United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

EPA-600/7-79-108
April 1979

EPA

Studies of Dust Cake Formation and Structure in Fabric Filtration: Second Year

Interagency Energy/Environment R&D Program Report

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Studies of Dust Cake Formation and Structure in Fabric Filtration: Second Year

by

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Grant No. R804926
Program Element No. EHE624A

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Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

ABSTRACT

This report describes progress toward the project objective: to explain changes in the performance of fabric filters on the basis of changes in the structure of the deposited dust cake. Whether improved performance (that is, greater collection efficiency with lower pressure drop) is obtained by imposition of electric fields, by making the filter fabric out of fibers having modified geometries, or by varying fabric construction, the improvement is associated with deposition of the dust close to the upstream region of the filter rather than deep within it. (In this work the dust cake is understood to include dust that penetrates into the filter fabric.)

An electric field applied to a fabric filter is more effective in reducing pressure drop if the fabric has loose fibers at the surface. When a dust cake is formed on such a fabric in the presence of a field, photographs of the cake surface show heavy deposition on protruding surface fibers. In contrast, after filtration without a field these fibers are bare, and the mass of dust penetrating into the fabric is greater. Thus the combination of applied field and protruding fibers results in reduced penetration into the filter and concomitant pressure drop reduction.

Without an imposed field, using fibers with deeply lobed rather than round cross sections results in improved performance, and the associated increase in upstream capture is attributed to induced localized fields due to the collection of the naturally charged aerosol particles. Using the principles evolved in our earlier studies of the effects of fiber geometry on performance, layered filters have been prepared having upstream and downstream layers made of fibers differing in linear density which give better performance than homogeneous fabrics. These fiber and fabric modifications that improve capture in the upstream fabric layers also allow more effective cleaning (that is, less long-term dust retention), which accounts for at least part of the reduction in pressure drop.

In general, it appears that collection closer to the upstream filter surface is associated with higher overall collection efficiency, easier cleaning, and lower pressure drop.

This report is submitted in fulfillment of Grant No. R804926-2 by Textile Research Institute under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from December 20, 1977 to December 19, 1978, and work was completed in December 1978.

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ACKNOWLEDGMENTS

The authors would like to express their appreciation to Dr, James H. Turner of the Environmental Protection Agency for his advice and encouragement throughout the period of this research. They would also like to thank Mr. Harold W. Lambert and Mr. Harry Buvel of TRI for their invaluable work on apparatus, Mr. John P. Hession for his assistance with microscopy, and Dr. Harriet G. Heilweil for her help with reports.

SECTION I

INTRODUCTION

The following report describes work that was done in the second year of a three-year program and must, therefore, be read as a continuation of the report issued a year earlier [4]. Similarly, some of the conclusions drawn are not final but relate to studies which continue and will be discussed further in the final, third-year report.

The main object of the work is to find explanations for observed changes in filtration performance that result from certain modifications of conventional fabric filtration technology. One such modification is the use of fibers having different geometric properties from those of fibers commonly used in filter fabrics (cross-sectional shape, surface roughness, linear density, etc.). Another is the application of electric fields to the fabrics. A third is the use of creped fabrics.

In each case some of the improvements in performance, which have taken the form of increased capture efficiency, reduced pressure drop, or both, appear to coincide with changes in dust cake characteristics. Therefore, a primary goal of the present work is the identification of features of the dust cake or of the fabric-dust system which may explain the observed changes in performance. A second goal is to use this information as a basis for the design of improved filter fabrics or systems.

The term "dust cake" tends to mislead because it conveys the image of a dust layer in contact with but separate from the filter fabric. In fact, there is considerable deposition within the fabric, so that a study of dust cake structure is really a study of the dust-laden surface layers of the fabric.

SECTION II

SUMMARY AND CONCLUSIONS

Studies of the local permeability of dust cakes formed with externally applied electric fields have shown that light and dark bands observed in top-view photographs are not due to uneven deposition across the fabric and therefore cannot be the basis for an explanation of the reduced pressure drop produced by a field. On the other hand, measurements of the depth of penetration of the dust into the fabric indicate that the effect of the electric field is to concentrate the dust accumulation in the upstream layers of the fabric, allowing less to penetrate deeper inside.

Study of the vertical cross-sectional structure of the dust cake as modified by an electric field was attempted by a photographic approach. An embedding procedure was developed which at first appeared to preserve the cake intact and to allow cross-sectioning of cake and filter fabric. It later became apparent, however, that the embedding process disturbs the features which are of greatest interest, namely the deposits on the surface fibers.

On the other hand, examination of top-view photographs of the filter-cake surfaces has revealed features indicating that reduction in pressure drop due to an electric field depends on fabric construction. Heavy deposition on fibers protruding from the fabric surface is evident in the photographs, suggesting that the shift of the dust deposit upstream is extreme. It has also been found that pressure drop is reduced by the electric field more or less depending on whether or not the fabric has a surface layer of loose fibers.

The question of whether, in addition to the changes in the position of the dust cake, there also occur microscopic changes at the single fiber level when an electric field is applied has been addressed by photographic studies of dust captured on single fibers. Initial results indicate that, whereas in the absence of an electric field dendrites tend to form, a field causes formation of a more uniform, nondendritic deposit. This finding is consistent with the lower pressure drop developed with a field.

Work was also continued on the effects of fabric or fiber geometry on dust cake formation in the absence of fields. The effects of fiber geometry were further examined by measuring dust deposition in different layers of fabrics made of round or trilobal fibers. The previous report presented data showing how when these fabrics are new (i.e., at the first cycle), dust tends to be captured more efficiently in the upstream layers. The amount of dust in the various layers of the filters after a number of conditioning cycles has now been measured, and the fabric made of trilobal fibers retains less dust in all layers. It is assumed that by favoring capture in the upstream layers, trilobal fibers also favor easier cleaning.

This results in less long-term dust retention and explains the lower pressure drops measured in the past with fabrics made of trilobal rather than round fibers.

Similar results were obtained with fabrics made of fibers with "Y," "X,"or "I" cross sections which had deeper and/or more lobes than the trilobal fibers used before. In each case, the performance, gauged by both penetration and cake resistance, was improved over the shallow-lobed trilobal fibers. Since this finding fits a theoretical prediction of better capture efficiency by many and deep-lobed fibers in an electric field, the hypothesis is that the improved performance is due to electric charges on the aerosol which when deposited in the fabric, generate an electric field.

Finally the study of composite fabrics has continued. It has long been felt that better filters,filters that are durable as well as effective and economical, could be produced by fairly simple modifications of fabric construction. An example is forming the fabric in dissimilar layers. Measurements on fabrics made of layers of relatively fine and coarse fibers (3 and 6-denier) over a large number ($\sim$50) of conditioning cycles gave several interesting results. As conditioning progresses, the relative ranking of different fabrics with respect to performance changes. The first result, therefore, is that in studies of this type, it is important to insure complete conditioning before drawing conclusions about relative performance. The second result is that the performance of such composite fabrics is quite different from what might be expected from knowledge of the performance of the component layers. There is thus a good potential for designing improved filter fabrics by this type of combination. The third result is that the differences in performance appear to be associated with the amount of dust retained in the fabric.

The work described in this report indicates that external application of electric fields, use of lobed fibers, and use of composite fabrics have a common effect: modifications that cause dust to be deposited closer to the upstream surface of the fabric bring about improvements in both efficiency and pressure drop.

SECTION III

EFFECTS OF EXTERNALLY-APPLIED ELECTRIC FIELDS

The largest improvements in fabric filtration performance have been obtained by the application of electric fields. Effects on capture efficiency have been reported by a number of workers [1,2,3,], but few commercial filter units designed to take advantage of such improved efficiency have appeared on the market. Little has been reported regarding reduction in pressure drop accompanying the application of electric fields, though this is perhaps more important than increased efficiency since it has potential for lowering the cost of filtration by fabrics. This may make electrically stimulated fabric filtration (ESFF) commercially attractive where improvements in efficiency alone might not. The mechanisms whereby efficiencies increase in the presence of electric fields have received a great deal of attention and are well understood, at least for clean filters. The cause of a reduction in pressure drop can only be conjectured at this time, though it is obviously related to some change in the dust cake structure. The exact nature of that change, however, is not known, and a better understanding of it was the aim of the studies described in the following section.

A. MICROPERMEABILITY SCANNER

In the preceding report [4] photographic evidence was given of nonuniformity of distribution in dust cakes formed on patch filters under the influence of electric fields. In most cases there appeared to be different amounts of dust deposited on or near the electrode wires than between them, and this suggested a possible mechanism for the pressure drop reduction effect with ESFF. If the electric field causes an uneven dust deposit to form, then the resistance to gas flow through the dust cake would be reduced, since (by analogy with electric resistance) if R is the overall resistance to flow and R_i is the resistance of an element of dust-cake area, the relationship would be of the form

$$R = \left[\Sigma \frac{1}{R_i}\right]^{-1} ,$$

where R becomes smaller with increasingly dissimilar R_i.

