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ASSESSMENT OF THE JORDAN CEMENT FACTORY, AMMAN

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I. EXECUTIVE SUMMARY

The author was requested by the World Environment Center and the U.S. Agency for International Development to make an environmental assessment of the Jordan Cement Factory plant at Fuhais, Jordan. While in Jordan, it was further requested that the author also visit the cement factory at Rashadiya.

A similar visit was made by a WEC sponsored team in 1983. Many of the recommendations made as a result of this earlier trip have been implemented by the Jordan Cement Factory but work can still be done to reduce emissions. The Fuhais Works is located adjacent to the town of Fuhais with the prevailing winds directing plant emissions over the community. Dust emissions from the cement works still constitute a significant detriment to the surrounding area. The emissions would be classified as nuisance dust, they are not toxic, and should not impose a significant threat to the health of the surrounding area with the exception of individuals having existing respiratory problems.

Both the Fuhais Works and the Rashadiya Works have equipment capable of controlling dust emissions. A significant problem exists from haul road generated dust and from dust associated with the outside storage of raw materials and clinker.

As recommended in the earlier study, lines 1-3 have been phased out. The remaining lines have acceptable control capabilities when properly maintained and operated. The number 5 line clinker cooler multiclone, however, has marginal capability for meeting today's standards.

The author felt that monitoring and maintenance of dust control equipment could be improved. Specifically, the addition of monitoring devices to fabric filters would be of benefit. Again it was found that quarry roads required upgrading and maintenance. The recommendation of having technically qualified plant personnel review dust collection operations was followed. Each plant has established departments for this purpose. The author met and talked with each of the environmental engineers. Both were conscientious and wished to do a good job. They expressed a desire for increasing their knowledge as to: environmental control strategies, proper equipment operation and maintenance, and system monitoring and testing. It is felt that providing the desired training would be of great benefit to these and other personnel.

In order to reduce plant emissions, the following main recommendations are made:

- Replace or augment line 5 multiclone with a gravel bed filter or an equivalent control technology.
- Discontinue the outside storage of raw materials and clinker (reduced production demand may accomplish this).
- Require prompt clean-up of exposed accumulated and/or spilled materials.
- Require routine monitoring and maintenance of dust control equipment with malfunction reports and followup reports of corrective action taken. This has been done to some extent but much more work needs to be done in this area.
- Upgrade quarry roads and provide effective dust suppression. Grading of roads has been done and shrubbery has been planted in an effort to reduce roadway dust, but more should be done.
- Provide engineering staff and maintenance personnel with training in the areas of operation and maintenance of environmental control equipment.
- Upgrade the routine inspection of dust collection equipment.
- Establish an air quality monitoring program in the vicinity of both plants in order to quantify emissions and determine the sources of these emissions. This should include training personnel in the making of opacity observations from point sources.

- Establish specific limitations for each point source and also for open source emissions. Once this is done, requirements for best available control technologies should be used to meet the required emission limit.

- Install transmissometers (opacity meters) for monitoring point sources of particulate emissions.

- Establish deadlines for meeting environmental goals.

II. INTRODUCTION

At the request of the Jordan Cement Factory, a visit was made to the Fuhais Cement Works and to the Rashadiya Cement Works by a representative of the World Environment Center during February, 1992. The cement factory has the desire of being a responsible member of the communities in which their plants are located. Therefore, they are concerned about the emission of pollutants and would like to minimize them where possible. Jordan does not, at this time, have particulate emission limits, but it is expected that pollution guidelines will be established in the near future. The visit was made in order to evaluate the acceptability of existing dust control equipment for meeting typical emission limits. Also, it was requested that current operation and maintenance of the equipment be evaluated.

Approximately one week was spent at the two cement factories with most of the time being spent at the Fuhais Works. Where possible, internal inspections of pollution control devices were made at both plants. The information gathered, its evaluation and recommendations for reducing particulate emissions are given in the report which follows.

THE CEMENT MANUFACTURING PROCESS

Cement is a material with adhesive and cohesive properties which allows it to bond mineral fragments into a compact whole. Portland cement, named after the Isle of Portland due to its having color and texture similar to limestone found there, was invented by Joseph Aspdin of Leeds, England in 1824. It is the most prevalent type of cement in use today.

Portland cement is made by grinding and blending lime containing compounds (limestone, marl, chalk, or shells) with materials containing silica and/or alumina (clay, shale, ashes, or slag). Iron ore and other minerals are sometimes added to obtain the required cement composition. The materials must be finely ground and intimately blended before being fed into the kiln.

Rotary kilns are used almost exclusively in the U. S. for the production of cement while some vertical kilns are used in Europe. Cement rotary kilns are long cylindrical refractory vessel which are slightly inclined. They are typically 4 to 5 meters in diameter and 50 to 200 meters long and rotate at a few revolutions per minute. Heat is generated by a burner at the lower end which is fueled by coal, oil, gas, etc. Temperatures in the kiln range from approximately 300°C at the upper end to as high as 1550°C at the lower end.

The raw material (feed) is introduced at the upper end of the kiln and slowly progresses toward the lower end of the kiln. As the material moves down the kiln, its temperature gradually increases. Initially, free moisture is driven off; then around 540°C, the combined moisture begins to disassociate. Calcining, or the release of carbon dioxide, begins with its disassociation from $MgCO_3$ at approximately 600°C and continues with its release from $CaCO_3$ at approximately 900°C. At a temperature of around 1350°C, the material sinters (liquids are formed which combine with solids) and fuses to form balls called clinker. The clinker exits into a cooler at the lower end of the kiln. After cooling, the clinker is stored until it is ground into the very fine powder known as cement. Gypsum, which is added to the clinker before grinding, is used to control the setting properties of the cement.

The composition of cement is rigidly controlled in order to obtain the desired physical properties for different applications. In the U. S. five types of portland cement are manufactured. Their compositions are listed below:

TYPES OF PORTLAND CEMENT

Constituent	Type I	Type II	Type III	Type IV	Type V
$3CaO\ SiO_2$ (%)	45	44	53	28	38
$2CaO\ SiO_2$ (%)	27	31	19	49	43
$3CaO\ Al_2O_3$ (%)	11	5	11	4	4
$4CaO\ Al_2O_3\ Fe_2O_3$ (%)	8	13	9	12	9
$CaSO_4$	3.1	2.8	4.0	3.2	2.7
MgO	2.9	2.5	2.0	1.8	1.9
Free CaO	0.5	0.4	0.7	0.2	0.5

In addition to these standard types of portland cement, many modified types are manufactured. Among these modified cements is possolanic cement. Which is made by grinding and blending from 15 to 85% pozzolanic material with the cement clinker. Pozzolana is a name given to volcanic ash, pumicite, and other siliceous rock.

SOURCES OF DUST AND THEIR CONTROL:

Due to the nature of the process, dust is generated in all of the steps of cement production by the "dry process" method (the method used by Jordan Cement). From the quarrying of the raw materials to the loading of cement for shipment, dust is produced and should be controlled.

Only a small fraction of the dust generated at the quarry by blasting and/or digging is in the size range which remains airborne under normal conditions. Most of the emissions associated with the quarry are produced by vehicular traffic on haul roads between the quarry and the plant. Motor vehicles, especially those equipped with diesel engines, generate significant quantities of carbon particulate. Wind erosion also contributes significantly to air suspended solids. Typically, haul road emissions are controlled by periodically wetting their surface, or through improving the surface by overlaying it with a course aggregate or by sealing it with a petroleum based product. Wind erosion is controlled by the erection of wind breaks and/or planting of vegetation for the same purpose.

Crushing, blending, conveying, transferring and storage of materials also generate dust. These emissions are typically controlled by performing the operations in enclosed spaces with, in some cases, ventilation systems. Ventilation systems used for this purpose include mechanical collectors or fabric filters.

The gas exiting the kiln at the feed end usually has a very high dust loading. Electrostatic precipitators and fabric filters are used to remove this dust. In many cases the precipitator or baghouse is preceded by a mechanical collector and/or a quench (gas cooling) tower. Where fabric filters are used, the quench tower reduces the gas temperature to avoid damage to the fabric. In the case of an electrostatic precipitator, gas quenching lowers the electrical resistivity of the dust. In both cases, the lower temperature decreases the volume of gas which must be treated.

Air used to cool the clinker entrains large quantities of dust. Mechanical collectors, fabric filters or other filter media are used in the collection of this dust. The handling and storage of clinker usually takes place in enclosed, ventilated areas to avoid dusting.

Blending the clinker with gypsum, etc. and grinding these to make the final product generates dust containing a high percentage of fine particles. Fabric filters or electrostatic precipitators are typically used to remove this dust from the gas stream. Fabric filters or mechanical collectors are used to control dust in cement packing plants.

III. FINDINGS

THE JORDAN CEMENT FACTORIES COMPANY, LTD.

The Jordan Cement Factories Company was established in 1951 as a public shareholding company. It has an agreement with the Hashemite Kingdom of Jordan which makes it the only entity in Jordan which can establish and operate cement factories. Production of cement was begun at the Fuhais plant in 1954 with one kiln which had a capacity of 200 tons per day of clinker. By 1963, three kilns were in operation. Kiln 4, with a capacity of 700 tons per day was installed in 1968. Kiln 5, with a capacity of 2000 tons was added in 1979 and Kiln 6, having a capacity of 3000 tons per day was installed in 1982. Kilns 1, 2, and 3 were decommissioned at the end of 1983. The Fuhais facility uses only one type cement, Pozzolana portland cement (PPC) which has improved properties with respect to strength and durability as compared to ordinary portland cement (OPC). Limestone, marly limestone and marl are obtained from an on-site quarry, while the other raw materials needed for the production of cement are obtained from local sources.

A second plant is located south of Amman near the town of Rashadiya. The Rashadiya Works has two kilns and produces two types of cement: ordinary portland cement (United States ASTM C 150-Type 1) and a sulfate resistant cement (United States ASTM C 150- Type V). Most of the raw materials are obtained locally, but iron ore used in the Type V cement is imported.

1992 VISIT AND EVALUATION OF AIR POLLUTION CONTROL

Both Jordan Cement Factories Company plants were visited during the week of February 17, 1992 at the request of company personnel. The visit was made to assess air

pollution control systems and strategies in use by JCF to control emissions from their facilities. The work was sponsored by the U.S. Agency for International Development through the World Environment Center.

A similar evaluation was made in November 1983. Many of the recommendations made as a result of that visit have been followed. These include:

- the decommissioning of kiln lines 1, 2, and 3;
- the paving of much of the yard and roadways of the Fuhais facility;
- the purchase of sweeping vehicles to remove dust from paved surfaces;
- the purchase of vacuuming equipment for clean up;
- the planting of shrubs and flowers on slopes and unpaved yards; and
- the formation of departments responsible for evaluating the performance of dust collecting equipment.

Some recommendations made as a result of the earlier visit had been partially implemented while others had not been followed. The implementation of earlier recommendations which were not made should reduce emissions. Therefore, they will again be made and expanded upon in this report. Previous recommendations which were implemented are as follows:

- At the Fuhais Works, Kilns 1, 2, and 3 (installed between 1954 and 1963) which did not have pollution control equipment meeting today's standards have been decommissioned. This eliminated major sources of dust emissions.
- Ten hectares of roads and yards at the Fuhais Works have been paved. More can be done in this area and will be discussed later in the report.
- Sweeping and vacuuming equipment have been purchased.
- Trees and shrubs have been planted in unpaved yards and on slopes to reduce wind blown dust.
- Departments have been formed at both plants to monitor the performance of the various dust collectors and to insure proper operation and maintenance.

As pointed out in the 1983 report: "A certain degree of impact on the surrounding area is unavoidable from any heavy industry such as a large cement plant." Dust is the major pollutant associated with cement production. For the most part, the dust would be classified as "nuisance particulate" and should not present a significant health hazard. One particulate associated with cement production which can present a health risk is free silica. Exposure to free silica or quartz dust can cause a lung disease, silicosis. Also, cement dust and other dusts associated with its production can be very caustic when combined with moisture. Therefore, every effort should be made to minimize emissions from the plants.

The close proximity of the Fuhais Works to the town of Fuhais and to the cement factory employee housing, the fact the plant is almost completely surrounded by hills, and the velocity and direction of the prevailing winds exacerbates the impact of the plant's particulate emissions. The Rashadiya Works is located in a rural area at a higher elevation relative to its surroundings, thus, particulate emissions from the Rashadiya Works do not have as severe an impact as those of the Fuhais Works. Most problems seen were common to both plants, therefore, to avoid duplication, these problems will be listed and discussed in general. Some specific problems will be mentioned with the plant where it was found being cited.

Dust from the quarry and from haul roads is still a significant problem at the Fuhais works. It is felt that similar problems exist at Rashadiya, but this was not confirmed since the area had experienced a heavy snow fall just prior to the visit, and all roads were wet from the melting snow. Most of the Rashadiya plant's roads were not paved, or if they were, they were covered with a thick layer of mud.

It has been found by a study done by the Harvard School of Public Health[1] that the average total suspended particulates (TSP) in the United States from open source (roads,

fields, construction, etc) far exceeds those produced by point sources. Appendix A is a copy of this report. Table 2 of the paper gives comparisons of annual open source emission rates for various sources within each of the 48 contiguous states. New Mexico (NM), Arizona (AZ), and Nevada (NV) have similar climate and terrain to that of Jordan, thus, one might expect the relative contributions to TSP from open sources to be similar. In each of these states, emissions from unpaved roads is the largest contributor to overall average TSP. In the vicinity of point sources, the emissions from the point sources contribute a larger percentage to the TSP of the area, but open sources are still significant.

A note published by M.N. Khattak in 1982[2] presents the findings of a study of the relationship between TSP and meteorological parameters on the campus of the University of Petroleum and Minerals, Dhahran, Saudi Arabia (See Appendix B). The level of ambient TSP found in this study should be comparable to that of Jordan, and also a similar relationship between natural and man produced particulate should exist. The study found that even though a relationship with wind speed and direction was found, a significant percentage of the particulates were associated with man's activities (see Figure 2 of Appendix B).

A final comment should be made with respect to exposure to suspended solids. As mentioned earlier, cement dust is not considered toxic, but exposure to high concentrations of respirable particulate can and does have an effect on pulmonary function. Appendix C is a copy of an article[3] showing a correlation between high TSP and changes in the pulmonary function of children. The study looked at the qualitative as well as the quantitative pulmonary function of a group of school children following exceedances of TSP standards. The effects were not seen immediately following exposure, but occurred

one or two weeks later. Also, it should be noted that while a statistically significant decrease in lung function was seen, it was physiologically small and appeared to be reversible.

The above comments were made in order to indicate the importance of reducing, where possible, open sources of dust emissions. While Jordan Cement has done quite a bit with regard to this issue, much can still be done. Improving and maintaining unpaved quarry and plant roads, and continuing the sweeping or vacuuming of paved areas should reduce open source emissions. Appendix D is a copy of an article which presents one method of reducing dust emissions from unpaved roads. Photographs 7, 8, 11, 12. 13 are indicative of unpaved areas which might be improved to reduce particulate produced by traffic and wind erosion.

A recommendation of the previous visit was to discontinue the stacking or storage of raw materials and clinker in open areas. Both plants still store a portion of their clinker and some raw materials out of doors. Photograph 29 shows clinker from Line 4 of the Fuhais Works being stacked in an open area. The long drop from conveyor to ground was generating a large quantity of air borne dust. If plans are to continue storing clinker in this manner, the installation of a flexible chute between the conveyor and the top of the pile would reduce dust generation. The enclosure behind the area in which the clinker was being stacked was open at both ends. For some wind conditions, this enclosure would serve as a funnel to increase wind speed which would exacerbate particulate entrainment. Photographs 2, 3 and 5 show other open storage areas at the Fuhais Works which are potential sources of particulate. It is recommended that the outside storage of soft/powdered raw material and clinker be minimized.

Within the plants, many conveyor spills, deposits from collector hoppers, deposits associated with equipment maintenance, etc. were seen. These deposits, in some cases, represented a safety hazard in that they led to unsure footing on stairs or gratings. Loose dust deposits within the plant should be cleaned up as soon as possible following a spill especially spills of raw materials since they typically contain higher concentrations of free silica than does cement.

The fabric filter (baghouse) is the most used collector in terms of number at the Fuhais Works. Table 1a lists 56 fabric filter collectors along with their sizes and volume of gas each was designed to treat. These filters range in size from one having a filter area of 32 M^2, treating 3,600 M^3/hr, to one having 396 M^2, treating 45,000 M^3/hr of gas. An internal inspection of only one fabric filter was made. This was a small one used to vent a clinker transfer conveyor at the Rashadiya Works. The following problems were noted:

- Several holes were found in the hopper shell. When in operation, this would reduce the draft at the inlet of the filter.
- All of the bags had extremely heavy dust loadings and appeared to be blinded (impermeable to gas flow). This would indicate an extremely high delta P during operation.
- One bag and its cage was disconnected from the tubesheet. This was, therefore, the most likely path for the gas through the filter, thus, the effectiveness of the filter was near negligible.

Two outlets of a fabric filter in the packing house of the Fuhais Works were dusting heavily. This was most likely due to broken bags. The evacuation screw from a filter in the Line 7 mill room was leaking. This was dropping dust onto the floor beneath the filter. This unit was not on at the time, so its performance was not monitored.

No means of monitoring tubesheet differential pressure (delta P) was seen on the baghouses which were looked at. The installations of differential pressure gauges or transducers across the tubesheets of all baghouses would be very helpful in monitoring

performance and in troubleshooting the units. It has been the experience of many fabric filter users, that cleaning effectiveness for on-line cleaning of pulse jet units is severely diminished or reduced to zero if tubesheet delta P exceeds 6 - 7 inches water gauge (1490 - 1740 pascal). The design of most of the smaller units of the Jordan Cement factory would necessitate on-line cleaning. The condition of the bags seen in the Rashadiya unit were such that the delta P would have been above the 1500 - 1700 pascal if all of the bags had been installed. Blinded or broken bags should be replaced if proper operation of the fabric filter is expected.

Three types of pulse-jet fabric filters are used by industry. These are classified as: high pressure, low volume; intermediate pressure and volume; and low pressure, high volume. Figure 1 gives a comparison of the operating parameters of the three types. In all cases effective cleaning depends upon an adequate supply of clean air at the proper pressure. Pressure gauges on the cleaning air supply at the inlet manifold of each fabric filter would also be of benefit. This would allow one to determine if a sufficient supply of clean air was available.

All fabric filters at the Jordan Cement Factory Works operate at relatively low temperatures, thus inexpensive felted fabrics are most likely used as filter media. The author did not determine the types of fabrics in use but it is assumed that an acrylic of some type would be the predominant fabric. The heavy dustcake seen on the Rashadiya baghouse was typical of what one would see for operation at or below the moisture dew point, or for ineffective cleaning. A more forgiving fabric for the above conditions is a singed felt fabric. With this fabric the loose fiber on the collecting surface has been burned away leaving nothing to which the dust nodules can attach.

A relatively inexpensive device for monitoring baghouse emissions has been developed by Auburn International of Danvers, Maine. This device called the Triboflow: Broken Bag Detector is very sensitive to the dust loading of the gas exiting a fabric filter, thus it can give an indication of small leaks in the filter media. Jordan Cement Factories might consider installing these devices in order to monitor baghouse emissions.

Electrostatic precipitators are used to collect the dust exiting the preheaters of the kilns at both cement plants. Precipitators are also used to remove the dust from the exhaust of the Line 6 and Line 7 cement mills. Table 2a is a partial listing of the electrostatic precipitators in use at the Fuhais Works. No information was obtained concerning the design specifications for the precipitators used at the kiln exit of line 4. This kiln has two single chambered precipitators in parallel followed by a two field single chambered unit in series. Prior to the late 1960's, electrostatic precipitators for use in cement applications were typically small units designed for collection efficiencies in the range of 90% to 95%. This efficiency was significantly higher than the inherent collection efficiency (65% to 70%) of the mechanical collectors which precipitators replaced. Many of these precipitators were never tested to see if they indeed met their design guarantee. With stricter environmental regulations, these low collection efficiencies were no longer sufficient and precipitators were designed and built for much higher efficiencies. Currently, precipitators are being designed for collection efficiencies in the range of 99% to 99.9%. Precipitators on dry process kilns are usually preceded by a gas quenching tower in order to reduce the gas temperature to a range which will insure a dust resistivity range sufficiently low enough for good precipitator electrical conditions. The moisture added to the gas also acts as a resistivity modifier. Figure 1 is a plot of resistivity verses temperature for cement dust. The three curves shown are for: raw mill on, raw mill off,

and raw mill off with dust annealed by heating at 750°C. The ideal resistivity for good electrical conditions is 1-2 x 10^{10} ohm-cm. One can see from the curves in Figure 1 that a temperature below 130°C would be required in order to have a favorable resistivity for the mill-on condition and a much lower resistivity would be required for the mill-off condition. The annealed curve produced in the laboratory would not be seen under field conditions. More will be written about these curves when specific problems encountered by the Jordan Cement Factory are discussed.

Precipitator performance depends to a great extent upon the particle size distribution of the dust to be collected. Particles having diameters greater than 5 μm are easily collected, as are particles having diameters below 0.1 μm. The collection efficiency of a precipitator as a function of particle size has its minimum at a diameter between 1 and 2 μm. Cement dust typically has a large concentration of particles in this 1 to 2 μm size range. This means that precipitators in cement applications must be relatively large if high collection efficiencies are to be obtained. Also the units must be properly maintained and operated.

Another problem which can seriously degrade ESP performance is high gas velocities. Collection efficiency is a function of treatment time. Also, for velocities above 2 to 2.5 m/sec, particle re-entrainment becomes a significant contributor to emissions. The quality of the gas flow distribution (distribution of local face velocities about the mean or average velocity) also plays a larger roll as the average velocity increases. Current designs are required to meet the Industrial Gas Cleaning Institute criteria that: "Within the treatment zone near the inlet and outlet faces of the precipitator collection chamber, the velocity shall have a minimum of 85% of the velocities not more than 1.15 times the average velocity, and 99% of the velocities not more than 1.40 times the average

velocity." A copy of the IGCI Publication No. EP-7 is included as an appendix to this report. Gas flow distribution problems were seen on the Line 6 kiln precipitator and will be discussed later.

Rapping system specifications depend to a large extent on the individual precipitator manufacturer's design and the particular precipitator application. Of primary concern is the system's ability to impart, to all surfaces treated by a given rapper, at least the minimum energy required to dislodge the dust. This must be done in a way which maintains the long term structural integrity of the collection plates, their attachments, and the discharge electrode system. Cement dusts tend to be very adhesive and/or cohesive. Thus, the minimum energy required to remove the dust from collection plates and discharge electrodes is, in general, greater than for other precipitator applications. With difficult dusts, the amount of plate surface (this includes the plane area of both collecting surfaces of the individual plates) to be rapped by an individual rapper should be no greater than 140 m^2. The design of the Jordan Cement Factory precipitators all meet this requirement.

Present day automatic voltage controllers for T/R sets are microprocessor based with the capability of networking for remote monitoring and control. Control can be performed by an operator or by process feedback. Most include options such as: back corona sensing and response, intermittent energization, energy management, and power-off rapping. Some vendors are supplying their earlier analog control and logic with A/D convertors to interface it with a microprocessor. Others have designed controllers which make use of the computing capability of processor. Also, the effort required to setup and adjust the various controllers differs markedly. Because of variations in design, logic, materials of construction, and other features; one finds a large variation in price between the different AVCs being offered. The automatic voltage controllers used at the

Fuhais and Rashadiya Works are not state-of-the-art but are adequate for the task. Replacement of the older saturable core reactor controllers seen on Line 4 of the Fuhais Works should improve performance however.

A brief internal inspection of the Line 6 kiln precipitator at the Fuhais works was made. The mechanical alignment of the collection plates and discharge electrodes in all fields was good. Localized areas having discharge electrode-to-plate spacings less than the minimum allowed for a given duct spacing can severely limit the currents and voltages which can be obtained. This in turn limits the collection efficiency of the units. The design plate-to-plate spacings of the unit was 300 mm. For good performance the discharge electrode-to-plate spacing should be within 150 ± 10 mm. All of the Line 6 precipitator plates and discharge electrode spacings appeared to be within tolerance.

The inlet perforated plate (distribution plate) of the Line 6 kiln precipitator had several large holes in it which had been caused by erosion due to high velocity in the gas stream (See photos # 54, 55, and 56). The leading edges of the collector plates behind the perforated plate also had holes in them due to dust erosion. The inlet duct work to this precipitator was being patched at the time of the visit, and the author was told that this had to be done annually. The wear patterns of the duct would indicate that the gas has a lot of angular momentum (swirl) with a large velocity component out of the direction of flow. This swirl may be causing the gas to channel in the inlet transition of the precipitator rather than spreading out as it should. The high velocity channels would then lead to damage seen in the perforated plates and precipitator internals. The installation of flow straighteners in the inlet duct work could eliminate this problem. A flow model study will be required to determine where and what type of flow straightening devices should be installed.

Regions of high velocity within a precipitator can severely degrade the performance of the unit. Re-entrainment due to scouring of collected material from the plates increases, rapping re-entrainment increases, and inherent collection efficiency in the region of high velocity decreases. Field measurements of the gas flow distribution across the inlet and outlet faces of the precipitator should be made to determine the quality of flow. This should be done under air load at design flow. If the distribution differs markedly from the IGCI criterion mentioned above, corrections to the flow should be made.

One morning was spent observing the operation of the Line 4 kiln and its two-field precipitator. The following data was obtained from the kiln control room:

Kiln inlet temperature		840°C
Inlet Oxygen		1.8%
Kiln speed		1.92 rpm
Raw mill feed rate		46.3 tn/hr
Oil consumption		260 lt/hr
Kiln outlet temperature		330°C
Raw mill inlet temperature		335°C
Precipitator inlet temperature:		
Control room:	A side	75°C
	B side	70°C
Mill room:	A side	130°C
	B side	110°C

Precipitator electrical conditions:

T/R SET	PRIMARY VOLTAGE (V)	PRIMARY CURRENT (A)	SECONDARY VOLTAGE (kV)	SECONDARY CURRENT (mA)
1	320	15	25	45
2	330	24	55	310

The differences seen in values of the precipitator inlet temperatures measured in the kiln control room as compared to those measured in the mill room were not understood. The mill room temperatures were more representative of what one would expect. As seen in the resistivity curves of Figure 2, one would expect good electrical conditions, that is, high voltage and high current for both T/R sets. The fact that the inlet field had very low voltage and current along with an observed high-spark rate was indicative of a problem

with this field. The electrical conditions would indicate close electrical clearances at some point within this precipitator field. During an upcoming outage, plant personnel should inspect the field and return the discharge electrode-to-plate clearances to their proper values for all electrodes. In areas where this cannot be done, the removal of discharge electrodes with less than the allowed tolerance in discharge electrode-to-plate spacing should be removed. Doing this should improve electrical conditions of the field and also improve the collection efficiency of the precipitator. The plant was having problems with Kiln 5 during the visit. On several occasions the auxiliary stack opened which vented the kiln-preheater emissions directly to the atmosphere. This problem was associated with high CO levels at the kiln exit. As plant personnel know, high CO levels are associated with poor combustion. The earlier report submitted by representatives of Dundee Cement included as an appendix a paper: "Flue gas analysis can help monitor kiln combustion system," by Brian W. Doyle (see Appendix D). Figure 1 of that paper shows the relationship between CO and excess air for a cement kiln. The data indicates a very rapid increase in CO as the oxygen concentration decreases from 2% to 1%. The CO level remains constant at a minimum value for oxygen concentrations greater than 2%. Control room data for Kiln 5 indicated a kiln-end oxygen concentration which was off scale high (greater than 8%) and a feed-end CO_2 of less than 3%. It was felt that neither of these values were correct. More typical values of CO_2 would be 20 - 25% and for O_2, 2 - 5%.

A second possibility for high levels of CO at the kiln exit would be poor mixing of the fuel and combustion air leading to poor fuel utilization. Plant personnel should check to see that air registers are properly set and, if a special fuel nozzle is used, it is performing as designed.

The Kiln 5 stack also showed high emissions when the raw mill was bypassed. The author was told that the gas was cooled to 200°C by water injection in the cooling tower when the raw mill was taken out of service. Using the mill-off resistivity curve of Figure 2, one can see that a resistivity of approximately 1×10^{12}ohm-cm would be expected if the Fuhais dust was similar to the dust represented by the data in Figure 2. One would expect poor electrical conditions within the precipitator and, as a consequence, poor precipitator performance if the dust resistivity was indeed 1×10^{12} ohm-cm. The plant should try lowering the temperature of the gas entering the precipitator to see if this will eliminate the poor performance when the mill is bypassed. The quench tower design may prevent lowering the temperature enough to eliminate the resistivity problem. If this is the case, retrofitting the tower with injection nozzles which produce a finer droplet size at higher flow rates might allow the reduction of the gas temperature to a more favorable range.

Air inleakage was very pronounced around the access doors of the operating kiln precipitator at the Rashadiya plant. Air inleakage is not only detrimental to precipitator performance, but it also increases the corrosion rate of the steel in the area around which the inleakage occurs. The performance of the unit is degraded if the cold air enters an electrical section before it has had time to adequately mix with the flue gases. The colder air lowers the breakdown voltage leading to sparking at lower than normal voltages. It is recommended that door gasketing be checked to insure that a proper seal can be obtained each time a door is opened. Hardened gasketing should be replaced and the seats checked to insure they are smooth and uniform.

Precipitator control rooms were visited at both plants in both cases the control rooms were dustier than they should have been. At the Fuhais plant, caged-switch gear exposed to ambient conditions was very dusty. The isolation insulators had heavy layers of

dust on their surfaces and the interiors of control cabinets were also very dusty. Dust on isolation insulators provide a leakage path to ground which reduces the amount of energy being supplied to the precipitator. While leakage currents may be small, they can still have a significant impact upon performance. Dust on electrical components within the control cabinets can modify the characteristics of the components. This in turn can change the performance of the controller. All electrical control rooms should be cleaned and isolated by keeping doors closed and filtering the air which enters them.

A copy of a precipitator inspection guide has been included as Appendix E to this report. It lists items which should be checked on a daily basis as well as those things which should be checked annually or during outages.

A mechanical collector off the clinker cooler of one of the Rashadiya Works lines was inspected. Several of the exit cones of this collector were worn with large holes in their sidewalls (see photo #33). These deteriorated exit cones would have a significant impact upon performance. Damaged cyclones would have a very low removal efficiency for particulate entering them. Also, the gas would not return within the cyclone as desired, but would travel into the hopper before turning where it could re-entrain additional material before exiting through some adjacent cyclone. All of the cyclones having eroded exit cones should be replaced.

Several of the cyclones had plugged entrances or exits. Pluggages should be removed to restore proper performance (photos #34 & 35 show areas of pluggage of the cyclone exits).

All of the engineers and operators who the author met were interested in improving the production and performance of plant equipment. Most expressed an interest in obtaining additional training with regard to the operation and maintenance of cement

production equipment and of pollution control devices. At both plants the position of environmental engineer has recently been established. The personnel holding these positions seemed to be very conscientious and each expressed a desire to learn more about the field in which they were working. Maintenance of equipment seemed to be lacking in many instances, not due to neglect, but due to the fact that proper maintenance procedures were not known. It is felt that providing training for plant personnel would be extremely beneficial in improving control device performance and as a consequence reducing particulate emissions. Key personnel may be sent for short courses offered by many organizations in the U.S. or in Europe. Also, many firms offer on-site training seminars in the operation and maintenance of control equipment. The latter option might be a more cost-effective way of providing training for a larger number of personnel.

Finally, copies of several recent fabric filter and precipitator papers which might be of help are included as an Appendix.

IV. CONCLUSIONS AND RECOMMENDATIONS

- Replace or augment line 5 multicyclone with a gravel bed filter or an equivalent control technology.

- Discontinue the outside storage of raw materials and clinker (reduced production demand may accomplish this).

- Require prompt clean-up of exposed accumulated and/or spilled materials especially spills of raw materials since they typically contain higher concentrations of free silica than does cement.

- Require routine monitoring and maintenance of dust control equipment with malfunction reports and follow-up reports of corrective action taken. This has been done to some extent but much more needs to be done in this area.

- Upgrade quarry roads and provide effective dust suppression. Continue the sweeping and vacuuming of paved areas in order to reduce dust emissions. Grading of roads has been done and shrubbery has been planted in an effort to reduce roadway dust, but more should be done.

- Provide engineering staff and maintenance personnel with training in the areas of operation and maintenance of environmental control equipment. Key personnel may be sent for short courses as offered by many organizations in the U.S. or in Europe. Also, many firms offer on-site training seminars in the operation and maintenance of control equipment which may be a more cost-effective way of providing training for a larger number of personnel.

- Upgrade the routine inspection of dust collection equipment.

- Establish an air quality monitoring program in the vicinity of both plants in order to quantify emissions and determine the sources of these emissions. This should include training personnel in the making of opacity observations from point sources.

- Establish specific limitations for each point source and also for open source emissions. Once this is done requirements for best available control technologies should be used to meet the required emission limit.

- Install transmissometers (opacity meters) for monitoring point sources of particulate emissions.

- Establish deadlines for meeting environmental goals.

- Install a flexible chute between the conveyor and the top of the clinker pile (as it is stored out of doors) in order to reduce dust emissions.

- Install differential pressure gauges or transducers across the tubesheets of all baghouses in order to help monitor performance and troubleshoot the units.

- Replace blinded or broken bags in the fabric filter in order to insure proper operation.

- Install pressure gauges on the cleaning air supply at the inlet manifold of each fabric filter in order to allow one to determine if a sufficient supply of clean air is available.

- Install a singed felt fabric (i.e. a fabric where the loose fiber on the collecting surface has been burned away leaving nothing to which the dust nodules can attach) in baghouses where operation may occur at or below the moisture dew point or where cleaning may be ineffective in order to minimize dustcake.

- Install a "Triboflow: Broken Bag Detector" (developed by Auburn International of Danvers, Maine) in baghouses in order to monitor emissions.

- Replace the older saturable core reactor controllers on Line 4 of the Fuhais Works in order to improve electrostatic precipitator performance.

- Install flow straighteners in the inlet duct work of the Line 6 kiln precipitator in order to eliminate gas "swirling". Conduct a flow model study to determine where and what type of flow straightening devices should be installed.

- Make field measurements of the gas flow distribution across the inlet and outlet faces of the electrostatic precipitators in order to determine quality of flow. This should be done under air load at design flow. If the distribution differs markedly from the following IGCI criterion:

  "Within the treatment zone near the inlet and outlet faces of the precipitator collection chamber, the velocity shall have a minimum of 85% of the velocities not more than 1.15 times the average velocity, and 99% of the velocities not more than 1.40 times the average velocity."

- During an upcoming outage, plant personnel should inspect the field of the Line 4 Kiln's two-field precipitator and return the discharge electrode-to-plate clearances to their proper values for all electrodes. In areas where this cannot be done, the removal of discharge electrodes with less than the allowed tolerance in discharge electrode-to-plate spacing should be removed. Doing this should improve electrical conditions of the field and also improve the collection efficiency of the precipitator.

- In order to reduce the Kiln 5 CO levels at the kiln exit, plant personnel should check to see that air registers are properly set and, if a special fuel nozzle is used, that it is performing as designed.

- In order to eliminate the poor performance of the Kiln 5 electrostatic precipitator when the raw mill is bypassed, the plant should try lowering the temperature of the gas entering the precipitator. The quench tower design may prevent lowering the temperature enough and, if this is the case, retrofitting the tower with injection nozzles which produce a finer droplet size at higher flow rates might allow the reduction of the gas temperature to a more favorable range.

- In order to reduce air inleakage, check the access door gasketing of the operating kiln precipitator at the Rashadiya plant to insure that a proper seal can be obtained each time a door is opened. Replace hardened gasketing and check the gasket seats to insure they are smooth and uniform.

- Clean and isolate from dust all electrical control rooms by keeping doors closed and filtering the air which enters them.

- Make daily, annual, and outage checks on electrostatic precipitators as per Appendix E, the precipitator inspection guide.

- Replace all cylcones having eroded exit cones.

- In order to restore proper performance, pluggages should be removed from all cyclones having plugged entrances or exits.

- Review the recent fabric filter and precipitator papers included in the Appendices of this report.

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Table 1a. Listing of fabric filter installations and some design parameters for the Fuhais Works of the Jordan Cement Factory.

LISTING OF FABRIC FILTER INSTALLATIONS FUHAIS WORKS OF JORDAN CEMENT COMPANY

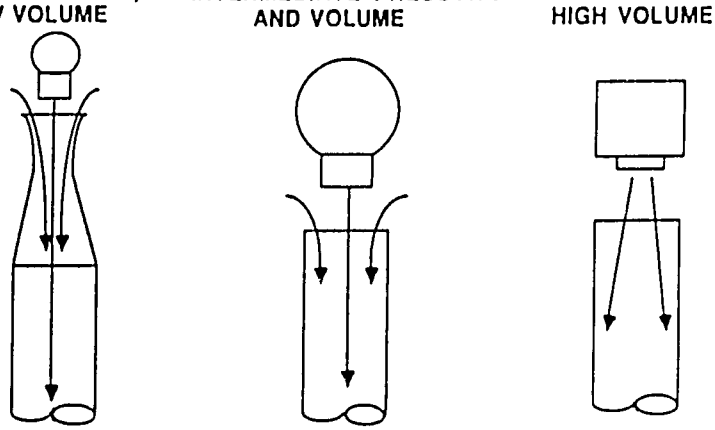
DESIGNATION	NUMBER COMP.	FILTER AREA (M2)	GAS VOLUME (M3/hr)	AIR/CLOTH RATIO (M/hr)
Raw Mat. Trans., Plt 4	2	38	5,000	131.6
Raw Mat. Mill No. 4, F1	2	60	7,200	120
Raw Mat. Mill No. 4, F2	2	48	5,400	112.5
Lime/Marl Crusher, F1	6	240	27,600	115
Lime/Marl Crusher, F2	2	60	7,020	117
Raw Mat. Trans., Plt 4,5,6,7	2	80	9,000	112.5
Raw Mat. Trans., Plt 5	2	38	5,000	131.6
Raw Mat. Mill No. 5, F1	2	48	5,400	112.5
Raw Mat. Mill No. 5, F2	2	60	7,200	120
Hammering Crusher (CR7)	9	396	45,000	114.6
Sampling Station & MVT, 621BF2	4	160	18,600	116.3
Sampling Station & MVT, 621BF3	1	32	3,600	112.5
Sampling Station & MVT, 623BF1	2	100	3,600	36
Sampling Station & MVT, 623BF2	2	88	10,200	115.9
Raw Mat. Trans., Plt 6, 624BF1	2	44	5,100	115.9
Raw Mat. Trans., Plt 6, 624BF2	2	48	4,200	87.5
Raw Mat. Trans., Plt 6, 624BF3	2	38	5,000	131.6
Raw Mat. Trans., Plt 6, 625BF1	3	132	15,000	131.6
Raw Mat. Trans., Plt 6, 625BF2	3	132	15,000	131.6
Raw Mat. Mill No. 6, F1	1	44	5,100	115.9
Raw Mat. Mill No. 6, F2	3	132	13,200	100
Raw Mat. Mill No. 6, F4	2	80	9,000	112.5
Preheater, Plt 6, 635BF1	5	220	21,000	95.5
Preheater, Plt 6, 636BF1	2	88	9,000	102.3
Preheater, Plt 6, 636BF1	2	88	10,200	115.9
Preheater, Plt 6, 641BF1	4	176	15,000	85.2
Clinker trans., 647BF1 Plt 4, 5, 6, & 7	4	176	19,800	112.5
Clinker trans., 647BF2 Plt 4, 5, 6, & 7	2	88	7,800	88.6
Clinker trans., 651BF1 Plt 4, 5, 6, & 7	2	88	7,800	88.6
Pozzolana Crusher, 652BF1	6	264	31,800	120.5
Pozzolana Crusher, 653BF1	1	44	5,100	115.9
Clinker trans., 653BF2 Plt 4, 5, 6, & 7	4	176	20,400	115.9
Pozzolana Crusher, 653BF3	2	88	10,200	115.9
Cement Mill No. 6, 655BF1	6	264	28,800	109.1
Cement Mill No. 7, 655BF2	2	80	9,000	112.5
Cement Mill No. 7, 655BF3	5	220	21,000	95.5
Cement Mill No. 7, 655BF4	5	220	25,800	117.3
Cement Mill No. 7, 656BF2	11	484	56,400	116.5
Cement Mill No. 6, 656BF1	11	486	56,400	116.0
Bulk Loading Plt., 658BF1	4	176	18,000	102.3
Bulk Loading Plt., 658BF2	4	176	18,000	102.3
Cement Mill No. 7, 658BF3	4	160	19,500	121.9
Packing Plant Supl 661BF1	2	32	3,600	112.5
Packing Plant 5, 6 662BF1	4	176	21,900	124.4
Packing Plant Supl 662BF2-5	6	264	31,500	119.3
Bulk Loading Plt., 664BF1	1	44	5,100	115.9
Bulk Loading Plt., 664BF2	1	44	5,100	115.9

DESIGNATION	NUMBER COMP.	FILTER AREA (M2)	GAS VOLUME (M3/hr)	AIR/CLOTH RATIO (M/hr)
Bulk Loading Plt., 664BF3	1	44	5,100	115.9
Bulk Loading Plt., 664BF4	1	44	5,100	115.9
Bulk Loading Plt., 664BF5	1	44	5,100	115.9
Bulk Loading Plt., 664BF6	1	44	5,100	115.9
Packing Plant 5, 6 PKP(Q09-01)		372		
Packing Plant 5, 6 PPKP(R20-03, 04, 05)		260		
Gypsum Crusher (Y06-01)		186		
Clinker Trans. Plt 4, 5, 6, 7 (L13-15)		260		
Lime/Marl, Pozz Crusher (C06-01)		260		

Table 2a. Listing of electrostatic precipitator installations and some design parameters for the Fuhais Works of the Jordan Cement Factory.

LISTING OF ELECTROSTATIC PRECIPITATOR INSTALLATIONS AT THE RASHADIYA PLANT OF JORDAN CEMENT COMPANY

DESIGNATION	NUMBER COMP.	NUMBER FIELDS	PLATE AREA (M2)	GAS VOLUME (M3/hr)	SCA (M2/M3/s)
Preheater, Pl. 5	1	2	7,360		
Preheater, Pl. 6	1	3	10,898	327,220	119.9
Cement Mill No. 6	2	2	3,750	54,000	161.9
Cement Mill No. 7	1	2	1,809	100,700	64.7



TYPICAL CHARACTERISTICS	HIGH PRESSURE, LOW VOLUME	INTERMEDIATE PRESSURE AND VOLUME	LOW PRESSURE, HIGH VOLUME
TANK PRESSURE, PSIG	90	20 - 30	10
SECONDARY/PRIMARY AIR	6 - 7	1 - 2	---
BAG LENGTH, FT (ON-LINE CLEAN)	12	20	20
BAG DIAMETER, IN	4.5	5	6 X 2.7 (OVAL)
NO. BAGS/VALVE	12	18	484
CLOTH AREA/VALVE, FT^2	172	462	12,600
CLEANING ENERGY, W/FT^2	4	0.8	0.8

Figure 1. Comparison of typical operating characteristics for high-pressure, intermediate-pressure, and low-pressure pulse cleaning. Note the venturi required for high-pressure pulsing to induce secondary air (cleaned flue gas) to assist in cleaning. For high-pressure pulsing, woven fiberglass bags up to 20 ft. long have been used with off-line cleaning.

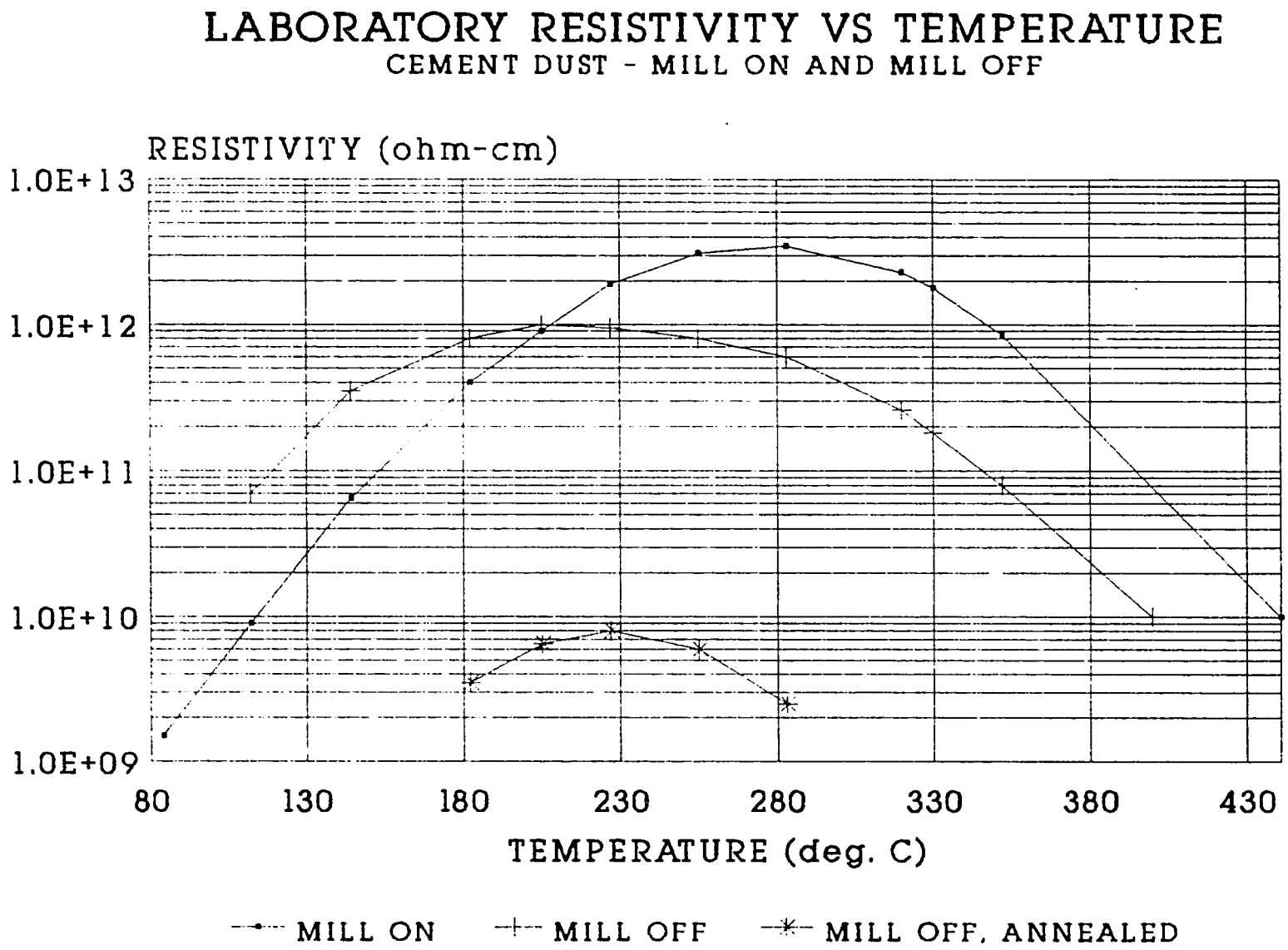


Figure 2. Resistivity versus temperature for dust collected from a cement kiln precipitator.

LIST OF PHOTOGRAPHS

1. Amsterdam Airport, picture taken by airport security personnel to check camera

2. Pozzolana storage

3. Raw material blending buildings can be seen behind overhead conveyor

4. Raw material storage, center of photo behind overhead conveyor

5. Outside clinker storage

6. Line 4 raw mill building with electrostatic precipitator on roof

7. South quarry and quarry haul road

8. Oil and water tanks with employee housing on the hill above them

9. Cement silos

10. Cement silos and example of vegetation planted for dust suppression

11. Pozzolana crusher building

12. Gypsum crusher building

13. Clinker storage building

14. View of headquarters building (at the base of the left conveyor support tower) and employee housing on the hill behind it as seen from the road near the pozzolana crusher

15-18. Panoramic view of facility from the south quarry road

19-20. Number 5 line precipitator reclaim hoppers

21. Number 5 raw mill feed conveyor showing bend of materials

22. Number 5 raw mill feed conveyor showing silica feed onto belt

23. Number 5 raw mill (ball mill)

24-25. Line 7 cement mill

26. Fabric filter (baghouse) in area of Line 7 cement mill, (note dust on floor beneath hopper evacuation screws)

27. Line 6 raw mill

28. Lower stages of Kiln 6 preheater at feed end of the kiln

29. Clinker from Line 4 being deposited on the ground after a drop of approximately 4 meters. (note dust which was being created)

30-30a. Nearby town of Salt

31. Plant engineer and driver with Dead Sea in background

32. M. Anderson and driver provided by JCF

33. View from clean side of Rashadiya Works clinker cooler multiclone showing the erosion of the exit cone of the center cyclone of the picture, similar can be seen in the cyclone beneath the boot toe

34. View from clean side of Rashadiya Works clinker cooler multiclone showing the pluggage of the upper right cyclone

35. View from clean side of Rashadiya Works clinker cooler multiclone showing the dust dropout on the clean side of the tube sheet

36. View of the Rashadiya employee housing from the roof of the raw mill building

37. Upper sections of the preheaters for the Rashadiya works kilns

38. Rashadiya Works spray tower in foreground a lower section of kiln preheater in background

39. Dusting from Rashadiya stack

40. Mr. Ali Alawneh, environmental manager, beside Rashadiya precipitator

41. Jordan Cement Factory driver (on left) and Rashadiya Works employee

42. MHA and Rashadiya employee

43. MHA and driver

44-48. Panoramic view of Amman from Hotel Window

49. Fuhais Works Line 6 kiln precipitator hopper discharge system

50-51. Fuhais Works Line 6 kiln precipitator inlet ductwork showing patches in area of excessive wear (erosion)

52. Fuhais Works Line 6 kiln precipitator inlet ductwork

53. Side view of Fuhais Line 6 precipitator

54. Area between the inlet splitter vanes and the distribution (perforated) plate of the Fuhais Line 6 precipitator, note the hole in the perforated plate just below the light

55. Looking into the inlet field of the Fuhais Line 6 kiln precipitator, holes in the leading edges of two of the plates can be seen. These holes were downstream of a hole in the perforated plate.

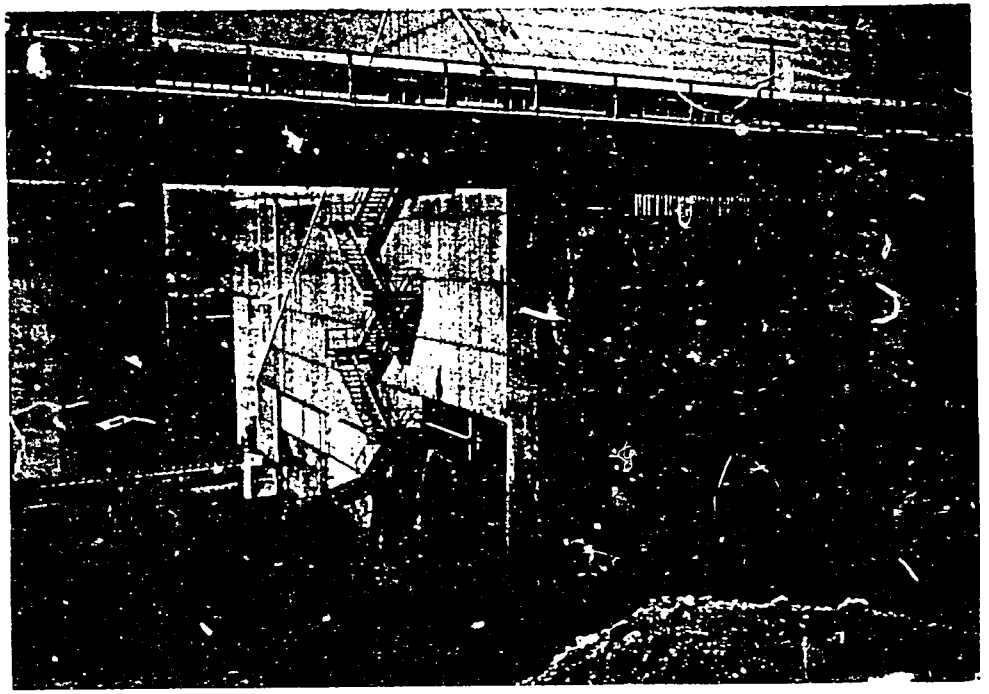
56. Hole in perforated plate created by the erosive effects of high velocity dust ladened gas.

57. Section of perforated plate which had dropped from its installed position.

58. View of discharge electrodes between the collector plates at the inlet of Precipitator

59-60. Fuhais Kiln #4 preheater and precipitators

61-62. Views of Fuhais Works kiln



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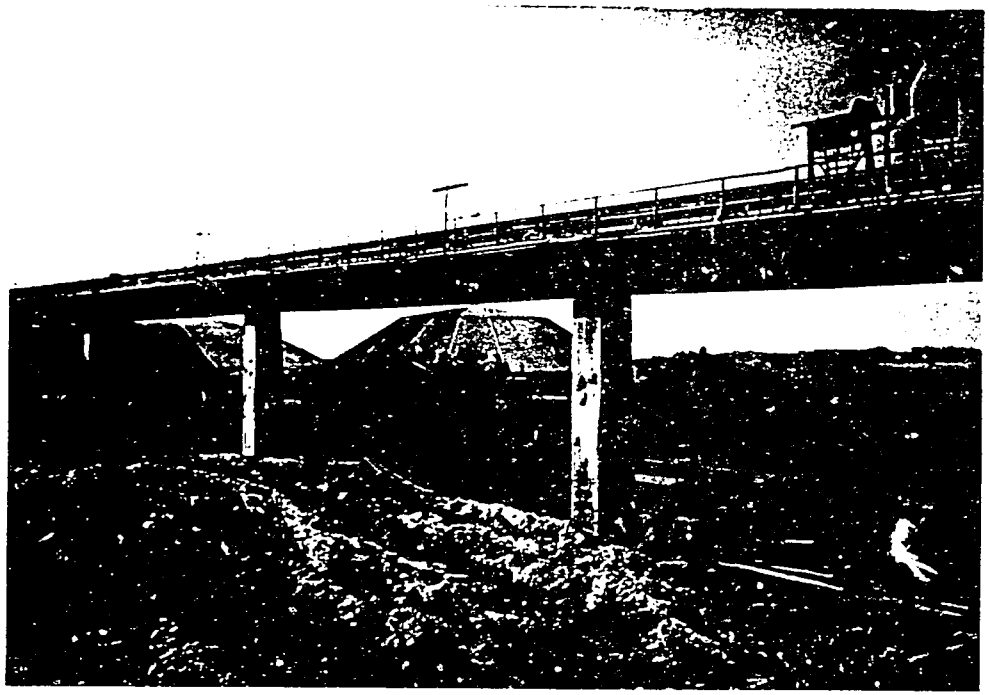

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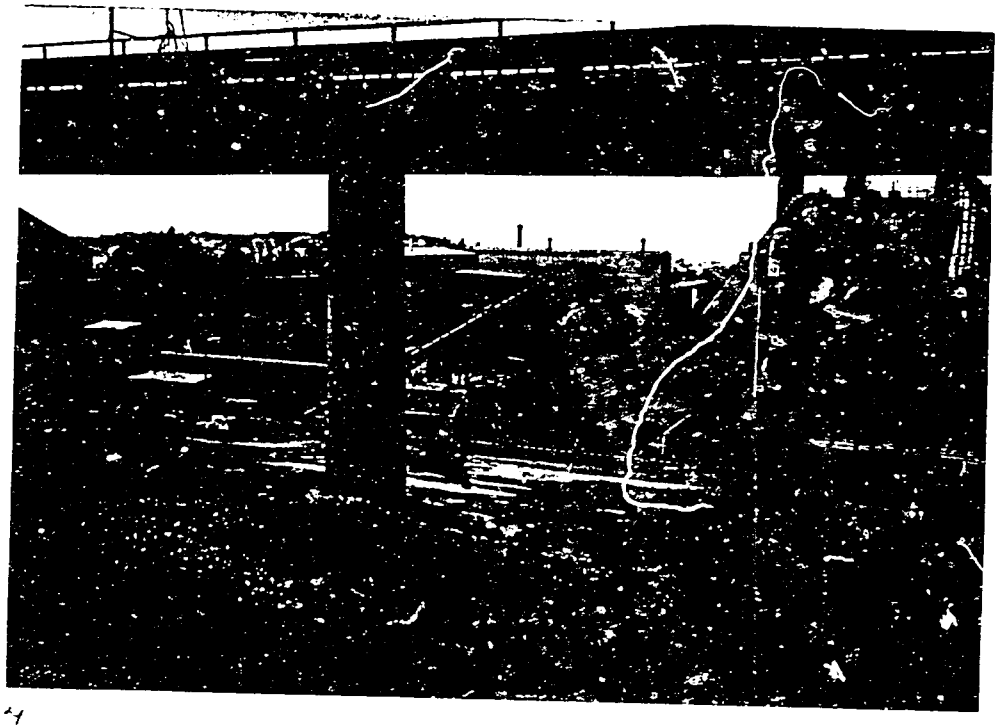

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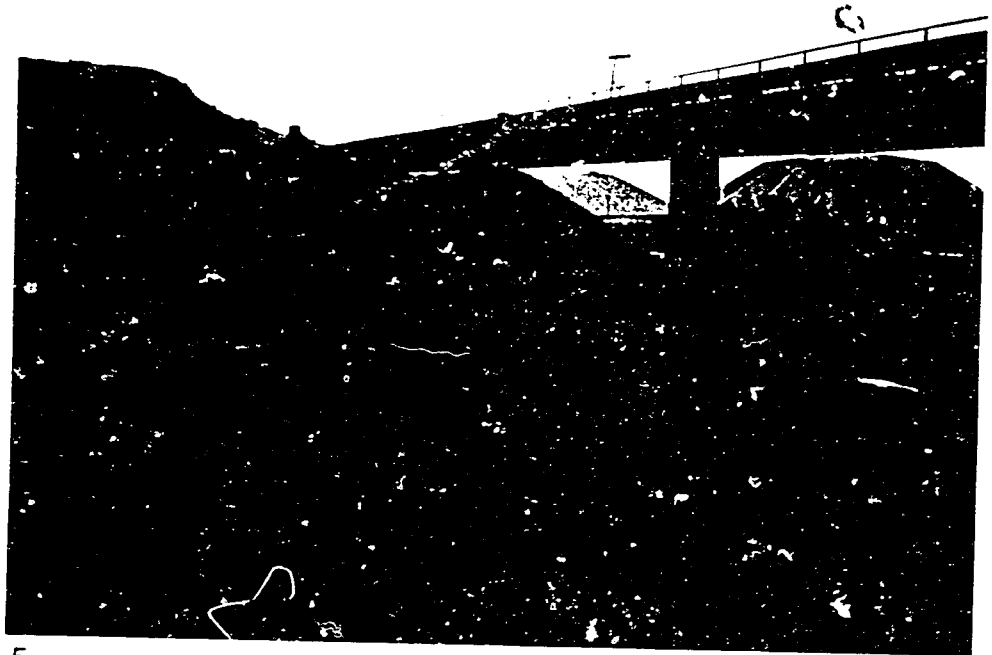

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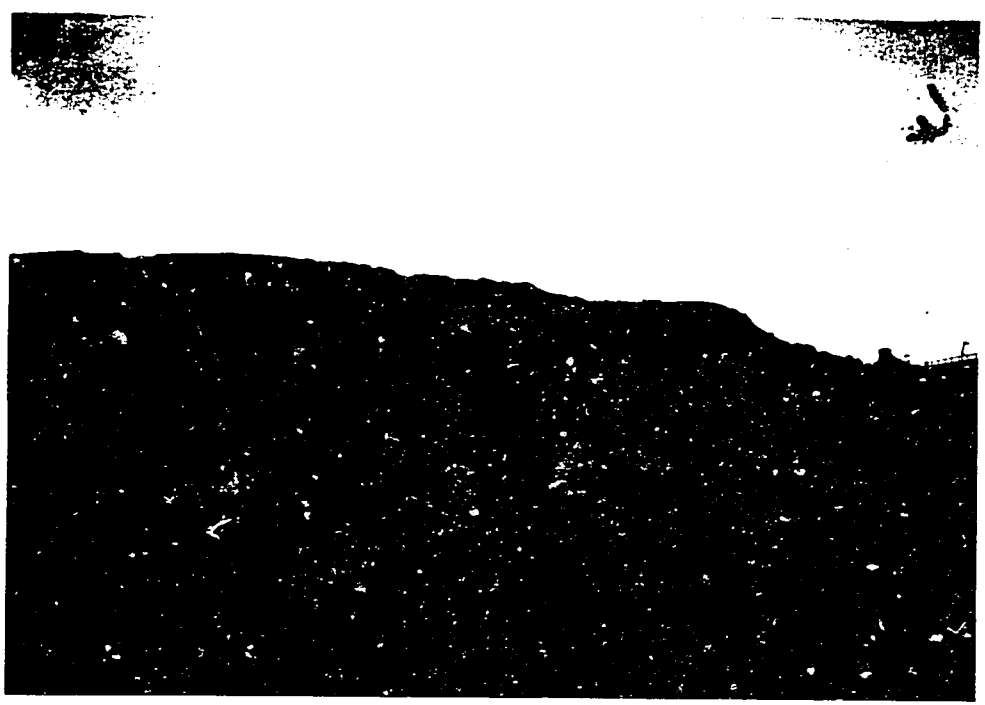

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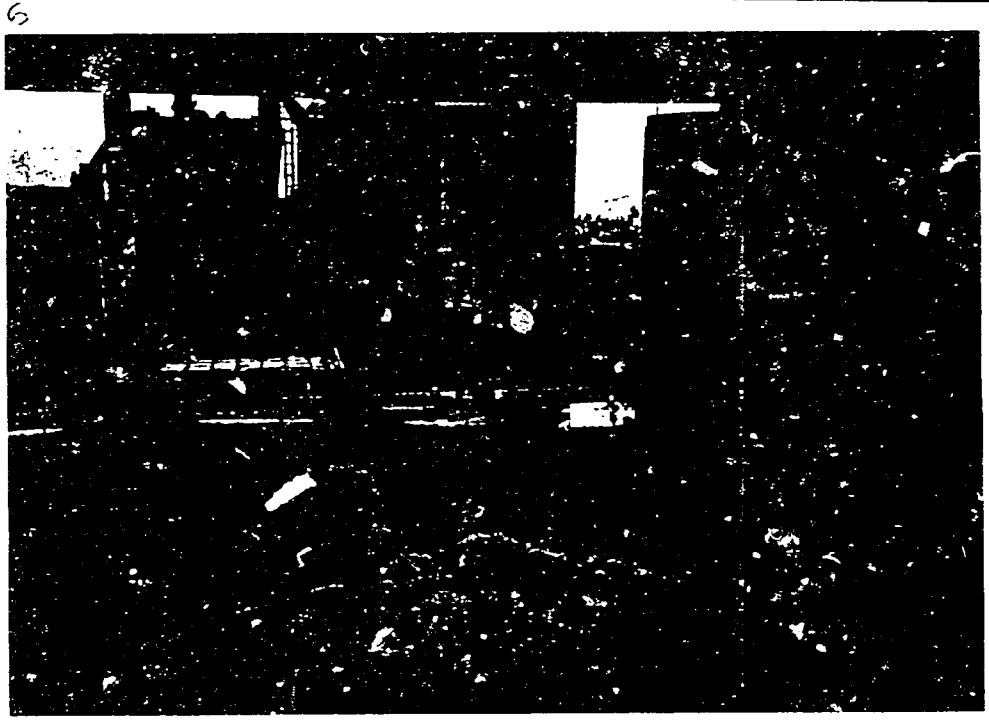

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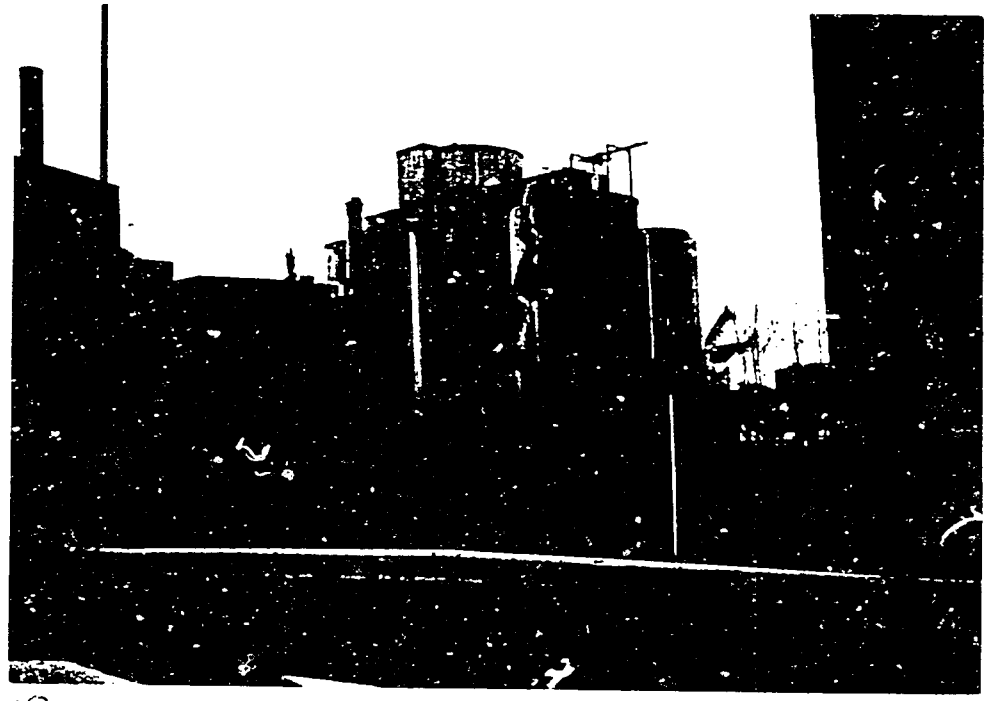

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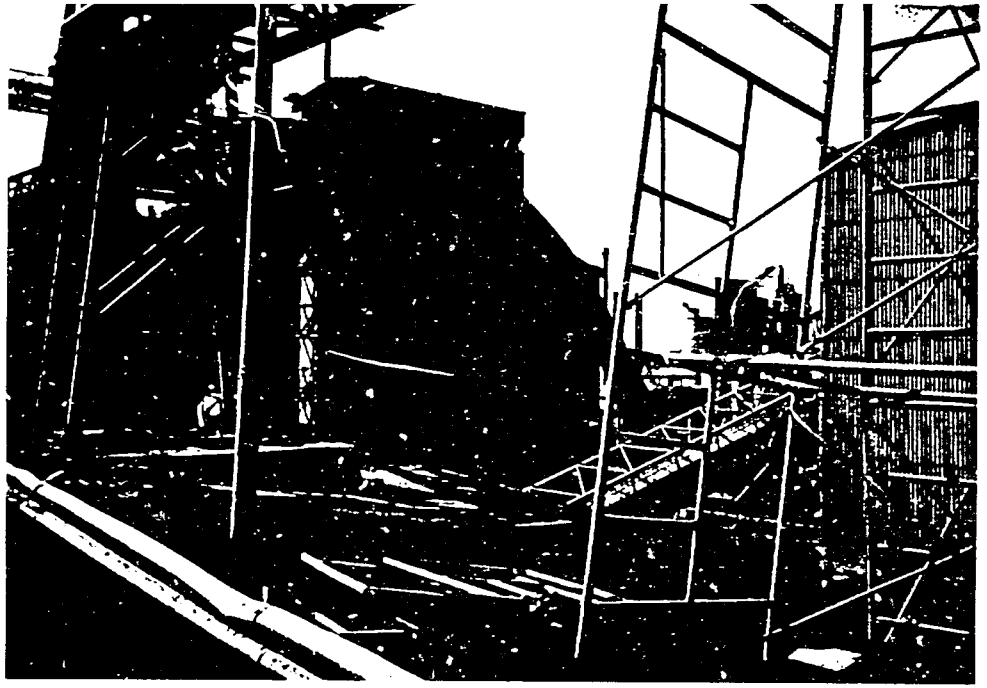

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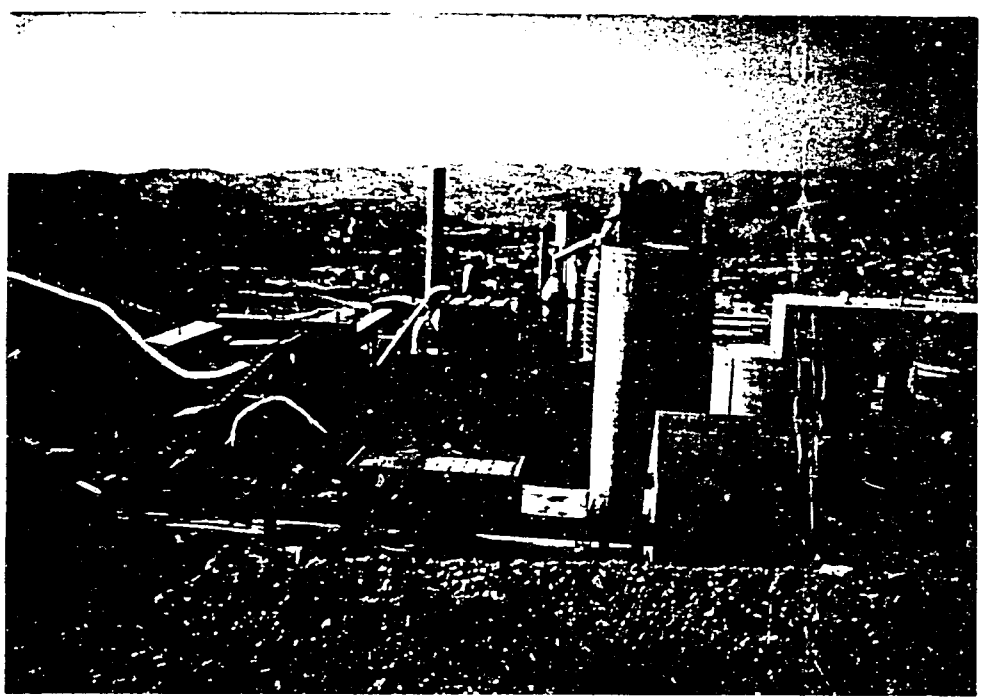

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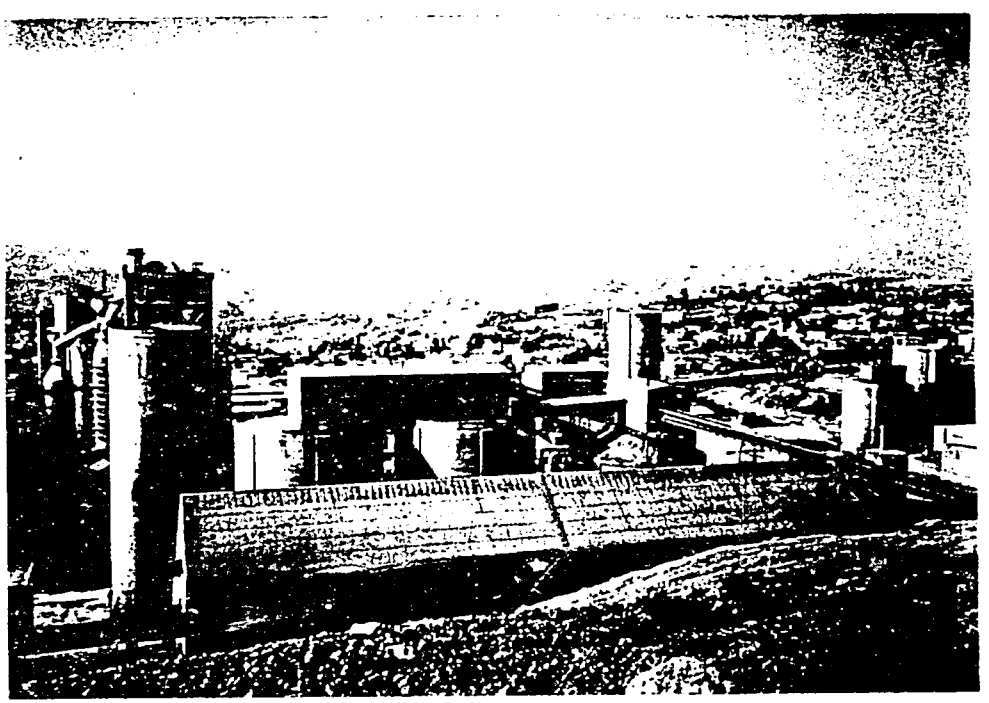

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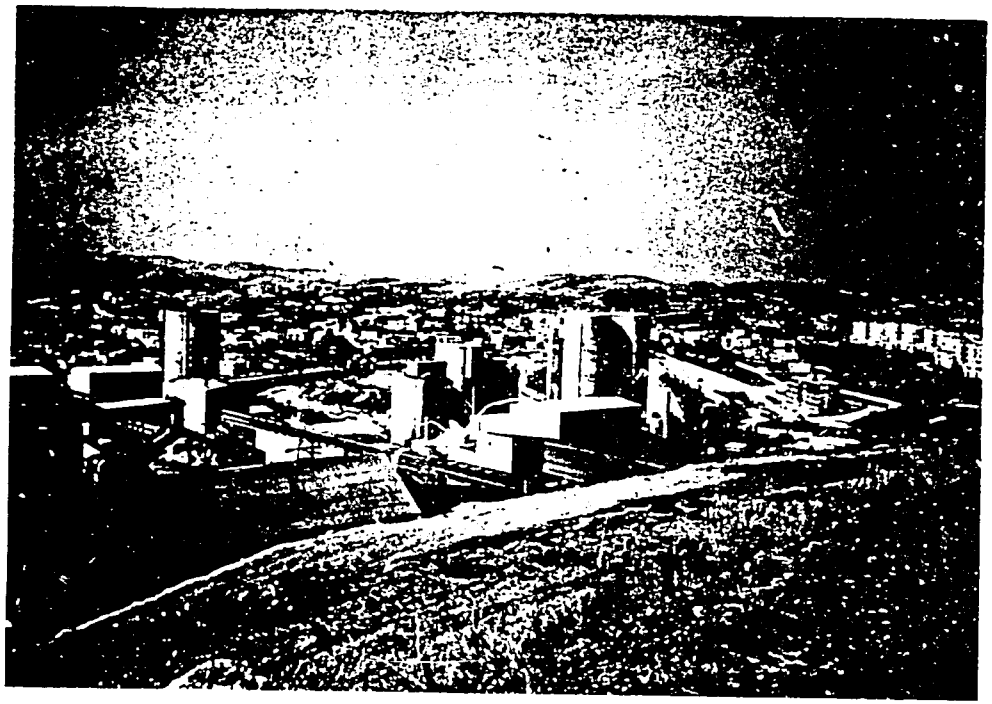

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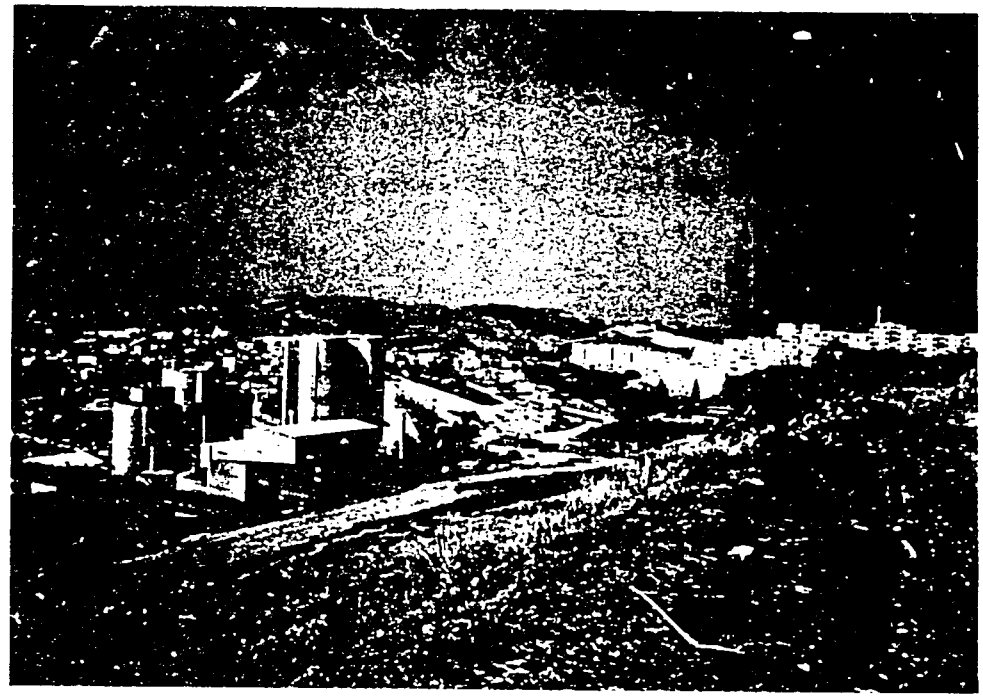

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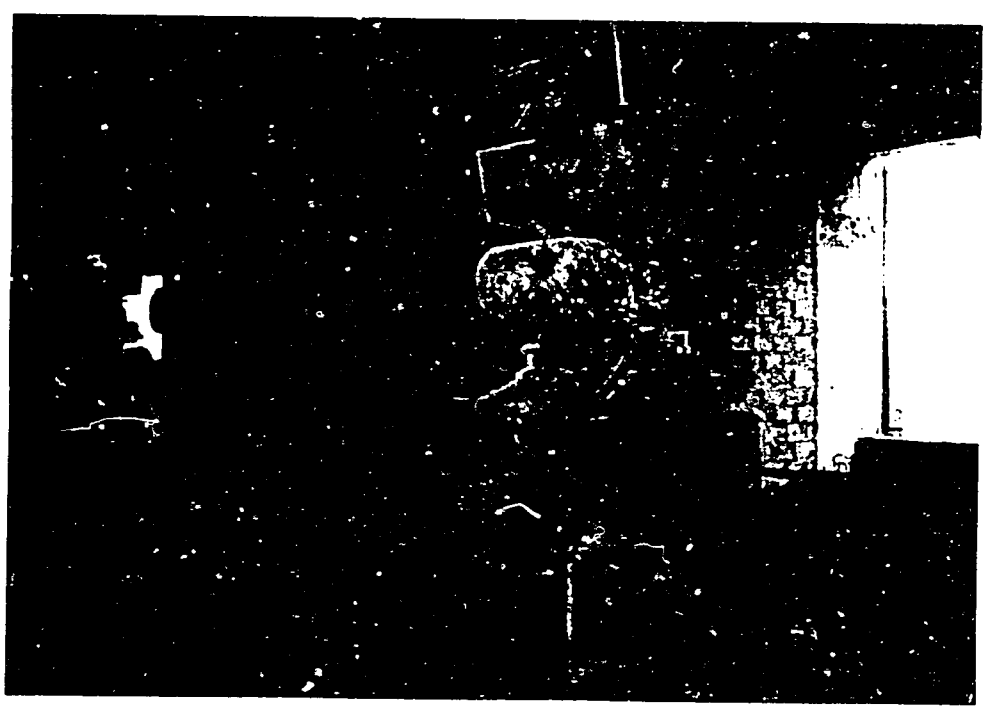

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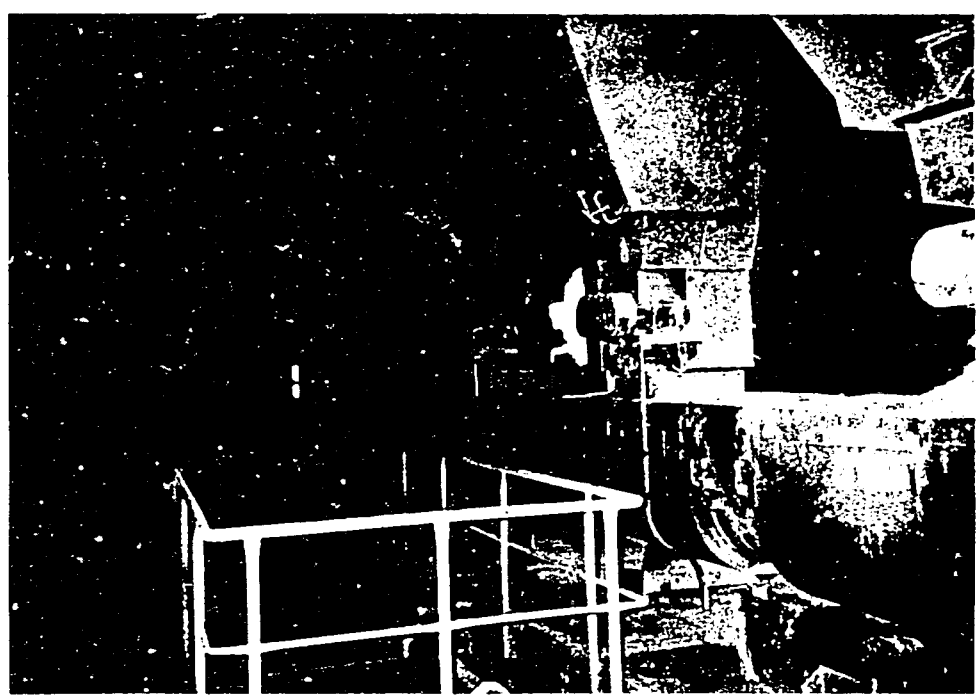

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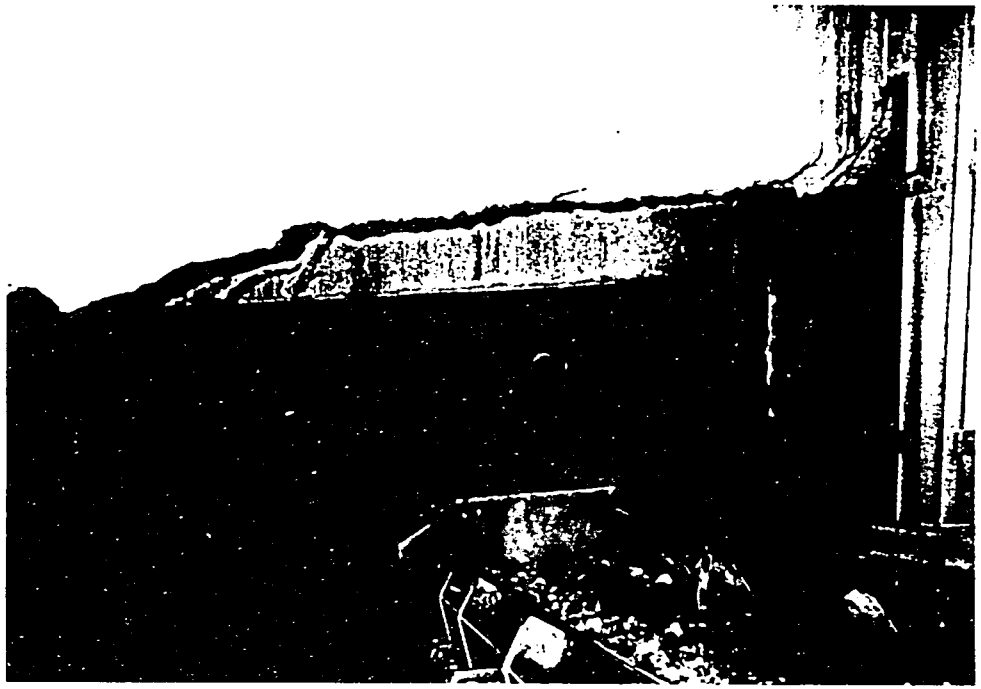

