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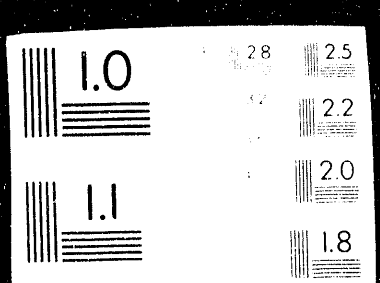

Table I   Results from experimental runs measuring the collection efficiency and precharger efficiency

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PULSED ELECTRON BEAM PRECHARGER

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PULSED ELECTRON BEAM PRECHARGER

Technical Progress Report Number Nine

September 1, 1991 - November 30, 1991

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I. INTRODUCTION AND CURRENT STATUS OF THE PROJECT

Quarter Nine of the Pulsed Electron Precharging project was principally devoted to reviewing and interpreting the experimental results obtained during the past eight quarters of the project.

We shall first briefly review the motivation for carrying out this 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 back-corona corona problem is described more fully in the next section of this report. This re-entrainment problem can be eliminated through 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 and resultant small corona currents required to avoid the back-corona problem.

Another approach to solving the problems inherent in collecting high resistivity fly ash in an electrostatic precipitator 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. This precharger can be optimized for the charging function while the downstream collector can be optimized for collection 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. In that previous work electrons from an ionization zone created by the electron beam were drawn across the flue gas stream by the application of a constant high potential. The maximum voltage was limited by the onset of sparking or production or production of opposite sign ions in the precharger.

Numerous studies 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 potentials exceeding the onset of sparking can be applied to gases without the initiation of spark production, the present research with pulsed anode potentials of short duration (≈ 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-potential pulse.

Although the present research has not been concerned with 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 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. The sulfur dioxide removal efficiency of the pulsed electron beam precharger has not be investigated in the present research, but should certainly be addressed in future research. We are very excited about the possibilities inherent in such future research.

The experimental apparatus and experimental results have been presented in great detail in previous Technical Progress Reports 1 through 8. The experimental apparatus was modified for pulsed operation during the periods covered by Technical Progress Reports 1 through 7. Technical Progess Report 8 discusses 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 this reporting period which was focussed on the understanding and interpretation of the experimental results previously presented.

II. PROGRESS DURING QUARTER NINE

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 our dc precharger using an anode to cathode voltage of 66 kV dc (4.7 kV/cm electric field). The collection efficiency was found to improve as the anode-to-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.

Since the electron current density (and hence volume charge density) in the active volume of the dc precharger is limited by the maximum cathode-anode 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 I. 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 collecor 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.

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.

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 -- 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:

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

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 short compared to the charging time constant τ, this equation takes the approximate form:

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

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 μs exposure to the pulses the charge collected by the aerosol particle is 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.

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 electrodes) which lead to sparks. The results obtained in the FSU pulsed electron beam precharger 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 electric field of 8 kV/cm. In addition, the electron velocities and densities are much greater than 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.

