic charging for the same conditions of electric field and charging flux exposure.

A comparison of these results with those of DuBard, et al. (1983) is shown in Fig. 12. Both experiments were performed using DES particles in nitrogen with a charging field of 5 kV/cm. There is qualitative agreement since both data sets are superior to ionic charging, show a linear dependence on particle size, and have similar slopes. However, the quantitative agreement is not as good, since the particle charge values were consistently higher in the present experiment. Differences in the two experiments such as unequal $N_e t$ values and time dependencies of the electric field do not readily explain the apparent discrepancy. In the present work, a “charge saturation” was observed with increasing electric field (see Fig. 8), which is consistent with Dubard’s work.

The data in Dutton (1975) shows that for a given value of E/N_g , argon has one of the highest values of D_T/μ . This means that the mean electron temperature is higher in argon than in most other gases under the same charging conditions. Consequently, the charge acquired by particles in argon should be larger than in other gases. If free electron charging produced the predicted higher values of charge in argon, it would be an important confirmation of the electric-field-enhanced high electron temperature diffusion mechanism. Therefore, the superior charging results in argon (Figs. 10, 11) offer strong support for the hypothesis that the dominant electron charging mechanism in this size regime is high electron temperature diffusion charging. Charging in argon shows the characteristic approximately linear variation of charge with particle radius, which is compatible with diffusion charging. For the same sized particles, the charge is not very different for the two values of electric field. This effect may be explained by the fact that the E/N_g values for this data

are such that there is very little change in D_T/μ for this variation of E/N_g (Dutton, 1975).

The high electron temperature charging model was constructed by using the field dependent electron temperature in the standard continuum-regime field-diffusion model while assuming that the electron density $N_e(r)$ could be approximated using the Boltzmann relation. Considering the uncertainties in the data, this model represents the data rather well, especially for the boundary condition $\nabla N_e|_{r=a} = 0$. The dependence of charge on size is predominantly linear. The "charge saturation" with increasing electric field may be partly explained by the "saturation" of electron temperature (or D_T/μ) with increasing field. Self precipitation of the highly charged particles may also be occurring at charge values above the "saturation" value. Future work should include the use of an alternating square wave voltage on the anode to reduce the possibility of the precipitation of the highly charged particles by the charging field. Also, the mean electron temperature (T_e) and the electron energy distribution need to be measured experimentally in order to reduce the uncertainty in the T_e and F values used in the theory.

Turbulence in the charging cell may alter the exposure time of the particles to the charging electron swarm. This variation in exposure time may contribute to the scatter in the particle charge data, although the main cause is probably the variation of the charging current due to the unstable nature of corona (caused by a lack of space charge) in non-electronegative gases. There is also an intrinsic variation in particle charge which is caused by the statistical nature of the charging process, and also by the distribution of electron energies (individual electrons have temperatures which differ from T_e).

In a typical electrostatic precipitator, the flue gas contains significant amounts of electronegative gases such as CO_2 , O_2 , and H_2O . The population of free electrons is generally low, and free electron charging probably does not significantly enhance particle charge values above conventional ionic charging values. At elevated temperatures, however, the electron attachment coefficient decreases

so the population of free electrons is higher (Dutton, 1975). Therefore, free electron charging may be significant in precipitators operating at higher temperatures.

The Florida State University electron beam precharger uses a high energy beam (100 keV) of electrons to ionize the flue gas. The charge species are separated by an applied electric field so that a monopolar charge flux is used to charge the particles. Electrons produced as delta rays by the primary beam have initial energies of several keV with the energy steadily decreasing (due to collisions with gas molecules), resulting in an electron energy distribution between 0.04 eV (thermal) and several keV. The thermal electrons (0.04 eV) are re-energized by the applied electric field to a mean energy of ~ 1 eV. Therefore, electron beam prechargers have electron populations which are larger in both number and energy than is the case for conventional electrostatic precipitators. The electron beam precharger should maintain high concentrations of free electrons since the electron attachment coefficient in air drops sharply for mean electron energies between ~ 0.1 and 1 eV. That is, electron attachment in air at atmospheric pressure (N.T.P.) is at a minimum for $E = 270$ V/cm to 2.7 kV/cm, which corresponds to $D_T/\mu = 0.1$ to 1 V. As mentioned previously, very high particle charges have been produced by a bench scale electron beam precharger, and the superior charging is attributed in part to free electron charging.