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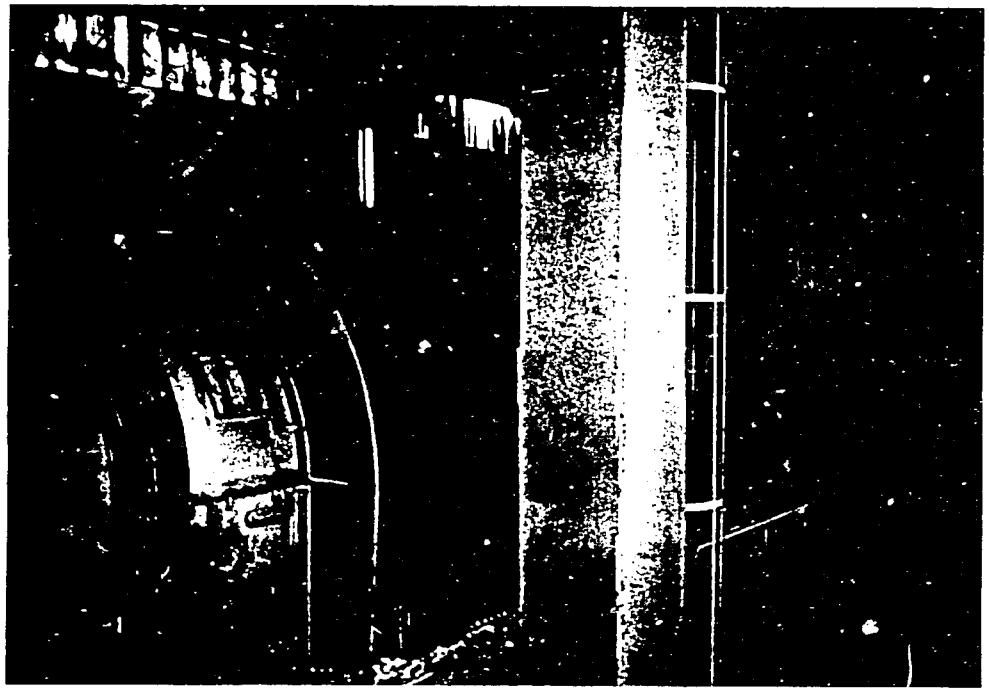

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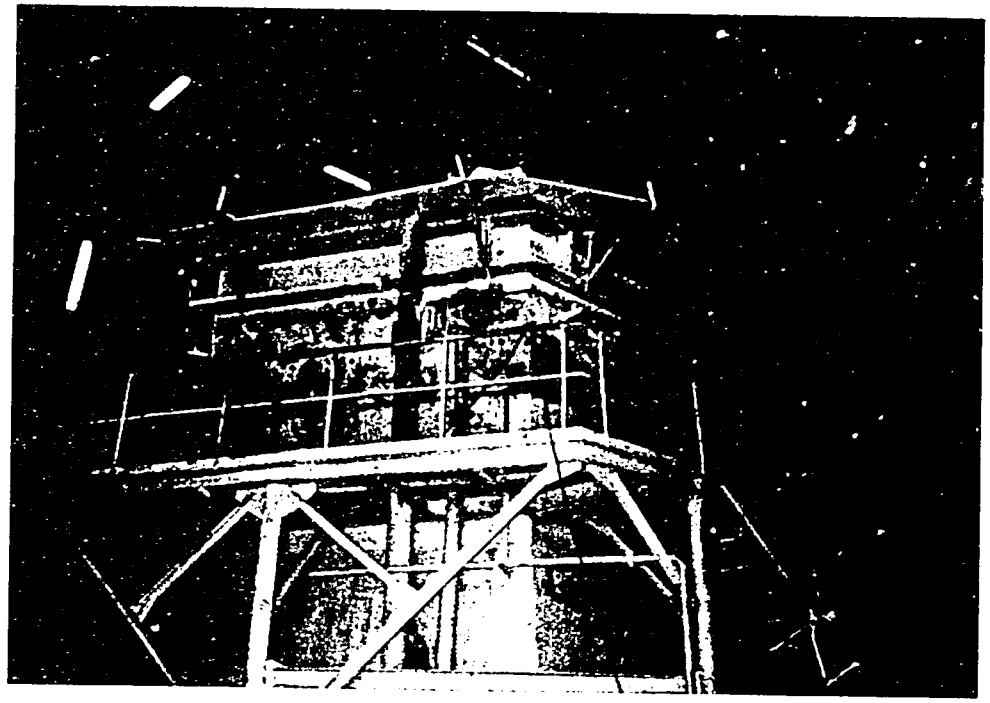

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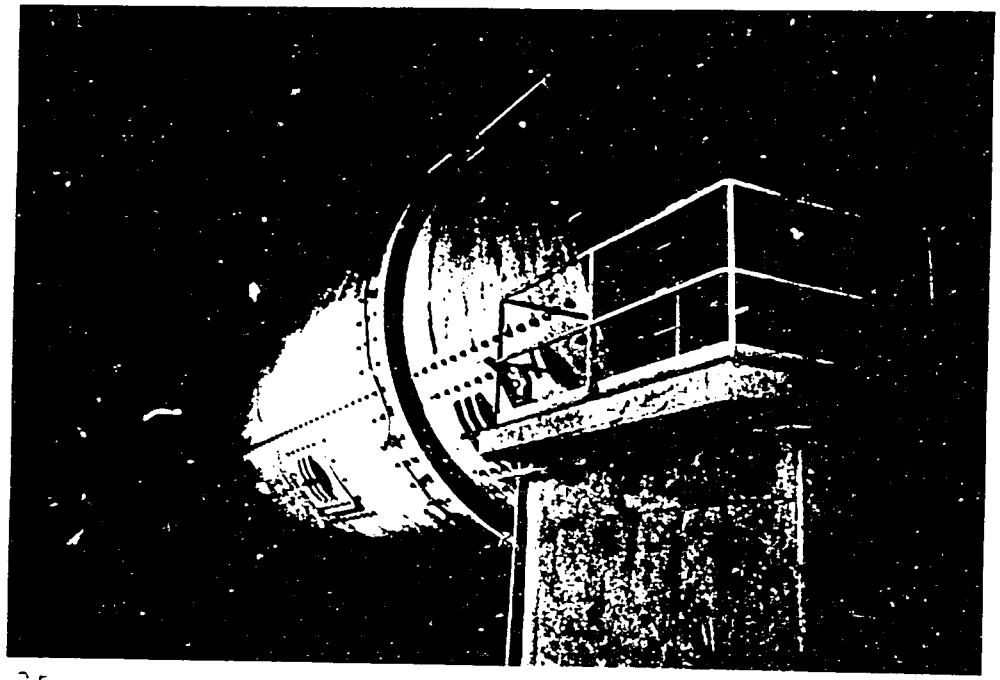

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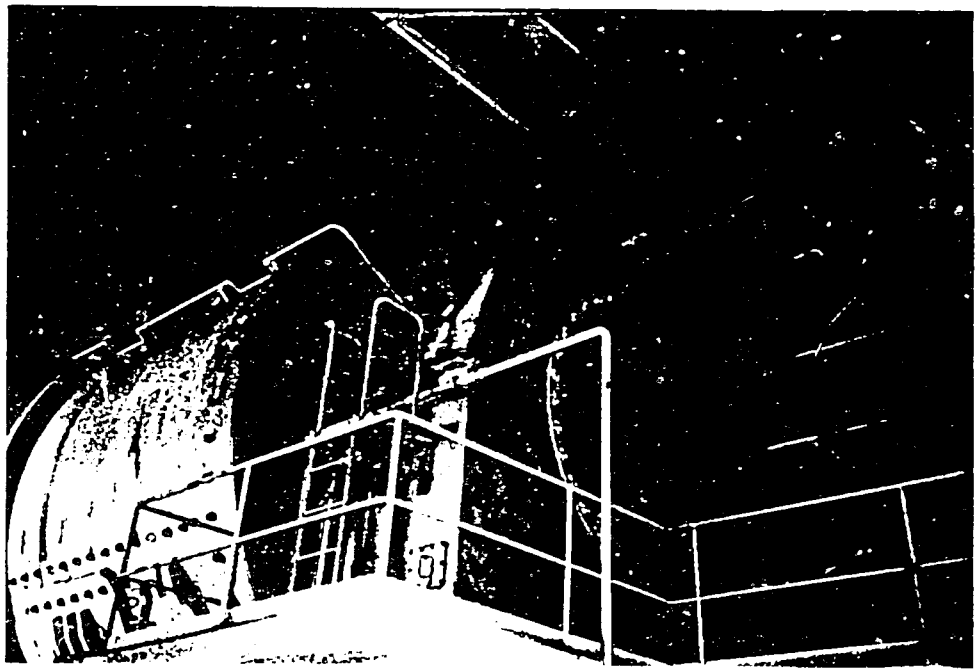

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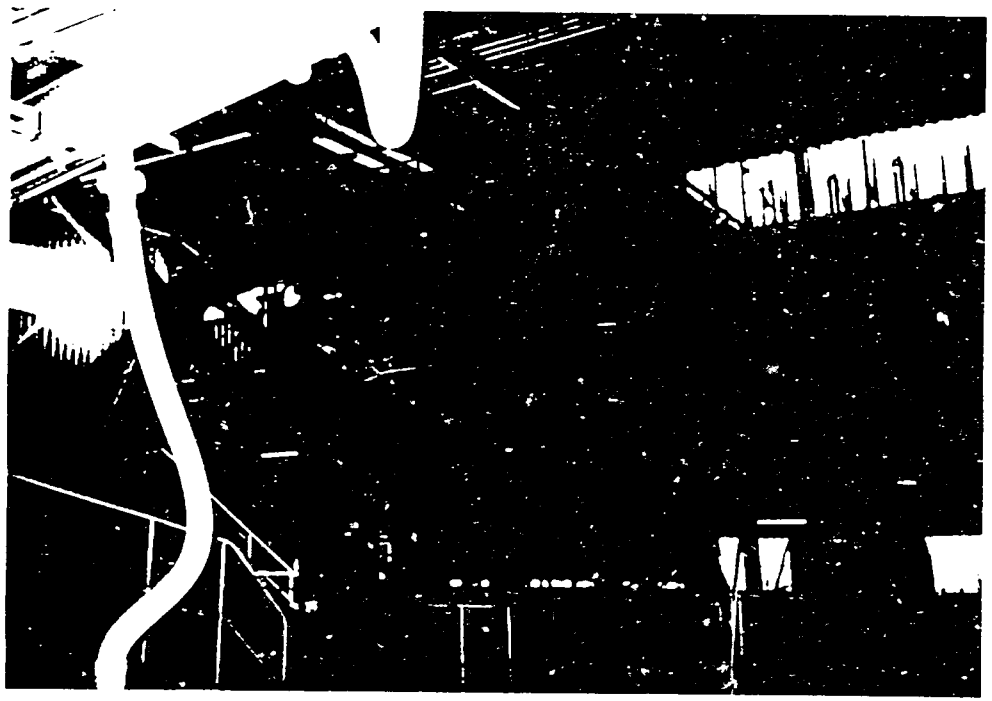

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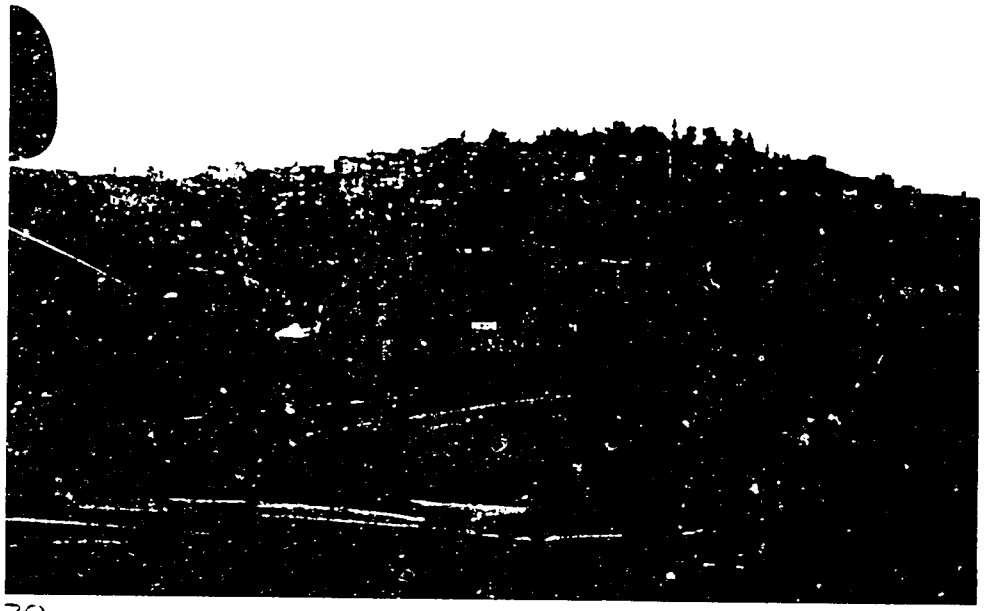

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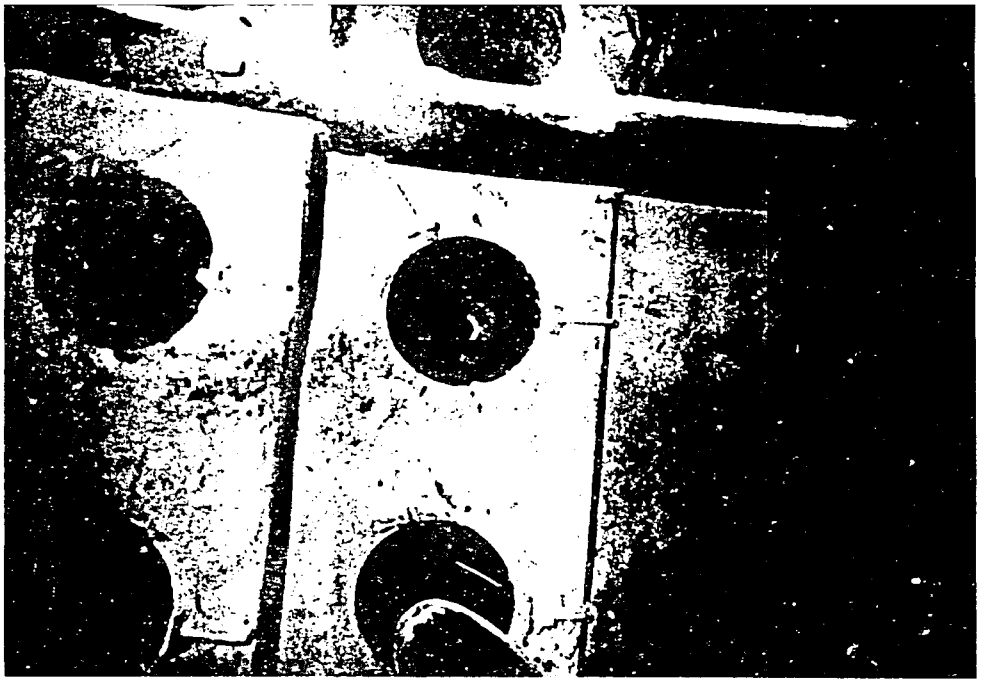

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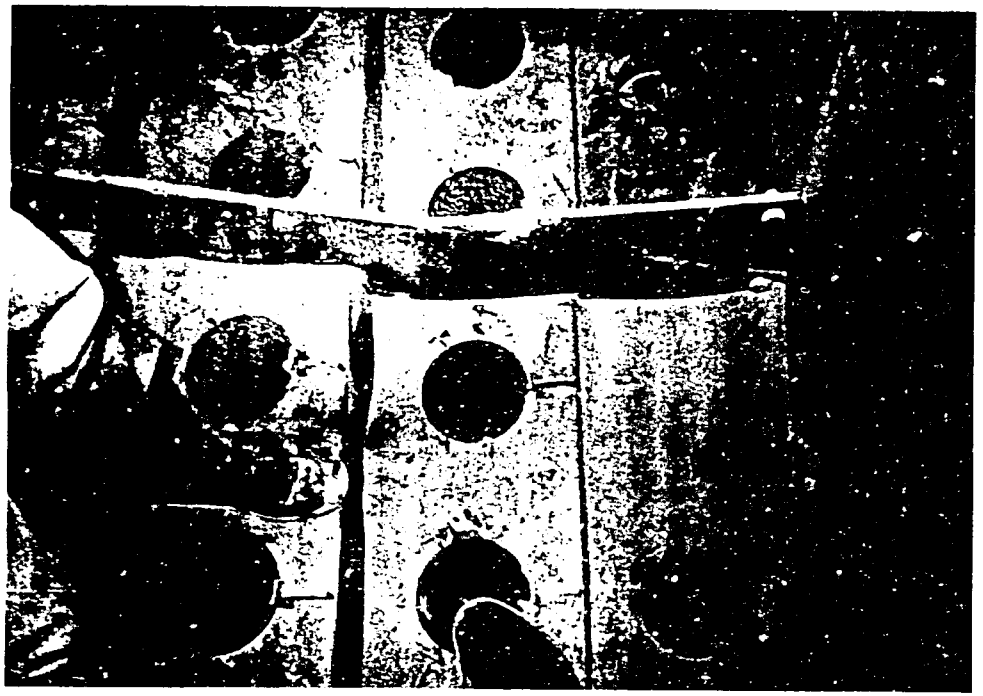

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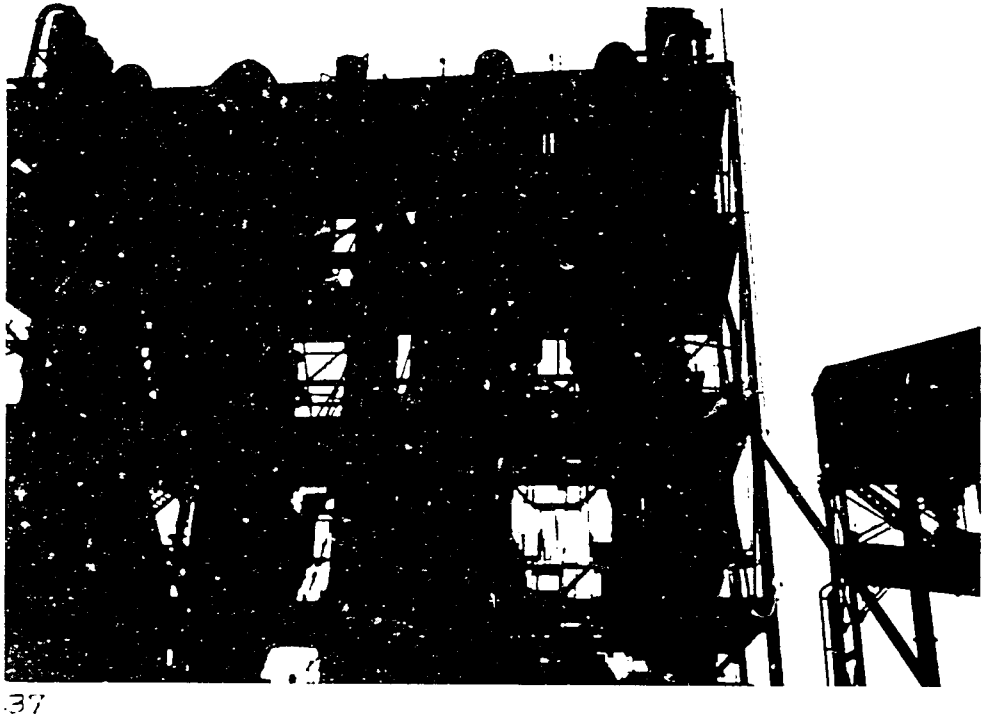

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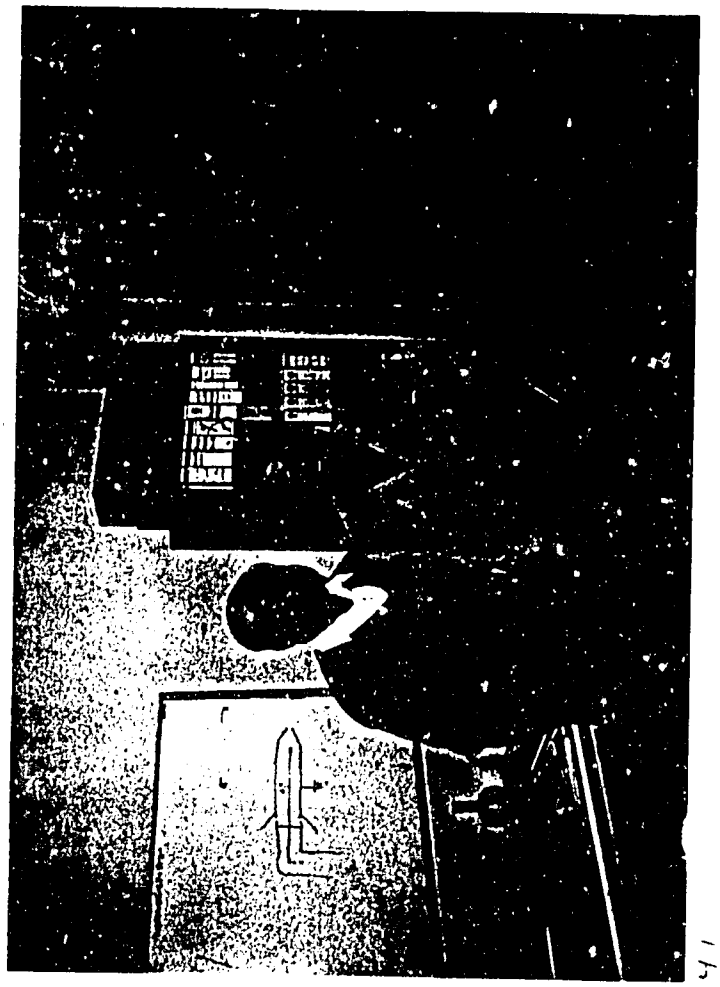

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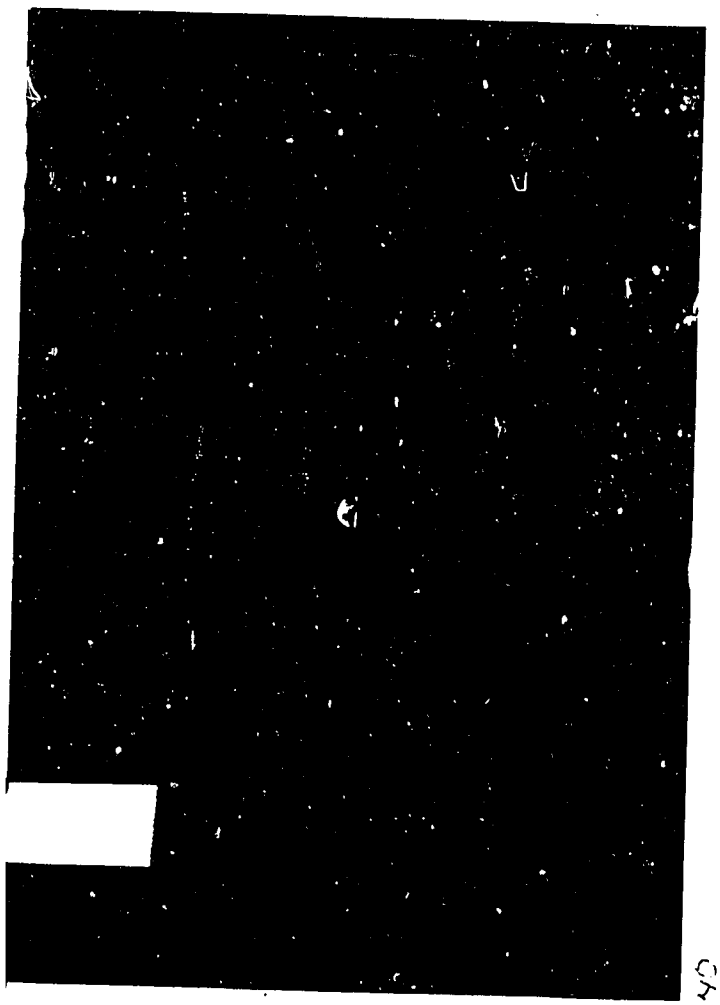

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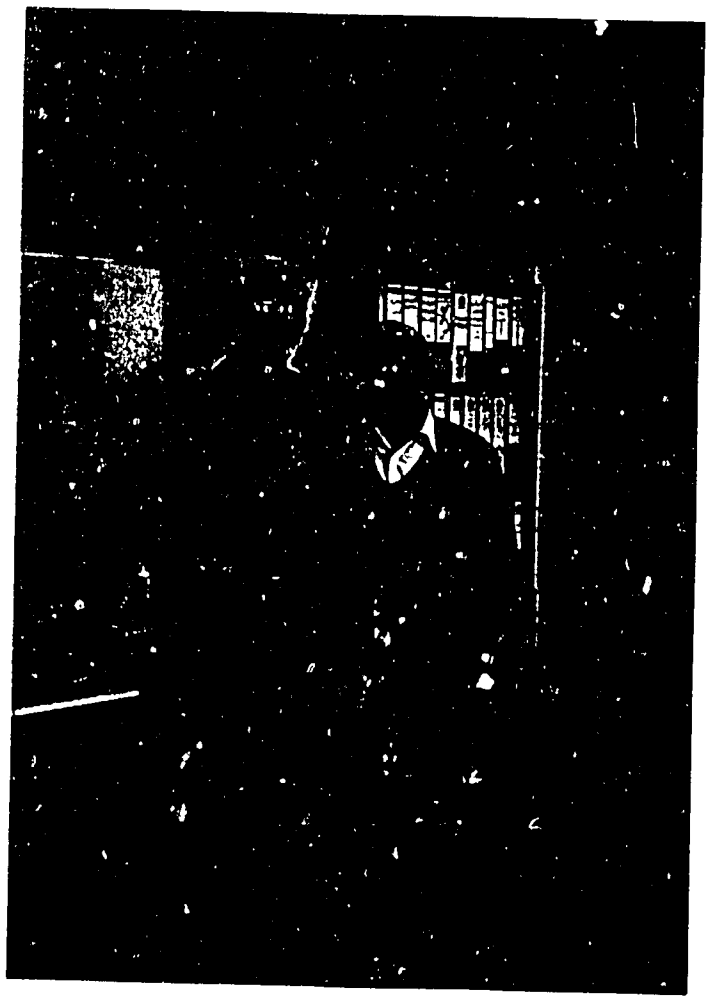

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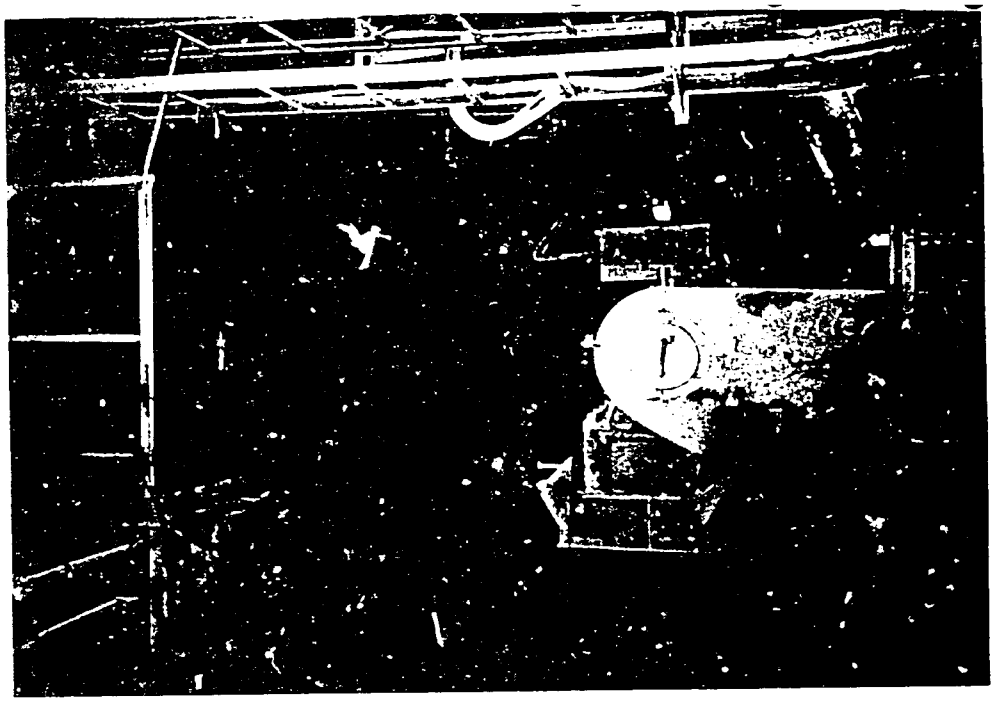

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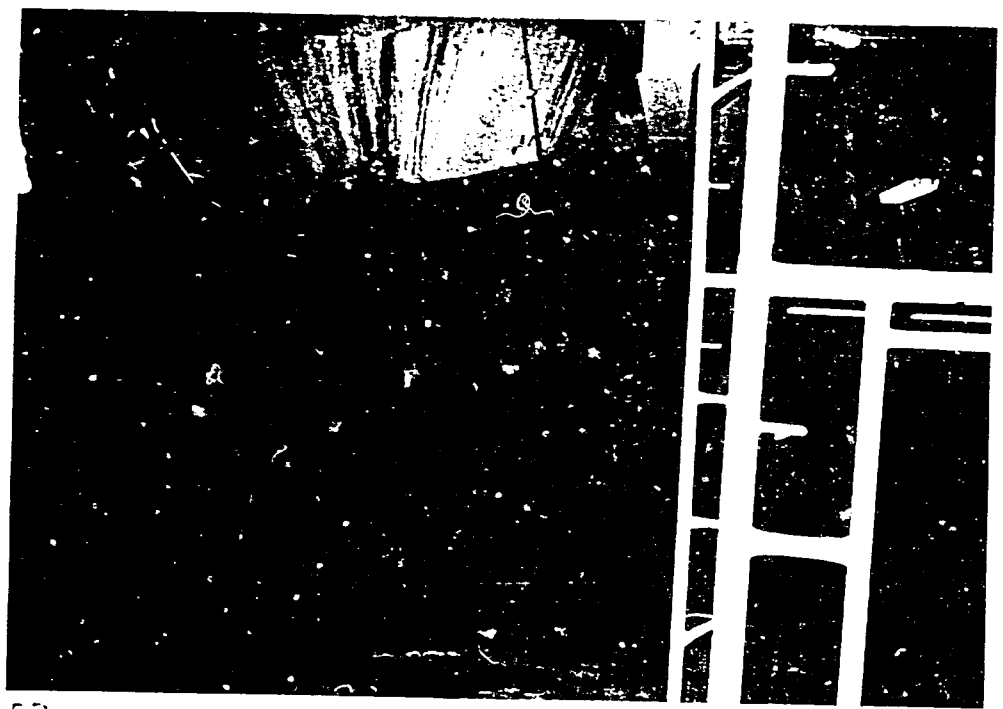

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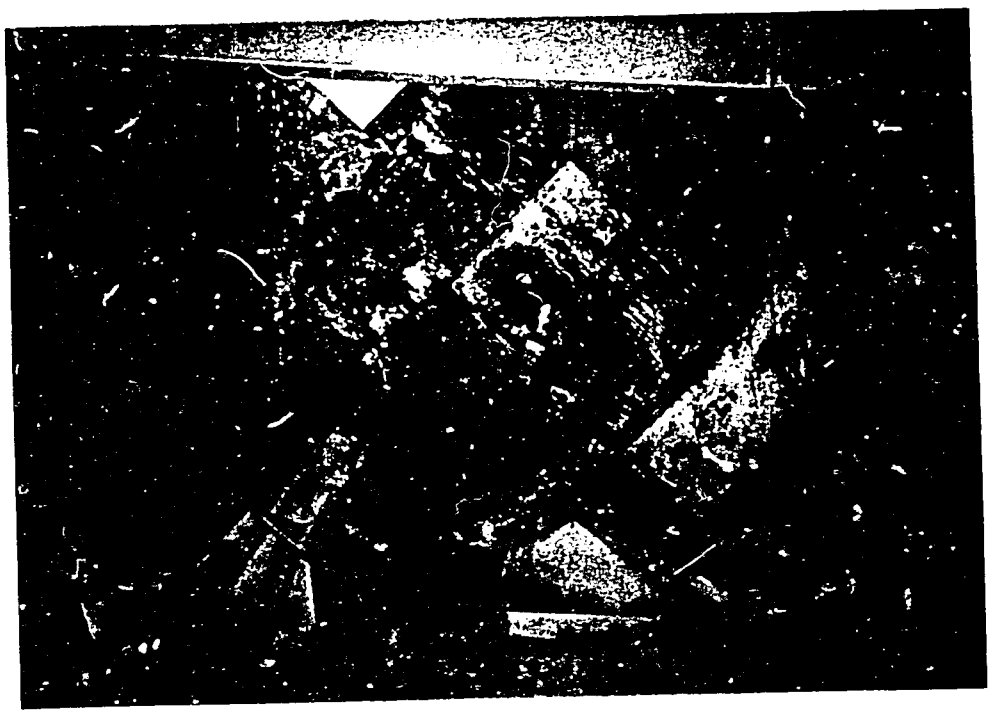

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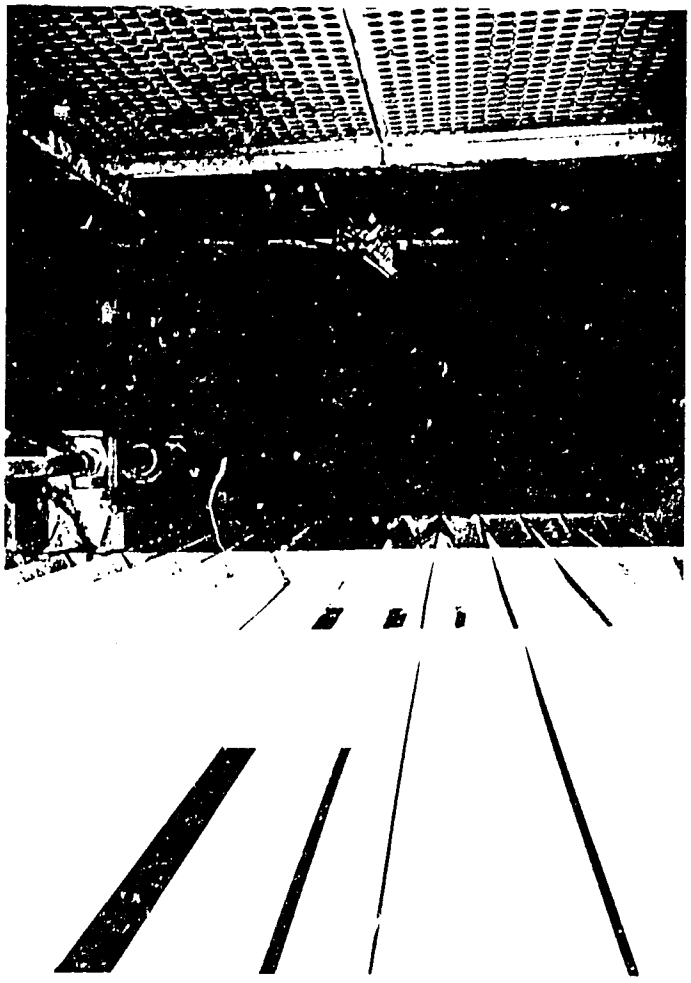

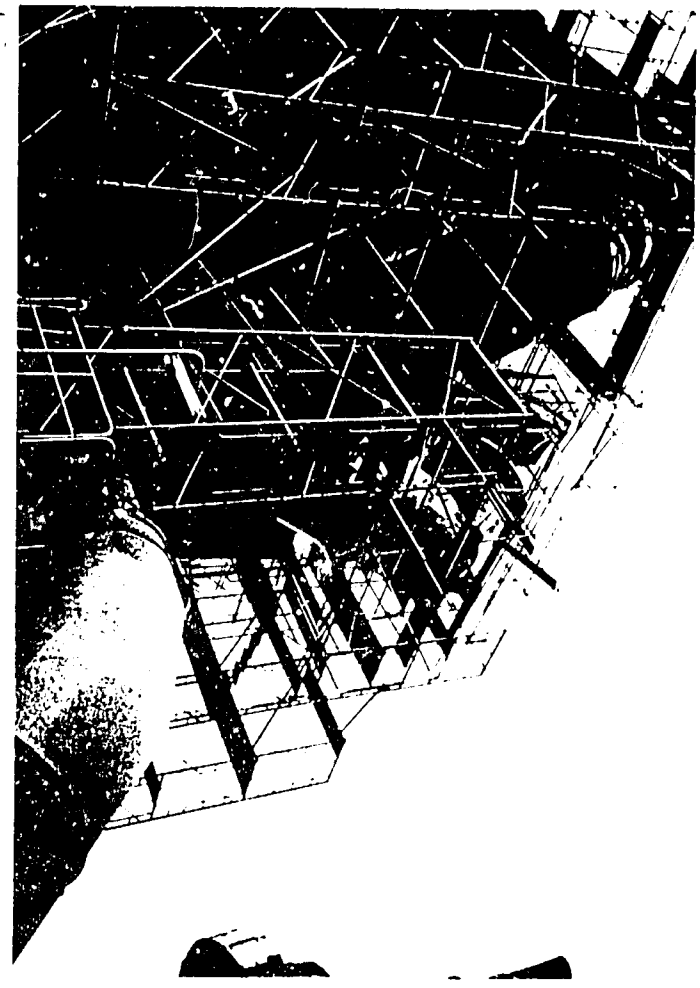

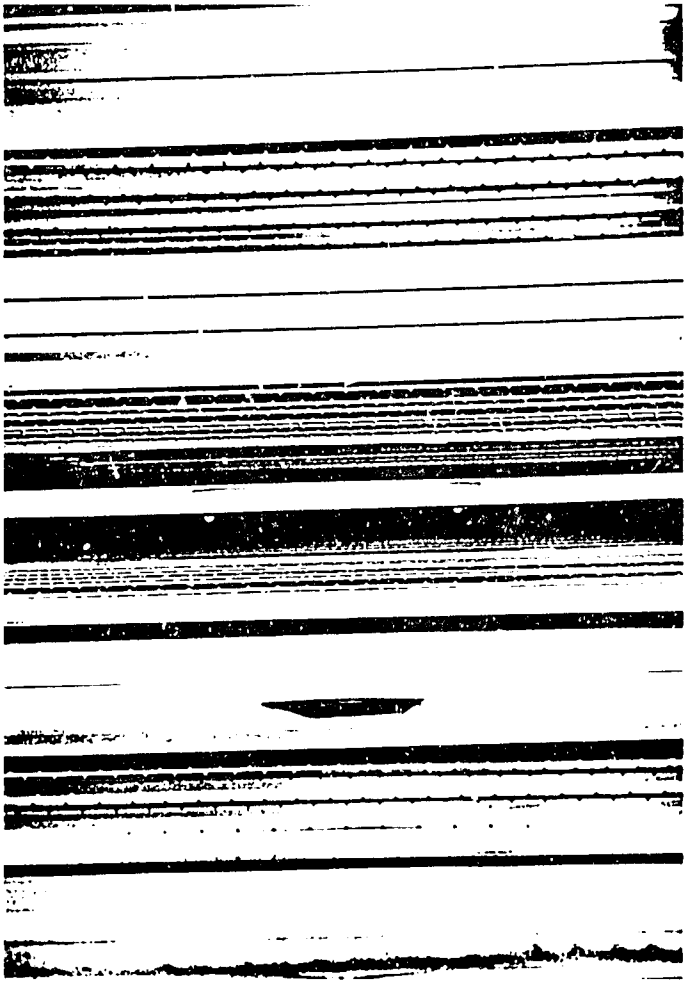

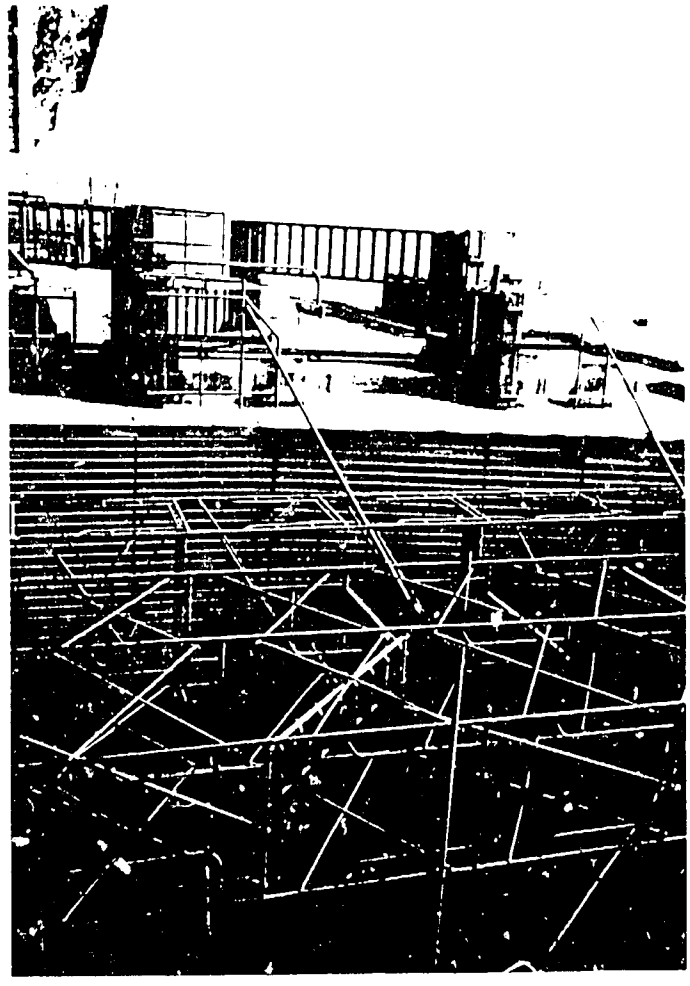

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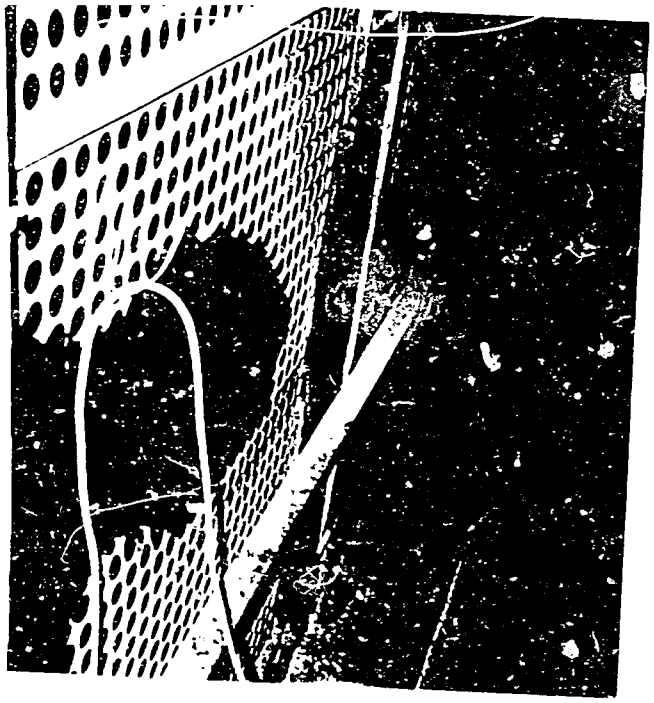

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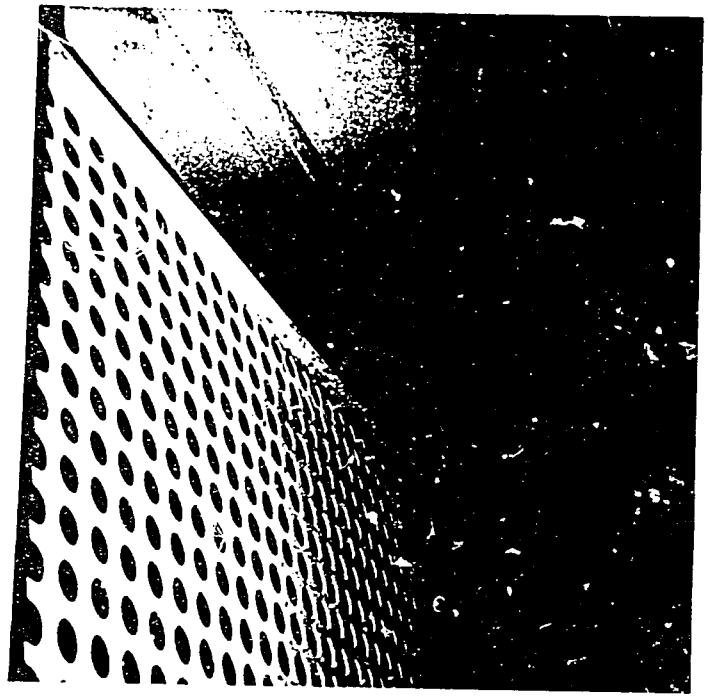

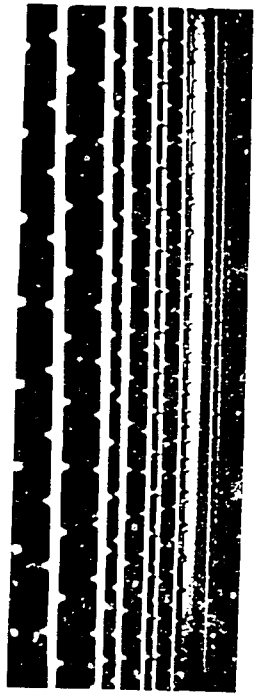

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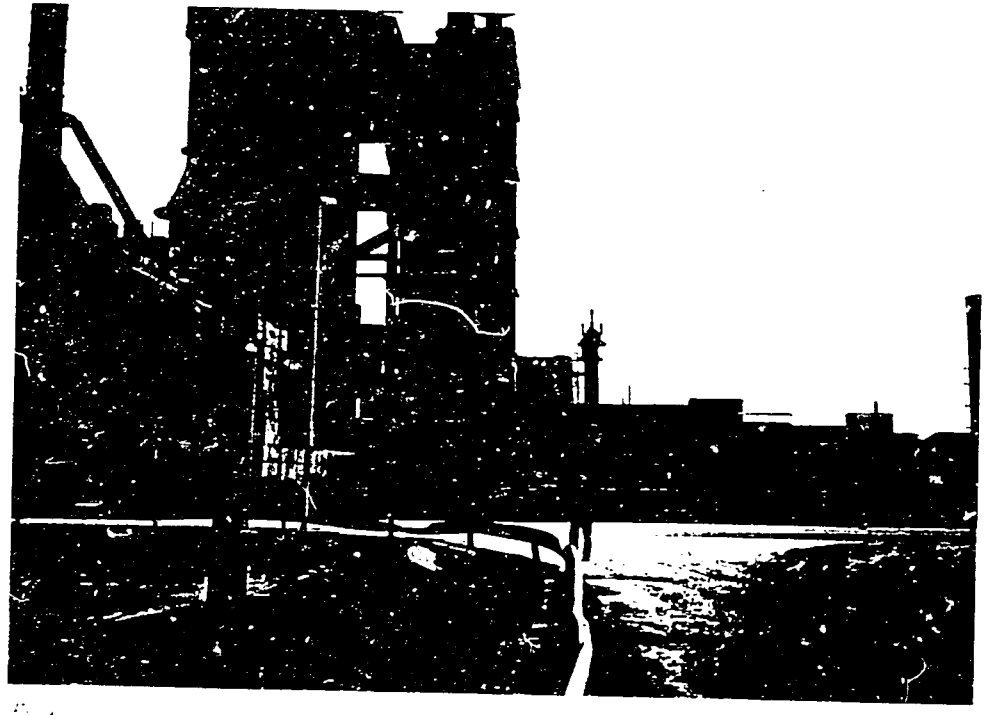

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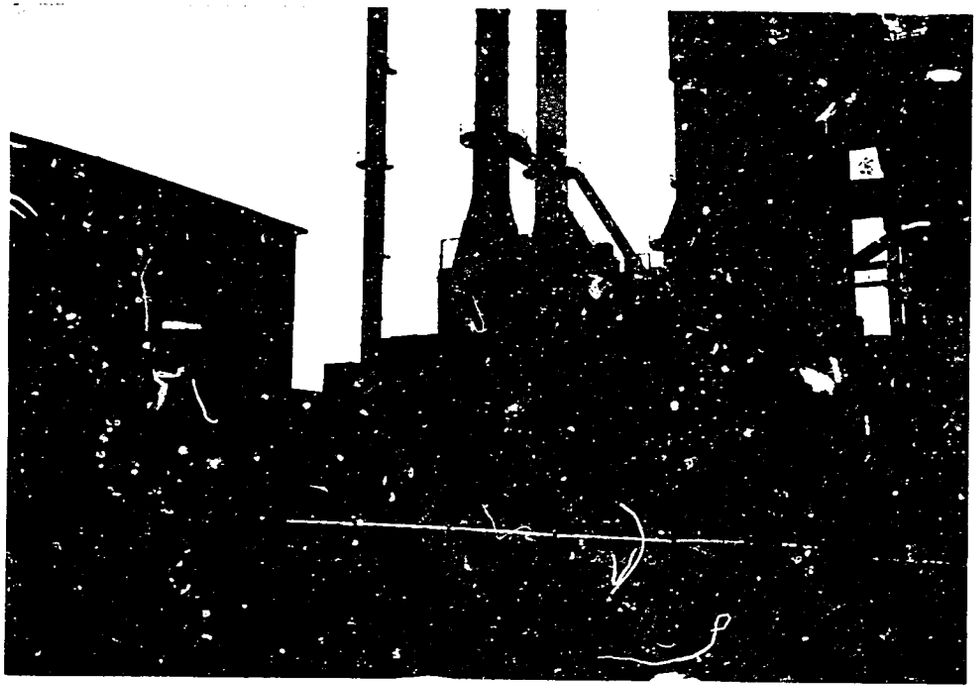

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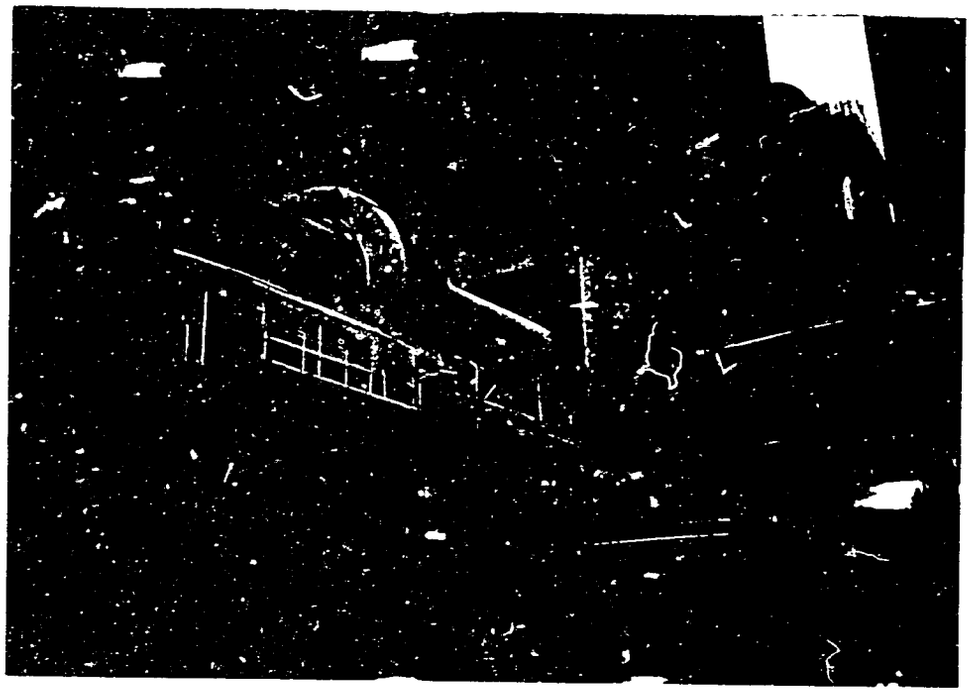

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RESUME' OF MARLIN H. ANDERSON, JR.

ADDRESS: 305 Marietta Drive
Hopkinsville, Kentucky 42240

PHONE: (502) 885-5420

GENERAL INFORMATION

Consultant	-1984
Vice President and General Manager	-1983 to 1984
Senior Physicist and Director of Field Services	-1982 to 1983
Research Physicist	-1978 to 1982
Assistant Professor	-1975 to 1978

EDUCATION

B.A. - Physics and Mathematics, Huntingdon College	-1965
M.S. - Physics and Mathematics, Auburn University	-1968
Ph.D.- Physics, Auburn University	-1977

MEMBERSHIPS

Kappa Mu Epsilon
Sigma Xi
Who's Who in American Colleges and Universities (1965)

CONSULTANT

As a consultant, Marlin Anderson has provided technical services to industry such as equipment inspection, analysis and optimization of system performance, on-site training programs and courses, and specialty testing. He has been involved in programs for the evaluation of precipitator performance with the application of new technologies including the DRI pre-charger and fluidized bed combustion. Mathematical modeling has been used as a diagnostic and as a predictive tool in his work. In 1986, he and James D. Parsons formed APCO Services, Inc., a consulting firm, through which their services are provided.

VICE PRESIDENT AND GENERAL MANAGER

In this position, he was primarily responsible for the technical services offered by Crestmont Associates, Inc. Dr. Anderson was responsible for the direction of the staff of the Environmental Control Technology Division (ENCOT) which was composed of professionals, technicians, and construction workers. He was actively involved in all phases of the business including theoretical analysis of existing performance capabilities, use of

mathematical modeling techniques for projection of precipitator performance, inspection of control devices, testing, presentation of findings and recommendations applicable to improved emission control capabilities, scheduling, estimating and marketing.

SENIOR PHYSICIST AND DIRECTOR OF FIELD SERVICES

Dr. Anderson joined Paul and McDonald Associates, Inc. in March, 1982 as a Senior Physicist. In that capacity he was involved in assisting users of particulate control technology, vendors and architect/engineers in providing effective particulate emission control. This included the evaluation of available particulate control technology for meeting specific needs, evaluation of the impact of different fuel sources on process operation and control device performance, and the assessment of appropriate equipment needs.

RESEARCH PHYSICIST

In 1978, Dr. Anderson joined Southern Research Institute as a Research Physicist in the Institute's Control Device Division. He conducted research dealing with the fundamental mechanisms involved in particulate collection devices such as: electrostatic precipitators, fabric filters and scrubbers. He was involved in the development of a mathematical model of electrostatic precipitator performance and in the measurement of parameters associated with the precipitation process. From 1979 to 1982, he was a Program Manager for projects which involved the pilot scale evaluation of new particulate control technology.
Dr. Anderson has been involved in the development of techniques and hardware for measuring electric potential distributions in wire duct geometries and for measuring the charge on individual particles charged in an electrostatic precipitator. He has been involved in the field evaluation of the High Intensity Ionizer, electrostatic precipitators, baghouses and a baghouse after a catalytic reactor for NOx removal. He has had experience in the design of mechanical devices, vacuum equipment and digital electronic circuitry.
Dr. Anderson has presented his work at meetings, in published reports and in journal articles.

ASSISTANT PROFESSOR OF PHYSICS AND MATHEMATICS

Dr. Anderson taught physics and mathematics at the undergraduate level. While at Huntingdon College, a colleague and he directed a National Science Foundation Summer Program for high school juniors from high schools with weak science departments. He has a strong background in experimental physics and applied mathematics with emphasis in the area of solid state physics and phenomena associated with corona discharges.

Partial List of M. H. Anderson's Experience in the Cement Industry

COMPANY	WORK PREFORMED
Medusa Portland Cement Wampum, Pennsylvania	Evaluation of Kiln #3 precipitator to determine the reason for degradation in precipitator performance when refuge derived fuels were being burned, and to make recommendations for performance improvement.
Lehigh Portland Cement Mitchell, Indiana	Precipitator inspections, evaluation of precipitator performance with recommendations for performance improvement, technical direction during precipitator repairs, adjustment of precipitator control equipment.
Lehigh Portland Cement Union Bridge, Maryland	Precipitator inspections and evaluation to determine requirements for improved performance and reliability.
Lehigh Portland Cement York, Pennsylvania	Inspection of precipitator to locate problems which were limiting performance.
Lafarge Canada Brookfield, Nova Scotia	Inspection of Kiln #3 ESP to determine cause of discharge electrode failures.
Lone Star Cement Oglesby, Illinois	Supervision of installation of current limiting reactors and set up of automatic voltage controllers.
Mountain Cement Laramie, Wyoming	Inspection of precipitator in order to locate problems which were limiting performance with recommendations for correction.
Missouri Portland Cement Kansas City, Missouri	Precipitator and process evaluations, including: dust properties, precipitator mechanical and electrical conditions, rapping study, performance projections, etc.
St. Mary's Cement St. Mary's, Ontario, Canada	Inspection of kiln, bypass, and clay precipitators to gather information for an evaluation of their performance in an effort to understand the degradation in performance which had been seen with time following shutdowns.

Tarmac Florida, Inc. Miami, Florida	Feasibility study to determine if the the gas stream from one kiln could be diverted to the precipitator of an unused kiln economically.

APPENDIX A

THE CONTRIBUTIONS OF OPEN SOURCES TO AMBIENT TSP LEVELS

By:

John S. Evans and Douglas W. Cooper
Harvard School of Public Health
Boston, Massachusetts 02115

ABSTRACT

We estimate that open sources (roads, fields, construction, etc.) contribute 400 x 10^6 tons/year of particles to the atmosphere in the U.S. Total U.S. point and area source particulate emissions are approximately 20 x 10^6 tons/year. Proposed open source control strategies cannot be assessed rationally without considering the influences of characteristic differences in patterns of location, particle size distributions, and emission heights of these two major source types, open sources and point sources. Simple physical and statistical models indicate that although open sources contribute less per ton of emissions to monitored TSP concentrations than point sources, due to their vast emission rates they account for a greater fraction of ambient mass concentration than point sources. Further analysis indicates that although open source control programs seem attractive on the basis of the cost-effectiveness of emissions reductions, and in some cases may be necessary to local compliance efforts, they may not provide an economically attractive means of achieving widespread reductions in ambient TSP levels.

THE CONTRIBUTIONS OF OPEN SOURCES TO AMBIENT TSP LEVELS

INTRODUCTION

Although over the last few years vast sums have been spent on the control of air pollution from point sources, in many areas of the United States the primary air quality criteria for total suspended particulates (TSP) are not being met. Figures 1 and 2 indicate the extent of non-compliance and the severity of the problem. Figure 1 shows that while there are violations of the annual TSP standard in every region of the country, widespread violations of both the annual and daily maximum TSP standards are most prevalent in the Southwest.[25] Figure 2 presents two alternative measures of the severity of a state's TSP problem. For each state we have calculated the arithmetic mean of both the geometric annual mean and the 90th percentile concentration reported by all of the TSP monitors in the state, using 1976 SAROAD data.[27] On the basis of this analysis it appears that most states which have high average geometric annual mean concentrations also have extremely high 90th percentile concentrations. The most severe TSP problems seem to be concentrated in two rather distinct regions, the Ohio River Valley and the Southwest.

Traditionally, it has been assumed that point sources (e.g., utility combustion, cement manufacture, metal processing) were the dominant anthropogenic sources of atmospheric particles. The notion was that while open sources, those sources too large in extent to be controlled by enclosure or ducting (such as unpaved roads, agricultural tilling, construction activities, surface mining...) might emit significant quantities of dust, the impact of these emissions would be highly localized and sporadic. Recently this belief has come to be questioned.

THE EVIDENCE FROM AIR SAMPLING

Table 1, from the work of Lynn et al. (1976),[28] indicates that approximately 65% of the mass collected by high-volume samplers in 14 U.S. cities under study was of mineral origin. The mineral component of TSP, consisting largely of quartz, calcite, hematite, and feldspars, is commonly attributed to wind erosion, resuspension of soil, quarrying, cement manufacturing, iron and steel processing, and fuel combustion (fly ash)(Dzubay(1979)).[8] The microscopy techniques used by Bradway and Record (1976)[1] permitted enough resolution of the mineral component so that fly ash could be excluded from it. Hematite (which might be primarily due to industrial emissions) accounted on the average for only 15% of the mineral component in these 14 cities (Lynn, et al.).[28] Several other studies of the composition of the ambient aerosol (and its sources) are of interest:

1. Microscopic analysis of high-volume filters collected on twenty days with TSP levels above 130 $\mu g/m^3$ in Evansville, Indiana, indicated high contributions

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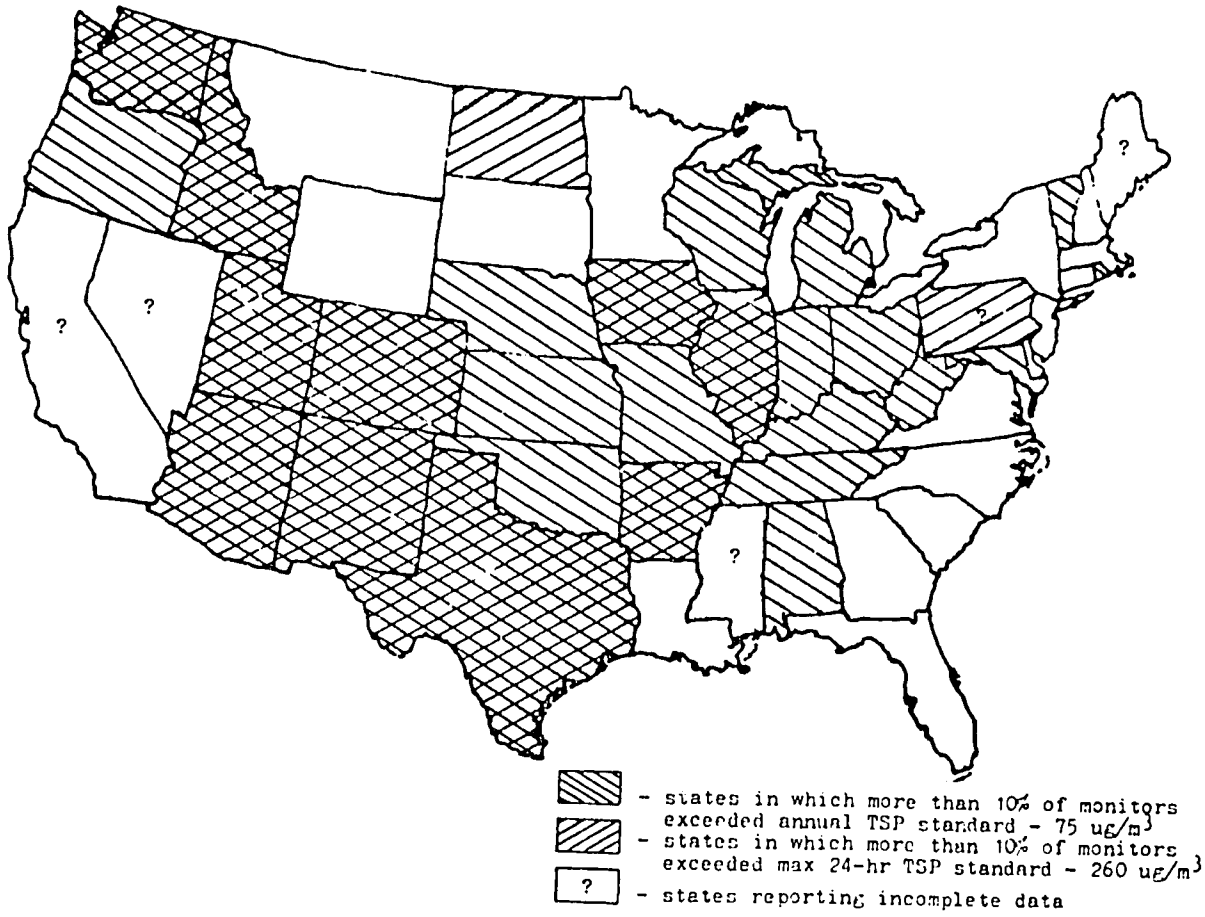

Figure 1. Noncompliance With Primary TSP Standards - 1977

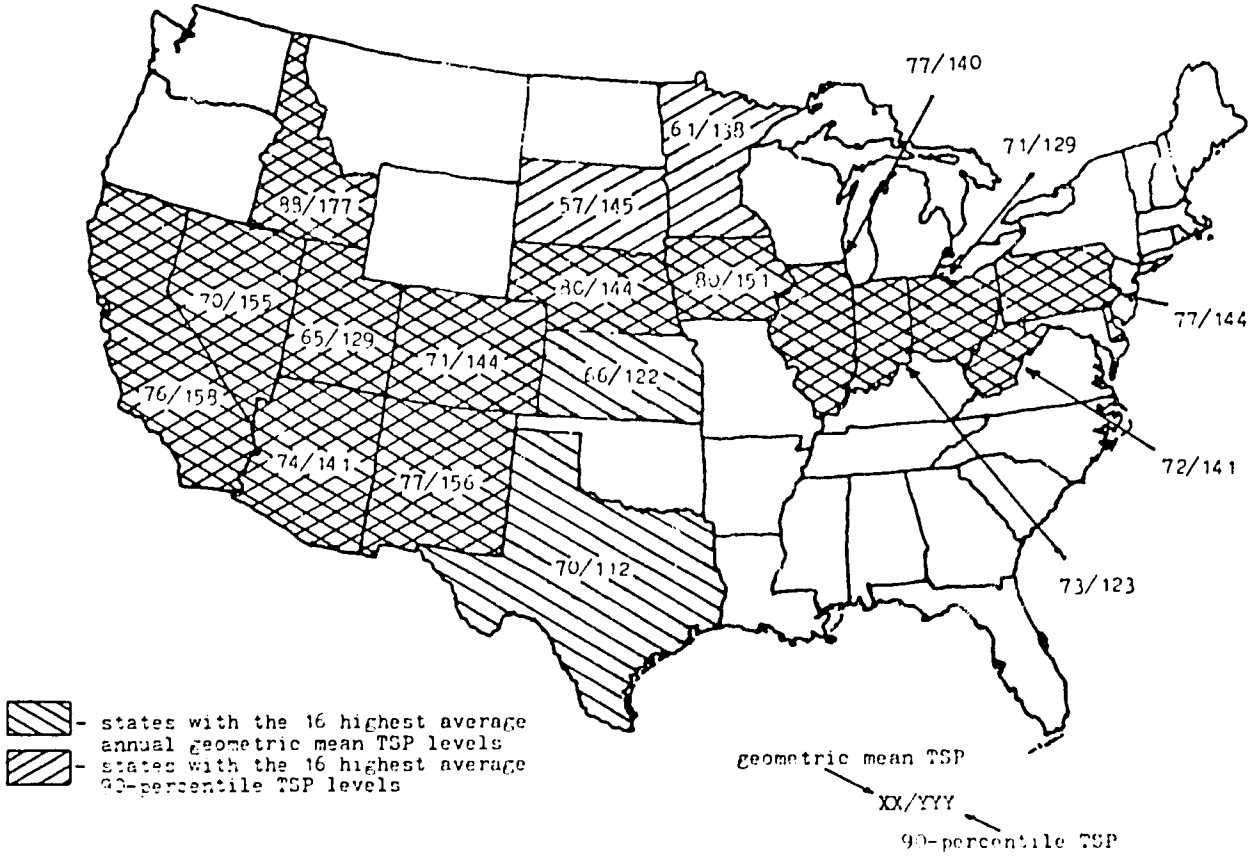

Figure 2. Severity of Ambient TSP Levels - 1976

Table 1. COMPOSITE SUMMARY OF MICROSCOPIC ANALYSIS IN 14 CITIES, $\mu g/m^3$ *

City	Minerals		Combustion products		Biological material		Miscellaneous	
	Average	Range	Average	Range	Average	Range	Average	Range
Heavily industrialized								
Cleveland	51	28-85	40	10-70	1	<1-5	8	tr-22
Birmingham[a]	66	14-90	22	2-86	2	0-8	10	0-50
Philadelphia[a]	64	6-93	33	6-89	1	0-10	2	0-30
Baltimore[a]	69	52-88	25	11-61	3	<1-11	3	0-26
St. Louis	75	21-99	21	1-79	<1	0-5	4	0-10
Cincinnati	51	24-88	44	9-84	1	<1-5	4	<1-20
Moderately industrialized								
Chattanooga	36	3-96	35	8-78	16	0-90	13	0-45
Denver	81	62-97	7	1-19	1	0-7	11	0-32
Seattle	60	30-96	27	1-62	3	tr-24	10	<1-40
Providence	64	28-92	22	4-68	1	0-5	13	0-35
Lightly industrialized								
Washington, D.C.	70	39-87	23	5-49	5	<1-47	2	<1-25
Oklahoma City	88	63-99	8	1-31	<1	<1-4	4	<1-30
Miami[b]	79	75-83	9	7-12	<1	<1	12	10-15
San Francisco	52	29-73	29	10-50	3	tr-10	16	0-35
All cities	65	3-99	25	1-89	3	0-90	7	0-50

[a]Excludes analyses of NASN site filters

[b]Analyses of NASN site filters only

*From Lynn, D. A. et al, National Assessment of the Urban Particulate Problem, EPA-450/3-76-024, (1976).

(approximately 60% by weight) of "alluvial dust." Among these data strong positive correlations existed between wind speed and TSP, and between wind speed and TSP of alluvial origin (Mukherji, et al. (1978)).[5]

ii. Hopke et al. (1976)[3] found, through factor and cluster analyses, that a "crustal factor" accounted for over 50% of the total variance in their data set, which consisted of the measured concentrations of 18 elements from over ninety samples collected at seven locations in Boston.

iii. Gaarenstroom et al. (1977)[4] demonstrated with factor analysis that at an urban monitor in Phoenix a "soil factor" explained 53% of the variance in a data set consisting primarily of measured elemental concentrations. For a similar data set taken at a desert location 60 miles outside of Phoenix this "soil factor" explained only 38% of the variance. Total particulate mass was heavily weighted (.84 in the urban location and .73 in the remote location) in both "soil factors." These heavy weights indicate high correlation between total mass and the "soil factor."

iv. Applying the chemical element balance method to elemental data from dichotomous samplers at ten RAPS sites in St. Louis, Dzubay (1979)[8] found that crustal shale and limestone accounted for 43% of total mass, 83% of the coarse fraction (2.4 μm ≤ aerodynamic diameter < 20 μm) and 9.8% of the fine fraction (aerodynamic diameter < 2.4 μm).

v. The results of Richard and Tan (1977),[9] who used microscopy, indicated that about 70% of the total mass collected by high-volume samplers in the Phoenix area consists of particles with diameters greater than 20 μm. Open sources (and fugitive industrial sources) emit much larger particles, on the average, than traditional point sources.

vi. Hammerle and Pierson (1975)[7] found that less than 30% of the mass of Fe, Ti, and Ca (all possibly of soil origin) collected on membrane filters in Pasadena was due to particles with aerodynamic diameters less than 1.5 μm, while about 80% of the total mass of Pb and Br was in this small size fraction. The percentage of Fe in the small size fraction was found to be negatively correlated with wind speed (as might be expected for soil dust), and positively correlated with precipitation. On the basis of a chemical element balance they estimated that 20% by weight of the particles collected were "soil dust."

vii. Using the chemical element balance method, Gartrell and Friedlander (1975)[2] have estimated that 19.8 $\mu g/m^3$ (23% of total mass) and 15.1 $\mu g/m^3$ (9% of total mass) of TSP collected in samples from Pasadena and Pomona, California was "soil dust."

viii. Examining the relative abundance of various elements in impactor samples collected in South Florida, Hardy et al. (1976)[6] concluded that urban enrichment of the large-particle size fraction may be attributed to soil dust.

On the basis of these estimates it would appear that open sources contribute significantly to measured TSP concentrations, particularly on days with high winds, offsetting the decrease in concentrations of material from traditional sources with relatively constant emission rates. Although open sources contribute primarily to the large size fraction, their impact on respirable/inhalable particulate concentrations is not negligible. In the remainder of this paper we estimate open source emission rates, and explore their relationships with measured TSP concentrations in an attempt to assess the necessity and practicality of open source controls.

OPEN SOURCE EMISSION RATES

One of the primary reasons for the current uncertainty as to the significance of open sources of TSP has been the unavailability of emissions estimates or acceptable methods for the estimation of emissions rates. Although Chepil, Woodruff and Siddoway(1965)[23] and others began working in the 1930's on the problem of estimating agricultural soil losses due to wind erosion, only recently has the relevance of their work to air pollution been recognized. Handy (1975)[18] and his colleagues at Iowa State University also made some early estimates of soil transport by the wind and more recently have published estimates of dust fallout near unpaved roads. Throughout the literature there are scattered discussions of the importance of other open sources; however, the first comprehensive discussions of the open source problem are those of Cowherd et al. (1974)[15,17](1976),[16] Jutze and Axetell (1974),[19] and Carpenter and Weant (1977).[22] Cowherd and his colleagues at Midwest Research Institute developed methodologies for the estimation of emissions from agricultural tilling, paved and unpaved roads, construction activities, and dirt airstrips. They noted that the wind erosion equation of Woodruff and Siddoway (1965)[23] might be adapted to permit estimation of dust emissions due to wind erosion of agricultural land.

Carpenter and Weant at Research Triangle Institute used NEDS data for emissions from dirt roads, landings and takeoffs from dirt airstrips, and agricultural tilling (based upon the work of Cowherd), and on emissions from open burning, agricultural slash burning, and coal refuse fires, in conjunction with data on conventional point and area sources, to demonstrate that in most (146) of the 150 AQCR's which violated TSP standards in 1976, over 50% of all emissions were from open sources. Jutze and Axetell, of PEDCo Environmental Specialists, estimated the emissions rates from unpaved roads, construction activities, agricultural wind erosion and tilling, tailings piles, aggregate storage piles, and feedlots for five AQCR's in the states of New Mexico, Nevada, Arizona, and California. As part of their study, field sampling programs were conducted to develop emission factors for unpaved roads, agricultural tilling, and construction activities.

Supplementing the methodology of Cowherd et al. with estimates of the emissions factors for forest fires and prescribed agricultural burning (Yamate et al.(1975)[24] and Ward et al.(1976)),[21] surface mining (Ochsner and Blackwood (1977)),[29] and tailings piles (Amick (1974)),[11] we developed the formula shown in Table 2 for estimating total annual open source emission rates for any region of interest. In order to estimate the total open source emissions rates for each state, we collected data, applicable to the mid-1970's, for each of the climatic, geologic, and economic factors which appear in the formula. The development of the formula and data base is described in detail in Evans et al. (1978).[10] Our open source emissions estimates are summarized in Table 3. These estimates indicate that nationally the largest open sources, in descending order, are: unpaved roads (319 x 10^6 tons/yr), construction activities (27 x 10^6 tons/yr), and wind erosion of cropland (23 x 10^6 tons/yr). Total U.S. open source emissions are estimated to be approximately 410 million tons per year. As a point of comparison, total point source emissions in the U.S. in the mid 70's were estimated to be about 20 million tons per year (CEQ(1976)).[14] On the basis of these estimates alone

Table 2. FORMULAS FOR ESTIMATING OPEN SOURCE EMISSION RATES

agricultural tilling emissions	where:
$E_A = (1.1\, S_a(s_i/5.5)/(PE/50)^2)(H)(T_1)/2000$	S_a - agricultural soil silt content (%) s_i - implement speed (mph) PE - Thornwaite's PE index H - acreage of harvested cropland T_1 - number of tillings per year = 3
agricultural wind erosion emissions	
$E_W = (.025\ I\ K\ C\ L'V')(H)/100$	I - soil erodibility index (tons/acre/yr) K - surface roughness C - climatic factor L' - unsheltered field width factor = 1.0 V' - vegetative cover factor
construction activity emissions	
$E_C = (1)(D)(E)(M)$	D - duration (months) E - extent (acres/10^6 \$) M - construction expenditure (10^6 \$)
forest fire emissions	
$E_F = (150\ F_F)(B)/2000$	F_F - available fuel (tons/acre) B - acres burned in wildfires
prescribed burning emissions	
$E_P = (50\ F_P)(P)/2000$	F_P - available fuel (tons/acre) P - acres burned in prescribed fires
surface coal mining emissions	
$E_M = ((1.7\ T_{me}) + (0.06\ T_{mw}))/2000$	T_{me} - tons mined in Eastern U.S. T_{mw} - tons mined in Western U.S.
other surface mining emissions	
$E_S = (2)(T)/2000$	T - tons handled at surface mines
paved road emissions	
$E_R = (0.013, (M_{Pr} \times 10\, U_r + M_{Pu} \times 10\, U_u)/2000$	M_{Pr} - miles of paved rural roads M_{Pu} - miles of paved urban roads U_r - rural use factor - vehicle miles/mile U_u - urban use factor - vehicle miles/mile
unpaved road emissions	
$E_u = (0.65\ S_r(\frac{s}{40})(\frac{d}{365})(M_{ur} \times U_r + M_{uu} \times U_u)/2000$	S_r - road surface silt content (%) s - vehicle speed (mph) d - number of dry days/year M_{ur} - miles of unpaved rural roads M_{uu} - miles of unpaved urban roads U_r - rural use factors - vehicle miles/mile U_u - urban use factors - vehicle miles/mile
tailings pile emissions	
$E_T = (0.133\ C)(A)$	C - climatic factor A - acres of tailings piles

total open source emissions

$$E_O = E_A + E_W + E_C + E_F + E_P + E_M + E_S + E_R + E_u + E_T$$

Table 3. OPEN SOURCE EMISSIONS RATE ESTIMATES (10^3 TONS/YR)

State	Tilling	Wind Erosion	Construction	Wild Fires	Prescribed Fires
AL	5.30	47.5	273.	102.00	15.60
AK	0.10	0.0	59.	646.80	0.00
AZ	117.00	713.1	139.	28.50	5.20
AR	14.60	159.3	141.	94.50	4.10
CA	126.00	3945.8	4854.	218.80	21.20
CO	158.00	881.6	117.	25.00	0.50
CT	0.50	4.1	333.	1.00	0.00
DE	0.60	8.6	10.	0.05	0.04
FL	5.00	92.2	766.	316.60	71.90
GA	8.45	91.5	455.	41.30	54.30
HI	2.30	0.0	62.	0.00	0.00
ID	88.80	987.8	24.	544.00	45.40
IL	151.00	1721.4	1415.	11.40	0.00
IN	52.40	842.6	773.	8.90	0.00
IA	142.00	2077.7	253.	1.90	0.00
KS	239.00	4769.0	245.	65.80	0.00
KY	15.10	122.1	270.	62.50	0.00
LA	14.40	90.7	870.	73.00	16.60
ME	1.20	10.4	87.	2.50	0.00
MD	2.10	44.6	128.	1.40	0.00
MA	0.50	6.4	1260.	8.40	0.00
MI	21.20	410.7	743.	7.70	0.30
MN	99.30	1610.6	452.	30.80	0.00
MS	12.90	71.9	138.	78.60	12.70
MO	61.70	858.8	346.	119.80	0.00
MT	200.00	1264.1	31.	99.60	52.90
NE	306.00	5218.9	197.	20.00	0.00
NV	68.00	1157.1	22.	14.80	0.00
NH	0.40	0.5	69.	0.46	0.00
NJ	1.60	15.7	844.	23.50	1.50
NM	50.30	842.3	61.	19.90	1.40
NY	20.10	149.6	1462.	6.00	0.00
NC	6.30	118.2	640.	75.10	8.80
ND	292.00	3553.3	80.	0.47	0.10
OH	44.20	822.8	1365.	5.20	0.00
OK	89.00	1177.9	332.	115.80	0.00
OR	39.40	48.2	212.	196.50	21.60
PA	21.60	81.6	2090.	12.90	0.00
RI	0.10	0.9	82.	0.70	0.00
SC	4.30	54.0	177.	43.60	29.10
SD	210.00	3119.6	39.	4.80	0.00
TN	10.90	41.2	333.	27.70	0.00
TX	386.00	5000.7	3760.	19.10	6.20
UT	78.40	653.4	203.	10.00	0.00
VT	1.90	8.1	17.	0.20	0.00
VA	5.30	71.0	212.	5.60	3.90
WA	14.60	64.3	447.	164.30	56.80
WV	2.84	5.6	215.	74.20	0.00
WI	49.00	663.1	218.	6.90	0.00
WY	56.30	638.8	59.	8.30	0.00

Table 3. (CONT'D)

State	Extraction: Coal	Extraction: Other	Tailings	Paved Roads	Unpaved Roads
AL	16.9	39.3	1.1	149.	3760.
AK	0.6	127.0	0.0	11.	1990.
AZ	0.2	187.0	156.7	92.	9740.
AR	0.4	38.0	1.0	73.	9340.
CA	0.0	171.0	141.5	803.	27530.
CO	0.2	33.8	17.0	89.	10080.
CT	0.0	15.1	0.4	117.	320.
DE	0.0	2.4	0.0	23.	70.
FL	0.0	235.0	2.6	386.	7010.
GA	0.0	54.6	1.3	212.	7010.
HI	0.0	9.0	0.0	26.	80.
ID	0.0	17.8	30.9	30.	4120.
IL	49.5	104.0	5.5	370.	7960.
IN	20.2	58.1	2.6	229.	6450.
IA	0.5	49.4	4.8	104.	11310.
KS	0.6	28.5	22.5	78.	14330.
KY	116.6	36.6	2.1	146.	4380.
LA	0.0	24.5	0.4	121.	3790.
ME	0.0	5.4	0.2	43.	710.
MD	2.0	30.5	0.8	154.	710.
MA	0.0	25.7	0.5	182.	680.
MI	0.0	139.0	6.7	345.	8830.
MN	0.0	216.0	20.4	139.	11560.
MS	0.0	18.2	0.2	81.	4260.
MO	3.9	56.1	19.3	175.	10330.
MT	0.4	33.9	11.6	28.	773.
NE	0.0	16.9	2.8	56.	10610.
NV	0.0	36.8	142.2	21.	4890.
NH	0.0	6.8	0.0	32.	1250.
NJ	0.0	44.9	1.8	304.	1950.
NM	0.3	42.5	44.0	48.	10640.
NY	0.0	75.6	10.0	414.	5160.
NC	0.0	57.1	2.0	220.	3860.
ND	0.0	5.1	1.5	17.	8800.
OH	38.6	95.9	6.3	403.	3820.
OK	2.0	32.0	6.5	123.	11860.
OR	0.0	45.0	1.4	83.	12110.
PA	68.4	90.7	4.0	424.	10100.
RI	0.0	3.2	0.1	36.	390.
SC	0.0	24.3	0.6	126.	1350.
SD	0.0	12.4	5.3	24.	6370.
TN	6.4	56.0	1.5	191.	4380.
TX	0.0	116.0	25.9	476.	28640.
UT	0.2	55.8	118.0	42.	5410.
VT	0.0	5.3	0.7	18.	1180.
VA	29.2	58.7	3.9	214.	2340.
WA	0.1	38.1	0.7	137.	6710.
WV	87.1	14.6	1.2	60.	3920.
WI	0.0	53.9	2.9	176.	3310.
WY	0.6	17.9	5.9	19.	2440.

it would seem that open sources might warrant further consideration. Proposed open source control strategies cannot be assessed rationally without considering the extent to which characteristic differences in patterns of location, particle size distributions, and emission heights of these two major source types (point sources and open sources) affect the contribution to TSP values per ton of emissions.

THE CONTRIBUTIONS OF OPEN AND POINT SOURCES TO TSP LEVELS

An evaluation of the impact of application of various control methodologies to a single specified open source, such as a particular mine, field, or stretch of unpaved road, would require site-specific dispersion calculations, but a basic assessment of the general relationship between open source emission rates and ambient TSP levels may be conducted without the benefit of site-by-site dispersion calculations. For example, using states as the unit of observation, and specifying semi-theoretical relationships ("models") linking source emissions and ambient concentrations, readily available meteorological and aerometric data may be used to estimate model parameters empirically. Although these models are not intended to supplant more traditional dispersion calculations, they may economically provide information useful to those faced with the determination of efficient and equitable courses for national policy.