In order to check this hypothesis, an apparatus was devised for measuring the permeability of the dust cake at a number of small areas on a patch filter. Of several designs tried, the one shown in Figure 1 was found to be the most satisfactory. After the dust cake has formed, the dust-laden fabric is carefully clamped between the perforated plates A and B. As shown in

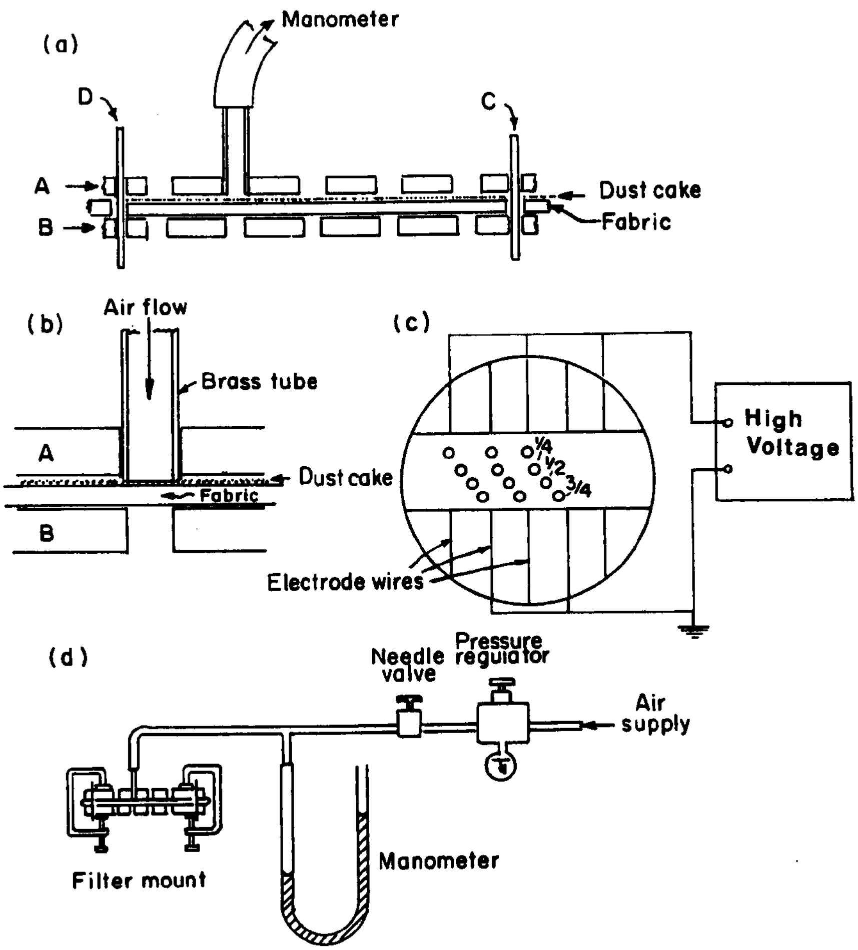


Figure 1. Micropermeability scanner: a) side view of filter mount; b) detail; c) top view; d) general layout.

Figure 1a, the pins C and D have the double function of insuring that the holes in the plates will be aligned, and also that, when the plates are placed on the fabric, there will be no lateral motion that could disturb the cake in the small areas to be measured. As shown in the detail, Figure 1b, the hole on the cake side is slightly larger than its counterpart on the downstream side of the fabric. A brass tube, which has a sliding fit into the cake-side hole, is placed in the hole and pressed against the fabric, making a tight seal. A steady stream of air passes down the tube and through the small area (∿6-mm diameter) of dust cake within the seal. The pressure drop across the dust cake is measured by the manometer (Figure 1d). The holes in plates A and B are arranged so as to scan across the patch at positions on the wire electrodes, and at 1/4, 1/2, and 3/4 of the distance between them, as shown in Figure 1c.

A sample of polyester (PET) needled felt was fitted with copper wire electrodes. The felt was a commercial filter fabric (the patch was cut from a purchased bag) having a central scrim and was composed of 9-denier polyester fibers compacted into a felt structure by a needling process. It is listed in Table I as the Carborundum PET nonwoven. The electrode wires were threaded just below the upstream surface by means of a sewing needle. Figure 1c shows how the electrodes were coupled to the power supply in this and all subsequent measurements involving filter patches fitted with electrodes. The filter was conditioned in the patch filter apparatus with applied fields of 0, 2, 4, and 6 kV/cm. The last cycle was interrupted before cleaning and the fabric lifted out with the dust cake. The cake was then scanned by making pressure-drop measurements at holes across the filter, according to the procedure outlined above. The flow of air in the tube was adjusted to be equal to the face velocity during formation of the dust cake. Consequently, the pressure drops measured could be directly compared with the final pressure drop ΔP_f obtained with the particular dust cake. The results are plotted in Figure 2. The four curves are permeability scans for cakes formed at the four electric field strengths. The pressure drops measured in each scan can be seen to correspond well with the final pressure drops ΔP_f measured as the cake was being formed, given in Figure 2.

The results in Figure 2 show no particular pattern of cake permeability with respect to position relative to the electrodes. Some fluctuations in cake permeability are seen, but these do not coincide with the electrode position and are not introduced by the field since they are present even when no voltage is applied. Therefore, the lower pressure drop is the result of a general increase in permeability of the entire cake. In fact, these results may be taken as proof that the hypothesis of pressure-drop reduction by unbalanced permeabilities is invalid. The patterns of apparently uneven distribution seen previously [4] still remain to be explained, but they appear to be irrelevant to the question of pressure-drop reduction by ESFF.

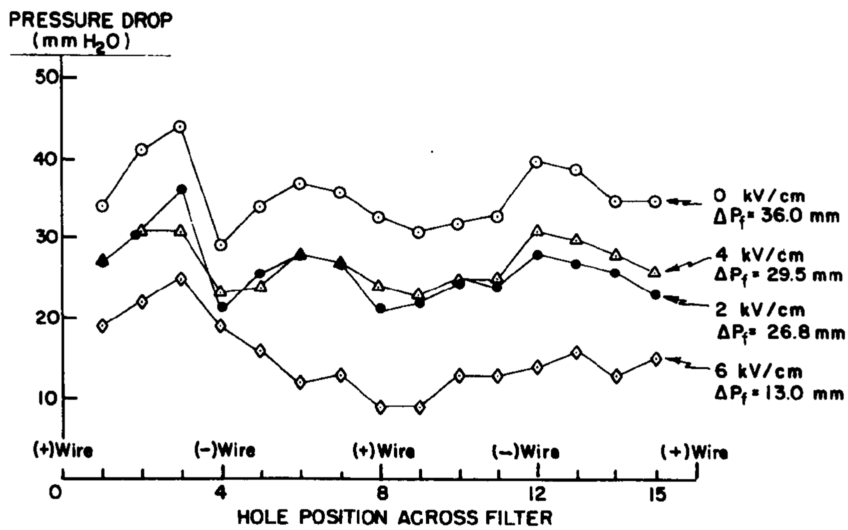


Figure 2. Scan of permeability (expressed as pressure drop at constant air flow) for dust cakes deposited at 0, 2, 4, and 6 kV/cm. ΔP_F values are for the entire patch.

B. MEASUREMENTS OF CAKE DEPTH

It was seen in the previous section that observed reductions in pressure drop cannot be accounted for by nonuniform dust distribution across the filter face. This implies that the amount of dust per unit area of filter surface is likely to be fairly uniform and that the patterns seen are due to differences in the depth of penetration of the dust into the fabric. To verify this, four sets of layered filters were made. Each set consisted of four thin separable nonwovens made by pressing a card web in a press for a given time and at a given pressure. The webs contained 15% of a binder fiber (vinyon). Copper wires, 150 μm in diameter, were threaded into the upstream layers of each set in the usual configuration (parallel wires, 15 mm apart, alternate wires grounded), and the sets used to filter a flyash aerosol. Only one 5-minute cycle was run, and each set was run at a different voltage. After a run the layers were separated and weighed. The total mass of dust collected on an absolute filter downstream of the main filter was also weighed. The fractions of dust captured by each layer and the efficiency of each layer are plotted in Figures 3 and 4. Only one set of these measurements was performed, so that each point in Figures 3 and 4 was obtained from only one measurement. However, the consistency of the trends within each curve and between curves was taken as sufficient to make duplicate measurements unnecessary.

When a field is applied, a major shift upstream occurs in the dust deposition. The fraction captured by the upstream layer (layer number 1) increases from about 50 to nearly 90%, while that captured on the three downstream layers decreases. As the field is increased to 4 and to 6 kV/cm, the fraction collected on the downstream layers increases with a slight decrease in the upstream layer that is not apparent in the log plot. The total penetration (given in Fig. 3) decreases considerably as field strength increases, with a sharp decline between 4 and 6 kV/cm. The calculated efficiencies for each layer, plotted in Figure 4, show a sharp increase for the two downstream layers at 6 kV/cm.

When the layers were separated after filtering, it was found that the penetration into the downstream layers was not uniform. Areas under the electrodes showed evidence of much greater penetration (Figs. 5 and 6). The deposits under the electrodes were visually more pronounced as field strength increased. This greater deposition below the wires is assumed to account for the measurements of greater fractional deposition on downstream layers with increasing field strength. The electrodes were 150-μm copper wires so that onset of corona discharge should have occurred below the lowest field used, i.e., 2 kV/cm. The possible relationship between these patterns of deposition and corona discharge will be discussed in a later section.