CONCLUSION

1. Free electron charging deposits a substantially higher charge on 0.1 - 3 μ m radius particles than is expected from ionic charging theory.
2. For free electron charging in this size range, the particle charge varies linearly with particle radius and with $\ln(N_0 t)$ (in agreement with diffusion charging theory).
3. The measured particle charge was much higher in argon than in nitrogen, which strongly supports the proposed mechanism of electric field enhancement of electron temperature in

electron diffusion charging.

4. The particle charge appears to "saturate" as the electric field is increased, and may be caused by the mean electron temperature "saturating" at high fields.
5. Electron field charging theory should have the same "saturation charge" limit value as ionic field charging theory, but high electron temperature diffusion charging theory predicts much higher particle charges than ionic diffusion charging. Therefore, the particle size region where field charging competes with (and finally dominates) diffusion charging should occur at larger particle sizes for electron charging than for ionic charging.
6. A high electron temperature continuum-regime field-diffusion model (HETFD) has been constructed using the field dependent electron temperature given by swarm data.
7. An approximate analytical solution to the HETFD model has been obtained by using Boltzmann's relation to describe the electron densities near the particle, and the predictions of this model are in reasonable agreement with the experimental data.
8. The differences between the theory and data may be due to both theoretical and experimental factors. Errors in the theory may be due to the approximation of using the Boltzmann relation for $N_e(r)$, and to the boundary conditions becoming more approximate as K_n approaches 1. Experimental factors which could lower the measured particle charge include: the presence of polyatomic gas impurities which lower the actual electron temperature, and possibly the precipitation of the highly charged particles.

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APPENDIX - Boltzmann Relation

In the continuum regime, $N(r, \theta, \phi)$ is obtained by numerically solving Eq. (19) or (20). For negative ions or electrons, $N(r, \theta, \phi)$ can be obtained from Eq. (20):

$$\bar{\Gamma} = -D\nabla N - \mu EN. \quad (A1)$$

The flux to the particle ($\bar{\Gamma}$) becomes small as the charge on the particle increases. As an approximation, we set $\bar{\Gamma} = 0$.

$$-D\nabla N - \mu EN = 0 \quad (A2)$$

$$\frac{\nabla N}{N} = \frac{-\mu E}{D}. \quad (A3)$$

The Einstein relation for electrons (from Eq. 18) is

$$KT_e = \frac{2F}{3} \left(\frac{D_T}{\mu} \right) e. \quad (A4)$$

Using the approximation that the electron energy distribution is Maxwellian ($F = 3/2$) yields a relation analagous to the ionic Einstein relation:

$$KT_e = \left(\frac{D_T}{\mu} \right) e, \quad (A5)$$

Using D and T for ions or D_T and T_e for electrons and substituting (A5) into (A3) yields

$$\frac{\nabla N}{N} = \frac{-eE}{KT}. \quad (\text{A6})$$

Equation (A6) can be solved in 3 dimensions, but the simple isotropic case of $E = E(r)$ (no applied field) is considered for brevity. Substituting $E(r) = \frac{-d\Phi(r)}{dr}$ into Eq. (A6) gives

$$\frac{dN(r)}{dr} \left[\frac{1}{N(r)} \right] = \frac{e}{KT} \frac{d\Phi(r)}{dr} \quad (\text{A7})$$