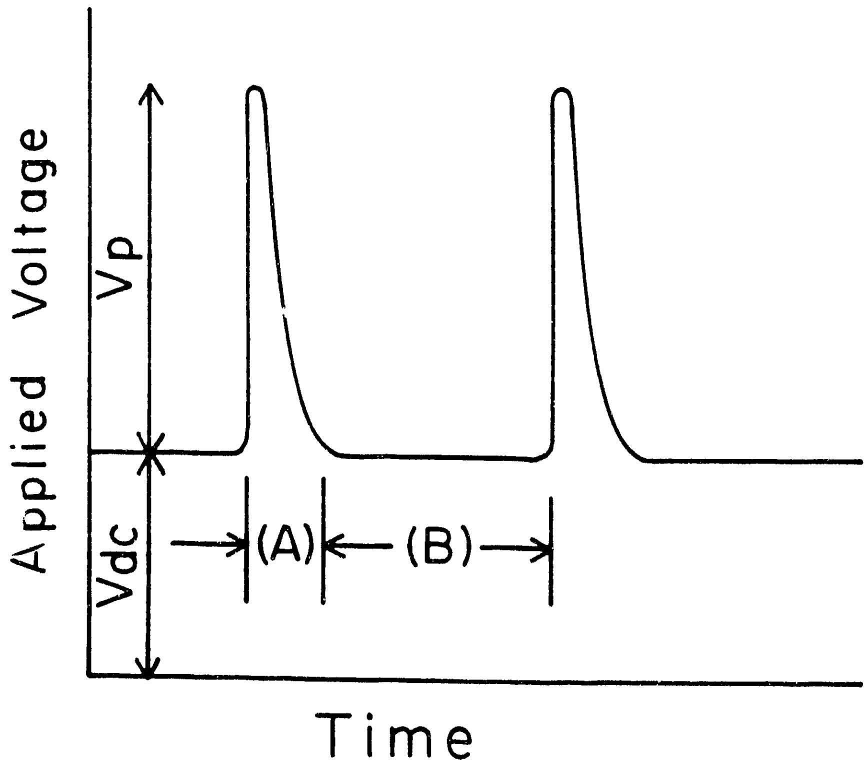
Even though the interior of a streamer is clearly a good place in which to effect the charging of particles, it does not logically follow that particles will be appreciably charged in a flue gas sample in which streamers are present. Conditions must also be such that a particle will be exposed to one 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 our precharger these free electrons are supplied by the electron beam in the manner discussed above, 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 no dc bias voltage but only pulsed overvoltage do not show useful charging of the particles (see Table I, 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 of particle charging observed with 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 avalance, which can then lead to the formation of a streamer.

The reader might wonder why the positive ions in the streamer would not neutralize the negative ions and electrons 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 the ions is approximately 1000 times less than that for electrons. After the pulse is over, the excess free electrons recombine with the positive ions before these slowly moving ions can be collected by the dust particles.

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 dc bias voltage of 20 kV dc and a pulse voltage of 66 kV, 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, since full voltage is applied between the anode and cathode for only about 0.001% 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 redesigned high electric field, low current collector.



(A) = Pulse-On Period
(B) = Pulse-Off Period
Vp = 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.

Table I. 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 of run B-100, which is 66 kV pulses superimposed on a 20 kV dc bias.

Constants:

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

Run Number	Comparison (Test Dust)	Precharger Voltage (kV)	Precharger E-Field (kV/cm)	Precharger Ion Current (μA)	Collection Efficiency (%)	α-Value (Collector + Precharger)
A-430	dc-only	--	--	--	86.1	--
	(Hydral)	55 dc	3.9	40	98.3	8.2
		66 dc	4.7	41	98.7	10.4
B-30	Pulse Voltage	--	--	--	89.8	--
	(Hydral)	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	--	--	--	93.2	--
	(Hydral)	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	--	--	--	88.2	--
	(Fly Ash)	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

III. DIRECTIONS FOR FURTHER RESEARCH

We believe that the greatest advantage of pulsed precharger operation will be found in a study of actual flue gas produced by the combustion of low sulfur coal and subsequently passed through the pulsed 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 to condensible sulfides -- the pulse energized electron reactor (PEER) device. The triggering electrons in the PEER device were produced by a pulsed corona. The corona was produced 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 SO_2 removal efficiency.

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 creation of electron avalanches and the resultant streamers are produced by the application of sufficient overvoltage and not from the particular electrode geometry. The SO_2 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 conversion measurements in the present device. 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 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 is passed through the pulsed E-beam precharger is expected to have a reduced resistivity because sulfides will be produced in 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, 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. This would be possible because 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.

IV. CONCLUSION

This research has resulted in the discovery of an important new way to charge aerosols 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 in the medium since the presence of only a few of these can produce a serious discharge of the aerosol particles.

Our experimental results lead us to believe that we have an intermittent bipolar medium in the precharger during the positive anode pulses, and that this medium results from the production of streamers in the overvoltaged gas. The 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 is so short that the relatively massive ions cannot attach to the aerosol particles during the pulse. After the pulse 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 time interval employed.

Our experimental results from the pulsed precharging 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.

V. PERSONNEL

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.

A. Scientific Investigators

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

B. Graduate Student Assistants

1. TBA

C. Undergraduate Student Assistants

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2. Misho Sarwar
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D. Part Time Secretaries

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

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