The above results appear paradoxical, since they mean that in the presence of an electric field the dust accumulation in a fabric is shifted in an upstream direction. The greater mass

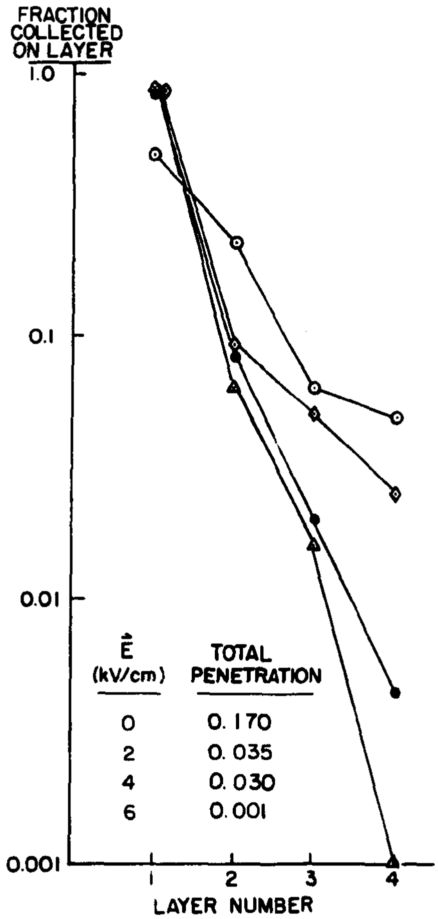


Figure 3. Fractional collection on layers of electrified layered filters. o - 0 kV/cm, Δ - 2 kV/cm, • - 4 kV/cm, ◊ - 6 kV/cm.

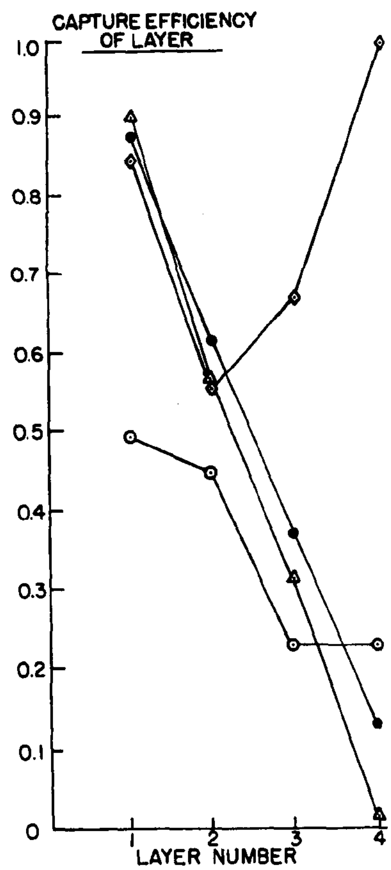


Figure 4. Capture efficiency of each layer of filters in Figure 3. o - 0 kV/cm, Δ - 2 kV/cm, • - 4 kV/cm, ◊ - 6 kV/cm.

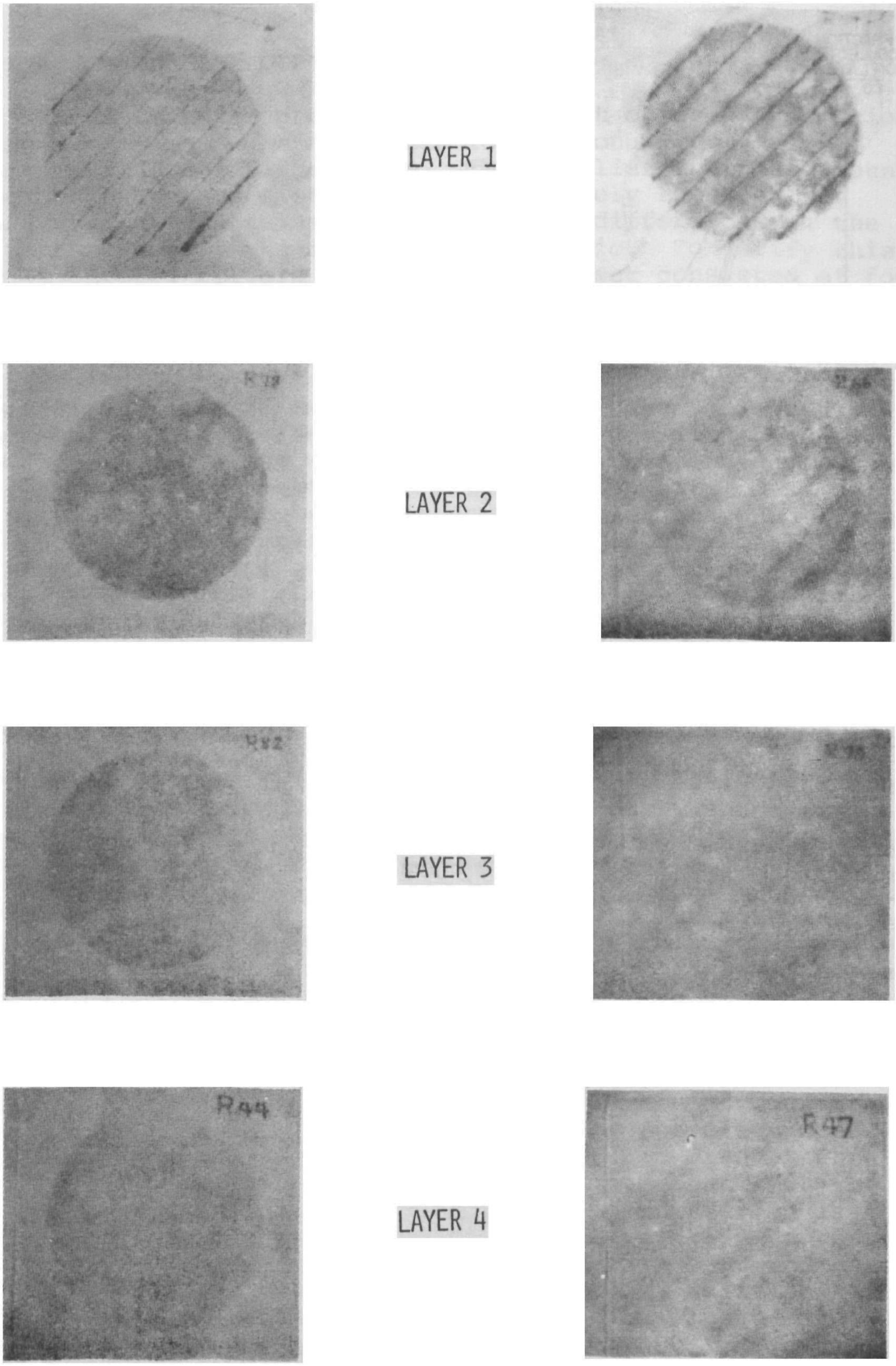


Figure 5. Upstream surfaces of layers of nonwoven fabrics of Figure 3 used to filter flyash at 0 (left) and 2 (right) kV/cm.