$$\int \frac{dN(r)}{N(r)} = \frac{e}{KT} \int d\Phi(r) + C \quad (\text{A8})$$

$$\ln N(r) = \frac{e}{KT} \Phi(r) + C. \quad (\text{A9})$$

Using the condition $N(r) = N_o$ when $\Phi(r) = 0$, the integration constant is given by

$$\ln N_o = C. \quad (\text{A10})$$

Substituting (A10) into (A9) yields

$$\ln \left[\frac{N(r)}{N_o} \right] = \frac{e}{KT} \Phi(r) \quad (\text{A11})$$

$$N(\mathbf{r}) = N_o \exp \left[\frac{e\Phi(\mathbf{r})}{KT} \right] \quad (\text{A12})$$

or in 3 dimensions

$$N(\mathbf{r}, \theta, \phi) = N_o \exp \left[\frac{e\Phi(\mathbf{r}, \theta, \phi)}{KT} \right]. \quad (\text{A13})$$

Or, using $U(\mathbf{r}, \theta, \phi) = \Phi(\mathbf{r}, \theta, \phi)(-e)$, Eq. (A13) can be written in the general form:

$$N(\mathbf{r}, \theta, \phi) = N_o \exp \left[\frac{-U(\mathbf{r}, \theta, \phi)}{KT} \right]. \quad (\text{A14})$$

Equation (A14) is the Boltzmann relation, and is the exact solution for the continuum flux equation (A1) when the ion or electron energy distribution is Maxwellian and when $\bar{\Gamma} = 0$ (equilibrium conditions). The Boltzmann relation is normally derived using kinetic theory (free molecular regime), but is actually valid for all Knudsen numbers under these conditions.

FIGURE CAPTIONS - Free Electron Charging . . .

Fig. 1. Circuit schematic of the particle charging cell.

Fig. 2. Gas flow system for the particle charging experiment.

Fig. 3. FSU charge/radius (q/a) measurement system.

Fig. 4. Ionic charging of DES particles in air.

Fig. 5. Free electron charging of DES particles in ultra-pure nitrogen. ($E = 0.21$ kV/cm).

Fig. 6. Free electron charging of DES particles in ultra-pure nitrogen. ($E = 0.82$ kV/cm).

Fig. 7. Free electron charging of DES particles in ultra-pure nitrogen. ($E = 6.6$ kV/cm).

Fig. 8. Free electron charging of $1.0\text{ }\mu\text{m}$ radius DES particles in ultra-pure nitrogen.

Fig. 9. Free electron charging 0.5 and $1.0\text{ }\mu\text{m}$ radius DES particles in ultra-pure nitrogen.

Fig. 10. Free electron charging of DES particles in ultra-pure argon. ($E = 0.416$ kV/cm).

Fig. 11. Free electron charging of DES particles in ultra-pure argon. ($E = 0.83$ kV/cm).

Fig. 12. Comparison of data of DuBard, et.al. and this experiment. Particle charge (electronic units) is plotted vs. particle diameter (not radius).

Figure 1.

Figure 2.

F.S.U. Charge / Radius Measurement System

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.

Figure 11.

Figure 12.

B. Pulse Energized Electron Reactor (PEER) Project

1. Introduction and Summary

Effluent gases containing sulfur dioxide, nitrogen oxides, and/or particulate matter are generated from many sources, including coal burning power plants, iron and steel plants, paper mills, acid production plants, internal combustion engines, and the like. These pollutants contribute to the formation of photochemical smog and acid rain, and are harmful to the human body when inhaled. The U.S. Government has recently imposed stringent new standards for particulate emissions, and limits for SO₂, NO_x, and air toxics emissions have been proposed.

Pollution control devices have been standard components of pulverized coal combustion plants for many years. The high capital and operational costs of such devices is the primary motivation for the development of more efficient emission control equipment. Typically, each component of the flue gas (fly ash, SO₂, NO_x, air toxics) requires a different process and device for removal. For example, many plants utilize wet or dry scrubbers for SO₂ removal, catalytic converters or low NO_x burners for NO_x control, and electrostatic precipitators or fabric filters for fly ash collection.