Using our own estimates of open source emissions rates, published estimates of point source emission rates(E.P.A."point" and "area" sources are considered as point sources)(U.S. E.P.A. (1976))[26] and climatological and aerometric data for 1976 (U.S. E.P.A. (1978) [25] and Holzworth (1972)[34]), we have explored the contributions of open and point sources to measured TSP levels. Our data are summarized in Table 4. (The state-by-state data will be made available on request.) Three models have been considered:

Model 1 - Rollback

$$TSP = a_{10} + a_{11}E_o + a_{12}E_p + a_{13}TSP_a + a_{14}P \qquad (1)$$

Model 2 - Modified ADTL

$$TSP = a_{20} + a_{21}\left[\frac{E_o/A}{u}\right] + a_{22}\left[\frac{E_p/A}{u}\right] + a_{23}TSP_a + a_{24}P \qquad (2)$$

Model 3 - Simple Box

$$TSP = a_{30} + a_{31}\left[\frac{E_o}{(H\cdot u)\sqrt{A}}\right] + a_{32}\left[\frac{E_p}{(H\cdot u)\sqrt{A}}\right] + a_{33}TSP_a + a_{34}P \qquad (3)$$

where: TSP = station-averaged annual geometric mean TSP level ($\mu g/m^3$)
E_o = total open source emission rate (10^3 tons/yr)
E_p = total point source emission rate (10^3 tons/yr)
TSP_a = perimeter-weighted, adjacent states station-averaged annual geometric mean TSP ($\mu g/m^3$)

Table 4. REGRESSION INPUTS

Input	Mean	Standard Deviation
TSP	58.8	12.9
E_o	8150.	7815.
E_p	307.	359.
P	110.6	34.3
TSP_a	55.7	10.0
$E_o/H \cdot u\sqrt{A}$	2.26	1.35
$E_p/H \cdot u\sqrt{A}$	0.120	0.136
A	72.3	87.8
u	9.2	1.40
$H \cdot u$	64.9	10.2

Table 5. REGRESSION RESULTS

Model	Factor: constant a_{i0} ($t_{a_{i0}}$)	open sources a_{i1} ($t_{a_{i1}}$)	open sources a_{i2} ($t_{a_{i2}}$)	adjacent TSP a_{i3} ($t_{a_{i3}}$)	precipitation a_{i4} ($t_{a_{i4}}$)	R^2 (R^2_{adj})
Rollback (i=1)	47. (3.7)	0.00029 (1.2)	0.011 (2.5)	0.29 (1.7)	-0.094 (-1.7)	39 34
ADTL (i=2)	49. (4.0)	0.35 (1.9)	4.4 (2.5)	0.33 (2.0)	-0.15 (-3.1)	42 36
Box (i=3)	50. (4.0)	2.2 (1.9)	29. (2.5)	0.32 (1.9)	-0.15 (-3.1)	42 37

Table 6. EXAMINATION OF RESIDUALS

model	overprediction state	standardized residual	underprediction state	standardized residual
rollback	(1) Wyoming	-2.8	Idaho	+3.2
	(2) Montana	-1.9	West Virginia	+1.7
	(3) North Dakota	-1.5	Nebraska	+1.4
box	(1) Wyoming	-2.6	Idaho	+3.6
	(2) Montana	-1.6	Nebraska	+1.5
	(3) North Dakota	-1.5	W. Virginia	+1.5

P = precipitation, number of days with rain (≥.01 inch) or snow (≥1 inch) per year

A = state area (1000 miles^2)

u = mean surface wind speed (mph)

H·u = mean annual (morning + afternoon/2) mixing height times mean annual wind speed averaged through mixing height (100 m^2/s)

The rollback model was chosen because of its simplicity and its history of application in air pollution policy determination (deNevers and Morris (1973)).[30] The other two were selected because they are somewhat more physically realistic, accounting at least partially for the effects of wind speed, mixing height, and state area. In the rollback model source contributions to TSP are assumed to be proportional to their emission rates. In the modified ADTL model, TSP concentrations are assumed to vary proportionally with emission rate per area and inversely with mean wind speed. In the box model source contributions to TSP are proportional to emissions rates and inversely proportional to the volumetric flow rate of dilution air (Hanna (1971) [31] and Benarie (1978)).[33] We have modified each of these models slightly, allowing for transport of particles from adjacent states and for the atmospheric cleansing effect of precipitation.

The results of ordinary least squares analyses of these data, cf. Table 5, indicate that even these simple models are descriptively useful. In Table 5 each empirical coefficient (e.g., a_{ij}) is reported along with its t-statistic; i.e., $t_{a_{ij}}$. The empirical coefficients reported are multipled by the appropriate terms to yield the full empirical model. For example, the full rollback model would be:

$$TSP = 47.0 + 0.00029\ E_o + 0.011\ E_p + 0.29\ TSP_a - 0.094\ P \qquad (4)$$

The t-statistics are indicators of the likelihood that an empirical coefficient at least as large as the one reported could have arisen by chance if the true coefficient were zero. Mathematically, the reported t-statistics are found simply by dividing the empirical coefficients, a_{ij}, by an estimate of their standard error; i.e.,

$$t_{a_{ij}} = \frac{a_{ij}}{s_{a_{ij}}} .$$

(The t-statistics are distributed with n - (k + 1) degrees of freedom; where n is the number of observations and k is the number of variables.) Thus, the larger the absolute value of the t-statistic the less likely that the true coefficient is zero. With 45 degrees of freedom, t values of 1.68 and 2.69 would be significant at the .05 and .005 levels respectively in a one-tailed test. In addition, the coefficient of determination, R^2, and the adjusted R^2 is reported for each model. The R^2 indicates the fraction of the variance in TSP which is accounted for by the model. The adjusted R^2, or corrected coefficient of determination, is a better measure of the adequacy of the model, which accounts for the use of degrees of freedom by the introduction of more independent variables. In addition to examining the coefficients individually, using the F-statistic we may explore the possibility that all of the true coefficients are zero. The F is mathematically equivalent to

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$$\frac{n - (k + 1)}{k} \cdot \frac{R^2}{1 - R^2},$$

and is distributed with k and n - (k + 1) degrees of freedom. An F value of 4.27 is significant at the 0.01 level for 4 and 45 degrees of freedom. Complete discussions of these statistical parameters are found in standard statistical texts, for example, those by Armitage, Wonnacutt and Wonnacutt, and Draper and Smith. Several features of these results should be noted. First, the sign of each empirical coefficient is in agreement with intuition. Second, in each equation point sources contribute more to TSP, per ton of emissions, than open sources. This would be expected as a result of the differences in particle size distributions and patterns of source location of these two source classes. Third, the coefficients of adjacent state TSP and precipitation seem to be reasonably stable. Finally, note that the explanatory power (as indicated by the adjusted R^2) of the models increases slightly with increasing physical sophistication of the model.

Although, as outlined above, many aspects of the results are encouraging, none of the models have impressive R^2 values. The relatively low R^2 may be due to improper specification of the model; i.e., specification of a linear relationship rather than a quadratic; failure to account for important variables; errors in the estimation of data; or simply due to the use of highly aggregated data. A side effect of the limited explanatory power of the models is a large constant term. It is not proper to consider the constant as "background." Rather it is a "catch-all," combining the influence of inadequate models and data bases with the effects of sources which have not been accounted for, for example, industrial fugitive sources, sources of secondary aerosols.

Often an analysis of the residuals from the regression is a useful tool for uncovering specification errors. Most commonly a plot of standardized residuals versus predicted values is visually inspected. The standardized residual is simply the observed value minus the predicted value divided by the square root of the mean square residual. The mean square residual is the average value of the square of the difference between the observed and predicted values. Such an analysis failed to reveal irregularities in our models. In addition to this simple visual analysis of residuals, we examined statistically the relationships between standardized residuals and several included and excluded independent variables in an attempt to detect second order effects and to identify new variables for subsequent inclusion. It is also useful to examine in detail the cases yielding the largest residuals. Occasionally such an analysis will reveal errors in data collection, data transcription, and/or inadequacy of models. The three largest positive and three largest negative standardized residuals from the rollback and box models are presented in Table 6. (For brevity, we omit further consideration of the ADTL model, which performed very similarly to the box model.)

No transcription errors were evident in the data for these six states. However, the physical proximity of the three consistently most overpredicted states is suggestive of some systematic deficiency in the data base and/or model.

Reflection upon the assumptions inherent in these approaches and upon the adequacy and accuracy of the data base revealed several potential sources of error. Among them:

i. In the box model we assume that each state may be represented as a box with a square base. The states are not squares.

ii. We are using as a dependent variable the station-averaged geometric mean annual TSP concentrations. Spatially-averaged arithmetic annual mean concentrations would be more appropriate.

iii. Arithmetic mean annual wind speed, rather than the mean annual resultant wind, is used to characterize dilution potential in the ADTL model.

iv. The influence of errors in measurement/estimation of data upon the empirical coefficients and regression statistics has not been evaluated.

v. The dependent variable, TSP, is not estimated with constant variance. States vary both in the variability of TSP levels within the state and the number of monitors employed to characterize TSP levels. Thus the least squares assumption of homoskedasticity is violated.

These problems are discussed in detail in a technical appendix to this paper, which will be made available. Here, we simply note that the empirical regression coefficients and the estimates of the standard errors of the coefficients, and therefore indirectly the accompanying t-statistics, are biased in the presence of measurement errors and heteroskedasticity, respectively. The combined effect of these problems is to <u>underestimate</u> the absolute values of the <u>coefficients</u>, <u>overestimate</u> their standard <u>errors</u>, and thus <u>underestimate</u> their <u>t-statistics</u>.

Using the empirical coefficients from the rollback and box models and the emissions estimates from Table 4 we may gain some insight into the contributions of point and open sources to ambient TSP levels. The <u>average</u> contributions of each term in the models to statewide TSP levels is found by inserting the mean values of the variables into the models. For the rollback and box models we have:

<u>Rollback Model</u>:

$$TSP = 47 + 0.00029\ E_o + 0.011\ E_p + 0.29\ TSP_a - 0.09\ P \qquad (5)$$

<u>Box Model</u>:

$$TSP = 50 + 2.2\left(\frac{E_o}{Hu\sqrt{A}}\right) + 29\left(\frac{E_p}{Hu\sqrt{A}}\right) + 0.32\ TSP_a - 0.15\ P \qquad (6)$$

The average contributions ($\mu g/m^3$) of each of the terms is as follows (rollback, box): unexplained (47,50), open (2.4,4.9), point (3.4,3.5), adjacent states (16.2,17.8), precipitation (-10.4,-17.0).

The large influences of adjacent state TSP and precipitation frequency, and the dominating "unexplained" term are at first troublesome. However, the adjacent states' contribution of between 16 and 18 $\mu g/m^3$ probably reflects primary aerosol background. The precipitation term includes any influence of rainfall on soil moisture and, indirectly, open source emission rates, which are not properly accounted for in the open source emissions rates, as well as the atmospheric cleansing effect of precipitation. The "unexplained" term has been discussed previously. It is possible to redistribute this "unexplained" constant among the independent variables by simply applying least squares regression methods to models without constants, i.e., rollback:

$$TSP = a_{11} E_o + a_{12} E_p + a_{13} TSP_a + a_{14} P \qquad (7)$$

The least squares estimate of the parameters in this equation are:

$$TSP = \underset{(1.58)}{0.0041} E_o + \underset{(1.84)}{0.0091} E_p + \underset{(8.15)}{0.834} TSP_a + \underset{(1.22)}{0.050} P \qquad (8)$$

Table 7 presents the results of calculations of the contributions of open and point sources to TSP in each state, using equations (5) and (6). (The computer output has been truncated to two decimal places.)

An examination of the data in Table 7 indicates that the ten states in which open sources contribute the smallest percentages to TSP are clustered in the South and Southeast. The ten states with the largest percentage open source contributions are all west of the Mississippi River.

THE CONTRIBUTION OF ROAD DUST TO TSP

Although it would be desirable to determine the contribution of each source category (e.g., agricultural tilling, surface mining, utility combustion) to measured TSP levels, an inspection of the full correlation matrix, Table 8, reveals a great deal of collinearity. For example, paved road emissions are highly correlated with construction emissions (+0.889), incineration emissions (+0.800), and vehicle exhaust emissions (+0.924); point source combustion emissions are highly correlated (+0.767) with industrial emissions; and unpaved road emissions are highly correlated with agricultural tilling emissions (+0.630), construction emissions (+0.688), and vehicle exhaust emissions (+0.691). The numbers in parentheses are correlation coefficients,

$$r = \frac{\Sigma(x_1-\bar{x}_1)(x_2-\bar{x}_2)}{\sqrt{\Sigma(x_1-\bar{x}_1)^2\Sigma(x_2-\bar{x}_2)^2}} \quad . \qquad (9)$$

In large samples from bivariate normal populations, the standard error of r is approximately $(1-r^2)/\sqrt{n}$.

With such severe collinearity and such a small data set (50 observations) it would be impractical to attempt to derive meaningful coefficients for each of the 15 emissions categories. Rather than generating 15 unstable and/or un-

Table 7. ESTIMATED MINIMUM OPEN AND POINT SOURCE CONTRIBUTIONS TO STATEWIDE TSP ($\mu g/m^3$)

State	Rollback Model		Box Model	
	open sources	point sources	open sources	point sources
AL	1.26	13.03	3.39	9.24
AK	0.66	0.26	0.14	0.01
AZ	3.19	1.28	2.68	0.28
AR	2.80	1.44	6.69	0.90
CA	10.77	5.92	11.12	1.61
CO	3.25	2.57	2.70	0.56
CT	0.22	0.49	4.72	2.74
DE	0.03	0.42	1.78	6.06
FL	2.46	2.59	5.16	1.43
GA	2.26	3.79	5.06	2.23
HI	0.05	0.56	1.01	2.92
ID	1.53	0.51	2.02	0.17
IL	3.36	10.33	7.97	6.44
IN	2.41	6.63	8.61	6.24
IA	3.98	4.32	8.85	2.53
KS	5.03	2.27	7.21	0.76
KY	1.48	5.98	4.66	4.95
LA	1.42	4.70	4.15	3.61
ME	0.24	0.62	0.83	0.55
MD	0.30	1.28	3.42	3.78
MA	0.61	1.26	8.48	4.57
MI	3.02	8.01	6.38	4.46
MN	4.03	2.10	6.12	0.83
MS	1.36	2.07	4.30	1.72
MO	3.39	4.16	5.96	1.92
MT	0.69	0.64	0.42	0.10
NE	4.69	3.34	6.57	1.23
NV	1.81	1.32	1.77	0.34
NH	0.38	0.18	4.71	0.60
NJ	0.90	1.43	11.93	4.96
NM	3.30	1.45	2.20	0.25
NY	2.06	3.13	4.45	1.76
NC	1.42	3.22	3.69	3.58
ND	3.64	0.93	5.55	0.37
OH	1.83	22.51	5.53	17.69
OK	2.90	1.35	6.08	0.64
OR	3.39	1.20	2.78	0.31
PA	3.68	9.81	8.65	6.07
RI	0.14	0.17	13.86	4.42
SC	0.24	2.17	2.23	2.46
SD	2.79	0.65	3.09	0.31
TN	1.13	4.63	4.45	3.76
TX	10.90	6.63	4.34	0.69
UT	1.07	0.65	2.04	0.24
VT	0.35	0.15	4.34	0.62
VA	0.54	0.73	2.62	4.06
WA	2.12	1.85	5.14	1.18
WV	1.03	3.37	6.31	4.61
WI	1.39	4.21	2.68	2.50
WY	0.72	0.87	0.71	0.23

Table 8. CORRELATION MATRIX - INDEPENDENT VARIABLES

Key:

c2 = E_A
c22 = E_W
c4 = E_C
c5 = E_F
c6 = E_P
c7 = E_M

c8 = E_S
c9 = E_R
c10 = E_u
c11 = E_T
c29 = P
c28 = TSP_a

point sources:
c13 = combustion
c14 = industrial
c15 = incineration
c16 = transportation
c17 = miscellaneous

	c2	c22	c4	c5	c6	c7
c22	0.922					
c4	0.267	0.394				
c5	-0.201	-0.122	0.224			
c6	-0.059	-0.106	0.049	0.293		
c7	-0.137	-0.140	0.099	0.245	-0.168	
c8	0.065	0.123	0.469	0.353	0.217	0.008
c9	0.036	0.192	0.287	0.246	0.131	0.167
c10	0.650	0.707	0.688	0.207	0.029	-0.033
c11	0.205	0.246	0.275	-0.028	-0.026	-0.133
c13	-0.151	-0.127	0.231	0.097	-0.113	0.499
c14	0.205	0.262	0.463	0.194	-0.042	0.356
c15	0.102	0.257	0.737	0.168	0.036	0.133
c16	0.271	0.356	0.928	0.253	0.107	0.065
c17	0.176	0.137	0.282	0.126	0.068	0.160
c29	-0.506	-0.513	-0.107	-0.042	-0.033	0.157
c28	0.297	0.359	0.076	-0.244	-0.187	0.169

	c6	c7	c10	c11	c13	c14
c7	0.073					
c10	0.468	0.042				
c11	0.367	0.164	0.366			
c13	0.178	0.426	-0.037	-0.167		
c14	0.270	0.542	0.366	0.005	0.767	
c15	0.437	0.600	0.436	0.199	0.453	0.560
c16	0.370	0.924	0.691	0.187	0.342	0.574
c17	0.092	0.239	0.323	-0.077	0.342	0.337
c29	-0.163	0.004	-0.477	-0.504	0.244	-0.125
c28	0.037	0.030	0.423	0.436	0.049	0.182

	c15	c16	c17	c29	c28	c23
c16	0.678					
c17	0.136	0.375				
c29	-0.338	-0.063	-0.094			
c28	0.182	0.036	0.171	-0.432		

interpretable coefficients, we grouped several source categories together in order to investigate the relative and absolute contributions of emissions from unpaved roads, the single largest source of particulate emissions, in comparison to all other point and open sources. Table 9 summarizes the data which was used in these final analyses, and the results of ordinary least squares regression applied to these data.

The relative magnitudes of the coefficients a_{11}, a_{12}, and a_{13} are the relative contributions to TSP (as modeled) per ton of emissions for the open sources except unpaved roads (E_{o-u}), unpaved roads, and the point sources. Thus the rollback model indicates that unpaved road emissions are about one-fiftieth as effective (per ton emitted) in contributing to TSP readings as are point sources and about one-third as effective as are other open sources. A similar interpretation holds for a_{21}, a_{22}, and a_{23}. The box model indicates somewhat greater effectiveness of unpaved road emissions: they are about one-twentieth as effective as point sources and about half as effective as other open sources. Given that the emissions from unpaved roads are about twenty times as great as those from point sources, unpaved road emissions seem to make a contribution to ambient TSP levels of the same magnitude as the contribution from point sources. The modeling results indicate that for paving of unpaved roads in general to be cost-effective, the cost per ton of emissions prevented would have to be more than an order of magnitude less expensive than point source controls. For specific cases, however, such as urban unpaved roads, the impact of the unpaved road emissions on urban TSP readings might be much higher than average, so that the paving of such roads might be cost-effective even when the cost per ton of emissions reduction is similar to the cost of controlling point sources.

CONCLUSION

The current TSP levels are well above National Ambient Air Quality Standards in many areas of the U.S. Both on the basis of inferential analyses of the chemical and elemental composition of TSP and our emission rate estimates and modeling, it appears that well over 50% of the ambient TSP in many regions are the result of open source emissions. Although in certain cases, open source controls may be necessary to comply with NAAQS, widespread reduction of ambient TSP levels by control of emissions from open sources may not be economically attractive in light of the relatively low contributions of these emissions to measured TSP levels per ton emitted.

We are currently conducting a study which has as its goal an analysis of the economics of open source control. Several of the open source emissions rate estimates are being revised, and advanced statistical techniques are being applied to our data in an effort to further resolve the importance of specific classes of open sources.

Table 9. EMPIRICAL ESTIMATION OF ROLE OF UNPAVED ROADS

Model 1 - Rollback[a]

$$TSP = a_{10} + a_{11}E_{(o-u)} + a_{12}E_u + a_{13}E_p + a_{14}TSP_a + a_{15}P$$

Model 2 - Box

$$TSP = a_{20} + a_{21}\frac{E_{(O-u)}}{H \cdot u\sqrt{A}} + a_{32}\frac{E_u}{H \cdot u\sqrt{A}} + a_{23}\frac{E_p}{H \cdot u\sqrt{A}} + a_{24}TSP_a + a_{25}P$$

Coefficients

	a_{i0} ($t_{a_{i0}}$)	a_{i1} ($t_{a_{i1}}$)	a_{i2} ($t_{a_{i2}}$)	a_{i3} ($t_{a_{i3}}$)	a_{i4} ($t_{a_{i4}}$)	a_{i5} ($t_{a_{i5}}$)	R^2 (R^2_{adj})
Rollback	46.6	0.0006	0.0002	0.011	0.30	-0.093	39
(i=1)	3.6	0.4	0.3	2.4	1.7	(-1.7)	(32)
Box	48.4	3.6	1.6	28.	0.33	-0.15	42
(i=2)	(3.8)	(1.1)	(0.9)	(2.3)	(1.9)	(-2.9)	(36)

Data Summary

variable	variable	mean
	$E_{(o-u)}$	1778
	E_u	6372.
	E_p	307.
	$E_{(o-u)}/(H \cdot u)\sqrt{A}$	0.64
	$E_u/(H \cdot u)\sqrt{A}$	1.71
	$E_p/(H \cdot u)\sqrt{A}$	0.120

[a] E_{o-u} = total open source emissions minus unpaved road emissions.

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Authors' Reply

Walter W. Heck, O. C. Taylor, Richard Adams, Gail Bingham, Joseph Miller, Eric Preston, and Leonard Weinstein

Research Management Committee for the National Crop Loss Assessment Network

Heuss has raised an important issue in his comment that is pertinent to any effects research: what is the natural background of ozone concentration? We agree that the issue is one that needs focus and resolution before reliable crop loss assessments can be made. However, there is no consensus in the scientific community on natural background ozone concentrations. Therefore, we chose not to address that issue in our paper (Heck *et al.*),[1] although we did use 0.025 ppm as an approximation of background concentrations.

Heuss apparently believes that both the design of experiments and the crop loss model analysis assumes a 0.025 ppm (maximum 7 h/day seasonal average) natural ozone background. In fact, the experimental design makes no assumptions about background concentrations. For the purpose of our experimental design, the ozone concentration in the CF chamber is not important nor is it controllable. We only needed to know the concentrations.

As stated (page 358, column 3, paragraph 2), we thought it appropriate to illustrate an analytical approach for development of crop loss functions from the NCLAN and similar data sets. Any background concentration could be used in the approach. The analysis was purposefully done so others could develop yield estimates based on their preferred background values.

Although we do not choose this forum to debate Heuss' suggested background ozone concentrations of 0.03 to 0.07 ppm (maximum 7 h/day seasonal average), we would make several points. 1) Accepting these values could suggest that all ozone at our test sites was from stratospheric incursion. 2) In Heuss' Reference 2, it is also stated that "... the summer average could be 0.007 to 0.020 ppm because of the spring-summer gradient."[2] 3) Heuss used data from rural and remote sites to strengthen his argument when a case could be made that no location in the continental U.S. can represent a reasonable estimate of natural background ozone concentrations.

The estimate of background ozone concentrations is likely to be important to any crop loss assessment. A second issue, equally as important, is the availability of reliable monitoring data from agricultural areas. Until these and other data deficiencies are resolved, all crop loss estimates will be conditional on the appropriateness of such data assumptions.

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Natural and Anthropogenic Atmospheric Particulates at UPM Campus, Dhahran, Saudi Arabia

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The atmospheric concentration of Total Suspended Particulates (TSP) and its relationship to meteorological parameters has been extensively studied in developed countries, especially those in the northern hemisphere. Sharp seasonal variations have been experienced due to both temperature and human activities. Little information is available on the concentration of TSP in the atmosphere of urban areas of desert regions such as Saudi Arabia under intense modernization.

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This paper presents TSP data obtained from daily measurements at one monitoring site in Dhahran, a semi urban area in the eastern part of Saudi Arabia. TSP concentrations were determined for 100 days, in the period from Nov. 20, 1980 to March 31, 1981. The samplings were continuous with constant flow rate, thus making it possible to differentiate the air borne particulates arising from natural and anthropogenic sources. Wind speed and wind direction were also monitored continuously to evaluate the effect of meteorological parameters on the TSP concentrations.

TSP samples were collected on a daily basis for 24 h starting from 8:00 A.M. till the next day at 8:00 A.M. on the roof top of the Old Administration Building at the University of Petroleum and Minerals in Dhahran. A Hi-Vol. Sampler (Sierra Model 305-2000) was used for collection of the ambient air particulates. Glass fiber filters (8 in. × 10 in.) capable of collecting particles within the size range of 100 to 0.1 μm diameter were used in the sampler. The mass concentrations of the TSP in $\mu g/m^3$ were determined by gravimetric measurement of the mass of collected particulates and the volume of air sampled. Wind speed and wind direction were monitored by Climatronics Wind Mark III Transmitter. Hourly readings were printed; 24 h maxima, minima, and means were calculated from the hourly averages.

Results and Discussion

Particulate matter is ubiquitous and can be obtained in relatively high volumes from a variety of sources and a variety of routes; thus, identifying the anthropogenic and natural particulates is not a simple and straightforward task. In this study, the TSP data appeared to be reasonably (log-normally) distributed, a fact which implies that the Dhahran atmosphere is subject to large-scale influences. The data in Table I reveal large variability in the results as evidenced by the confidence intervals; the maximum values are significantly higher than maximum levels measured in some developed areas with recognized particulate contamination problems.

Figure 1 presents 100 days of continuous (24 h) daily total particulate concentration. A weekly cyclical pattern of TSP concentrations is apparent. To elaborate and enhance this phenomena, the TSP concentrations were distributed on weekdays and weekends and these concentrations were plotted against the days as shown in Figure 2. The data exhibited lower particulate levels on weekends than on weekdays. It is clearly evident that a large portion (33–50%) of the particulates in the Dhahran atmosphere are anthropogenic in nature. Figure 2 also shows the wind speed during the sampling period indicating that the meteorological parameters do not affect the TSP concentrations in the study area. Figure 2 further shows huge variations in the human activity in the study area. It is worth mentioning that during this study period, several exceptionally high values of TSP were measured with concentrations of 2923, 1907, 2354, and 1037 $\mu g/m^3$ for Dec. 11, 12, 1980 and Feb. 23, March 18, 1981 respectively. These high values were due to the high northerly winds (Shammals) with blowing sands. The geometric mean for the entire period is 339 $\mu g/m^3$.

Table I. Summary of total suspended particulate[a] (TSP) results.

Days	Number of samples	Maximum value $\mu g/m^3$	Geometric mean ($\mu g/m^3$)	Confidence limits Lower	Upper
Saturdays	14	856	357	294	590
Sundays	17	762	376	322	490
Mondays	14	757	333	264	532
Tuesdays	16	880	406	286	460
Wednesdays	15	1037	412	283	509
Thursdays	15	481	286	183	263
Fridays	15	388	241	200	280

[a] The above data represents 24 h TSP samples taken on a daily basis from Nov. 20, 1980 till March 31, 1981 by Hi-Vol sampler at fixed sampling site.

General Conclusions

A repetitive cyclical variation in atmospheric TSP at Dhahran was observed, with high values occurring during the weekdays and lower values during the weekends. This weekly

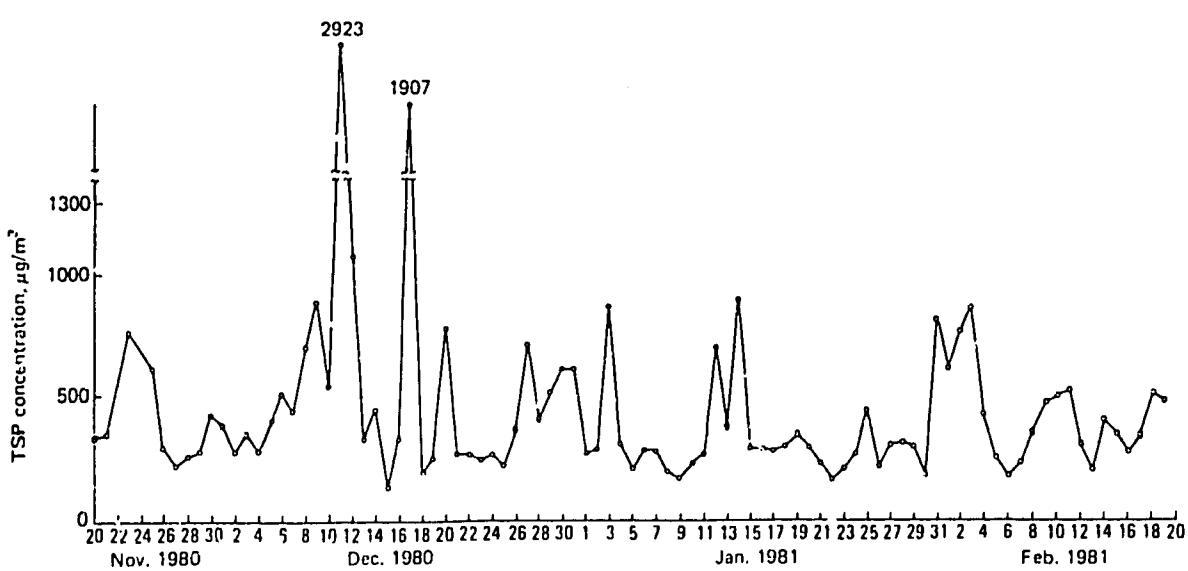

Figure 1. Daily variation of 24 h TSP concentrations at U.P.M. Campus, Dhahran.

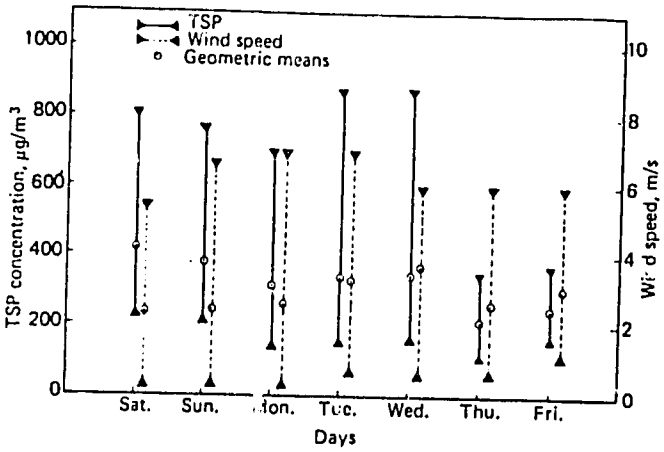

Figure 2. Dhahran ambient air TSP distribution and concentration on weekdays and weekends.

variation in TSP strongly indicates that an appreciable portion of the particulates are anthropogenic in nature, since there are large variations of human activities in the study area. Based on this observation, it is, therefore, possible to predict the critical periods when control action should be taken.

Although the individual values of the measured TSP have a direct relationship with wind speed and wind direction, the average values obtained for the weekdays and weekends are nevertheless minimally affected by wind speed and wind direction.

Acknowledgments

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Dr. Khattak is with the Ministry of Higher Education, University of Petroleum and Minerals, Research Institute, Dhahran, Saudi Arabia.

CALENDAR

November 15-17, 1982

The Pacific Northwest International Section of the APCA will hold its 1982 Annual General Meeting at the Hotel Vancouver, Vancouver, British Columbia, Canada. For details contact P. Sagert, P.O. Box 49287, Suite #1764, Bentall—4, 1055 Dunsmuir Street, Vancouver, British Columbia. V7X 1L3.

November 16-18, 1982

A symposium on iron and steel pollution abatement technology for 1982 will be held at the William Penn Hotel, Pittsburgh, Pa. Sponsors are the U.S. EPA, AISI, and APCA's Iron and Steel Committee. For details, contact F. A. Ayer, Research Triangle Institute, P.O. Box 12194, Research Triangle Park, NC 27709; (919)541-6260.

November 18-19, 1982

The Bureau of National Affairs will conduct the Ninth Annual Environment and Safety Briefing Sessions at the Marbury House in Washington, D.C. For details, contact the Environment and Safety Briefing Sessions Registrar, BNA Conferences, Suite S-602, 1231 25th Street, N.W., Washington, D.C., or telephone toll free 800-424-9890 or (202) 452-4420 in the Washington, D.C., metropolitan area.

December 7-9, 1982

The 5th International Coal Utilization Exhibition and Conference will be presented at the Astrohall in Houston, Texas. The conference will be divided into five simultaneous sessions which examine the complete chain of coal utilization from beneficiation through transportation, storage and handling, conversion to energy, and environmental considerations. For details, contact David I. Johnson, Executive Director, Coal Technology '82; phone (713) 879-8929.

January 30-February 2, 1983

The ASME Industrial Pollution Control Symposium will be conducted at the Hyatt Regency Houston Hotel, Houston, TX, as part of the Energy-sources Technology Conference and Exhibition. For details, contact Frank Demarest. ASME Industrial Pollution Control Symposium, P.O. Box 59489, Dallas, TX; (214) 247-1747.

May 16-20, 1983

The 6th World Congress on Air Quality will be held in Paris, France. The Congress is sponsored by the International Union of Air Pollution Prevention Associations. For details, contact APCA, P.O. Box 2861, Pittsburgh, PA 15230.

March 22-24, 1983

An APCA specialty conference on "Measurement and Monitoring of Non-criteria (toxic) Contaminants" will be held at the Knickerbocker Hotel, Chicago, Illinois. Conference will be sponsored by APCA's TP-5, TP-6 and TP-7 technical committees and hosted by the Lake Michigan States Section. For details, contact Frank Werderitch, Materials Services Corp., Lyons, IL 60534; (312) 442-5440.

June 19-24, 1983

The 76th Annual Meeting and Exhibition of the Air Pollution Control Association will be held at the Georgia World Congress Center, Atlanta, Georgia. For details, contact APCA Headquarters, P.O. Box 2861, Pittsburgh, PA 15230.

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Cement Producer Modifies Evaporative Cooling System To Enhance Precipitator Performance

Any cement producer who invests millions of dollars into a new plant, including all the hardware for air pollution control, has a right to expect a trouble-free operation. But that's not the way it worked out at first for Kaiser Cement at its Longhorn, TX facility. Instead, the brand new plant was experiencing problems associated with its air pollution control system.

The gas cleaning system at Longhorn, like those at many cement plants, consists of a pre-conditioning tower followed by an electrostatic precipitator.

The precipitator removes particulates, (cement kiln dust) before hot gas from the process is passed to the atmosphere through a stack. Before the gas enters the precipitator, however, it must first be treated in an evaporative cooling tower. Here, small droplets of water are atomized into the hot gas, cooling it, reducing volume and adding moisture

It was clear from the beginning that the Longhorn gas cleaning system was not always working properly. Under some conditions, especially when the evaporative cooling tower was not in use, precipitator performance was adequate. The cooling tower was not needed when the roller mill was in operation. Then, hot gas from the preheater/precalciner was diverted into the mill to partially dry freshly quarried rock. This process, of course, also cooled and humidified the gas, thereby conditioning it adequately for the precipitator.

But when the roller mill was undergoing maintenance and consequently was not operating, the evaporative cooling tower was then put into operation. The problem was that particle resistivity was much higher than expected for a given set of conditions. Therefore, to adequately condition gases for the precipitator, lower temperatures and higher moistures were required which were beyond the capabilities of the cooling tower. This affected precipitator efficiency and caused higher than allowable emissions.

Alternatives Considered

At first, Longhorn tried to get the original cooling tower to cool the hot gases down even lower—to 280°F. But, in doing so the water droplets injected by hydraulic type spray nozzles were not evaporating properly and caused agglomeration and eventually formed small nodules of the cement kiln dust. In addition, even at this lower temperature, the cooling tower did not adequately condition the dust particles for adequate precipitation.

Since they could not operate out of compliance with clean air standards, Longhorn temporarily had to cut the volume of gas going through the precipitator. That could be achieved only by temporarily cutting production by about half—down to some 45 tons per hour when the roller mill was down. At this lower gas volume the precipitator could just about meet standards.

Clearly, the key to the problem lay in controlling the performance of water droplets in the tower to evaporate quickly and adequately condition the gases. That meant controlling the size of water droplets over a wide range of temperatures and gas volumes to accommodate varying conditions found in actual operation. Such variations are encountered, for example, during startup or shutdown of the kiln or the roller mill.

But, as noted, with hydraulic water nozzles there was no practical way to achieve the needed size control. Would major modifications of the expensive tower and/or precipitator be required? Less costly alternatives were sought.

Retrofit Spray Heads

Plant manager Alan Redeker investigated a different type of nozzle—an alternative to hydraulic types. Called Sonicool®

spray lances, their manufacturer claimed they could deliver very finely atomized droplets over wide range of temperatures and gas flows. Ordinarily these nozzles are employed in cooling towers especially designed for them. Those towers are smaller than conventional ones because the lances work well even at higher gas flow rates.

Would they work in the large conventional tower at Longhorn? The manufacturer, Sonic Development Corporation of Mahwah, NJ, thought so, and proposed a minimum-risk two-stage approach to their use.

Stage I: Sonic would ship, off the shelf, twelve lances, together with engineering drawings and hardware. This would enable Kaiser crews to install them side by side with the existing hydraulic nozzles. They would also suggest a suitable source of compressed air to be fed into the lances along with the water. (It's the presence of compressed air that makes the big difference between sonic type spray heads and conventional all-hydraulic nozzles.) Longhorn would disconnect the old nozzles, and operate the new lances manually to see if they solved the problem.

It took only two weeks to ship, install and activate the new lances. Initial results were not only accurate, but actually much better than originally expected.

Finely atomized water droplets were able to cool the hot gases down to 250°F, and more importantly adequately condition the gases for the precipitator. Even without full instrumentation or the precision made possible by automatic control, precipitator performance improved substantially.

In addition, the finely atomized water droplets evaporated long before hitting bottom of the Longhorn Tower. Their size and volume is controlled by varying compressed air. Sonic engineers calculate, in fact, that they evaporate in about 4.9 seconds, or half-way down their 100-ft drop path. No more nodules or moisture problems inside the tower.

After a short test period, Longhorn was able to maintain full production during roller mill downtime and still stay in compliance with air quality standards. Simultaneously they placed orders to proceed with Stage II as soon as possible.

Stage II

A field representative from Sonic surveyed the tower and recommended specific steps for a complete retrofit, particularly supplementary instrumentation. The sonic system automatically senses temperature changes and modifies air and water pressure accordingly. This produces droplets of the right size for the prevailing conditions.

Sonic shipped complete engineering plans, necessary instruments and controls and additional supplementary hardware. Stage II installation was completed in early 1981, about three months after the decision to try retrofitting with new spray equipment. The old hydraulic spray heads were simply left in place.

With SoniCool lances installed and a new air compressor operating at the base of the tower the extreme flexibility of the system became clear. The unit, guaranteed only to reduce gas temperatures from 700°F down to 250°F, has easily met that guarantee.

Today, plume opacity easily meets the standards set by the Texas Air Control Board and EPA.

Control Technology Newsbriefs . . .

The Electric Power Research Institute (EPRI) awarded consulting engineers Brown and Caldwell a contract in October for a portion of EPRI's research into integrated environmental control systems for coal-fired electric power plants. The project is testing the interaction of processes used to meet environmental regulations for air emissions and liquid, solid, and thermal discharges. Brown and Caldwell is conducting the work at EPRI's Arapahoe Test Facility next to the Arapahoe Power Station operated by the Public Service Company of Colorado.

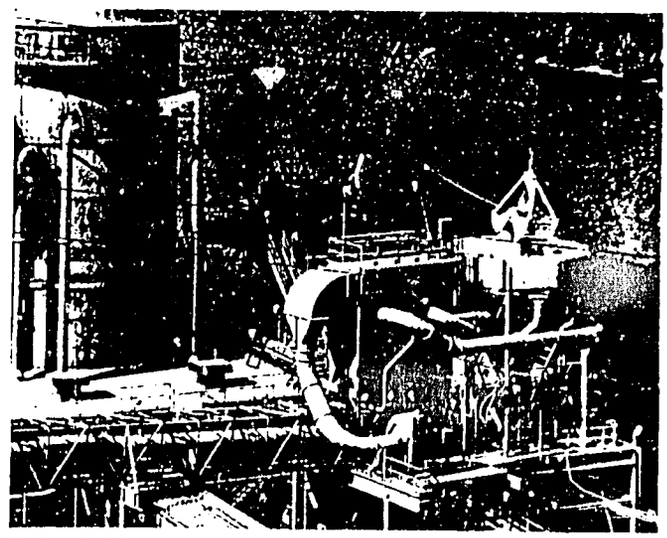
Environmental control can represent nearly half the cost of building and operating a coal-fired plant. By evaluating the interactions that occur when processes are combined, researchers hope to determine the most efficient method of integrating designs for environmental control systems and reducing these costs.

Brown and Caldwell will initially test two configurations of systems used to reduce nitrogen oxides, sulfur dioxide, and particulates in air emissions. Pilot tests on flue gas from the power station with varying emission levels and under varying conditions, such as low-temperature operation and transient operation, will yield data on how each unit process affects the others. Initial tests will focus on using a wet SO_2 scrubber and baghouse and a spray dryer and baghouse. Researchers will also evaluate solids disposal problems and the use of cooling tower blowdown as makeup water in the emission control systems. Major subconsultants include York Research Consultants of Lakewood, Colorado, Stanley Consultants of Muscatine, Iowa, and A. V. Slack of Sheffield, Alabama.

As a fuel, coal generates tremendous amounts of ash as well as heat. And for utilities who burn coal to produce electricity, ash is a burdensome waste product. However, the two Pennsylvania-based operating companies of the General Public Utilities System are undertaking innovative projects to lessen the burdens associated with ash disposal.

Metropolitan Edison Company of Reading, and Pennsylvania Electric Company of Johnstown are currently disposing of some 265,000 tons of ash each year through private marketing and construction companies. The ash by-product is being used in landfills, for use in road base, and in concrete blocks.

Dr. Shepard Bartnoff, GPU's executive vice president of electric operations, said that while the amounts involved are small in comparison to the total amount of ash generated annually at each plant, economic and environmental advantages of marketing ash are spurring the utilities to expand their ash sales and commercial disposal programs.



A clamshell bucket unloader unloads Thiosorbic® lime from a covered river barge into a transfer hopper at West Penn Power Company's Mitchell Station, a facility located approximately 20 miles upriver from Pittsburgh. The lime is being used as reagent material in the flue gas desulfurization (FGD) system recently installed on the Mitchell Station's 291-megawatt Unit No. 3. Prepared by Dravo Lime Company specifically for FGD applications, Thiosorbic lime is shipped from Dravo's production facility in Maysville, Ky., to a total of 13 coal-fired generating units. With a total capability of 3,621 megawatts at nine generating stations, West Penn Power Company is one of three operating subsidiaries of the Allegheny Power System.

Change in Pulmonary Function in Children Associated with Air Pollution Episodes

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Pulmonary function of approximately 200 school children in Steubenville, OH was measured before and immediately following air pollution alerts in the fall of 1978 and 1979. TSP concentrations exceeded the National Primary Ambient Air Quality 24 h standards in 1978. SO_2 exceeded the standard in 1979. The children were then reexamined in three weekly visits following each alert. Estimated mean Forced Vital Capacity (FVC) was approximately 2% lower following each alert, although the lowest means were observed one to two weeks after the episodes. Forced Expired Volume in 0.75 sec ($FEV_{0.75}$) did not change during the 1978 study, but was 4% lower immediately following the 1979 alert. The children were measured again in five weekly examinations in the spring and fall of 1980. Air pollution levels did not exceed the standards on either occasion. In the spring of 1980, estimated mean FVC and $FEV_{0.75}$ showed a decline similar to that observed following the alerts in 1978 and 1979. In the fall of 1980, there were no significant differences in the estimated mean FVC or $FEV_{0.75}$ between the examinations. A total of 335 children were tested in the four studies, including 194 who participated in more than one study. The evidence for each child from all the studies was combined in a regression analysis of pulmonary function on TSP and SO_2 average concentrations in the previous 24 h. The distribution of the individual regression coefficients was centered significantly below zero, implying a decrease in pulmonary function with increasing TSP and SO_2 concentrations. The magnitude of the median change was less than 1% of the mean FVC and $FEV_{0.75}$ over the range of TSP and SO_2 concentrations observed.

Studies of short-term changes in pulmonary function after exposure to environmental agents are fraught with difficult methodological issues. Laboratory based clinical studies under controlled exposure conditions often deal with single pollutants and breathing conditions which at best are unnatural. The responsiveness of volunteers may not be applicable to the general population. Epidemiologic studies are constrained by the difficulties of predicting episodes of severe air pollution; responses may be difficult to detect against a background of uncontrolled variation. Yet, epidemiological studies may offer the best opportunity for characterizing changes in lung function in the general population during an air pollution episode.

Stebbings *et al.* measured lung function of school children daily for seven days following an air pollution episode in November of 1975 in the Pittsburgh area.[1] Beginning two days after the air pollution peak, they measured lung function of school children in four schools exposed to the episode, and two control schools outside the area of high pollution levels. No clear association of health effects with particulate matter or SO_2 concentrations was found for the whole population. A subsequent analysis[2] detected a strong upward trend in Forced Vital Capacity (FVC) after the episode among the exposed children who were the most reactive. This suggested an improvement following the episode, with a recovery time of approximately one week. Effects which reversed in less than 48 h could not be measured since the study lacked baseline measurements on these children before the air pollution episode. Follow-up of the children was possibly too short to see complete recovery.

As part of an ongoing prospective study of the health effects of air pollutants in six communities (Harvard Six Cities Study),[2] a subset of approximately 200 participating school children living in Steubenville, OH, a community in which dramatic and significant short-term changes in SO_2 and TSP pollution concentrations frequently occur, was identified.

A pool of children who were experienced in performing the test was available, as well as local people trained in pulmonary function testing of children, a history of cooperation with the local schools, health department, and air pollution control agency, and finally, a reasonable probability of dramatic short term air pollution exposures. This presented an opportunity to study the effects of naturally occurring acute air pollution exposures on children.

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Steubenville is an industrial community of 31,000 people on the Ohio River approximately 65 km west of Pittsburgh. Steel production and its associated industries are the primary local sources of air pollution. Topographically, these industries are located in the valley in Steubenville and the surrounding communities. The downtown commercial district and the older residential areas also are located in the valley. To the west, the valley rises approximately 125 m to a largely residential plateau.

Historically TSP concentrations have frequently exceeded the National Primary Ambient Air Quality 24 h standard of 260 $\mu g/m^3$. In 1976, the North Ohio Valley Air Authority (NOVAA) reported TSP concentrations above 260 $\mu g/m^3$ on 54 days. SO_2 concentrations occasionally exceed the 24 h standard of 365 $\mu g/m^3$.

Based on the results of the Pittsburgh study, it was proposed to measure lung function in the Steubenville school children before a naturally occurring air pollution episode. Once an episode occurred, the children would be retested in four weekly examinations, beginning as soon as possible after the exposure. Using this protocol, the children in Steubenville were studied on four separate occasions between 1978 and 1980. This paper presents the results of individual and pooled analysis of these studies.

Method

Pulmonary function was measured by forced expiration into a Collins Survey Spirometer, with the child sitting with free mobility without a nose clip. Each child was tested at least five times, but not more than eight. From the acceptable blows determined by the tester, Forced Vital Capacity (FVC) and Forced Expired Volume in 0.75 seconds ($FEV_{0.75}$) were measured. All values were corrected to body temperature and water saturation. The mean of the best three measurements within 150 mL of each other were calculated.[4] FVC and $FEV_{0.75}$ were considered independently.

The NOVAA reports average pollution concentrations for the 24 h ending at 8 A.M. each day. TSP are collected by high volume samplers and SO_2 by a Phillips colorimetric monitor. The SO_2 monitor is audited quarterly by an outside agency with NBS traceable reference gases. The air pollution measurements reported here have been adjusted based on the least squares linear regression of the reference concentrations on the reported instrument readings. Mean temperature is also reported by NOVAA.

First each study was analyzed independently. The mean levels of lung function at each examination were estimated and the baseline means compared to the means at each subsequent examination. The hypothesis of equality of mean values was also tested on all examinations.

Since children were occasionally absent for an examination, the analysis was corrected for missing values. Children with less than three examinations during a study were not included. Each child's set of lung function measurements (either $FEV_{0.75}$ or FVC) was modeled as a multivariate normal observation. The mean and covariance matrix were estimated by maximum likelihood using the EM algorithm,[5] an iterative procedure based on the missing information principle. The estimated variances of the differences between baseline and subsequent means were obtained from the appropriate terms in the estimated covariance matrix. The ratio of the difference divided by its standard deviation was compared to critical values of the normal distribution. The hypothesis of equal means on all days was tested by the Hotelling's T^2 statistic,[6] using critical values of the χ^2 distribution with n-1 degrees of freedom, where n is the number of examinations.

Then the results from all four studies were combined in a regression analysis of the relation between lung function and air pollution for each child. In this analysis, a model of the following form was fitted:

$$y_{ijk} = \beta_i x_{ijk} + \alpha_{ik} + \epsilon_{ijk} \quad (1)$$

where y_{ijk} is the lung function for child i on examination j during the kth study, x_{ijk} is the average air pollution for the 24 h preceding the examination, β_i is the regression coefficient of lung function against air pollution for child i, α_{ik} is the intercept for child i during study k, and ϵ_{ijk} is an error term. Growth during each study was assumed to be negligible. The regression coefficients, β_i, were estimated for each child by least squares. The median of the regression coefficients for all children was tested against a hypothesized value of zero using a Wilcoxon Signed Rank Test.[7] There is sufficient evidence that air pollution has a deleterious effect on lung function that

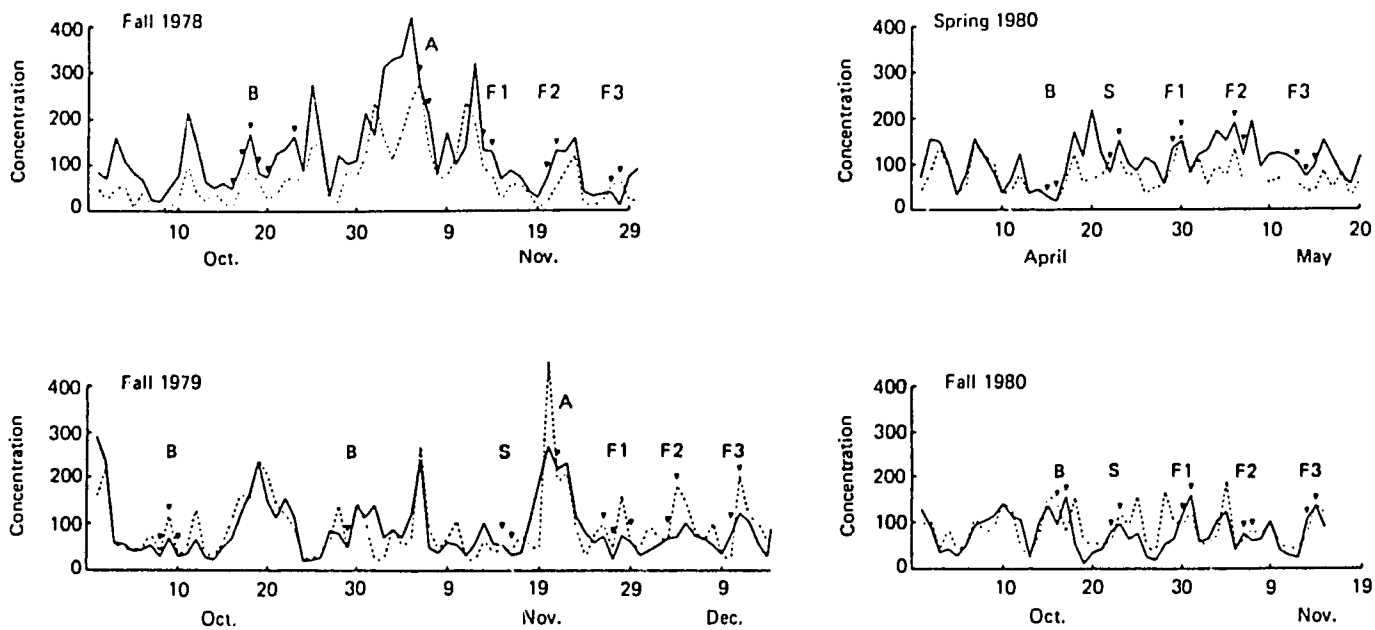

Figure 1. Daily mean TSP (—) and SO_2 (- - -) concentrations (μ/gm^3) during four study periods. Inverted triangles indicate lung function testing days. (B = Baseline, A = Alert, S = Sham Alert, F1 = Follow-up 1, F2 = Follow-up 2, F3 = Follow-up 3.)

one-sided statistics are appropriate. The distribution of the regression coefficients of lung function measurements on TSP, SO_2, and average temperature was examined.

Results

Fall 1978

In the fall of 1978, between October 16 and 23, baseline lung function, height, and weight were determined for one third and one fourth grade class in each of two public and two parochial schools. On Thursday morning, November 2, NOVAA reported TSP levels of 312 $\mu g/m^3$ (Figure 1). TSP concentrations reached a maximum of 422 $\mu g/m^3$ on Sunday, November 5. The maximum SO_2 concentration during this period was 281/$\mu g/m^3$ on November 6.

NOVAA advised of the air pollution alert. The local field team was mobilized and the children retested on November 7 and 8, noted by A on Figure 1. The children were retested on each of the following three weeks, F1, F2, and F3 on Figure 1. There were 193 children with more than two observations during the five examinations.

Fall 1979

The study was repeated in the fall of 1979. Baseline measurements were made on 3rd and 4th grade school children in October. By mid-November, there had been no reported TSP measurements above the 24 h standard (Figure 1). Therefore it was decided, as a control experiment, to test the responses of the children to repeated testing without high air pollution exposures. On November 15 and 16, the children were retested in a sham alert (S).

Four days later, on November 20, NOVAA reported TSP concentrations of 271 $\mu g/m^3$ and SO_2 concentrations of 455 $\mu g/m^3$, both above the 24 h standards. The local field team was mobilized to retest the children on Wednesday the 21st. Unfortunately this was the day before Thanksgiving; the two parochial schools were closed and attendance was low in the public schools. Sixty-nine of the children in the study were present and retested. As before, all of the children were retested in the following three weeks. A total of 184 children had more than two observations, including 78 who had been examined in the fall 1978 study.

Spring 1980

The following spring, these same children were again tested in a sham alert for five consecutive weeks. TSP concentrations during this period (Figure 1) had a maximum value of 220 $\mu g/m^3$. Maximum SO_2 concentration was 169 $\mu g/m^3$. Both TSP and SO_2 concentrations were very low during the baseline measurements. There were 184 children with more than two observations.

Fall 1980

The following fall the 4th and 5th grade school children in the four schools were tested for five consecutive weeks. One-hundred & eighty-one children were tested more than twice, including 169 children examined in previous studies. During this period, TSP concentrations were relatively low (Figure 1) with a maximum of 159 $\mu g/m^3$ which was observed during the baseline examination period. The maximum SO_2 was 190 $\mu g/m^3$.

Analysis of Lung Function Means

The estimated means for each examination in the four studies are summarized in Table I. In the fall 1978 study, the estimated mean baseline FVC of the 193 children examined was 1.943 L. Following the TSP alert, the estimated mean FVC dropped to 1.913 L. The difference from the baseline mean, −30 mL, was statistically significant ($p < 0.01$). The following week, F1, the estimated mean FVC was 1.899 L, a statistically significant difference of 44 mL from the baseline mean ($p < 0.001$). The estimated mean in the second follow-up week, F2, was still lower, 1.891 L. The difference of 52 mL was also statistically significant. In the last week, F3, the estimated mean, 1.909 L, returned towards the baseline value, but was still significantly less (33 mL, $p < 0.001$). The Hotelling's T^2 test of equal means for all the examinations showed a very significant difference between the examinations ($p < 0.001$).

The estimated $FEV_{0.75}$ means during the fall 1978 study were nearly equal on all examinations. The maximum difference from the estimated baseline mean was less than 7 mL. No statistically significant differences were found between the examinations.

In the fall of 1979, a more consistent pattern was seen between the estimated mean FVC and $FEV_{0.75}$ levels. Both measurements were significantly different from the hypothesized model of equal means for each examination.

Estimated mean FVC increased between the baseline examination, 1.904 L, and the sham alert, 1.915 L, but the difference was not statistically significant. Following the actual TSP and SO_2 alert, mean FVC dropped to 1.878 L, which was significantly less than the baseline mean. Mean FVC was also significantly less the following week, 1.873 L. In the second follow-up week, mean FVC returned towards the baseline mean, but dropped again in the third follow-up week. Both of these values were significantly less than the baseline mean.

Fall 1979 $FEV_{0.75}$ estimated means were equal for the baseline and sham alert examinations. For the four examinations following the actual alert, all the estimated $FEV_{0.75}$ means were significantly less than the baseline mean ($p < 0.01$). The largest difference, −57 mL, was observed on the examination following the alert.

In the spring 1980 study, when air pollution levels did not exceed the 24 h standards, both the estimated FVC and $FEV_{0.75}$ showed significant differences between the examinations. Both measurements were significantly lower than the estimated baseline means the first and second weeks of follow-up, F1 and F2.

In the fall of 1980, air pollution levels were even lower than those observed during the spring 1980 study. The estimated means of FVC and $FEV_{0.75}$ were slightly less than baseline for most of the examinations, but none of the differences was statistically significant.

Regression Analysis

The measurements from all four studies were combined in a regression analysis of the relationship between lung function and air pollution concentrations. The results for each child were pooled across all the studies in which he/she participated. Of the 335 children examined, 194 were tested during more than one study.

The combined results for each child were used to calculate a regression coefficient of lung function on the average air pollution for the 24 h ending at 8 A.M. on the day of the examination. A different intercept for each study was allowed when a child participated in more than one, to allow for the effect of growth on lung function between studies. The effects of growth during each study were ignored. The regression coefficient of lung function against air pollution was assumed to be constant over all studies for each child, but to vary among children.

As an example, Figure 2 presents all of the FVC measurements for a child who was examined in all four studies, plotted against TSP concentrations. This child had at least four observations in each study and had a good correlation between

Table I. Estimated examination mean, difference from baseline, and statistical significance of the difference for each of the four studies, plus Hotelling's T^2 for difference between examinations. Lung function values are in liters.

Study (No. Children)		No. Obs.	Examination Base	Sham	Alert	F1	F2	F3	T^2
Fall 1978 (N = 193)	FVC	890	1.943		1.913	1.899	1.891	1.909	23.31[c]
					−0.030[b]	−0.044[c]	−0.052[c]	−0.034[b]	
	$FEV_{0.75}$	889	1.531		1.524	1.528	1.532	1.531	0.75
					−0.007	−0.003	+0.001	+0.001	
Fall 1979 (N = 184)	FVC	982	1.904	1.915	1.878	1.873	1.882	1.870	34.93[c]
				+0.011	−0.025[a]	−0.030[b]	−0.021	−0.034[a]	
	$FEV_{0.75}$	980	1.530	1.530	1.473	1.493	1.498	1.492	33.82[c]
				0.000	−0.057[c]	−0.037[c]	−0.032[b]	−0.038[b]	
Spring 1980 (N = 184)	FVC	841	1.987	1.975		1.953	1.948	1.971	34.14[c]
				−0.012		−0.035[c]	−0.039[c]	−0.017	
	$FEV_{0.75}$	836	1.576	1.569		1.557	1.551	1.560	11.40[a]
				−0.006		−0.019[b]	−0.025[a]	−0.015	
Fall 1980 (N = 181)	FVC	826	2.081	2.077		2.075	2.075	2.072	1.02
				−0.005		−0.008	−0.007	−0.009	
	$FEV_{0.75}$	824	1.644	1.638		1.635	1.646	1.636	2.84
				−0.006		−0.008	+0.003	−0.007	

[a] $p < 0.05$.
[b] $p < 0.01$.
[c] $p < 0.001$.

FVC and TSP. The child shows about a 10% growth in FVC between 1978 and 1979. Her growth was somewhat less between 1979 and the two 1980 studies.

The five 1978 measurements suggest a linear decrease in FVC with increasing TSP concentrations between 11 and 211 $\mu g/m^3$. The 1979 measurements have more scatter, but they also suggest a linear relationship with TSP. The 1980 measurements have a much narrower range of TSP exposures. Two of the FVC measurements were anomalous, but the trend is consistent with the relationship seen in the 1978 and 1979 measurements.

Assuming a linear relationship between FVC and TSP which is constant over the four studies, the data can be described by four parallel lines passing through the mean FVC and TSP value for each study. The slope for this child implies a decrease in FVC of −0.56 mL for each $\mu g/m^3$ increase in TSP. The correlation coefficient for the regression was −0.59.

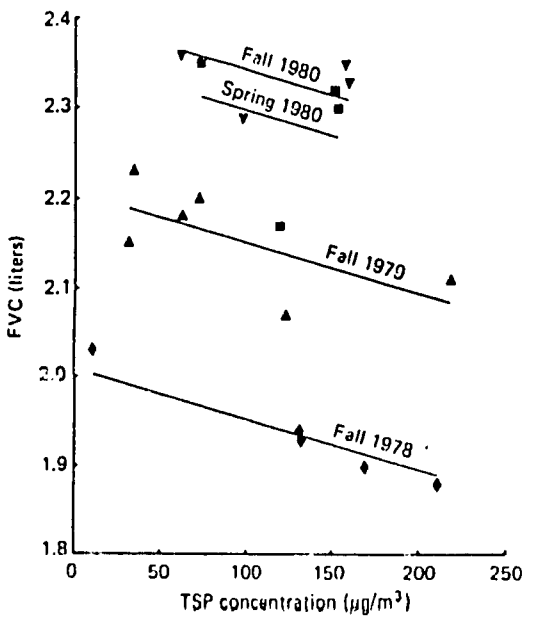

Figure 2. FVC measurements vs. TSP concentrations for 24 h before lung function measurements for child #2005. Values for all four studies indicated (♦ Fall 1978; ▲ Fall 1979; ■ Spring 1980; ▼ Fall 1980.) Least squares regression lines assume parallel effect across all four studies

In a similar manner, the slope of FVC vs. TSP was calculated for the 330 children with three or more observations during any of the four studies. Thus, data are included in this analysis even if the child was absent during one or two of the examinations during a study. Five children did not have three measurements in any study and were eliminated. TSP ranged between 11 and 272 $\mu g/m^3$.

The distribution of slopes of FVC vs. TSP for the entire sample is shown in Figure 3. 59% of the children had slopes less than zero, that is decreasing FVC with increasing TSP. The median slope was −0.081 mL/$\mu g/m^3$. This is significantly less than zero ($p < 0.001$), by a Wilcoxon Signed Rank Test.

The relationship of FVC with daily mean SO_2 and temperature was also calculated for each child. The quartiles of the distribution of the individual regression coefficient and the signed rank statistics are presented in Table II. The median FVC vs. SO_2 slope was −0.057 mL/$\mu g/m^3$. This was also significantly less than zero ($p < 0.01$). SO_2 ranged between 0 and 281 $\mu g/m^3$. The relationship with mean daily temperature was not significantly different from zero.

A similar analysis was also performed with $FEV_{0.75}$ as the lung function measurement (Table II). Only the relationships between SO_2 and TSP with $FEV_{0.75}$ were found to be significantly less than zero.

Discussion

The mean FVC values show a small, but statistically significant decrease from baseline levels following the high pollution episodes in 1978 and 1979. The largest decreases in FVC were observed one or two weeks after the episode, rather than immediately following as was expected. Estimated mean $FEV_{0.75}$ did not change during the 1978 study, but did decline significantly immediately after the high pollution episode in 1979.

While air pollution concentrations above the 24 h standard in the spring 1980 study were not observed, significantly lower lung functions in the examinations following baseline measurement were seen. This study was notable for the very low air pollution concentrations during the baseline examinations.

In the fall of 1980, very low air pollution concentrations were observed during the entire testing period, as well as very small decreases in the estimated mean lung functions for each of the examinations.

In general, mean lung functions on the second and later examinations were lower than baseline in all four studies. The lowest mean lung functions were observed during the examinations following the high air pollution episodes. The largest decreases were not seen immediately following these episodes, but one or two weeks later. Factors other than air pollution which might be causing these changes should be considered.

The observed lower lung functions could be an artifact related to the testing procedure. For example, the children or interviewers may lose interest during repeated testing. The measurement requires a maximal effort by the child. The interviewers are trained to elicit this effort on each attempt and to continue testing, up to eight attempts, until the child has given three attempts with his or her best effort. The three best results are determined by computer and averaged. The consistency of the method is demonstrated by the very small examination to examination variability in the fall 1980 study (Table 1). Therefore it is believed that the variability of repeated measurements alone is much smaller than the variability between examinations.

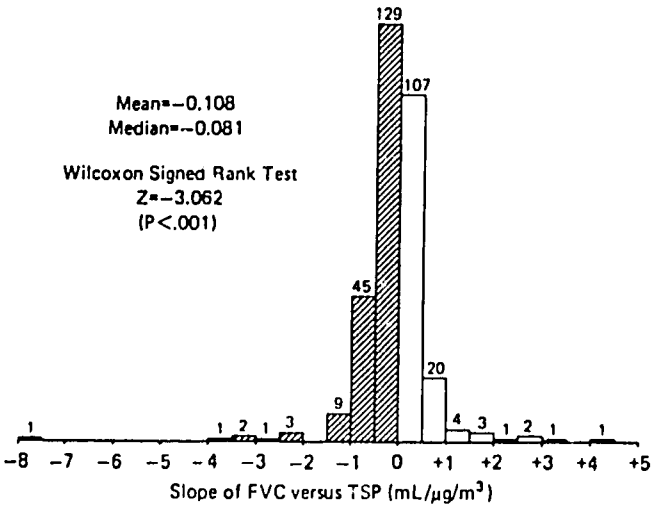

Figure 3. Distribution of slopes of FVC vs. TSP concentration of each of 330 children in analysis. Hatched bars are slopes less than zero.

The reported prevalence of coughs, colds, and other respiratory symptoms in these children during the examinations was also considered. While the children with these symptoms did show very dramatic changes in their lung functions, the elimination of these children did not substantially alter the estimated mean changes. Moreover, air pollution may act by aggravating these symptoms. Therefore, the examinations during which the child reported respiratory disease symptoms were not eliminated from the reported results.

The potential for errors in the air pollution measurements was considered. As was noted earlier, the SO_2 monitor in Steubenville was checked quarterly by an outside agency with a multi-point calibration against NBS traceable reference gases. The first such audit was conducted on March 8, 1979, approximately three months after the fall 1978 study. The SO_2 monitor had a very linear response, but the instrument response was approximately 15% low. Similar results were found in multi-point calibrations on April 3 and May 22. After adjustment of the instrument response, another audit was conducted on November 1, during the fall 1979 study. The SO_2 instrument was within 2% of the reference values. Audits were also performed on March 14, 1980, just before the spring 1980 study, and November 14, 1980, just after the fall 1980 study. In both cases, the SO_2 instrument was within 4% of the reference values. Flow calibration of the TSP samplers during the audits were all within 5% of the reference values. For each study, the SO_2 concentrations reported in this paper have been adjusted based on the least squares linear regression of the reference concentrations on the monitor response during the closest audit. No adjustments to the TSP concentrations were made.

While the reported air pollution concentrations appear to represent the exposure during the studies, they did not conform to the pattern proposed in the response model. The studies were designed to measure baseline lung function during a clean period. This would be followed within a few weeks by a short exposure period, the alert, with concentrations much higher than any other period. Pulmonary function would be measured during or immediately following the alert. The pollution would then drop to relatively low concentrations and the children would be retested weekly. The actual exposure was considerably different. The baseline periods were not necessarily periods of low air pollution. During the fall 1978 study, three of the baseline measurement days had TSP concentrations above 150 $\mu g/m^3$ (Figure 1). Pollution exposure also was characterized by several short high pollution periods, rather than one. For example, during the 1978 alert study (Figure 1), the TSP concentration exceeded the 24 h standard not only between November 2 and 6, but also on October 25 and November 12.

Thus the actual air pollution exposure did not correspond to the working model in the study design. It should not be surprising that the estimated mean lung functions for each examination did not correspond to the hypothesized response model of decline immediately following the acute exposure with recovery over the next few weeks.

The alternative regression analysis assumes a linear relationship within each study period and for each child between lung function and 24 h mean air pollution concentrations or temperature. It was assumed that the child recovers within a day or two.

For each child, the evidence from all measurements in all four studies was used to calculate the relationship between lung function and air pollution. The distribution of individual regression coefficients of FVC and $FEV_{0.75}$ on 24 h average air pollution concentrations have been examined. Rank order statistics have shown the distribution of regression coefficients to be centered on a value significantly less than zero for TSP and SO_2.

Table II. Quartiles of the distribution of individual regression coefficients of FVC and $FEV_{0.75}$ vs. TSP, SO_2, and temperature. Slopes are in mL/μg/m^3 for TSP and SO_2 and in mL/°F for temperature. Z is test of significance for slopes less than zero.

	$FEV_{0.75}$				FVC			
	Quartiles				Quartiles			
	25%	50%	75%	Z	25%	50%	75%	Z
TSP	−0.306	−0.018	+0.212	1.69[b]	−0.386	−0.081	+0.239	3.06[c]
SO_2	−0.396	−0.046	+0.288	2.34[b]	−0.426	−0.057	+0.248	2.77[b]
Temperature	−1.941	−0.029	+1.832	0.34	−1.758	+0.030	+1.862	0.20

[b] $p < 0.01$, one-sided Wilcoxon Signed Rank Test.
[c] $p < 0.001$.

As with most studies of naturally occurring exposures to air pollution, the effects of TSP and SO_2 exposure are difficult to separate. The collinearity of these pollutants is clearly seen in Figure 1. For the examination days in this study, their correlation was 0.74. No significant relationship was found with temperature.

A linear model was assumed as a first approximation to the effect of air pollution on pulmonary function. The 24 h average air pollution concentrations were almost entirely below the current National Ambient Air Quality Standards. The observed changes in lung function were physiologically small. Over the range of TSP concentrations observed, 11 to 272 $\mu g/m^3$, the predicted median change in FVC is only −21 mL, and in $FEV_{0.75}$ it was only −5 mL, that is 1% of the mean or less. Of course, half of the children had declines in lung function larger than this. The predicted changes associated with SO_2 over the range of observations, 0 to 281 $\mu g/m^3$, were −16 mL FVC and −13 mL $FEV_{0.75}$.

In a study of repeated lung function measurements of second grade school children in Yugoslavia, Šarić, Fugaš, and Hrustić[8] reported decreased mean $FEV_{1.0}$ of approximately 5% percent of predicted values, associated with higher average SO_2 concentrations on the day of the examinations during four weekly examinations in the fall of 1977. Average SO_2 ranged between 89 and 235 $\mu g/m^3$. A similar tendency was reported the following spring, but the range of SO_2 concentrations was much less. No association was found with smoke concentrations.

Stebbings and Fogleman[2] examined the distribution of individual regression coefficients of FVC and $FEV_{0.75}$ on time in their study of Pittsburgh area school children following a high particulate pollution episode. They hypothesized that a deleterious effect of the pollution episode would be seen as an increase in pulmonary function with time over the study period. They reported an excess of positive slopes of FVC on time in the exposed children. Selecting a group of 26 children with the largest positive slopes from the 168 children in the exposed group, and extrapolating their mean regression back to the time of the episode, they estimated a decrease in lung function of 450 mL in the sensitive group. Peak coefficient of haze measurements corresponded roughly to TSP (maximum one hour) of 700 $\mu g/m^3$.

Conclusions

Repeated measurements of the lung function of 335 school children in Steubenville, OH has shown a statistically significant but physiologically small, and apparently reversible, linear decline of FVC and $FEV_{0.75}$ levels with increases in TSP and SO_2 24 h mean concentrations between approximately 0 and 275 $\mu g/m^3$.

Although the data fit a linear model, a nonlinear or threshold model cannot be precluded within the range of exposures considered or at higher concentrations. The analysis reported has been limited to 24 h average concentrations. Investigations are continuing to determine if longer averaging times or maximum values over shorter averaging times have a higher association with change in lung function. Data are also available from the later studies for pollutants other than TSP and SO_2. These data are also being analyzed to rank the pollutants in order of their association with lung function changes.

Acknowledgments

This study depended on the voluntary participation of the principals, staff, parents, and students of the Buena Vista, Garfield, Holy Rosary, and St. Anthony's schools in Steubenville. Pulmonary function testing was directed by Eleanor Beaman and Jeanne Brent Morgan. Air pollution data were collected and supplied by Pat DeLuca, Dan Zorbini, and the staff of the North Ohio Valley Air Authority. Data analysis was programmed by Dean Harris and David Glicksberg. Most importantly, this study was supported in part by NIH grant ES01108, EPRI grant RP 1001, and EPA contracts 68-02-3201 and 3644.

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Flue gas analysis can help monitor kiln combustion system

Offers promise of real time measurements

By Brian W. Doyle

A kiln combustion system includes control systems for fuel firing rate, air flow rate, and a number of burner or coal mill adjustments—all of which are used directly in control of the kiln firing. Most or all of these controls are operated by a human operator rather than being directly coupled into an automatic control system. In either type of system, instruments are required to show either the human or automatic controller what is happening so that the appropriate response can be made. One of the problems with combustion in a cement kiln is that there has not been any practical way to measure burn zone temperature profile or the flow (and accumulation) of material within the kiln. This has meant a heavy operator reliance on indirect instruments, visual observation, and intuition; automatic controls simply are not practical in this environment.

The rotary cement kiln, by its very nature, is hard to instrument adequately. However, there is a need for the best achievable instrumentation and as much automatic control as possible. A lapse of optimum conditions on a cement kiln can be expensive. Underfiring leads to unburned clinker and direct loss of production time on the kiln. Overfiring wastes fuel and can damage the refractory. Swings or fluctuations in firing rate stress the refractory and can contribute to pushes or instability in the material movement in the kiln. Improperly set burners or excess air levels cause reducing atmospheres that have negative effects on the clinker qualities and contribute to gypsum buildups in the back of the kiln. These are factors that increase production costs or make the cement less marketable, so there can be a strong "bottom line" motivation to maintain optimum combustion conditions in the kiln.

Measurements on a rotary kiln are restricted to data on what enters and leaves at the two ends,

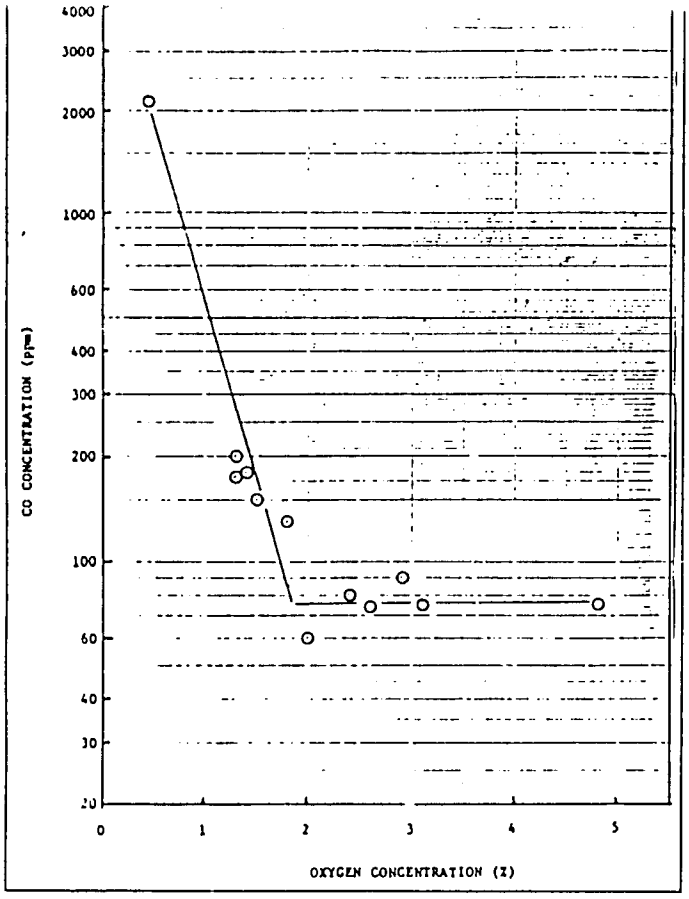

Fig. 1 Typical Relation of CO to Excess Air with Data from a Cement Kiln.

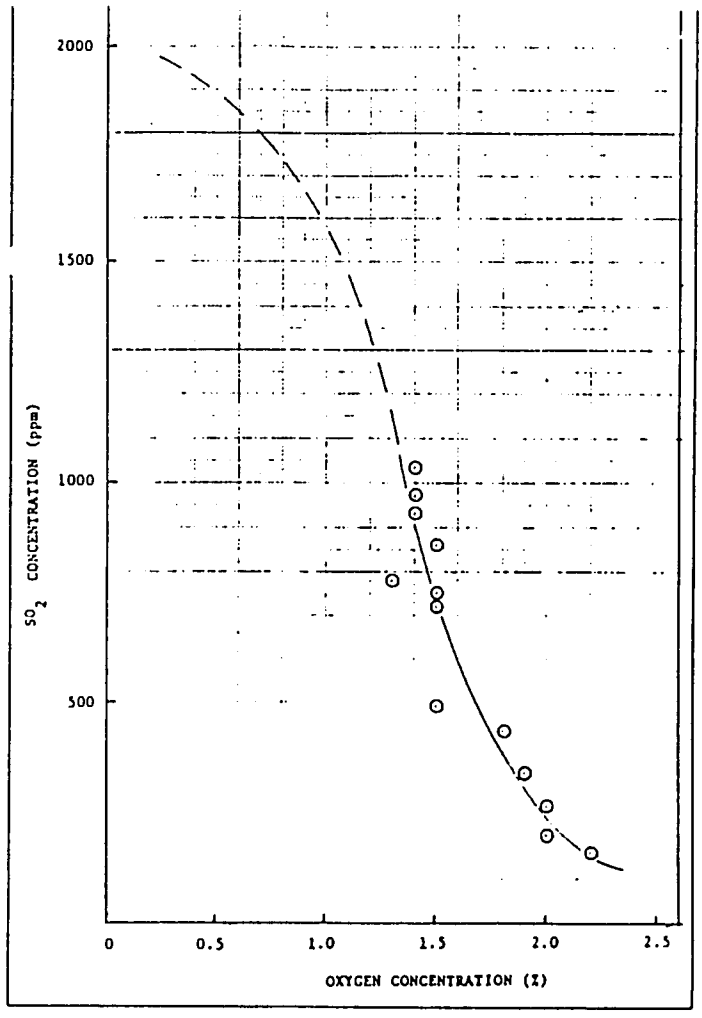

Fig. 2 Typical Dependence of SO_2 on Excess Air with Data from a Long Dry Kiln

visual assessment of the firing end, and limited temperature data from the shell or external slip rings. Properties of the emerging clinker are one of the most important indicators of kiln operation, but this data is not available until hours after clinker formation. Other important indicators, such as cement strength or refractory life, take days or weeks to determine and so are not useful as monitors of operation. The firing system needs to be controlled from instruments that give a real time indication. This is the reason for current interest in flue gas composition monitoring.

Flue Gas Measurements

Combustion performance on any type of system can be substantially characterized using measurements of the flue gas composition. This is true on a boiler, a furnace, or a cement kiln. Many of the necessary instrument systems have been developed only in recent years, most in response to the requirements for air pollution monitoring. However, these systems can be adapted for process monitoring as a spin-off from air pollution technology. Flue gas analyzing systems currently available are fast, accurate, and reliable in an industrial environment, and this has been demonstrated at a number of cement plants.

Several constituents of the flue gas are of interest in combustion monitoring on a cement kiln (Ref. 1). Operators are familiar with oxygen (O_2) analyzers, which give a basic measure of excess air, and should be the basis for controlling air flow rate through the kiln. These instruments can be coupled to an automatic air flow control, but seldom are in practice. The older generation of O_2 analyzers is not sufficiently reliable, and many systems need additional logic built into the coupling to avoid instabilities or other problems. However, future systems will make increasing use of automatic air flow control based on an O_2 indicator.

A second flue gas constituent that characterizes combustion is carbon monoxide (CO). This is equivalent to a "combustibles" measurement, but current CO instruments are three orders of magnitude more sensitive and there is no comparison to the old "combustibles" instrument. CO (as well as combustibles and black smoke) have a dependence on excess air level (shown typically in Fig. 1). When the fire is starved for air, there is a reducing atmosphere and CO is formed instead of CO_2.

The presence of CO indicates that the combustion air flow should be increased or the fuel flow decreased. While it can serve as a useful diagnostic or monitoring tool on a kiln, CO is not a good gas to use in an automatic control system on most cement kilns. A kiln should be run with reducing atmosphere minimized i.e. with CO at a minimum level. This means the O_2 should be higher than the level at which the CO curve bends upward in Fig. 1. Here a CO reading shows

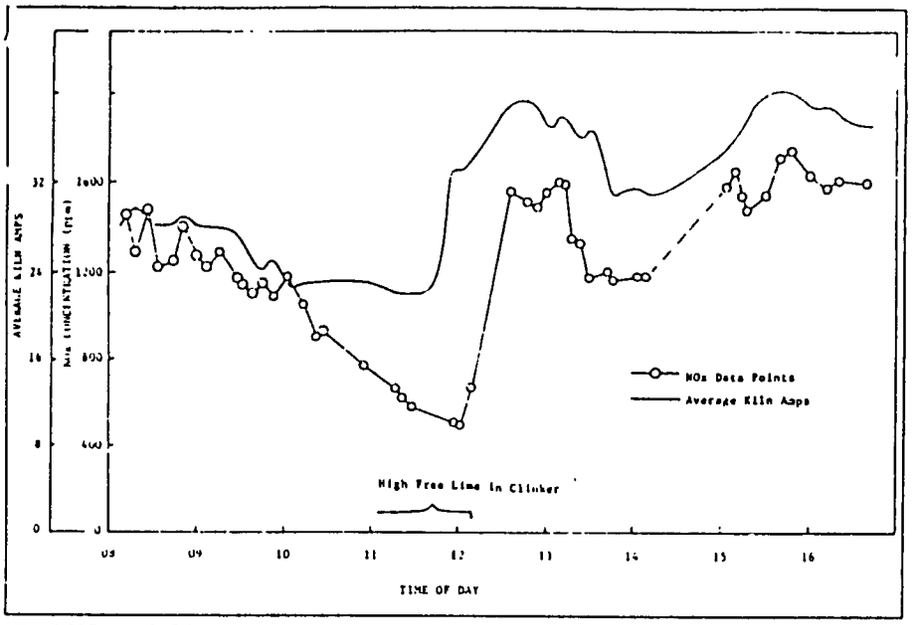

Fig. 3 NOx and Kiln Amps Data Covering a Time Period When Underburned Clinker Was Produced

a minimum constant value in the range where excess air level should be controlled. While CO is useful in showing combustion problems, it is not well suited to an automatically coupled control system.