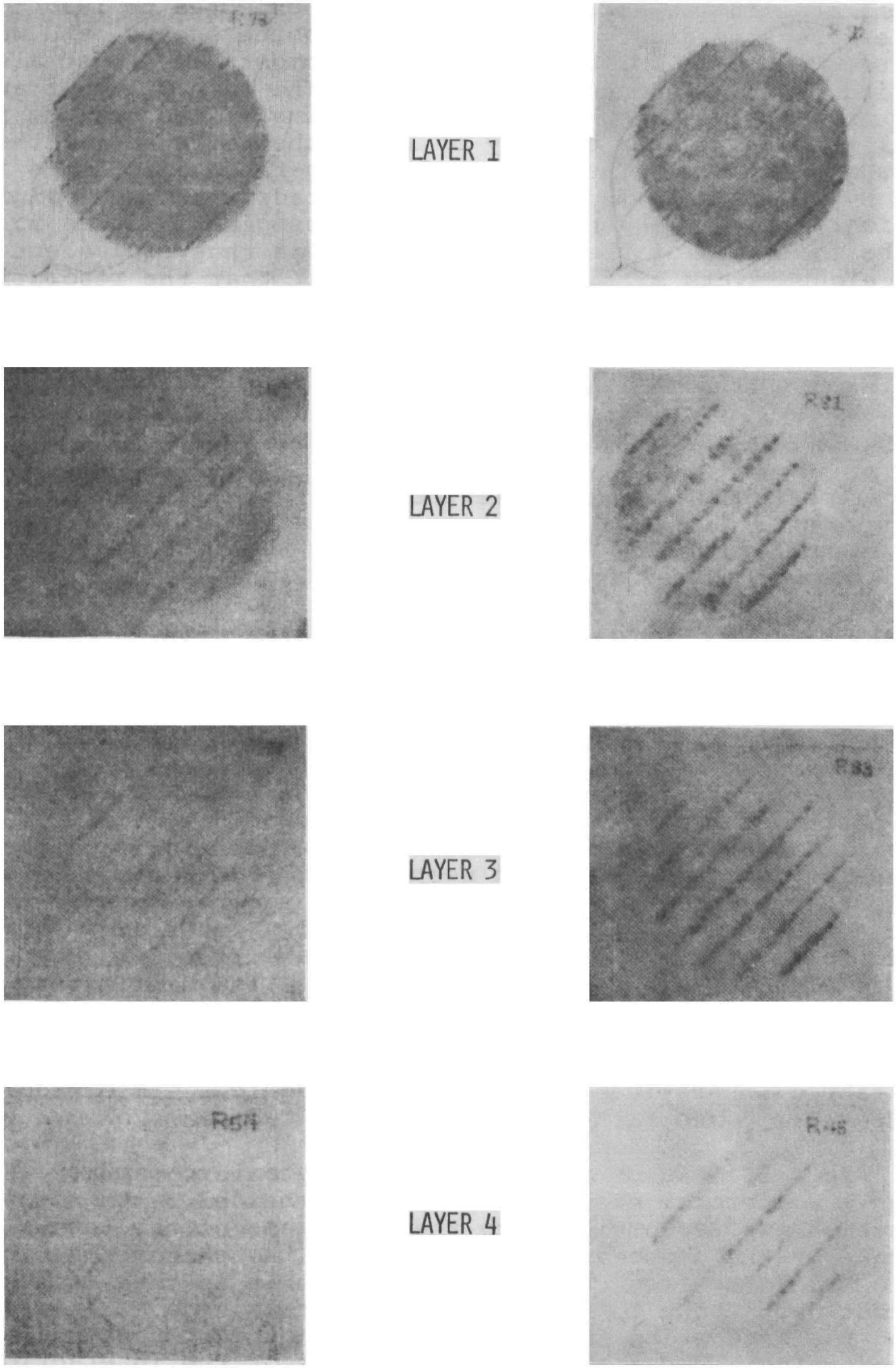


Figure 6. Upstream surfaces of layers of nonwoven fabrics of Figure 3 used to filter flyash at 4 (left) and 6 (right) kV/cm.

concentrated in the first layer would be expected to lead to greater pressure drop. In fact, the opposite occurs, and we must conclude that cake formation in the uppermost layer must also be modified by the presence of the field. The mass per unit area of layer number 1 was about 62 g/m^2. Assuming a fiber volume fraction of 0.1 and a polyester density of 1.38, the thickness of the top layers was 0.45 mm. The average fiber-to-fiber distance s is given by $s = (2\pi a^2/\alpha)^{1/2}$, where a = fiber radius and α = volume fraction. For the 3-denier fibers in these felts, s was 55 μm and the thickness of the upstream layer was thus equivalent to about eight layers of fibers. It was felt that the resolution of the method was not sufficient to examine in greater detail the events occurring in such small depths of fabric. Therefore, a different method was tried as described in the following section.

C. NEW EMBEDDING PROCEDURE FOR CAKE CROSS-SECTIONING

It has been reported previously [4] that microscopical examination of dust-cake formation by scanning electron microscopy (SEM) is not informative, for the reasons that only the cake surface can be examined and that the electron beam appears to disturb the cake structure by removing particles. To avoid these difficulties, various embedding and sectioning techniques were tried. After some unsuccessful attempts, a procedure was found that appears promising.

A problem associated with flooding a fabric filter bearing a dust cake with embedding fluid is the disturbance of the cake by the fluid. In some cases the dust cake can actually be caused to float off the fabric. The new procedure consists simply of extremely gradual addition of embedding fluid to the dish in which the fabric sample lies, so that the fluid seeps upward towards the cake by capillary action. A small piece (about 1 square inch) of the fabric with the dust cake on it is carefully cut from a patch and laid in the bottom of an aluminum dish, cake side up. The embedding fluid is added to the bottom of the dish, a few millimeters from the edge of the fabric, a drop about every 15 s. Addition of fluid is stopped when the sample gives the appearance of being only wetted, rather than submerged. Figure 7 shows, however, that even at this stage fabric interstices are filled thoroughly. The embedding fluid was "Epon 812," manufactured by the Shell Chemical Co.

Figure 7 is a composite optical photomicrograph of a section through a commercial needled PET sample embedded in this fashion. The section exposes a view into the thickness of the fabric. The dust cake is the dense area at the top of the photograph, and the air flow would be from the top downwards. It is interesting to note that dust tends to lodge on the upstream side of fibers, supporting the assumption that the dust was not displaced by the medium. The photo also gives a simple illustration of the interaction of fabric and dust. At the upstream surface the heavy dust accumulation clearly presents few paths for dust penetration. Further

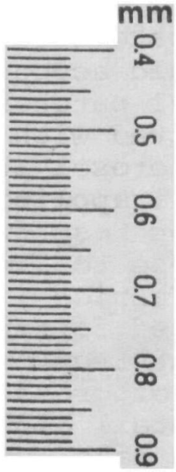


Figure 7. Photomicrograph of cross section through commercial needled PET filter fabric and dust cake.

downstream dust can pass freely between fibers and is only captured when it impacts on one. Particles are seen throughout the filter, but their number gradually decreases as depth into the filter increases. The importance of cake formation, permeability, and stability is somewhat better understood after examination of the photo.

D. PHOTOGRAPHIC ANALYSIS OF DUST CAKES

The method described in the previous section was now used to determine the special features of the cake structure formed in the presence of an electric field that would account for the lower pressure drop usually found. Two identical patches of commercial needled PET fabric were used. One was fitted with electrodes. Both were used to filter a 5-g/m^3 flyash aerosol at a face velocity of 6 cm/s (12 ft/min) with a 9-kV potential applied to the electrodes in the one patch. The pressure drop rose from 2 to 18 mm H_2O without a field. With the field it rose to 3 mm. This strong effect is frequently obtained with clean fabrics (i.e., fabrics that have not been "conditioned" by repeated filtering and cleaning). Afterwards, small pieces of fabric were cut from each patch and embedded as described above. Micrographs of cross sections from each sample are shown in Figure 8. The detail of the cake structure is disappointing since, in both cases, the cake appears as a compact structure. There is no obvious difference between the two cakes and nothing that can be identified with lower pressure drop due to ESFF.

In a different approach, the cakes were photographed with a camera fitted with a close-up lens. Photos obtained in this fashion are shown in Figure 9. Here substantial differences can be seen at once. In the absence of an external field, the dust deposits in a smooth compact cake. Fibers protruding from the fabric surface are free of dust. With the field applied, a great deal of deposition occurs on these protruding fibers, and the entire appearance of the cake is changed.

The contrast between Figures 8 and 9 suggests that the embedding procedure is not suitable for examination of the upstream boundary of the dust cake. The differences between Figures 9a and 9b are not apparent in Figures 8a and 8b.

E. EFFECT OF FABRIC STRUCTURE

Measurements of the change in performance obtained by electrical stimulation of various fabrics indicate a strong dependence of the effect on fabric structure. Table I gives results obtained with woven and nonwoven (felted) fabrics made of glass and polyester fibers. It can be seen that on application of an electric field, a reduction in pressure drop is obtained only with the nonwoven felts. The three woven fabrics (made of untextured