Much recent concern has been focused on air toxics, primarily mercury, beryllium, arsenic, and radionucleotides, that are emitted from coal-fired boilers. Conventional flue gas cleanup methods for SO₂ removal such as calcium or limestone scrubbers suffer from the disadvantages that they are very expensive in both capital and operating costs, they do not remove nitrogen oxides or air toxics, and they generate large amounts of waste calcium sulfate that must be disposed of in landfills. A number of alternate techniques for flue gas cleanup based on the use of large pulsed electric fields, high energy electron beams, and combinations of high electric

fields and electron beams have been under development for the last ten years. These processes have the potential to reduce the costs for cleanup, to simultaneously remove nitrogen oxides, air toxics and sulfur dioxide, to aid in particle removal, and, with the injection of ammonia, to produce the salable fertilizer byproducts ammonium sulfate and ammonium nitrate.

A combined treatment process that yields an acceptable removal of SO_2 , NO_x , particulate emissions, and air toxics from flue gas using a single compact system promises several advantages with regard to capital investment and operational costs. Synergistic effects in the removal process between the particles and the gas phase components can further improve the economic feasibility. A relatively simple system which could be retrofit to an existing electrostatic precipitator or a baghouse would be especially attractive.

2. Pulsed Streamer Corona Research Efforts

The present work deals with a relatively new process for cleaning up flue gas that uses pulsed corona discharges, which is known as pulsed energized electron reactor (PEER) technology. PEER technology was discovered at FSU when attempts were made to improve the efficiency of E-beam processes for gas phase cleanup. In order to improve the efficiency of electron beam treatment processes for gas phase cleanup, various combinations of high energy electron beams with either ac pulsed power or dc continuous power electric fields were evaluated at FSU. It was found that when the gas treatment system was operated with a large ac pulsed power electric field with no high energy electron beam, more than 90% of the SO_2 was removed from a room temperature test gas containing moist air and approximately 1000 ppm of SO_2 . Therefore, only the pulsed electrical field, and not the electron beam, was necessary for high SO_2 removal efficiency. This technology uses fast rise time pulsed streamer corona in a pulse energized electron reactor (PEER).

The early PEER experiments therefore established a new method of SO_2/NO_x control. Process parameters such as the power consumption, temperature, and residence time in the bench-scale reactor were studied. Fly ash was found to increase SO_2 removal and NO_x was also simultaneously removed. PEER can also be used to convert the gaseous SO_2 and NO_x into liquid acid aerosols and subsequently into solid aerosol particles which can be collected downstream by conventional devices such as electrostatic precipitators or fabric filters. Corona discharge has also been found to be effective in removing mercury vapors from incinerator gas.

A program of laboratory PEER experiments were carried out recently at FSU with the active collaboration of Combustion Engineering, Inc., (C-E) during December, 1988. The objective was to measure PEER SO_2 removal performance at 150°C (a realistic process temperature) with a short residence time (1.5 seconds) and with the addition of water only. Experiments were conducted using the new FSU PEER reactor test bed, and gas distribution system which is a unique facility in the United States (Figure 1).

From the high energy electron beam work, it was anticipated that streamer corona would also be effective for NO_x removal. A second series of recent PEER experiments was carried out in collaboration with the F.L. Smidth (FLS) Company of Denmark during the summer of 1989. These experiments considered NO_x removal as well as improvements in the propagation of positive streamer corona in the presence of the electronegative constituents of flue gas, and improvements in the power efficiency. The PEER system hardware assembled for the experiments with Combustion Engineering (now Asea Brown Boveri) was also employed in this work. Experiments included a variation of temperature, electrode geometry, dc bias voltage, and water vapor content.