A third measureable flue gas constituent is sulfur dioxide (SO_2). Sulfur introduced to the kiln in the fuel or the feed will be emitted as SO_2, absorbed in the clinker, or absorbed in the dust. Monitoring SO_2 emissions provides a real time indication of how much sulfur is not being retained in the clinker or dust. SO_2 is useful for diagnostic purposes although it cannot be used in an automatic control system. Typically, SO_2 will depend on kiln excess air levels in a manner shown in Fig. 2. At low excess air levels, the reducing atmosphere precludes the oxidation to SO_3 or SO_4 that is necessary for clinker or dust retention. SO_2 monitoring can be used to show a reducing atmosphere in the load even when the combustion above the load has sufficient excess air. Typical values for SO_2 depend upon the chemistry of the feed and the type of kiln system. On a precalcining system, SO_2 can be absorbed or released in the kiln independent of precalciner absorption. Thus, the value of SO_2 as a diagnostic monitor varies considerably from one kiln to another. While SO_2 will probably see increasing use as a diagnostic tool on cement kilns (especially precalcining systems), it probably will be some time before it is coupled into an automatic control system.

The last and most interesting flue gas constituent is nitric oxide (NO). To avoid any confusion, I will use the term NOx that signifies the sum of NO and NO_2. NO_2 usually is present in much smaller amounts than NO. The amount of NOx formed in the burning zone and measured at the kiln exhaust (or points downstream) is related directly to burn zone temperature. On many kilns, the relation between burn zone temperature and NOx concentration is so well defined that a NOx instrument provides a highly reliable and sensitive measure of burn zone temperature. In at least one instance, (Ref. 2), a NOx instrument provides the burn zone temperature input to an automatic control system. It replaces the kiln amps in this control scheme.

NOx appears to represent effectively burn zone temperature in many situations; Fig. 3 shows an example of NOx response during an upset period on a precalciner kiln. Note the large change in NOx compared to the change in kiln amps. However, NOx concentration is influenced by other factors and, on some systems, this influence is relatively strong. Excess air will influence NOx on any combustion system because it affects the amount of oxygen available to form NOx. The significance of this influence varies substantially from one kiln to another. The NOx data in Fig. 3 was corrected systematically for O_2 changes in order to suppress the excess air influence. Insufflation of dust in the burn zone influences NOx depending upon the insufflation method and the amount of dust. Secondary air temperature and burner adjustments (position, primary air velocity, etc.) also influence NOx levels. All these effects are specific to individual kilns. Thus, the value of NOx as a temperature indicator depends on the combustion system configuration; these factors should be assessed before a major commitment to an NOx monitor is made.

Instrument systems and automatic control concepts

The gas constituents discussed here can be measured with instrument systems developed for air pollution control purposes. When applied to process monitoring or control, the instrument systems do not need the precision required for EPA type systems, but they should be highly reliable and free of drift. Thus, systems that meet EPA criteria should be considered although the EPA certification procedure probably is not necessary.

On any kiln, O_2 must be measured at the kiln exit, and it should serve to define the air flow rate or fuel trim. A second O_2 measurement is necessary downstream of a precalcining tower to monitor the second combustion zone. Sampling for CO, SO_2, and NO can be done at any of several locations. However, the location chosen also should have an O_2 instrument so that dilution effects on the other gases can be computed. This means that useful data can be taken in the stack of a long kiln or in the bypass duct of a precalciner, but a second O_2 measurement is required. Samples drawn from downstream of a fan give a representative sample due to mixing in the fan, while samples at the kiln exit may not be representative due to a partially stratified flow. Initial test measurements or advice from a knowledgeable consultant should be considered when setting up a new gas monitoring system.

If the measured data (flue gas analysis in this case) correlate

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then one can consider coupling the instrument reading to the control. This almost always requires some intermediate logic with input from other instruments. This is particularly true of a cement kiln combustion system when the operation is interrelated with that of the cooler and (frequently) with a precalciner or preheater. Digital logic, such as that developed by F. L. Smidth in their "Fuzzy Logic" system (Ref. 3), is an appropriate way to couple instrument readings with kiln controls. This system programs a computer to duplicate an experienced operator's thinking in making control adjustments. It requires that a number of numerical factors associated with the decision making process be developed for each specific kiln. Hence, while the results may well prove worthwhile, the task of coupling an instrument to a control system should not be underestimated.

Flue gas analysis is a promising method of monitoring kiln combustion system operation. Its merits should be assessed separately for each kiln. If an established system shows that it works well for human operators, then one should make a second assessment regarding coupling into an automatic control system.

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SECTION V

L. Maintenance Schedule:

DAILY

Record electrical values.

Check hoppers and dust removal system.

Visually check system for leaks.

WEEKLY

Check rappers and vibrators for proper operation.

Inspect interior of the T/R control panel.

MONTHLY

Inspect interior of insulator housings for dust accumulation.

Check for good seal at access doors.

Check insulators for cracks.

QUARTERLY

Check and clean rapper and vibrator switch contacts.

SEMIANNUALLY

Conduct a detailed visual inspection of the external precipitator areas. Check for signs of deterioration, abnormal vibration, noise, leaks, etc.

Clean and lubricate all access door linkages, interlock covers, etc.

ANNUALLY

Conduct internal inspection. Check plates and electrodes for uneven dust deposits. This may be caused by hanger binding, loose or misaligned hammers, damaged anvils, or by improper gas flow distribution.

Check, clean, and adjust all contactors and switch gear.

AT SHUTDOWN

Check condition of all safety grounding devices.

Precipitator Inspection and Maintenance

A. On Start-Up

When the precipitator is first started up, it is recommended that an inspection be made at short intervals (i.e., weekly) of the dust buildup inside the insulators. This is to determine whether frequent cleaning is necessary. An excess buildup of dust inside the insulators could result in shorting out the precipitator. While buildup at these points is not common, the tendency to build up varies with each installation. Therefore, it is important to check the rate of buildup for each precipitator.

B. During Scheduled Plant Shutdown

It is recommended that at each scheduled plant shutdown, the precipitator be inspected as follows:

1. Precipitator Shell and Hoppers

   Inspect the precipitator shell and hoppers and see that nothing is defective, that there are no air leaks in the shell access doors or ports, at hopper outlets, etc.

2. Interlocks

   Inspect all airlocks and see that they are not operationally defective, damaged, or that the dust covers are not missing.

3. Insulator Housings

   a. Open the Cover Plates in the Support Flanges (on top of the supporting insulators) and remove any heavy deposits of dust that have settled inside the insulators by wiping with a clean dry cloth. NEVER use a moist cloth on these insulators, except to remove hardened deposits. Then, use a rag moistened with a safe liquid equivalent to carbon tetrachloride.

   b. Check the Supporting Insulators and the Vibrators and see that they are not broken or cracked. If broken, they must be replaced. (See instructions on replacing equipment).

4. Inside Supports

   See that the Inside Supports (supports for the Emitting Frames) are free from any heavy deposits of dust.

5. Collecting Electrodes

   Check the Collecting Electrodes for wear.

6. Emitting Electrodes

Replace any broken or missing electrodes. (See instructions on replacing equipment.)

7. Emitting Rapping System

Inspect the emitting vibrating mechanisms for undue wear and breakage. Run the vibrators and see that they operate satisfactorily.

8. Collecting Rapping Mechanism

Inspect the collecting rapping mechanism for undue wear and breakage. Run the rapping mechanism and see that it operates satisfactorily.

9. Hoppers

Check the hoppers and remove any dust that has built up in the corners of the hoppers or on the hopper cross beams, so that the dust will not interfere with the emitting system.

WARNING

Extreme caution should be taken when entering hot precipitators. Cooling of the fly ash may take several days.

C. Daily

1. Transformer-rectifier readings should be recorded and compared daily with baseline values established at installation because:

   a. Slight variations can be a warning of impending trouble; for example, partial or total rapper failure.

   b. Abnormal readings, while indicating a serious problem, can aid in diagnosing the probable cause (for example, a low but steady voltage reading indicates a high-resistance ground--such as ash piled up in a plugged hopper or from clinker formation on a wire).

2. Check control room ventilation to minimize the possibility of overheated control components (which can cause drift of control set points and accelerate deterioration of sensitive solid-state devices).

3. Check hopper skin temperature at the throat and sides.

   a. If temperature of <u>one or more</u> hoppers seems comparatively low, this could mean:

      1. That ash is not flowing through the hopper, indicating bridging, plugging, or failure of the Ash System and has held ash in the hopper long enough for it to cool, causing ash collected later to pile up at the top.

   b. If temperature of <u>all</u> hoppers appears low, check:

      1. To determine if ash-conveyor system is stopped.

      2. If dust accumulation is of sufficient quantity that conveyor can no longer handle all the fly ash.

      3. That the Hopper Vibrators and Heaters are operating.

      4. If temperature is excessively high, there is a possibility of fire in the hopper, which can be caused by:

         . Ash buildup in the hopper

         . Air leakage in the system

D. <u>Quarterly</u>

   1. Verify the calibration of the cabinet meters, as they are subject to drift, in order to avoid possibility of false indications of precipitator performance.

   2. Inspect high voltage T/R switch clips for signs of arching.

E. <u>Semi-Annually</u>

   1. Inspect exterior for corrosion, loose insulation, damage, and loose joints.

   2. Make a special inspection of points on the precipitator where gas can leak out, creating fugitive emissions.

F. <u>Annually</u>

   1. Scheduled outages should be of sufficient duration to allow for a thorough internal inspection for:

      a. Possible gas or air leaks at gasketed connections.

      b. Corrosion where heat loss is greatest, or where gas temperatures are low.

      c. Possible misalignment of internal components.

2. Inspect high voltage switchgear for possible binding, misalignment, or defective interlocks which create a safety hazard.

3. Clean all insulators - support bushings, rapper insulators, collection plates and electrode wires, and inspect all bushings for hairline cracks.

4. Check all expansion joints and slide plates.

G. Situational

Certain preventative maintenance and safety checks are so important that any outage of sufficient length should be used to perform them without waiting for scheduled downtime.

Examples:

1. Compare airload meter readings with baseline values to detect possible performance deterioration before any process start-up.

   NOTE: Meter readings taken IMMEDIATELY upon restoring precipitator to service serve as a check on any change that may have resulted from maintenance work done during the outage.

2. Check critical internal alignments.

3. Check control cabinet interiors during any outage of 24 hours or more.

4. Check grounding devices, alarms, interlocks, and other safety equipment when outages exceed 72 hours.

5. Hoppers should be emptied and thoroughly cleaned when unit is taken out of service.

Keep an accurate daily log of all aspects of precipitator operation, as this assists the preventative maintenance effort by providing clues to probable causes for changes in performance and establishes usage rates for appropriate spare parts stockage levels.

DB:S3090/1/PCPTH

PRECIPITATOR OPERATION

Pre-Start-Up Inspection

Before implementing the following start-up procedures, it is necessary that all precipitator components be thoroughly inspected to verify that all equipment is ready for operation.

General:

1. Visually inspect the mechanical dust collector units, induced draft fans and dust handling equipment before the system is operated.

2. CLOSE and SECURE all access hatches prior to operation.

3. It is imperative that all system internal areas be completely free of tools, scrap and foreign material before the fan(s) is starter.

4. Verify that primary power is available to THERMOSTATICALLY CONTROLLED HEATER if provided. Circuit breakers for this equipment may have to be ENERGIZED several hours prior to system operation.

5. Check all interlocks and voltage control modules.

6. Check main OFF/TEST Selector Switch and place in OFF position.

7. Check grounding connections.

Rapper System:

1. Ground the power unit in the control cubicle.

2. Check distributor switch rapper connections.

3. Check ground return leads for proper connections to sectionalized control adjustments.

4. Check for proper mechanical adjustment.

5. Adjust each manual sectional control for proper rapping intensity.

6. Check spark rate feed back circuit and signals for proper connections.

Rectifiers and Transformers:

1. Check all connections, switches and insulators.

2. Check oil (liquid) levels.

3. See that high tension duct vent ports are installed and free.

4. Be sure grounds are completed on transformer-rectifiers, bus duct and conduits.

Routine Start-Up

If hot gases are to be passed through the precipitator, the system should be warmed up to operating temperature before gas flows are started.

All inspection ports should be closed and dampers adjusted for proper airflow.

In wet precipitators, the liquid supply should be turned on and adjusted.

High voltage current should be energized.

Start collector and discharge electrode rappers if provided on the system.

Turn on product discharge system.

Bring fan to full RPM with exit damper closed.

Adjust damper for desired gas flow.

Record system pressure drop and fan pressure drop.

NOTE: If the system is not equipped with external heating facilities, reverse the procedure so that the inlet gases enter before the precipitator is energized. When the precipitator reaches operating temperature, turn on the high voltage power.

NOTE: If the precipitator contains air and a potentially explosive gas mixture is introduced into the unit, it is necessary to purge the system first with an inert gas.

NOTE: Any conveying systems that follow the hopper conveyor must be turned on before the hopper conveyor.

Routine Operation

Check pressure drops and see that no unusually high or low recordings are observed.

Maintain precipitator current at normal level. Deviations greater than about 5% of normal current should be corrected.

Sparking rate should be maintained at optimum density.

Rapper frequency and intensity should be maintained to give maximum collection efficiency.

Check to see that thermostatically controlled heaters are properly operating.

If combustible gases are present in the precipitator, check the gas composition to be sure it is not in the explosive range.

See that all water cooling requirements are being properly met. This includes any water cooled bearings or pump stuffing boxes. Also check all drive belt tensions daily. Periodically test operate fan inlet dampers to verify that the dampers are free to move fully closed and fully opened. Inspect all electrode and collector rapper mechanisms daily for defective systems. Examine insulators daily to see that no deterioration is occurring. Lubricate hopper conveyors and valves daily. Lubricate dampers and louvers to see that they function freely.

Instrumentation to register current, voltage and spark rates to the precipitator has norms which can be red-lined on the instruments. Abnormal readings are a sure sign of trouble, and if these signs are ignored, serious equipment failures can result in excessive emissions and plant shutdown for correction. Shutdown can usually be avoided by heeding warning signals.

Routine Shutdown

Shutdown in reverse fashion from startup. That is, de-energize precipitator, purge if necessary, then shut off gas flow. When all collectors and electrodes have been rapped clean, discontinue use of rappers. When hoppers are empty, turn off conveyors and discontinue any liquid washing.

MAINTENANCE

Discharge electrode failure is the number one cause of operational breakdown. After this, in order of highest mechanical failure are rapper malfunctions, insulator failures, shorts caused by dust buildup, hopper plugging and transformer-rectifier failures. Most of these problems result when proper preventative measures are not heeded. For example, discharge electrode failures, which is the most frequent problem, could be reduced if the hoppers are properly discharged and cleaned to prevent grounding out and burning off of the discharge electrodes. Failure to inspect rappers over extended rapping cycles also causes discharge electrode breakage through fatigue failure.

GAS FLOW

In addition to the electrical and rapping problems mentioned, the remaining possible precipitator problems can be classified generally as gas flow and mechanical. Uneven gas flow can cause erosion of the collection plates thereby reducing efficiency. Uneven gas flow can also cause dust fallout and accumulation on turning vanes and on the ductwork. This eventually plugs the distribution plates and results in further uneven gas flow and system upset.

RAPPERS

Rapping, which in itself is a mechanical system, is necessary for both collection and discharge electrodes. However, it is only effective if the force is transmitted to these electrodes. Variation in the design of the supporting structure and in the electrodes themselves can result in inadequate rapping. In many fly ash installation, rapping accelerations of 30 g's are required. Rapping acceleration should be checked with an accelerometer mounted on the plates to assure proper rapping adequacy.

Fly ash buildup on the collecting plates should normally be about 1/8 to 1/4". If the buildup exceeds this, the intensity of the plate rappers should be increased. If the collecting plates are clean, this may be an indication of high gas velocity or too low an operating voltage.

COLLECTING PLATES

Collecting plates should be checked for proper alignment and spacing. Hangers and spacers at the top and bottom should be adjusted so that they do not bind the plates or prevent proper rapping. If corrosion is present, it is necessary to check for this.

HOPPERS

Hoppers should be checked periodically to be sure they empty properly and to be sure that corrosion is not occurring. Corrosion is likely to be most severe at points where dust builds up. Check the heating system and insulation on the hoppers to be sure that it is adequate to prevent condensation.

INSULATORS

Insulator compartments and housings must be checked frequently. Be sure that corrosive gases do not leak from the precipitator into this area as dirt deposits will result in electrical insulation breakdown.

ELECTRICAL

The spark rate control must be inspected to be sure that the proper number of sparks per minute are being maintained. The spark rate control can be adjusted if necessary.

The current and voltage limit controls must be checked and properly adjusted to prevent damage to the electrical components in the system.

Any electrical surge, overload and automated systems must be checked.

Transformer liquid levels should be checked to be sure they are filled to the proper level.

Most rectifiers utilize vacuum tube or solid state systems. Normal vacuum tube life ranges from 12,000=20,000 hours and servicing usually involves replacement of defective tubes. Solid state rectifiers are usually trouble-free and require little maintenance other than periodic check of transformer oil.

Relays should be disassembled and contacts cleaned once a year when recalibrated.

Any filter elements present in the system must be removed and cleaned or replaced periodically.

ELECTRODES

Precipitator wires, which may amount to 30,000 feet of wire/unit, will frequently require servicing even under the best maintenance and operating situations.

STRUCTURAL

Check for air leaks and maintain all services above the dew point to prevent corrosion inside the precipitator. Inspect the collecting plates for evidence of back corona.

TYPICAL MAINTENANCE SCHEDULE

Annual Inspection

A. Internal Inspection

1. Observe dust deposits on collecting plates and wire before cleaning - 1 1/4" deposit is normal. If metal plates are clean, there is a possibility that a section is shorting out. If more than 1/4" of dust is on the plates, rappers are not cleaning.

2. Observe dust buildup and corona tufs on wires.

3. Interior corrosion - corrosion could indicate air leakage through housing or moisture carryover from air heater washer.

4. Check plate alignment and spacing.

5. Check to see that discharge wire spacers and hanger weights are in place. Measure to be sure the wires hang midway between plates.

6. Replace broken wires.

B. Hopper Inspection

1. Check for dust buildup in corners.

2. Check high tension weights - if one has dropped 3", this indicates a broken wire.

3. Check hopper valve for debris.

C. Penthouse Inspection

1. Check for corrosion due to condensation and/or leakage of gas into housing.

2. Excessive dust in penthouse indicates air sealing pressure too low.

3. Clean all high tension insulators.

4. Check that all electrical connections are secure.

D. Transformer-Rectifier Inspection

1. Check liquid level.

2. Clean lines, insulators, bushings and terminals.

3. Check surge arrestors, spark gap should be 1/32".

E. Control Cabinet Inspection

1. Clean and dress relay contacts.

F. Check and calibrate all instrument and controls.

Quarterly Inspection

A. Rappers

1. Clean, replace and lubricate distributor switch contacts.

2. Check rapper assembly for free movement.

B. Vibrators

1. Check contacts on load cams.

2. Check vibrators to see that they operate at proper intervals.

Shift Inspection

A. Electrical reading for each control unit should be recorded and checked for abnormal readings.

B. Check rapper controls.

C. Check vibrator controls.

GAS FLOW MODEL STUDIES

Publication EP-7

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INTRODUCTION

In August 1969, I.G.C.I. first published bulletin EP-7 in an effort to alert purchasers and operators of electrostatic precipitators to the significant influence of gas distribution on collection efficiency. I.G.C.I. also established criteria that defined satisfactory gas distribution within the precipitator.

Since that time, electrostatic precipitator collection requirements have increased and suppliers, purchasers and operators are more aware of the influence of gas distribution on collection efficiency. The quality of construction, extent of systems, testing procedures and instrumentation in the art of model studying also have advanced considerably since 1969.

Therefore, the objectives of this revision are to establish precipitator gas velocity distribution criteria that reflect the best of today's technology and operating experience, to outline techniques, and to recommend procedures for model testing, instrumentation, modeling parameters and flow distribution responsibility.

DECISION TO MODEL

During the pre-contract design stage, the layout of the gas inlet and outlet transport flues and the transition connectors to the E.S.P. should be critically reviewed by the precipitator supplier to ensure that the proposed layout will provide proper gas flow distribution. This review procedure should be performed regardless of whether or not the detailed design and erection of the flues and transitions will be done by the supplier. At this time, the decision is made as to whether a model study is required and the extent of flow distribution obligations outlined. The precipitator supplier's experience and technical expertise establish his confidence and willingness to proceed without a model study. Typically, a model study will not be waived on large installations since modeling costs represent a small portion of the contract value and the model ensures that proper gas flow will be achieved at optimum pressure loss through the system.

Other factors influencing this decision are:

1. *Guaranteed precipitator operating efficiency.* Gas flow uniformity becomes particularly important for operating efficiencies in excess of 99.0% due to:

   - The tendency for the smaller particles to more closely follow the gas flow streamlines.

   - The increased need for almost total suppression of gas bypassing and hopper sweepage. Thus, the higher the guaranteed operating efficiency of a precipitator, the more important the optimization of the gas flow.

2. *Standardization of Design* — If an installation is a copy of another existing installation, which has satisfactory collection efficiency, the model study may be omitted. If an installation is substantially the same as another, it should be recognized that apparent minor differences in geometry can result in considerable differences in flow distribution.

3. *Symmetry of Design* — Many large precipitator systems are subdivided into several identical symmetrical parts. In certain arrangements only one of the symmetrical divisions need to be modeled.

4. *System Pressure Drop* — If the system pressure loss is guaranteed, the model study will assure minimizing dynamic losses and will locate areas of maximum loss. System losses should be reported as total pressure differences.

RESPONSIBILITY FOR FLOW DISTRIBUTION

There should be a definite understanding and agreement between the purchaser and the precipitator supplier concerning responsibility for gas distribution as it affects collection efficiency performance guarantees.

A great number of different relationships between the purchaser and the precipitator supplier can and do exist with respect to the design and construction of the flue-diffuser system leading to and away from the precipitator. In general, the precipitator supplier takes responsibility for the gas flow uniformity when the following conditions are met:

1. The supplier either provides the flue-diffuser design, or has review and veto power over the purchaser's general layout design.

2. The supplier either provides the final detailed erection drawings, or has review and veto power over the details of the internal flow control devices in the flue-diffuser system. The review may be based on either previous experience, or on the results of a model study.

3. The supplier either erects the flue-diffuser system, or has the opportunity to inspect the flues and require any necessary corrections before the installation becomes operational, to insure that the gas flow control devices have been properly fabricated and installed.

4. Velocity measurements are made in the completed precipitator to determine whether the gas flow distribution is acceptable.

One important distinction must be recognized. The usual primary guarantee offered by a precipitator supplier is the collection efficiency and outlet emissions of the precipitator. A flow uniformity guarantee, if offered, is usually subordinate to the primary guarantee and comes into play when collection efficiency is deficient by virtue of unsatisfactory flow uniformity.

GAS FLOW UNIFORMITY STANDARDS

Maximum theoretical precipitator collection efficiency results from perfectly uniform gas velocity. However, due to the inevitable formation of low speed, viscous, boundary-layer like regions in the collection chamber, and the fact that mechanical and re-entrainment considerations generally require shaped, non-planar, collecting surfaces, completely uniform flow throughout is neither achievable or desired. Another consideration is that a sheltered low speed zone is usually deliberately established above the hoppers in order to minimize hopper sweepage.

Nevertheless, gas flow uniformity is desirable to maximize the operating efficiency of the precipitator. The following standards define today's practical limits of gas flow uniformity recommended in precipitator modeling. Depending upon site and design specific circumstances full scale flow uniformity can be expected to be somewhat less than that measured in the model.

1. Within the treatment zone near the inlet and outlet faces of the precipitator collection chamber the velocity pattern shall have a minimum of 85% of the velocities not more than 1.15 times the average velocity, and 99% of the velocities not more than 1.40 times the average velocity.

2. Consideration is often given to having lower than average gas velocity at the upper and lower extremities of the collecting plate to minimize flow over and under the treatment zone. Lower velocity near the bottom of the collecting plate is particularly important to minimize re-entrainment and hopper losses.

3. For large precipitators subdivided into several chambers, but serving a single source, the uniformity criteria given in A above should be considered as a combination of all chambers and evaluated as a single unit.

4. The individual chamber average velocities should be compared with the overall average velocity to ensure that they do not deviate from it by more than 10%.

5. Baffles, large structural members and rapping mechanisms can cause dead zones immediately downstream of them. It is not meaningful to include the velocity measurement made in these dead zones with the rest of the velocity data, therefore, these test points may be excluded from the above determinations, provided that all the excluded velocities are less than the average velocity.

Special circumstances such as aerodynamically inferior duct configurations required by limited space availability or the need to prevent dust dropout in horizontal or sloping ductwork when transporting large dust loadings may force the supplier to deviate from the criteria given above. Alternate solutions such as increasing the size of the precipitator are often employed to address these problems.

VELOCITY MEASUREMENT INSTRUMENTATION AND PROCEDURES

The success of a gas flow modeling effort is dependent on the accuracy with which velocity data is obtained both in the laboratory and in the field.

1. Laboratory velocity measurement instrumentation should:

   - Be reasonably accurate and be repeatable within 2% of the reading or 0.5% of full meter scale. In this service absolute accuracy is less important than relative accuracy and repeatability. Field instrumentation may sacrifice the criteria above somewhat in exchange for ruggedness.

   - Have, for electronic instrumentation, an overall system response time of under one second.

   - The system (sensor, signal conditioners, readout/printout conditioner) should be recalibrated frequently as required.

2. Both laboratory and field velocity measurement procedure should:

   - Have a minimum number of test points equal to one-ninth the cross sectional area of the actual precipitator face (in square feet). To assure proper evaluation of the velocity pattern a minimum of every third gas passage should be tested. Each passage can then be subdivided into equal points required to meet minimum requirements. However, the vertical test points should not be further apart than 10% of the collecting plate height.

   - Preferably have the data taken within three feet downstream of the leading edges of the first bank of collecting plates and within three feet upstream of the trailing edges of the last bank of collecting plates.

   - Have either continuous traverses recorded or discrete point measurements taken and recorded.

3. The two most common types of velocity measurements instruments used are electronic ("hot wire") anemometers and pitot tubes. A hot wire anemometer should have an output signal strength adequate to provide reliable results and must be frequently cleaned of dust contamination in field use.

Commonly used electronic anemometers only measure the magnitude of the principal velocity component, and not the direction, or magnitude, of the true velocity vector. The use of streamers, smoke and other qualitative devices are recommended for use in locating flow eddies and recirculating zones.

Draft gauge — pitot tube systems may be used instead of electronic anemometers to measure usual duct system velocities, but they are not well suited to measure the low velocities (normally less than 600 FPM) found within precipitator treatment zones.

Two types are commonly used: Prandtl ("L-Head") pitot tubes are capable of higher accuracy (± 1% under ideal conditions), but are susceptible to clogging problems and their use may be precluded in locations with limited access. Stauscheibe ("S-Type") pitot tubes are less accurate than Prandtl ("L-Head") pitot tubes, but are less susceptible to clogging and more versatile in locations with limited access. They also provide slightly higher pressure differences which is helpful when measuring low velocities. It is recommended that the calibration of this type of pitot tube be checked regularly over the full range of velocities.

MODELING PARAMETERS AND TECHNIQUES

The use of models for velocity distribution studies must be made with a thorough awareness of the laws of Fluid Mechanics. The dimensionless Reynolds Number defines the ratio of inertial to viscous forces acting on the fluid. Because of the scale factor, the use of full-scale installation velocities result in a Reynolds Number of the model being lower than that of the full-size counterpart.

However, as long as the Reynolds Number is high enough to insure that the flow is fully turbulent throughout the model (above approximately 4000), a reliable gas flow model of the precipitator system can be made using 1/16, or larger scale construction. In the flues and diffusers (nozzles), the Reynolds Numbers are sufficiently high (typically 1×10^5 to 1×10^6) so that the dynamic losses in the model and full scale are similar. The model flow is unquestionably fully developed turbulent flow.

However, between the precipitator collecting plates, the field Reynolds Number can be less than 10,000. Therefore, since it is necessary to maintain turbulent flow (Reynolds Number above approximately 4000) in the model, either the distance between parallel collecting plates can be increased, or the velocity through the collection chamber can be increased.

It is important that the collecting plates be represented for each field in the geometric model since the plates act to preserve existing horizontal distributions. Hence, the absence of one, or several groups of plates could make the modeled outlet velocity distribution different than it is in the actual unit.

In constant cross sectional area flues, it is not normally critical to model the details of internal structural members provided that they block less than five percent of the cross section area and their positioning will not result in their acting as a baffle. However, in the diffuser (nozzle) regions, accurate modeling of structural strut-work is important in obtaining close correspondence between the model and the field.

MODELING PROCEDURE

A geometric gas flow model study has many stages, the omission of any one of which detracts from the overall value of the study:

1. During the early design stage, the layout of the gas inlet and outlet transport flues and

diffusers (nozzles) should be critically reviewed by the precipitator supplier to ensure that the proposed design layout will not lead to unsolvable gas flow uniformity problems. This review procedure should be performed regardless of whether or not the detailed design and erection of the flues and diffusers will be done by the supplier, since for the great majority of precipitators the construction scheduling is such that major changes in the flue layout at the time of completion of the geometric model study would cause delays and added expense. The precipitator supplier's previous experience and gas flow technical expertise will help insure a good flue and diffuser (nozzle) design.

Any subsequent changes made in the flue design drawings should again be reviewed by the supplier.

2. After duct layout is approved by all parties, model construction can begin. Should the arrangement of equipment and flues require verification or modification, the model construction should be delayed until purchaser's approval is received.

3. After checking that the geometric model has been accurately constructed, and is free of leaks, velocity measurements should be made to establish that the flow exiting the inlet flue system and entering the precipitator diffuser (nozzles) is reasonably uniform. If not, alterations should be made in the vaning of the various turns of the transport flue system until satisfactory uniformity is achieved. At this point in the study, the inlet and outlet flue vaning may also be revised in order to minimize the precipitator system's dynamic pressure drop.

4. Streamers, smoke, dust and other qualitative techniques should be used to locate regions of separated or recirculating flow where particulate dropout could be troublesome.

5. For multi-chamber precipitators, the velocity data should be examined to see if one, or more, of the chambers is receiving too large a share of the flow. Flow in each chamber should be within ±10% of its theoretical share.

6. Inlet and outlet velocity traverses in the precipitator collection chamber should be made to determine if the uniformity standards given in Section IV are achieved.

   Any modifications in the flow distribution devices should be evaluated with another velocity traverse. The sequence of velocity traverse — control device modifications — velocity traverse, etc., should be repeated until an acceptable flow uniformity is achieved.

7. If field adjustable gas control devices are to be used (i.e., louver-type dampers), then both the maximum and minimum as well as the optimal settings of the devices should be established during the model study, in order to establish over what range the device may be fine-tuned in the field without adversely affecting other gas flow factors.

8. Another qualitative test which should be performed during the geometric model study is the injection of neutral buoyancy smoke into the roof and hopper regions of the collection chamber, particularly near the outlet, to check that significant amounts of gas are not exiting the precipitator without passing through the collecting plates ("sneakage"), and that there are not strong flows in the hopper regions (hopper sweepage), which could cause excessive reentrainment.

If the smoke tests indicate that extensive sneakage or hopper sweepage is occuring, then steps should be taken to minimize the effect, since this has a direct harmful impact upon the operating efficiency of the precipitator.

9. The results of the model study are then incorporated into the final precipitator design drawings.

10. After field erection of the system is completed, a thorough inspection of flues and diffusers (nozzles) should be made to ensure that the gas flow control and distribution devices have been properly located and installed in the full scale system.

11. Before the precipitator system is first brought on line, velocity traverses should be made at the inlet and outlet of the collecting chambers at the same locations that the laboratory tests were made. These measurements serve to establish the degree of agreement between the model and full scale flow pattern.

    If field adjustable gas flow devices were included in the precipitator, then velocity measurement should be made before and after each change in their setting.

APPENDIX G

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APPENDIX G-1

Effect of Dust Size Distribution on the Collection Efficiency of Pulse-Jet Fabric Filters

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For dust collectors other than filters, collection efficiency for particles of one size is not greatly affected by the size distribution of the accompanying dust. Each particle is collected independently of the particles accompanying it and independently of particles previously collected. A fractional efficiency curve, showing the relationship between particle size and collection efficiency, can be developed using any test dust and then used to predict efficiency on any other dust for which particle size is defined in an equivalent way.

Particle collection in filters, however, depends upon the amount and properties of the dust previously collected by the filter because collected dust is the medium upon which subsequent dust collects. For this reason, performance characteristics such as efficiency and pressure drop in a fabric filter will probably vary with changing dust size distribution even when fabric characteristics and filter operating characteristics remain the same. This extra degree of complexity may help explain why no model is presently available to predict the sizes and concentrations of particles that penetrate a dust-conditioned fabric filter. These models are available for cyclones, scrubbers, and electrostatic precipitators, for which the size distribution of previously collected dust does not directly affect collection efficiency.[1]

Theory

Little work has been done to identify explicitly the effect of dust size distribution on collection efficiency in a fabric filter. Usually, the size distribution effect is confounded with the effect of other variables. For example, Davis and Frazier modified the size distribution of dust to a reverse-air-cleaned filter by passing the inlet gas through cyclones.[2] In addition to changing inlet dust distribution, the cyclones changed inlet dust concentration. Other experimenters have chosen to work with one dust and thereby avoided changing inlet dust size distribution.[3,4]

Models have been proposed to interpret the overall mass emissions from a pulse-jet cleaned fabric filter. In our model,[3] the outlet flux from the filter, N_o, is the sum of outlet fluxes due to dust passing straight through the filter, N_{st}, and that due to seepage, N_{se}:

$$N_o = N_{st} + N_{se} \qquad (1)$$

Flux is the mass of dust passing through the bag area per unit time, kg m^{-2} s^{-1}, and can be found from the product of outlet dust concentration and filtration velocity. Seepage is any process by which dust is first collected, then penetrates later; it arises due to a failure of the fabric to retain collected dust rather than a failure to collect dust in the first place.

Data for the collection of fly ash on fabrics of two types suggested that straight through penetration was negligible compared to seepage.[3] In this case,

$$N_o \approx N_{se} = k\,\frac{w^2 v}{t} \qquad (2)$$

where seepage is caused by impact of the fabric on its supporting cage after pulse-jet cleaning.[3] In this equation, w is the mass of dust per unit area on the filter, v is superficial filtration velocity, t is the time between cleaning pulses, and k is a constant which depends on the elastic properties and dust release characteristics of the fabric. This theory is not developed sufficiently to allow prediction of the sizes of particles which penetrate fabric filters; it deals only with the overall mass emission rate. The theory does predict that if changes in dust size distribution increase the amount of dust on the bags, then overall mass outlet flux will increase.

Experiments

The present experiments were undertaken to determine the effect of dust size distribution on performance of a pulse-jet cleaned filter with all other variables constant. A three-bag, pulse-jet filter was used as described elsewhere.[5] This filter was identical to an industrial filter in all regards except for the limited number of bags. Filter operating characteristics are given in Table I.

The dust used in these experiments, ground limestone, was sifted through a 700 μm screen; this became the "standard" test dust. A portion of the standard dust was sifted through a 100 μm screen. Dust which passed through the 100 μm screen was called "fine" dust, and that which did not pass through was called "coarse" dust. Dusts with four different size distributions were made

Table I. Test conditions.

Bags	
Number:	New set of 3 bags for each test dust
Size:	114 mm dia., 2.44 m long
Fabric:	Polyester felt, no surface treatment
Permeability:	0.15 ms^{-1} at 125 Pa
Pulses	
Frequency:	Once per minute to each bag
Pressure:	690 kPa
Operation	
Velocity:	75 mm s^{-1} superficial velocity
Inlet mass concentration:	10.5 g m^{-3}

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by blending the coarse, standard, and fine test dusts. A dust with size properties between those of the fine and standard dusts was made by mixing equal weights of fine and standard dusts; similarly, a dust with size properties between those of the standard and coarse dusts was made by mixing equal weights of standard and coarse dusts. Coarse dust alone was not used in these tests because fabric filter would not ordinarily be selected for collection of a dust with no particles smaller than 100 μm diameter. The size distributions of these five dusts, determined by a sieve analysis, are given in Figure 1.

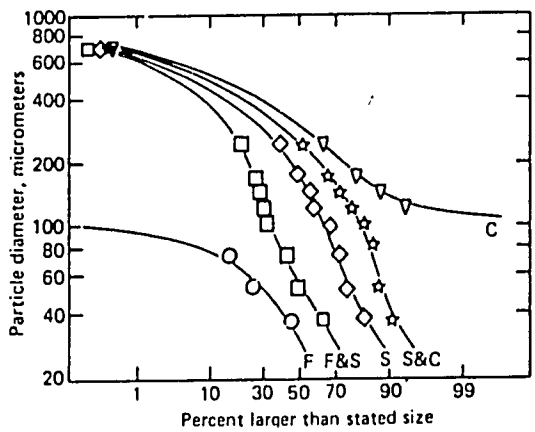

Figure 1. Cumulative size distributions for fine (f), equal-weight mixtures of fine and standard (f&s), standard (s), equal-weight mixtures of standard and coarse (s&c), and coarse (c) dusts.

A new set of three bags was used for experiments involving each dust. The bags were conditioned by operating the filter for about 24 h, until pressure drop and penetration became approximately constant. Isokinetic samples were taken to determine particulate mass concentrations upstream and downstream of the filter. The upstream sample was taken using glass fiber mat paper and weighed using an analytical balance; the downstream sample was taken using polyvinyl chloride membrane paper and weighed using a microbalance sensitive to 1 μg. Repeated samples were taken to be certain that the upstream dust concentration was constant and to determine when penetration reached a steady state, constant value.

At steady state, two measurements of penetration were made, each three hours long, so that sufficient dust could be collected on the downstream sampling filter. Final pressure drop readings were made at this time. After all samples were taken, the bags were removed carefully and weighed; subtraction of initial bag weight gave the mass of dust on the bags at the time penetration measurements were made. Division of dust mass by bag area gave the areal density of the dust deposit, w.

For each dust, two independent experiments were conducted so that a total of eight experiments was run for the four test dusts. The same three bags were used in replicate experiments with the same test dust. The experiments were run in random order.

Results

Pressure drop was not affected significantly by changes in dust size distribution in these tests. For all four test dusts, final pressure drop was about 500 ± 25 Pa (2.0 ± 0.1 in. of water), an increase of 125 Pa above that across the installed new bags. This result was somewhat surprising, because theory[6-8] predicts the finer dust would develop a dust deposit with higher specific resistance (K_2). Pressure drop across the dust deposit should increase with increasing K_2. In addition, more of the finer dust was retained by the bags as discussed below. Pressure drop should also increase with increasing dust deposit, w. Evidently, these effects were not sufficient to cause a measurable difference in pressure drop.

The amount of dust retained by the bags at steady state, w, is plotted against dust type in Figure 2. In general, the bags retained less coarse dust than fine dust. Several reasons may be given. First, the coarser dust particles will be more likely to fall to the dust hopper directly upon entering the filter, so that less of the coarser dust may deposit on the bags. However, much more dust was present on the bags than was fed to the bags between cleaning pulses, so that direct fallout alone cannot account for the reduced amount of coarser dust on the bags. Second, once collected on the bags, coarser dust particles may be more easily removed from the bag during cleaning. Finally, coarser particles and agglomerates of coarse particles will fall more readily to the dust hopper after cleaning, and be less likely to redeposit on a nearby bag or on the cleaned bag itself. Redeposition of dust freed from the bag during a cleaning pulse has been shown in theory and experiments to increase the amount of dust on the bags at steady state.[9]

The bags collecting fine-standard dust mixture retained an unusually large amount of dust. The bags used for collecting this dust may have been more retentive than those used for the other dusts. Subsequent visual examination showed that the surface of these bags looked as if it had been needled more intensively at manufacture than the bags used to collect fine dust, even though all bags came from the same manufacturer at the same time. This subjective evaluation is not conclusive, but does suggest that subtle structural differences in the bags may cause substantial differences in bag performance.

Penetration is plotted against dust type, also in Figure 2. In general, penetration was lower for the coarser dusts. This may occur for several reasons. First, it may be more difficult for larger particles to pass through passages in the dust-fabric matrix, and to penetrate the filter. Second, the reduced amount of dust carried by the bags conditioned with coarser dust will lead to reduced seepage of dust through the bags as shown by Eq. (2).

Eq. (2) was derived with the assumption that seepage alone accounts for all dust that penetrates the filter. This assumption can be tested by plotting the term w^2v/t against outlet flux, N_o, for the present data. If this plot gives a straight line with one-to-one slope on a log-log plot as predicted by Eq. (2), then overall mass penetration is explainable by seepage alone. This plot is given in Figure 3, which also shows a least-squares line with one-to-one slope. Be-

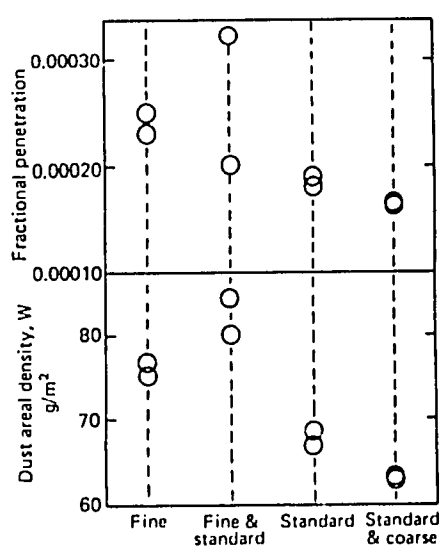

Figure 2. Fractional penetration (above) and dust areal density (below) versus dust size distribution.

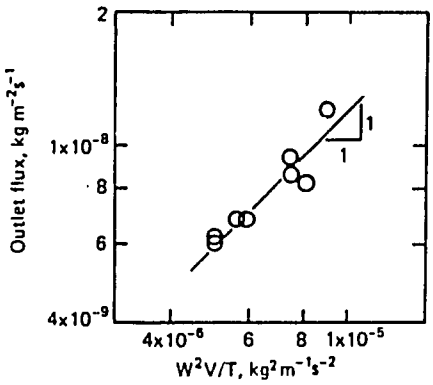

Figure 3. Outlet mass flux vs w^2v/t data and best-fit line with one-to-one slope.

cause the data cluster about this line, they suggest that seepage alone does account for all the penetration through the filter. Further, because the data for all four dust size distributions cluster about the same line, dust size distribution seems to have less effect on filter emission than the amount of dust, w, carried by the bag. Of course, dust size distribution itself affects the amount of dust carried by the bag, as discussed above. Work is continuing to determine the sizes of particles which pass through the filter, and to relate these measurements to theory.

Conclusions

The present results show that less coarse dust than fine dust will be carried by a pulse-jet cleaned filter bag at steady state, all else remaining the same. Penetration of the coarse dust is less than for the fine dust, all else remaining the same. These results are consistent with seepage theory, which says that the amount of dust on the bags at steady state affects penetration. Pressure drop was unaffected by change in dust size distribution in these tests.

Acknowledgment

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Comment: Sulfur Standards in the State of Maine

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The following comment is provided to "An Approach to Setting a Sulfur Standard for Coal," a paper by S. S. Butcher and D. W. Dixon, *JAPCA* 31(6): 673–675 (1981).[1] This paper was also presented as primary evidence in May 1 and May 5, 1981 public hearings before the Maine Department of Environmental Protection (MDEP) as a basis of proposed further lowering of sulfur standards for coal conversions in Maine. It describes a relationship between multiple sources of sulfur emission in Maine and the impacts from these sources.

This paper is not sufficient evidence to either support the dramatic regulatory changes proposed, or to explain the authors' suggested understanding of the relative relationship of (all) sources (emitters) and impacts (receptors). By comparison, currently accepted, more sophisticated models (than the one developed by the authors), which *only analyze one* source, are constantly undergoing regulatory and peer review and revision prior to and during authorized use.

Analysis

The proposed approach by S. S. Butcher *et al.*, attempts to describe complex relationships regarding, *not one single* source and its respective impact, *but instead multiple* sources throughout the State of Maine and their combined relative impacts.

By comparison, the MDEP and EPA have specified substantially more complex and sophisticated modeling by (major) applicants as a prerequisite to acceptance of an application for an air emission license, *for analysis of only a single source.* There has been much discussion regarding the appropriateness and applicability of even these models—i.e., CRYSTR, ISCST, etc., and the tendency of the MDEP Staff has been to use the more conservative results of these various analyses as representative of the particular, *single* plant's (source's) impact on the adjacent area.

The above described models have undergone substantial peer review both by many regulatory review bodies at the state and federal level, expert air quality consultants throughout the U.S., and many applicants with in-house air quality expertise.

Independent air quality consultants, for example, who have completed many air modeling analyses on the Mason Station Coal Conversion, using a variety of accepted EPA air quality models, and who are in constant touch with EPA model authors regarding the *proper use* of such models, were unable to reach any definitive conclusions regarding the validity of the Butcher *et al.* assumptions or conclusions. Typically, such a modeling technique will undergo several years of independent peer review and validity testing, subsequent adjustments and revisions, and only then final acceptance by EPA for use as a predictive tool which applicants could use.

If the shoe was on the other foot, it is highly unlikely that

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either the EPA or State agencies would ever accept the Butcher model level of sophistication and state of validation as sufficient for impact analysis in the submission of an air emission license application for even a "single" source in Maine. The real test of acceptability for a model, which is being called upon to predict a complex, multiple source, multiple impact relationship *throughout* the State, is that it have at least as rigorous a review as that given models for single sources.

The Butcher *et al.* model does not/cannot address the contribution of sources outside the State of Maine in evaluating the in-state source(s)–receptors relationship, but even more important, the Butcher *et al.* model does not account for major physical changes an applicant's facilities will be required to undergo, by virtue of the fact that a new or revised air emission license is being sought. MDEP Staff's suggestion at May 1 and May 5, 1981 workshop hearings, that the DEP does not order or mandate applicants (such as CMP) to add additional pollution control equipment such as Good Engineering Practice (GEP) stacks to prevent downwash, or other pollution control equipment, is an oversimplification of the actual burden placed on the applicant by the MDEP staff. Experienced applicants and the regulatory agencies recognize that taller stacks or other pollution control equipment will be required and any approach to standard setting should recognize this fact.

The MDEP staff and major applicants, such as CMP, usually discuss a major project before submission of an application. At these informal meetings, staff indicates its preference and what will be expected from the applicant at such meetings. These meetings are held to expedite the process, while developing an understanding of what staff will require. An applicant could wait until the staff rejected the application because a GEP stack or currently accepted pollution control equipment was not proposed, and perhaps lose six months to a year in schedule, or instead recognize that these will be required based on EPA or MDEP practice and factor them into the air quality design from the beginning. Most prudent applicants would follow the latter course.

The mere fact that staff did not "order" the applicant to install such equipment, does not alter the fact that they will be installed, will have an impact on emissions and receptors, and, therefore, should have been considered in the Butcher *et al.* modeling analysis.

Application

In CMP's example, i.e., the Mason Station Coal Conversion,[2] CMP is proposing to *limit* sulfur emissions to 1.33 lb/million Btu *mean*, which is the oil equivalent of the State-allowed 2.5% sulfur oil. State-wide oil to coal equivalency was stated by staff as their objective in 1980 and 1981 workshops held to receive comments on the currently proposed regulations.

According to testimony by staff on May 1, 1981, the Butcher *et al.* model does not take into consideration physical plant changes when evaluating the before and after coal conversion impacts. *For instance, the installation of the Good Engineering Practice (GEP) stack on the to-be-coal converted Mason units will result in a reduction of short-term impacts by a factor of 6 in the 24-h case and a factor of 8 in the 3-h case, below that which Butcher et al. assumed.* Reductions stemming from this kind of modification are ignored in the Butcher *et al.* paper, making it unnecessarily conservative.

Staff at the May 1, 1981 workshop asked the Board to disregard Mason Station as only one example of many applicants coming before the MDEP/BEP. CMP noted to the staff, and subsequently verified, that 85% of the *potential* coal conversion switches from residual oil is represented by *only the 10 major* sources in the State. These large sources will all undoubtedly be required to submit a detailed analysis to the MDEP or EPA, and are all likely to be required to upgrade their pollution control systems. Any such upgrading is not considered in the Butcher *et al.* model.

Conclusions

In summary, the modeled impact reductions in the example above are, in fact, illustrative of the kinds of effects which may occur with coal conversions anticipated in Maine.

In fact, it may be that when impact reductions of major sources are considered, the combined impacts of all large and small, potential coal conversions may well result in a net reduction below 2.5% sulfur oil equivalency, which could then allow small sources to burn a "statutory" sulfur level in coal greater than pre-conversion oil use.

For these reasons, CMP has recommended that MDEP Staff consider a *dual regulation* that would allow the small sources, which contribute 15%± of the fuel use in Maine (10 major sources account for approximately 85% of total emissions in Maine), to burn conservatively 1.2 lb/million Btu *mean* coal without extensive modeling analyses, and allow large users to demonstrate the acceptability of 1.33 lb/million Btu mean coal as a long-term average (2.5% oil equivalent), while meeting all standards and increments. Further, these major source applicants could demonstrate to the MDEP a cap on the maximum, mean sulfur coal shipment which could be burned, while meeting a long-term oil equivalent sulfur level (1.33 lb/million Btu *mean*) and also meet all short-term standards and increments.

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Authors' Reply

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The major portion of the note by LeBlanc and Thompson appears to be concerned with an application for a coal conversion at a relatively large (for Maine) point source. As specified in the first sentence of our note,[1] the proposed method is designed [illegible] assessing the impact of *widespread* conversion of *small* [illegible] stion sources from oil to coal. Our approach has roo[illegible] ne empirical work of Larsen[2] and Saltzman[3] and [illegible] of mass balance implicit in many

DEMONSTRATION OF A PULSE-JET FABRIC FILTER AT THE TU ELECTRIC BIG BROWN STATION

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ABSTRACT

TU Electric Company and the Electric Power Research Institute (EPRI) sponsored a project to characterize the performance of pulse-jet baghouses filtering particulate matter from lignite-fired boilers. This evaluation was conducted by ADA Technologies, Inc. using one of the EPRI 1 MWe Transportable Pulse-Jet (TPJ) fabric filter pilot plants. The project was conducted at the 575 MW Big Brown Unit 1 of the TU Electric Company in Fairfield, TX.

This paper summarizes the performance results from tests conducted on two pulse-jet cleaning systems: high-pressure, low-volume (HPLV) and low-pressure, high-volume (LPHV). Pulse-jet performance was evaluated at an air-to-cloth ratio of 4.0 acfm/ft^2 using Ryton/Ryton felt for 2800 hours in the LPHV configuration and 1800 hours in the HPLV configuration. After 1800 service hours the two systems performed similarly. Tubesheet pressure drop was controlled at nominally 4.0 inches H_2O by cleaning pulse rates of approximately 40 pulses per hour. The outlet particulate matter emission rate was measured to be 0.008 lb/MMBtu with a collection efficiency of 99.95% for the LPHV system. Leaks around the bag flange and the tubesheet in the HPLV test were responsible for high outlet emission measurements. Inspection of the HPLV fabric showed insignificant particle penetration, therefore it is predicted that the two cleaning systems would also operate similarly in terms of collection efficiencies.

PROJECT OVERVIEW

This evaluation began in February, 1990 and was carried out over a 14 month period. The objective of the test was to document the performance of pulse-jet baghouse cleaning methods filtering fly ash produced by burning lignite coal. Pulse-jet performance was evaluated in terms of: 1) cleaning pulse rate at a filtering air-to-cloth (A/C) ratio of 4 acfm/ft^2 and controlled average pressure drop across the tubesheet of 4 in. H_2O; 2) particulate matter collection efficiency and overall emissions; and 3) operations and maintenance requirements for the pilot plant.

Pulse-jet cleaning methods can be categorized into three general regimes: low-pressure, high-volume (LPHV); intermediate-pressure, intermediate-volume (IPIV); and high-pressure, low-volume (HPLV) pulsing. A general classification of the pulse pressure associated with each of the three cleaning systems is presented below (1):

Cleaning Method	Typical Pulse Pressure
LPHV	10 to 15 psig
IPIV	20 to 30 psig
HPLV	50 to 100 psig

The test plan included the evaluation of two of the three different cleaning configurations. The test configurations were defined to be the LPHV cleaning system with Ryton/Ryton felt bags and the HPLV cleaning system, also with Ryton/Ryton felt bags. The LPHV pulsing is a relatively new development in pulse cleaning. LPHV pulsing utilizes a circular arrangement of oval-shaped bags, with pulse nozzles attached to a central rotating manifold located above the bags. In this design, a higher volume pulse of low pressure air is used, which permits the use of blowers rather than compressors to supply the pulse cleaning air (2,3).

With the HPLV pulse, a high pressure burst of air is injected through an array of fixed nozzles (blow pipes) located above the bags. The nozzles are simple holes drilled in a manifold pipe. The bags are laid out in a rectangular array, such that a single manifold pipe cleans a row of bags. A venturi is positioned at the top of each bag to induce secondary air flow (equal to two or three times the compressed air volume) to assist in bag cleaning. Both the LPHV and the HPLV pulse cleaning systems have been proven to be effective in removing dust from the bags (2,3).

Ash characteristics may significantly affect the ability of a fabric filter to achieve high collection efficiencies. TU Electric's Monticello plant, which burns a Wilcox group Texas lignite coal, is equipped with shake/deflate cleaned baghouses in parallel with electrostatic precipitators (ESPs). The baghouses have demonstrated low collection efficiencies and high pressure drop since start-up because of the unique characteristics of the ash. Specialized bag materials and flue gas conditioning have improved performance (4).

Big Brown also burns a Wilcox group lignite. Pilot-scale baghouse studies using ash from Big Brown coal with reverse gas, shake/deflate, and pulse-jet cleaning methods indicate that the ash has characteristics similar to the Monticello ash (5). The ash particles are noncohesive, have few surface deposits and, in micrographs, appear as smooth spheres

which tend to penetrate into the filtering fabric and may lead to severe bleed-through. The unusually noncohesive particles form an unstable dustcake on the fabric surface. Since the dustcake is the primary filtering medium for shake/deflate and reverse gas cleaned baghouses, low collection efficiencies can be expected. Depending on the fabric, higher collection efficiencies can be achieved with a pulse-jet cleaned baghouse because the bag acts as the primary filtering medium.

Pulse-jet pilot-scale tests conducted at the University of North Dakota Energy Research Center using Big Brown coal resulted in low collection efficiencies (55 to 95.6%). These tests were performed at A/C ratios of 8.2 to 8.8 with both a woven glass and a glass felt fabric (5). The smooth, spherical ash particles tended to penetrate through the smooth glass fibers, especially at high face velocities. However, higher efficiencies can be expected with operation at lower A/C ratios and with specialized bag fabrics.

The specific goals in this study were: 1) to operate both a LPHV and HPLV pulse-jet on ash produced from lignite coal; 2) to attain emission rates significantly below NSPS limits of 0.03 lb/MMBtu; and 3) to reach a steady state cleaning pulse rate in order to permit an accurate assessment of bag performance for both test configurations.

PILOT PLANT DESCRIPTION

The Transportable Pulse-Jet (TPJ) fabric filter pilot plant arrived at the Big Brown station in Fairfield, Texas on January 25, 1990. The unit is designed to filter 5000 acfm of hot flue gas and has interchangeable tubesheets to accommodate different cleaning systems and bag arrangements. The TPJ is located on the south side of the Unit 1 ESPs. The host boiler is a 575 MW Combustion Engineering tangentially fired steam generator. The unit is operated as base loaded plant in the TU Electric generation grid.

Big Brown fires a medium to low sulfur Texas lignite. This coal has an "as received" heat rate of 6600 BTU/lb. A coal and ash analysis was performed by Southern Research Institute (SRI) on samples taken in July, 1990. An analysis was performed by Hazen Research, Inc. on a sample of coal taken in April, 1991. Table 1 presents the results of the coal ultimate, proximate and mineral analyses and ash mineral analysis. There was flue gas conditioning upstream of the ESP which consisted of a continuous feed of 10 to 12 ppm of SO_3 and 8 ppm of ammonia. In the TPJ baseline configuration, the inlet slipstream was located between the SO_3 and ammonia injection points, therefore only SO_3 was added to the flue gas that passed through the TPJ.

For both the LPHV and the HPLV systems, the bags were hung from an overhead tubesheet, were closed at the bottom, and were open at the top where the clean gas exited the bags. To support the bags during filtering, a wire cage was inserted into the bag. Flue gas entered the compartment at the bottom and passed through the bags from outside to inside, depositing the particulate matter on the outside of the bags. The flue gas then exited the bags through the openings in the tubesheet and flowed out of the compartment through the outlet plenum on the clean side of the tubesheet. Flue gas in the outlet duct passed through the flow control damper, the flow measuring venturi, the opacity monitor and into the ID fan. On the positive side of the ID fan the flue gas flowed through another venturi, located beneath the ash hopper. This venturi functioned as an eductor to remove ash from the hopper. Ash was fed into the eductor by a rotary valve.

Table 1

Mineral Analysis of Ashed Coal and Dustcake Ash (%)

	Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3
Dustcake Ash*	0.02	0.51	1.1	2.7	11.9	5.5	21.2
Ashed Coal*	0.01	0.62	0.88	2.8	15.7	3.9	12.7
Ashed Coal**	0.01	0.3	1.05	3.68	7.39	4.97	14.01
	SiO_2	TiO_2	P_2O_5	SO_3	LOI	sol SO_4	Eq pH
Dustcake Ash*	52.2	1.2	0.05	0.7	0.3	1.1	10.3
Ashed Coal*	47.4	1.1	0.05	11.9	88.9	--	--
Ashed Coal**	58.2	1.21	0.09	7.95			

*Southern Research Institute 7/90, **Hazen Research, Inc. 4/91

Coal Analysis (as Received, %)

C	H	N	S	O by Diff	Ash	Volatile	BTU/lb	Coal % Moisture
38.29	2.90	0.92	0.80	9.80	15.68	27.88	6608	31.61

Hazen Research, Inc. 4/91

To remove dust cake from the filter bags, pulse jets use a short, powerful burst of compressed air which is introduced at the top of the bag in the reverse direction to filtration. The air burst propagates rapidly as a pressure wave down the length of the bag, causing the bag to accelerate away from the cage and then to immediately collapse back on the cage (6). This rapid flexing of the fabric dislodges the dust, which falls into the ash collection hopper below. During the pilot tests, hopper ash was fed back into the TPJ gas stream through the rotary valve and returned to the host duct.

Two options were available for the initiation and control of the pulse cleaning sequence in the TPJ: 1) a pressure initiate/terminate sequence and 2) a timer sequence that cleans at a specified time interval for a predetermined length of time. The pressure drop initiate/terminate sequence was used exclusively for both cleaning systems. The control element for the pressure initiate/terminate cleaning methodology was a differential pressure gauge. The gauge measured differential pressure across the tubesheet and had two latching relays that could be set at distinct pressure differentials. The gauge was set to begin cleaning (or pulsing) when the tubesheet pressure drop reached 5.0 inches H_2O, and stop pulsing when the pressure drop instantaneously fell below 3.0 inches H_2O. This method maintained the tubesheet pressure drop at nominally 4.0 inches H_2O. In the second method, a timer was used to control the time between cleans as well as the duration of the clean. The major difference between the two cleaning methods was the parameter which was controlled. Pressure drop was directly controlled with the pressure drop initiate/terminate methodology and pulse-jet performance was monitored in terms of pulse rate. With the timer methodology, pulse rate was controlled and performance was monitored as pressure drop. Because pressure drop is a significant cost and operations variable in power production, it was of interest in this program to document how the pulse-jet baghouse performance at a fixed pressure drop condition.

Low-Pressure, High-Volume Configuration

The LPHV tubesheet was designed to be similar in geometry to a full scale LPHV pulse-jet fabric filter compartment. The single LPHV TPJ compartment has 48 bags arranged in three concentric circles. A commercial full-scale compartment typically has over 300 bags in twelve concentric circles. The bags were made from a 16 oz/yd^2 glazed Ryton felt on a Ryton scrim, with the glazed surface on the clean side. The bags were manufactured to fit the "standard" LPHV 14 vertical wire and 62 horizontal wire cages and to snap into a "standard" LPHV oval tubesheet hole. The bags are hung from the tubesheet at the top cuff of the bags by a 1" wide stainless steel snap band covered with woven glass fabric. Heavy woven glass tape was rolled and stitched to form a double-beaded gasket. This gasket was attached to the top cuff with adhesive and seals the bag to the tubesheet. The cages were inserted into the bags and hung from the tubesheet. The bag dimensions were 20 feet in length with a circumference of 15.5 inches and an active filtering area of 25 ft^2/bag. A quality assurance (QA) inspection was performed on the filter bags by Grubb Filtration Testing Services (GFTS). With a full compartment of 48 bags installed, the total fabric filtering area in the TPJ was 1200 ft^2. To achieve an A/C ratio of 4.0 acfm/ft^2, the flow rate through the TPJ was set at 4800 ft^3/min.

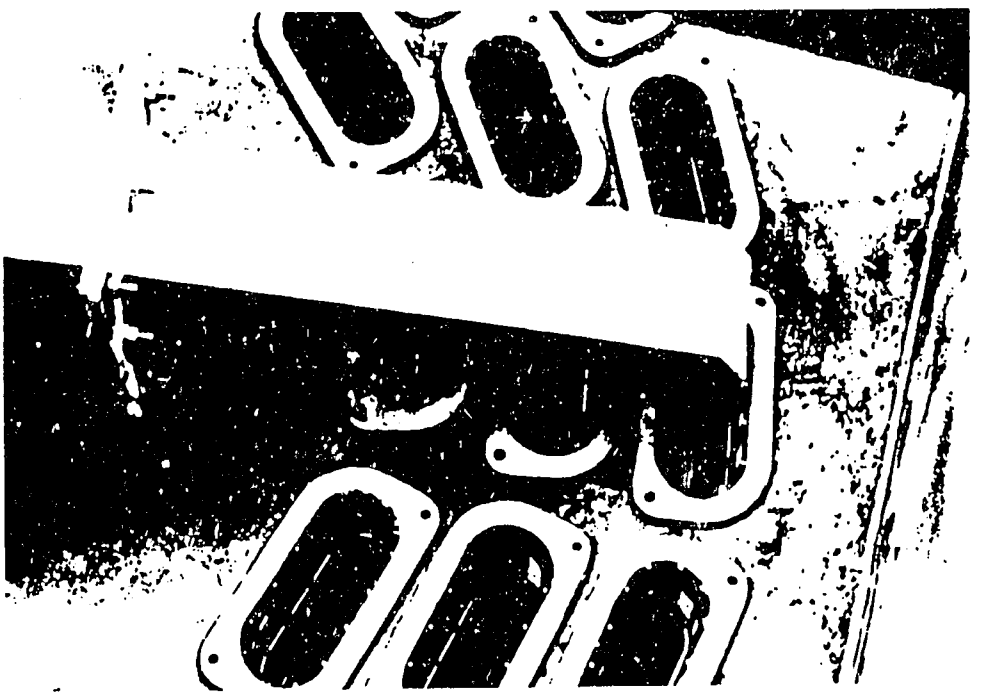

Figure 1. Three Nozzles on the LPHV Rotating Manifold Arm.

At the initiation of a clean cycle in the LPHV TPJ, a positive displacement blower was activated to pressurize an air reservoir at the top of the vessel. When the reservoir pressure reached approximately 12.5 psig, a pilot actuated solenoid valve opened a 6.25-inch diaphragm valve and released approximately 2 ft^3 of pressurized air into the single, rotating manifold arm. The cleaning pulse entered the top of the bags through one of three nozzles on the rotating manifold arm. Figure 1 is a photograph of the three nozzles on the rotating manifold arm. This photograph shows that the nozzles were located on the radii at which the bag cut-outs in the tubesheet were centered; however, as shown in this picture, the nozzles were not necessarily aligned with a bag opening during a pulse.

High Pressure, Low-Volume Configuration

The HPLV tubesheet was designed for a total of 42 round bags in a rectangular pattern (six rows of seven bags). The bags are nominally six inches in diameter and twenty feet in length. Each bag has a filtering area of 31.4 ft^2, for a total compartment fabric filtering area of 1319 ft^2. The bag fabric used in the HPLV tests was a Ryton felt. The bags are constructed of 18 oz/yd^2 glazed Ryton felt with a Ryton scrim. Bags installed for this test had the glazed surface on the clean side of the fabric. The top of the bags had an annular flange attached, which consisted of two layers of 10 oz/yd^2 Ryton encapsulating a wire ring. This flange laid flat on the tubesheet and sealed the bag to the tubesheet after the cage and venturi were set into place.

Figure 2 is a photograph of the clean side of the HPLV tubesheet. In this photograph, three of the two-inch pulse pipes are shown. The pulse pipes carry high pressure air to the opening of the bags, where holes drilled in the under side of the pulse pipe direct air through the venturi inserted into each bag top. There are six pulse pipes, each cleaning seven bags. Unlike the LPHV system, there is an individual nozzle directly above each bag opening. Each bag has a cage inserted to support the fabric during pulsing and a venturi which accelerates and directs the air flow along the length of the bag. The cages have ten vertical wires and thirty horizontal wire rings on eight inch centers. The venturis are bolted to the tubesheet, which applies pressure to the lip of the cage and to the annular flanges attached to the top of the bags. This arrangement seals the bag to prevent unfiltered flue gas from leaking around the top.

Figure 2. Clean Side of HPLV Tubesheet.

The high pressure air reservoir sits on the upper level of the TPJ with a direct air feed to each of the six pulse pipes. One of the six pulse valves is activated when the TPJ begins a cleaning sequence. A pulse is activated every ten seconds, cycling continually between the six valves for the duration of the cleaning sequence. It is possible that any one of the six

valves can be the first valve in the cleaning sequence. Pressure in the air reservoir was set at 60 psig.

A calculation of the total mass of air released during one cleaning pulse for both the LPHV and HPLV systems was performed. Calculations were based on pressures in the air reservoirs before and after a pulse, dimension of the pulse valve orifice, length of time that the valve was open, and total area of the nozzles. The results of the calculations for two pulse conditions are presented in Table 2.

Table 2. TPJ Pulse Conditions.

Method	Pressure (psig)	Pulsed Area (ft^2)	Mass air/pulse (lb/pulse)
LPHV	12.5	75	0.146
HPLV	60	219.8	0.166

Total mass of air for the HPLV system was calculated at 0.757lb air/1000ft^2 pulsed fabric, while total mass of air for the LPHV system was calculated at 1.95lb air/1000ft^2 pulsed fabric. These calculations show that the LPHV system flows a greater mass of air than the HPLV system to clean the same fabric area. A rough calculation indicates that the power required to provide the pulsing air for the HPLV system is twice that for the LPHV system. However, for a pilot-scale unit this size, the cost to provide pulsing air is insignificant in both cases. It is important to note that the Goyen valves used in the HPLV test were larger than valves typically used in HPLV applications. Larger valves were purposely installed to compensate for the 20-foot bag length and the 18 ounce Ryton felt. Most HPLV applications have used lighter, shorter, fiberglass bags and flow less air than calculated for this TPJ configuration.

Pilot Plant Control

The TPJ was operated from a main control panel, located in a trailer near the TPJ housing. The relay logic in the control panel was designed to control both the LPHV and HPLV cleaning systems as well as overall pilot plant operation. The operator has the option to run in either manual or automatic modes. The manual mode was typically used during start-up and trouble shooting because each component of the unit could be isolated and tested. During normal operation in this test program, the automatic control mode was used.

In the automatic mode, relays in the control panel were programmed to stop the ID fan and trip the unit off-line when certain upset conditions occur. These alarm conditions included:

1) Duct temperatures below 250°F or above 400°F.
2) Loss of rotation of the cleaning manifold arm (LPHV system).
3) Loss of rotation of the rotary valve.
4) High ash level alarm in the hopper.
5) Tubesheet pressure drop above 10 inches H_2O.

Typical alarm conditions encountered during this test were caused by low temperatures after the host boiler tripped off-line and high tube sheet pressure drop readings when the hopper

was full of ash. When an alarm trip occurred, flow through the TPJ was stopped without cleaning of the bags or ambient air purging of the compartment. As soon as the trip condition was discovered, the bags were manually pulsed to remove the residual dustcake and the hopper was emptied either via the rotary valve or vacuum truck.

One of the objectives of this test program was to document TPJ fabric filter performance as a function of accumulated service hours. To accomplish this, a microprocessor-based data logger was used in conjunction with data transfer and analysis software developed by ADA. The data logger system allowed unattended operation of the TPJ pilot plant. Remote access to the data logger permitted a daily download of data for analysis and the early identification of operational problems. The following parameters were monitored by the data logger:

1) Big Brown Unit 1 Boiler Load (Megawatts).
2) Big Brown Excess O_2 (%).
3) Big Brown Duct Temperature at TPJ slipstream inlet (°F).
4) TPJ Inlet Temperature (°F).
5) Tubesheet Pressure Drop (inches H_2O).
6) TPJ Outlet Opacity (%).
7) Cleaning Pulse Tank Pressure (Psig).
8) Count of Cleaning Pulses.
9) Count of Cleaning Cycles.

The selected data logger combined precision measurement capability with processing and control function in a single battery-operated system. There were eight differential analog input channels and four pulse count channels on the unit. Microprocessor control allowed the user to program data scaling and preprocessing functions, as well as alarm limits. The data logger was programmed to acquire data on ten second intervals, performed a five minute average of all inputs in engineering units, and stored the results in a time stamped array in RAM. The data logger was equipped with a telephone modem so that data could be transferred daily to ADA offices in Denver; remote programming was also possible via modem.

In addition to the data channels monitored continuously by the data logger, manual measurements were made periodically in each test configuration. Manual measurements included:

1) Velocity profiles of the inlet and outlet duct.
2) Inlet and outlet mass concentration measurements.
3) Bag weights.
4) Coal analysis.
5) Dustcake analysis.
6) Fabric analysis.

Velocity profiles were obtained during each site visit to confirm flow rate through the TPJ. EPA Reference Method 2 was used to determine the velocities. Mass concentration measurements were made at the inlet and outlet sampling locations to document the collection efficiency of the TPJ fabric filter. The in-stack collection technique specified in EPA

Reference Method 17 was used to determine the total particulate mass loading at the sampling locations.

High capacity BGI thimble holders were used at the inlet and 47 mm Gelman filter holders were used at the outlet to collect the particulate matter samples. A minimum of three tests were made at each test condition. The 47 mm fiberglass filters were stack conditioned for a minimum of 5 hours prior to testing to neutralize all reactive sites and prevent false changes in substrate weight due to flue gas reaction with the filter.

A representative coal sample, a sample of dustcake ash and fabric samples were all sent to Southern Research Institute for analysis. Coal ultimate and proximate analyses and ash elemental analysis were performed by Hazen Research Inc. of Golden, Colorado. Fabric samples were analyzed by GFTS. Bags were weighed upon removal for analysis or at the end of a test period. When a bag was removed from the tubesheet, it was placed in a plastic garbage sack. These sacks were then lowered to the ground level and weighed on a scale in the plant.

TRANSPORTABLE PULSE-JET PERFORMANCE

Pulse-jet performance was evaluated for each cleaning method in terms of: 1) cleaning pulse rate for an air-to-cloth ratio of 4.0 acfm/ft^2 and controlled average pressure drop across the tubesheet of 4.0 in. H_2O; and 2) particulate matter collection efficiency and overall emissions. The results for the two cleaning methods are presented separately in the following sections.

Low-Pressure, High-Volume Performance

The TPJ pilot plant accumulated 2800 service hours through September 14, 1990 with Low-Pressure, High-Volume (LPHV) cleaning and Ryton/Ryton fabric, except for a short period from 1900 through 2200 hours when the TPJ was configured as compact hybrid particulate collector (COHPAC). During COHPAC operation, the TPJ filtering A/C ratio was set at 15 acfm/ft^2.

Operation and Maintenance History. The TPJ was put into service filtering flue gas on February 16, 1990. Because of an extended period of system troubleshooting at start-up, the TPJ experienced nearly 20 start-up/shut-down sequences during this test period. In addition to start-up problems there were also system alarm trips, maintenance outages and four Unit 1 boiler tube leaks. The primary alarm trip conditions were high ash levels in the hopper and high/low duct temperatures. Maintenance outages included trouble shooting high current drawn by the ID fan and replacement of degraded silicon expansion joint seals. In June, the TPJ operated for a prolonged period of time at a low flow rate as a result of false flow indicators. The flow rate was below the designed system flow rate and caused the operating temperatures to be lower than standard conditions. The TPJ temperature during this upset condition fluctuated around the acid dew point. Results presented in the following sections show that operation in this mode was detrimental to TPJ performance in terms of pulse rate and residual dustcake weight.

Pulse Rate and Tubesheet Pressure Drop. Figure 3 illustrates the tubesheet pressure drop and pulse cleaning rate in terms of pulses per hour for the LPHV test period. Pulse rate data are plotted from 24-hour averages and the pressure drop data are plotted from 6-hour

averages. Erratic pulse rates during the first 460 hours of operation can be correlated to start-up problems. After 460 hours the pulse rate showed a decreasing trend. At 860 and 900 hours, slight increases in pulse rate were correlated to a change in the fuel quality. During these episodes, plant records showed that the average heat rate of the coal in BTU/KWH and the percent ash increased. It is noteworthy that the TPJ pulse rate was able to recover to previous values after the poor fuel episodes.

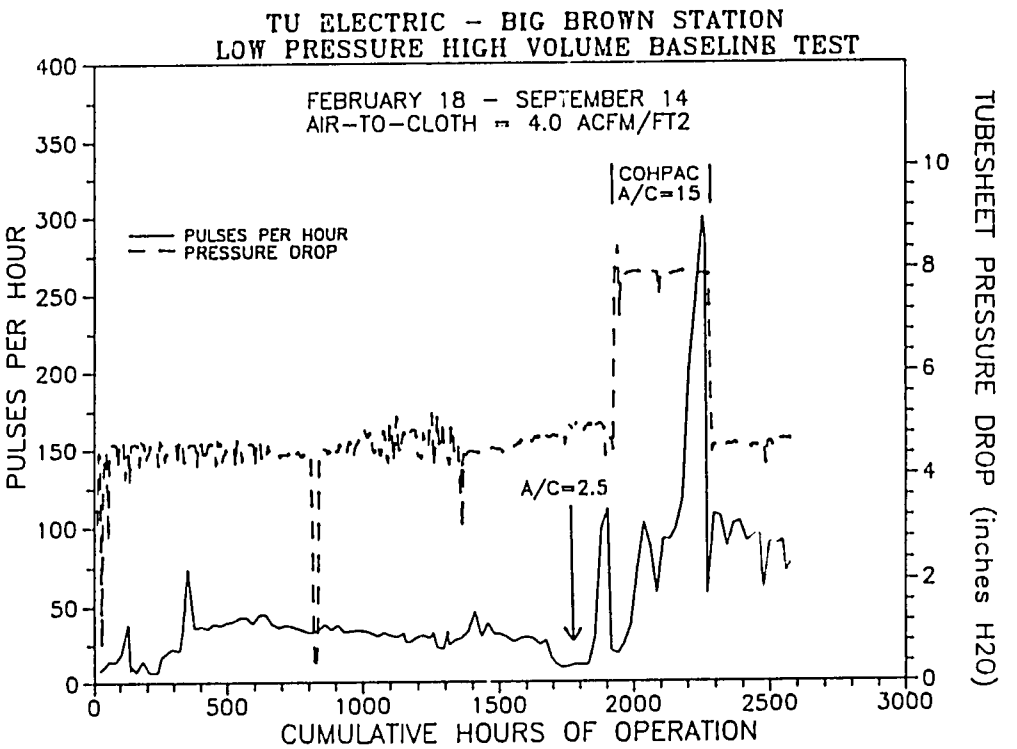

Figure 3. LPHV tubesheet pressure drop and pulse cleaning rate.

During the first 1800 service hours, the average pulse rate was 30 pulses per hour, which was equivalent to the entire baghouse being cleaned 1.8 times every hour. Between 1700 and 1850 hours the TPJ operated at an A/C ratio of 2.5 acfm/ft^2. Following the low flow/low temperature episode, the A/C ratio was increased and maintained at 4.0 acfm/ft^2, resulting in an increase of the pulse rate to 90 pulses per hour. Between 1900 and 2200 hours the TPJ was operated in the COHPAC configuration. At 2200 hours the A/C was again set at 4.0 acfm/ft^2 and the pulse rate returned to levels experienced immediately before the COHPAC test. The TPJ never fully recovered to the very low pulse rate values observed early in the test program, but appeared to stabilize at approximately 100 pulses per hour.

In Figure 3, the average pressure drop is seen to be relatively constant at 4.5 inches H_2O because of the pressure drop initiate/terminate cleaning methodology. This methodology is intended to maintain pressure drop in the range between 3-5 in. H_2O. The only exception was during operation in the COHPAC configuration when the pressure drop increased above 8.0 inches H_2O. Although the pulse rate fluctuated, the tubesheet pressure drop was maintained in the desired range. The pressure drop values presented in this graph are 6 hour averages.

Collection Efficiency. Particulate matter tests were performed at the inlet and outlet of the TPJ in March, 1990 and July, 1990. Results of the particulate tests are presented in Table 3. Inlet and outlet tests run simultaneously are grouped together. The results from the March

test series show that the particulate matter inlet and outlet concentrations averaged 5.3 gr/dscf and 0.0029 gr/dscf, respectively. Total particulate matter efficiency averaged 99.95%, with the outlet emissions equivalent to 0.0056 lb/MMBtu. The July results show the average inlet concentration to be 7.1 gr/dscf while the outlet averaged 0.0037 gr/dscf. In this test series the total average collection efficiency was again 99.95%, however the equivalent outlet emissions were slightly higher at 0.0072 lb/MMBtu. The overall collection efficiency between the two sets of tests compare favorably, even though there was a 25% increase in inlet concentration and the pulse rate was significantly higher in the second set of tests.

TABLE 3. Particle Mass Concentration Tests

DATE	TEST	% H_2O	gr/dscf	lb/MMBtu	% Eff.	Load(MW)
3/14/90	INLET	16.0	6.15			514
3/14/90	INLET	15.0	5.74			521
3/14/90	OUTLET	14.7	0.0042	0.0080	99.93	516
3/15/90	INLET	14.0	4.52			501
3/15/90	OUTLET	18.5	0.0024	0.0050	99.95	503
3/15/90	INLET	12.5	4.77			502
3/15/90	INLET	13.4	5.34			410
3/15/90	OUTLET	13.3	0.0022	0.0042	99.97	462
7/10/90	INLET	15.0	5.70			527
7/10/90	OUTLET	14.8	0.0041	0.0078	99.93	530
7/10/90	INLET	13.7	6.91			528
7/10/90	INLET	15.2	8.00			530
7/10/90	OUTLET	14.5	0.0029	0.0055	99.96	525
7/11/90	INLET	14.3	8.02			523
7/11/90	OUTLET	13.7	0.0043	0.0082	99.95	523

Bag Weights. Bags were weighed at the conclusion of the LPHV test. Bags were pulsed three times prior to removal. The average total weight of the bag and dustcake weight was 20 pounds. A clean bag weighs approximately 4 pounds; thus the average residual dustcake areal loading was calculated to be 0.8 pounds/ft^2. This is much heavier than expected for a pulse-jet bag. As documented above, the TPJ was operated at marginal temperatures (close to the calculated acid dew point of approximately 290°F (7)) between 1700 and 1850 service hours and during the 20 start-up/shut-down sequences. It is believed that operation near and below the acid dewpoint contributed to the formation of the heavy dustcake found on the TPJ bags during LPHV operation.

Fabric Analysis. Laboratory analysis of fabric and dustcake samples were performed by Southern Research Institute (SRI). The results from this analysis state that "a small portion of the ash collected on the filtering surface infiltrates into the fabric, but that most of the collected dustcake ash particles remain on the filtering surface of the fabric (8)." It is possible, over time, that the fly ash could continue to penetrate into the fabric until the fabric was essentially blinded. In this situation the permeability of the fabric would decrease and cause an unacceptably high pressure drop. At this point it may not be necessary to replace the bags; however it may be possible to remove the bags and wash them if they are in sound physical condition.

GFTS performed a fabric analysis of top, middle and bottom sections of the same bag described above. In addition, GFTS was also sent two additional bags that were removed at

different time periods. GFTS performed Mullen Burst strength analysis tests on fabric samples removed after 130, 1930 and 2200 service hours. After 130 service hour, tests showed a 15% loss in fabric strength. It is documented that Ryton felts tend to lose strength at a rapid rate during the first 1500 hours of operation. The analysis after 1930 service hours showed a 35% loss in strength. This fabric was cut from the same bag as the sample sent to SRI. This value is less than normally measured, showing good retention of fabric strength. After 2200 service hours the Ryton fabric showed a 55% loss of strength. This value shows a higher than normal amount of strength loss in a short period of operation. During this period the TPJ was operated in the COHPAC configuration and experience high pressure drop and pulse rate and low operating temperatures. This mode of operation appears to have accelerated fabric degradation.

High-Pressure, Low-Volume Performance

The low pressure cleaning head was removed in January 1991 and replaced with a high pressure head design. The TPJ accumulated 1800 hours of operation in the HPLV test configuration between February 7 and April 22, 1991.

Operation and Maintenance History. Operation for the TPJ with the HPLV cleaning configuration was much more consistent than for the LPHV configuration. The TPJ went through 4 start-up/shut-down sequences over the test period, two of which were caused by Unit 1 boiler tube leaks. The LPHV configuration was the initial TPJ configuration at the Big Brown Station. Many of the potential maintenance problems were identified during the LPHV test and corrected before initiation of the HPLV test.

Pulse Rate. Figure 4 presents pulse rate and tubesheet pressure drop as a function of service hours for this test. Pulse rate increased steadily during the first 150 hours of operation and then increased dramatically for the following 75 hours, at which time lignite from the storage pile was fired. Freshly mined lignite was unavailable because heavy rains flooded the mining pits. The poor quality of the lignite also affected host boiler operation, as Unit 1 was forced to decrease load below 300 MW. TPJ performance recovered after mining operations and lignite supply returned to normal.

Between 300 and 1200 hours the pulse rate was relatively low at 20 pulses per hour; however the decreasing trend between 500 and 1200 hours is atypical. At some point between 500 and 1200 hours the fan belts began to stretch, causing the flow to decrease. The pressure drop data show that the fan performance may have degraded over time, as the pressure drop decreased throughout this period. At 1250 hours the flow rate was measured to be equivalent to an A/C ratio of 3.3 acfm/ft^2. The fan belts were tightened and the flow rate was increased to an A/C of 4.0 acfm/ft^2. From 1250 hours to the end of the test, the pulse rate fluctuated between 35 and 48 pulses per hour, which translates to the entire TPJ being cleaned 5.83 and 8 times per hour. Although pulse rate fluctuated, tubesheet pressure drop remained steady at 4.2 inches H_2O by the pressure drop initiate/terminate cleaning methodology.

Collection Efficiency. Five inlet and three outlet particle mass concentration tests were performed in April, 1991. Test procedures followed EPA Method 17 test protocol. Results from these mass concentration tests are presented in Table 4. Inlet and outlet tests run simultaneously are grouped together. The average inlet concentration was 4.68 gr/dscf.

The average outlet concentration was measured to be 0.0087 gr/dscf, or an average emission rate of 0.017 lb/MMBtu. The collection efficiency across the pulse-jet baghouse was measured at only 99.81%, which is very poor. Inspection of the fabric at the end of the test showed insignificant particle penetration into the fabric and therefore this high penetration rate is predominantly attributed to severe leaks around the bag flange and the tubesheet.