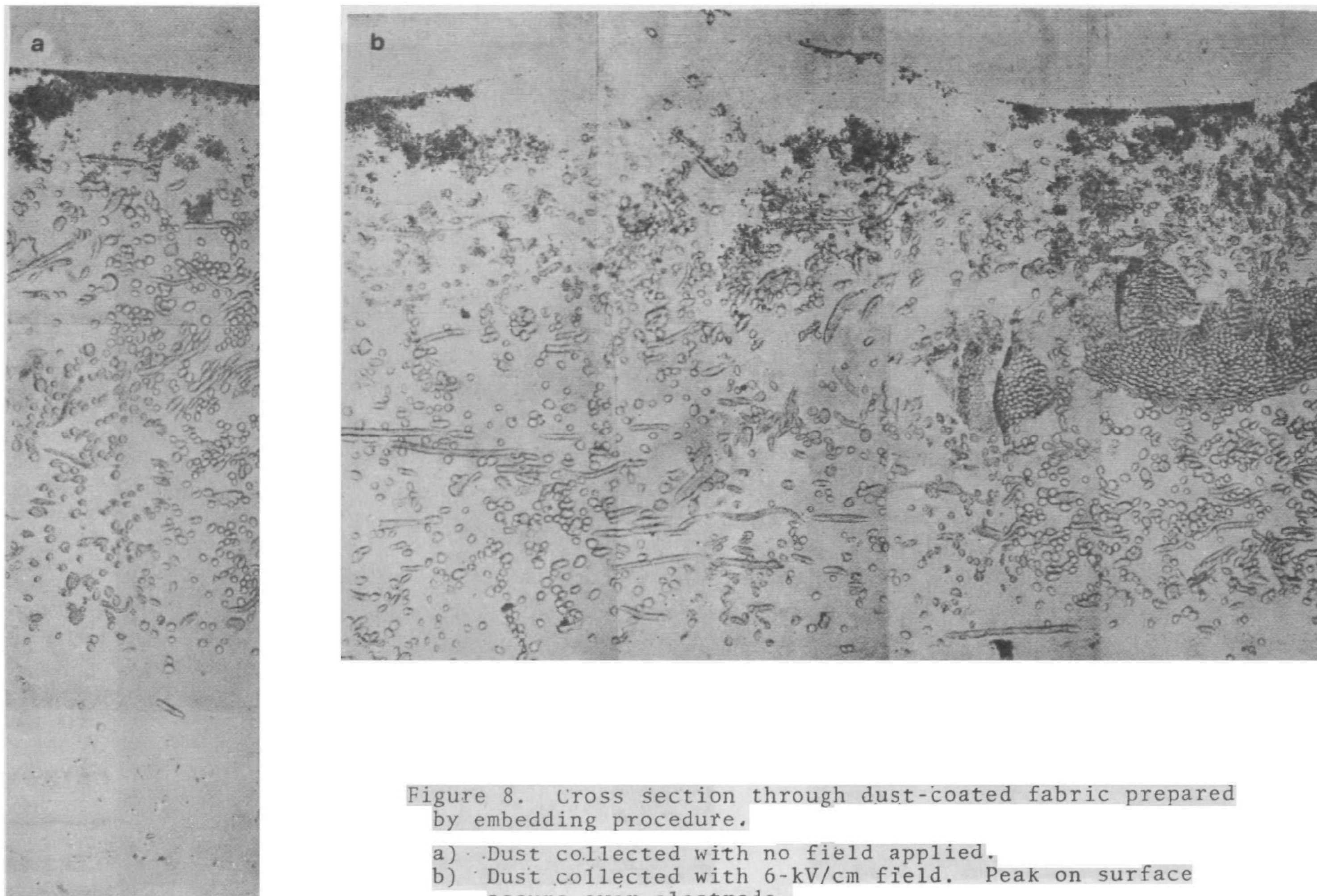


Figure 8. Cross section through dust-coated fabric prepared by embedding procedure.

a) Dust collected with no field applied.
b) Dust collected with 6-kV/cm field. Peak on surface occurs over electrode.

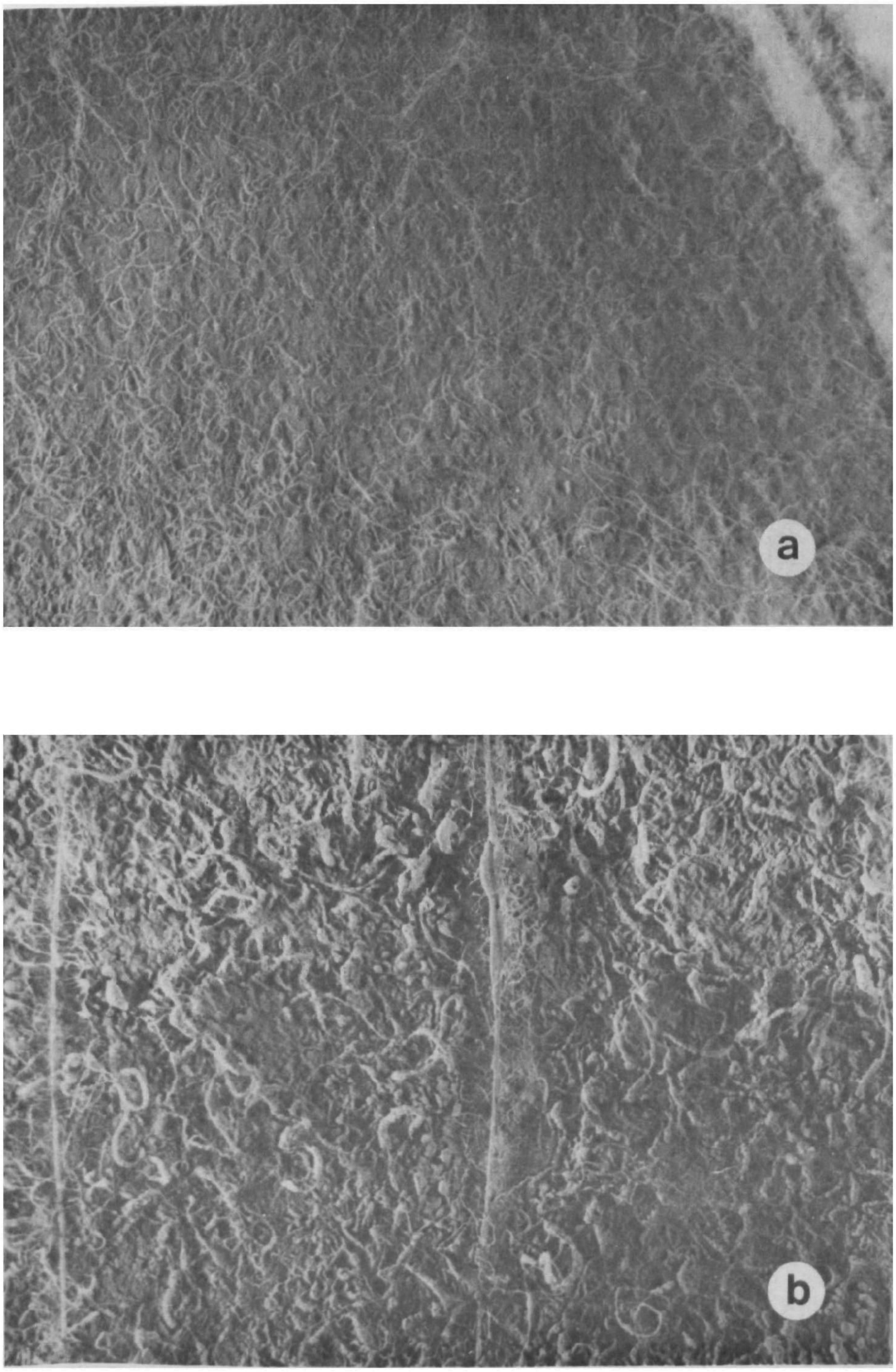


Figure 9. Photographs of the surfaces of the dust-laden filters in Figure 8.
a) Dust collected with no field applied.
b) Dust collected with 6-kV/cm field.

TABLE I. EFFICIENCIES AND PRESSURE DROP CHANGES DUE TO ELECTRIC FIELD OF 2 kV/cm APPLIED TO WOVEN AND NONWOVEN GLASS AND PET FABRICS

Producer	Burlington	Criswell	Owens-Corning*	Milliken*	Carborundum
Style No.	486/38	445-57/DC2	-	-	918-4049-4563-0517
Type	Woven (2x2 Twill)	Woven (3x1 Twill)	Nonwoven	Woven Fila. (2x1 Twill)	Nonwoven
Material	Glass	Glass	Glass	PET	PET
Wt. (g/m^2)	519	366	473	231	546
Wt. (oz/yd^2)	15.3	10.8	12.9	6.8	16.1
ΔP(field)/ΔP(no field) (ΔP in mm of water)	41/42	92/83	28/49	53/55	25/47
%E(field)/%E(no field)	70.2/57.0	86.7/69.6	-	99.7/99.2	99.9/98.9

* Experimental fabric

yarn) give no reduction. On the other hand, it is interesting to note that all fabrics show increased capture efficiencies when the electric field is applied. It is conceivable, therefore, that the mechanisms whereby penetration and pressure drop are reduced are not the same.

Further evidence of the importance of fabric structure to the response to electrostatic stimulation is given by results of an experiment in which a flyash aerosol was filtered through a glass fabric aided by the application of an electric field of average strength 6 kV/cm. The glass fabric was woven from a combination of textured and untextured yarn. (Texturing means treating a yarn to impart a kind of permanent wave to each component filament. In an untextured yarn the filaments are straight and closely packed. Texturing separates the filaments and increases the effective volume of the yarn by increasing the void volume between filaments.) The weave was such that one face of the fabric was entirely covered with textured yarn. This was the face designed by the manufacturer to be exposed to the incoming dirty gas. The other face was roughly half covered by untextured yarn. Two samples of this fabric were fitted with electrodes, in one attached to the textured face, in the other to the face having some untextured yarns exposed. The electrodes were coupled to a power supply as shown in Figure 1c. Figure 10 shows pressure drop ratios (PDR) obtained with the two arrangements. With no field applied, the pressure drop was virtually equal at 36 mm H_2O with either face upstream. When an average field of 6 kV/cm was applied, however, the pressure drop was reduced 67% to 12 mm H_2O with the textured face upstream, but only 40% to 22 mm H_2O with the partially untextured face upstream.

From these facts, the hypothesis can be proposed that in order to increase pressure drop reductions, the fabric must have an upstream layer of low fiber volume fraction. The electric field causes the cake to form preferentially in this low density region by capture on single fibers, rather than further downstream in the denser portion of the fabric where the cake forms by bridging. Where the low density region is absent, as in untextured filament fabrics, no such changes in cake structure can be induced by the field, and there are practically no changes in pressure drop.