In parallel with the FSU effort, a number of investigators, particularly in Europe and Japan, have performed preliminary

Figure 1. The FSU Pulse Energized Electron Reactor Laboratory Scale Test System, showing the PEER Module.

experimental and theoretical studies of the PEER process. However, many aspects of the PEER system are still not well understood. For example, a number of operating conditions such as temperature, water vapor content, energy input efficiency, and gas composition have been varied in laboratory studies. These investigations have shown that indeed the use of pulsed streamer corona discharge is a potential alternative SO_2/NO_x , air toxic and particle removal process. However, these preliminary investigations were performed without guidelines from more fundamental studies of the process, therefore they have limited predictive capability for scale-up and design. In addition, these previous studies have not addressed such issues as the effects of diffusion, mixing and flow hydrodynamics, mass transfer, and detailed spacial variations of the reacting species concentrations. The many reacting species participate in numerous and complicated reaction pathways that must be elucidated for optimization and design.

PEER is different from high or low energy electron beam processes because it uses only a pulsed power supply and it does not need an electron beam generator. PEER is more power efficient than E-beam process. In addition to the PEER work, low and high energy E-beam ionization for the electrostatic removal of particulate pollutants and for the conversion of SO_2 and NO_x was successfully pioneered and demonstrated in laboratory experiments at the Florida State University. High energy electron beam technologies (300 - 1000 keV) are still being investigated for the removal of SO_2 from flue gas. The reaction chemistry for E-beam processes has been studied and some of these investigations may be useful for an analysis of PEER.

3. Future Research

In summary, general aspects of the PEER process have been studied, however, much remains to be understood in order to develop reliable methodologies for design, scale-up, and optimization of

the process for industrial applications and to evaluate the feasibility of removing air toxics from flue gas. Therefore, the overall goal of the PEER research project is to use fundamental principles of chemical reactor design to optimize the design of the pulse energized electron reactor for the removal of sulfur dioxide, nitrogen oxides, air toxics, and particles from coal fired power plant flue gas. This effort includes chemical kinetics and reactor simulation (i.e. modeling of swarm characterization, chemical reactions, and aerosol formation) closely coupled with experiments to understand the behavior of the process with respect to important process parameters such as reactor residence time, feed composition (including water content), energy efficiency, and electrode geometry. It is anticipated that future studies will play a very important role in an eventual scale up (of the new process) to a pilot plant or even larger installations.

VIII. PUBLICATIONS, PRESENTATIONS, PARTICIPATIONS, AND VISITORS

A. Publications

1. "Aerosol Particle Charging by Free Electrons".

The paper reprinted in Section VIII-A, entitled "Aerosol Particle Charging by Free Electrons", authored by D.B. O'Hara, J.S. Clements, W.C. Finney, and R.H. Davis, all at that time of the Aerosol Physics Group, FSU, was published during the contract lapse period of March -- August, 1989. It appeared in print in the Journal of Aerosol Science, Volume 20, Number 3, pp. 313 -- 330, 1989. Because of its importance as a stand-alone work and its relevance to the ongoing development of the pulsed electron beam precharger, the article was reprinted in its entirety in Section VII-A.

2. "Combined Removal of SO₂, NO_x, and Fly Ash from Flue Gas Using Pulsed Streamer Corona".

The paper entitled "Combined Removal of SO₂, NO_x, and Fly Ash from Flue Gas Using Pulsed Streamer Corona", authored by J. Sidney Clements, Akira Q. Mizuno, Wright C. Finney, and R. H. Davis, was recently published in the IEEE Transactions on Industry Applications, Volume IA-25, No. 1, pp. 62-69, January/February, 1989. The conference version of the paper was originally presented at the Industry Applications Society Annual Meeting held in Denver, CO, in September of 1986. The revised paper details a technology using positive pulsed streamer corona in a module similar to an electrostatic precipitator for the simultaneous removal of the gaseous pollutants SO₂, and NO_x, and the particulate effluent fly ash.

3. "Use of an Electron Beam for Particle Charging".