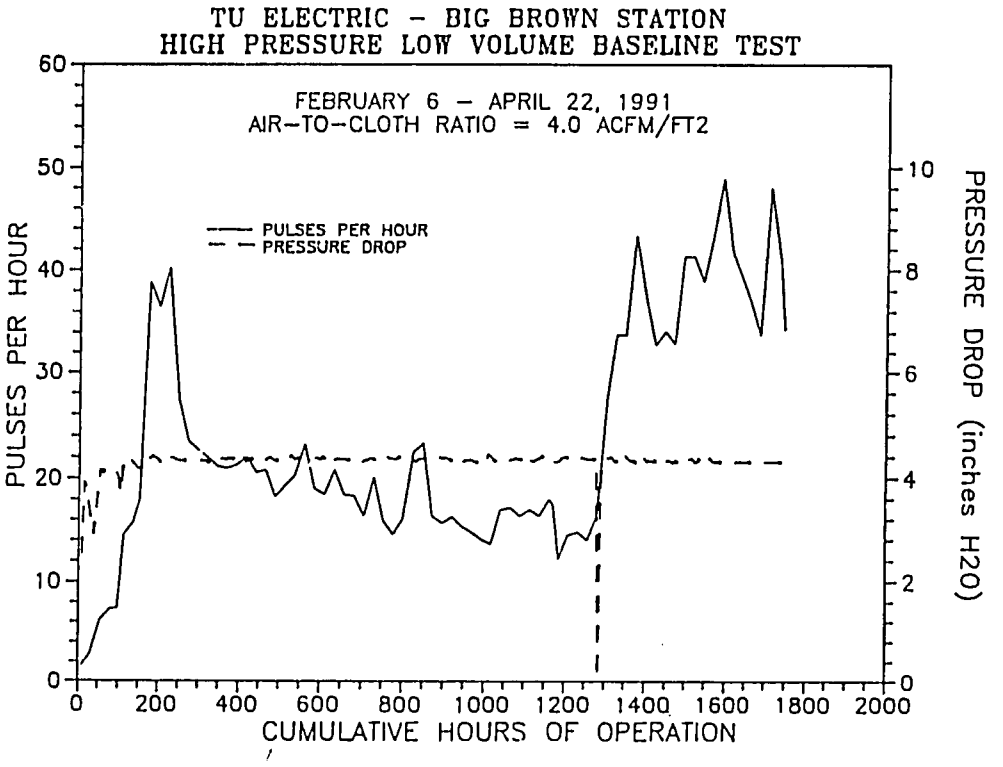

Figure 4. HPLV pulse rate and tubesheet pressure drop.

Coal, Ash and Fabric Analysis. When the bags were removed at the end of this test, the bags had a crusty, tenacious dustcake attached to the fabric at the top and bottom of the bag. The dustcakes appeared to form on the bag in places near cool spots in the compartment: outside walls, the hopper, and the tubesheet. As documented in the LPHV test, operation at or below acid dewpoint appears to contribute to the formation of heavy residual dustcakes. The average bag weight from the bags was 14 lbs, which is an areal loading of 0.33 lb/ft^2. This is much lighter than the areal loading measured in the LPHV baseline tests (0.8 lb/ft^2). An areal loading of 0.3 lb/ft^2 is a typical value for pulse-jet bags; however these bags only experienced 1800 hours of operation (less than three months) so the effects of long term operation can not be inferred from these results.

TABLE 4. Particle Mass Concentration Tests

DATE	TEST	% H_2O	gr/dscf	lb/MMBtu	% Eff.	Load(MW)
4/3/91	INLET	12.9	4.46			544
4/3/91	OUTLET	14.1	0.0083	0.0160	99.81	545
4/3/91	INLET	14.5	4.69			565
4/3/91	INLET	12.7	5.19			540
4/3/91	OUTLET	14.3	0.0101	0.0193	99.80	552
4/4/91	INLET	13.7	4.40			547
4/4/91	INLET	14.5	4.66			558
4/4/91	OUTLET	13.9	0.0077	0.0148	99.83	543

CONCLUSIONS AND RECOMMENDATIONS

A 2800 hour demonstration of a LPHV pulse-jet fabric filter and an 1800 hour demonstration of a HPLV pulse-jet fabric filter were completed at the TU Electric Big Brown Station. Overall, the pulse-jet performance results from both the LPHV and HPLV cleaning systems were very encouraging. A summary of the results follows.

SUMMARY

Both cleaning systems were able to maintain an average tubesheet pressure drop below 5.0 inches H_2O by the pressure initiate/terminate cleaning methodology. At 1800 hours of operation the two cleaning systems performed similarly in terms of pulse rate: each system required less than 40 pulses per hour to maintain a tubesheet pressure drop below 5.0 inches H_2O. After 2800 hours of operation the pulse rate for the LPHV system increased to 100 pulses per hour. This increase was coincident to a prolonged period of operation below or close to the calculated acid dewpoint. At all times, however, the pulse rates for both systems were within the range of pulse rates typically experienced at pulse-jets filtering flue gas from coal fired boilers. TPJ data for the LPHV configuration at 1800 and 2800 hours, and the HPLV configuration at 1800 hours are presented in Table 5.

Table 5. LPHV and HPLV Operating Data Comparison.

Configuration	Service Hours (hours)	Pulse Rate (pph)	dP (in. H_2O)	Emission Rate (lb/MMBtu)	Efficiency (%)
LPHV	1800	35	4.5	0.006	99.95
LPHV	2800	100	4.5	0.008	99.95
HPLV	1800	40	4.3	0.017	99.81

Outlet emission rates were measured below NSPS limits for both systems, although leaks around the bag flange and the tubesheet in the HPLV test made these results marginal at best. The Ryton/Ryton fabric removed at the end of the HPLV test showed no signs of particle penetration. Based on this observation and the use of Ryton felt in both tests, it is predicted that the HPLV system would operate at efficiencies similar to the LPHV system. Neither system produced the high collection efficiencies, greater than 99.99%, achieved at similar pilot scale tests on U.S. coal fired boilers. However, compared to results from woven fiberglass operation at the Monticello Station and tests on glass felt at the University of North Dakota, the results obtained in this test program show a significant improvement in particle collection efficiency (4,5). This relatively high rate of particle collection is attributed to the filtering mechanism of a pulse-jet (the fabric, not the dustcake, acts as the primary filtering medium) and the use of a heavy Ryton felt with the plain, fuzzy surface of the fabric exposed to the particle laden flue gas. Flue gas conditioning at the Monticello Station has greatly improved baghouse collection efficiency; it is possible that the addition of flue gas conditioning agents upstream of the pulse-jet fabric filter may result in collection efficiencies greater than 99.99%. In this test SO_3 was added to the flue gas. Based on data obtained at the Monticello Station, the addition of SO_3 alone does not improve fabric filter performance and therefore should not have affected the results in this test.

Heavy residual dustcakes were formed on the bags during the LPHV test. This tenacious dustcake was discovered after a prolonged period of operation at or below acid dew point. The plain-side-out fabric used in this test may also have contributed to the formation of the

heavy dustcake by providing the filaments on which the dustcake could form. It is possible that a smooth filtering surface may have prevented the formation of this dustcake, although this fabric may have a detrimental effect on the collection efficiency. A similar phenomenon was also observed in the HPLV test; once again a heavier than expected dustcake formed in areas which were suspected of low temperature excursions. Therefore, it is important that the pulse-jet fabric filter is designed to operate well above the calculated acid dewpoint.

The results from this test program show:

1. The LPHV and HPLV cleaning system performed similarly;
2. Both systems performed in an acceptable range of pulse rates;
3. Tubesheet pressure drop was maintained below 5.0 inches H_2O;
4. Collection efficiency for 18 oz/yd^2 Ryton felt was 99.95%; and
5. It is important to maintain operating temperatures above acid dewpoint.

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APPENDIX G-3

THE EPRI PILOT PULSE-JET BAGHOUSE FACILITY AT PLANT SCHOLZ

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THE EPRI PILOT PULSE-JET BAGHOUSE FACILITY AT PLANT SCHOLZ

ABSTRACT

The Electric Power Research Institute is currently directing their fabric filtration research efforts toward pulse-jet baghouses. Pulse-jet baghouses have the potential to be 40-50 percent smaller and 30-40 percent less expensive than conventional reverse gas baghouses for new and retrofit applications. Southern Company Services Inc. developed the project concept of converting three compartments of the pilot baghouse at Plant Scholz to pulse-jet operation. The pulse-jet baghouse systems under investigation were procured from General Electric Environmental Services, Flakt Inc., and Howden Environmental Systems Inc., and represent three different cleaning concepts associated with pulse-jet technology. Compartments with high, medium, and low pressure pulsing will be operated side-by-side along with a reverse gas sonic assist compartment. A comprehensive test program conducted with Southern Research Institute is underway to investigate parameters such as pulsing energies, bag length, fabrics, and cleaning modes.

THE EPRI PILOT PULSE-JET BAGHOUSE FACILITY AT PLANT SCHOLZ

INTRODUCTION

Maintaining low emissions concurrent with low flow resistance and low capital and maintenance costs dictates baghouse economics. Reverse-gas-cleaned (RG) baghouses which have low air-to-cloth ratios (low ratio) have been good systems for achieving low particulate emissions. However, baghouses which impart more cleaning energy to the bags operate at lower levels of flow resistance. Therefore, they can be built smaller and operated less expensively, offering economic advantages over RG cleaned units. The effects that high energy cleaning techniques have on baglife, equipment maintenance, and energy consumption remain unknown.

Pulse-jet (PJ) cleaned fabric filters with high air-to-cloth ratios (high ratio) have recently become an attractive particulate-control option for U. S. utilities. PJ fabric filters also incorporate high energy cleaning techniques. Interest in pulse-jet cleaning followed improvements in fabrics and systems with enhanced reliability. These advances offer the possibility of significantly reducing the costs of particulate-controls while maintaining low emissions and operating costs. Pulse-jet cleaning results in lower resistance to gas flow than reverse-gas, reverse-gas-sonic-assist (RG/S), or shake/deflate (S/D) cleaning, thereby allowing smaller baghouses to filter the same volume of flue gas. Although PJ cleaned baghouses are used extensively with industrial boilers and a number of utility power plants in Europe and Australia, they are not presently used by the U.S. electric utility industry due to emissions and bag life concerns (1).

In 1982 Electric Power Research Institute (EPRI) sponsored the construction and operation of a fabric screening and high sulfur bag house pilot facility (HSFP) utilizing a 10-MWe gas slipstream at the Gulf Power Company Plant Scholz site. Plant Scholz Steam Plant consists of two 1953 vintage 40-MW, Babcock and Wilcox, front-fired pulverized-coal boilers with General Electric turbine generators. The boilers are rated at 475 x 10^6 Btu/h maximum heat input with 850 psig steam at 900°F. The 10-MWe slipstream originates downstream of the air heater and returns to Plant Scholz Unit 2 immediately upstream of the electrostatic precipitator.

The high-sulfur coal fabric filter research program at Plant Scholz was initiated to quantify fabric filter design parameters for a low-ratio baghouse, and to develop operating guidelines that would address the problems encountered in the application of the technology. This research, completed in December 1988 included conventional reverse gas, shake/deflate and sonic assist reverse gas cleaning method optimizations, and evaluations of exposed surface texturization, flue gas conditioning, and experimental fabrics. EPRI report CS-6061 describes this work.

Southern Company Services Inc. (SCS), developed a project concept of converting three of the five compartments of the Plant Scholz pilot facility to pulse-jet operation to address U.S. electric utility industry concerns with emissions and bag life. During the latter half of 1989, R. N. Pyle Construction Co. of Pensacola, FL, made the required plant modifications engineered by Baskerville-Donovan, also of Pensacola, FL. These modifications where conducted under the supervision of SCS & Southern Research Institute (SRI).

PROJECT SCOPE

The research conducted at the EPRI HSFP is designed to address utility concerns with high ratio fabric filter. Comparisons of PJ with RG/S cleaning will be made to evaluate the relative merits of low-ratio and high-ratio fabric filters.

Since several different PJ cleaning designs are commercially available, the three most widely marketed technologies where chosen to be compared (2). These three technologies are: low-pressure/high-volume, intermediate-pressure/intermediate-volume, high-pressure/high-volume. The comparison of these technologies will produce design and operating information for full-scale utility application of PJ cleaning. The initial comparison tests will be conducted while the boiler is fired with an eastern, sub-bituminous coal, containing 3% sulfur over a period of one year. The second phase of testing, if approved, will be based on low sulfur fuel.

This research seeks to determine if PJ cleaning meets utility needs in terms of initial capital expenditures and operating and maintenance costs. A further goal is to establish the particulate collection performance of the PJ cleaned fabric filters and to demonstrate whether particulate emissions rates either meet or surpass current and anticipated performance standards.

LOW RATIO VS. HIGH RATIO FABRIC FILTERS

Most utility baghouses currently being operated are low ratio fabric filters which employ some method of reverse gas cleaning. With RG cleaning, residual dustcakes tend to build over a period of several months. The dustcakes can become undesirably thick (up to 1 in.) and heavy (up to 1.5 lb/ft^2 or 150 lb/bag) in extreme cases. RG/S bag cleaning, utilized in Compartment #1 of the Plant Scholz pilot facility, utilizes a sonic horn to add energy to the cleaning process as illustrated in Figure 1. Due to the low-energy cleaning methods used with low ratio or inside-collectors, bags must always be isolated from the flue gas flow to achieve effective cleaning (off-line cleaning).

In PJ systems or high ratio fabric filters, a valving and manifold arrangement directs a compressed air pulse down one or more rows of bags within a compartment to remove the dustcake. PJ cleaned baghouses collect ash on the outside of the bags and incorporate metal cages on the inside to prevent bag collapse. This is why high ratio baghouses are typically called outside collectors. The air pulse propagates rapidly as a pressure wave down the length of the bag, causing the bag to accelerate away from the cage and then to immediately collapse back onto the cage. This rapid flexing of the fabric dislodges the dust, which falls into the ash collection hopper below. Figure 2 illustrates PJ cleaning during filtering, purging prior to shutdown or maintenance, and cleaning. The three major PJ technologies illustrated in Figure 3 are: low-pressure/high-volume, intermediate-pressure/intermediate-volume, high-pressure/high-volume.

Most baghouse types are compartmentalized, but only PJ systems are typically designed to clean the bags on-line without isolating compartments from the flue gas flow. This is accomplished by sequentially pulsing selected bags while the remainder continue to filter flue gas. On-line cleaning greatly simplifies overall fabric filter operation. However, since some of the dislodged dust is immediately reentrained back onto the bags, it may be necessary, in some designs, to use off-line cleaning for certain fuels to maintain pressure drop and outlet emissions within acceptable bounds.

In either low ratio or high ratio fabric filters, compartmentalized design permits maintenance to be performed without requiring an outage of the entire fabric filter. Compartmentalization is achieved with inlet and outlet dampers for isolation purposes. Current experience on operating units indicates that on-line cleaning is feasible and highly successful.

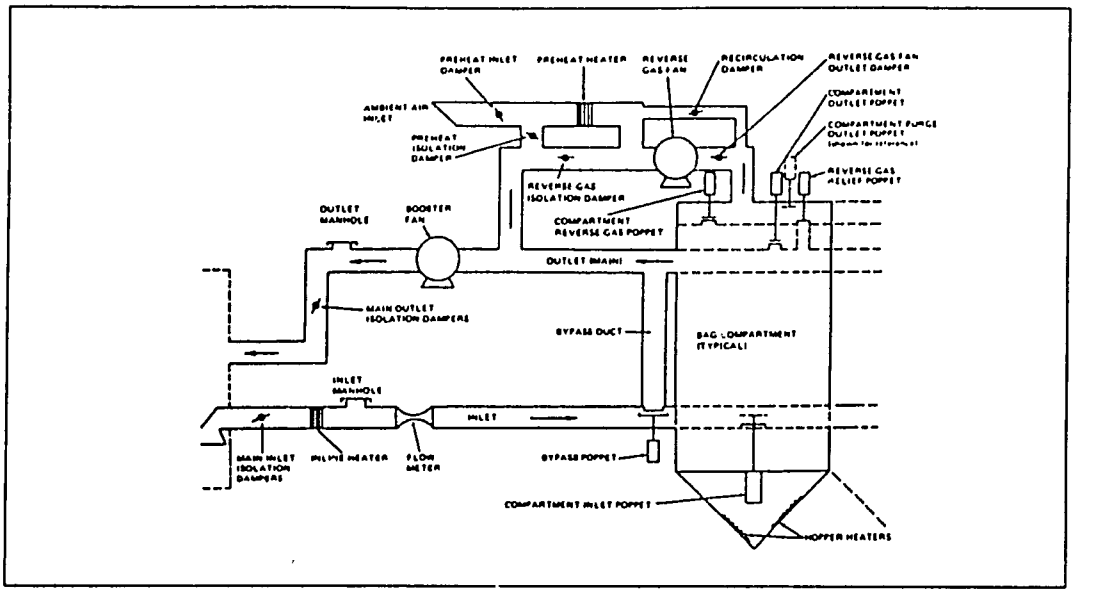

Figure 1. Schematic of a reverse-gas baghouse at Plant Scholz.

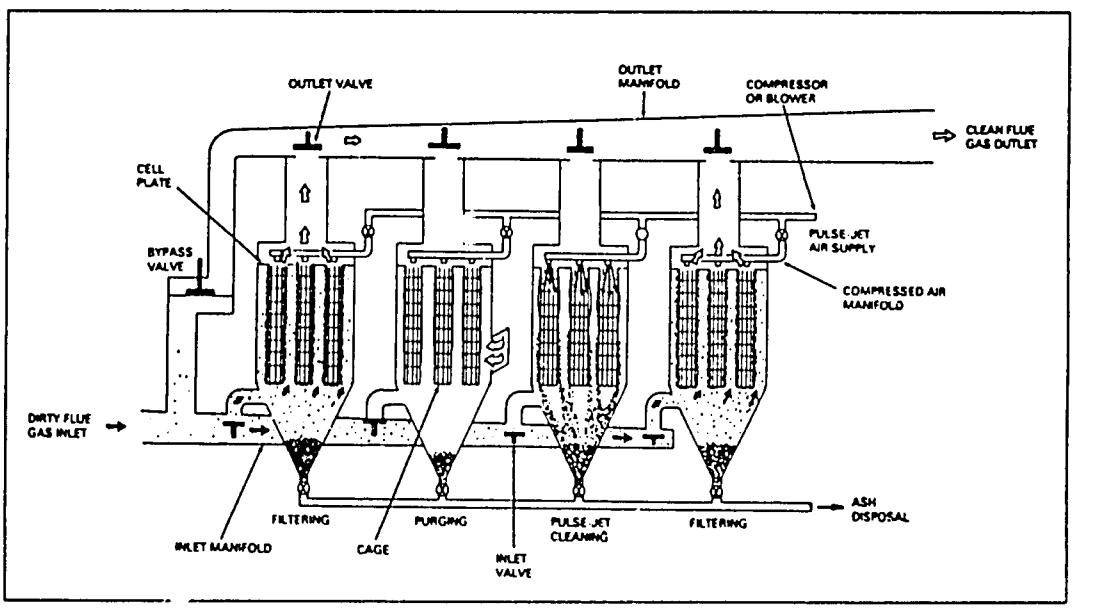

Figure 2. Schematic of compartments in a pulse-jet-cleaned baghouse filtering flue gas, purging (or ventilating) prior to maintenance, cleaning bags, and filtering flue gas again (2).

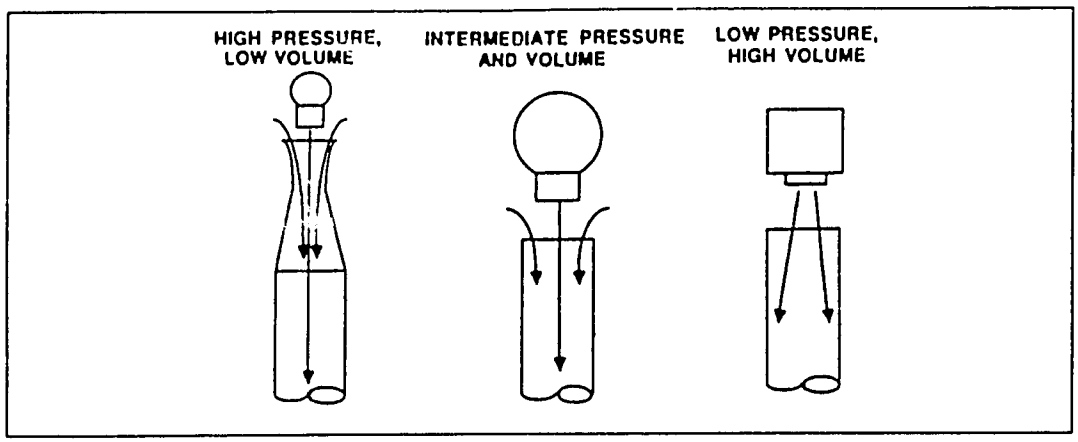

Figure 3. Comparison of typical operating characteristics for high-pressure, intermediated-pressure, and low-pressure pulse-jet cleaning (3).

DESCRIPTION OF THE PILOT PLANT

Four of the five original HSFP baghouse compartments are in use for the evaluation of PJ cleaning. Compartment #1 uses RG/S cleaning at a filtering air-to-cloth ratio (A/C) of 2.5 acfm/ft^2. Compartment #2 has been converted to low pressure, high volume, PJ cleaning (LPHV) using equipment suppled by Howden Environmental Systems, Inc. Compartment #3 has been converted to intermediate pressure, intermediate volume, PJ cleaning (IPIV) using a system supplied by Flakt, Inc. Finally, Compartment #4 has been converted to high pressure, low volume, PJ cleaning (HPLV) using equipment supplied by General Electric Environmental Services, Inc. All three of the PJ compartments will be operated at an A/C of 4.0 acfm/ft^2. Details of each technology are presented in Table 1.

Reverse Gas/Sonic - Compartment #1.

With reverse gas cleaning, an auxiliary fan forces a relatively gentle flow of filtered flue gas (1-2 ft/min at the fabric surface) backwards through the compartment and the bags to be cleaned. This causes the bags to partially collapse inward and dislodge the dustcake. This dust falls through the bags, the thimble, and the tubesheet into the hopper. Also, metal rings sewn into the bags about 4-5 ft. apart along their length prevent complete collapse (2).

Reverse-gas/sonic (RG/S) bag cleaning incorporates low-frequency pneumatic horns, sounded simultaneously with the normal reverse-gas flow to add energy to the cleaning process. Sonic enhancement has been shown to reduce gas flow resistance and dustcake weights by as much as 50% below those achieved by RG cleaning alone, without increasing emissions or decreasing bag life. High sound pressures (80-160 Pa) in the low frequency range (below 250-300 Hz) have proven most effective for dustcake removal.

Table 1

SUMMARY OF DESIGN AND OPERATION SPECIFICATIONS (6)

	RG/S	LPHV	IPIV	HPLV
Location	Comp.#1	Comp.#2	Comp.#3	Comp.#4
Manufacturer	G. E.	Howden	Flakt	G. E.
Number of bags	28	72	70	56
Bag diameter (nominal), in.	12	4.9	5	6.0
Bag length (nominal), ft	35	20	20	20
Measured filter area, ft^2	2,915	1,861	1,901	1,807
Tubesheet design	Rectangular	Circular	Rectangular	Rectangular
	7 rows	4 circles	7 rows	8 rows
	6 bags/row*	24, 20, 16, 12	10 bags/row	7 bags/row
Cleaning air header volume, ft^3	N/A	22	13.6	8.4
Cleaning air header pressure, psi	N/A	11	28**	~40 75
Available air volume ft3/bag/pulse	N/A	2.1	1.4	0.3
Filtering air-to-cloth ratio, $acfm/ft^2$	2.5	4	4	4

*Two rows are capped off.
**Header pressure is ≈23 psi on Comp.#2 after first pulse in each clean cycle

Low Pressure High Volume - Compartment #2.

LPHV pulsing utilizes a novel, circular arrangement of oval-shaped bags, with nozzles attached to a rotating cleaning manifold located above the bags as illustrated in Figure 4. This design, developed by Howden, Inc., utilizes a high volume pulse of only 10 psig. The high volume low pressure pulse permits the use of blowers rather than compressors to supply the pulse cleaning air. This allows bag lengths up to 20 ft., reduced cleaning energy, fewer pulse distribution valves, on-line cleaning, and simplified configurations and components.

The tubesheet in the LPHV compartment contains 72 holes for bag installation. The holes are 2-3/4 in. by 3-5/8 in. rectangles with semi-circles of 1-3/8 in. radius at each end. These tubesheet holes have the same area as a circle with a diameter of 5.05 in. The tubesheet holes are arranged in four concentric circles to allow cleaning by a single rotating blowpipe. The bags are cleaned by compressed air pulses at 10 to 15 psi. The blowpipe contains four nozzles that are aligned over the circumferential rows. The diameters of the four circumferential rows measure 61.5 in., 52.5 in., 43.5 in., and 34.5 in., respectively.

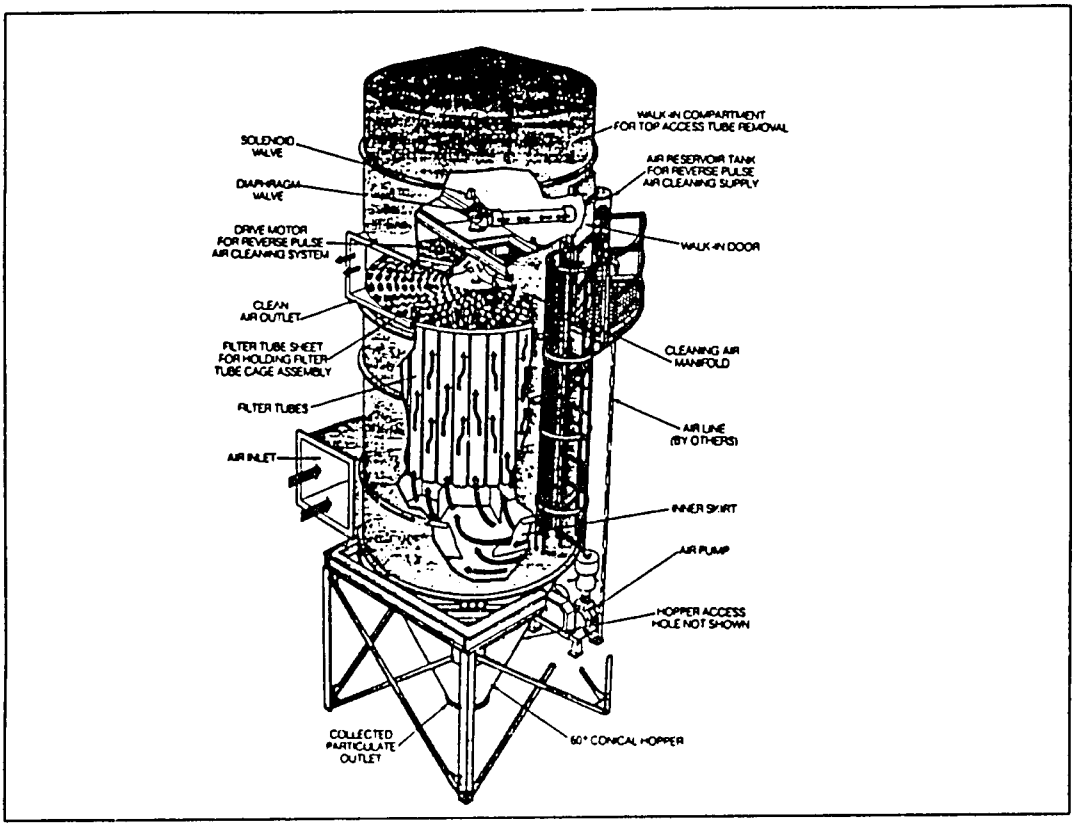

Figure 4. Schematic of one compartment of a low-pressure/high-volume, pulse-jet fabric filter supplied by Howden Environmental Systems. Oval bags are arranged in concentric circles, with up to 484 bags per compartment. The bags are cleaned by pulses from the manifold arm which rotates at one revolution per minute. Cleaning air, supplied to the manifold by blowers, is introduced to the manifold through a central dump valve. The cleaning air is injected into the bags via nozzles in the pulse air manifold.

A production LPHV fabric filter system incorporates blowers to fill the low pressure air storage tank. However, the Plant Scholz pilot facility incorporates high pressure air, reduced to 12 psi by a regulator, to simulate the blower.

Intermediate Pressure Intermediate Volume - Compartment #3.

Flakt, Inc. developed the IPIV design, installed at the pilot facility, for large, custom, high temperature, metallurgical fume and fly ash applications. A look at the gas path and distribution will indicate that, in effect, there is an integral pre-collector within the unit. The gas entering the inlet plenum turns vertically up and is evenly distributed across the side of the compartment at very low velocities and then continues in the horizontal and/or downward direction depositing particulate on the bags. This side entry method

minimizes reentrainment, fabric abrasion, and pressure drop that is otherwise prevalent with designs allowing introduction of dust laden gas into hoppers below the bags (4).

The IPIV design typically uses between 15 and 30 psi compressed air. A unique pulsing valve eliminates the necessity of the tubesheet venturi required in high pressure PJ systems. The primary air expands directly into the filter bag minimizing the induced air to one or two times the primary air effecting a short, quick but deep pulse. Figure 5-a illustrates the pulse valve mounted integral to the pressure tank. The valve consists of two parts, the solenoid pilot valve and the main pulse valve. In this figure, the pulse valve is in the open position with compressed air passing through the distribution pipe and into the bags for cleaning. A main feature of this design is the large diameter of the pulse valve (2" diameter) which minimizes pressure drop to the distributing pipe.

Figure 5-b shows the complete IPIV fabric filter cleaning system, general location of the pressure tank and pulse valve from which compressed air is directed through the lateral pipe through nozzles into the bags.

The tubesheet in the IPIV compartment is made up of a 7 by 10 array of 5.31 in. (135 mm) diameter circular holes. The IPIV bags are cleaned by pulses of compressed air at 20 to 30 psi that are directed down into ten bags at a time from one of the seven blow pipes in the compartment..

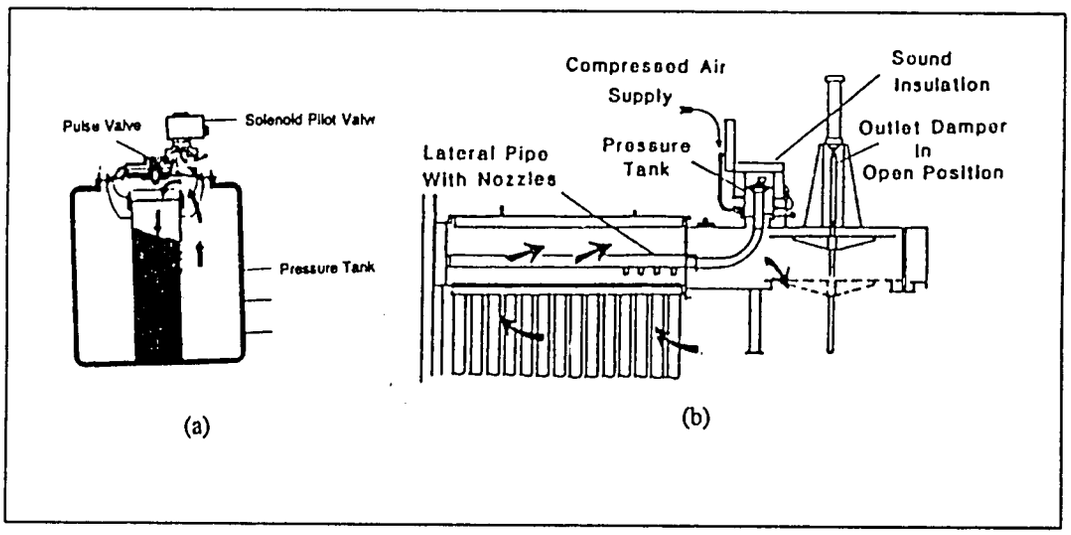

Figure 5. IPIV design pulse valve mounted integral to the pressure tank (a). IPIV fabric filter cleaning system, general location of the pressure tank (b) (4).

High Pressure Low Volume - Compartment #4.

During the normal filtering mode of the HPLV fabric filter system, the particulate laden flue gas enters the compartment (1,200 fpm), energy efficient inlet opening located in the straight side of the casing approximately sixteen inches below the filter bag bottoms. Strategically positioned inlet duct turning vanes produce uniform flow distribution as the gas enters the module. The flue gas passes through the bags and exits the filtering area at the top of each bag at the tubesheet level. The cleaned gas enters an open plenum

above the tubesheet and exits the module through the outlet poppet damper. The discharge from each module enters the outlet manifold which terminates at a single outlet ductwork connection (5).

The HPLV fabric filter system is intended for off-line cleaning. During the cleaning mode, one module at a time is disengaged from normal filtering service by closing the outlet poppet damper, thus isolating the module from ID fan suction. The compressed air pulsing system is then activated to sequentially clean each row of bags in the isolated module. This pulsing system consists of a compressed air inlet accumulator manifold and cylindrical distribution headers over each row of bags. Each distribution header directs a pulse of compressed air (70-90 psig) through the venturi located in the opening at the top of the bag. The venturi extends 4" into the bag, and the top is flush with the bag cage to permit access. The venturi is believed to enhance the uniformity of the pulse pressure wave as it travels the length of the bag, thereby improving cleaning and reducing the deceleration of the bag against the cage.

After all bags in a module have been cleaned, the module remains off-line for an adjustable period of time to allow settling of the particulate into the hopper. The outlet poppet damper is then opened, and the cleaned module returns to the normal filtering mode. The next module is sequentially selected and the process repeated.

The HPLV tubesheet consists of 56 6-in. holes arranged in eight rows of seven holes each. HPLV cleaning uses compressed air at 40 to 90 psi. Table 1 summarizes the design specifications of the fabric filter cleaning systems that are being tested at the HSFP (6).

OPERATION

Three SRI employees conduct the studies at the Plant Scholz pilot facility. These studies include monitoring and updating the data acquisition systems, manual testing, and overall onsite management of the project. Three R. N. Pyle employees maintain the equipment and controls, and operate the facility 160 hrs/wk. The facility is equipped with its own control room where the automatic data acquisition system is housed.

The unit is equipped with a General Electric Series Six Programmable Controller (PC). This PC is programmed to automatically control cleaning, flow, alarms, and trips. This gives the facility operators the ability select cleaning modes (time, Δp, manual/automatic, on/off-line), air-to-cloth ratios, and pulsing characteristics for each compartment. Each compartment, excluding Compartment #1-RG/S, is set to initialize a clean when the tubesheet pressure drop reaches 5.0"wtr. Compartment #1-RB/S is set to be cleaned every 90 minutes regardless of tubesheet pressure drop. Table 2 shows other operational characteristics of each compartment cleaning cycle.

All instrumentation has been calibrated prior to the initial filtering of hot flue gas on December 6, 1989. At vendor request, the bags have been precoated with a substance marketed as Neutralite, sufficient to coat each square foot of filter with ≈0.07 lb. by while under a air load. It is estimated that from 25% to 50% of the pre-coat material actually adhered to the bags. The precoat is expected to improve filtering and provide some bag protection. Two gallons of fluorescent powder have also been injected into the system with the Neutralite. This powder, marketed as Visolite,is normally used for leak detection, but in this instance was also used as a tracer to determine the fate of the precoat.

Table 2

SUMMARY OF NORMAL OPERATING MODES

Compartment	Clean mode	Clean Init.	Automatic Cleaning Logic
#1 - RG/S	Off-line	90 min. time initialized.	Reduce baghouse flow by ≈7,000 acfm, close compartment poppet damper, RG & sonic horn initiated for 1 minute, shut-off RG & sonic horn, open compartment isolation poppet damper, ramp baghouse flow back to set point.
#2 - LPHV	On-line	5.0"wtr.	Initiate pulse cleaning and maintain until tubesheet Δp drops below 3"wtr.
#3 - IPIV	On-line	5.0"wtr.	Initiate pulse cleaning and maintain until tubesheet Δp drops below 3"wtr.
#4 - HPLV	Off-line	5.0"wtr.	Reduce baghouse flow by ≈7,000 acfm, close compartment poppet damper, initiate pulse cleaning, after all solenoids fire, open compartment isolation poppet damper, ramp baghouse flow back to set point.

The facility is being operated continuously during the first phase of testing. Facility outages will obviously follow Plant Scholz Unit # 2 scheduled and forced outages. The 10 MWe slip stream remains constant regardless of plant unit load. However, unit load swings affect inlet temperature and other temperature related operating characteristics.

DATA ACQUISTION & REPORTING

Both SCS & SRI issue monthly status reports to EPRI and the participating vendors. These reports include performance, operating, and maintenance updates and any insights into the outcome of the research. Pulse-jet operating problems are discussed with their respective vendors as soon as possible in an attempt to optimize the corresponding PJ technologies.

Table 3 shows the methods the operating variable data are being collected at the facility. The data is collected and recorded automatically every one to five minutes. The data is then archived once per day. The archived data will be used in the overall performance evaluation of each PJ system compared to RG/S.

Table 3

METHODS OF MONITORING OPERATING VARIABLES

Parameter	Method
Flow rate	Total flow venturi & inlet damper microprocessor controlled system booster fan; Compartments #2-#4 each have flow venturis & outlet butterfly damper microprocessor flow controls.
Temperature	Thermocouples.
System pressure	Electronic transducers.
System pressure drop	Electronic transducers.
Tube sheet pressure drop	Electronic transducers.
Pulse-Jet Header Pressure	Electronic transducers.
Cleaning Activity	Digital signals linked to data acquisition software to quantitatively determine cleaning activity.
Inlet particle concentration	Mass train; Optical Monitor (ESC Model P-5A).
Inlet particle size distribution	Cyclone; cascade impactors.
Outlet particle concentration	Mass train; Optical Monitor (Tribaflo).
Outlet particle size distribution	Cascade impactors.
Opacity	Specially developed system.
Flyash unburned carbon	Loss of weight after 4 hr. temperature burn.
Sulfur dioxide, SO_2	Continuous commercial monitor.
Nitrogen oxides, NO_X	Continuous commercial monitor.
Sulfur trioxide, SO_3	Controlled condensation train; Continuous Monitor (Severn Sciences, Ltd.).
Dew point	Wet bulb thermometer; Land Acid Dew Point Meter.
Data acquisition	IBM PC-AT computer

As a backup, the following data are logged manually each hour:

- Ambient Temperature (°)F
- Barometric Pressure ("Hg. abs.)
- Air Heater Outlet Temperature (°F)
- Baghouse Inlet Temperature (°F)
- Baghouse Outlet Temperature (°F)
- Compartment Operating Mode
- Baghouse Pressure Drop
- Baghouse Outlet Static Pressure ("wtr.g.)
- Compartment Tubesheet Pressure Drop ("wtr.)
- Baghouse Flowrate (acfm)
- Compartment Flowrate (acfm)
- Reverse Gas Flowrate (acfm)
- Reverse Gas Temperature (°F)
- Reverse Gas Static Pressure ("wtr.)

After compiling all the operating and performance data, SRI will conduct an economic analysis of the evaluated fabric filter technologies. This economic analysis will include:

- Capital Cost
- Operating Cost; air hp / clean (compressor hp + reverse gas hp) x number of cleans
- Maintenance Cost; life cycle cost of bag replacement + replacement of other parts due to corrosion or mechanical failures.

This report is expected to be completed after the second phase of testing. The research completion date is dependent upon bag life determination.

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3. R. C. Carr, A. T. Vandewall, W. B. Smith. "Pulse-Jet Fabric Filters For The U.S. Utility Industry."

4. A. Wiktorsson, Flakt, Inc. "Current Status: Future Potential For HRFF Technology Applied to Utility Coal Fired Boilers." July, 1981.

5. February 8, 1990, Correspondence with T. Lugar of General Electric Environmental Services, Inc.

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APPENDIX G-4

A SURVEY OF THE PERFORMANCE OF PULSE-JET BAGHOUSES FOR APPLICATION TO COAL-FIRED BOILERS, WORLDWIDE

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A SURVEY OF THE PERFORMANCE OF PULSE-JET BAGHOUSES FOR APPLICATION TO COAL-FIRED BOILERS, WORLDWIDE

ABSTRACT

Pulse-jet fabric filters (PJFFs) are widely used in U.S. industrial boiler applications and in utility and industrial boilers abroad. Their smaller size and reduced cost relative to more conventional baghouses make PJFFs appear to be a particularly attractive particulate control option for utility and industrial boilers: for both new plants as well as retrofits and for the range of boiler type from stoker- to pulverized-fired boilers and fluidized bed combustors.

This paper summarizes and presents preliminary results of a survey funded by the Electric Power Research Institute and the Canadian Electric Association to characterize the performance of and operating experiences with PJFFs applied to coal-fired boilers. The survey involved site visits to interview technical and plant personnel involved in the design, installation and day-to-day operation of PJFFs. In this way, actual field experiences worldwide with PJFF performance in terms of outlet emissions and pressure drop, different types of pulse-jet cleaning methods and fabrics, startup/shutdown and O&M procedures, and the myriad design details were compared.

A SURVEY OF THE PERFORMANCE OF PULSE-JET BAGHOUSES FOR APPLICATION TO COAL-FIRED BOILERS, WORLDWIDE

INTRODUCTION

Pulse-jet fabric filters (PJFFs) are widely used in U.S. industrial boiler applications and in utility and industrial boilers abroad. Due to their smaller size and reduced cost relative to more conventional fabric filters, pulse-jet baghouses appear to be a new generation of alternative particulate control options for U.S. utility and industrial boilers; for both new plants as well as retrofits and for the range of boiler types from small stoker-fired to pulverized coal-fired boilers, fluidized bed combustors and other advanced power generation systems. Pulse-jet baghouses have been applied downstream of spray dryer absorbers and dry sorbent injection as well. Also, despite the use of gas-to-cloth ratios which are typically larger for PJFFs relative to more conventional reverse-gas fabric filters, PJFFs have demonstrated similar operating pressure drops.

The first pulse-jet fabric filter was installed over thirty years ago, in the mid-1950s. The first PJFFs served primarily as process equipment to collect valuable product from pulverizing mills (1). It wasn't until the early to mid-1970's, twenty years later, that pulse-jet technology was applied to the collection of flyash from coal-fired boilers. Since that time, the use of and design details incorporated in PJFFs used to collect flyash have evolved in distinctly different directions throughout the world. In the United States, PJFFs have been perceived primarily as a "low-cost" alternative for smaller industrial boilers as opposed to the reverse-gas fabric filters more conventionally applied to utility boilers. Whereas, in Canada, Europe, Australia and Japan, PJFFs have seen a wider application to both small industrial boilers as well as larger-sized utility boilers.

The primary evolutionary differences involve the type of pulse-cleaning method used and the types of fabrics used. Also, other design details vary from continent to continent. What differences could such trends make with respect to the applicability and maintainability of PJFFs for boiler applications? Particularly of interest is whether these design details

significantly affect baghouse performance in terms of pressure drop, outlet emissions, and bag life.

Thus, the Electric Power Research Institute (EPRI) and the Canadian Electric Association (CEA) have funded this survey to obtain information on the performance and operating and maintenance histories of PJFF installations worldwide. Actual PJFF installations were identified and contacted in the U.S., Canada, Australia, Japan and Europe to allow direct site visits and interviews with operating plant personnel. Thereby, the performance of PJFFs in terms of outlet emissions, pressure drop and bag life and any significant issues and problem areas could be identified and/or verified by up-to-date information.

Visited were sites which represent the gamut of boiler type in use today at utility and larger industrial boiler installations, primarily: pulverized coal, stoker and fluidized bed combustors. Also, sites were selected to represent the range of cleaning methods and the types of fabrics from woven fiberglass to the various felts in use today. Additionally, PJFFs downstream of spray dryer absorbers for SO_2 control, catalytic deNox systems and in use with dry sorbent injection were visited to verify the viability of pulse-jet technology in combination with such technologies.

There are well over 300 installations of pulse-jet baghouses applied to coal-fired boilers worldwide (2). This survey involved direct site visits and/or interviews with personnel directly involved with PJFF installations at over thirty utility and industrial plants. The information and data gathered represents PJFFs installed on over 70 separate units.

This paper presents preliminary findings of this Pulse-Jet Baghouse User's Survey. More detailed results will be available under the final report for this EPRI project, RP1129-21.

MAJOR ISSUES AND TRENDS

The major issues and trends facing the application of pulse-jet baghouses today can be distilled into the following general categories:

- cleaning method and suitability for long bags
- fabrics and suitability of woven fiberglass versus the various synthetic felts available today
- off-line versus on-line cleaning
- maintainability and suitability of pulse-jet baghouses for large boiler installations

- air-to-cloth ratio
- performance in terms of outlet emissions, pressure drop and bag life.

Most of these variables are interrelated and it is difficult to lump them into distinct categories without consideration of the other variables. Therefore, the discussion that follows is only loosely organized into the above categories and may jump around.

Cleaning Method and Long Bags

Pulse-jet cleaning methods have evolved into three basic types which can be generally characterized in terms of the pressure and volume of the pulse air used. These methods are high-pressure/low-volume (HP/LV), medium pressure and volume (MP/MV) and low-pressure/high-volume (LP/HV) pulsing. The details of these cleaning methods and the purported advantages of each are well documented in the literature. However, for general classification purposes, the ranges of pulse pressures used by each method are summarized in the following:

	Typical Pulse Pressure	
Cleaning Method	psig	bar
• HP/LV	50 to 100	3.4 to 6.9
• MP/MV	20 to 30	1.4 to 2.1
• LP/HV	7.5 to 10	0.5 to 0.7

The original PJFF design used the HP/LV cleaning method; and traditionally, most pulse-jet applications in the United States have been primarily of the HP/LV type. Whereas, in Canada, Australia and Europe, the predominant cleaning modes on larger boilers have been the MP/MV and LP/HV.

The LP/HV and MP/MV pulsing modes have been more recently developed and their designers claim some advantages over the original HP/LV mode. The LP/HV and MP/MV modes are said to consume less energy, yet are able to deliver more of that energy into the pulse. The alleged stronger pulse is said to penetrate further into the bags before dissipating; and thus, the perception that longer bags of up to 20 feet or more can be applied effectively on LP/HV and IP/IV collector. Whereas, some believe that bag lengths should be limited to 12 to 14 feet on HP/LV pulse-jets.

Is such a perceived disadvantage of the HP/LV indeed true? This is a critical question for larger PJFF installations since longer bags mean fewer bags to provide the same air-to-cloth ratio. Fewer bags mean fewer parts such as cages, pulse pipes, diaphragm and solenoid

valves and bags that require replacement. Additionally, and particularly important for retrofits, the prospect of smaller plan areas if "long" bags are viable is appealing.

So far in our analysis of the data gathered on the site visits, we are not able to say definitively that one cleaning method is superior to the others. This is due to the numerous variables which are interdependent. Attempts are still underway to normalize the variables to determine if it can be proven with this database as to whether or not one method is superior. We can say that we have visited three sites which use HP/LV pulse jets and bags with lengths of approximately 19 and 20 feet. The operators of these baghouses are pleased with them, have achieved reasonable bag lives and pressure drops and, in one case, have maintained exceptionally low outlet emission levels.

This suggests then that so far all three cleaning methods appear to be viable contenders. However, in any case, anyone contemplating the installation of a PJFF with long bags should ensure that the bidders and manufacturer finally selected have current field experience and/or at least extensive pilot investigations to prove the applicability of their cleaning method to long bags with the type of fabrics anticipated and treating dust of similar properties and difficulty. In other words, successful experience with long bags collecting flyash from, for example, a stoker-fired boiler may not be sufficient experience to justify that OEM's experience on the more-difficult ashes typical of PC-fired boilers or fluidized bed combustors.

Fabrics

In general, felted fabrics have been preferred for pulse-jet applications since typically the fabric is relied upon more for filtering than the filter cake, as in the case of more conventional, less-energetic cleaning methods such as reverse-gas and shake-and-deflate fabric filters. For early applications of PJFFs in the United States, today's felts which can withstand flue gas conditions were not available. This prompted an evolution in the U.S. toward woven fiberglass bags, primarily in HP/LV units. Off-line cleaning, in which compartments are isolated from the flue gas stream for cleaning, was developed in part to accommodate the more fragile woven fiberglass fabric; and perhaps this evolution was accompanied somewhat by a trend towards more conservative air-to-cloth ratios.

Fiberglass fabrics were appealing due to their ability to withstand gas temperatures of up to 500° which are approached by many industrial boilers in the U.S. and more forgiving of upset temperatures for larger boilers employing regenerative-type air heaters. Note that one of the original advantages of pulse-jet cleaning over the more conventional fabric filter designs is the ability to pulse and thus clean rows of bags in a compartment while the remainder of bags in that compartment are still "on-line," operating in the filtering mode.

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Since the early applications of PJFFs, Nomex™ and Teflon™ fabrics have become available. Also, more recently, felts made of homopolymer acrylic (Dralon-T™) and polyphenylene sulfide (PPS or Ryton™) have been used successfully in coal-fired boiler applications.

Experience in Canada, Australia and Europe has been primarily with these various felted fabrics. Homopolymer acrylic has proved to be a very good fabric for applications at less than 285°F; such as, downstream of spray dryers or of boilers firing low sulfur coal and which have no risk of high excursion temperatures. The Ryton™, Daytex™ and Nomex™ felts must be operated at temperatures of less than about 400°F. and felted Teflon™ can operate at somewhat higher temperatures, perhaps of up to 475°F.

Fiberglass Versus The Felts. Recently in the United States, and paralleling the success of felts in other countries, there has been a trend away from fiberglass towards felted fabrics for PJFF applications. Many installations that initially experienced difficulties with fiberglass, for numerous reasons, changed to felts. Also, it seems that many new installations of PJFFs on industrial boilers are more frequently being specified with felts as the preferred fabric. Is such a trend justified?

Qualitatively, the results of this study indicate that observing proper design and construction tolerances, woven fiberglass bags can work and provide reasonable bag lives and pressure drops while still maintaining very low outlet emissions comparable with those achieved by felts. However, it is generally conceded in the industry that fiberglass is less forgiving than the synthetic felts. Care must be taken in ensuring proper bag and cage fit and exceptional care must be exercised in installing the filter bags. Also, fiberglass bags are more susceptible to abrasion and related design and construction problems which may exacerbate abrasion such as pulse pipe misalignment, flue gas maldistribution and hopper dust removal problems. Nevertheless, and as in the case of selecting any fabric, the proper design parameters must be considered in selecting woven glass or any felt.

For example, Nomex™ felt has been applied with varying degrees of success. Barring major installation and fabrication errors, failure of Nomex™ often can be traced to not observing this fiber's lack of tolerance of moisture and acid attack at high temperature. However, it certainly seems a suitable fabric for application to low sulfur flue gas, such as after fluidized bed boilers and even spray dryers.

An interesting alternative not pursued in general on this continent is homopolymer acrylic or Dralon-T™. With great success, this low temperature felt is almost exclusively applied in Australia. This fabric has been useful by virtue of the low sulfur Australian coals and the use of air tempering systems which admit ambient air to cool the flue gas. Filter bags made of 16

oz./sq yd Dralon-T™ can cost as little as half that of bags made of 22 oz. fiberglass (1). Therefore, this would appear to be an interesting fabric to pursue in cases where acid content and other properties of the flue gas are such to allow low flue gas operating temperatures. Of course, the economics of cooling the flue gas either via a tempering/dilution system or a gas-to-air heat exchanger must be weighed against the savings in bag cost.

Felts of Ryton™ or PPS exhibit exceptional resistance to high gas temperatures and corrosive gases; and thus are finding a wider application to coal-fired boilers despite a cost difference of at least 50% over that of woven glass bags for a 16 oz. Ryton™ cloth. Note heavier weights of Ryton™ of 22 to 27 oz. are often applied and may be necessary on domestic felts to ensure the achieving of low emission levels.

These fabrics and their effects on PJFF performance in terms of outlet emission, pressure drop and bag life are discussed further below.

Maintainability/Suitability. Many contemplating the application of a PJFF to a large utility or industrial boiler often have expressed concern about the prospect of exceptional maintenance problems due to the greater number of parts in a PJFF compared to more-conventional fabric filters. The excessive and constant failure of diaphragm valves, solenoids, and cages has been a major fear; and thus, an area of investigation for this survey.

The general concensus of this survey is that pulse-jet baghouses are suitable particulate control collectors for the range of coal-fired boilers from small industrial boilers to large utility boilers. Currently, there exist numerous, very large installations handling flue gas volumes of up to 1.1×10^6 acfm. Few, if any, installations visited reported excessive diaphragm valve and solenoid failures. In the few installations where the failure rate was perceived to be a problem, diaphragm failure was usually resolved by substituting materials. In many cases with an excessive failure rate of diaphragms, the cause could be traced to either insufficient cooling of the pulse air or excessive condensation of moisture in excessively long compressed air lines from a remote plant-air system.

Another possible cause suspected in one installation was acid attack from flue gas backing up into the pulse pipes during lengthy periods in which cleaning was not taking place. It appears that the installations in which special care was taken to individually design and supply pulse air systems which are devoted to the baghouse did not suffer excessive diaphragm failures. Provided future systems are adequately designed, massive failures of diaphragms should not be a problem even in large installations.

Several years ago, it was commonly believed that one could expect to throw away one's

complement of cages almost with every bag changeout. In fact, in early cost comparisons of pulse-jet baghouses versus reverse gas or shake-and-deflate baghouses, many would assume that the cages were replaced with every bag changeout. This survey indicates that as long as high quality cages are used, excessive loss should not be expected. This concern perhaps stems from earlier days in which cheaper cages of thin gauge wire commonly were used. Also, in the early days of using woven fiberglass, a wire mesh cage was common. Such early cages of thin gauge wire or mesh were easily deformed and broken and difficult to reuse. However, it was found that well-made cages, of heavy-gauge wire of from 3 to 4 mm, have been quite serviceable and exceptionally reusable.

Materials of construction of the cages must be considered and made compatible with the flue gas conditions. Often, plain carbon steel cages have proven suitable; whereas, an exceptionally moist or corrosive flue gas may require the use of a protective coating on the cages. Epoxy-type coatings have been effective at lower flue gas temperatures typical downstream of spray dryer absorbers. Special note should be taken that galvanized coatings may be ineffective and perhaps even counterproductive in flue gases which are corrosive and with high chloride contents. Many horror-stories of premature and excessive cage failure from the past could have been avoided by use of proper materials.

Thus, it can be seen that the fears of a constant maintenance headache in tracking down and replacing continually-failing components such as solenoids and diaphragms as well as damaged cages are unfounded. Relatively large utility installations of PJFFs are currently in place and have not demonstrated such problems; provided proper components are used and design details are observed.

Currently, many U.S. utilities are contemplating plant-life extensions of older plants which use small ESPs. Also, coal switching brought about by potential acid rain legislation or other reasons and PM_{10} regulations may make smaller, existing ESPs unsuitable for future use. Also, hot-side ESPs are notorious for their difficulties in collecting ash from low-sulfur, low-sodium coals. PJFFs have been retrofitted into existing cold-side ESP casings in utility boilers abroad and on industrial process applications in this country. In general, these retrofits have performed quite well and promise to be a retrofit option where sufficient precipitator plan area is available and the extensive outage times would not prove uneconomical.

The Electricity Commission of New South Wales pioneered the retrofit of PJFFs into existing ESP casings at their Wangi Station in 1976. This innovative installation was undertaken out of necessity to temporarily extend the lives of three aging units while awaiting new capacity to come on line during a short fall of generating capacity on their system. This HP/LV retrofit

was, in general, successful at extending the lives of these plants; however, perceived problems with higher pressure drop, shorter component life, and shorter bag life compared to adjacent retrofits of shaker baghouses led the ECNSW to depend more on that type of technology for the bulk of their installations in which there was sufficient room.

Since then, successful retrofits at the Kyndby Power Station in Denmark, at the installation of the Östereichische Draukraftwerke in St. Andra, Austria as well as the quite famous and innovative retrofits of PJFFs into the Munmorah Station, Units 3 and 4 of the ECNSW demonstrate the viability of such retrofits. The major concerns always are availability of sufficient plant area to allow retrofit of adequate air-to-cloth ratios and the cost of the lengthy outage times required. Also, usually long bags are essential to allow such retrofits to contain sufficient cloth area.

Air-to-Cloth Ratio

An early perceived benefit of pulse-jet collectors, due to their higher energy cleaning method, was the use of exceptionally high air-to-cloth ratios of from 5 to 7 fpm. Since these early days, however, there has been a healthy trend towards lower air-to-cloth ratios to ensure reasonable pressure drops, less frequent cleaning and thus longer bag lives and lower outlet emissions. Figure 1 is a plot of design air-to-cloth ratio versus startup date for the population of PJFF sites visited. With a little imagination, a trend towards lower air-to-cloth ratios can be identified on this plot. In general, the larger air-to-cloth ratios still being installed as of late involve felted applications in Europe. Note that the general trend for a conservative design is towards air-to-cloth ratios of about 4 or less fpm for felted bags. Currently, it is generally conceded that air-to-cloth ratios for woven fiberglass applications should be closer to 3 fpm or less to allow off-line cleaning, less frequent cleaning, to ensure long bag life and to accommodate the higher pressure drops which appear to be typical of glass bags.

PERFORMANCE

Ultimately, how well PJFFs perform in terms of pressure drop, outlet emissions and bag life determine whether or not this technology will be suitable for general application to large industrial and utility boilers. The following summarizes preliminary findings of this survey with respect to PJFF performance.

Pressure Drop

Consistent with previous literature, this survey confirms that pressure drop characteristics of well designed and built PJFFs are reasonable. Figure 2 is a plot of flange-to-flange pressure drop versus air-to-cloth ratio. In general, this plot indicates reasonable total flange-to-flange pressure drops which can be tolerated by boiler installations. Note first of all that in most

cases the lower air-to-cloth ratios on the Figure are indicative of those plants operating at lower loads than design at the time of the visit. Note also that these pressure drops represent actual ΔPs observed at the time of the site visit. The air-to-cloth ratios are based on actual observed flue gas volumes which were estimated stoichiometrically based on boiler operating parameters and flue gas conditions at the time of the visit.

Looking at Figure 2 with a little imagination, one can picture a line drawn from the origin through the maximum values of pressure drop. It is interesting to note that most of these points represent PJFFs which are installed on fluidized bed boilers and/or using woven glass. This is consistent with general opinions in the industry that the use of heavier woven glass bags can result in somewhat higher pressure drops. Also, general observations are that fluidized bed boilers can generate a particulate which is difficult to remove from the cloth and thus results in higher pressure drops.

Coincidentally, many of these PJFFs also are of the HP/LV cleaning method. This might suggest an inferiority of this cleaning method; however, these data points are joined closely by numerous points representing the other two cleaning methods. Also, indicated on the Figure are points A and B which help define the lower range of the plot. These points represent HP/LV installations which incidentally use synthetic felts. Although, recent discussions with personnel at plant A indicate that some nine months after our site visit, pressure drop and opacity levels have been rising alarmingly at this PJFF bagged with Ryton™ felt.

This problem raises the issue of maintainability of synthetic felts. Several of the installations which were visited have washed felted bags with success. One facility has had experience with both Nomex™ and Ryton™. Their opinion is that the Ryton™ fabric perhaps survived the cleaning ordeal with somewhat less stress than the Nomex™ cloth. Nevertheless, their technique of using a water lance was a successful procedure in restoring reasonable pressure drops after episodes of blinded bags due to tubeleaks. The lances were supplied by normal water from the mains and sprayed water from the insides of the bags in a radial pattern.

Also, another facility has successfully washed Ryton™ bags by means of a gentle washing cycle in industrial washing machines. These bags subsequently were hung to dry. Testing of the washed fabric revealed an increase in permeability and a 25% increase in outlet emissions; although, the original emissions were quite low and the result was that the plant was still in compliance with its limitations. Reasonable pressure drops were restored to this facility.

Teflon™ felt has proven to be an incredibly durable fabric and can withstand numerous washings. One installation has washed their Teflon™ bags up to six times to recover from episodes of excessive blinding and bleedthrough. However, their calculations indicated that they would have to achieve many more washings and years of life for the bags to justify purchasing more Teflon™ due to its excessive cost relative to other applicable fabrics. Nevertheless, Teflon™ should still find application to unique difficult applications and, of course, will continue to play a major role as a treatment for fibers to prevent abrasion and corrosion and will be applied as membranes.

Also, another site has successfully hand-cleaned woven glass bags in place by use of a compressed air lance. As a result of this method, this PJFF was restored to original pressure drops after experiencing bag blinding due to excessive slip of ammonia past their catalytic deNox system upstream of the baghouse. Despite fiberglass's noted fragility, these bags achieved a minimum life of 1-1/2 years with up to two years expected. The bags were changed out after 1-1/2 years due only to the requirements of a scheduled maintenance outage.

Tubesheet Pressure Drop

Figure 3 is a plot of tubesheet pressure drop versus air-to-cloth ratio for the sites visited. As in the case of Figure 2 above which represents flange-to-flange pressure drops, these data points also represent actual observed tubesheet pressure drops plotted against actual operating air-to-cloth ratio. Likewise, the air-to-cloth ratios were calculated based on the cloth in service at the time and flue gas volume calculated stoichiometrically.

These points display a pattern consistent with the flange-to-flange pressure drops on Figure 2. The same grouping of PJFFs installed on fluidized bed boilers and/or using woven fiberglass still applies to the points on Figure 3.

Note that Figure 4 is essentially the same plot of tubesheet pressure drop versus air-to-cloth ratio; however, superimposed are shaded areas which represent ranges of pressure drop and air-to-cloth ratio for full-scale and pilot reverse-gas and shake-and-deflate baghouses. Also presented is a projection of pressure drops versus air-to-cloth ratios for pulse-jet baghouses. Note that the data gathered by this survey tends to fall within the originally projected performance regime for pulse-jet baghouses but does spread over and border on the regime thought to be exclusive to shake-and-deflate and reverse-gas baghouses. However, note that the PJFFs whose performance does approach that of the reverse-gas and shake-and-deflate baghouses tend to be the applications to fluidized bed boilers which are thought to be more difficult.

Particulate Emissions

Figure 5 summarizes the range of particulate emissions levels measured by the various facilities visited and groups them according to basic fabric type. Note that the category of "woven glass" represents lighterweight woven fiberglass weighing 16 oz./sq. yd. or less. Note that this bar represents the range of stack tests for only four installations; however, this data tends to corroborate current knowledge that lighterweight woven glass is not a particularly suitable fabric for a facility which must consistently achieve New Source Performance Standards or lower. On the other hand, the heavier weight woven fiberglass bags of 22 oz./sq. yd. or higher are quite capable of achieving lower emission levels.

Once again, a small population represents this range of data, four sites. However, most of the data values hover towards the low end of the scale and one of these lower data points represent a test after one year's worth of service. Incidentally, as of the date of that test, the particular facility had not lost one filter bag. Presumably, the other two sites at the low end of the range were tested early in their lives. One of the sites easily achieved 1-1/2 years of bag life or more with a failure of only two bags. This site used woven glass with a weight of 27 oz./sq. yd.

By contrast, the third site at this low emission level is required to remain at this emission level and zero visible emissions. This plant has been faced with a constant changeout weekly of at least a few bags to ensure maintaining compliance. This bag changeout requirement, was exacerbated by a severe abrasion of the bags at their bottoms. Apparently, this abrasion has been traced to primarily poor flow distribution of gas and dust into the hopper entry of each compartment. Direct impingement of the dust on the bags results in severe abrasion and forming of large wear holes just above the bags' "bumper" cuffs. Additional abrasion might be due to filling of the hoppers with ash and subsequent recirculation of ash and impingement on the bag bottoms due to temporarily disturbed flow patterns.

Thus, as can be seen from Figure 5, heavy weight woven fiberglass can be competitive with felts in terms of outlet emission levels. However, as always, the cheaper cost of the fabric must be weighed against other mitigating factors such as lower air-to-cloth ratios which may be required, the relative fragility of the fabric and its exceptional sensitivity to mishandling and abrasion.

A disappointment of the survey was the inability to schedule within budget and schedule constraints visits to sites currently using felted fiberglass, Tefaire™, P84, fabrics with GoreTex™ membrane or other such exotic fabrics. As can be seen, Figure 5 contains emission data from one of two sites which previously had been early users of felted

fiberglass. As can be seen, emissions from this vintage installation were rather high.

Bag Life

As can be seen, bag life can be dependent upon many factors including outlet emission limitation and the design details incorporated in the installation. Ultra low emission limitations can require continual changeout of bags, especially if design and operating problems accelerate bag wear and failure.

As indicated up above, some fiberglass installations have achieved 1-1/2 to 2 years of bag life. One of the installations using 22 oz. woven glass had experienced a 5-1/2 year bag life to date with only two small failures. This is remarkable and rivals the bag lives hoped for on some of the better installations of felt. Part of this success may be due to the use of 40-wire cages to support the woven glass bags and an exceptionally low air-to-cloth ratio of close to 2 fpm.

In general, however, felts are considered to exhibit longer bag lives than most fiberglass installations. Synthetic felts are much more resilient and capable of withstanding the constant flexing during pulse cleaning and perhaps are less sensitive to abrasion than woven glass. Indeed, Ryton™ and similar felts under different names can exhibit exceptionally long bag lives. One installation had experienced lives of 6 or 7 years on its first complement of bags made of felted PPS. However, subsequent bag lives after this first set were considerably reduced and now 3-1/2 years may be more typical. This is due to several reasons, not the least of which is the continual operation of this plant at higher loads and thus exceptionally high air-to-cloth ratios. This baghouse now is in a continual cleaning cycle which has taken its toll on bag life. Also, control of procurement of replacement filter bags was turned over from the engineering and operating personnel to the purchasing function of this company. This, along with less attention to maintenance and bag installation, also may have contributed to shorter bag life.

Nevertheless, it may not be unreasonable to expect Ryton™ to maintain its mechanical properties and survive in a flue gas environment for four years or more based on many plants' experiences. However, there is a concern about the ability of Ryton™ felts in this country to withstand bleedthrough of the particulate and subsequent blinding and excess emissions.

And, in general, comments from several sites visits indicate that the quality of domestic felts may be sub-par compared to foreign products. This points at a minimum to a need for increased efforts at specification and quality control during the bag and felt fabrication process.

Given the proper flue gas conditions; namely low enough temperatures and sulfur content of the flue gas, Nomex™ has proven to be a suitable fabric for PJFF applications. Nomex™ felts have survived in numerous plants for up to 1-1/2 years with less than ideal and recommended flue gas conditions. Two-and-one-half year bag lives and more, possibly up to 4 years, have been documented downstream of spray dryers and fluidized bed boilers where sulfur dioxide and trioxide levels are consistently low. Note that some fluidized bed boilers have experienced difficulties of excessive levels of SO_3 concentrations during slumped-bed operation. If such operational upsets are contemplated or experienced by a fluidized bed application, effective use of Nomex™ may be precluded.

CONCLUSIONS

This survey has verified that pulse-jet baghouses have been applied successfully to coal-fired boilers worldwide. Although once feared to present a maintenance headache for large utility and industrial boiler applications, well designed and built PJFF installations have proven such concerns to be unfounded.

However, to ensure adequate performance and long life, design, fabrication and construction details cannot be ignored. Poor gas flow distribution into compartments, misaligned and poorly made pulse pipes, cheap construction and components, and misapplication of fabrics are the contributing factors to those installations which have exhibited disappointing performance in terms of pressure drop, outlet emissions and short bag life.

Pulse-jet baghouses should not be thought of as a cheap alternative particulate collector for smaller boilers. However, an installation which works well due to high quality design and construction still holds the promise of cost savings due to their smaller size relative to more conventional collectors. To achieve today's more stringent emission requirements, generally more conservative air-to-cloth ratios than applied in the past are required. Whereas, at one time, an air-to-cloth ratio of 5 to 7 fpm was considered adequate for a PJFF; these days, air-to-cloth ratios approaching 4 fpm or less should be considered for a new installation using felted cloth. Lower air-to-cloth ratios in the range of 3 fpm or lower should be considered for those installations which plan to use woven fiberglass.

ACKNOWLEDGMENTS

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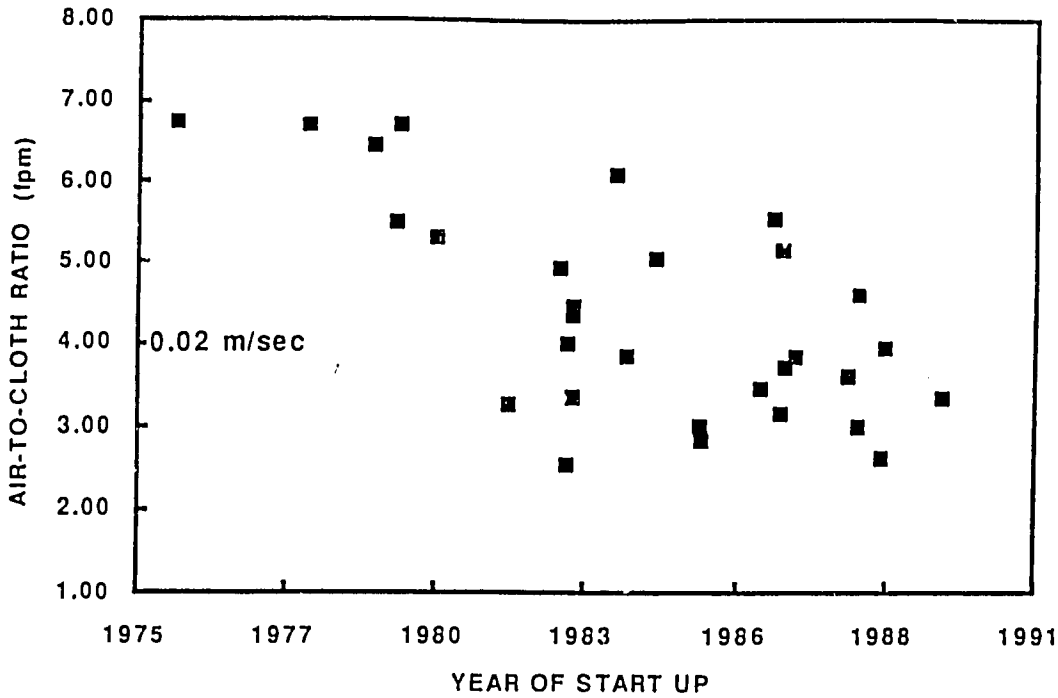

Figure 1. Design Air-to-Cloth Ratio Vs. Start-Up Date

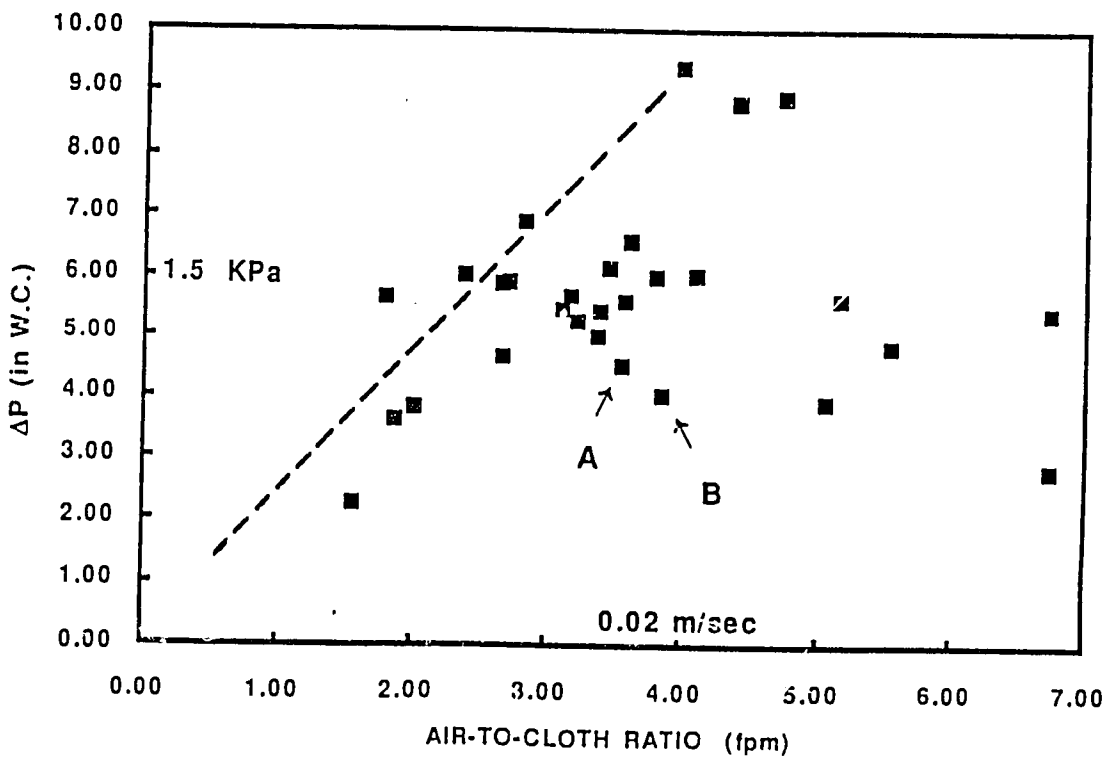

Figure 2. Flange-to-Flange ΔP Vs Air-to-Cloth Ratio

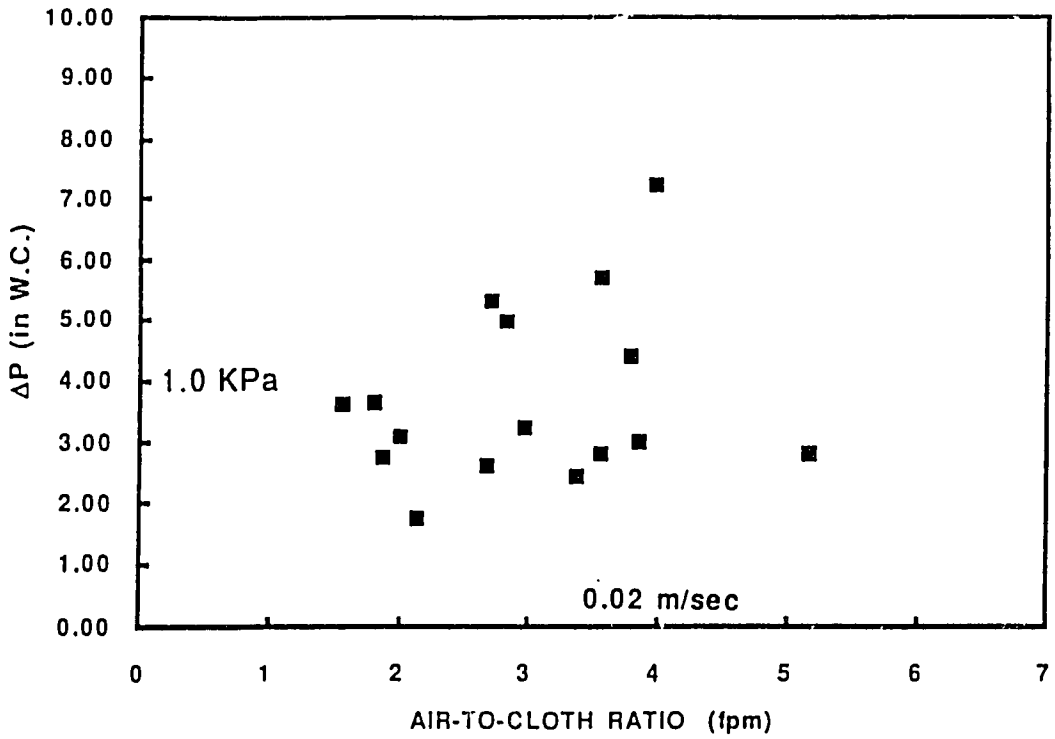

Figure 3. Tubesheet ΔP Vs Air-to-Cloth Ratio

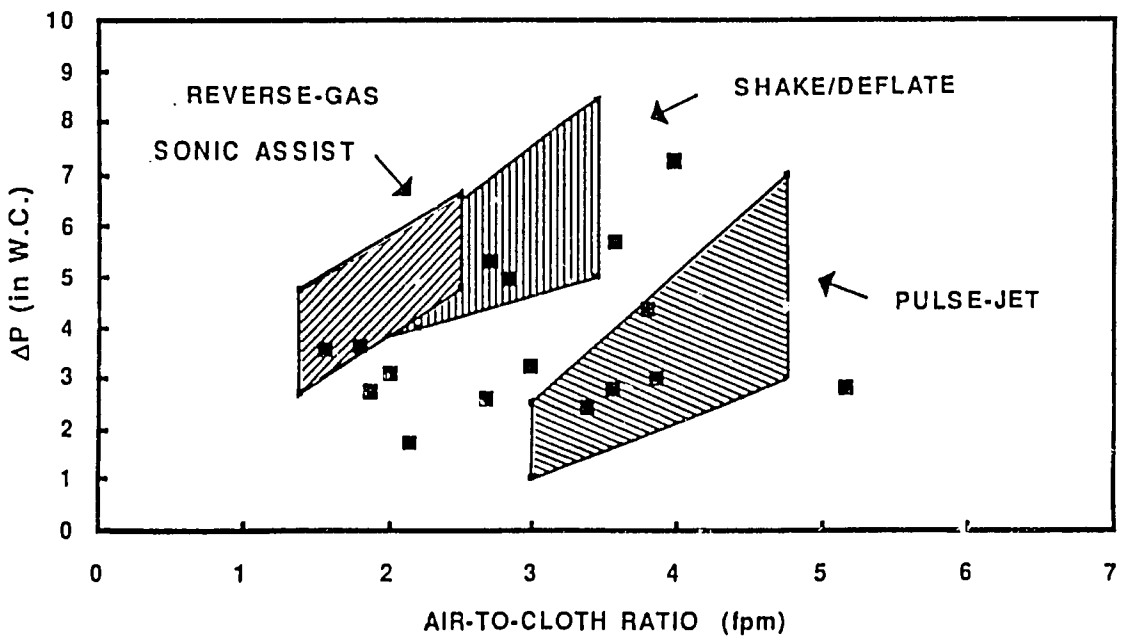

Figure 4. Tubesheet ΔP Vs Air-to-Cloth Ratio

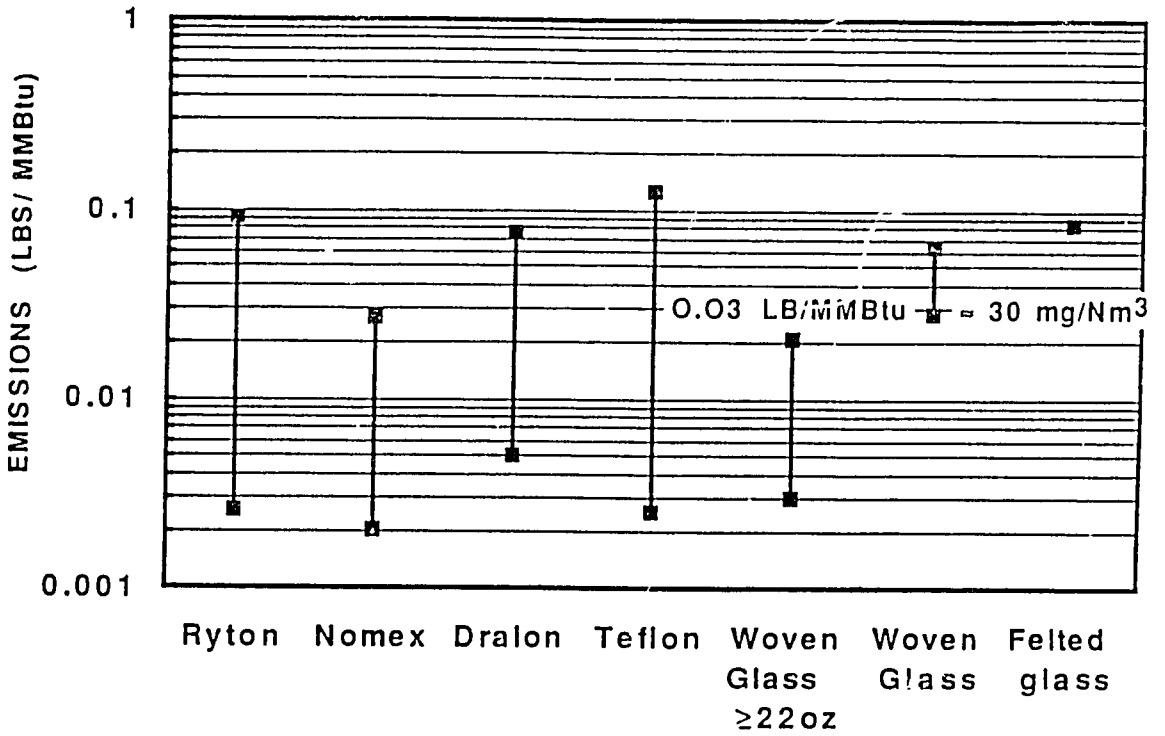

Figure 5. Particulate Emissions Vs Fabric

APPENDIX G-5

A BAGHOUSE PERFORMANCE MONITOR EXPERT SOFTWARE SYSTEM

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ABSTRACT

Recognizing the lack of integrated baghouse instrumentation and continuous performance feedback available at most baghouse sites, the Electric Power Research Institute has funded the development of a software package that provides the user a means of monitoring his system for stable operation and identifying the root cause of problems as they develop. Easy access by operators to current and historical operating data is a feature of the software along with the built in expertise of baghouse consultants for the analysis and troubleshooting of common problems.

During 1990, this system was demonstrated for 12 months at the Baltimore Gas & Electric Company's C. P. Crane Power Station, Baltimore, MD, USA. During this period, it was utilized daily by control room operators to monitor and troubleshoot a 200 MW - 900,000 ACFM baghouse. This paper describes the system as installed at Crane; defines the procedures developed and utilized by plant operators and engineers; and discusses the benefits derived by the plant.

The BPMES program runs on a desktop personal computer and can be applied to any baghouse system.

A BAGHOUSE PERFORMANCE MONITOR EXPERT SOFTWARE SYSTEM

INTRODUCTION

In 1989, ETS began the development of BPMES, Baghouse Performance Monitor Expert System, a software package, under the sponsorship of EPRI, the Electrical Power Research Institute. The purpose and features were first described in a paper given at Filtech 1989, and at the 8th Particulate EPA/EPRI Conference held in San Diego, California.

During 1990, the BPMES software was demonstrated at the C.P. Crane Station of Baltimore Gas and Electric Co., Baltimore, Maryland, USA. Over a 12 month period, the software was utilized by plant control room operators and engineers to monitor and troubleshoot a 200 MW, 900,000 ACFM reverse air baghouse controlling emissions from a coal fired boiler. During this demonstration period, the software was modified and debugged utilizing input and feedback from plant personnel who were utilizing it on a daily basis; EPRI reviewers who assessed it from a general use viewpoint; and ETS baghouse experts who were involved in other similar projects.

The result, is a completely functional software package which along with ETS' BPM, Baghouse Performance Monitor, hardware, can provide plant personnel the means of monitoring their baghouse for stable operation and identifying the root cause of problems as they develop. It is the first such particulate control operations advisor available to the baghouse industry.

Through its monitoring, trending, and diagnostic capabilities, the BPMES can help operators improve baghouse availability and decrease costs. It does this, first, by collecting and storing baghouse operation and performance data in a comprehensive database with easy access by the user. When displayed on an IBM compatible PC computer as long term trend graphs, this data can alert operators to subtle, gradual, baghouse performance degradation which would lead to critical problems. If the problem is a fast developing one, the program will automatically detect exceedances of normal operating limits and produce a warning message on the computer screen. If a problem is noted, short term expanded-time scale data can be retrieved for troubleshooting. Then, using the expert advisor portion of the software, an operator can obtain expert advice and assistance in analyzing graphical data to identify probable causes of the problem. Individual baghouse components such as dampers, sonic horns, compressors, pulse valves, ash veying, fans, etc. can be monitored for proper operation. The software also provides suggestions for remedial action.