The manner in which accumulation of dust in the low density surface region may accomplish pressure drop reduction may be gauged from the photo in Figure 9b and from Figure 11, which is a cross section of the fabric shown in Figure 9 but with no dust. The dust in Figure 9b forms heavy encrustations on the surface fibers visible in Figure 9a. These encrustations look like cylinders with diameters that range from 0.25 to 0.5 mm. The broken-line circle in Figure 11 represents the cross section of one such 0.25-mm cylinder to scale, as if it had formed on the protruding fiber visible at the top of the photograph. This procedure is a construction of the kind of cross section that would have been obtained in

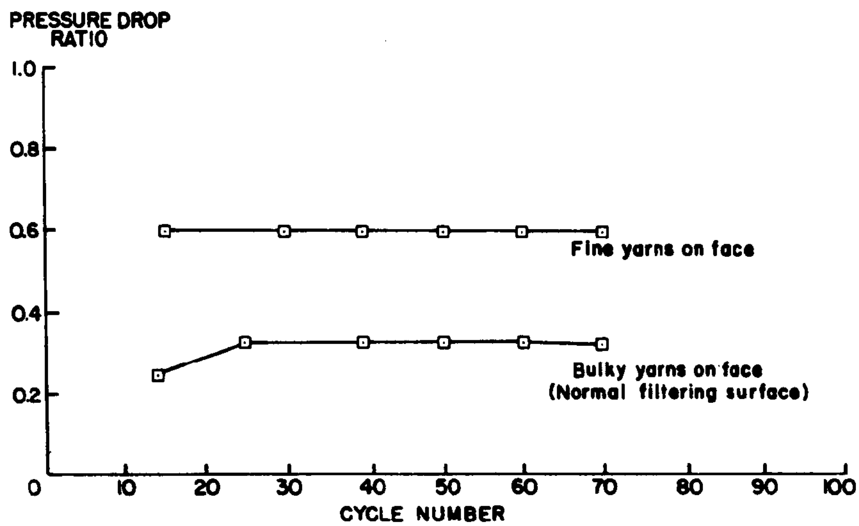


Figure 10. Effect of fabric upstream surface structure on pressure drop ratio. Woven glass bag. Applied field: 6 kV/cm.

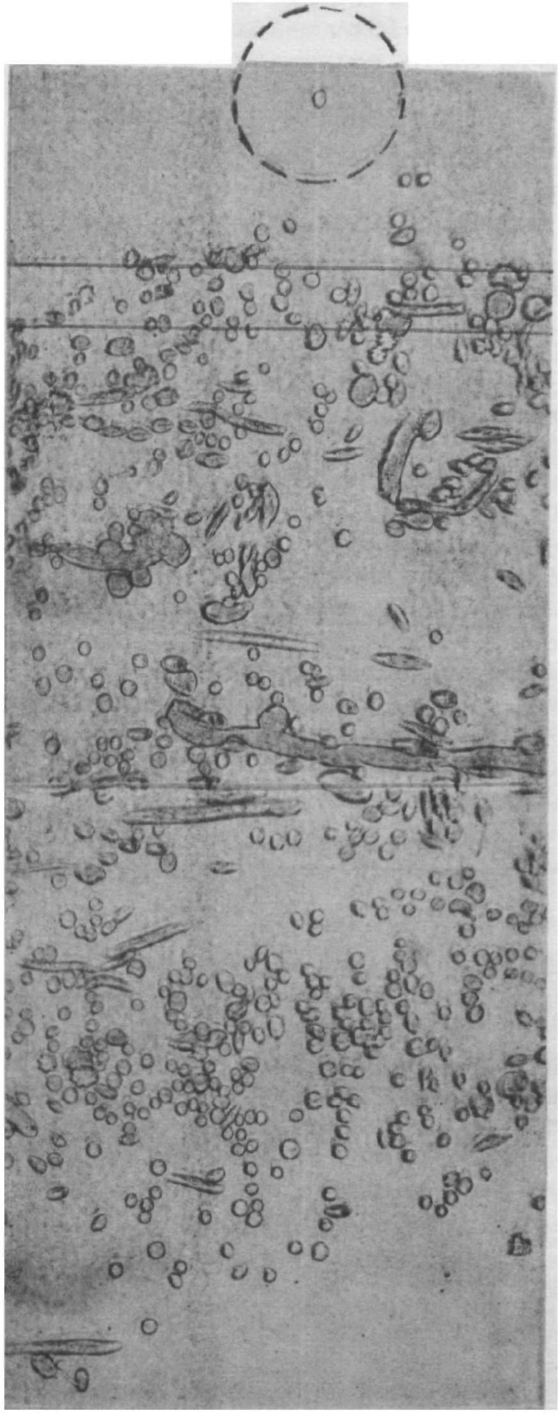


Figure 11. Cross section through the fabric used for Figure 9 but with no dust. Broken circle indicates diameter of dust encrustation on surface fiber as in Figure 9b. Horizontal band indicates equivalent thickness of dust layer.

Figure 8a if the cross-sectioning technique had been successful. Isolated fibers that protrude above the fabric appear to have a remarkable ability to collect dust in an electric field. The dust cake photographed in Figure 9b had an areal density of $9x10^{-3} g/cm^2$. The bulk density of the dust was approximately 1, so this mass is equivalent to a layer 90 μm thick. This is also drawn in Figure 11 as a horizontal band. It is interesting to note that if a parallel array of cylindrical accumulations 0.25 mm in diameter spaced 0.4 mm apart were formed on the surface, all of the deposited dust would be located in these cylinders. Inspection of Figure 9b shows that structures of this type occur with almost this frequency. The pressure drop increase due to the cake formed in Figure 9a was 18 mm of water; that due to the cake in Figure 9b was only 1 mm of water. These observations provide a clearer picture of the changes in dust cake structure that account for the reduction in pressure drop with ESFF. Previous accounts of these changes have offered only qualitative observations such as that in the presence of a field the cake was "more porous".

F. STUDIES OF DENDRITE FORMATION

A separate approach to explain the mechanism of pressure drop reduction by ESFF was the study of the microstructure of dust cake formations. By this is meant the structure of the dust collection at the single fiber level, as opposed to the structure of the cake as revealed, for example, by the weighing of filter layers described in a previous section. It appeared possible that the observed effect on pressure drop might be a result of changes in the dust cake microstructure as well as in the macrostructure.

Basic structural configurations for the flyash deposits may be postulated. Two extreme cases are shown in Figure 12. In case (a) all the particles stack on top of each other, forming a dendrite at a specific location on the fiber. The opposing possibility is illustrated by diagram (b), where the particles coat the fiber surface uniformly before they build the next layer of the filter cake. Theoretically these two cases ought to give markedly different filtration performance. Butra [5] quite reasonably suggests that a flyash deposit like (a) will collect particles much more efficiently than the uniform coat (b). It is interesting to note that the flyash used at TRI has a particle size distribution such that the submicron particles, because of their sheer numbers ($\sim 10^5/cm^3$), could build more extensive dendrites than the larger particles. If the cake develops by surface coating, however, then the small particles become less dominant in the collection process, but may still be important if they act as a glue and enhance adhesion between larger particles.

As for the pressure drop, structure (b) should have less drag, and consequently, a filter whose fibers become coated uniformly with particles should have a lower pressure drop than one whose fibers sprout dendritic growths. This argument applies to collection of particles on fibers (initial filtration stage) or to the capture of

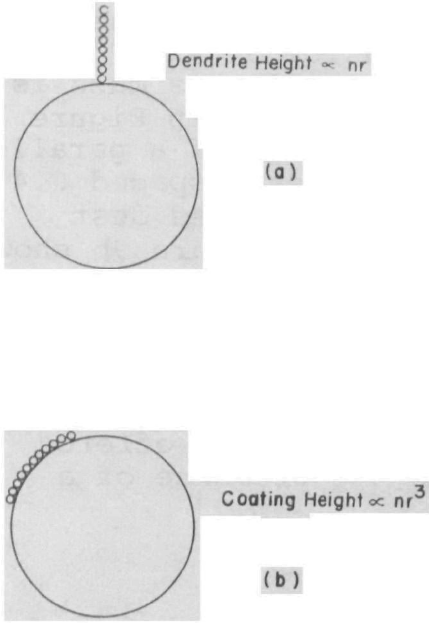


Figure 12. Basic structural configurations for flyash deposits (schematic).

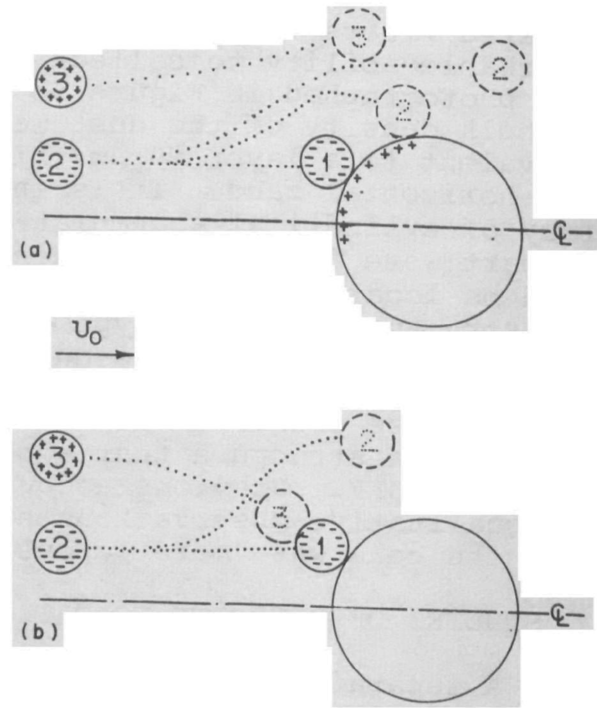


Figure 13. Collection of charged particles on (a) charged and (b) neutral surfaces (schematic).