A paper entitled "Use of an Electron Beam for Particle Charging", authored by Akira Q. Mizuno, J. Sidney Clements, and Robert H. Davis, was published during this quarter in the IEEE Transactions on Industry Applications, Volume IA - 26, No. 1, pp. 29 - 35, January/February, 1990. This paper was originally presented at the IEEE - Industry Applications Society Annual Meeting held in Chicago, Illinois, in October of 1984. It was also published in preliminary reviewed form in the Conference Record of the Annual Meeting, pp. 1215-1219. Electron beam precharging was investigated in this study using 1.1 and 3.0 μm particles in a bi-electrode electron beam precharger geometry. Particle charge levels higher than that expected by ionic field charging theory were found; free electron charging is thought to be responsible for the difference.

4. "Flue Gas Cleanup Technology Utilizing Energetic Electrons".

The Final Contract Report entitled "Flue Gas Cleanup Technology Utilizing Energetic Electrons", by R. H. Davis and W. C. Finney (396 pp.), covers the work performed under the U.S. Department of Energy Contract Number DE-AC22-86PC91021, for the period May 6, 1986 - March 5, 1989. Two major Tasks incorporating more than twenty sub-Tasks were specified in the original two-year contract plus a four month no-cost extension, while six additional tasks were completed in a six-month funded contract extension period. This report was submitted to the Pittsburgh Energy Technology Center, U.S. DOE, on February 23, 1990 and was accepted by PETC on March 12, 1990.

B. Presentations

1. 1989 Flue Gas Cleanup Peer Review Meeting -- Bethesda, MD.

The Office of Program Analysis, located within the Office of Energy Research (OER) of the U.S. Department of Energy conducted an assessment of the research projects in the Fossil Energy Flue Gas Cleanup Program during 1989. The review of Flue Gas Cleanup projects occurred during a workshop held at the Hyatt Regency Hotel, Bethesda, MD, on August 22-24, 1989. Prof. R.H. Davis, Principal Investigator of the U.S. DOE contract entitled "Flue Gas Cleanup Technology Utilizing Energetic Electrons" presented a summary of the project results and outlook to a peer review panel. A Project Output Statement and other relevant information concerning the work of the Aerosol Physics Group at FSU was also submitted to the reviewers.

2. Peer Review Assessment of Research Projects in the Fossil Energy Advanced Research Programs.

A peer review assessment of the research projects in the Fossil Energy Advanced Research programs was conducted during the fourth quarter of this contract. The review was performed as part of the program evaluation activities by the Office of Fossil Energy and the Office of Program Analysis, which is in the Office of Energy Research. Each project was reviewed in one of several review sessions held during the summer and fall of 1990. This project, entitled "Pulsed Electron Beam Precharger", U.S. DOE contract No. DE-FG22-89PC89768, was reviewed by a panel ten technical experts on August 21, 1990, in Bethesda, MD. The purpose of the review was to gather information from contractors in order to allow an assessment of the project's quality and relevance to the programmatic mission of the DOE.

The review process consisted of an oral presentation by Mr. Wright C. Finney to the review panel preceded by the submission of a written summary of the work performed on the contract. Composed of a number of separate subsections, the written portion of the review process consisted of the following outline headings:

1. Project Title
2. Patentable Inventions
3. Principal Project Personnel
4. Additional Project Personnel
5. Project Overview
6. Scientific and Technical Content
7. Project Output

The Project Overview and the Project Output are included in several sections of this report; the entire written summary of the project information was submitted to the OER Assessment Office at Oak Ridge National Laboratory on June 5, 1990. Oral review of the project was conducted on August 21, 1990, and consisted of a 65 minute presentation and question/answer session.

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

Early during the period covered by this contract, one of the investigators was invited to give the departmental colloquium to the Department of Chemical Engineering, Florida A & M University / Florida State University College of Engineering, Tallahassee, FL. Professors Bruce R. Locke and Pedro Z. Arce hosted Mr. Wright C. Finney of the FSU Aerosol Physics Group 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 (RO_x) (fly ash). 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.