One of the key premises used throughout BPMES is that relative comparison of current with normal and acceptable baghouse operation is easier and better than assessing just absolute values. Thus, easy collection, storage and retrieval of a normal operating database is incorporated throughout. The ability for local operators to store comments and local procedures related to operation and maintenance is also a valuable included tool. Thus, BPMES not only helps transfer the knowledge of baghouse diagnostic experts to less experienced personnel who need this insight for daily O&M, but important locally acquired knowledge can be captured and transferred as well.

The result is consistent baghouse operation, lower operating and maintenance costs, fewer unscheduled outages, and added protection against process deratings or compliance violations.

SYSTEM ARRANGEMENT AT CRANE STATION

BG&E's Crane Station has two 200 MW cyclone coal fired boilers each with a 10 compartment, 5220 bag, reverse air/sonic assist baghouse. An ETS BPM system is installed on each baghouse and is monitored with the BPMES software located in the boiler control room. The EPRI demonstration program was carried out on the Unit 1 system and this paper will focus on its operation.

The Unit 1 baghouse system and its instrumentation is described on figure 1. A list of monitored parameters and their usefulness, is shown in table 1. The BPM's Control and Monitoring Module (CMM) collects parameter inputs from the plants main operations computer; individual specialty sensors not delivered to the main computer; and individual bag and compartment flow, temperature and pressure drop signals generated by the BPM's Signal Conditioning Module (SCM). The BPMES software, located in a dedicated personal computer in the boiler control room, automatically transfers the collected data once each hour, from the CMM to the computer's database. Upon transfer, the data is checked for exceedances outside pre-established parameter limits, and if found, generates an alarm message on the computer screen.

A useful feature of the BPMES is the incorporation of a modem telecommunication device that allows the user to monitor one or more systems from a single remote site or to access the data from more than one analysis station. This provides engineers and managers easy access to current and historical data from plant and engineering offices. During the demonstration period, ETS was periodically monitoring operations remotely, from 400 miles away in Roanoke, Virginia.

DATA MANAGEMENT AND DISPLAY

Two databases are kept, a one hour average trend file and a five second average troubleshooting file. The trend data is kept in a continuous file and may be displayed in one day, three days, one week, one month or one year formats. See figures 2-4 for examples. The data file may be entered at any point through a specific date entry screen. Once in a graph, the total data file can be continuously scanned in selected increments. The troubleshooting data is kept in 24-hour files which can be displayed and scanned in any user settable time duration. See figure 5 for an example of flange to flange pressure drop through a cleaning cycle. Several years of trend data can remain stored and instantly available on the 60 MBYTE hard disk. The troubleshooting data files are automatically managed to retain the past several days of data and discard older files unless moved to a special reference section by the operators. All data can be easily archived to floppy disks for storage and future reference if desired. The secret to any data collection and display system is the ability to easily sort and keep useful data and discard all other. Through trial and error we have achieved the ability to reach this important objective.

The databases can be displayed in several types of graphical formats as listed on table 2 and shown in figures 6-8. The data can also be produced in numerical form and built into user established reports.

CURRENT MONITORING PROCEDURES UTILIZED AT CRANE

Early in the demonstration, it became evident that explicit procedures needed to be developed for specific troubleshooting tasks. Table 3 lists the procedures developed for the operators. Each procedure contains a brief explanation of its

purpose along with a step by step procedure. An example of such a procedure is shown on table 4.

The software itself also contains a menu heading called Expert Help to help guide the user in diagnosing and troubleshooting problems. Figure 9 shows a computer screen leading the user through the logic of troubleshooting a high baghouse pressure drop problem. The program assists the user by listing the logical paths the user should investigate while searching for the solution to the problem. Each menu selection also contains text help messages unique to the selection and several of the menu selections automatically switch the user to a graph of the data that corresponds to the problem.

As stated above, comparison of current operation with historical, normal and good operation is utilized throughout BPMES. The example in figure 10 shows how the templates of normal operation are used to identify a specific problem.

The operator can check damper operation by highlighting the specific compartment in the upper section and obtaining the expanded view of the specific compartment in the lower figure. To determine if damper operation is faulty, the operator can compare the actual data with the template previously stored to show what normal operation should look like. In this case, the comparison shows that the re-inflation damper did not open. Figure 11 shows the same plot with a "teaching" template on the upper half of the graph. These templates may be selected by the user to help explain what normal operation should look like.

THE PURPOSE OF THE BPM/BPMES SYSTEM AT CRANE

Since start up in 1983 and 1984, the baghouses have experienced high pressure drop due to equipment malfunction, high fabric/dustcake resistance to gas flow of the fine cyclone furnace produced flyash, and exposure to oil ash during start up. To avoid deratings, it became critical to the plant to find and correct operational problems promptly. It was also desirable to extend bag life beyond the two year life experienced under these same conditions.

THE BENEFITS DERIVED TO DATE

Since installation of the BPM/BPMES system, baghouse deratings have been reduced and will continue to be in the future due to the monitoring, warning, and troubleshooting capability now made available to plant personnel by the BPMES system. The system allows problems to be detected and deficiencies corrected before pressure drop increases to levels causing deratings. Operating power costs are reduced, and BG&E expects to extend bag life at least one year. The savings in bag set costs alone over the next 12 years is projected to be one million dollars.

Since installation, operators have used BPMES to identify and troubleshoot problems involving bag failures, sonic horn malfunctions, ash removal pluggages, abnormal compartment damper operation, and instrument/controls malfunctions. One such problem occurred during September, 1990, when the BPMES identified a compartment with an unusual reverse gas flow profile. The compartment was immediately pulled off line. During the physical inspection that followed, it was discovered that the flyash hopper was almost completely full. If left unresolved the compartment would have filled to the bag level potentially destroying 522 bags at a total replacement cost of $50,000. Instead the compartment was isolated, the hopper emptied and the compartment returned to service three days later.

Other uses of the system have included monitoring and establishing procedures for new bag set bag precoating and start up; monitoring the plant flyash system

condition; and maintaining historical maintenance records for each baghouse. The system has also been useful for testing the effectiveness of alternative operational modes, fabrics for future bag sets, and other baghouse or flue gas related equipment and materials.

SUMMARY

BPMES has been successfully demonstrated on a full scale utility boiler baghouse and has become a permanent operational tool at the C.P. Crane station. The BPMES software in conjunction with the BPM hardware has proved very useful in identifying and solving baghouse system problems in the past and BG&E personnel has projected an operational cost savings of $1.6 over the next 20 years due to its monitoring and troubleshooting capabilities. This along with the added protection from boiler deratings and compliance violations makes this a very productive and worthwhile system addition.

FIGURE 1

BPMES SYSTEM OVERVIEW

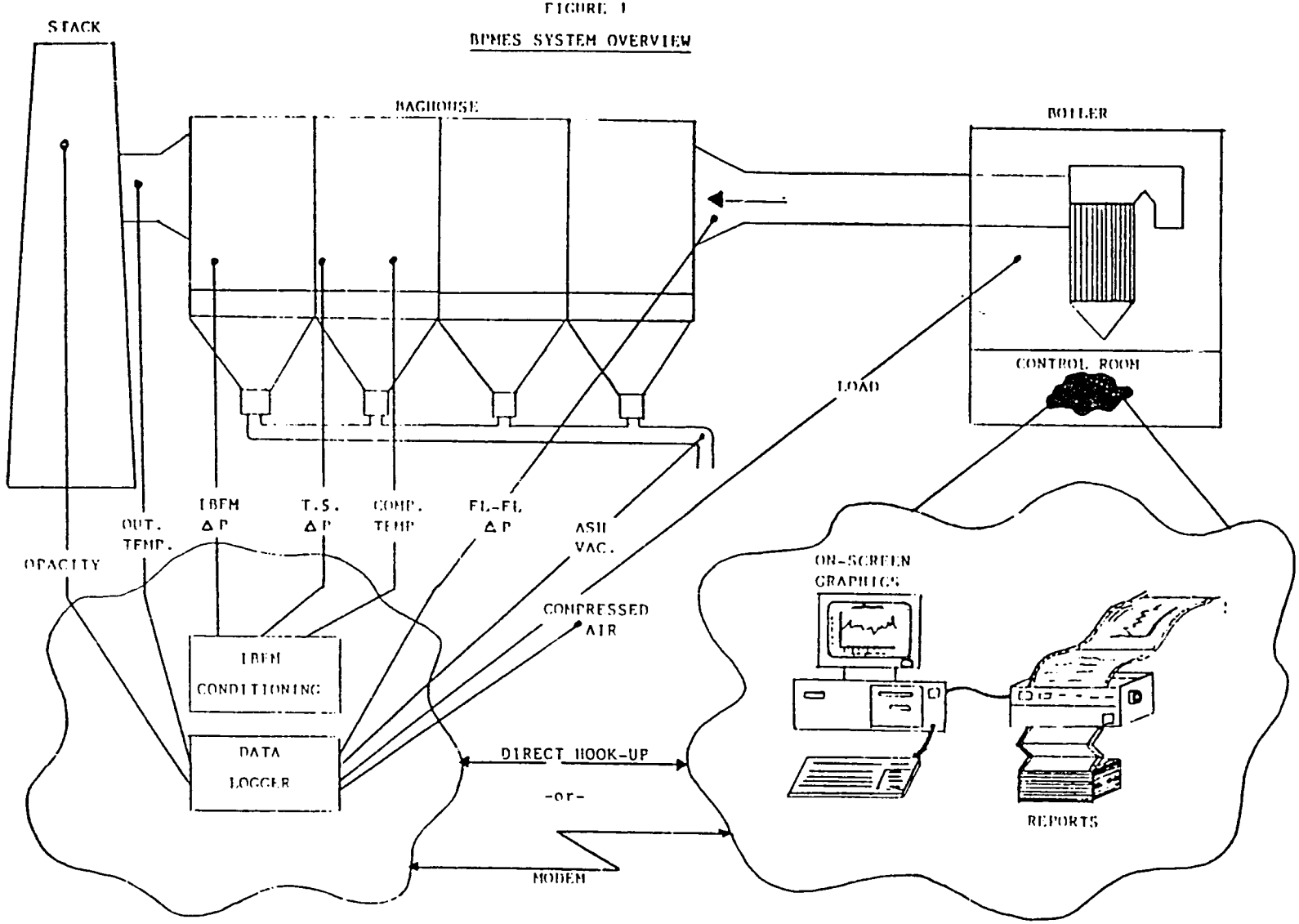
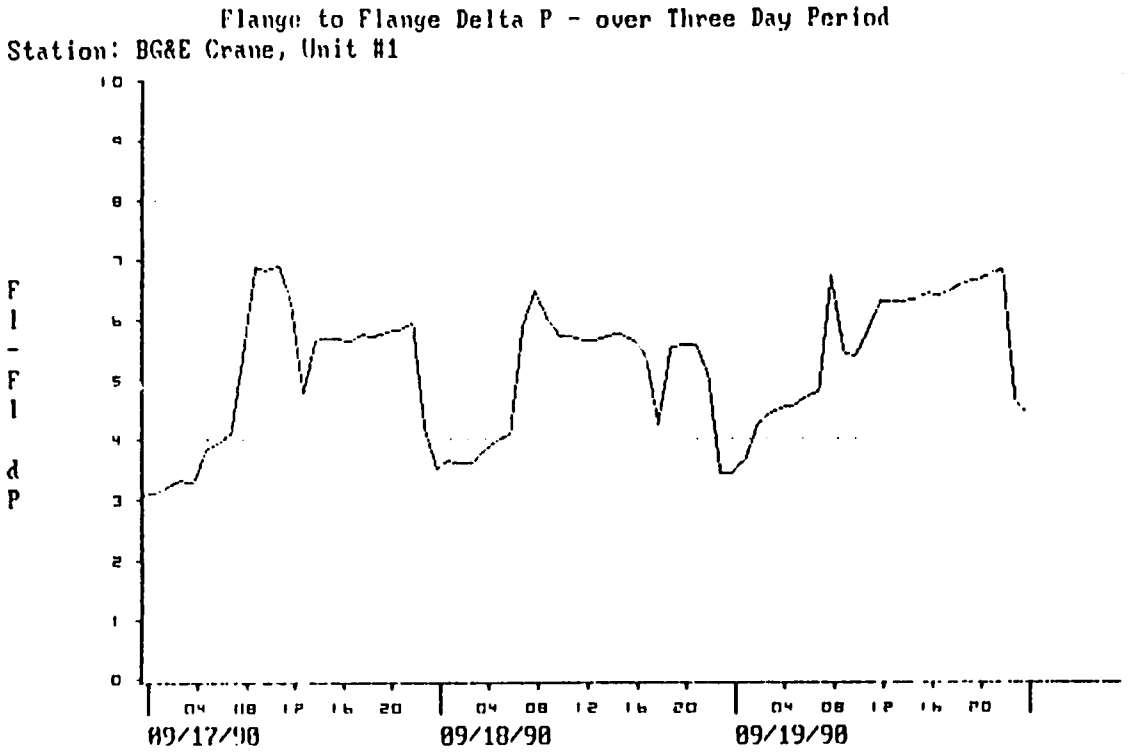


FIGURE 2

EXAMPLE OF 3 DAY TREND

GRAPH USING 1 HOUR AVERAGES



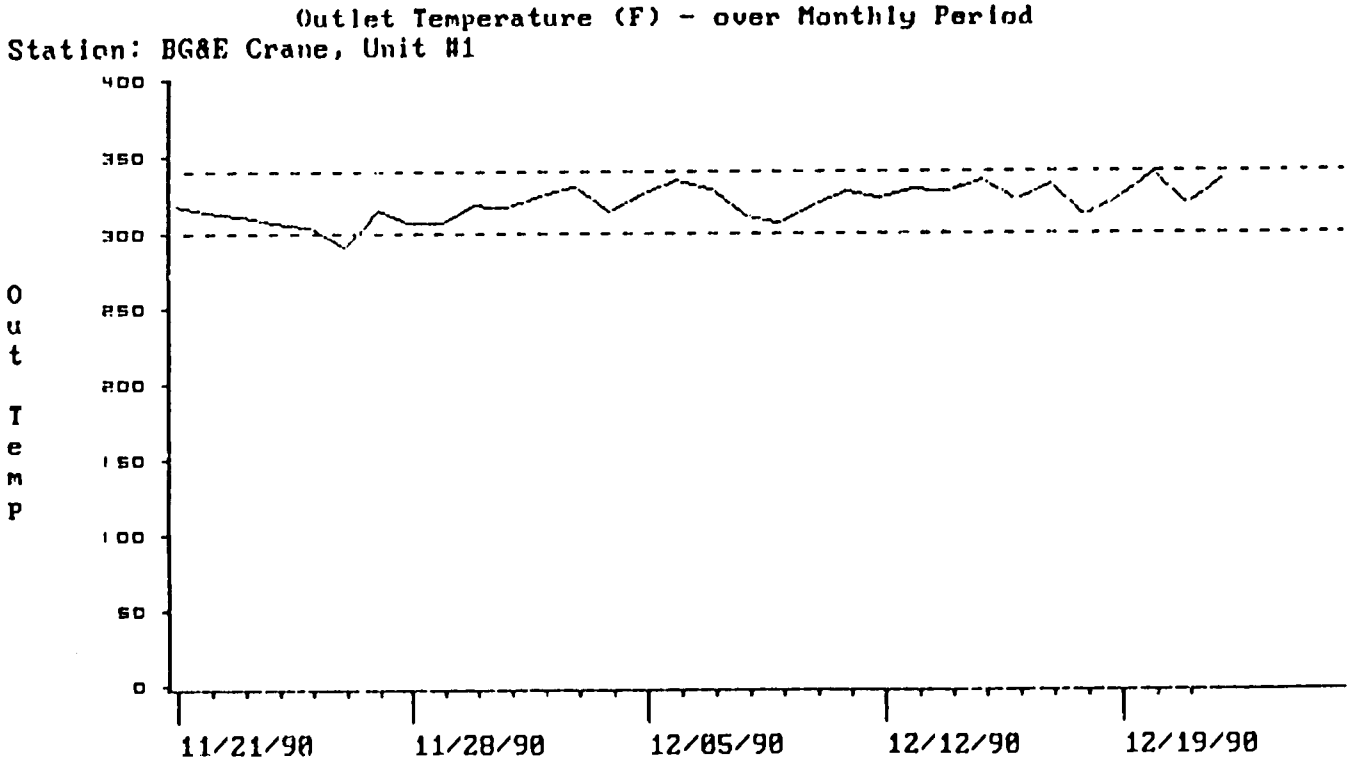


FIGURE 3

EXAMPLE OF 1 MONTH TREND

GRAPH USING DAILY AVERAGES

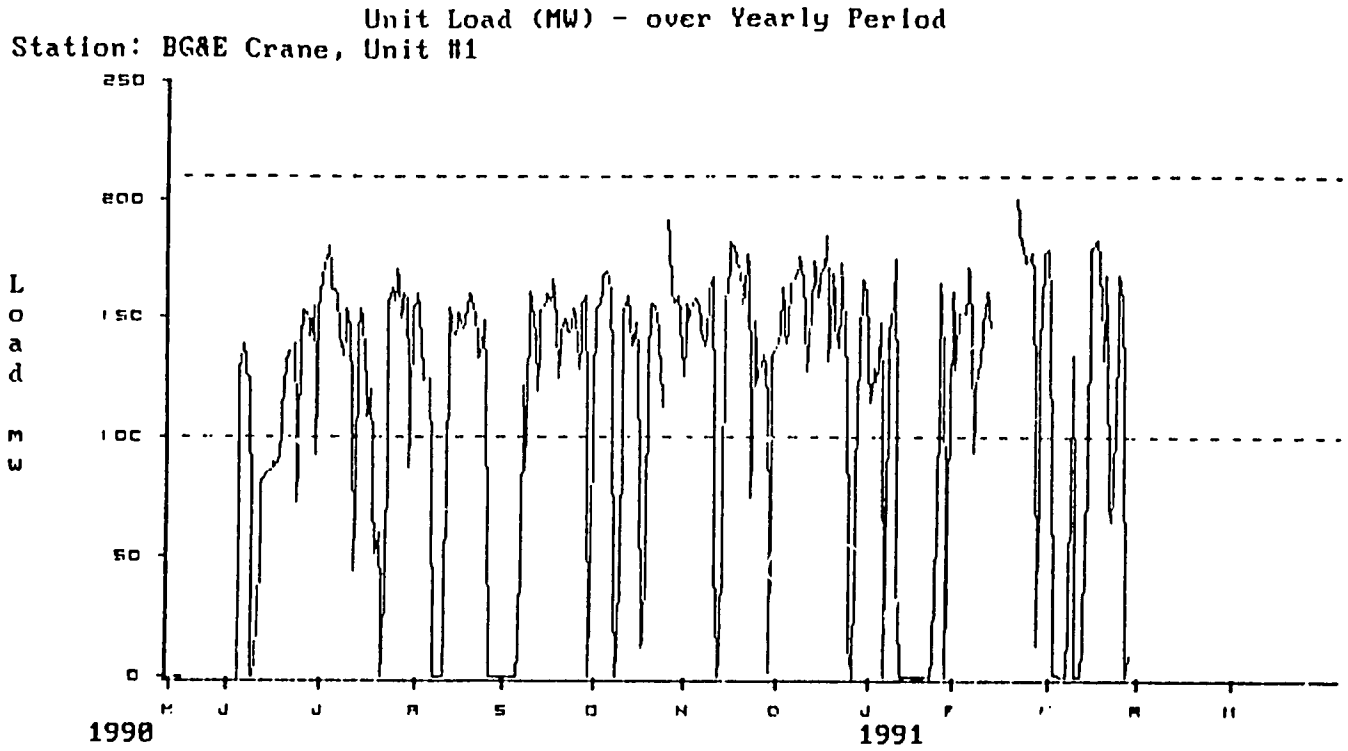


FIGURE 4

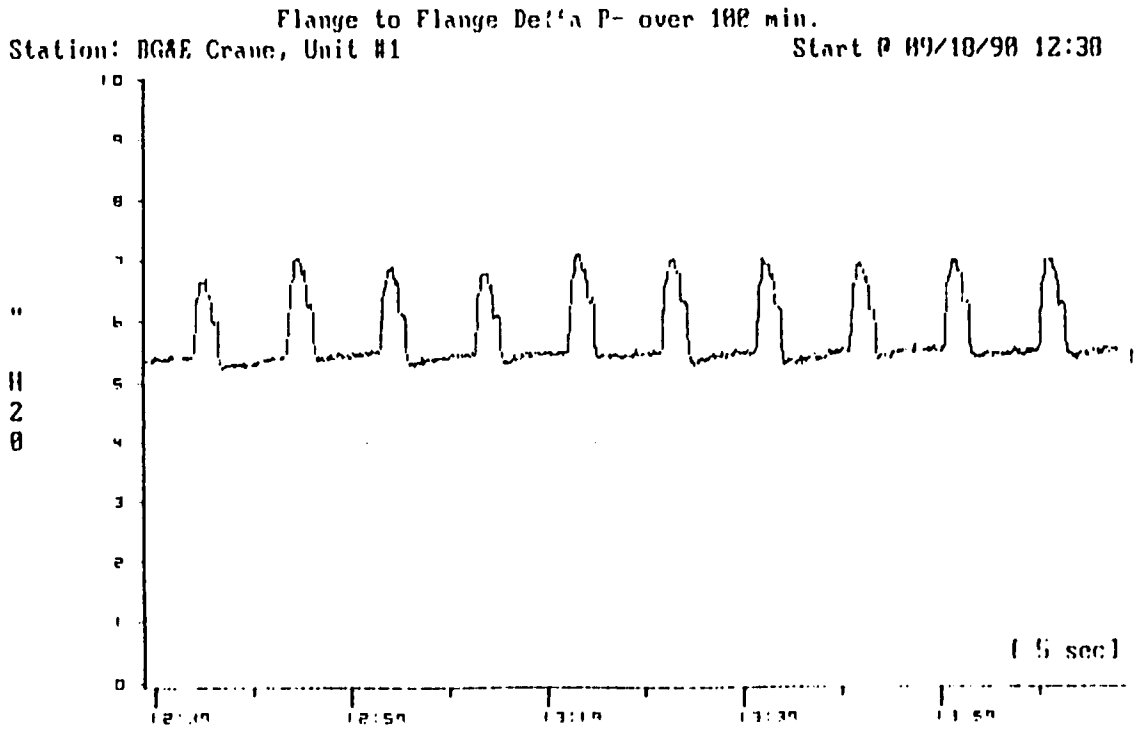
EXAMPLE OF 1 YEAR TREND

GRAPH USING DAILY AVERAGES

FIGURE 5

FLANGE TO FLANGE PRESSURE DROP

DURING A CLEANING CYCLE



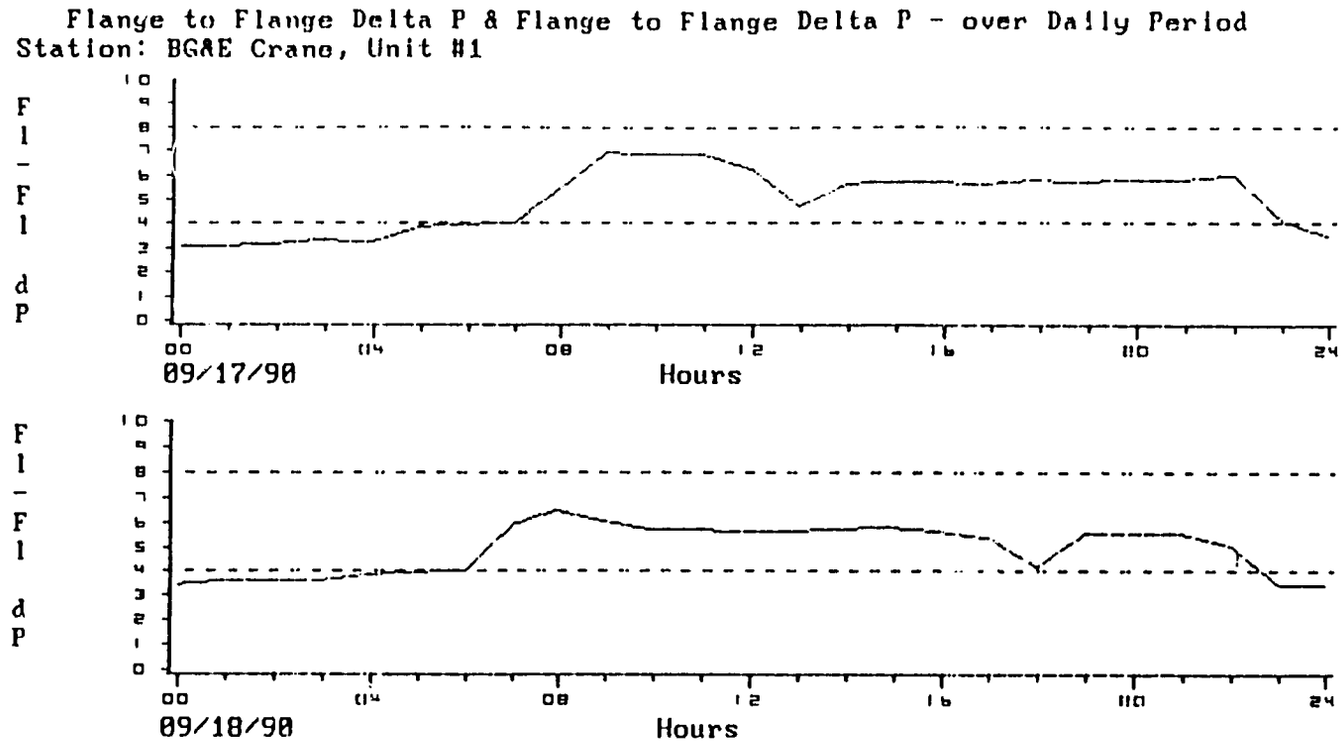


FIGURE 6

EXAMPLE OF DUAL TIME PERIOD GRAPH AND DOUBLE GRAPH

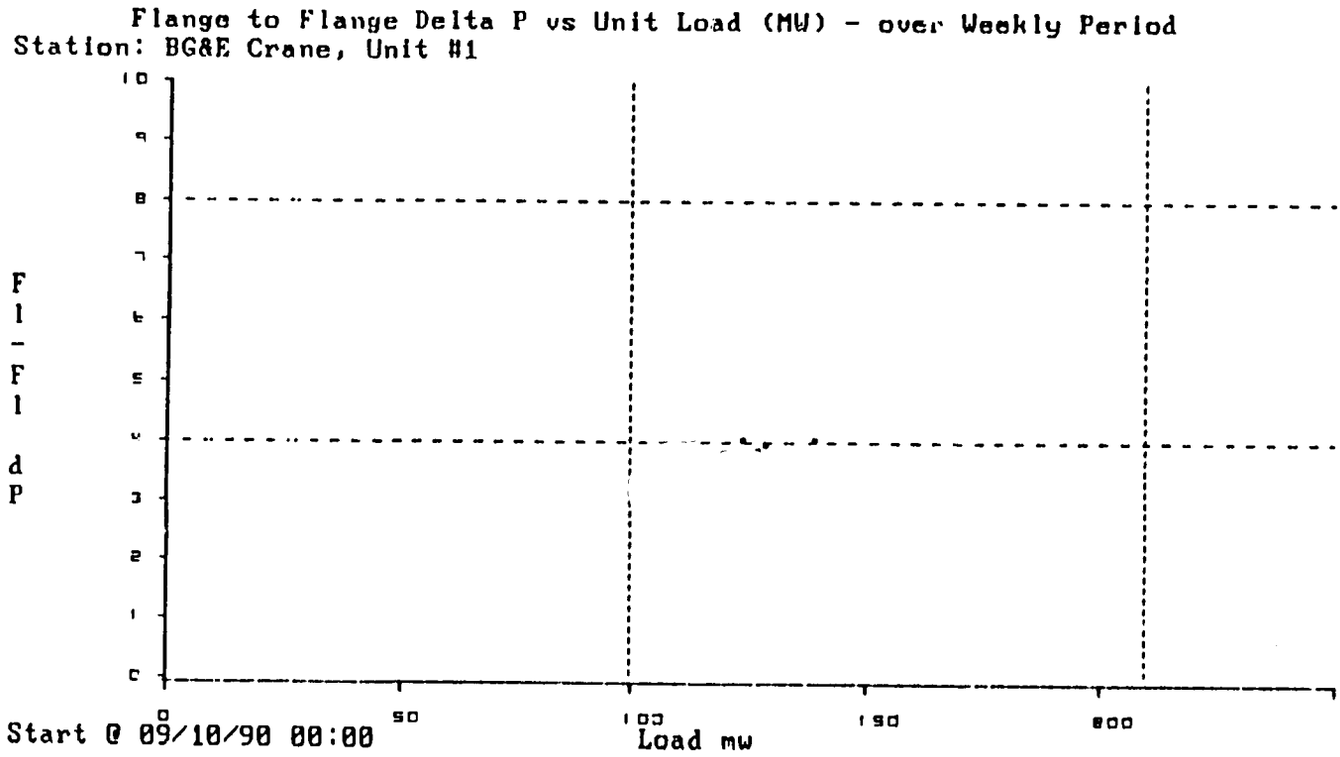


FIGURE 7

EXAMPLE OF FLANGE TO FLANGE ΔP AND LOAD PARAMETER VERSUS PARAMETER GRAPH

FIGURE 8

EXAMPLE OF A TROUBLESHOOTING GRAPH

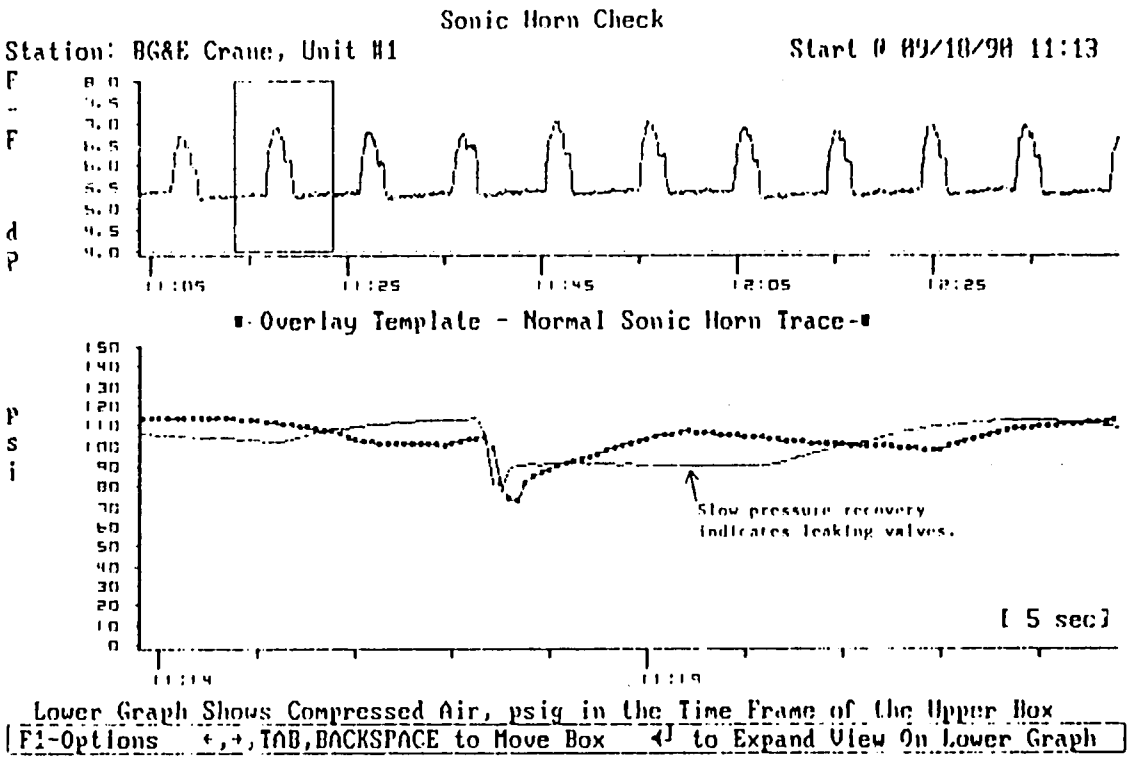


FIGURE 9

EXPERT HELP LOGIC SCREEN

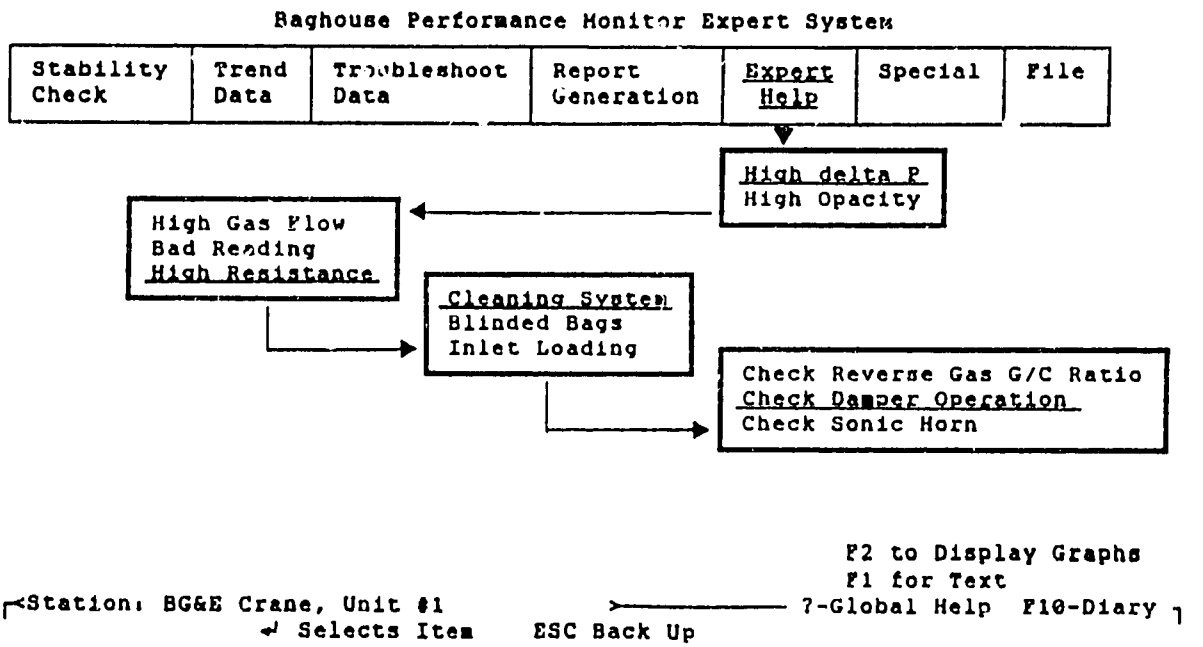
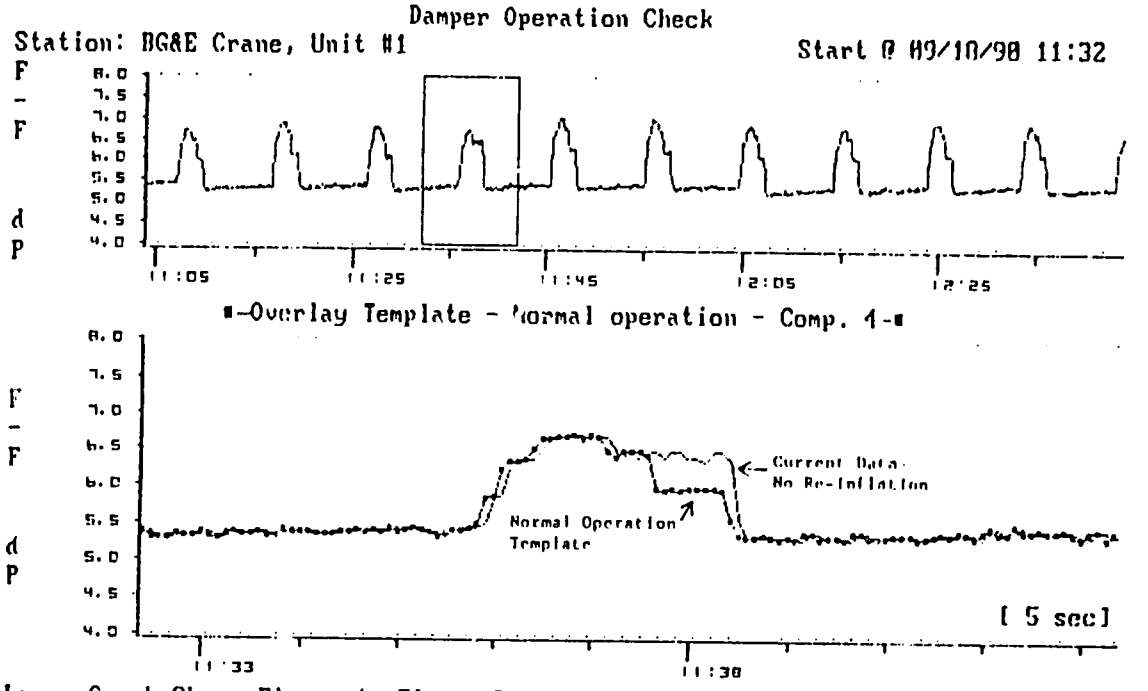


FIGURE 10

DAMPER OPERATION CHECK

TROUBLESHOOTING TEMPLATE GRAPH

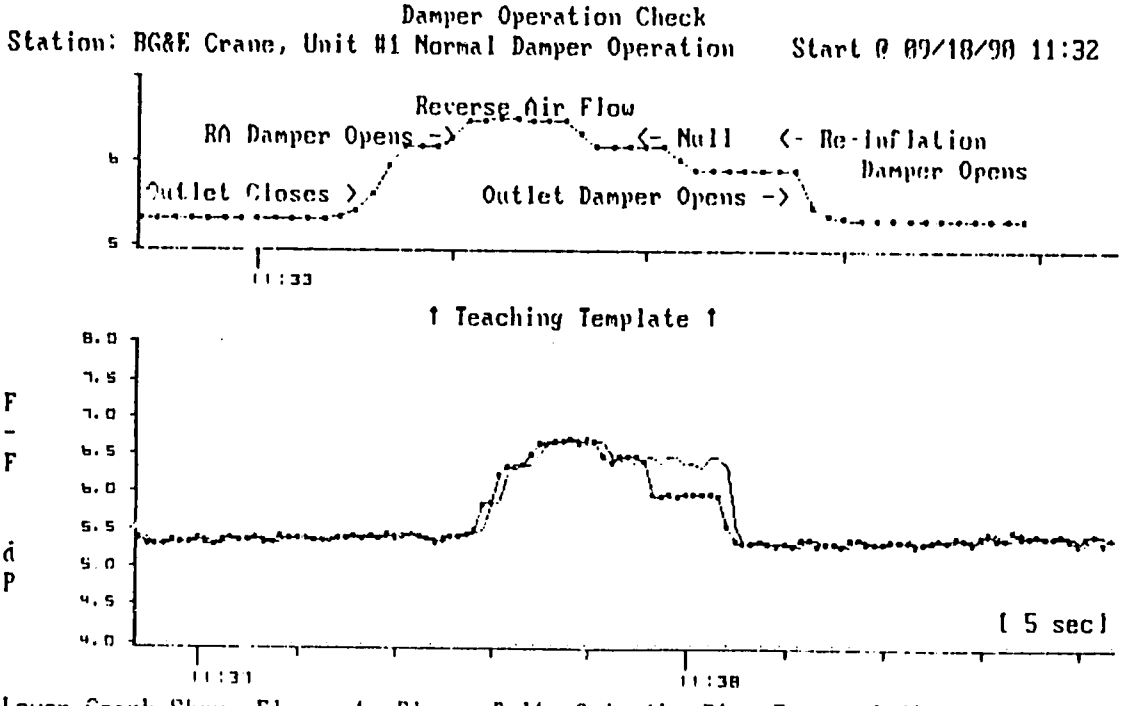


Lower Graph Shows Flange to Flange Delta P in the Time Frame of the Upper Box

F1-Options ←,→,TAB,BACKSPACE to Move Box ↵ to Expand View On Lower Graph

FIGURE 11

DAMPER OPERATION CHECK WITH TEACHING TEMPLATE



Lower Graph Shows Flange to Flange Delta P in the Time Frame of the Upper Box

F1-Options ←,→,TAB,BACKSPACE to Move Box ↵ to Expand View On Lower Graph

Table 1

LIST OF MONITORED PARAMETERS

PARAMETER	USEFULNESS
Compartment Temperature	Used to determine if the compartment has been subjected to abnormal temperatures. Also used to calculate individual bag G/C.
Compartment ΔP	Used to troubleshoot compartment operation. Also used to calculate drag.
IBFM Δh (flow)	Used to calculate flow and drag through an individual bag. Also used to quantify reverse air cleaning energy.
IBFM Channel	Used to identify the IBFM being monitored.
Flange to Flange ΔP	Used to troubleshoot damper operation and also used with other signals for determining cleaning cycle position and compartment I.D.
B.H. Outlet Temperature	Used to determine if the baghouse has been subjected to abnormally low or high temperatures.
Opacity	Used in conjunction with flange to flange ΔP as a tool to locate failed bags.
Compressed Air Pressure	Used to verify normal operation of sonic horns.
Flyash Vacuum	Used to verify that the ash removal system is operating properly. Identifies hopper pluggage and other system problem.
Boiler Load	Used to determine the percent of full capacity at which the boiler is operating and to produce full load normalized flow and pressure drop parameters.
Projected Values	Used to determine the "full load" values of signals when boiler is operating at less than full load. This provides more meaningful trending.

Table 2

LIST OF GRAPHICAL DATA DISPLAY FORMATS

Display Format	Trend Data Base	Troubleshooting Data Base
Single Graph	✓	✓
Double Graph	✓	✓
Parameter vs Parameter	✓	
Dual Time Graph	✓	
Template Graph		✓

Table 3

BPMES USE PROCEDURES FOR O&M PERSONNEL

Procedure	USAGE FREQUENCY	
	Shift	Monthly
Alarm Message Review	X	
Auto-Call Operation Check	X	
Damper Operation Check	X	X (Detailed)
Source of Opacity Check	X	
Sonic Horn/Compressed Air Check	X	
Ash System Check	X	
Reverse Air Level Check		X
Full Load - FL-FL ΔP Trend Check		X
Full Load - Gas Flow Trend Check		X

Table 4

PROCEDURE M-4
OPACITY CHECK

Purpose:

1) To check for any upward trend in the opacity trace or repetitive spikes indicating bag failure.

2) Identify location or failure if indicated.

Background:

Normal operation will generate stack opacity trace within the 3 to 4% range with little or no increase in opacity following a compartment's cleaning.

If excessive spikes do occur in the opacity trace, the source of the opacity increase will normally be a broken bag in the compartment that was just returned to service following bag cleaning. This compartment can be identified using the special Source of Opacity Troubleshooting screen.

Procedures:

1) Once a shift or whenever a high opacity alarm message is issued, review the most recent Troubleshooting file during which a cleaning cycle has been captured.

2) Set up the screen as follows:
   - Type of graph - Single
   - Graph selection - Source of Opacity Check
   - Y-axis:
     Flange to Flange dP, High Scale = 8, Lo Scale = 5
     Opacity, High Scale = 20, Lo Scale = 0
     (Adjust as necessary for current levels)
   - Time = 120 minutes

The output should look similar to Figure _____.

3) Verify that the opacity level is below the lower dotted line. If not, verify that there are no abnormal spikes following any compartments cleaning. Utilize the Normal Template for reference if required.

4) If abnormal opacity levels or excessive spikes are found, page up to scan the recent database and confirm that it is repetitive during prior cleaning cycles.

5) Utilize the troubleshooting techniques described in the expert help to identify the source of the high opacity and provide maintenance with the necessary information to repair.

APPENDIX G-6

A WORLDWIDE SURVEY OF PULSE-JET BAGHOUSE PERFORMANCE ON COAL-FIRED BOILERS

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A WORLDWIDE SURVEY OF PULSE-JET BAGHOUSE PERFORMANCE ON COAL-FIRED BOILERS

ABSTRACT

Pulse-jet fabric filters (PJFFs) are widely used in U.S. industrial boiler applications and in utility and industrial boilers abroad. Their smaller size and reduced cost relative to more conventional baghouses make PJFFs appear to be a particularly attractive particulate control option for utility and industrial boilers: for both new plants as well as retrofits and for the range of boiler type from stoker- to pulverized-fired boilers and fluidized-bed combustors.

This paper presents the results of a survey co-funded by the Electric Power Research Institute and the Canadian Electric Association to characterize the performance of and operating experiences with PJFFs applied to coal-fired boilers. The survey involved site visits to interview technical and plant personnel involved in the design, installation and day-to-day operation of PJFFs worldwide. Actual field experiences with PJFF performance in terms of outlet emissions, pressure drop and bag life for different types of pulse-jet cleaning methods, fabrics and boilers were compared.

A WORLDWIDE SURVEY OF PULSE-JET BAGHOUSE PERFORMANCE ON COAL-FIRED BOILERS

INTRODUCTION

Pulse-jet fabric filters (PJFFs) are widely used in U.S. industrial boiler applications and in utility and industrial boilers abroad. Due to their smaller size and lower capital cost relative to more conventional fabric filters, PJFFs appear to be an attractive particulate control option for U.S. utilities; for both new power plants as well as retrofits, and for the range of utility boiler types from small stoker-fired to pulverized coal-fired (PC) boilers, fluidized bed combustors (FBCs) and other advanced power generation systems.

There are over 300 PJFFs installed on industrial and utility coal-fired boilers worldwide (1). This paper summarizes key findings of a survey sponsored by EPRI and the Canadian Electric Association of site visits to over 30 full-scale installations representing over 70 individual units in the United States, Canada, Europe, Japan and Australia (2). The site visits were conducted to interview technical and plant personnel involved in the design, installation and day-to-day operation of the PJFFs. The results summarized in this paper characterize the performance of these PJFFs in terms of pressure drop, outlet emissions and bag life, and verify the maintainability and suitability of PJFFs for application to large utility and industrial boilers on the North American continent.

EVOLUTION AND TRENDS IN PJFF TECHNOLOGIES

The first PJFF was installed thirty-three years ago, in the mid-1950's, as process equipment to collect valuable product from pulverizing mills. (3) It wasn't until the early to mid-1970's, twenty years later, that pulse-jet technology was applied to the collection of flyash from coal-fired boilers. Since that time, the use of and design details incorporated in PJFFs used to collect flyash from coal-fired boilers have evolved in distinctly different directions throughout the world. As utilities around the world have gained successful experience, there has been a distinct trend toward the application of PJFFs to larger units.

In the United States, PJFFs have been used primarily for smaller industrial boilers as opposed to the reverse-gas fabric filters more conventionally applied to utility boilers. Virtually all of the PJFF installations in Japan are on relatively small industrial boilers, with the largest treating

255,000 acfm (120 m^3/s). By comparison, in Canada, Europe and Australia, PJFFs have seen a wider application to small industrial as well as larger-sized utility boilers.

For example, retrofits of PJFFs in operation on the 350-MW Munmorah Station Units 3 and 4 in Australia are each rated to handle 1.02 Macfm (481 m^3/s). The retrofits currently procured for the four, 500-MW units at the Liddell Station of the Electricity Commission of New South Wales (ECNSW) are becoming the largest PJFF installations in the world, with each unit treating 1.8 Macfm (850 m^3/s). The first of these units is currently in operation. In Europe, it is common to see PJFFs, both as retrofits and new installations, designed to treat flue gas volumes ranging from 730 kacfm to 1.15 Macfm (345 to 543 m^3/s).

The largest PJFF installation on a PC-fired utility boiler on the North American continent was started up in 1979 on the 150-MW unit of the Milner Station of Alberta Power Limited in Canada. Until rivaled by larger installations in Europe and the retrofits at the Munmorah Station in Australia, this unit remained for many years the largest boiler PJFF installation in the world. Another installation by Flakt Canada was on Unit #1 of the Wabamun Station of TransAlta Utilities Corporation. The retrofit on this 70-MW, PC-fired unit started up in 1983.

Due to success of reverse-gas baghouses on utility boilers, the utility industry in the United States has become quite comfortable with the reverse-gas technology for application to coal-fired boilers. With the exception of three quite small and atypical installations on utility boilers, the bulk of PJFF installations in the United States have been on industrial boilers. The tendency still is for these installations to be small; the PJFFs typically handling 200,000 acfm (94 m^3/s) or less. The largest installation treats the combined exhausts of 772,000 acfm (364 m^3/s) from five stoker- and pulverized-coal-fired boilers. (1).

PJFFs have been successfully applied downstream of all types of boilers ranging from PC- and stoker-fired units to bubbling and circulating-fluidized-bed combustors (AFBCs and CFBCs). Additionally, PJFFs have been installed downstream of boilers employing spray dryer absorbers, furnace sorbent injection, duct injection of dry sorbents, and SCR deNO_x units.

The Trend Towards More Conservative Air-to-Cloth Ratios

An early perceived benefit of pulse-jet collectors, due to their higher energy cleaning method, was the use of exceptionally high air-to-cloth ratios of from 5 to 7 ft/min (0.025 to 0.036 m/s). Since the first boiler PJFFs, there has been a trend towards operating at lower air-to-cloth ratios to ensure reasonable pressure drops, less frequent cleaning and thus longer bag lives and lower outlet emissions.

Figure 1 is a plot of design, gross air-to-cloth ratio versus startup date for the population of PJFF sites visited for this survey; and demonstrates the apparent trend towards lower air-to-

cloth ratios. In general, the higher air-to-cloth ratios still being installed as of late involve applications of felt in Europe. The general trend for a conservative design is towards air-to-cloth ratios of about 4 ft/min (0.02 m/s) for felted bags, and lower for woven fiberglass applications.

However, factors other than the type of fabric must also be considered when selecting an air-to-cloth ratio. Factors such as the type of fuel and firing method and the resultant ash properties, the duty cycle of the boiler and PJFF, the inlet ash loading, the cleaning method and the interaction of these factors and others with the selected fabric must be taken into account.

Design and O&M Issues

Pulse-jet cleaning methods have evolved into three basic types that can be generally characterized in terms of the pressure and volume of the pulse air used. These methods are high-pressure/low-volume (HP/LV), intermediate pressure and volume (IP/IV) and low-pressure/high-volume (LP/HV) pulsing. The range of pulse pressures used by each method are summarized in Table 1.

Table 1

RANGES OF PULSE PRESSURE VS. CLEANING METHOD

	Typical Pulse Pressure	
Cleaning Method	psig	bar
HP/LV	40 to 100	2.8 to 6.9
IP/IV	15 to 30	1.0 to 2.1
LP/HV	7.5 to 10	0.5 to 0.7

The original PJFF design used the HP/LV cleaning method; and traditionally, most pulse-jet applications in the United States have been primarily of the HP/LV type. Whereas, in Canada, Australia and Europe, the predominant cleaning modes on larger boilers have been the IP/IV and LP/HV designs.

Bag Length. PJFF installations on utility boilers benefit from the use of long filter bags since longer bags mean fewer bags to provide the same air-to-cloth ratio. Fewer bags require less plan area and fewer parts such as cages, pulse pipes, diaphragm and solenoid valves and bags that require placement.

It is possible to use filter bags that are 20 ft (6.1 m) or longer to minimize plan area requirements for retrofits into constricted sites. Filter bags up to 20 ft in length have been successfully used in properly designed low- and high-pressure PJFFs, while bags up to 26 ft

(8.0-m) have proven themselves in intermediate-pressure units. The successful retrofit of 24-ft bags at the Munmorah Station and pilot testing of 26-ft (8.0-m) bags have given the ECNSW confidence to retrofit an IP/IV type PJFF with 26-ft-long bags on four 500-MW units at the Liddell Station. The first of these Liddell units is currently in operation.

This suggests that all three cleaning methods could operate with filter bags of up to 20-ft (6.1-m) long or even longer. However, in contemplating the installation of a PJFF with long bags with lengths between 16 to 20 feet (4.9 to 6.1 m) and beyond, one should ensure that the bidders have current field experience and/or extensive pilot investigations to prove the applicability of their cleaning methods to long bags with the type of fabrics anticipated and treating dust of similar properties and difficulty.

Reliability Concerns. Potential PJFF users have been concerned that there will be increased operation and maintenance problems and costs due to short bag lives and increased number of components such as solenoids, diaphragm valves, and cages. To the contrary, few installations we visited reported any problems with baghouse components. However, this survey demonstrates that design, fabrication and construction details cannot be ignored, if performance and long component and bag life are to be ensured. Poor gas flow distribution into compartments, high velocities between bags, misaligned and poorly made pulse pipes, cheap construction materials and components, misapplication of fabrics and poor startup and shutdown procedures are factors that have contributed to excessive component failure, pressure drop, outlet emissions and bag replacement rates in the few installations which reported such problems.

Fabrics

The types of fabrics, their durabilities and their qualities have evolved considerably since the first PJFF was installed on an industrial process in the mid-1950's. This evolution has differed markedly among countries, due largely to differences in start-up dates and process/environmental requirements. In the United States, the most common fabric has been woven fiberglass, which has operating temperature limits of about 500°F (260°C). There is a recent trend toward the use of either needle felts or polytetrafluoroethylene (PTFE) membranes (such as GORE-TEX) on woven glass. These materials are favored in CFBC applications, where woven glass bags have performed inadequately, or in new installations, where very stringent emission limitations have dictated the use of media that are more efficient than conventional woven glass.

Experience in Canada, Australia and Europe has been primarily with various felted fabrics. Homopolymer acrylic (Dralon T) has proved to be a very good fabric for applications at less than 284°F (140°C) such as downstream of spray dryers or with boilers firing low sulfur coal and which use air tempering systems or other techniques to avoid high temperature

excursions. Felts made of polyphenylene sulfide (PPS or Ryton) and aramid (Nomex) fibers are operated at temperatures of less than 400°F (204°C). Glass (Huyglas), polyimide (P84), and Teflon felts can operate at somewhat higher temperatures, perhaps up to 500°F (260°C).

Woven Fiberglass Versus Synthetic Felts. Recently in the United States, and paralleling the success of felts in other countries, more PJFF installations are using synthetic felts. However, for early applications of PJFFs in the United States, fiberglass was the only material of reasonable cost that could withstand flue gas conditions. This, in conjunction with the favorable experience gained with woven fiberglass in reverse-gas installations, prompted an evolution in the U.S. toward woven fiberglass PJFF bags, primarily in HP/LV units. Woven fiberglass fabrics were appealing due to their ability to withstand gas temperatures of up to 500°F (260°C), approached by many industrial boilers in the U.S., and to be more forgiving of upset temperatures for larger boilers employing regenerative-type air heaters. Some early attempts at using the few felts available at the time in the U.S. resulted in premature failures of the bags. Since these early PC applications, bags made of Huyglas and Ryton felts have been used with varying degrees of success in a range of coal-fired boiler applications. More recently, the use of PJFFs downstream of spray dryers and FBCs has provided more opportunities to apply felts made of Nomex and Dralon T.

This study indicates that by observing proper design and construction tolerances, woven fiberglass bags can work and provide reasonable bag lives and pressure drops while still maintaining very low outlet emissions comparable with those achieved by felts. However, fiberglass is less forgiving than synthetic felts and care must be taken in ensuring proper bag and cage fit and in installing the filter bags. Also, fiberglass bags are more susceptible to abrasion and related design and construction problems that may exacerbate abrasion such as pulse pipe misalignment, flue gas maldistribution and hopper dust removal problems. Off-line cleaning, in which compartments are isolated from the flue gas stream for cleaning, was developed in part to accommodate the more fragile woven fiberglass fabric.

There are two basic types of woven fiberglass in use in boiler PJFFs. The conventional double-warp face 16 oz/yd^2 (540 g/m^2) woven fiberglass fabric is not a particularly suitable fabric for a facility that must consistently achieve New Source Performance Standards or lower. On the other hand, bags that are made of fiberglass cloth of 22 oz/yd^2 (750 g/m^2) or heavier and properly woven in the conventional double filling-face weave are quite capable of achieving lower emission levels comparable to levels from synthetic felts. However, the heavier weight fiberglass tends to exhibit lower operating permeabilities than felts; and thus, higher pressure drops for a given air-to-cloth ratio can be expected. Thus, PJFFs using woven glass should be sized more conservatively and operated at lower air-to-cloth ratios than those using felts.

Comments from some sites suggest that quality control problems in felting and in bag manufacturing in North America have sometimes resulted in disappointing performance of felted bags. This points at a minimum to a need for increased efforts at specification and quality control during the bag and felt fabrication process.

Retrofit of PJFFs into ESP Casings. Recent Clean Air Act amendments make many existing ESPs undersized as utilities contemplate coal switching and using dry sulfur oxide control technologies. PJFFs have been retrofitted into existing ESP casings in utility boilers abroad and on industrial process applications in the United States. In general, these retrofits have performed quite well. Such retrofits are a viable option for reducing particulate emissions where sufficient precipitator plan area is available.

The first utility applications of PJFFs involved retrofits into existing electrostatic precipitator (ESP) casings in Australia. These PJFFs were retrofitted due to limited space in which to install new baghouses. Today, retrofits into ESP casings of two 350-MW units of the ECNSW's Munmorah Station are operating successfully. Similar retrofits into ESP casings of four 500-MW units at the ECNSW's Liddell Station are being installed; the first unit has started up. Also, unique retrofits into ESP casings in Europe demonstrate the viability of such an option to upgrade particulate control on this continent.

PERFORMANCE

The potential for the application of pulse-jet fabric filters (PJFFs) to utility and large industrial boilers depends on PJFF performance in terms of pressure drop, outlet emissions and bag life. This survey involved visits to gather operating, maintenance and performance data at 36 sites representing 71 separate boiler/baghouse units, including concurrent and historical information regarding outlet emissions, pressure drop and bag life experience. The major findings of this survey with respect to PJFF performance are summarized below.

Pressure Drop

Consistent with previous literature, this survey confirms that pressure drop characteristics of well-designed and well-built PJFFs are reasonable and in general lower than exhibited by conventional reverse-gas baghouses operating at equivalent air-to-cloth ratios. Figure 2 is a plot of flange-to-flange pressure drop versus operating air-to-cloth ratio for all data gathered during the site visits to PJFF installations on pulverized coal- (PC) and stoker-fired boilers. The air-to-cloth ratios are based on the cloth area in service and on actual flue gas volumes observed at the time of the visit. In most cases, the observed flue gas volumes were calculated stoichiometrically based on boiler operating parameters and flue gas conditions at the time of the visit.

Superimposed on Figure 2 are shaded areas that represent ranges of pressure drop versus air-to-cloth ratio for shake-and-deflate (S/D) and reverse-gas-with-sonic-assist (RG/S) baghouses on utility boilers (4). Figure 2 indicates that for a given air-to-cloth ratio, flange-to-flange pressure drops are lower for PJFF installations on PC-fired boilers than for RG/S and S/D applications, and enable PJFFs to be sized and operated at higher air-to-cloth ratios than RG/S and S/D baghouses.

The scatter in Figure 2 is due mostly to the wide variety of coal types, fabrics, inlet loadings, ash characteristics and operation history of the bags. Also, the mechanical losses over and above the pressure drop across the tubesheet can vary significantly from one design to another. The nature of the pulse-jet cleaning cycle is such that it also can affect the pressure drop of a PJFF depending upon how the cycle is initiated and its timing and sequencing. Overall, the relationship between flange-to-flange pressure drop and air-to-cloth (A/C) ratio can be reasonably approximated for PC applications by:

$$\text{Flange-To-Flange } \Delta P = (1.7) \times (A/C) \quad \pm 40\% \qquad (1)$$

where air-to-cloth ratio is expressed in ft/min and pressure drop is expressed in inches H_2O.

Figure 3 is a plot of available tubesheet pressure drop information versus air-to-cloth ratio for PJFFs applied to PC- and stoker-fired boilers. The tubesheet pressure drop can be approximated for PC applications by the relationship:

$$\text{Tubesheet } \Delta P = (1.3) \times (A/C) \quad \pm 50\% \qquad (2)$$

where air-to-cloth ratio is expressed in ft/min and pressure drop is expressed in inches H_2O.

Effect of Boiler Type on Pressure Drop. Boiler type affects pressure drop performance of PJFFs. Note that the PJFF data values plotted on Figure 2 represent both PC- and stoker-fired units. In general, the PJFFs on stoker-fired boilers visited in the survey operate at lower pressure drops for a given air-to-cloth ratio than PC-fired applications. This was expected since the flyash particles generated by stoker firing tend to be coarser and more irregular than the ash produced by PC boilers.

This survey also indicates that PJFF pressure drop for AFBCs and CFBCs are slightly higher than for PC-fired boilers (about 1 in Wg or 0.25 kPa difference at an air-to-cloth ratio of 4 ft/min). Figure 4 shows flange-to-flange pressure drop versus air-to-cloth ratio for PJFFs applied to both circulating-fluidized-bed (CFBC) and bubbling-bed (AFBC) combustors. Flange-to-flange pressure drop for FBC applications of PJFFs can be approximated by:

$$\text{Flange-To-Flange } \Delta P = (1.9) \times (A/C) \quad \pm 30\% \qquad (3)$$

where air-to-cloth ratio is expressed in ft/min and pressure drop is expressed in inches H_2O.

Equation 3 is plotted on Figure 4. Also shown on Figure 4 is a plot of equation 1, the approximation of flange-to-flange pressure drop versus air-to-cloth ratio for PJFFs on PC boilers. These plots indicate surprisingly similar PJFF pressure drop performance for fluidized bed and PC-fired boilers.

The same FBC datapoints gathered by this survey when compared to data compiled by other EPRI-sponsored work suggest superior pressure drop performance by PJFFs than conventional reverse-gas, reverse-gas with sonic assist, and shake-deflate fabric filters for FBC applications. See reference (5) for a further discussion and graph of this comparison.

In addition to boiler type, other upstream conditions can affect particle properties and hence drag and operating pressure drop. The site visits included several installations that combine SO_2 removal with the PJFF; e.g., spray dryer absorbers and duct and furnace sorbent injection. These units tended to operate at lower pressure drops when compared to PC-fired applications operating at equivalent air-to-cloth ratios. This suggests that units employing either spray dryers or duct and furnace sorbent injection should not in general be a problem for pulse-jet applications.

Effect of Fabric on Pressure Drop. Fabric selection can affect PJFF pressure drop. Figure 5 compares tubesheet pressure drop versus air-to-cloth ratio for PC and FBC PJFFs employing felted fabrics to those using conventional woven fiberglass in weights of 16 oz./yd^2 (540 g/m^3) and 22 oz./yd^2 (750 g/m^3) or greater. This graph suggests that for a given air-to-cloth ratio, PJFFs using felted fabrics perform at pressure drops that are 1 to 2 in Wg lower than PJFFs using woven fiberglass bags. In other words, an air-to-cloth ratio of 4 ft/min (0.020 m/s) is adequate for many felted applications, whereas an air-to-cloth of 3 ft/min (0.015 m/s) may be necessary for woven glass to operate at the same pressure drop.

Particulate Emissions

Modern, well-built and properly maintained PJFFs using a variety of fabrics are quite capable of meeting EPA's New Source Performance Standards (NSPS) of 0.03 lb/10^6 Btu (approximately 30 mg/Nm^3). As shown on Figure 6, a significant number of the sites surveyed reported emission levels of well below the NSPS and comparable to emission levels achieved by conventional low-ratio baghouses. Inspection of the graph reveals that 75% of all the test results are less than the NSPS and 35% of the available test results were less than 0.01 lb/10^6 Btu ($\approx$ 10 mg/Nm^3). Opacities were usually well below 5%. Those units exhibiting emission levels in excess of the NSPS were older installations, early PJFF applications that are not required to meet stringent emission regulations, and installations operating at high air-to-cloth ratios and high cleaning frequencies.

The results presented in Figure 6 also have been sorted into two fabric categories. The first category includes the conventional heavier weight (≥ 22 oz/yd^2 or 750 g/m^2) woven fiberglass bags and all needle felts except Teflon. The second general category includes Teflon felt and conventional lightweight woven fiberglass of 16 oz/yd^2 (540 g/m^2). This second category was broken out from the rest since it was found to be more difficult to consistently achieve low emission levels with these fabrics. The lower collection efficiency of Teflon felts can probably be attributed to the large diameter Teflon fibers used. All conventional lightweight woven fiberglass bags applied today are constructed of double-warp face 16 oz/yd^2 cloth. This cloth design was observed to exhibit lower collection efficiency than any other group of fabrics observed in this survey.

By contrast, the conventional, double-filling face woven fiberglass bags of 22 oz/yd^2 (750 g/m^2) or greater are quite capable of achieving lower emission levels. Test results from the installations using these conventional, double-filling face woven glass bags exhibited emission levels consistently less than 0.02 lb/10^6 Btu (≈ 20 mg/Nm^3).

No correlations of air-to-cloth ratio versus outlet emissions could be observed in the data taken as a whole; although specific case histories of individual installations exhibited dramatic correlations between decreasing air-to-cloth ratios and decreasing emissions. Two such sites were required to provide additional cloth area by the installation of additional compartments so as to decrease emission levels to comply with the prevailing standards.

Bag Life

This survey suggests that for a properly designed and built PJFF with the appropriate fabric selection one can expect good felt bags to reach and exceed three years bag life. Bags constructed of Teflon and Ryton felt were found to provide bag lives of 3 to 4 years or more for a variety of flue gas conditions. Provided the bags are not subjected simultaneously to high temperature and acid/hydrolysis conditions, Nomex bags can provide similar lives downstream of spray dryers or FBCs. Dralon T appears to be an inexpensive and effective alternative; however, temperatures must be kept low (less than 260°F) and usually cooling of the flue gas is required. The information obtained during the survey for other felts such as P84, Huyglas and Tefaire was insufficient to project potential bag life.

This survey suggests that 2-year bag lives or longer are possible for woven glass bags constructed of conventional double-filling face cloth of 22 oz/yd^2 (750 g/m^2) or heavier; provided that the fabric and bags are fabricated properly and that the PJFF incorporates conservative air-to-cloth ratios, proper bag-to-cage fit and proper design details. However, the authors are aware of installations that apparently have observed such proper design and construction details but were unable to achieve reasonable bag lives with no firm evidence as to why the bags failed prematurely. Anyone contemplating the use of woven fiberglass bags

should ensure that the OEMs under consideration have successful experience with the cloth applied to similar boiler and flue gas conditions.

Synthetic felt bags are more forgiving of inadequacies in PJFF and bag design and construction and thus consistently exhibit longer bag lives than most woven glass installations. However, woven fiberglass bags can be purchased at a significantly lower cost than Nomex or Ryton bags. Thus, the tradeoff of bag life versus bag cost should be considered.

CONCLUSIONS

This survey has verified that pulse-jet baghouses have been applied successfully to coal-fired boilers worldwide. Although once feared to present a maintenance headache for large utility and industrial boiler applications, well designed and built PJFF installations have proven such concerns to be unfounded. To ensure adequate performance and long component life, design fabrication and construction details cannot be ignored. Poor gas flow distribution into compartments, high velocities between bags, misaligned and poorly made pulse pipes, cheap construction materials and components, misapplication of fabrics and poor startup and shutdown procedures are factors that have contributed to excessive component failure, pressure drop, outlet emissions and bag replacement rates in the few installations which reported such problems.

For a given air-to-cloth ratio, pressure drops are lower for PJFFs than for reverse-gas-with-sonic-assist (RG/S) and shake-and-deflate (S/D) baghouses on all types of boilers. This enables PJFFs to be sized and operated at higher air-to-cloth ratios than RG/S and S/D baghouses. Our survey shows that an average flange-to-flange pressure drop of 4 to 6 in Wg (1.0 to 1.5 kPa) can be expected for PJFFs using needle felts and operating at an air-to-cloth ratio of 4 ft/min (0.020 m/s).

Modern, well-built and properly maintained PJFFs using a variety of fabrics are quite capable of meeting EPA's New Source Performance Standards (NSPS) of 0.03 lb/10^6 Btu (approximately 30 mg/Nm^3). A significant number of the sites surveyed reported emission levels of well below the NSPS and comparable to emission levels achieved by conventional low-ratio baghouses. To achieve today's more stringent emission requirements, generally more conservative air-to-cloth ratios than applied in the past are required. Whereas, at once time, an air-to-cloth ratio of 5 to 7 fpm was considered adequate for a PJFF; these days, air-to-cloth ratios approaching 4 fpm or less should be considered for a new installation using felted cloth. Lower air-to-cloth ratios in the range of 3 fpm or lower should be considered for those installations which plan to use woven fiberglass.

For a properly designed and built PJFF with the appropriate fabric selection one can expect good felt bags to reach and exceed three years life. Bags constructed of Teflon and Ryton felt

were found to provide bag lives of 3 to 4 years or more for a variety of flue gas conditions. Provided the bags are not subjected simultaneously to high temperature and acid/hydrolysis conditions, Nomex bags can provide similar lives downstream of spray dryers or FBCs. Two-year bag lives or longer are possible for woven glass bags constructed of conventional double-filling face cloth of 22 oz/yd^2 (750 g/m^2) or heavier; provided that the fabric and bags are fabricated properly and that the PJFF incorporates conservative air-to-cloth ratios, proper bag-to-cage fit and proper design details.

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- the Howden companies worldwide including, James Howden Australia, Howden Environmental Systems and their licensee in Japan, Mitsubishi
- Environmental Elements Corporation
- Wheelabrator Air Pollution Control and their licensee in Japan, Sinto Dustcollector
- Lurgi GmbH
- Bühler Brothers, Ltd. and Bühler-Miag
- Heinrich Lühr, GmbH and Interel in the U.S.A.

And, finally, we graciously thank the owners and operators of the plants which allowed site visits and their innovative plant operating, maintenance and engineering personnel who contributed considerable amounts of time, effort and expertise.

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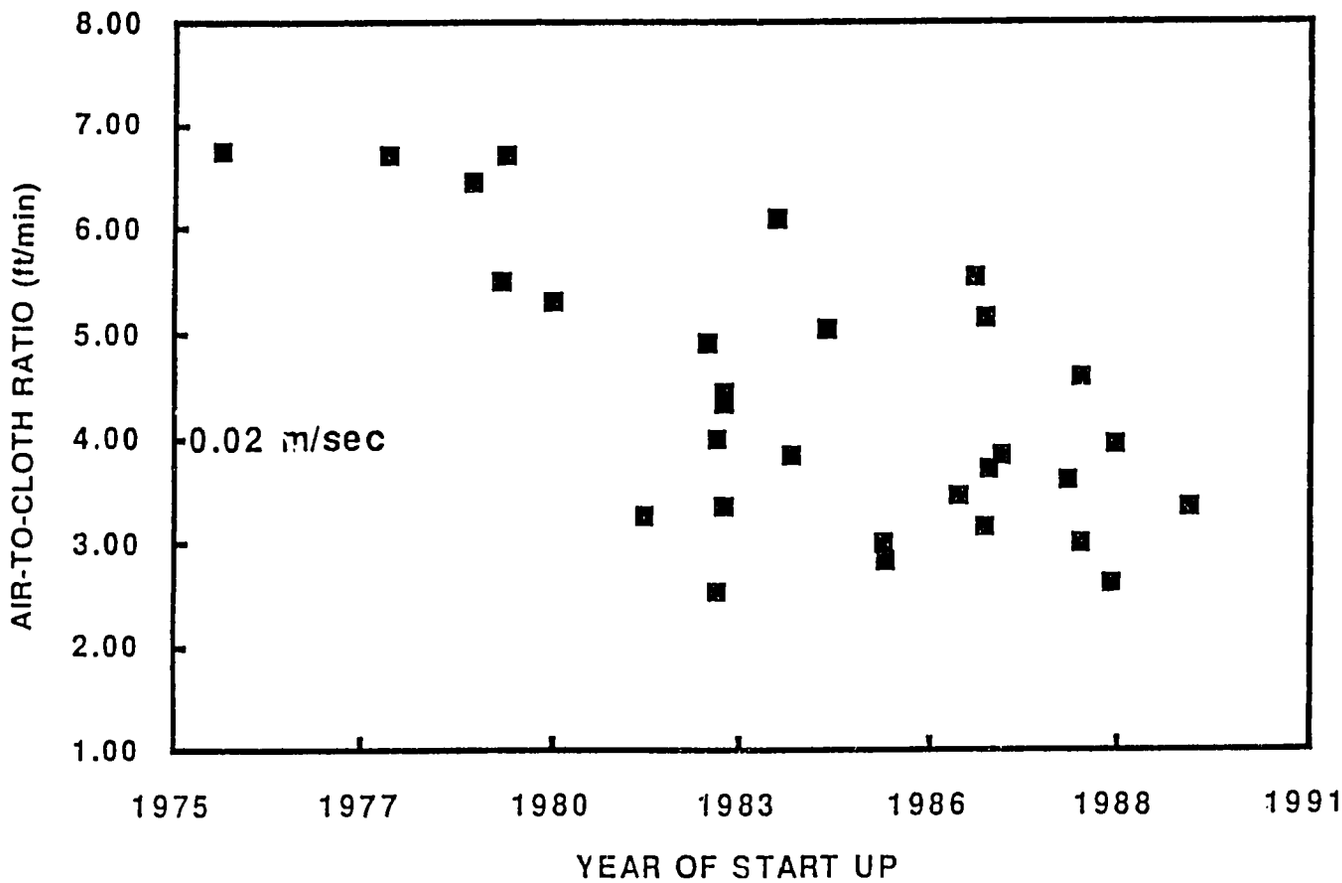

Figure 1. Design Air-to-Cloth Ratio vs. Start-up Date

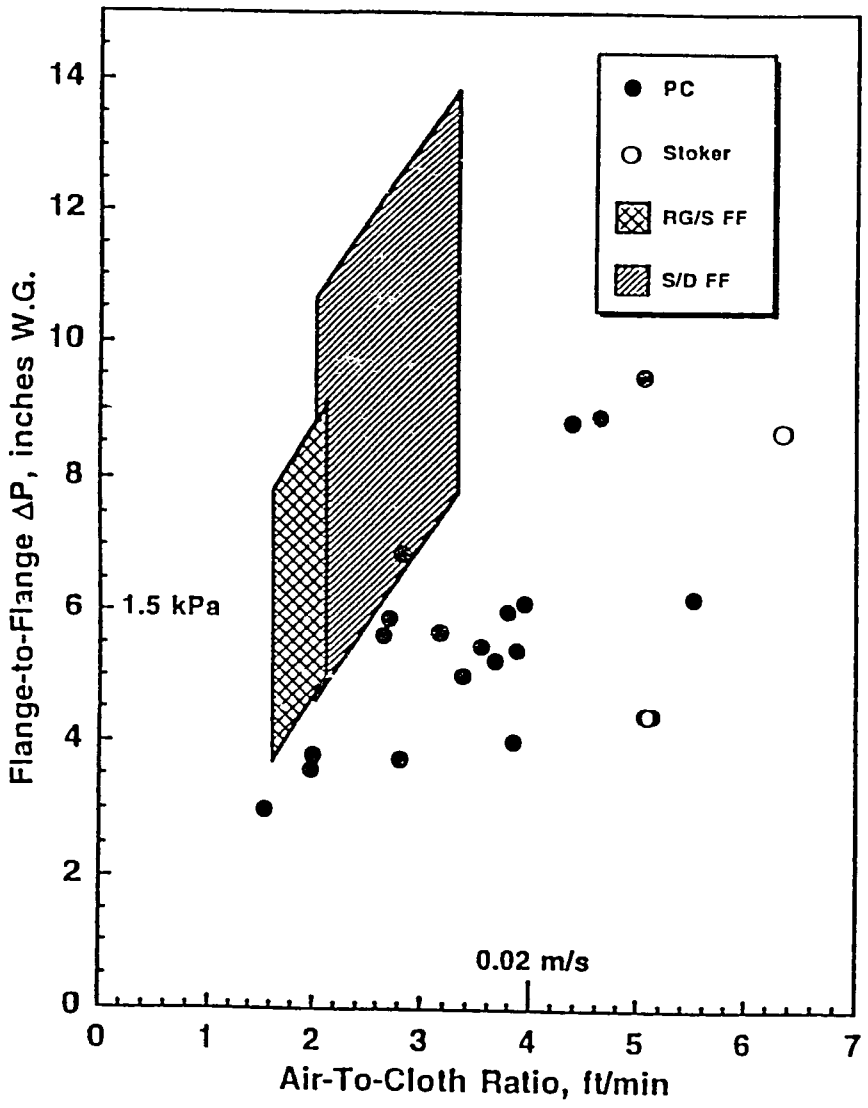

Figure 2. Flange-to-flange pressure drop vs. air-to-cloth ratio for PJFFs on PC-fired and stoker-fired boilers compared to reverse-gas with sonic assist and shake-and-deflate baghouses.

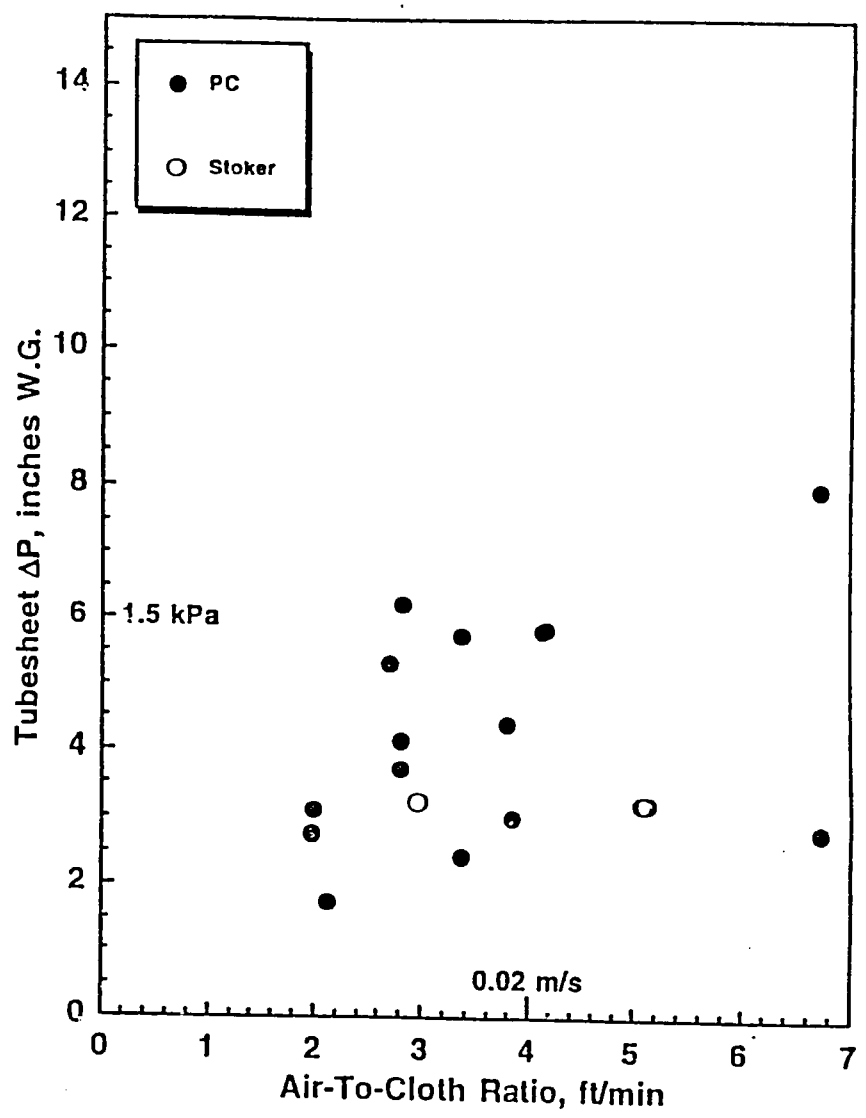

Figure 3. Tubesheet pressure drop vs. air-to-cloth ratio for PJFFs on PC- and stoker-fired boilers.

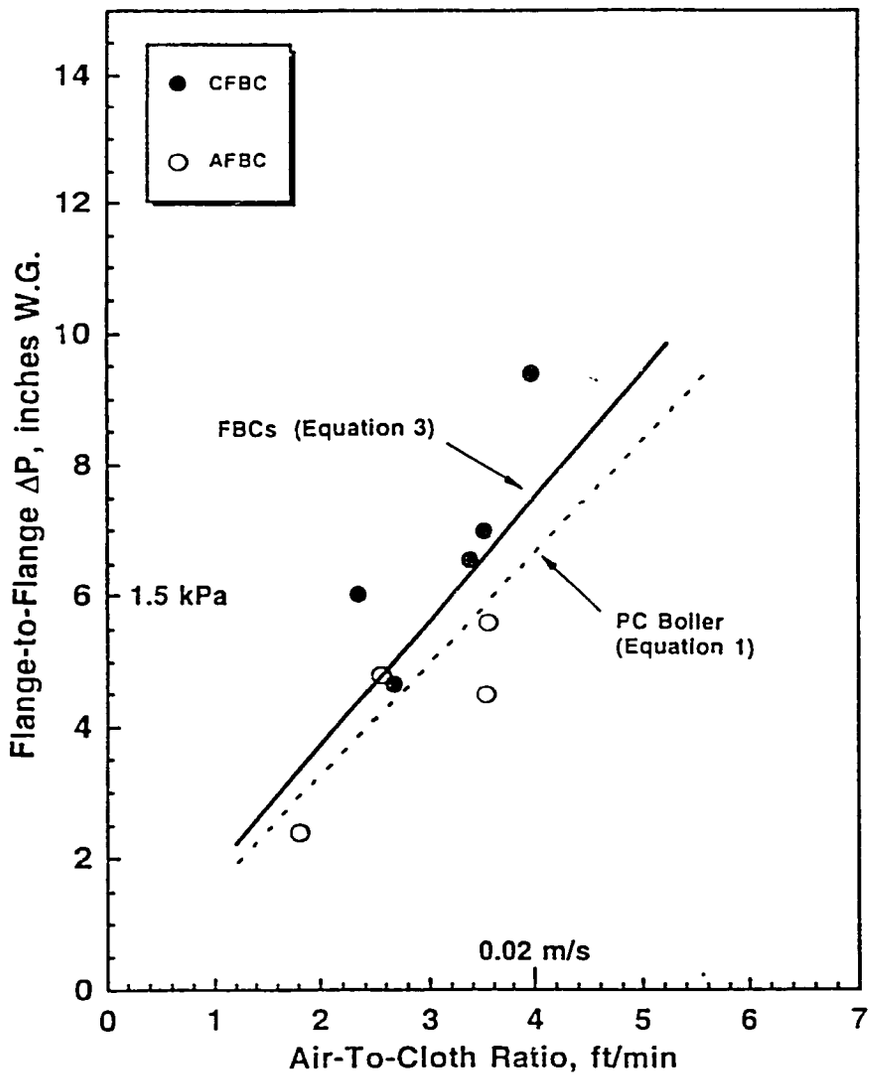

Figure 4. Flange-to-flange pressure drop vs. air-to-cloth ratio for PJFFs on fluidized- bed combustors.