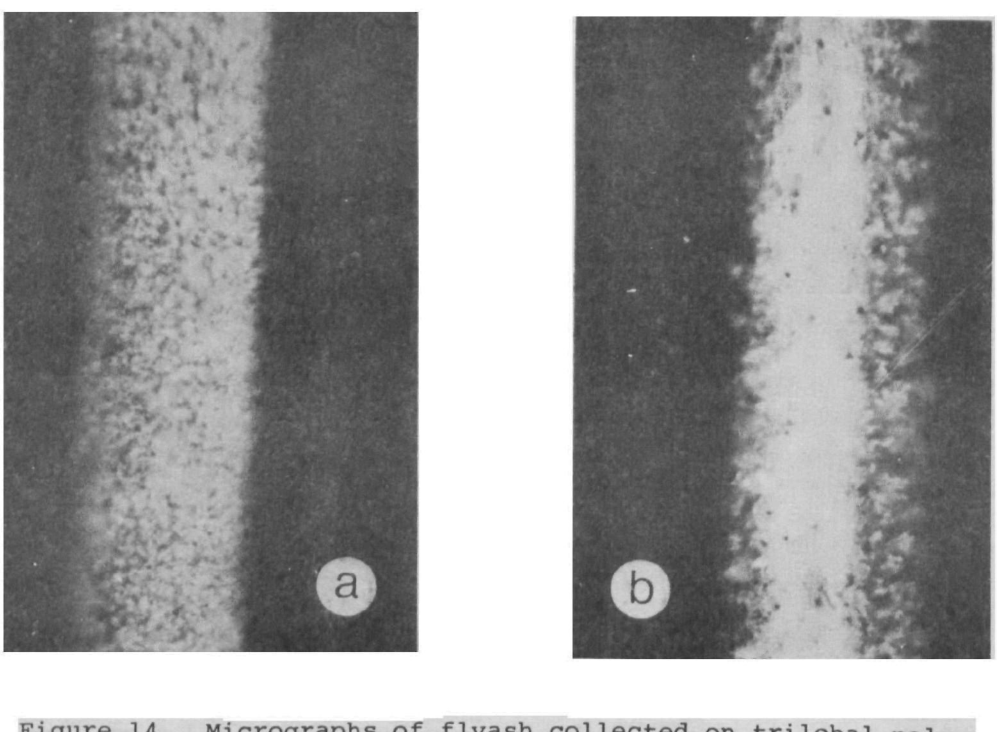


Figure 14. Micrographs of flyash collected on trilobal polyester fibers (a) with no applied electric field and (b) with a 4.2-kV/cm field.

particles by particles previously collected by fibers (later filtration stages). Of course these structures represent extremes and the actual structures are most likely combinations of the two.

It may be asked next, what conditions favor the growth of one structure over the other? Since the high collection efficiencies we have observed strongly suggest that the particles have some electric charge, it is logical to consider the collection of charged particles on charged and neutral surfaces. Figure 13 illustrates these situations. The small solid circles represent particle positions, the small dashed circles represent possible future positions of the particles, the dotted lines denote particle trajectories, and the large circles stand for fibers or larger flyash particles. In case (a) the collector is charged-either naturally, or by applying an external field,-and the particles are more strongly attracted or repelled by the collector surface than by each other, hence producing a uniform coat. In case (b), however, the collector is neutral, and the particle-particle electrical interaction dominates, giving a dendritic growth. Hence, the application of an electric field is expected to yield a lower pressure drop, since the cake microstructure will be more compact (ignoring, for the moment, macroscopic distribution effects). However, it does not follow from this analysis that the field should give a poorer efficiency. Even though the field will suppress dendrite growth, it also adds a force which drives additional particles to the collector, the net effect being to increase collection.

In order to verify these postulates, the structure of cakes deposited on individual fibers arranged in a regular, parallel array in the presence or absence of a field was investigated microscopically. The arrays were made of 120-μm fibers spread roughly 3 fiber diameters apart, the average interfiber distance in a nonwoven fabric filter. They were exposed to the flyash for 330 s and observed from the near stagnation point. From the results, shown in Figure 14, it is clear that the cake produced in the absence of an electric field is more dendritic and fluffy than the deposit formed with a field. Once more, the field does not entirely eliminate dendrites, but serves to stunt their growth. This should produce a lower drag and may be a factor in the reduction in pressure drop with ESFF.

G. EFFECT OF CORONA

It is often observed that the wire electrodes used to produce the electric field are bare, and the regions of fabric immediately surrounding the wires are clean on the side of the filter facing the flow, while dark bands mark the positions of the wires on the otherwise clean downstream face. In the experiments using layered filters, these effects were photographed (Figs. 5 and 6). It appears, therefore, that the particles in the region of the wires are more difficult to capture and penetrate farther into the filter. This effect suggests that the aerosol is charged in the vicinity of the wires, probably by an ion cloud surrounding the wire.

The field in a vacuum at the surface of two parallel cylindrical conductors of diameter D whose centers are placed a distance S apart and maintained at a potential difference V is:

$$E_{surface} = \frac{V\,[(S/D)^2-1]^{\frac{1}{2}}}{(S-D)\,\ln\{(S/D) + [(S/D)^2-1]^{\frac{1}{2}}\}} \;.$$

The variation of surface field calculated from this equation with voltage for different size wires separated by 15 mm (the separation most often used in our experiments) is shown in Figure 15. It should be emphasized that this derivation neglects the effect of fibers and particles on the field and should be used with caution when applied to electrodes in a patch. When the surface field is approximately 30 kV/cm, corona, or the ionization of air in the vicinity of the wire, occurs. The convective velocity of the ions due to the bulk flow is of the order of 10^{-1} m/s, but the field-induced velocity is roughly 10^4 m/s, and so the ions travel instantly towards the opposite electrode. Although the ion cloud may not reach the other electrode due to interference from the fibers and cake and collisions with air molecules, it does charge the fibers and aerosol near the wire to the same sign, and the two repel each other, resulting in no collection and clean fabric regions.

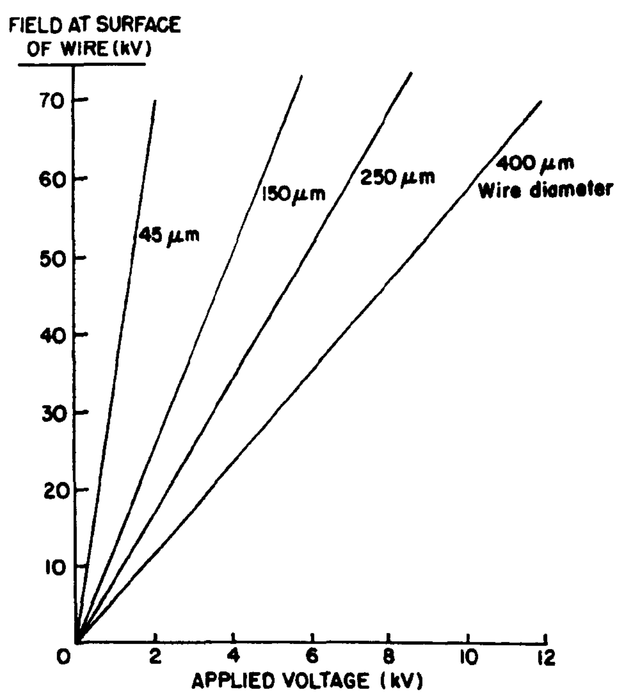


Figure 15. Variation of calculated surface field with applied voltage for wires of different diameters.

After passing through the region of like-charged fibers, the aerosol is caught. However, once the particles form a layer or two on the fibers, the collection decreases since particles passing near the now coated and hence charged fibers will be repelled as they were from the clean charged fibers near the electrodes. The particles must then pass to fibers deeper in the bed to be captured, resulting in deeper penetration under the wires.

SECTION IV

EFFECTS OF FIBER GEOMETRY

A. MECHANISM OF PRESSURE DROP REDUCTION WITH TRILOBAL FIBER FILTERS

In the previous report [4], it was concluded likely that trilobal fibers enhance capture, not only because of reduced inter-fiber distance, but also by the presence of localized electric fields. Calculations indicated that in the presence of electric fields, lobed fibers result in greater collection efficiencies than round fibers. If the aerosol contains charged particles, their deposition will set up localized electric fields near the upstream fabric surface. In the presence of these fields, capture of subsequent particles will be more efficient on lobed fibers. Further studies have yielded data consistent with this theory, and have indicated how this mechanism may also be responsible for the reduced pressure drop obtained with trilobal fiber filters.