4. 1991 UCR/HBCU Contractors' Review Meeting -- "Pulsed Electron Beam Precharger".

The annual University Coal Research (UCR) and Historically Black Colleges and Universities (HBCU) Contractors' Review Meeting, sponsored by the U.S. Department of Energy/Pittsburgh Technology Center, was held June 25 - 27, 1991, in Pittsburgh, PA. Mr. Wright C. Finney of the Aerosol Physics Group presented a paper entitled "Pulsed Electron Beam Precharger", which summarized the research work on pulsed anode electron beam precharging, with an emphasis on recent experimental results. In addition, a written Abstract and Highlight Accomplishments detailing the project output was submitted to the conference chairman for internal use and for distribution at the meeting. This presentation is required of all projects at the completion of the second year of the DOE/PETC contract.

C. Participations

1. 1990 Contractors' Review Meeting of Research Projects in the University Coal Research Program.

A review meeting for the Contractors in the University Coal Research (UCR) and Historically Black Colleges and Universities (HBCU) Programs was held on July 16-19, 1990, in Pittsburgh, PA. This annual conference which began in 1984 is sponsored by the Pittsburgh Energy Technology Center of the U.S. DOE, and principal investigators of all grants in the above programs are required to attend. The meeting was designed to assemble all of the contractors and PETC project personnel in order to effect a mutually beneficial transfer of information concerning project research. Prof. W. Neil Shelton represented the Aerosol Physics Group, Florida State University, and participated in the Contractors' Review Meeting.

As part of the review process, the University Coal Research program requested the submission of an Abstract and Highlight Accomplishments of the contract research and an abbreviated list of published and submitted articles, and completed and forthcoming presentations. For the Aerosol Physics Group DOE Contract No. DE-FG22-89PC89768, entitled "Pulsed Electron Beam Precharger", the submitted information has been reprinted in this section. Since the education of new scientists and engineers is one priority of these programs, a listing of degree-seeking students affiliated with the Aerosol Physics Group is included.

D. Visitors to the Laboratory

1. Dr. W.K. Rhim, Jet Propulsion Laboratory, Pasadena, CA.

The Aerosol Physics Group at Florida State University was visited by Dr. Won-Kyu Rhim of the Modular Containerless Processing Facility, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, on February 12-13, 1990. His primary interest in visiting FSU was in learning more about various uses of small electron beam sources. The 100 keV maximum energy MINACC electron beam accelerator which was designed and constructed entirely at FSU became Dr. Rhim's principal focus during his visit. His group at JPL is interested in charging high temperature material samples for electrostatic levitation and containment in a microgravity environment. Since the Aerosol Physics Group has expertise in small, low energy (< 100 keV) electron guns, a lively discussion concerning various accelerator configurations ensued between the two parties. A tour of the Electron Beam Precipitator laboratory was followed by an in-depth description of the particle charging research currently being conducted at FSU. A continuing dialogue between the two parties concerning electron beam technology is planned.

2. Dr. Kauko Janka, Tampella Company, Finland.

The Aerosol Physics Laboratory was visited by Dr. Kauko 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.

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IX. PERSONNEL

A. Current and Past Personnel Listing

The following is a list of persons who worked on this project. This list does not include support personnel in Physics Department facilities such as machine shops, electronic shops, or in illustrative services.

Scientific Investigators

1.	Dr. W. Neil Shelton	Principal Investigator
2.	Mr. Wright C. Finney	Associate in Research
3.	Dr. Robert H. Davis	Former Principal Investig.

Graduate Student Assistants

1. TBA

Undergraduate Student Assistants

1. David Eibeck
2. Arnnie Gibson
3. Chris Oswald
4. Misho Sarwar
5. John Blair

Part-time Secretaries

1. Natalie Duguid
2. Cheryl Brown
3. Amy Maxey
4. Nancy Lochner
5. Pat Clark

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END

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