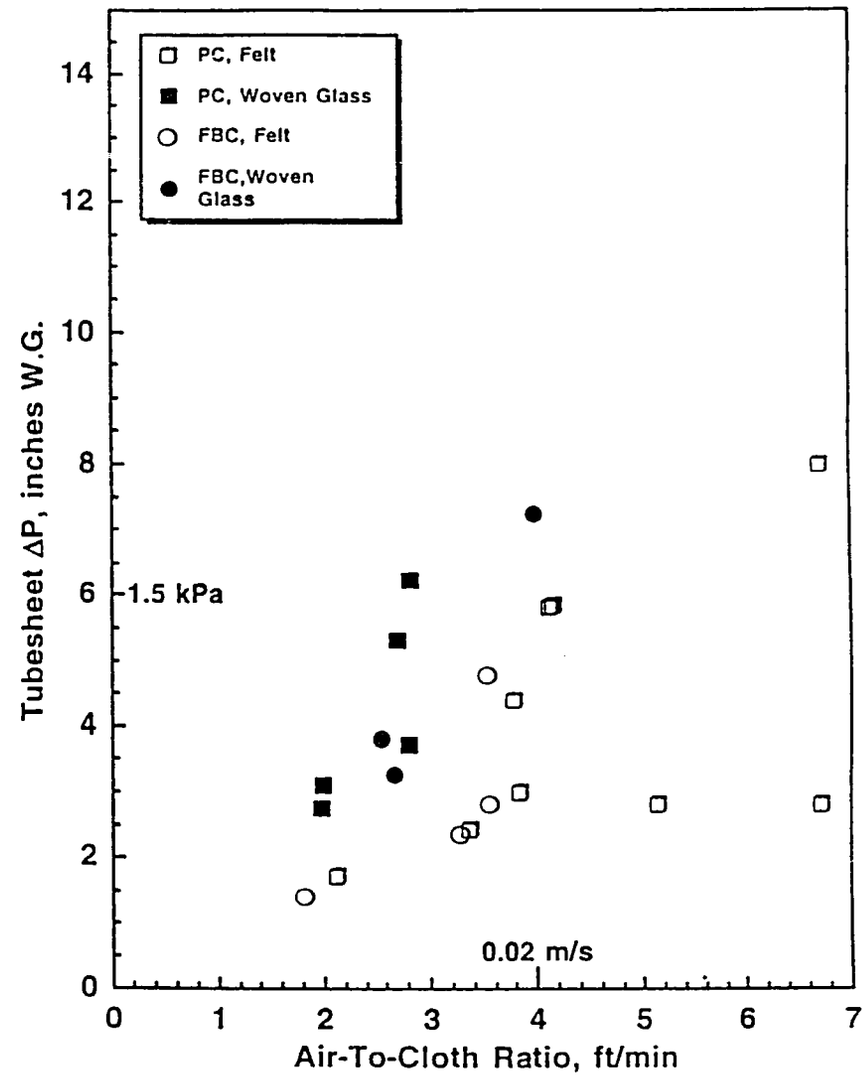

Figure 5. Tubesheet pressure drop vs. air-to cloth ratio for PJFFs on PC-fired boilers and fluidized-bed combustors.

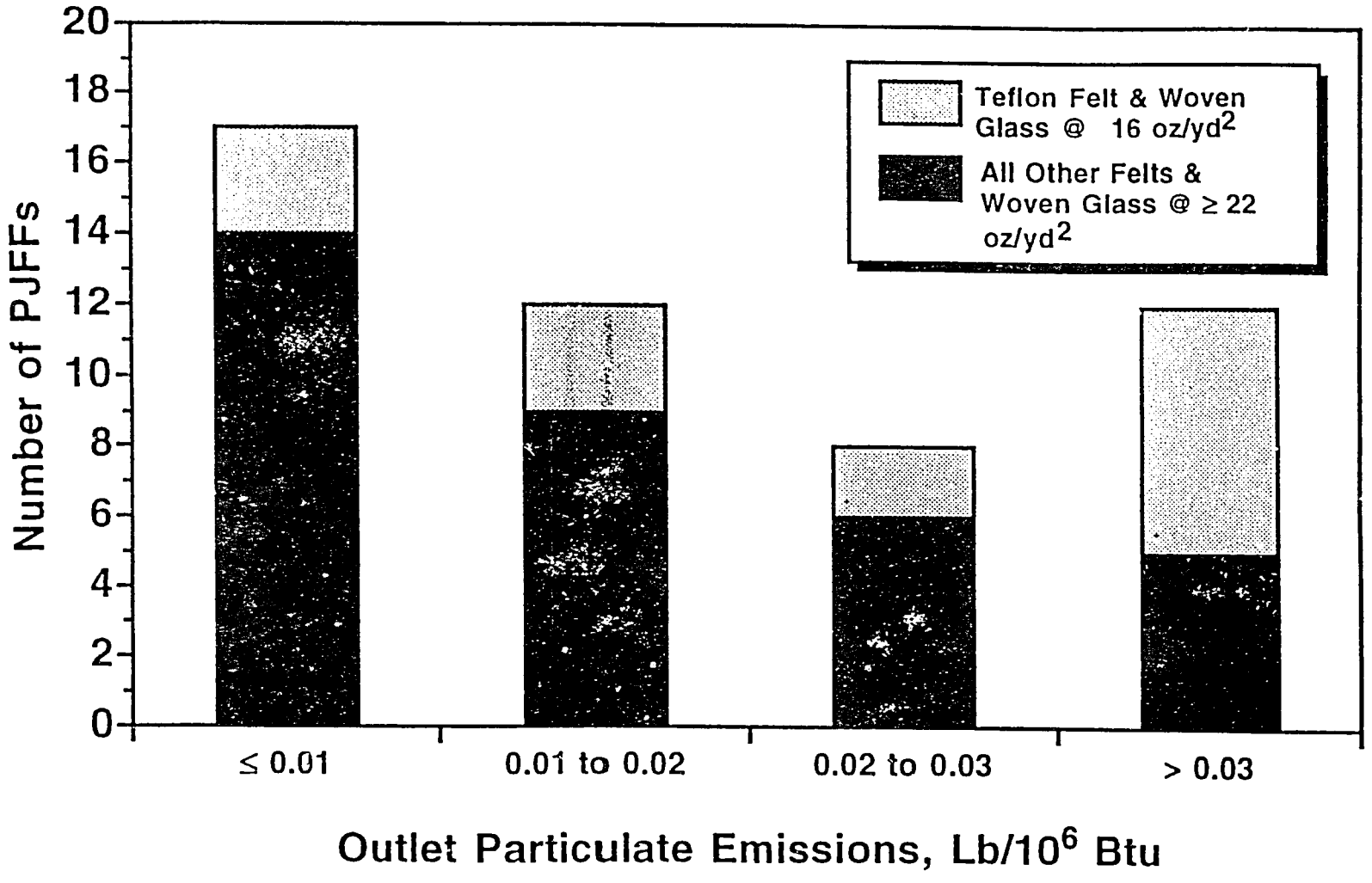

Figure 6. Particulate Mass Emissions for all Baghouses in Survey

APPENDIX G-7

FABRIC SELECTION...
EFFICIENCIES AND ECONOMICS

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FABRIC SELECTION...EFFICIENCIES AND ECONOMICS

by Donna Witt, BHA Group, Inc.

For today's production sector, operating at maximum efficiency while purchasing equipment has become a real challenge. Fabric selection for your fabric filter dust collectors represents a major investment as well as a highly technical decision which warrants extensive evaluation. There are many fabrics and fabric blends available for the combustion industry today, with each fabric taking on characteristics from the fiber used to produce the material. The following are the primary fibers used in fabric construction for our industry and their typical characteristics.

FIBER CHARACTERISTICS

Acrylic

A manufactured fiber in which the fiber-forming substance is any long chain synthetic polymer composed of at least 86% acrylonitrile. Acrylics offer a good combination of abrasion and heat resistance under both wet and dry conditions. They have the ability to withstand a hot acidic atmosphere. In dry heat, acrylics are superior to nylon and natural fibers, but inferior to polyesters, Teflon® and Nomex® nylon. In moist heat, they are rated below Teflon and Nomex, but superior to polyesters, nylon, rayon and natural fibers. Homopolymers, composed of 100% acrylonitrile units, offer a good hydrolytic resistance, and are recommended for temperatures up to 284°F, while copolymers are recommended for temperatures up to 248°F.

Acrylics provide satisfactory resistance to moist mineral or organic acids and are superior to aromatic aramids, polyamides, polyesters and cellulose fibers but less resistant than other synthetics. They offer fair resistance to alkali, being equal to polyester, but less resistant than most other synthetic fibers. Acrylics are resistant to most common organic solvents.

Nomex®

Nomex® is used in systems with elevated dry heat temperatures. It can withstand continuous operating temperatures up to 375°F and still maintain its excellent physical properties and dimensional stability. It will not melt, but rapidly deteriorates at temperatures above 700°F. Nomex is unaffected by small amounts of water vapor at high temperatures. When exposed to saturated steam at high temperatures, Nomex will progressively lose strength.

Nomex has excellent flex resistance at room temperatures, about equal to polyester fibers. After aging at temperatures above 275°F, its abrasion and flex resistance remains good. Nomex withstands attacks by mold minerals and organic acids, mild alkalies and most hydrocarbons. It is unaffected by fluorines and gas from metallurgical and rock-processing operations. However, highly active oxidizing agents such as sulfur oxides will rapidly degrade Nomex.

Ryton®

Ryton® is a manufactured thermoplastic fiber formed of a long-chain synthetic polysulfide with at least 85% of the sulfide linkages attached directly to two aromatic rings. This fiber may be converted into either woven or felted filter media with good filtration properties, abrasion resistance and stability. Ryton provides very good performance in operating temperatures up to 375°F with surges up to 450°F. It has a melting point of 545°F and is rated nonflammable. Ryton exhibits excellent resistance to chemical attack by most acids and alkalies. Only bromine in some instances and strong oxidizing agents cause degradation. Ryton is not soluble in any known solvent below 392°F. Above this temperature, the fiber shows limited solubility in a few solvents. It is not recommended for applications with more than 15% oxygen present.

P84®

P84® is a thermostable organic fiber of synthetic origin. Its properties are characterized by the copolymide structure. The irregularly lobed P84 fiber has proven to produce a highly efficient felted filter media with excellent filtration and release properties. It has acceptable abrasion resistance and stability. P84 has a maximum continuous operating temperature of 500°F and will withstand short temperature surges to 580°F. P84 will not support combustion. Resistance to all common organic solvents is very good. Resistance to mineral and organic acids is good and resistance to alkalies is fair within the pH range of 5-9. Highly alkaline environments–especially at the higher temperature limits of the fiber–should be avoided. P84's resistance to oxidizing agents is fair.

Glass Felt

Huyglas® filter fabric has a scrim supported, resin coated, 100% fiberglass needled felt structure. This product was designed for use in high temperature pulse-jet baghouses. Huyglas felt has good filtration properties, but proper bag-to-cage fit and support are critical to maximize performance. The maximum continuous operating temperature for Huyglas fabric is 500°F and will withstand short term surges to 550°F. Huyglas fabric will not support combustion. Huyglas fabric exhibits good resistance to acids and alkalies with the exception of fluorides which can attack all glass-based fabrics. Resistance to organic solvents and oxidizing agents is generally very good.

Teflon®

Teflon® is a manufactured fiber composed of long chain carbon molecules in which all of the available bonds are completely saturated with fluorine. These strong carbon-to-fluorine bonds create fibers that are exceptionally stable to both heat and chemicals. Teflon is the most chemically resistant fiber used in filtration.

Teflon is not affected by any known solvents except some prefluorinated organic liquids at temperatures above 570°F. At elevated temperatures, it resists the effects of concentrated organic acid, alkalies, mineral acid, organic solvents and oxidizing agents. Teflon fibers remain flexible and non-brittle at temperatures ranging from -100°F to 550°F. Exposure to temperatures above 550°F will cause some decomposition, although it is slow to develop.

The low friction properties of Teflon fibers provide excellent cake discharge. In addition, Teflon's chemical inertness and resistance to dry and moist heat degradation makes it ideal for use under severe conditions.

Woven Fiberglass

Fiberglass is used extensively in high temperature applications. Fiberglass has proven its ability to operate effectively at 500°F and is considered a cost-effective alternative when compared to other synthetic products. Fiberglass has high tensile strength properties and good stability. When constructed with texturized yarns in a twill weave design, fiberglass is an efficient filter media. Fiberglass absorbs no moisture. With proper finish and under normal conditions, it is resistant to the effects of normal strength acids. It degrades when exposed to hydrofluoric acids, hot phosphoric acids and concentrated sulfuric acids.

When coronized (heat cleaned) and properly finished and cured, fiberglass will perform in most hot gas applications. Operating conditions and gas stream chemistry review is recommended for the fiberglass construction and finish selection.

Each fiber's performance is effected by system operating parameters. Temperatures, abrasion, energy absorption, filtration properties, moist heat hydrolysis, chemical resistance and cost should all be considered when evaluating a fabric for your specific application. The following chart is a guideline to use when evaluating fabric properties.

	Acrylic	Fiber-glass Woven	Fiber-glass Tri-Loft™	Nomex®	Ryton®	P84	Glass Felt	Teflon®
Temperature (°F) Maximum continuous operating temperature	275°(a)	500°	500°	375°	375°	500° (a)	500°	500°(a)
Abrasion General mechanical durability	Good	Fair (b)	Fair (b)	Excellent	Good	Fair (b)	Fair (b)	Good
Energy Absorption Ability to withstand cleaning action	Good	Fair	Good	Good	Good	Good	Good	Good
Filtration Properties Ability to collect particulate & maintain airflow at acceptable level	Good	Fair	Good	Very Good	Good	Excellent	Good	Fair
Moist Heat Review gas stream chemistry	Excellent	Excellent	Excellent	Good	Excellent	Good	Excellent	Excellent
Alkalines Review gas stream chemistry	Fair	Fair	Good	Good	Excellent	Fair	Good	Excellent
Mineral Acids (Inorganic) gas stream chemistry	Good	Poor (c)	Good	Poor	Excellent	Good	Good	Excellent
15% Oxygen 15% at 350°F	Excellent	Excellent	Excellent	Excellent	Poor	Excellent	Excellent	Excellent
Relative Value $$ = Low $$$$$$ = High	$$	$$$	$$$	$$$	$$$$	$$$$$	$$$$	$$$$$$

(a) = *Stability factor* (b) = *Sensitive bag-to-cage fit* (c) = *Fair with Acid Resistant finish*

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COLLECTION EFFICIENCY AND OPERATING PARAMETERS

In order for a baghouse to operate efficiently, the fabric filter must be capable of capturing and then releasing the particulate. The fabric filter serves as a support structure for the dustcake that develops during the filtration process. It is the dustcake itself that actually does the filtering of particulate. In order to make the best fabric selection, it is imperative to analyze the particulate within the collector. It is important to ask three questions regarding particulate:

- How fine is the particulate?
- What percentage of the particulate is below 1 micron?
- What is the particle size distribution?

A 1-5 micron count is usually easily collected on the filtration surface of a standard felted media. Particulate 1 micron or below in size may not be captured on the bag and can critically effect plant operations. Particulate distribution is just as important as the size of the particulate. In order to create the most efficient dustcake with adequate release properties, particulate with varying shapes and sizes should be evenly distributed on the collection surface of the bag. This protects the fabric from leakage while still allowing sufficient airflow for filtration.

One way to determine filtration efficiency (highest collection with lowest resistance) with a given particle size and distribution is the Variable Environmental Simulation Analysis (VESA) test. This test is a method by which a collector's operating parameters are duplicated to evaluate fabric candidates. The VESA test is a chamber test run with the identical grain loading, air velocities and baghouse particulate as the collector. The information the VESA test can yield is the particle size analysis of the ash as well as the filtration efficiencies of the fabric candidates.

The efficiency of a fabric is the relationship of the inlet grain loading to the outlet emissions:

$$\textbf{Fabric efficiency} = \frac{(I-O) \times 100}{I}$$

I = Inlet Grain Loading
O= Outlet Emissions

The following is an example of the results from a VESA test performed on a fluidized bed boiler. The inlet grain loading is 12 GR/DSCF. The outlet emissions limitation is .01GR/DSCF. Using this information, the required filter efficiency can be calculated.

Example:

$$\textbf{Efficiency limit} = \frac{(I-O) \times 100}{I} = \frac{(12-.01)}{12} \times 100 = 99.917\%$$

The data gathered by the VESA test is then compared with the efficiency limit. On the following page is the result of a VESA test:

Fabric	Efficiency	GR/DSCF
14 oz. P84	99.990%	.0012
14 oz. Nomex®	99.981%	.0024
16 oz. Tri-Loft®	99.970%	.0036
Huyck 1701	99.970%	.0036
Ryton®	99.947%	.0064
22 oz. Glass	99.923%	.0092

Converting grains/DSCF to lbs/Hr:

$$F(x) = \frac{(\text{SCFM})\ (\text{Outlet Emissions})}{7{,}000\ \text{Gr/lb}} \times (60) = \text{lbs/Hr}$$

F(limit) = 4.88 lbs/hr

F(P84) = .586 lbs/hr
F(Nomex) = 1.172 lbs/hr
F(Tri-Loft) = 1.759 lbs/hr
F(Huyck) = 1.759 lbs/hr
F(Ryton) = 3.13 lbs/hr
F(22 oz. woven glass) = 4.495 lbs/hr

This information must then be evaluated along with chemical, thermal, physical and cost variables. The VESA test will provide fabric candidates from an emissions standpoint. The remaining factors can be accurately evaluated by knowing the system's operational parameters.

FABRIC CONSTRUCTION

It is important to remember the basis of dry dust collection and filtration when utilizing a textile media. The fabric performs very little of the actual filtering, yet provides a substratum or matrix for the dustcake to form. This primary dustcake, if allowed to properly develop with adequate thickness and porosity, collects the particulate and allows air to flow through the fabric. Therefore, it is critical to consider a fabric construction that forms a collection surface permitting development of a loose and porous cake. The ultimate construction must also provide for cake release to occur with the cleaning cycle, as a good regeneration of permeability.

As with any filtration fabric, durability is a critical feature. The fabric must be designed to withstand mechanical forces; i.e. tensile stress and abrasion. The following illustrations represent the construction basics for both felted and woven fiberglass fabric, with the concentration being on woven fiberglass products.

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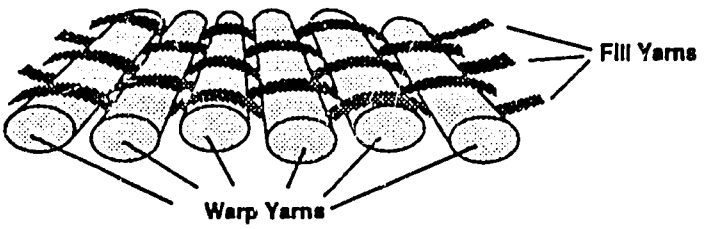
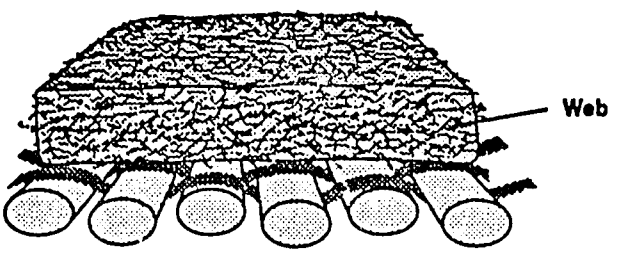
FELT FABRIC CONSTRUCTION

Base fabric



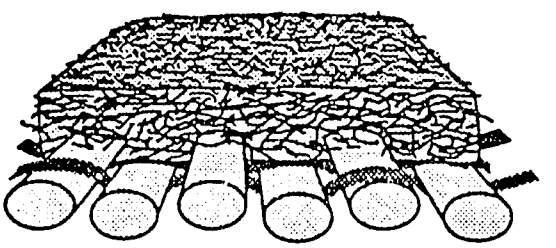
Step 1: A woven fabric is used as a base on which the felt is built.

Web on base



Step 2: A web of carded fibers is laid on the base fabric.

Web needled into base



Step 3: Together they are passed through the needling machine where barbed needles punch the web fibers into the woven base fabric. This operation may be repeated with several webs to increase fabric thickness.

WEIGHTS

Weights: oz./sq. yd. commonly used:

Nomex®:	14 and 16 oz.
Ryton®:	16 oz. (some 18 and 22 oz.)
P84:	14 oz.
Huyck felt:	16 and 26 oz.
Teflon:	21 and 23 oz.

Finishes (Mechanical)

Calendar :	Compressing or compaction process for density
Heat Set:	Pre-shrinking for thermal stability
Singe:	Surface fiber is removed by controlled direct flame to enhance cake release.
Glaze:	Surface fiber is melted and compressed to a smooth finish

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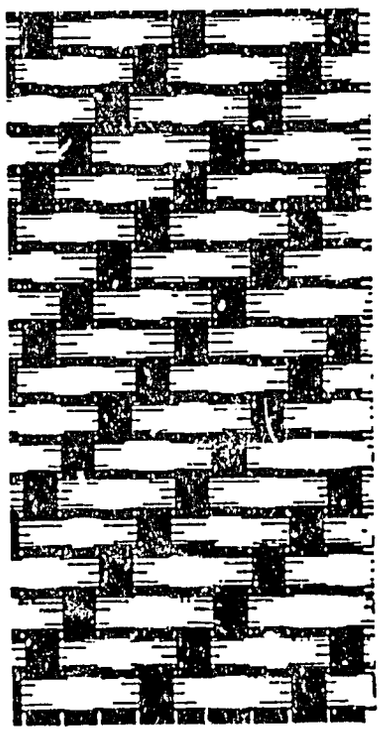
WOVEN FIBERGLASS CONSTRUCTION

Woven fiberglass filtration fabrics utilize two basic types of yarn. The first type, called filament yarn, is characterized by a tightly wound, rod-like appearance which presents a slick flat surface with a very small surface area. The dustcake formed on an all-filament fabric is very dense and compact due to its flat surface area. As a result, filament fabric has limited airflow capacity, but good dust release characteristics.

The second yarn type is called a texturized yarn. As a texturized yarn is manufactured, bursts of air are applied to the glass, giving it a loft or bulky appearance to maximize filtration efficiency. These physical characteristics provide a fabric with a much larger filtration surface area. Due to the bulkier nature of the texturized fabric, a more porous dustcake is formed on the surface of the filter media. This loose dustcake provides greater airflow than filament fabrics while still promoting dust release. The additional surface area results in a fabric which has better abrasion resistance, as well as increased collection efficiency and airflow characteristics when compared to a filament fabric. The actual construction method of a fiberglass woven media is extremely important in realizing optimum filtering capability and bag life. The nature of the fiberglass yarn is such that is extremely susceptible to abrasion, both against itself and against other surfaces. Therefore, it is common that in the warp (lengthwise) direction, where much of the bag's integral strength resides, a non-plied filament yarn be utilized. In fiberglass construction nomenclature, this is designated as a singles yarn. Testing has shown that original MIT flex cycle endurance is greater with singles yarns when compared to plied yarns. However, in the fill direction (bag circumference), where much of the filtration occurs, singles yarns do not provide adequate surface area to accomplish this task.

Because the texturized yarns do not provide the strength of continuous yarns, several texturized yarns are plied together to provide greater strength. This process also increases the yarn bulk, providing a loftier surface for efficient collection and filtration. These construction techniques allow for both strength in the warp direction and filtering efficiency in the fill direction while not sacrificing bag integrity.



3x1 Twill Weave (Fill Side)

Woven fiberglass fabrics typically use a twill type weave which features the following:

- A fundamental weave common to woven filtration fabrics
- High bulk yarns are normally used
- Characterized by the warp yarn passing over more than one fill yarn
- Has more surface (bulked) area on one side, allowing for filtration efficiency
- Structure is flexible which allows for yarn movement and has less tendency to blind
- Interstices (voids at crossover points of warp and fill yarns) are hidden by yarn and are more difficult to penetrate
- a straight twill has a defined warp yarn surface of a diagonal channeled pattern
- A broken twill or "crowfoot" is similar to straight twill in crossover points but without the diagonal pattern
- Satin or sateen weave is a twill with more defined warp and fill yarn surfaces

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Chemical Finishes

Fabric weights commonly used for Pulse-Jet & Reverse Air Collectors	
9-10 oz.	Reverse Air Only
12 oz. Nominal	Reverse Air Tri-loft
13.5 oz.	Reverse Air Only
16 oz.	Pulse-Jet Only
22 oz.	Pulse-Jet Only
16 oz.	Tri-loft for Pulse-Jet

SGT: A blend of silicone oils, graphite and PTFE to provide yarn lubrication or protection from abrasion. Minimal protection from chemical attack.

Acid Resistant: Acid resistant polymers, PTFE, graphite and silicone oils forming a protective barrier around glass surface to shield from attack.

Teflon B®: PTFE particle encapsulation of glass fibers to prevent abrasion; can be attacked chemically by acids or alkalies.

Blue Max CRF/70: A formula composed of a polymer ; prevents chemical attack of glass filaments, and PTFE provides superior abrasion resistance. Resistant to acid and alkali attack.

TRI-LOFT FABRIC

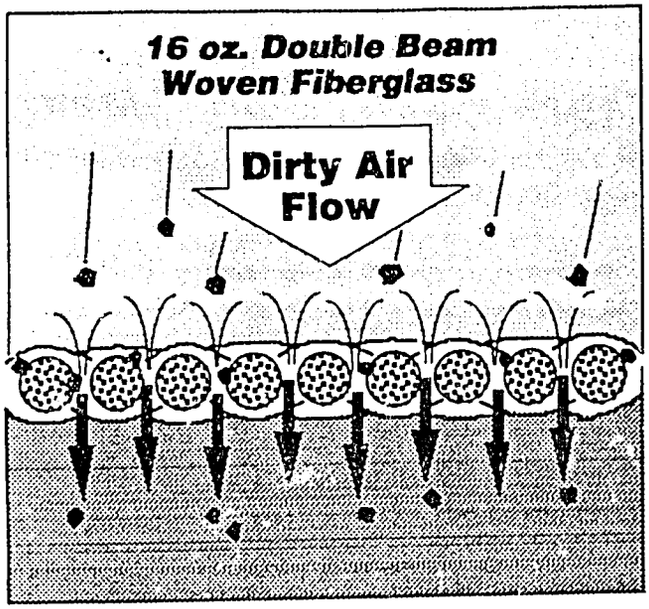
A new fabric has been designed and proven to solve airflow and emission problems in the combustion industry. The following design characteristics improve airflow capability as well as prevent blinding and bleedthrough of filter bags.

- Tri-Loft is constructed of highly texturized bulky yarns on the filtration surface adding surface area, depth and felt-like density. These three-dimensional characteristics provide maximum efficiencies and high airflow capabilities. Durability is also enhanced with increased resistance to abrasion from particulate or other mechanical forces.

- Blue-Max-CRF/70® is an advanced chemical resistant finish providing state-of-the-art glass fiber encapsulation. Loss On Ignition (LOI) = 9% minimum. This finish provides superior resistance to acid attack and alkaline conditions. Increased flex endurance and abrasion resistance extend durability and bag life. Excellent dustcake release properties provide for lower operating pressure and improved airflow capabilities.

- Tri-Loft offers a fiberglass media for chemically active gas streams with operating temperatures to 500°F. The unique construction provide a lower cost alternative to other high temperature fabrics.

The illustrations on the following page are designed as examples of problems Tri-Loft solves when compared to conventional pulse-jet woven fiberglass fabrics:

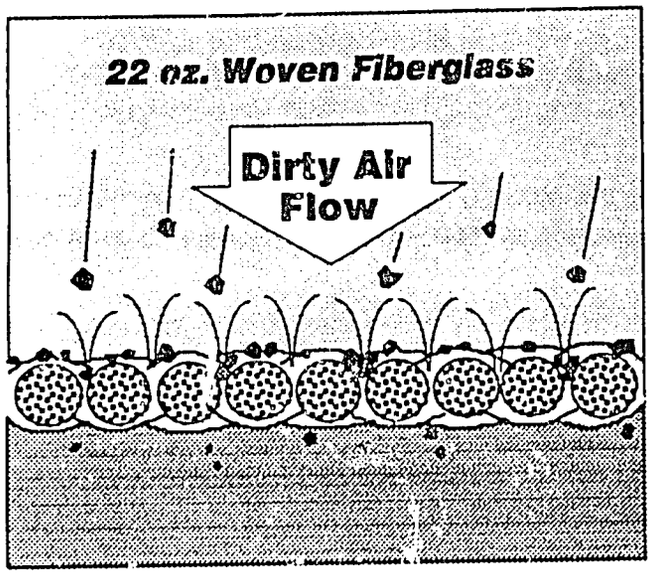


Common Problem:

Fine particulate leakage occurs through weave interstices.

Minimal collection surface area exists for developing porous primary dustcake.

Failures occur due to overcleaning.



Common Problem:

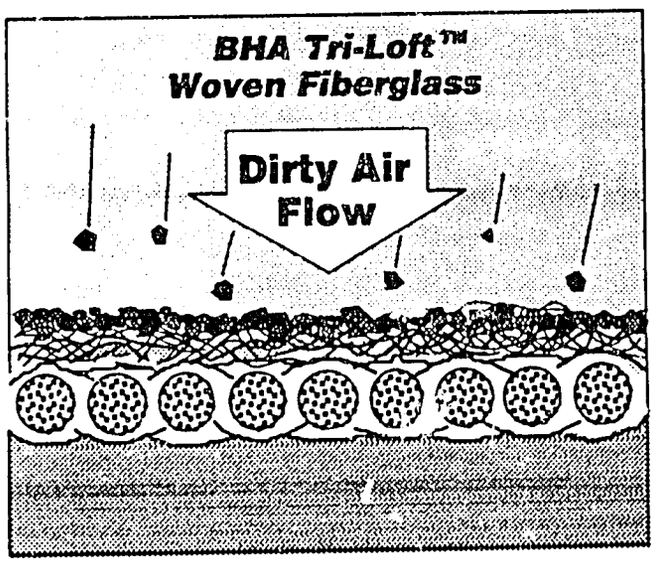
Limited airflow due to tighter weave

Minimal collection surface area exists for developing porous primary dustcake.

Dust impingement and blinding occur due to exposed weave interstices.

High pressure drop causes fine particulate to leak through interstices.

Failures occur due to overcleaning.



Solution:

Lofty surface area protects weave interstices from fine particulate leakage, dust impingement and blinding.

Development of porous primary dustcake on lofty surface area allows for even airflow, low operating pressure drop and reduced cleaning cycles.

Improved mechanical durability with high texturization and Blue Max-CRF/70 finish. Improved abrasion resistance and cake release.

Tri-Loft has been extensively tested through independent laboratories that simulate actual baghouse conditions. Below are test results from two of the numerous scientific test performed comparing conventional woven fiberglass fabrics to Tri-loft used in a pulse-jet as well as reverse air collectors:

All data was taken from a simultaneous 12 hour test with dust loading at 10 grains/ACF with 4:1 air-to-cloth ratio. Pulse cleaning was performed at same frequency and duration for each fabric tested.

Pulse-Jet Fabric Type	Operating Efficiency	Percentage Leakage	Operating Pressure
16 oz. Tri-loft	99.996%	.004%	3.90" w.c.
22 oz. Woven Fiberglass	99.958*	.042%	3.85" w.c.
16 oz. Double Beam	99.936%	.064%	3.20" w.c.

All data was taken from a simultaneous 40 hour test with dust loading at 15 grains/ACF with 2.7:1 air-to-cloth ratio. Reverse air cleaning was performed at the same frequency and duration for each fabric.

Reverse Air Fabric Type	Operating Efficiency	Percentage Leakage	Operating Pressure
9.5 oz. Woven Fiberglass	99.881%	.119%	3.90" w.c.
13.5 oz. Woven Fiberglass	99.980%	.020%	4.60" w.c.
Tri-Loft Woven Fiberglass	99.992	.008%	3.90" w.c.

CASE STUDY

Baghouse Specifications:

Baghouse Type:	Wheelabrator UltraJet III
Inlet Temperature:	300°F
Gross Air-To-Cloth Ratio:	3.5:1
Net Air-To-Cloth Ratio:	4.75:1
Inlet Loading Design:	2.5 Grains/ACF
Inlet Loading Estimate:	5.0 Grains/ACF
Particulate Description:	Median population count 0.672 micron 70.66% of particulate under 1 micron
Outlet Emission Requirements:	.0098 grains/ACF or 98.804% efficiency

Boiler and Fuel Description:

Foster Wheeler stoker fired boiler followed by mechanical collector
Low Sulfur Bituminous Coal (.62% sulfur)

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Historical Perspective

This facility originally installed 22 oz. fiberglass and the system was started up with one row of mechanical collectors removed. Eight to 10 months into the operation, the row of mechanical collectors was re-installed. This decreased the uniform size of the particulate. Within 4-6 months, differential pressure climbed to a point where the filter bags had to be removed.

They re-installed 22 oz. fiberglass and within three months, the units were in constant cleaning and experiencing differential pressure of 8"-9" and were experiencing opacity problems. After 8 months of service, the differential pressure was 10"-11" and as high as 12-13". The baghouse was still cleaning constantly and the opacity was running betwen 12-18%. The filter bags were showing signs of wear; holes were occuring. This type of operation caused boiler draft to be reduced. This boiler load resulted in a decreased production of electricity.

A VESA test was conducted to determine which fabric would best improve their situation. The test results are shown below:

Delta P	Fabric	VESA Result
3.2	P84	99.995
3.6	16 oz. Hyglass	99.993
3.4	14 oz. Nomex	99.990
3.6	16 oz. Ryton	99.985
3.5	Tri-Loft	99.905
3.7	18 oz. Ryton	99.991
4.2	GL04	99.905
4.3	GL59	99.958

Result:

Tri-Loft was installed in late December, 1990. Differential pressure has been consistent between 4"-5.5". During peak periods, the unit cleans on the average of 4 rows every hour. Boiler load during peak periods is operating at 110-115% capacity. Opacity is low and stack is free from emissions.

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APPENDIX G-8

NEW CONCEPTS FOR CONTROL OF FUGITIVE PARTICLE EMISSIONS FROM UNPAVED ROADS

by

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ABSTRACT

An analysis of the forces that produce emissions from unpaved roads shows that if fine material can be reduced or moisture increased, emissions will be reduced. Instead of collecting emissions, this new approach would decrease the emissions by reducing the fine material or by making minor increases in the moisture content of the road. In either case, a stable, rot-resistant, water-permeable fabric would be used to separate road ballast from the subsoil. Preliminary evaluation and economic analysis indicate that roads constructed in this way can be cheaper than conventional unpaved roads when subsoil load-bearing characteristics are poor.

Construction and testing of a prototype road is anticipated in 1979. The paper describes the theoretical analysis, preliminary results, and economic analysis of the idea.

INTRODUCTION

Fugitive emissions from vehicular movement on unpaved industrial haul roads are a major source of respirable emissions in urban areas. Current control methods, which include water wetting, treatment with surface agents, soil stabilization, paving, and traffic control, have thier own merits and limitations. Environmental problems could result from surface agents (such as oil) leaching into streams. Safety problems could result from slippery and dangerous road conditions. High initial cost and subsequent maintenance and repair costs make otherwise effective control measures (such as paving) impractical.

A new concept for emissions control has been proposed based on the use of a civil engineering fabric, which is synthetic, stable, water-permeable, rot-resistant, and usually employed in road stabilization. Laid below the haul road overburden, this tough fabric, termed "Road Carpet", separates the fine soil particles in the roadbed from the coarse aggregate, as shown in Figure 1. This action prevents the fine material from reaching the road surface so that dust emissions are reduced.

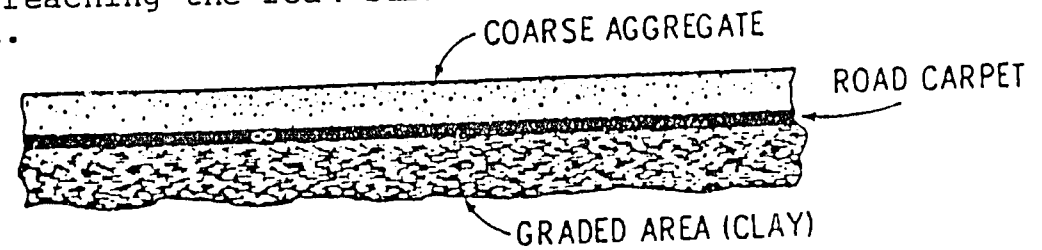

Figure 1. The Road Carpet concept, which spreads the vehicular load, prevents moisture from eroding the graded area, and keeps dirt from reaching the tires where it can be picked up and dispersed.

This report is a summary of work conducted to date on EPA contract 68-02-3107. Further details of the work are available in "Assessment of Road Carpet for Control of Fugitive Emissions from Unpaved Roads", by T. R. Blackwood; report submitted to the U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, March 1979.

GENERAL THEORY OF "ROAD CARPET" OPERATION

The fundamental concept in the use of a fabric roadbed stabilizer, or road carpet, for the control of fine particle emissions from haul roads is the prevention of vortex entrainment and saltation effects by the separation of fine roadbed materials from the coarse aggregate. Large aggregate is prevented from settling, while fines (less than 70 μm) are filtered by gravitation and hydraulic action. Road carpet can be made from spun-bonded, thin-film polypropylene on nylon sheet (Celanese), continuous filament polyester fibers needled to

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form a highly permeable fabric (Monsanto Company), or other spun or needle-punched synthetic materials. The mechanical interlocking of fibers makes a formed fabric with the durability and toughness required. Designed for road construction use, this fabric is laid over poor load-bearing soils to help support and contain the overburden aggregate. It spreads the concentrated stress from heavy-wheeled traffic over a wider area, siphons away ground water, and contains fine soil particles in the roadbed that can otherwise contaminate road ballast.

The use of road carpet results in no health or safety hazards or in any other unfavorable environmental impacts. In developing these fabrics, various synthetic polymers, including nylon, propylene, and polyester were screened and evaluated. Fabrics made from any of these products generally are resistant to mildew, mild acids, and alkali, and are rot and vermin proof.

Removal of Fines Contaminating the Ballast

When fine material enters the ballast, from either the aggregate or traffic, rainfall should carry it down to the fabric. If the fines do not pass through the fabric, they will build up and eventually contaminate the ballast. However, preliminary studies indicate that some fines do pass through some of the fabrics. In tests of clay blockage rates with vertical water flow, BIDIM and Cerex fabrics reached a limited blockage of 4 to 18 percent of the fabric area. Other fabrics, as shown in Figures 2 and 3, became essentially plugged with clay and bentonite solutions. These results indicate that the fabric will permit passage of the particles vertically and could be consolidated into the subsurface.

To further evaluate the particle transport characteristics of the fabric, tests were conducted on the horizontal flow through the fabric. The fabric to be tested was placed in the apparatus shown in Figure 4, which resembles a bell jar. A constant head of water was maintained and the horizontal flow measured. In-plane (horizontal flow) transmissability for several fabrics was deduced from these tests and is given in Table 1. In-plane transmissability of water is four to nine times higher for BIDIM than other fabrics. Additional flow studies were conducted with typical road dirt suspended in the water solutions. This composite was suspended in water, and, after settling of the large aggregate (greater than 70 μm), the slurry was sent to the bell jar to measure the in-plane flow of the slurry.

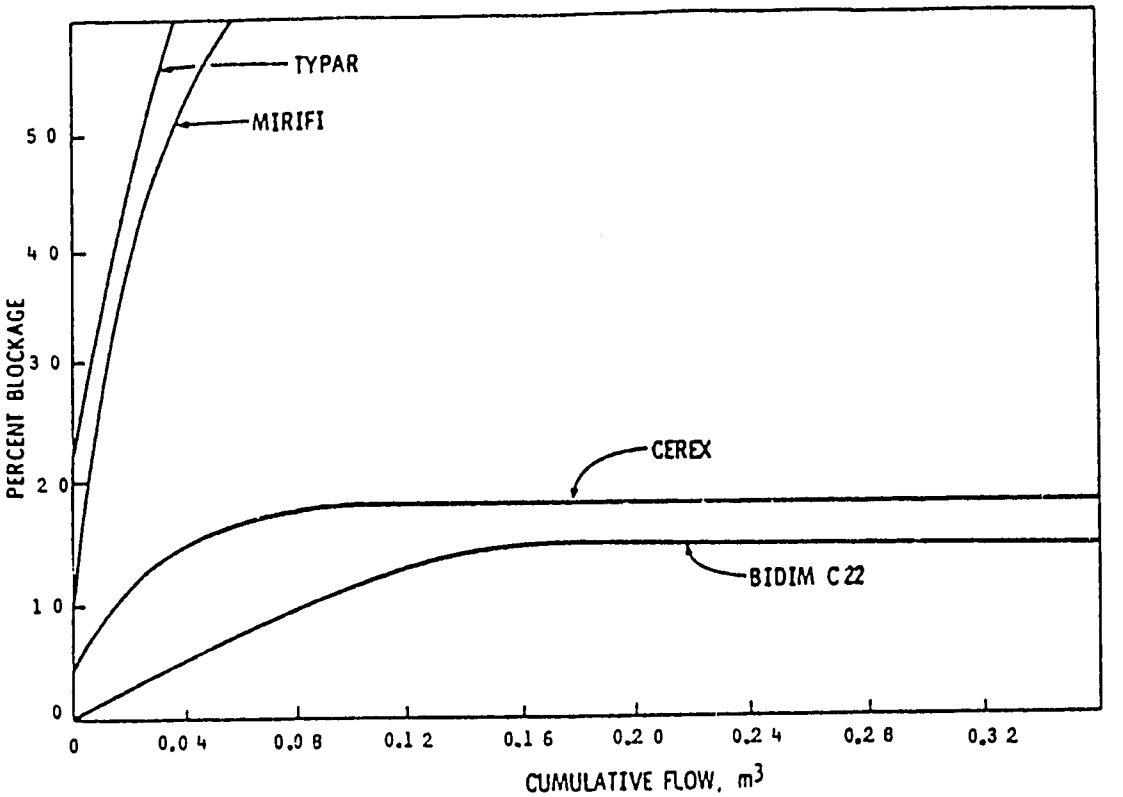

Figure 2. Blockage of fabric due to bentonite clay in water.

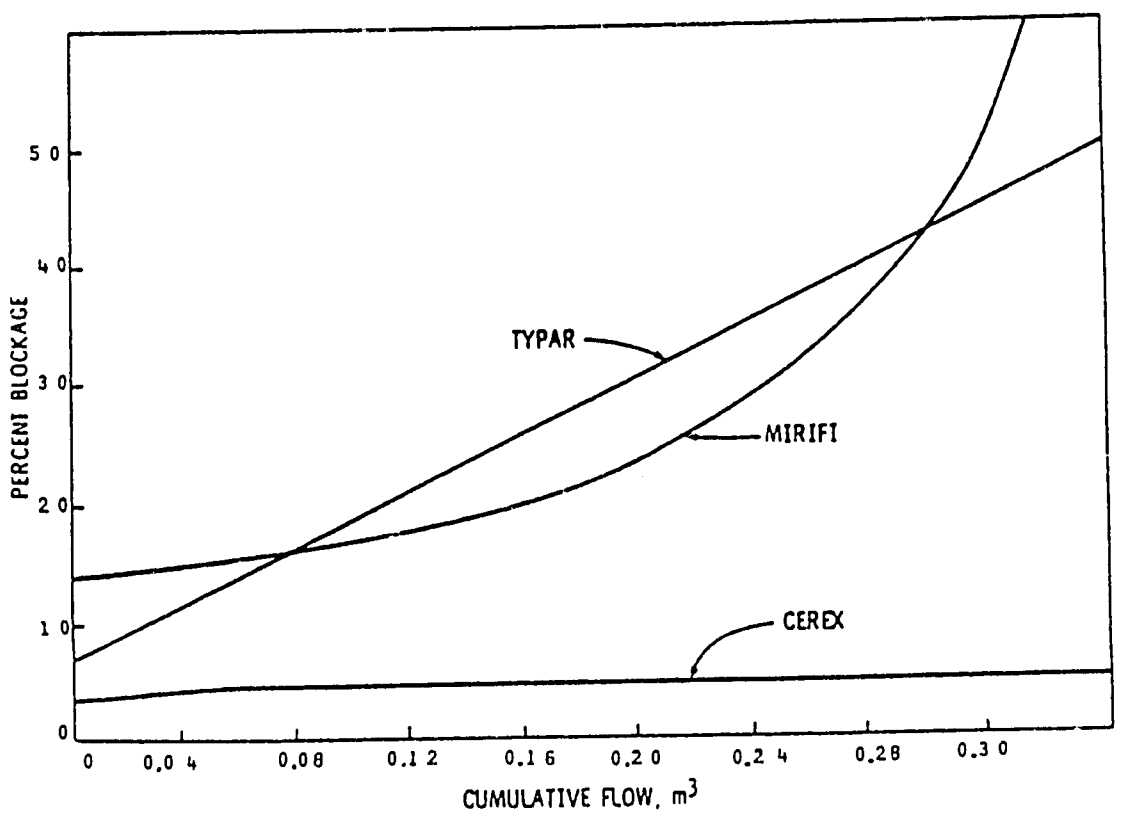

Figure 3. Blockage of fabric due to Hoytville clay in water.

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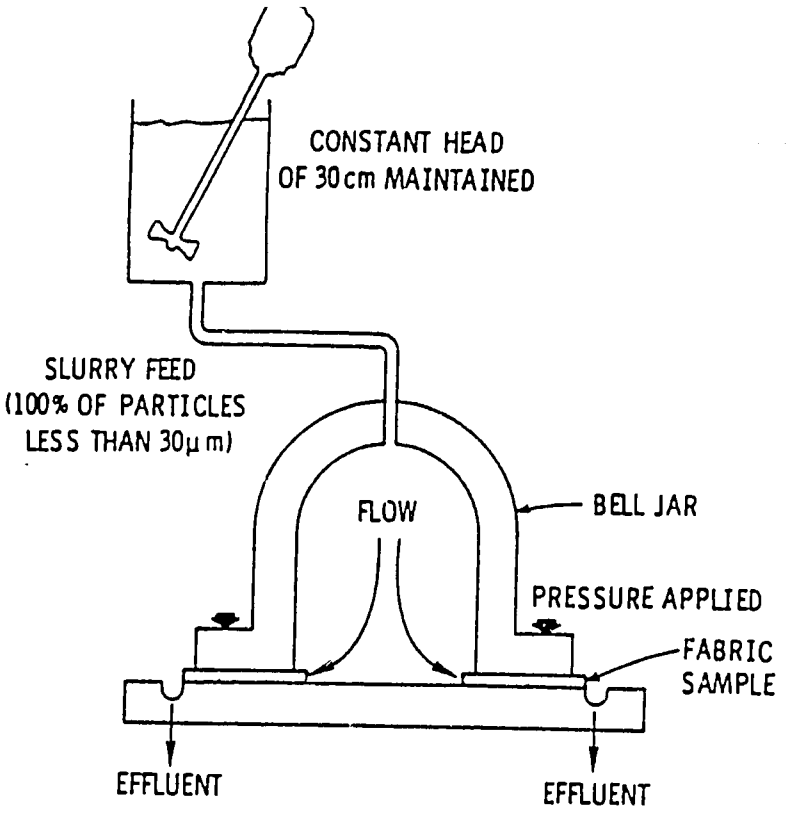

Figure 4. Laboratory Instrument used to evaluate in-plane flow of slurries through fabrics.

Table 1. IN-PLANE WATER TRANSPORT OF FABRICS

Fabric	Transmissability, 10^{-} cm /s
BIDIM C22	16
BIDIM C34	26
BIDIM C38	36
MIRAFI 140	4
TYPAR	1

Table 2 compares the vertical and horizontal flow rates for the BIDIM fabric with and without the presence of solids (i.e., clean water vs. slurry). The horizontal flow is reduced to about 40 percent of the initial clean water flowrate, but the fabric is not completely occluded. It is anticipated that, in the real world, pulsations of flow and channeling may increase the effective flow rate. This was verified in experimental work by momentarily raising the pressure on the fabric. Pulsations resulted from the compression and expansion of the fabric under the load of vehicles. A 17 percent increase in flow was observed due to these pulsations. Channeling is a common phenomenon due to the nonhomogeneity of the aggregate and soil adjacent to the fabric.

Table 2. COMPARISON OF FLOWRATES THROUGH BIDIM FABRIC

Direction	Flowrate, m/min Fabric C-22	Fabric C-34
Vertical:		
Clean water	22	15
Slurry[a]	19	13
Horizontal:		
Clean water	1.7	1.9
Slurry[b]	0.69	0.88

[a]Slurry contains bentonite clay; flowrate is the limit at steady state.

[b]Slurry contains typical road dirt; flowrate is the limit at steady state.

Particle Separation by Size

The holes in the fabric are approximately 70 μm in diameter and will permit passage of particles up to that size depending upon particle shape. Because the fabric does not "blind", the effective size of the holes is not reduced significantly, and all particles smaller than 15 μm (the size of interest) should pass through the fabric vertically. If the soil is soft (cone penetrometer less than 1,000 kPa), these particles would be consolidated with the exisitng soil. When firm soil (soil penetrometer greater than 1,200 kPa) is present, consolidation would be difficult. Because the presence of the fine soil particles does not plug the fabric during horizontal water flow, some if not all of the fines could be purged along with normal water flow. The median particle size that passed through the fabric during the horizontal flow tests was about 3 μm. Particles as large as 20 μm also came through the fabric. This means that only the very small particles would pass horizontally over firm soil; however, some channeling would exist and carry off the intermediate size particles (3 to 15 μm).

ALTERNATIVE CONTROL CONCEPTS

The siphoning action of road carpets such as BIDIM fabric can be applied to maintain a minimum moisture in the orad, as shown in Figure 5. Water passes through the fabric from the upper to the lower drainage pipe. Fines that enter the fabric can be settled out of the recirculating water lines. In dry regions of the United States, this concept would minimize the water used because the losses occur only by evaporation. If the graded surface is porous, a waterproof liner would be laid between the fabric and the graded surface to prevent excessive water loss.

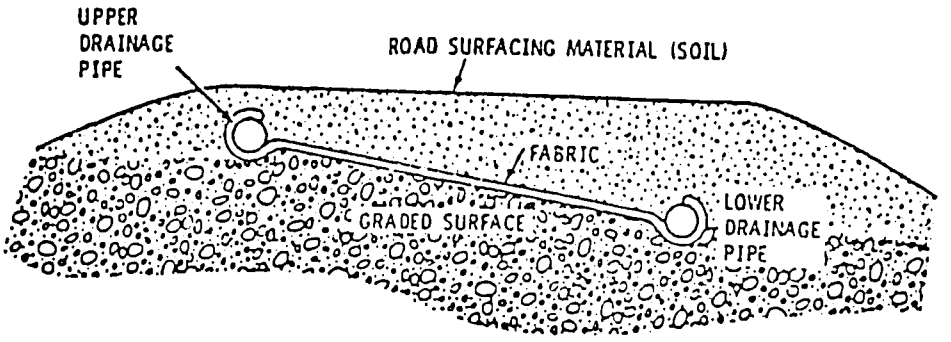

Figure 5. Self-watering road for emission control. Water is pumped from the lower drainage pipe to the upper drainage pipe externally.

ECONOMICS OF THE ROAD CARPET CONCEPT

Capital and operating costs of various control options differ with each alternative. Cost comparisons have been made between the cost of new roads constructed with a fabric base and conventional subsurface preparation.

For very soft soil (cone penetrometer index less than 600 kPa), road construciton cost decreases with increasing fabric thickness because the fabric spreads the stress and can replace 0.5 to 0.75 meters of rock. For soft soil (cone penetrometer index less than 1,000 kPa), the road containing fabric is only 40 to 50 percent cheaper. On firm or existing aggregate-covered roads, the road would cost about 10 percent more. The maintenance cost of a conventional road would be higher than for one containing road carpet; this will offset the difference in capital costs.

For cost comparisons, road width was assumed to be 10 meters. Eighteen metric ton axle loads were assumed for 10:00-20 tires. The design curve for BIDIM fabric is given in Figure 6.

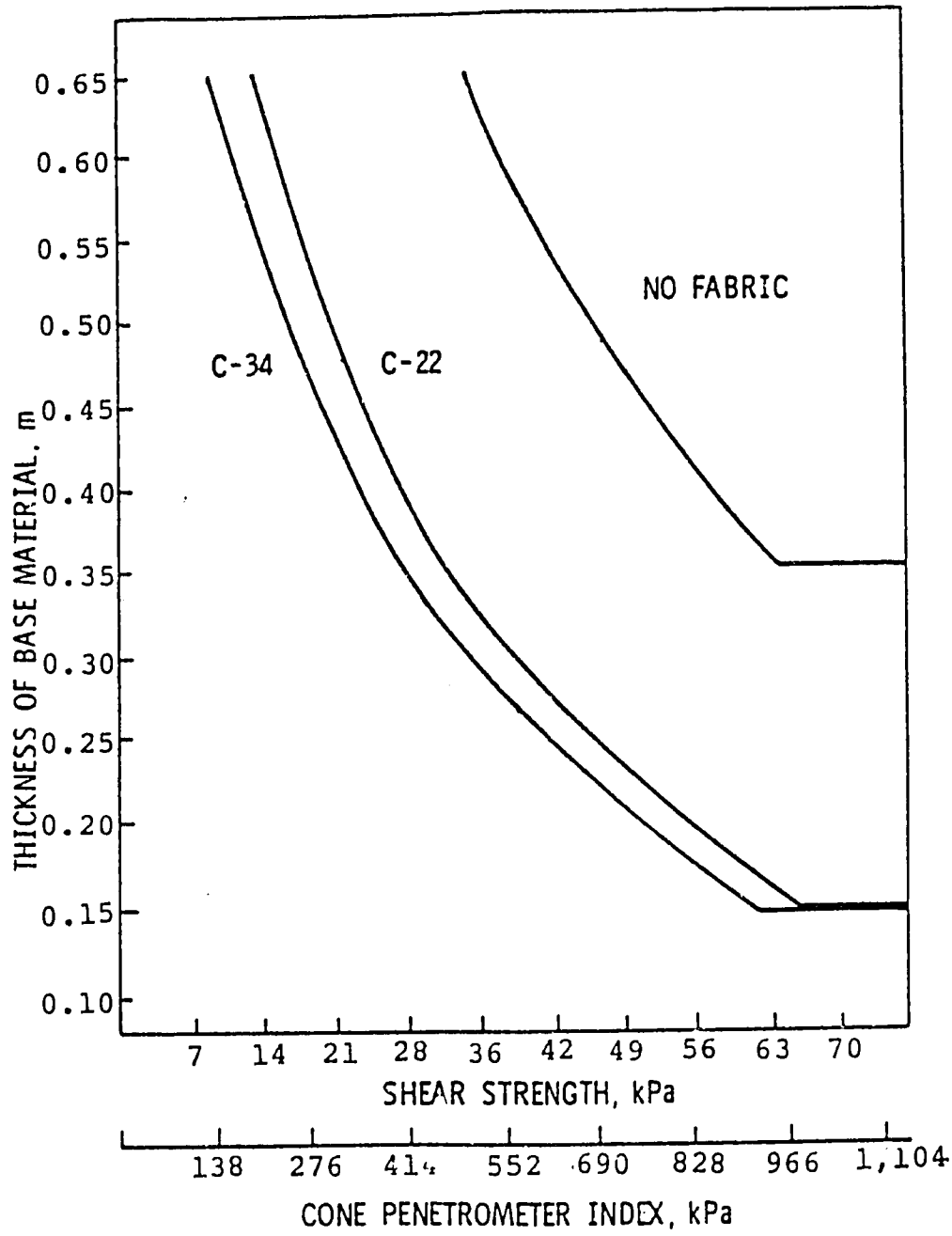

Figure 6. Design curves for 18 metric ton axle load on 10:00-20 tires for BIDIM fabric.

The installed cost of one kilometer of conventional road would be $44,000 on soft soil and $27,000 on firm soil. The main difference is the depth of aggregate required (soft soil needs 0.36 meter and firm soil needs 0.2 meter). Using a fabric costing $0.86 per square meter, the cost of one kilometer is $30,000.

Watering and repair of a conventional road cost about $6,700 per kilometer per year. Oiling of the road instead of watering would cost about $6,200.

The amoritized costs for conventional control measures and for the road carpet are summarized in Table 3. The life expectancy of the fabric in the road is unknown; experience indicates that 12 years would not be an unreasonable estimate. A haul road may last for the life of the plant (25 years) with proper maintenance.

Table 3. AMORTIZED COSTS OF DUST CONTROL ON UNPAVED ROADS (1979)

Type of road and/or dust control	Cost, $/km
Unpaved road on firm soil (no control); $27,400 over 25 years (17% interest)	4,750
Watering and ballast replacement	6,750
Oiling and ballast replacement	6,200
Ordinary road with watering and ballast replacement	11,500
Ordinary road with oiling and ballast replacement	10,950
Fabric unpaved road; $30,000 over 12 years (17% interest)	6,000
Ballast replacement	1,600
Fabric road with ballast replacement	7,600

The road constructed with fabric is cheaper than one which is watered or oiled. Better data would be required on ballast replacement and watering costs due to the high inflation that is presently occurring. With conventional roads, a higher percentage of the yearly cost is required for perpetual care. This would make an even higher capital cost more attractive, if the life expectancy were better than anticipated.

APPENDIX G-9

FABRIC FILTER EMISSIONS, STUDY OF THEIR VARIABILITY

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For presentation at the EPA/EPRI Seventh Symposium on the Transfer and Utilization of Particulate Control Technology, March, 1988, Nashville.

ABSTRACT

The fabric filter has taken a significant portion of the electric utility emission control market. One of the reasons has been the belief that emissions from fabric filters are almost always low and are more predictable than emissions from electrostatic precipitators.

A data base of over 50 operating fabric filters indicates wide variation of emissions. This paper presents part of the data base and examines the influence of design and operating variables on particulate emissions. Parameters possibly affecting emissions include air to cloth ratio, type of fabric filter (reverse air or pulse clean), bag length, bag attachment method, fabric weight, fabric type, inlet particulate concentration, year of startup, gas temperature, ash characteristics, and plant size. Unfortunately, due to the many design and operating variables at each plant, it was not possible to create accurate correlations. However, several interesting conclusions are reached.

A discussion is presented of what can be incorporated into the design and operation to help assure very low emissions and what variables affecting performance need further investigation.

INTRODUCTION

In 1984 Mr. A. Khosla and I presented a paper (1) comparing the performance of fabric filters and electrostatic precipitators on total particulate, fine particulate and trace element emissions. The paper included a data base of 20 fabric filters and 18 well-designed precipitators. The paper concluded that the average total particulate emissions of the operating fabric filters was about the same as the well-designed precipitators, but that the fabric filters were superior for fine particulate and trace element emission control.

Since 1984, the fabric filter data base has grown from 20 to nearly 60 units. The fabric filter emissions of the operating units continues to vary over a wide range. The purpose of this paper is to examine the data base to determine if the data indicate reasons for this large range of performance.

Recently we have been asked by several state agencies to design for emission levels well under the new source performance standards. It is no longer a system of "can we comply with the EPA new source performance standards". Sometimes we hear "well, Smith Unit 2 has emissions of 0.001 grains per cubic foot so we expect you to do as well". If a plant starts up and achieves emission levels far below what was anticipated, due to some quirk of luck or combination of circumstances not understood by science, it cannot be expected that the next one can be designed and guaranteed for as low of an emission rate. The range of data and analysis presented in this paper will show that design of a fabric filter for ultra low emissions is not a well understood science, its not even a black art.

THE FABRIC FILTER DATA BASE

Table 1 shows a summary of the emission data from the design and performance data base. The data base consists of information which has been published about each fabric filter. We are grateful for the efforts of a great number of individuals who have shared their knowledge by preparing technical papers to help the industry. Each emission data point on Table 1 is referenced to its source. The table shows a small portion of the total data base which includes design and operating data for each installation.

Not all leterature references show emissions in terms of both pounds per million Btu and grains per actual cubic foot. For these plants, an estimate of a conversion to the missing emission unit has been made. This conversion is affected by operating excess air and plant altitude. With these data missing for some plants, the conversion may be slightly high for some

while low for others. However, the data averages should be very representative.

The data from each fabric filter should not be interpreted as what occurs daily at each plant. It is expected that emissions vary from month to month. Some plants showing high emissions have been improved. For example, the literature shows rather high emissions for the W. W. Samis Station. These emissions (within the plant's regulatory limit) probably have subsequently been reduced because the reported emission data were from a period when the fabric filters were experiencing severe operating difficulties. On the other hand, some of the other units may have been "tuned up" for the emission tests and emissions may have increased since. However, it is hoped that by use of all the data, the overall influence of design and operating conditions could be seen. The following sections examine these design and operating variables.

TOTAL EMISSION VARIATION

The average emission from the fabric filters is 0.021 pounds of particulate per million Btu. This corresponds to 0.0068 grains per actual cubic foot. Table 1 indicates a considerable range of emissions. Figures 1 and 2 illustrate this wide range of emissions. The data are arranged in ascending order. Separate figures are shown for emissions in terms of pounds/million Btu and grains/acf.

The data indicate that 80 percent of the operating fabric filters are performing better than the electric utility new source performance standard of 0.03 pound per million Btu. I n that the compliance is not 100 percent, may be a surprise. However, some of the units do not need to comply with this emission standard. Thus, it is not meant to imply that certain plants have emission rates that are too high. However, the question remains regarding why there is such a large variation of emissions. The fabric filter, unlike an electrostatic precipitator, cannot be designed for a given emission level or percent particulate removal. The units experiencing unusually high or low emissions were not designed that way. There must be other reasons for the emission variation.

If one were to be faced with a regulatory agency requesting design for very low emissions, the data could be used to show the probability of success. For example if one had to design for an emission rate of 0.02 pounds per million Btu, Figure 1 would indicate that only about 40 out of 57 units are achieving it. The chances of success would be only about 70 percent, not very comforting. Engineers like to design with higher confidence levels. Thus, one may eventually face decisions regarding how to design fabric filters for lower emissions.

HISTORIC TREND OF EMISSIONS

Figure 3 shows the trend of emissions from fabric filters starting up during the indicated years. It is not known whether emissions have increased or decreazsed for each unit since the emission data were reported. However, the group of "typical" data in the lower portion of the figure indicates that emissions have been creeping up with time as new units come on line. In 1984, when the previous survey (1) was completed, the average emission from the operating fabric filters was 0.0040 grains/acf. This data base consisted of the first 20 units shown on Table 1. Now, in 1988, the average emission from all listed fabric filters has increased to 0.0068 grains/acf. Again, this is not the effect of ageing. These are emission data from new units.

DESIGN TRENDS WITH TIME

Figure 4 shows that fabric filters have been applied to increasing sizes of plants over the years. The number of bags per compartment has been increasing (Figure 5). However, the length of bags generally has not been increasing (Figure 6). Also, the ratio of bag length to diameter has not changed much with time (Figure 7).

EFFECT OF DESIGN ON EMISSIONS

NUMBER OF COMPARTMENTS AND BAGS PER COMPARTMENT

The number of compartments does not affect the emissions for the group of performance data (Figure 8). One might think that with a large number of compartments, for a given size of unit, maintenance would be easier. Figure 9 may indicate a slight trend of increasing emissions when the number of bags per compartment increases. Increasing the number of bags per compartment may affect willingness to do maintenance and it may also affect the ease of achieving uniform gas distribution.

FABRIC FILTER SIZE

Emissions have increased slightly as the overall capacity of the fabric filter has increased (Figure 10). Some have speculated that, as fabric filters were applied to larger units, the maintenance tasks would overwhelm the plant staff. However, it appears that this has not been a strong trend.

AIR TO CLOTH RATIO

Figure 11 indicates that there is not a strong correlation of air-to-cloth-ratio to emissions. This even appears to be the case when one focuses only on the units designed for relatively low ratios and operating with low emissions (Figure 12).

Some of the literature references do not report the gas flow rates and number of out of service compartments during testing. This causes difficulty in estimating operating air to cloth ratios. Design values were used when actual operating values were not reported. This lack of accurate information may be a partial cause for the scatter on Figure 11. Another potential cause of the scatter is the unknown frequency of cleaning cycles. It has been reported that adjustments to cleaning frequencies have greatly affected emissions at some plants, reduced cleaning frequency being beneficial.

It would be reasonable to conclude that a lower air to cloth ratio, lower velocity through the fabric, would reduce pressure drop and leakage through holes and would also allow bridging of ash over holes. Laboratory tests at the University of Tennessee (2) indicated that emissions more than tripled when the air to cloth ratio doubled. Other laboratory tests also showed an increase of emissions (3). Tests by DuPont (4) on simulated pulse-jet operation also confirmed the benefit of lower air to cloth ratio on emissions.

How does all this laboratory work compare to field experience? Data has been published for two plants where the ratio was varied by testing at different gas flow rates. These data should be beneficial because they do not include all the variables influencing Figures 11 and 12. Figure 13 shows that emissions increased at the Kramer Station as gas flow and air to cloth ratio were decreased (5). Data from the Parish Unit 8 (Figure 14) also shows this trend (6). Tests were conducted at Parish on four separate parallel fabric filter trains for Unit 8. One train showed wide scatter. The other three trains all showed the same trend, as shown on Figure 14.

At reduced gas flow and boiler load, the quantity of ash entering the fabric filter decreases. The velocity through leakage holes decreases, but the emissions increase. It may be a quirk, or, it could be because the cleaning cycle is not optimized at reduced loads. It is not known whether cleaning frequency was determined automatically by pressure drop increase or set for a given time interval. Perhaps cleaning was removing too much of the ash from the fabric causing more leak-through. Less frequent cleaning at reduced load may reduce emissions.

It is believed that decreased air to cloth ratio would be beneficial in reducing emissions, based on the above referenced

laboratory data; but, more field work needs to be done on full size units to demonstrate this.

BAG LENGTH TO DIAMETER RATIO

As the ratio of bag length to diameter increases, more flue gas must pass through the opening at the inlet. This should increase wear, erosion, and lead to premature bag failure and increased emissions. This may be true over wide ranges of length to diameter ratio, and over longer periods of operation, however, the narrow range of data in the data base leads to no conclusions (Figure 15).

GAS TEMPERATURE

Flue gas temperature may affect emissions. Some have demonstrated that certain ashes become more cohesive at reduced temperatures, or under the influence of more humidity with water spraying. The ash would then tend to bridge over and not leak through pin hole openings. Unfortunately, this theory is not supported by the bulk of the data base, as showm on Figure 16. It is not even supported by the data from a single brand of fabric filter, some of whose units have spray dryers upstream, reducing gas temperature (Figure 17). However, recently completed pilot tests, partially sponsored by Bechtel and Ahlstrom, indicated a benefit in water spraying ahead of the fabric filter to reduce temperature (Figure 18).

TYPE OF FABRIC FILTER

Data base emissions from the three types of fabric filters are as follows.

Average Fabric Filter Emissions

Type of Cleaning	Number of Units	Emissions Grains/acf	Emissions Lbs/mmBtu
Reverse Air	41	0.0060	0.019
Shake-Deflate	6	0.0058	0.023
Pulse-Jet	9	0.0100	0.031

The data indicate that the pulse-jet type cleaning fabric filters have considerably higher emissions than the other types. The shake-deflate type has a slightly higher emission on a pounds per million Btu basis than the reverse air type. The difference in the above ranking, based on outlet concentration and on pounds per million Btu, is due to the shake-deflate design having three units at high altitude where a given particulate concentration translates into a higher number of pounds per million Btu.

An EPRI study concluded that "In short term testing, emissions from shake-deflate cleaned bags, while well within applicable regulations, were approximately three times higher than from reverse gas cleaned bags" (7). These were carefully controlled tests, however, the magnitude of their results are not supported by the above field data. It is noted that a data base of only six shake-deflate units is not nearly as statistically significant as the much larger reverse air clean data base.

It is interesting to note that one of the claimed advantages of the shake-deflate type cleaning is its superiority in cleaning and keeping the pressure drop down. One of the answers to pressure buildup for reverse clean fabric filters has been the installation of sonic horns. The previously mentioned EPRI study also concluded that "Particulate emissions from reverse gas/sonic cleaned bags appear to be approximately equal to emissions from bags cleaned by reverse gas alone". Thus, if horns had been installed on any of the reverse air clean systems, the emissions may not have been any higher and the above ranking would remain.

BRAND OF FABRIC FILTER

It was thought that some of the brand-dependent aspects of fabric filter design might affect the emissions. These may include method of bag attachment to the tubesheet, compartment inlet design, etc. The following is a summary of emission data for each of the brands having at least three operating fabric filters.

Average Emissions for Various Brands

Brand	Number of Units	Emissions Grains/acf	Emissions Lbs/mmBtu
A	13	0.0029	0.013
B	8	0.0044	0.011
C	3	0.0047	0.014
D	9	0.0057	0.017
E	6	0.0058	0.023
F	4	0.0200	0.068

The wide range of emissions points to the possible conclusion that emissions depend on brand design features. This, however, may be a false conclusion. The study of brand features and their influence on emissions is beyond the scope of this paper.

FABRIC TYPE

A detailed study of the influence of the type of fabric and its manufacturing technique is also beyond the scope of this paper. There are dozens of differences in bag specifications which will influence emissions. For example, some have found that increasing fabric texturization from 25 percent to 100 percent reduces emissions by over 50 percent (8). However, it is not known whether this conclusion, for one set of tests at one plant, is universally applicable. Fabric differences probably are the reason for some of the emission variation in our data base.

It is not possible to reach conclusions based on the data bank information because the overwhelming majority of fabric filters of the reverse air clean type use fiberglass bags. Thus, comparison to other fabric materials is not possible. Furthermore, their weave, texturization, manufacturing technique, etc. generally are not stated in the literature.

FABRIC WEIGHT

As with fabric type, there is insufficient information in the data bank to reach conclusions. Most of the reverse air clean fabric filters use 9.5 to 10.5 ounce fabric. Only a few use 13 ounce fabric and none reportedly uses 16 ounce fabric. For several of the units, the weight of fabric has not been reported. Thus, data correlations showing the effect of fabric weight on emissions are not possible.

INLET ASH CONCENTRATION

The fabric filter has a reputation for producing emission particulate concentrations which are not dependent on inlet concentrations. However, the effect of leakages through holes in the fabric and leakages around the fabric should produce increasing emissions as fuel ash content increases. Various laboratory tests have confirmed this. Also, more frequent cleaning, due to higher fuel ash content, leads to higher emissions. One could, with some imagination, come to this conclusion based on the data bank information reflected in Figure 19. Unfortunately, because of the scatter of other variables, a strong correlation is not noted.

To design for ultra-low emissions, the effect of fuel ash content and the amount of leakage and bypass gas are important factors needing further investigation. It appears that a lower ash content would reduce emissions by reducing leakage and also by allowing less frequent fabric cleaning.

FUEL AND ASH PROPERTIES

Several papers have recently been presented showing that fuel properties affect the emission level. Laboratory research has indicated that increasing amounts of sodium, phosphorous and magnesium in the ash may reduce emissions (9). A study of the ash constituents and their influence on emissions has not been attempted for this paper. However, one variable which was studied is the coal sulfur content. The available information does not show a correlation of fuel sulfur to emissions.

Ash shape will also affect emissions. Fuel and combustion properties at the Monticello Station have produced slippery round spheres of ash which bleed through the fabric more readily than most ash. On the other hand, ash produced in fluidized bed combustors is less likely to penetrate fabric because of its jagged geometry, due to lower furnace temperature. The area of fuel properties and combustion characteristics needs further investigation.

GAS CONDITIONING

Gas conditioning has been used extensively for aiding the performance of electrostatic precipitators. It thus is of interest that gas conditioning has been found to benefit fabric filter emissions. Tests at the Monticello Station (8) indicate a more than 50 percent reduction of emissions with use of ammonia gas conditioning. This was observed for several different fabrics. It is possible that the ammonia makes the ash more cohesive and therefore less likely to bleed through the fabric. The Monticello ash has been reported to have a unique bleed through characteristic. Thus, the ammonia conditioning test results may not be applicable to all plants.

Laboratory tests in North Dakota (9) indicate dramatic reductions of emissions for certain conditions and ashes with use of ammonia and sulfur trioxide gas conditioning. It is possible that some of the scatter of emissions in our data bank is due to naturally occurring gas conditioning, i.e., variations in flue gas moisture, variation in conversion of sulfur dioxide to sulfur trioxide among boilers, etc. Flue gas conditioning is an interesting area needing further testing to see if it is beneficial to conditions other than those at the Monticello Station. It is noted that new units in California are being required to install ammonia injection systems for NOX control. It is possible that unreacted ammonia may have a positive side benefit, increasing particulate removal in the fabric filter.

COMBINED EFFECTS

The previously discussed graphs do not paint a very positive correlation of design and operating parameter influences on emissions. Part of this may be due to the vast number of inter-related variables. Analysis of variable combinations may eventually show better correlations. For example, if it were postulated that both increasing air to cloth ratio and increasing bag length (more erosion potential) would increase emissions, a correlation of the mathematical product of these variables to emissions would be useful. Figure 20 shows this correlation. It is possibly significant that the only units having emissions higher than 0.02 pounds per million Btus, also have bag length-times-air-to-cloth-ratio indices of over 55. This is but a first attempt at inter-related parameter correlation.

CONCLUSIONS

The data from operating fabric filters indicate that a wide range of emissions can be expected. It is difficult to use the data to show that specific design differences influence emissions. This is because of the existence of too many design and operating variables. One could conclude that fabric filter design is rather forgiving, wide ranges in design do not predictably affect emissions. This, however, is believed to be a false conclusion. If one could spend enough time and money pilot testing variables, conclusions could be reached regarding their influence on emissions.

It is not thought that the industry has the financial capability for the level of testing which would be required to reduce fabric filter design from that of a black art to that of a science. Therefore, it is of interest to continue to develop correlations from expanding data beses and laboratory tests.

Differences in design and operation influencing emissions probably include most of the following.

1. Fabric leaks
2. Bypass damper leakage
3. Cleaning frequencies and techniques
4. Fuel and combustion characteristics
5. Maintenance quality
6. Fabric weight and design
7. Height to diameter ratio
8. Air to cloth ratio
9. Gas temperature, humidity and SO3 content
10. Fabric filter brand-specific features

In cases where emissions must be designed for levels considerably below the utility boiler new source performance standards, 0.03 pound per million Btu, it is advisable to take special precautions in the fabric filter design. These may include the following.

1. Elimination of bypass duct or use of double bypass dampers with purge air.
2. Use of a lower air to cloth ratio combined with less frequent cleaning.
3. Selection of specific fabric materials, types and construction.
4. Possible use of gas conditioning, if proven in more tests at other plants..
5. Use of reverse air rather than pulse-jet cleaning.
6. Possible use of a reduced temperature by revising the air preheater design or installation of a spray dryer upstream of the fabric filter. This would be especially helpful in jurisdictions which include condensable material as particulate. Some of the condensed material would be removed by the fabric filter at reduced temperature.

Emissions may also be reduced by putting more effort into maintenance. One could speculate that the plants having higher emissions may have less maintenance, but this would be an unfair accusation against some of these plant staffs. There simply is not much data regarding maintenance level correlation to emissions.

The above list of design features for low emissions are tentative conclusions. Each represents an area where more research is needed. Much of the research which has been done is aimed at areas other than how to achieve lower than new source performance standard emissions. However, there are many cases where it is necessary to go to lower emission levels. With the average of all emission data showing levels two thirds as high as the new source performance standards, there is little room for error. If, for example, we had to design for one third lower emissions, 0.02 pound per million Btu, there would only be a 70 percent chance of achieving it, based on experience at 57 plants. This is not a comfortable design margin.

Some of the problems of operating data interpretation would be lessened if there was a test and reporting standard listing what information would be useful. So often we see test results and wonder, if only they had taken fuel samples or if only they had noted how many compartments were out of service or what the cleaning cycle was. Documentation of operating conditions when reporting test results would be helpful in developing performance correlations.

ACKNOWLEDGEMENTS

The author wishes to express appreciation to the 36 authors, and their numerous coauthors, listed in the references. It is the hard work of these people who have reported design and operating data which made this data analysis possible. Special thanks go to Mr. Walter Piulle and EPRI who have provided so many good data bases over the years, including the referenced (32, 33 & 34) fabric filter data bases.

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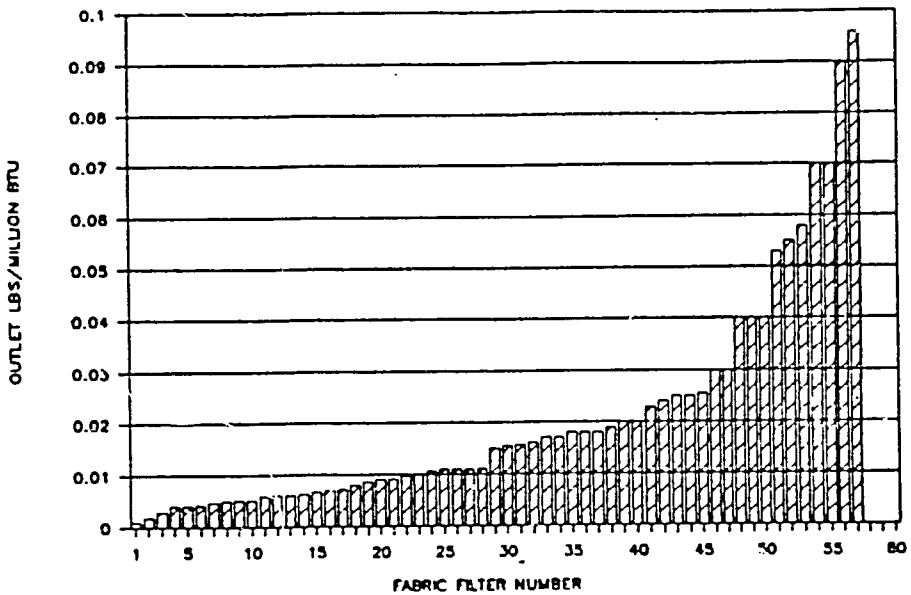

Figure 1. Emissions, Lbs./mmBtu, 57 plants.

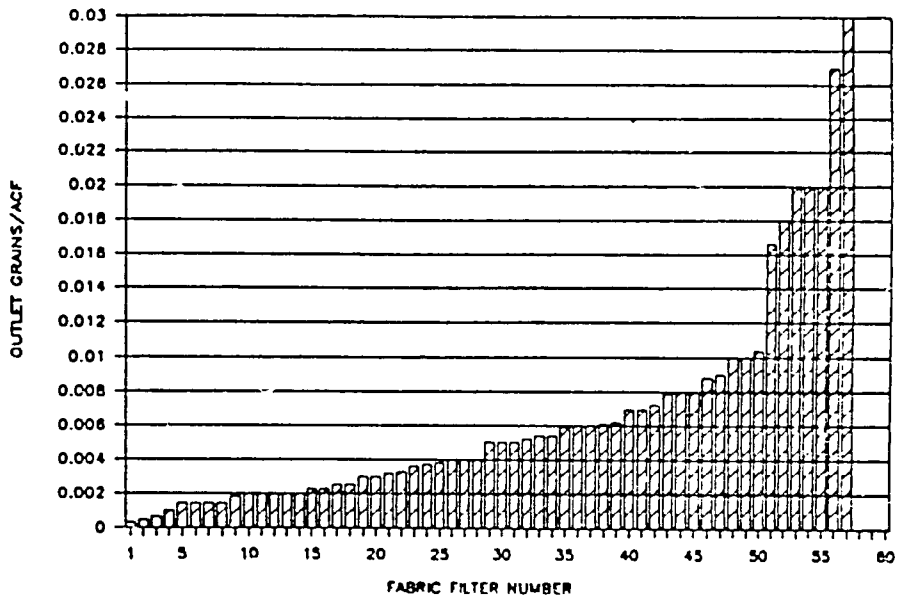

Figure 2. Emissions, grains/acf, 57 plants.

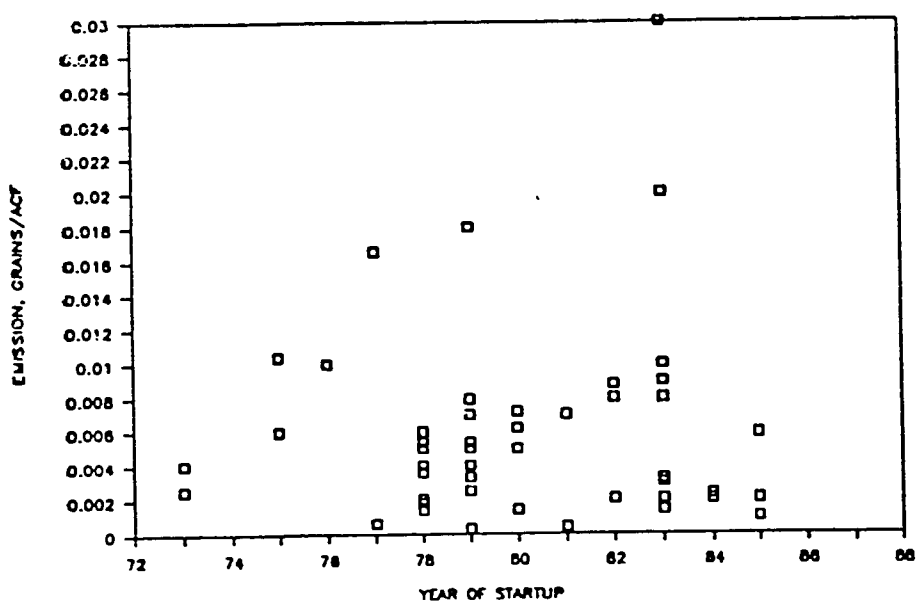

Figure 3. Emissions versus year of start-up.

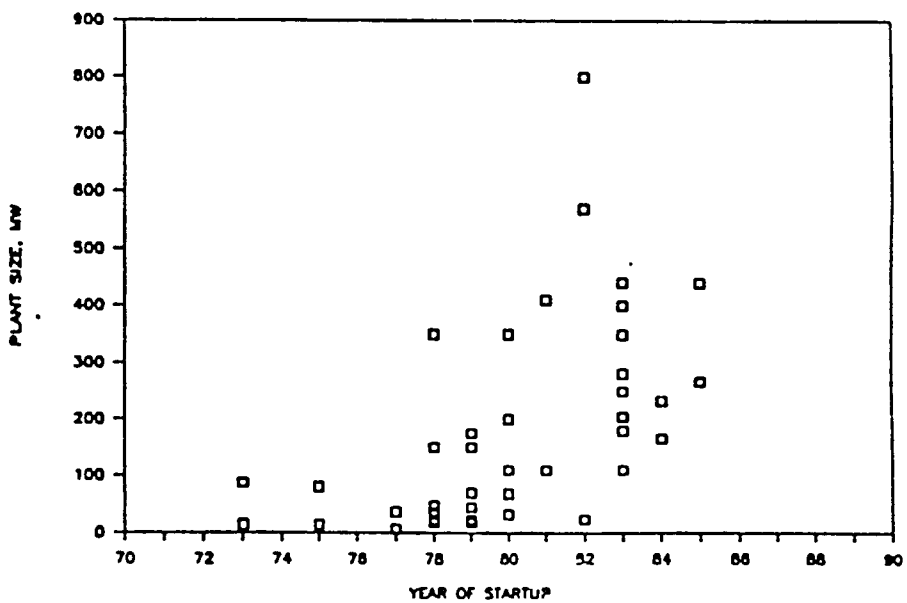

Figure 4. Fabric filter plant sizes.

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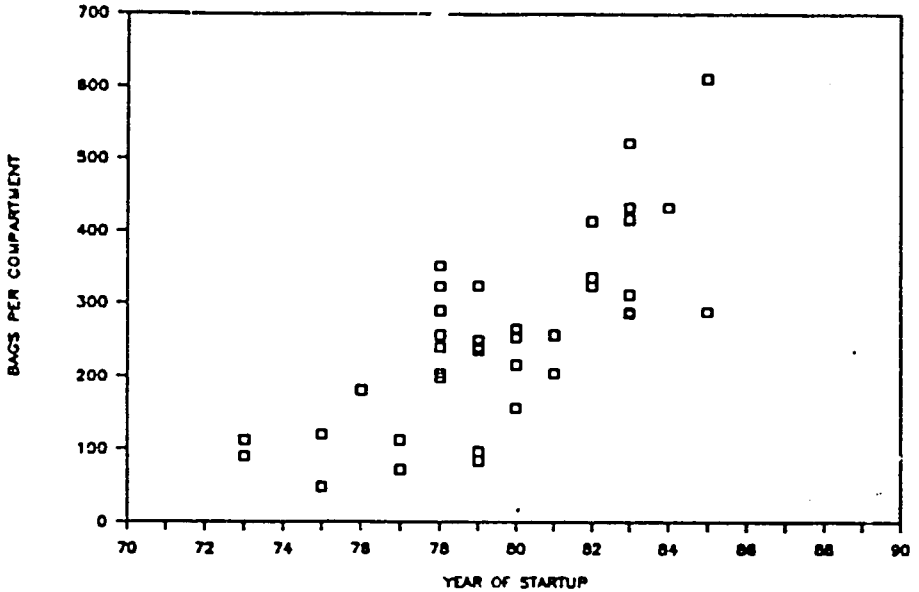

Figure 5. Compartment size growth.

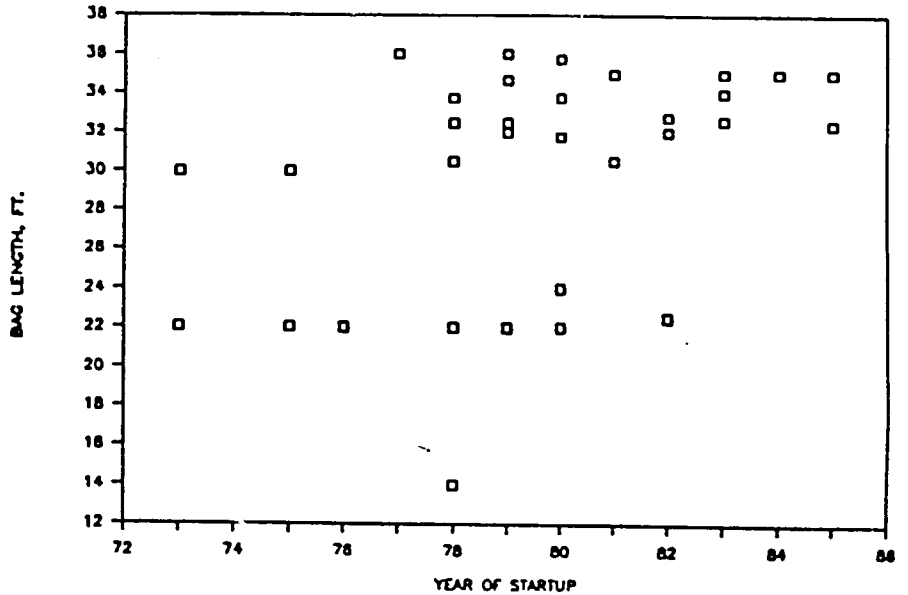

Figure 6. Bag length history.

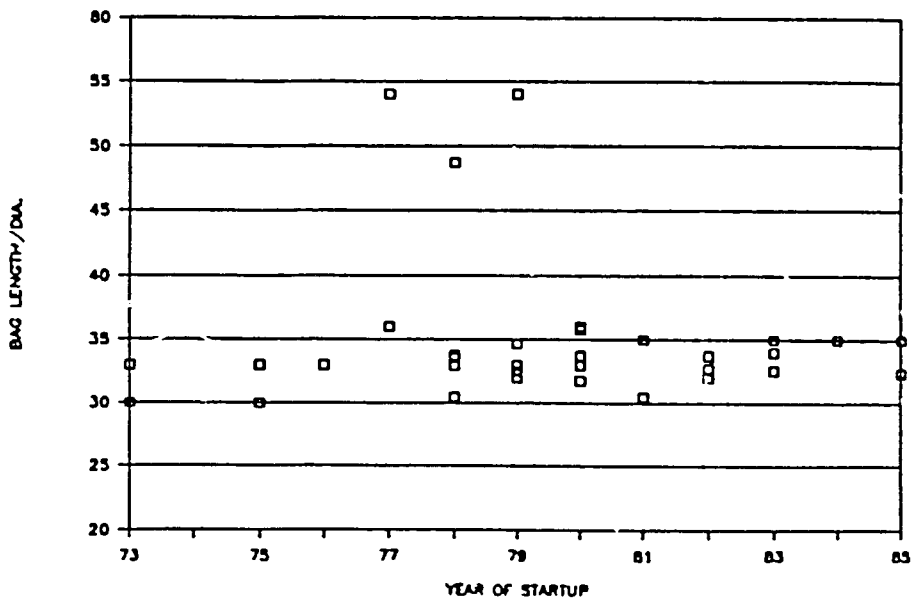

Figure 7. Bag length/diameter.

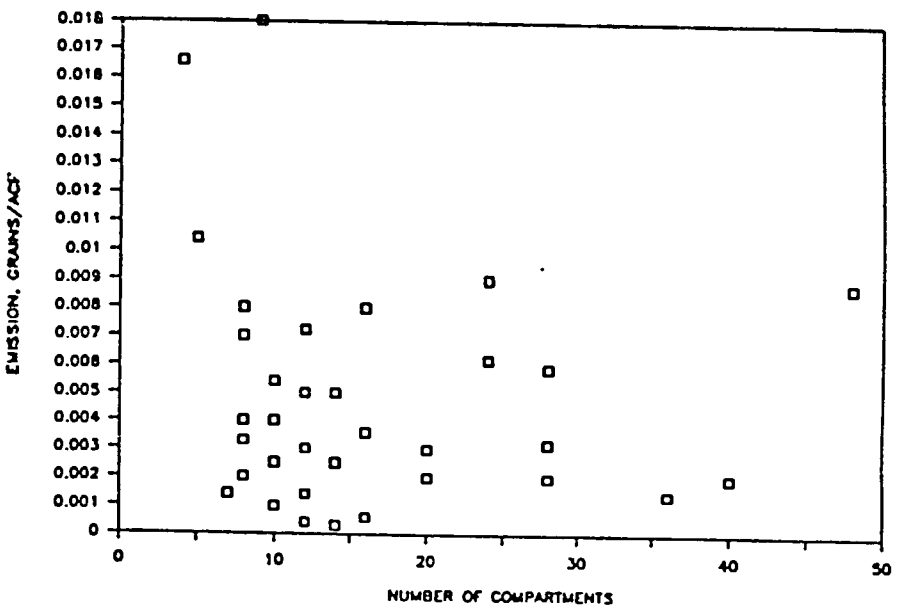

Figure 8. Emissions vs. number compartments.

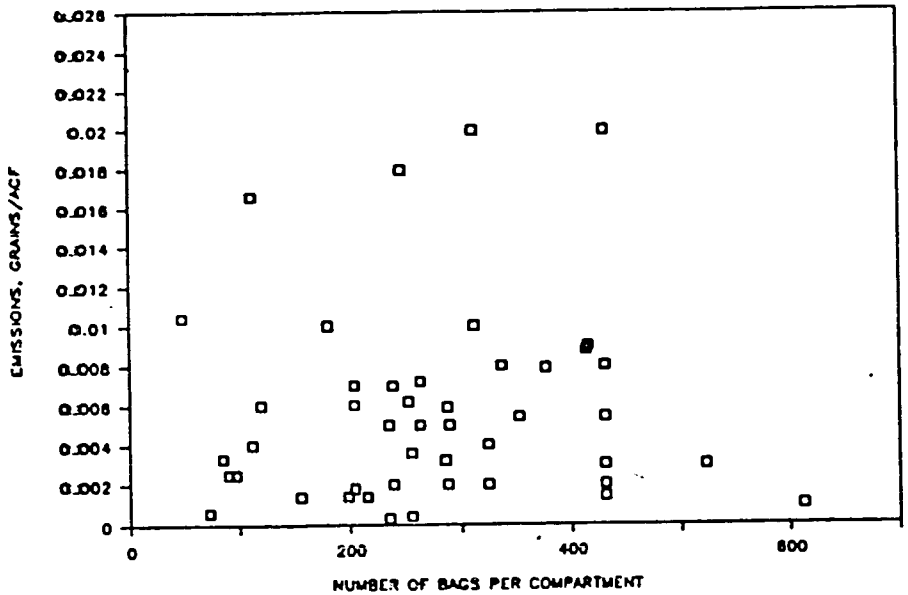

Figure 9. Emissions vs. bags/compartment.

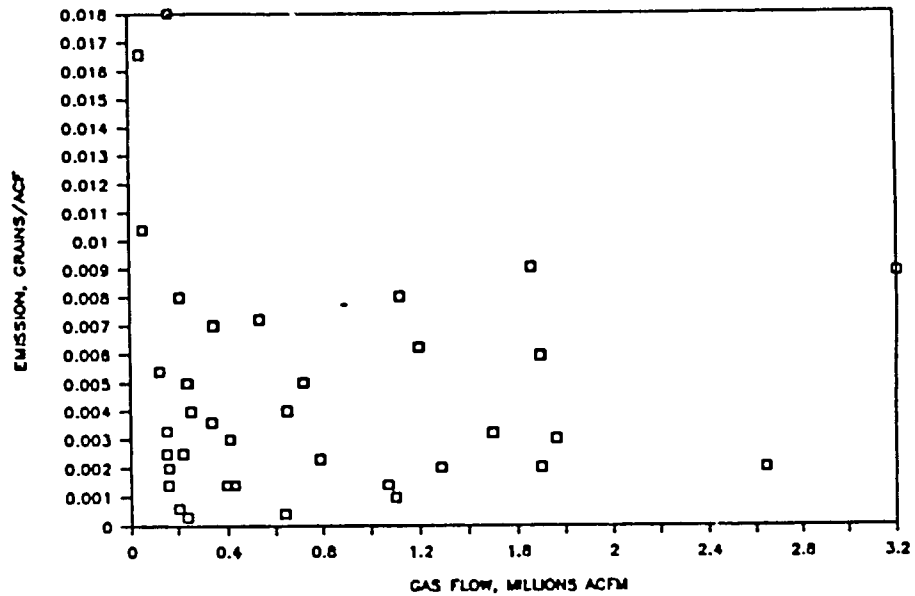

Figure 10. Emissions vs. gas flow.

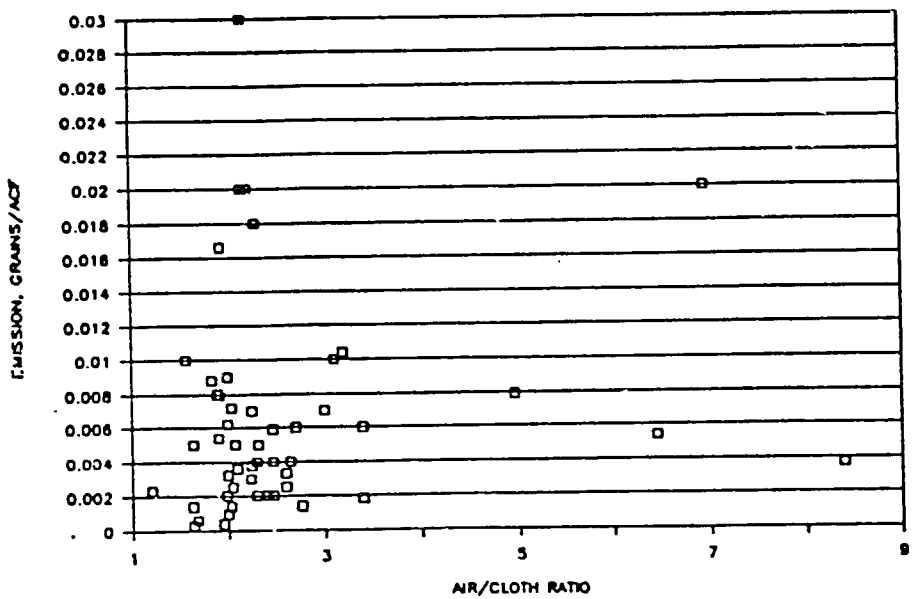

Figure 11. Emissions vs. A/C, all reverse air units.

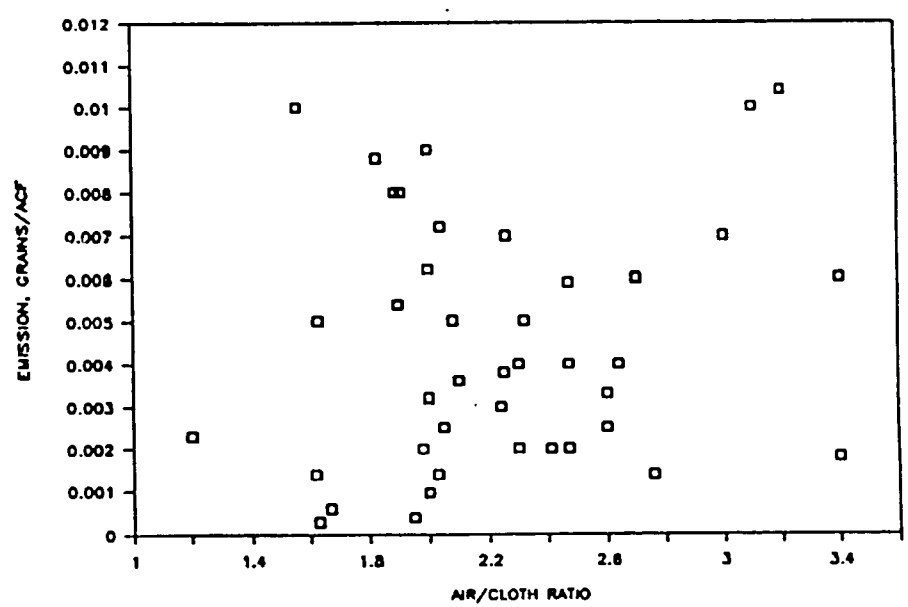

Figure 12. Emissions vs. A/C, low emission units.

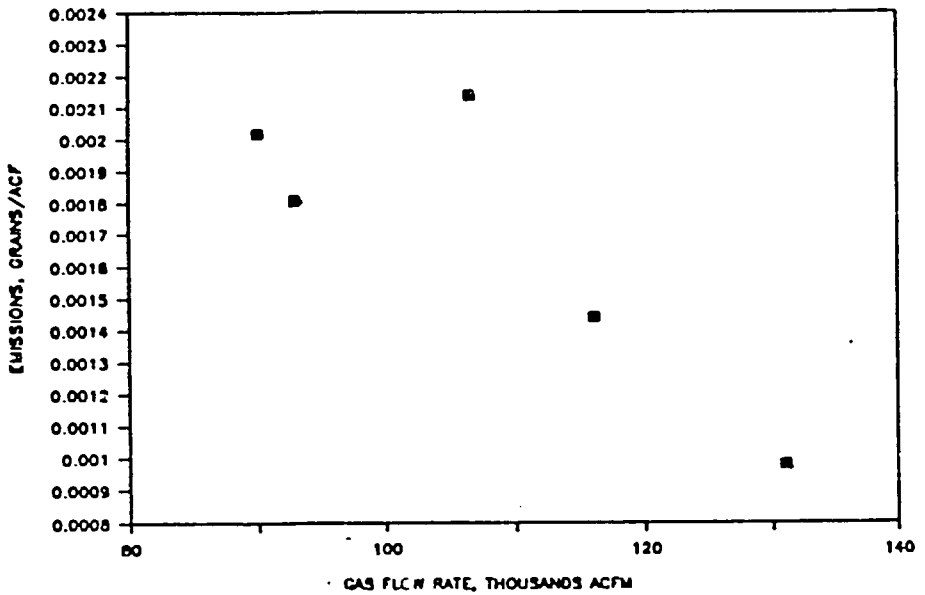

Figure 13. Emissions vs. gas flow, Kramer.

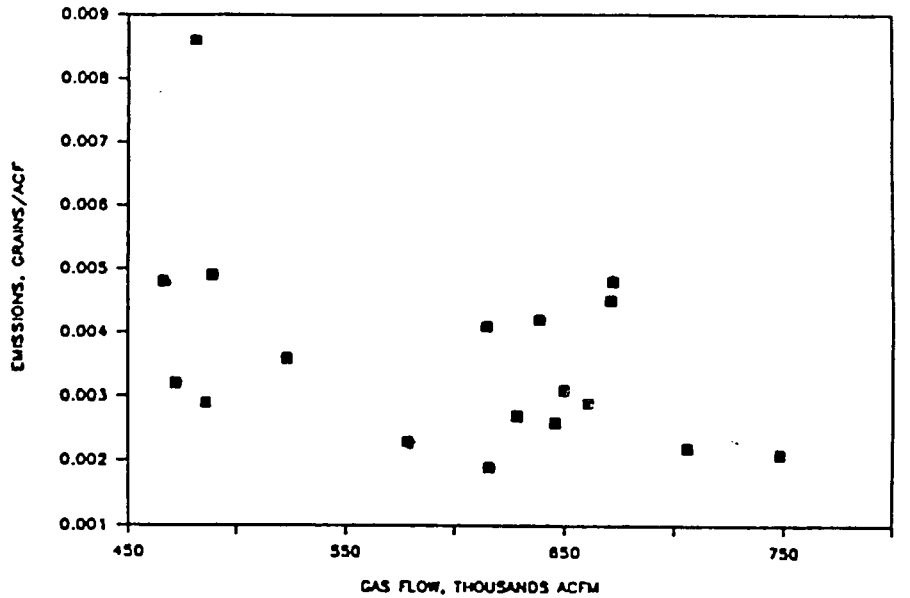

Figure 14. Emissions vs. gas flow, Parish.

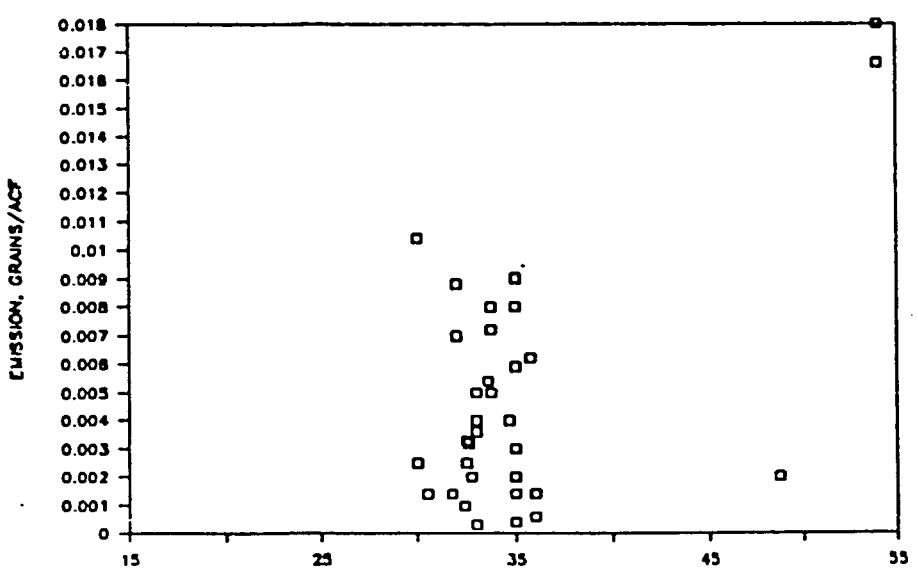

Figure 15. Emissions vs. bag L/D.

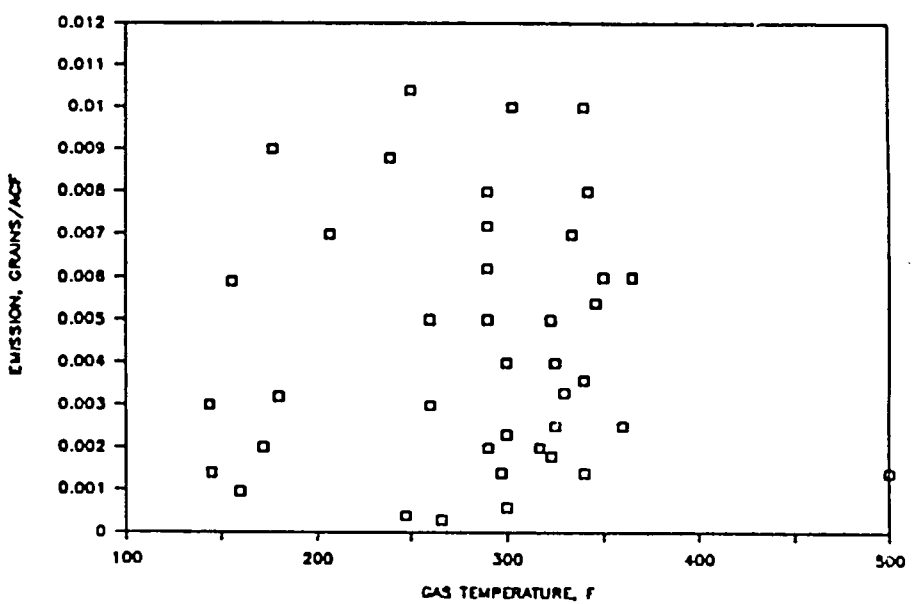

Figure 16. Emissions vs. temperature.

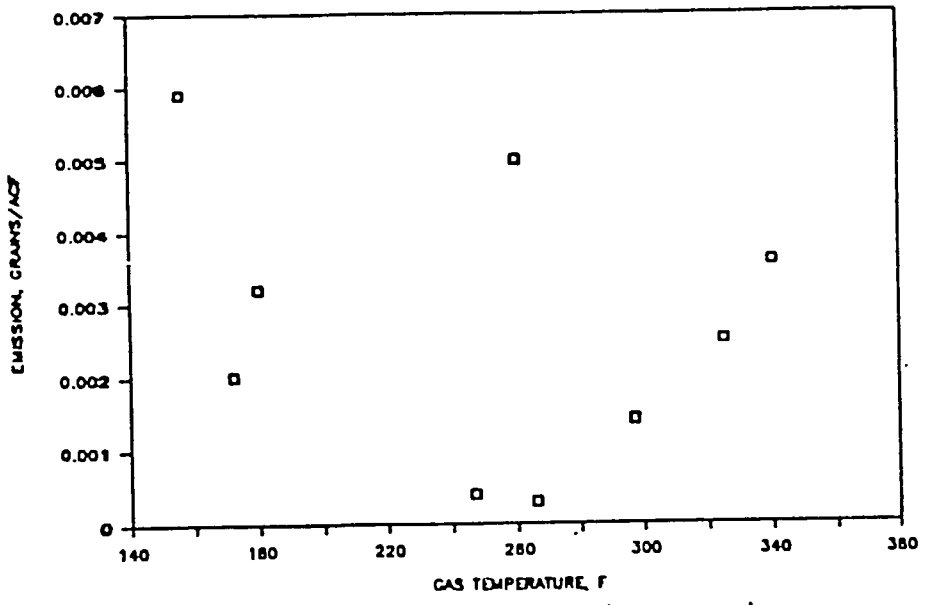

Figure 17. Emissions vs. temperature, one brand of fabric filter.

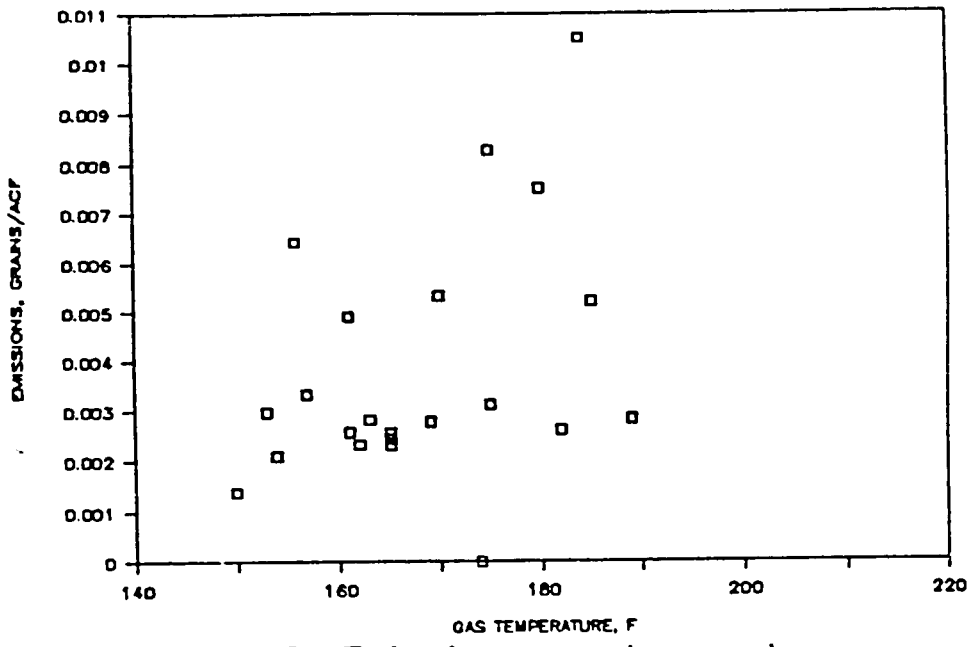

Figure 18. Emissions vs. temperature, pilot test results.

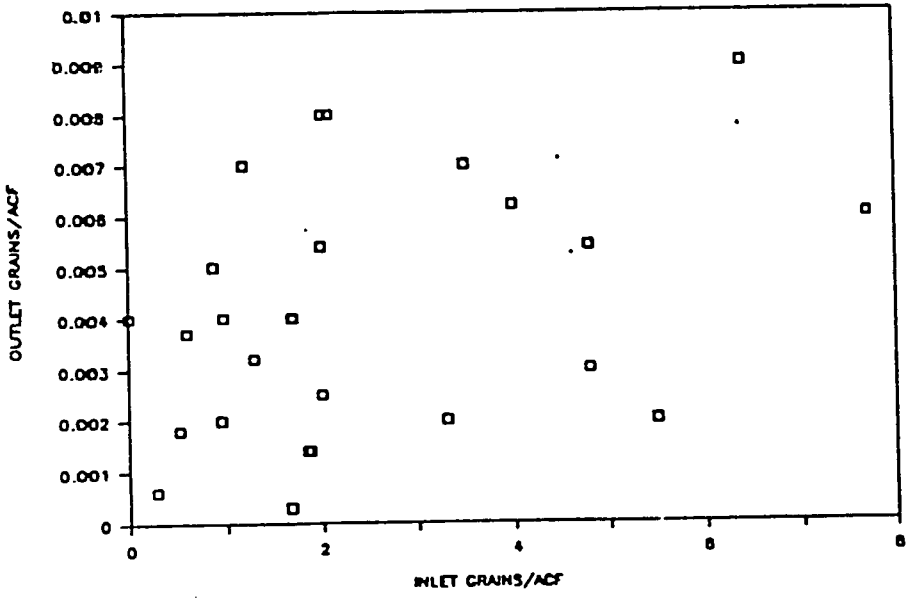

Figure 19. Emissions vs. inlet ash.

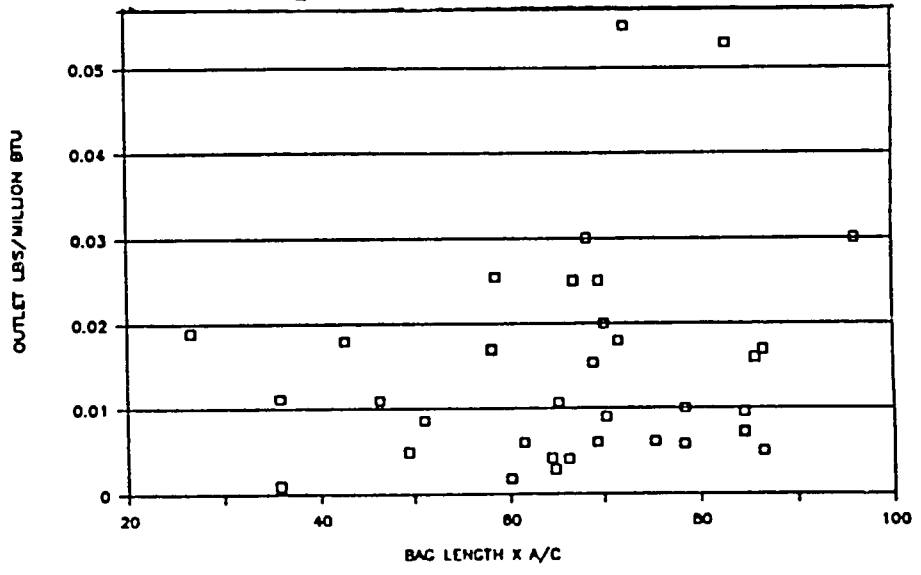

Figure 20. Emission vs. bag length X A/C.

TABLE 1

FABRIC FILTER EMISSION DATA

PLANT & UNIT	GRAINS/ACF	LBS/MM BTU	CLEAN	REF.
HOLTWOOD 17	0.0060	0.0400	SD	10&32
SUNBURY 1&2	0.0025	0.0060	R	42&32
NUCLA 2	0.0040	0.0080	SD	11,12&32
KRAMER 3	0.0006	0.0017	R	13&34
CAMEO 1	0.0020	0.0058	R	14&34
COORS 4	0.0100	0.0400	SD	15
ELK RIVER 3	0.0039	0.0170	R	16&34
SHAWNEE 5&6	0.0040	0.0160	R	17&33
HARRINGTON 2	0.0060	0.0200	SD	19&33
H. R. MILNER 1	0.0054	0.0156	PJ	36
MARTIN DRAKE 6	0.0014	0.0049	R	21&32
WAYNESBORO	0.0036	0.0110	R	22
CAT. TRACTOR	0.0038	0.0110	R	23
HANES	0.0037	0.0118	PJ	24
R. D. NIXON 1	0.0014	0.0041	R	25&37
ARAPAHOE 3	0.0003	0.0008	R	26
MISSOURI CITY 1&2	0.0081	0.0180	R	27&33
COORS 5	0.0079	0.0230	PJ	28
HARRINGTON 3	0.0060	0.0200	SD	29&34
BRUNNER ISLAND 1	0.0062	0.0180	R	32
ANTELOPE VALLEY 1	0.0020	0.0050	R	33
ANTELOPE VALLEY 2	0.0059	0.0170	R	33
ANTELOPE VALLEY 3	0.0020	0.0050	R	33
BULLOCK 1&2	0.0166	0.0250	R	32
CAT. TRACTOR	0.0023	0.0067	PJ	34
CHEROKEE 2	0.0072	0.0154	R	33
CHEROKEE 3	0.0050	0.0090	R	33
CLARK 1	0.0054	0.0190	R	34
CLAY BOSWELL	0.0070	0.0550	R	33
COYOTE 1	0.0070	0.0240	SD	32
CRAIG 3	0.0090	0.0200	R	33
CRISP 1	0.0104	0.0300	R	34
DULUTH 1	0.0014	0.0040	R	33
ESCALANTE 1	0.0020	0.0060	R	35
FOUR CORNERS 4&5	0.0088	0.0255	R	30
GEN. MOTORS	0.0052	0.0150	PJ	34
HOLCOMB 1	0.0032	0.0107	R	33
HUNTER 3	0.0030	0.0100	R	33
JAMES RIVER	0.0061	0.0180	PJ	41
KAW 1	0.0180	0.0530	R	33
KAW 3	0.0050	0.0086	R	33
LON D. WRIGHT 6	0.0033	0.0096	R	33
LON D. WRIGHT 7	0.0025	0.0072	R	33
LONGWORTH 3	0.0270	0.0957	PJ	32
NORTH VALMY 1	0.0010	0.0028	R	39
REID GARDNER 4	0.0080	0.0250	R	33
RIVERSIDE 4	0.0014	0.0040	R	40
RIVERSIDE 6	0.0004	0.0300	R	33
VALMONT 5	0.0023	0.0045	R	33
W.H. SAMIS 1	0.0200	0.0700	R	33
W.H. SAMIS 2	0.0300	0.0900	R	33
W.H. SAMIS 3	0.0100	0.0400	R	33
W.H. SAMIS 4	0.0200	0.0700	R	33
W.A. PARISH 8	0.0020	0.0061	R	6
WABAMUN 1	0.0200	0.0580	PJ	33
CROMBY 1	0.0120	0.0350	PJ	43
	---	---		
AVERAGE	0.0068	0.0218		

NOTES:

1. Where literature data shows only grains/acf or only pounds per million Btu, estimates have been made of the other units.

2. For some plants, various literature references may reflect more than one series of tests. For these plants, generally, the more current data are used.

APPENDIX G-10

LIMITATIONS TO EFFECTIVE ESP PERFORMANCE: A THEORETICAL REVIEW

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ABSTRACT

This paper reviews critical factors affecting electrostatic precipitator performance such as fine particle size, excessive particulate space charge, high resistivity and reentrainment. Through modelling of the ESP process the potentially adverse effects of these factors are illustrated. Finally, means of dealing with each type of problem are discussed.

LIMITATIONS TO EFFECTIVE ESP PERFORMANCE: A THEORETICAL REVIEW

INTRODUCTION

In order for electrostatic precipitation to remain a leading option for high-efficiency particulate emission control it is necessary to understand the factors which can limit the effectiveness of ESP performance and to know how to deal with them. Factors such as particle size, space charge, resistivity and reentrainment can have a profound effect on ESP performance. This paper is intended to provide some insight to the nature of performance limitations which can arise when these variables are outside their normal ranges, through modelling of the ESP process. Practical means for overcoming the limitations are also suggested.

ESP MODEL

The Research-Cottrell ESP computer model was used to study the effects of particle size, space charge, resistivity and reentrainment on ESP performance. It is a theoretical model of the ESP process and has been described elsewhere[1].

The model handles particle size by assuming a log-normal size distribution. ESP performance is tracked incrementally through the precipitator by integrating over the size distribution at each increment. Changing electrical, particulate and gas conditions are accounted for in each increment.

Particulate space charge is calculated by integrating the charge on each particle over the size distribution. Each particle's charge is dependent on its size and the effective charging field. The model accounts for the particulate space charge contribution to the total field strength at its position in the ESP considering electrical breakdown criteria. Although high particulate space charge enhances the particulate collecting field, it also causes corona suppression which promotes reentrainment. These opposing effects are accounted for in the model.

High resistivity effects are modelled by calculating the voltage gradient in the collected dust layer as the product of the resistivity times the local current density. When this gradient reaches a critical value, electrical breakdown is initiated in the dust layer and power input is limited. At higher resistivities this power limitation becomes severe and ESP performance can be seriously impaired. The effects of this resistivity limitation are shown through reduced ionic space charge fields and poorer current distribution. This latter effect comes about because of the fewer number of corona discharge sites as total current decreases. The model accounts for it based on information published by Lawless[2].

In modelling particulate reentrainment three types of reentrainment are considered: electrical, rapping and flow. Pontius[3] shows that the net force holding particulate matter to the collecting electrode is composed of electrical and cohesive components. The cohesive force, T, is a specific characteristic of any given dust sample. The electrical force is made up of two opposing forces, one dependent on the square of the electric field at the surface of the dust layer which tends to reentrain the collected dust, and the other dependent on the dust dielectric constant, resistivity and current density which tends to hold the dust on the collecting surface. In evaluating reentrainment at any location in the ESP the model calculates the electrical forces, and, if the net force is attractive, the model assumes no electrical reentrainment, but always assumes some fraction, e.g. 10%, of the collected dust is reentrained from a given location by flow or rapping, and has to be recollected downstream. If the electrical force favors reentrainment then the model adds electrical reentrainment to that by rapping and flow in an amount depending on the relative value of the electrical force to T. An arbitrary maximum fraction of material reentrained from any given location, e.g. 85%, is applied to account for local effects, agglomeration, material falling to the hoppers, etc. Although the modelling of reentrainment is inexact by its nature, the present model allows the exploration of trends in ESP performance when affected by reentrainment as governed by the physical factors described above.

ESP PERFORMANCE LIMITATIONS

This section discusses the effects of particle size distribution, particulate space charge, resistivity and reentrainment on ESP performance. The computer model described above was used to generate the information presented. All runs were made varying about a base operation as described in Table 1.

Particle Size Distribution: A precipitator's ability to collect particles varies greatly with particle size. For example, a precipitator collecting 5 micron particles at 99.6% theoretically has only a 63% collection efficiency for 0.5 micron particles whereas its theoretical efficiency is back up to 98% for 0.05 micron particles. A minimum in collection efficiency occurs for normal flue gas conditions at about 0.3 microns. In order to determine overall ESP collection efficiency it is necessary to integrate over the particle size distribution, normally assuming a log-normal distribution. ESP performance declines as the mass median diameter (mmd) decreases towards 0.3 microns and as standard deviation (sd) increases. Figure 1 shows this effect. An SCA of 302 is needed to achieve 99.9% collection efficiency for the base case (mmd of 10 and sd of 3). As the mmd decreases the SCA requirement increases to a value of 800 at mmd of 2 microns. If the sd value were 2 instead of 3, collection would be easier; an SCA of 223 would yield 99.9% efficiency for mmd of 10 microns and 577 would suffice for mmd of 2.

These examples illustrate the importance of particle size distribution in sizing ESPs for a given collection efficiency level. Any potential means for biasing the particle size distribution toward a coarser distribution can have very beneficial impact on ESP sizing.

Particulate Space Charge: As suspended particulate matter enters the ESP the particles become charged to an amount directly dependent on the surface area of each particle. The integral of all of these charges at a given location in the ESP is the particulate space charge, and it contributes to the electric fields in the ESP. The contribution of particulate space charge to the collecting field is proportional to the particulate space charge times the half plate spacing. This field also contributes to electrical breakdown in the ESP. Furthermore when the field is high it can have the effect of suppressing corona generation, thereby limiting or quenching ionic current flow which is vital to further particle charging and holding of collected particulate on the collecting electrode. The particulate space charge effect is greater at wider plate spacings, at higher particulate concentrations and with finer particle size distributions because of the higher surface to mass ratio associated with fine particles. On the one hand particulate space charge is favorable because it provides a uniformly distributed strong collecting field. On the other hand it promotes reentrainment by virtue of the strong collecting field accompanied by suppressed current. The combined effect of these opposing tendencies is generally negative although cases exist where the net effect may be positive.

Figure 2 shows the effect of particulate space charge on ESP sizing for 99.9% collection efficiency through increased particulate inlet loading. As the loading is increased from the base case of 2 grains per actual cubic foot to 20 the ESP size requirement increases from an SCA of 302 to 357. Note that at the lower loadings particulate space charge is not very important and the rate of rise in SCA requirement is slow. At the higher loadings, however, the rate of rise is greater indicating that the negative aspects of high particulate space charge are beginning to dominate.

Figure 3 illustrates corona suppression as caused by increased particulate space charge associated with increased particulate loading. It shows average current density versus fractional distance through the ESP for four values of inlet particulate loading: 1,2,8 and 16 gr/acf. For 1 gr/acf current rises rapidly starting near the ESP entrance and reaches 90% of its final value about 40% through the ESP. However for the higher loadings of 8 and 16 gr/acf the suppression of current is very noticeable. For 16 gr/acf current is suppressed during the first half of the ESP, and current does not reach 90% of its final value until over 80% of the way through the ESP.

<u>Resistivity:</u> When power input to an ESP is limited by electrical breakdown in the dust layer due to high resistivity, performance falls off quickly as resistivity increases. Figure 4 illustrates the effect, plotting the SCA required for 99.9% collection efficiency versus resistivity. At about 10^{11} ohm-cm power input begins to be limited by breakdown of the dust layer. Between 10^{11} and $2x10^{12}$ ohm-cm the fall off of ESP performance is very rapid, SCA requirement increasing from 294 to 1200. For resistivities over $2x10^{12}$ performance does not fall off as rapidly because at the very high resistivities energization is already very poor and the meager performance is sustained primarily by the static field provided by the discharge electrode voltage.

The primary cause of poorer performance caused by high resistivity is the reduced level of current density which causes dust layer breakdown. In the ESP model the current density which is used to calculate the dust layer voltage gradient is the maximum current density which exists directly opposite the corona discharge sites. In addition to this effect

performance deteriorates because, as total current declines the number of corona sites decreases causing poor current distribution and weaker average collecting fields. Figure 5 illustrates this effect. It plots both maximum and average current density (mA/m^2) and shows that, as resistivity increases, average current density becomes a smaller fraction of the maximum, indicating the poorer distribution. For example, at moderate resistivities the average current is 76% of the maximum whereas at 10^{12} ohm-cm it is only 16% of the maximum, pointing out the large area of collecting surface which is seeing below maximum current at the high resistivity operation.

In Figure 4 note that there is some fall off in performance below 10^{10} ohm-cm. This is due to reentrainment caused by reduced particulate holding force at low-resistivity. This low-resistivity effect can be much more severe depending on the effective reentrainment parameters for the particulate being collected.

Reentrainment of Collected Particulate: The parameters used in modelling reentrainment were discussed before. The base case used values of 3 for the cohesive force parameter and 0.1 for the reentrainment fraction and calculated an SCA requirement of 302 ft^2/1000 acfm for 99.9% collection efficiency. In order to estimate the SCA requirement if reentrainment-free operation were possible, the reentrainment fraction was set to 0 and the cohesive force was set to a very large value. The resulting SCA was 261, meaning that, at the moderate reentrainment used in the base case, the base ESP is oversized by 18% to allow for reentrainment. Higher reentrainment would, of course, require even greater ESP oversizing. Figure 6 shows the increase in ESP size needed for 99.9% collection as a function of the reentrainment fraction; the cohesive force was set at 3 in generating this figure. It can be seen that as the reentrainment fraction exceeds 0.4 the SCA requirement increases very rapidly.

Figure 7 shows the effect of the cohesive force parameter on precipitator size. It shows that for values over 2 there is little change in the ESP size requirement. However, as the parameter decreases below 2, reentrainment becomes severe, and the required ESP size increases rapidly.

Figures 6 and 7 illustrate the importance of keeping reentrainment under control, both by good flow quality design and rapping practice as well as by influencing the cohesivity of the dust if it has reentraining tendencies. It is not feasible to allow high reentrainment to degrade the electrostatic precipitation process, especially when it is important to keep ESP size viable in face of more stringent performance requirements.

MEANS OF DEALING WITH ESP PERFORMANCE LIMITATIONS

There are many ways of dealing with each class of ESP limitation discussed above, and these means are subjects of much of recent ESP literature and will be subjects of much future ESP literature. It is beyond the scope of this paper to do more than briefly mention the more promising of these techniques.

Fine Particulate: Agglomeration in the suspended phase prior to the ESP comes to mind as the most desirable way to handle the collection of fine particles. However, for most practical applications particle concentration is not high enough to allow timely agglomeration even if surface conditioning agents assure 100% cohesion of particles that do make contact in the gas stream. Agglomeration can be promoted, however, when particles contact each other on the ESP collecting plates, by use of cohesivity conditioning agents. Doing so discourages reentrainment of fines so that, once collected, they will not have to be recollected as fines. This is not a perfect cure for the fine particulate collection problem but does lessen the degree of the problem.

Other means of dealing with the precipitation of fines include process changes to avoid the fines, particle growth by condensation (if it is feasible to pass through a dew point), and creation of high particulate concentrations which allow timely agglomeration.

Particulate Space Charge: Particulate space charge has potential for being a problem only in the inlet section or two of a precipitator. This suggests that one way to handle it is to use narrower plate spacing at the inlet since wider plate spacing can aggravate the particulate space charge problem. Another way to deal with it is to use a higher emitting discharge electrode design in the inlet sections of the ESP. Increased electrical sectionalization in the inlet fields is also helpful.

Because particulate space charge is increased by high particulate loading and fine particulate, means for reducing fine particulate and total particulate concentration can be helpful. Mechanical collectors come to mind as a means for reducing inlet particle concentration; however, they remove essentially only the larger particulates and may not have much impact in reducing the space charge which is concentrated largely in the fine particulate fraction.

High Resistivity: Chemical conditioning is a generally accepted way of dealing with high resistivity. Injection of trace quantities of SO_3 or other agents can condition the surface of the particles so that their resistivity is reduced into the moderate resistivity range, completely removing the high resistivity problem. In some cases moisture addition is effective as a conditioning agent because resistivity decreases with increasing moisture depending on the flue gas temperature and chemistry. Sodium conditioning has also been shown to be effective in reducing resistivity.

Pulse energization is another purely electrical means which has been proven to be effective in lessening the high resistivity limitation, although it is not quite as effective as conditioning.

Temperature control is another means of coping with high resistivity. By operating the ESP at the high temperature or low temperature side of the resistivity curve it is possible to avoid the high resistivity portion of the curve and effect a problem-free operation. Evaporative cooling is an effective way of achieving cold-side operation because it reduces resistivity by both the temperature effect and the humidity effect. In the extreme, if cooling is carried below the dewpoint, wet operation of the precipitator is free of resistivity limitations and brings with it added advantages in fine particulate and reentrainment control potential. In applications which allow wet operation it should certainly be considered.

Two-stage electrostatic precipitation is theoretically appealing because it allows separate optimization of the charging and collecting functions of the ESP. It is possible for certain high-resistivity applications to use two-stage precipitation or one of its modifications to advantage. No such systems have had commercial success yet however.

Reentrainment: Much particulate reentrainment can be eliminated by careful precipitator design to lessen the effects of electrical, flow and rapping reentrainment. Innovative design may also be necessary to achieve a true minimum in reentrainment. For example, the discharge/collecting electrode system can be designed to promote better current and field distribution which will discourage electrical reentrainment; perhaps a "wavy plate" design will evolve.

Flow reentrainment can be reduced by achieving tight control over flow distribution and direction by using physical and computer flow modelling to guide the design and placement of baffles, vanes and perforated plates in the ESP system.

To reduce rapping reentrainment, rapping system design and its operating philosophy must be reviewed. The goal of the rapping system should not be simply to hit the collecting plates as hard as possible to dislodge the dust, but rather it should be designed and operated to hit the plates as gently as possible with even distribution of the rapping forces in order to promote shear-force dislodgement of the dust. Ideally such practice allows the dust layer to "slide" down the collecting surface into the hoppers rather than be forcefully propelled back into the gas stream.

Probably the most promising means of dealing with reentrainment is conditioning of the dust particle surface with an agent which will enhance its cohesivity so that it is not easily reentrained by less-than-ideal electrical and flow conditions. This will help take the pressure off the expectation of perfect ESP design and operation and allow for a practical, minimum-reentrainment design. Cohesivity conditioning can also have the desirable effect of causing agglomeration of fine particles to larger particles on the collecting surface so that any reentrained particulate will be coarser and more easily recollected. Wet ESP operation may be considered a form of cohesivity conditioning and is effective in eliminating particulate

reentrainment. It should be considered where practical because it carries with it advantages in fine particulate and resistivity management.

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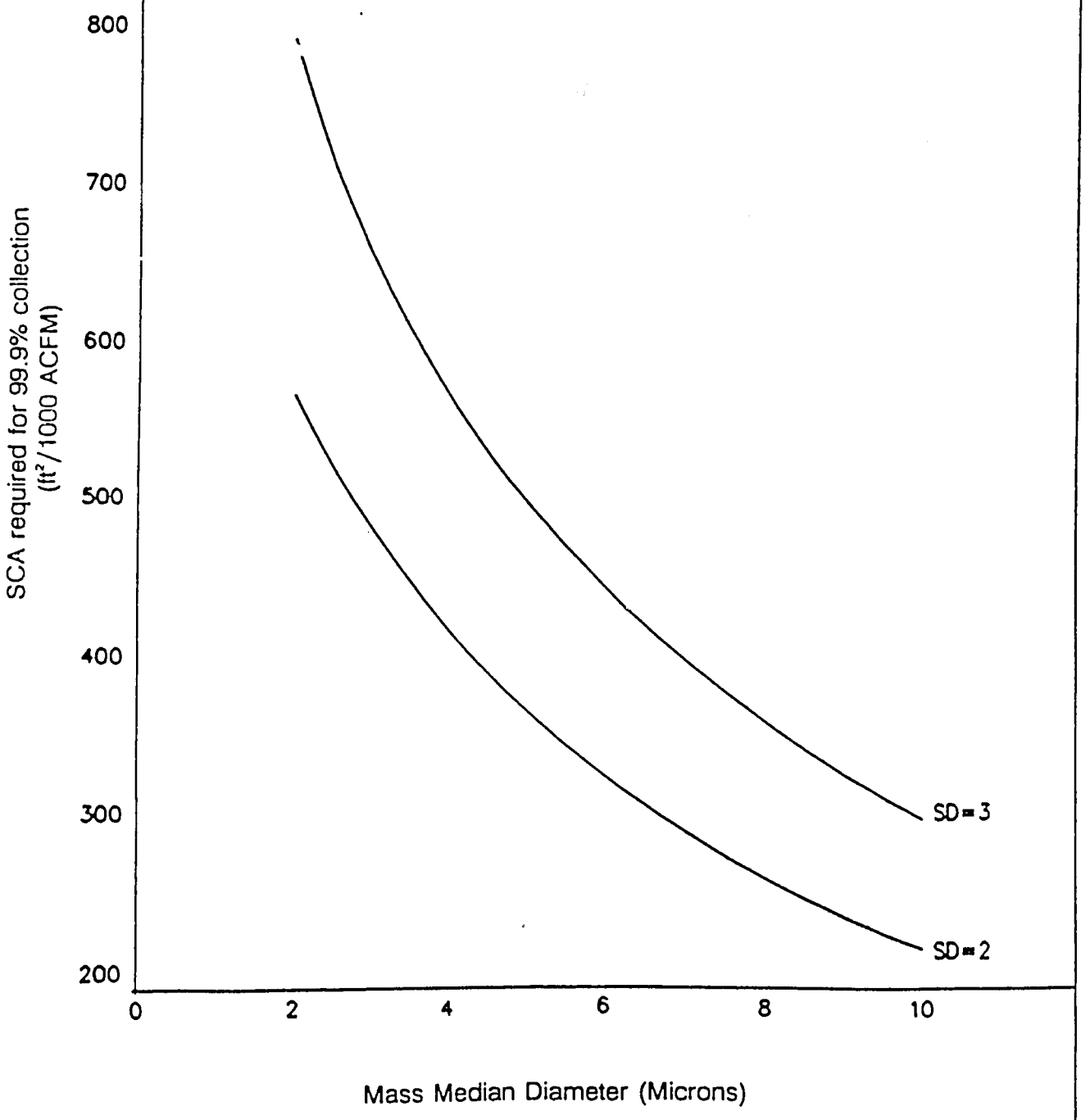

Figure 1. Effect of particle size distribution on precipitator size

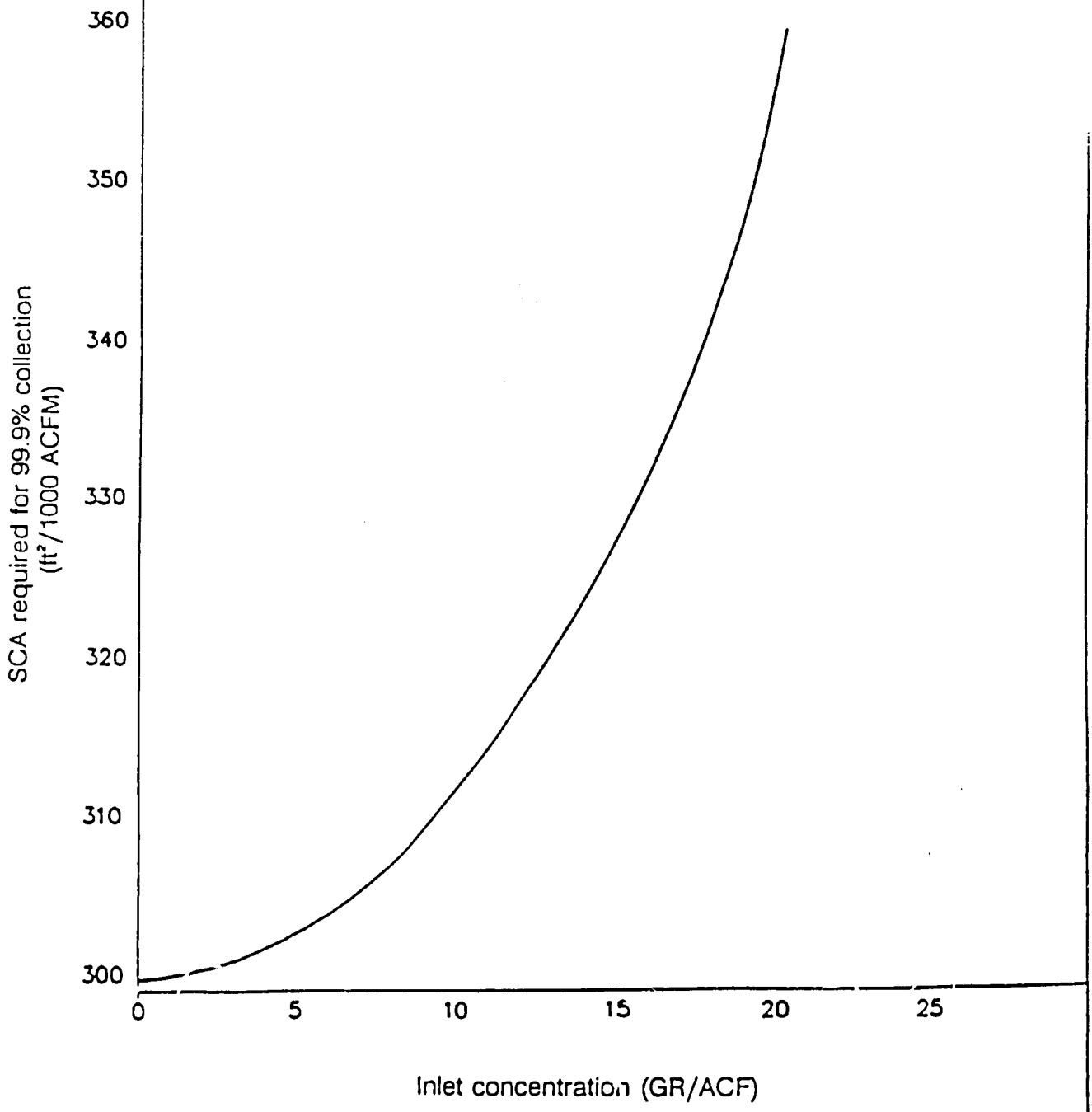

Figure 2. Effect of particulate space charge on precipitator size

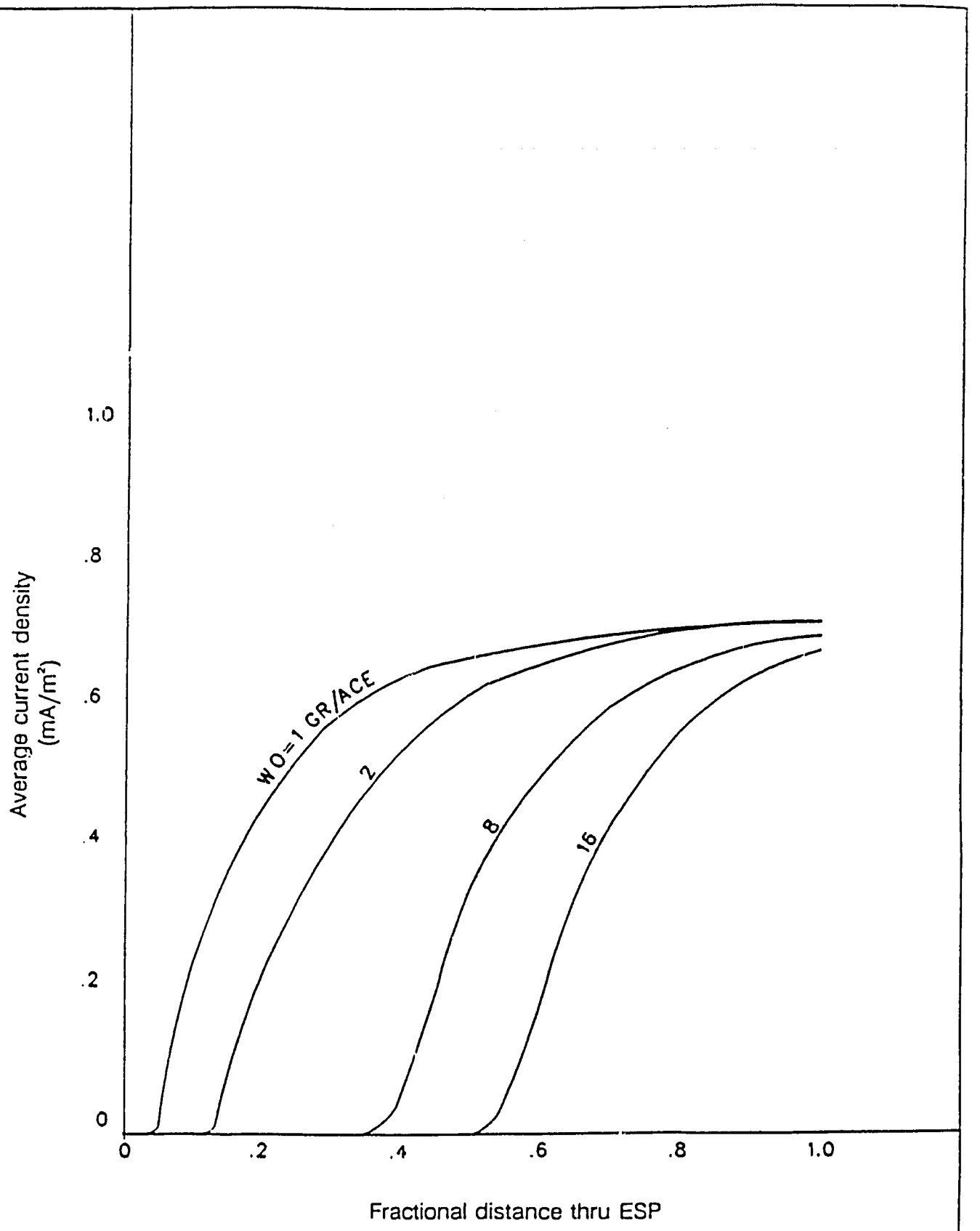

Figure 3. Corona suppression caused by particulate space charge

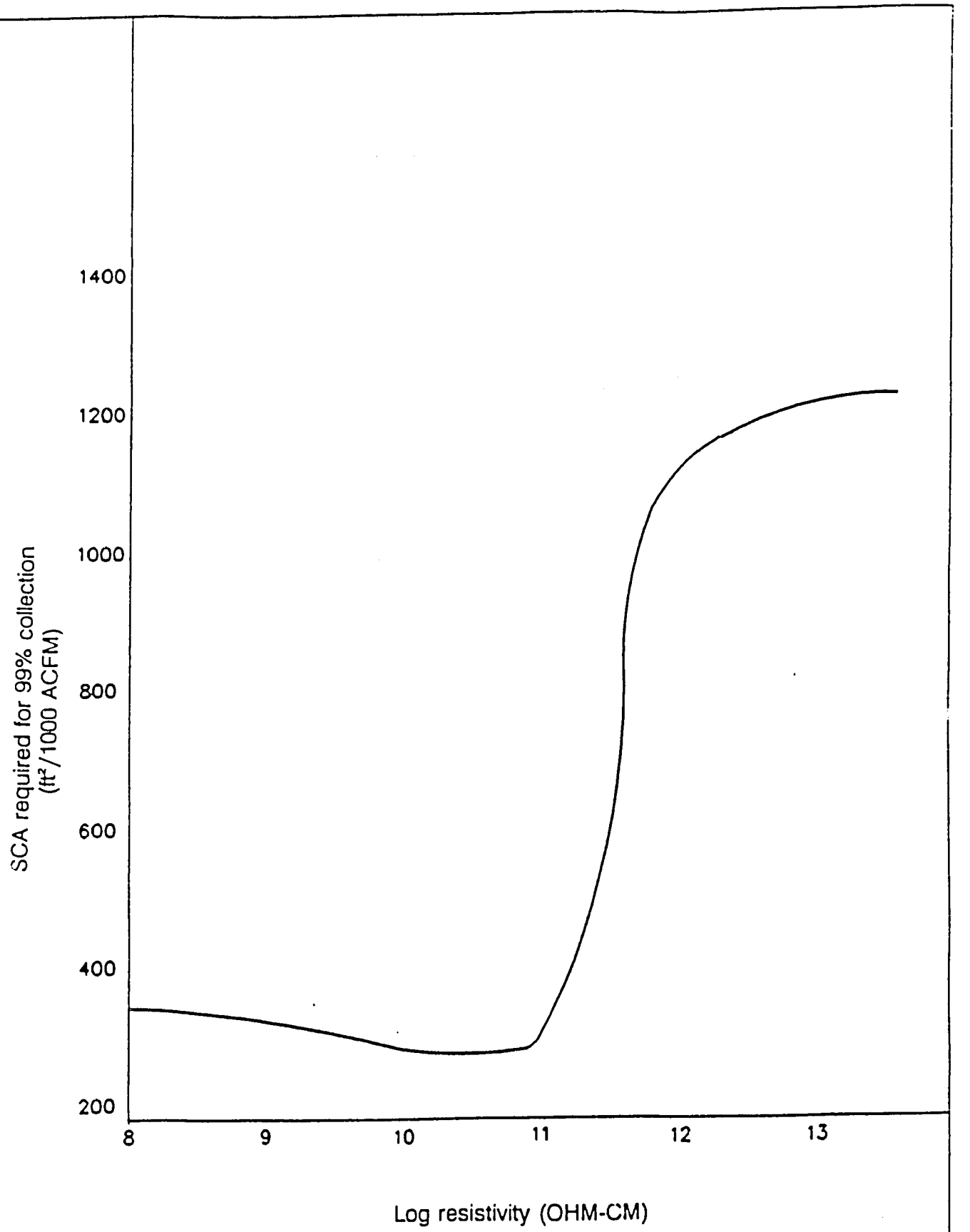

Figure 4. Effect of resistivity on precipitator size

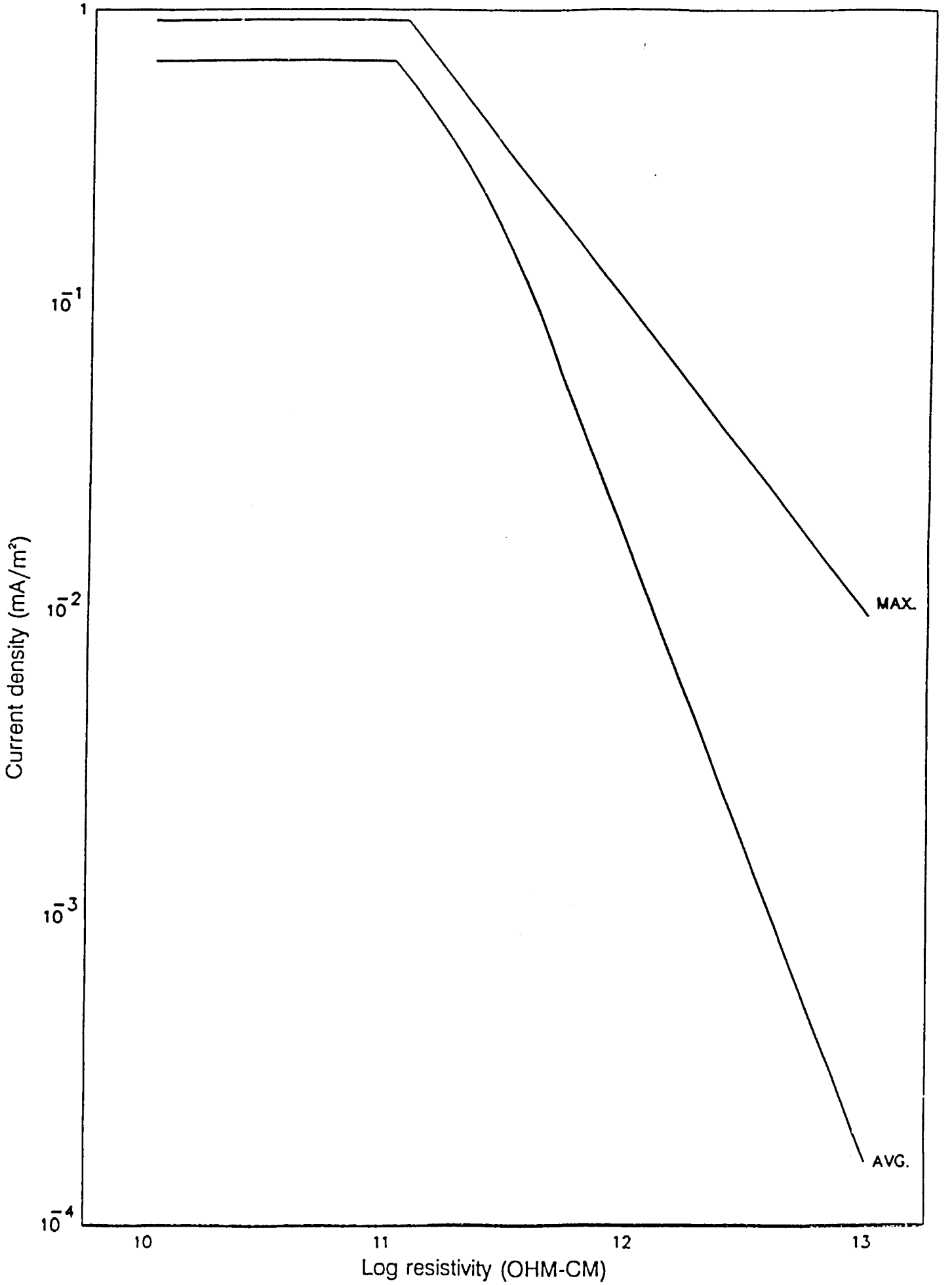

Figure 5. Effect of resistivity on current density

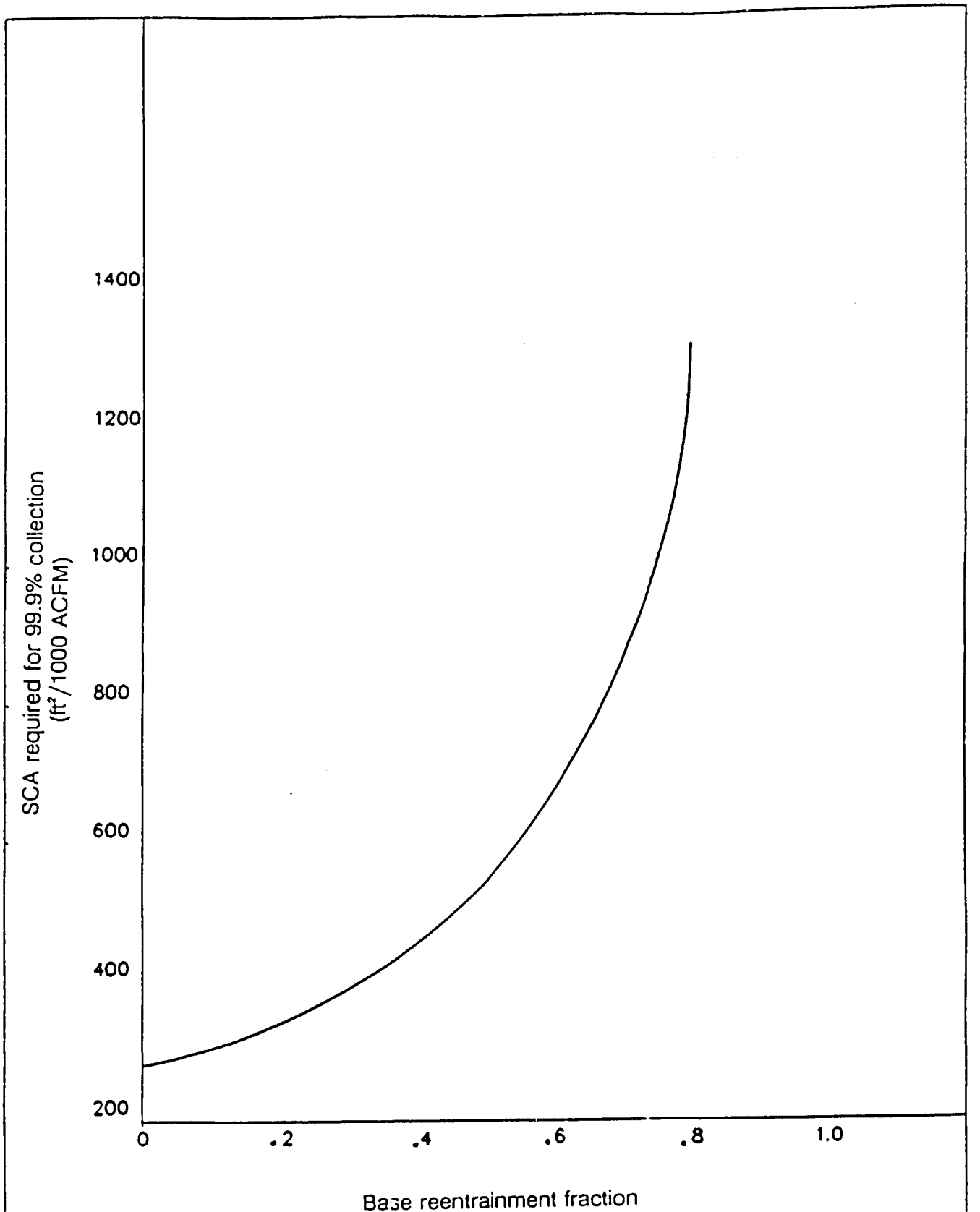

Figure 6. Effect of reentrainment fraction on precipitator size

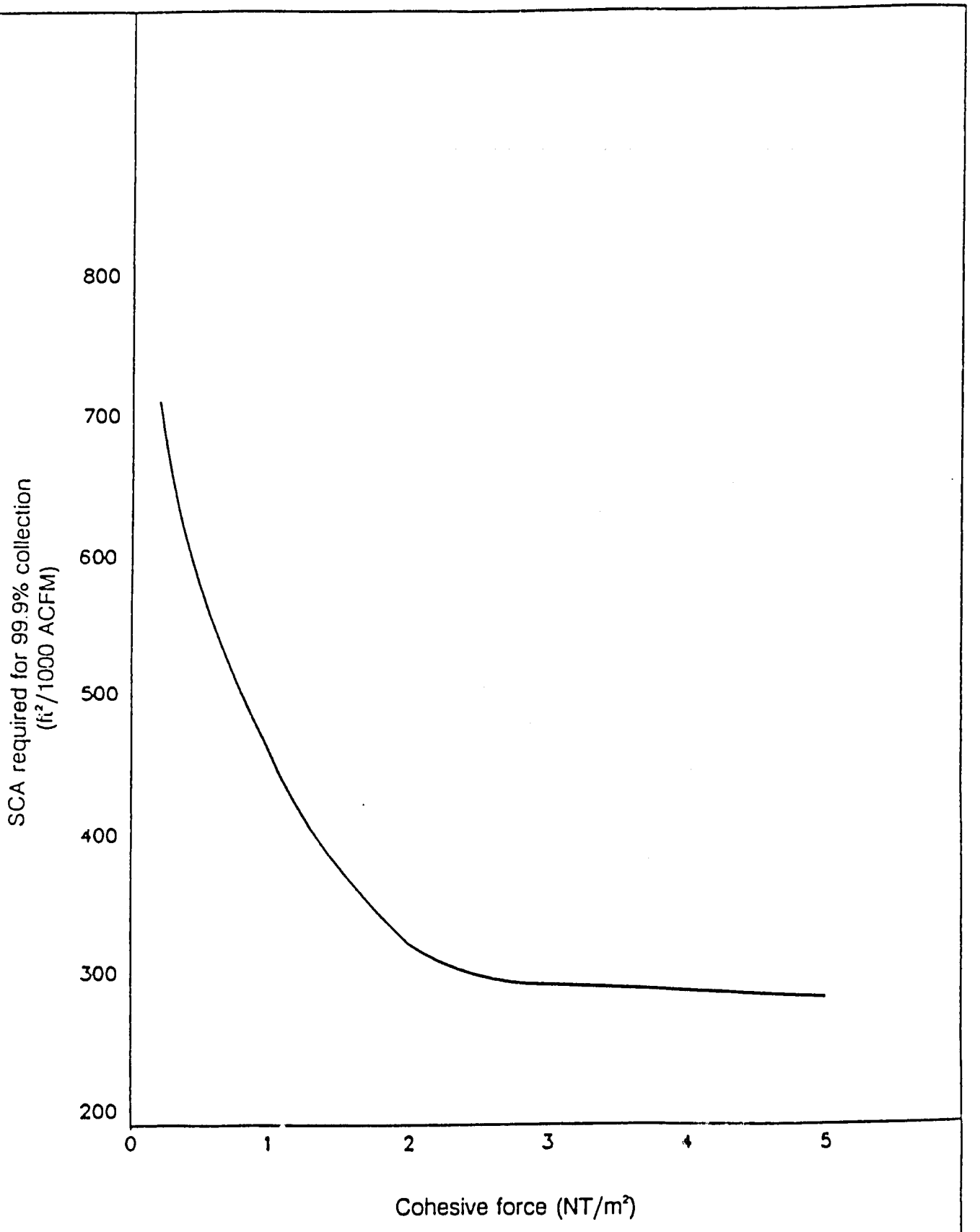

Figure 7. Effect of cohesivity factor on precipitator size

Table 1

VALUES OF INPUT VARIABLES USED AS BASE CASE

Temperature (F)	300
Inlet loading (gr/acf)	2
Dielectric constant	6
CE spacing (in)	12
DE diameter (wire type) (in)	0.109
Resistivity (ohm-cm)	1E10
Mass median diameter (micron)	10
Geometric standard deviation	3
Cohesive force factor (Nt/m2)	3
Reentrainment fraction	0.1

APPENDIX G-11

Some practical suggestions for

Upgrading Fabric Filter Performance

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Some practical suggestions for

Upgrading Fabric Filter Performance

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FABRIC FILTERS are reliable air pollution control devices, but plant engineers occasionally encounter operational problems with them. Table I classifies the problems into three major categories: (1) stack emissions that violate EPA regulations, (2) insufficient draft at dust-generation points, and (3) excessive maintenance costs. This article explains how to identify and define these problems, analyze their causes, and find solutions to them.

Identifying the Problem—Noncomplying emissions result when a fabric filter fails to remove specified-size particulates. The problem is usually caused by fabric aging, abrasion, chemical attack, burning, or rips and tears. Inadequate sealing and leakage of dust through plate joints also can cause this.

Insufficient draft at dust generation points results from fabric blinding, inleakage, or blockage somewhere in the piping or filter housing system. Failure of the induced-draft-fan drive and wheel erosion are other potential causes.

Excessive maintenance costs result when filter fabrics blind, plug, or fail, and if cleaning devices or other mechanical components malfunction.

A properly specified and applied fabric filter system, operating under original design conditions, should respond quickly to corrective action if it exhibits any of these problems. Improved operation and maintenance procedures, coupled with routine repairs, generally are all that is required to resolve the difficulty.

Approaching the Problem—Careful identification of a fabric filter problem is critical to an economical and timely solution. An incorrect diagnosis can waste money and time and extend downtime of a plant's essential production equipment.

Input from plant personnel and records are important aids to defining the problem. Operational logs

Upgraded fabric filter has twice its original gas-handling capacity, but occupies same amount of floor space. Modification consisted of welding a conversion cap (plenum section) to top of gutted filter housing. Cap slightly increased height of unit and converted it to pulse cleaning. Workers are shown installing cages for felted bags.

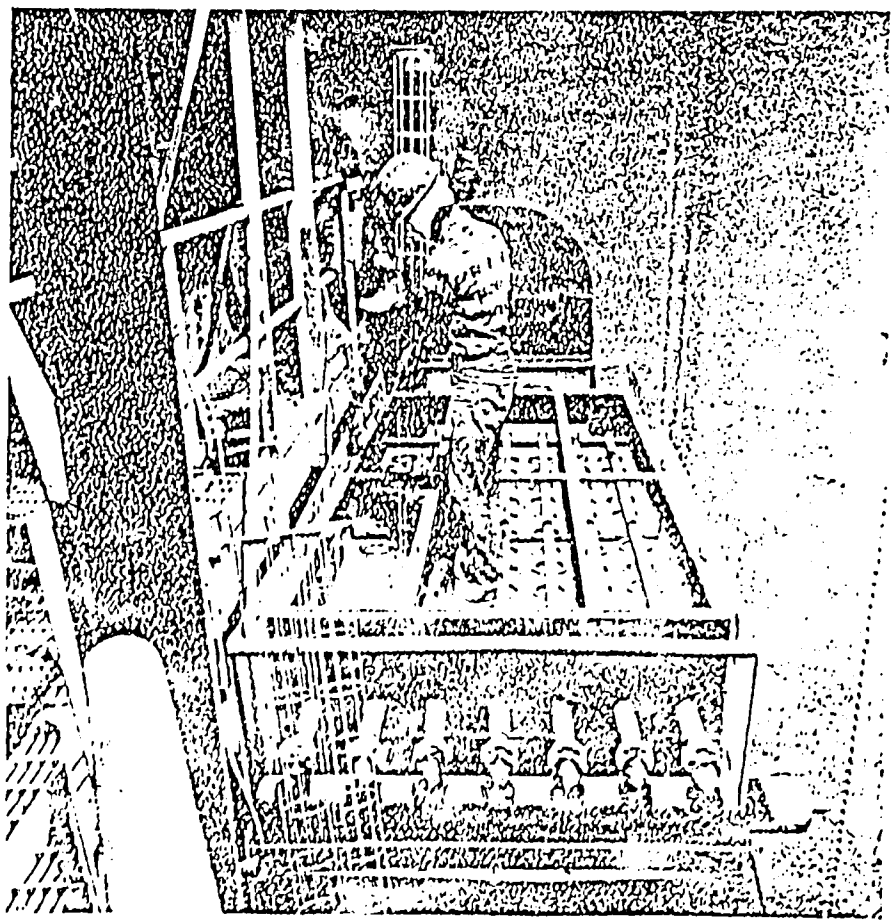

TABLE I. COMMON FABRIC FILTER PROBLEMS AND POTENTIAL SOLUTIONS

Problem	Possible Cause	Verification Method	Potential Solution
Excessive stack emission rate—noncompliance with EPA regulations	Dust leaks through joints and collars	Internal inspection at clean-to-dirty-air plate joints and collars	Clean joints and seal or weld
	Bleeding or seepage through intact filter	Inspect internal parts for light dust coating on clean air side (as opposed to dust pile)	Replace fabric and substitute suitable material
	Holes or tears in fabric	Inspect each fabric filter	Replace fabric and restore or add baffle plates
	Supercleaned fabric allows dust to bleed through	Analyze cleaning frequency and intensity	Reduce cleaning frequency and intensity
Dust is not captured at point of generation—insufficient draft	Blinded or plugged bags	Read pressure drop across fabric filter	Vacuum, dry clean, wash or replace fabric
	Moisture in air stream produces mud in bags	Inspect fabric	Change process conditions to remove moisture or increase temperature to above dewpoint
	Broken or defective cleaning devices	Inspect fabric cleaning devices	Repair or replace
	Air leaks into dirty air piping or blocked pipe or hood.	Inspect hoods and dirty air piping	Repair, or patch piping and replace gaskets; clear blockage
	Broken or slipping fan-drive belts	Inspect induced-draft fan drive	Replace or tighten belts
	Missing or eroded fan-wheel blades	Inspect induced-draft fan wheel	Replace fan wheel
	Defective timer parts or wrong timing	Inspect timer	Replace timer parts or adjust timing
	Filled or plugged hopper because of defective conveyor drive, discharge valve, or discharge valve drive	Inspect hopper discharge equipment	Replace defective drive or conveyor parts
	Dust buildup forces bags into tube sheet holes and reduces air flow	Inspect interior or housing for heavy dust deposits on clean air side	Repair clean-to-dirty-air [illegible] and remove dust from clean air side
	Air leaks into holes in housing or hopper	Inspect exterior of fabric filter housing and hopper	Patch holes or repair gasketing
	Air or dust leaks into manifolding and reduces air flow from dust point	Inspect all butterfly and poppet valves and their operators and controls	Repair or replace parts, operators, or controls
Various problems related to excessive maintenance costs—mechanical failures, reduced service life of cleaning mechanism and fabrics	Infrequent or inadequate lubrication of equipment (causing wear and early failure)	Consult operation and maintenance manual to compare with current practices	Lubricate according to instructions prescribed in manual
	Erosion of or absence of interior baffle plates (considerably reducing fabric life)	Inspect fabric filter interior baffle plates	Restore or install baffle plates
	Operating cleaning devices more often than required (shortening their service life as well as that of the fabrics)	Check fabric cleaning timing for correct adjustment as instructed by supplier	Adjust cleaning frequency to design condition
	Unnecessary cleaning intensity (wastes energy and needlessly stresses fabric, as well as fabric suspension and cleaning devices)	Check intensity of fabric cleaning devices against supplier's instructions—air pressure and volume in compressed air cleaning, and amplitude in fabric-agitation systems	Adjust air pressure and volume to design specifications, adjust amplitude in fabric-agitation systems

"The type and magnitude of the fabric filter problem dictates who should do the inspections, tests, analysis, problem solving, equipment selection, and installation."

TABLE II. COMPARISON OF FABRIC FILTER REPLACEMENT AND CONVERSION COSTS*

	Replacement	Conversion
Equipment, dollars per acfm	0.72 to 1.72	0.43 to 1.03
Erection, percent of equipment	130	100
Operation, dollars per year per acfm	0.10	0.10
Maintenance, dollars per year per acfm	0.07 to 0.36	0.07 to 0.36

*Estimated 1979 costs

Note: Costs of demolishing and removing existing equipment, foundations, and structures are not included.

that list air flows, temperatures, pressure drops, frequency of fabric changes, and maintenance actions serve as a base to identify deviations from normal operation.

Previous inspection reports and general observations also are helpful. The collected data can be supplemented by inlet grain loading, stack emission, dust, and fabric analysis test results. Current air flow, temperature, and pressure-drop measurements are also necessary for proper evaluation.

Inplant changes that boost production rates often increase air volumes, temperatures, and dust inlet grain loadings. Analysis and comparison of the existing statistics with the original design conditions may confirm the need for modifications to cope with new conditions.

Solving the Problem—Process changes can cause substantial increases in air flows and noncomplying stack emissions. An obvious solution to the problem is to return the process to its original operating conditions. If this solution is impossible, then a fabric change or additional air filtration capability may be needed.

Process changes can also cause pressure drop increases across the filter. Insufficient draft may occur at dust-collection hoods. Again, the ideal solution is to return the process to its original operating conditions. If this is not possible, then increasing fabric-cleaning frequency and intensity or adding more cloth area may be required.

If space limitations prevent the installation of additional cloth area, efforts should be made to increase the filtration capability of the existing system. For example, prefabricated conversion caps installed on top of a gutted fabric filter housing can greatly increase air-flow capacity. These caps are self-contained top sections of dust collectors that include fabrics and cleaning systems. The units provide more capacity without significantly changing the overall dimensions of the filter (see photograph). Such conversions normally cost less than replacement with a new, higher capacity unit, Table II.

Persistent excessive maintenance costs may require radical changes of equipment. For example, noisy, highly stressed pneumatic shakers can be replaced with quiet, mildly stressed mechanical shakers. But substituting a new filter fabric for the originally specified cloth is not recommended. A careful balance must be maintained between the fabric and the cleaning device. If relationship is disturbed, excessive static pressure losses can result or dust may escape through the fabric material.

Electromechanical timers can be replaced with reliable, solid-state electronic devices. Restoration or the addition of baffling will reduce abrasion and minimize fabric replacement needs.

Team Effort Required—The type and magnitude of the fabric filter problem dictates who should do the inspections, tests, analysis, problem solving, equipment selection, and installation. However, both the plant engineer and the process engineer must get involved. Consulting engineers, testing laboratories, and equipment manufacturers' personnel can provide assistance, too.

Determining who should be involved is a decision that the plant engineer is usually best qualified to make. If the equipment is still within the contracted warranty period (or a guarantee is in effect) the original supplier should be called in to fulfill his obligation. Obtaining assistance from a reputable supplier willing to assume total responsibility for the installation can be the fastest, most economical, and most efficient approach to a fabric filter problem.

Repairs and modifications can also be made using qualified inplant personnel. Consultants may be required to conduct tests and make recommendations, but plant engineering personnel can purchase the equipment, hire installation contractors, and provide overall project management.