The layered filter technique was used (see p. 7) to measure penetration and single fiber efficiency for new trilobal and round fiber filters. Now, similar data have been obtained with conditioned filters. Measurements of flyash retained before cleaning have been made at the first, twentieth, and fortieth cycles, and plotted in Figure 16. It can be seen that at the first cycle upstream layers in the trilobal filter collect slightly more than those in the round fabrics. However, as conditioning progresses a reversal takes place, and the round fabric is seen to retain more dust in all layers. This is equivalent to saying that the dust is cleaned more easily from the trilobal fabric, probably because the dust cake is formed closer to the upstream surface in this fabric. This lower dust retention is accompanied by a lower pressure drop. There is thus a plausible connection between lower penetration and lower pressure drop when trilobal fibers are used instead of round.

B. X AND Y-SHAPED FIBERS

Progress in the study of effects of fiber cross-sectional shape on filtration performance is limited in part by the lack of appropriate fiber samples. Thus, in studies of the effects of the number of lobes in the cross section, the validity of the results has, in the past, been diminished because no tetralobal fibers were available, and the pentalobal fibers used had very shallow lobes. Moreover, no series of fibers with a range of lobe depths has to date been available. Samples of fibers with cross-sectional shapes different from those used previously have now been obtained. These include nominal X, Y, and I shapes, with linear densities of 3,5, and 8 denier. The fibers were of crimped acetate supplied by the Celanese Fibers Company.

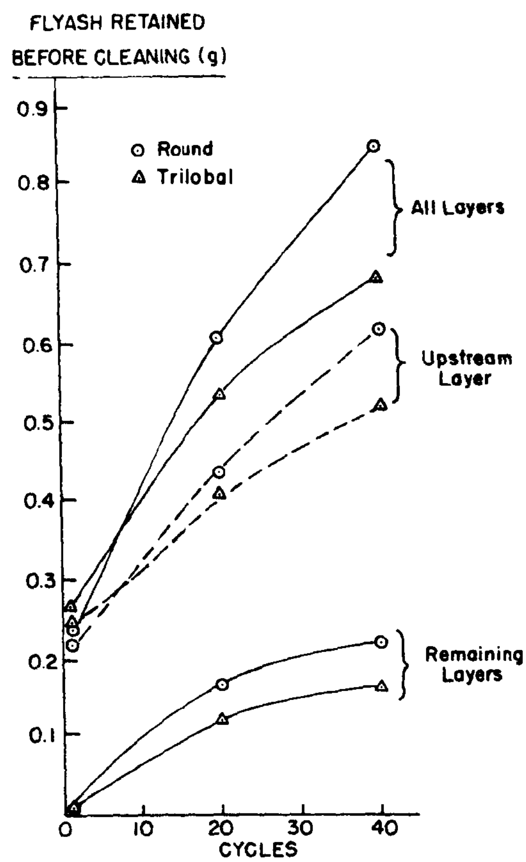
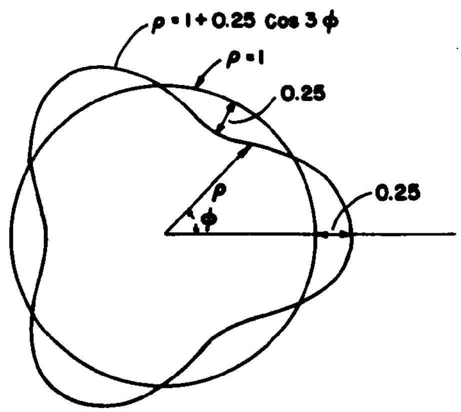


Figure 16. Flyash retained by layered filters as conditioning proceeds.

Cross sections of these fibers are shown in Figures 17 and 18. Figures 17b, c, and d are the 3-, 5-, and 8-denier Y fibers. These have deeper lobes than the PET trilobal fiber used hitherto whose cross section is shown for comparison in Figure 17a. The cross-sectional shape of a fiber can be described by an equation in polar coordinates for a curve of the same shape. In the equation

$$\rho = 1 + \varepsilon \cos m\phi ,$$

ρ is the radius vector, m the number of lobes, ϕ the vectorial angle, and ε is a measure of lobe depth. The diagram below shows an example. When $\varepsilon = 0$, the cross section is circular. Whereas the trilobal PET fibers had an ε value of about 0.25, the Y-shaped acetate fibers have ε values of about 0.6. Figure 18 shows cross sections of I and X fibers. These shapes are generally more irregular than the Y, and ε values are more difficult to calculate.



Nonwoven felt patches were made from each of these fibers, and the fabric properties are listed in Table 2. The performance of each felt was measured on the patch apparatus using a flyash aerosol with a concentration of $3.3 g/m^3$. The aerosol was neither precharged nor neutralized, and no electrodes were placed in the fabrics. Measurements of pressure drop and penetration were made after 20 conditioning cycles. These are plotted in Figures 19 and 20. It is interesting to note that felts made with these deep-lobe fibers have better performance than those made with the PET trilobal fibers. Thus, in Figure 19 the pressure drop for Y fibers is

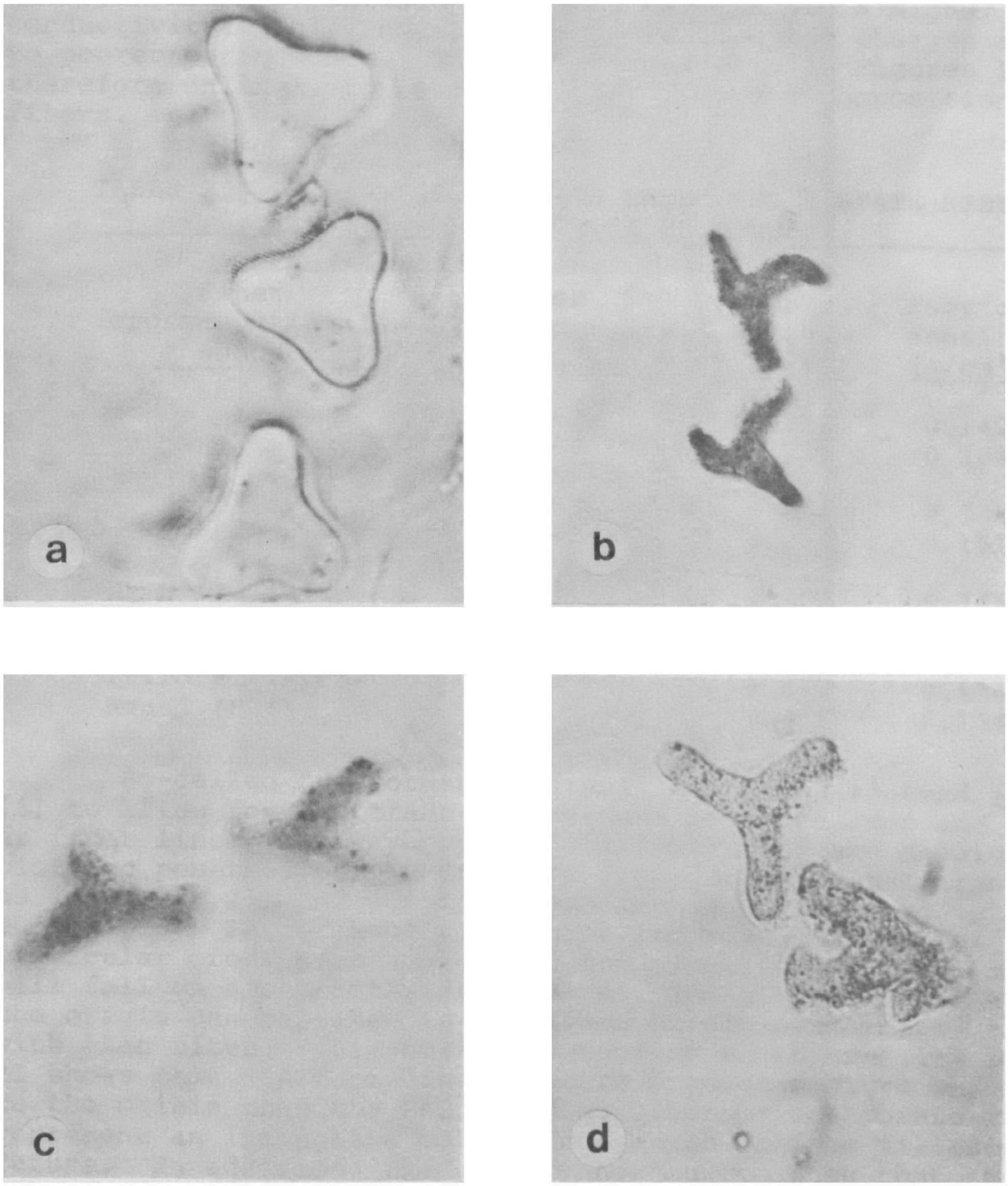


Figure 17. SEM cross sections of trilobal fibers: a) 3-den PET, shallow lobe; b) 3-den Y, acetate; c) 5-den Y, acetate; d) 8-den Y, acetate.

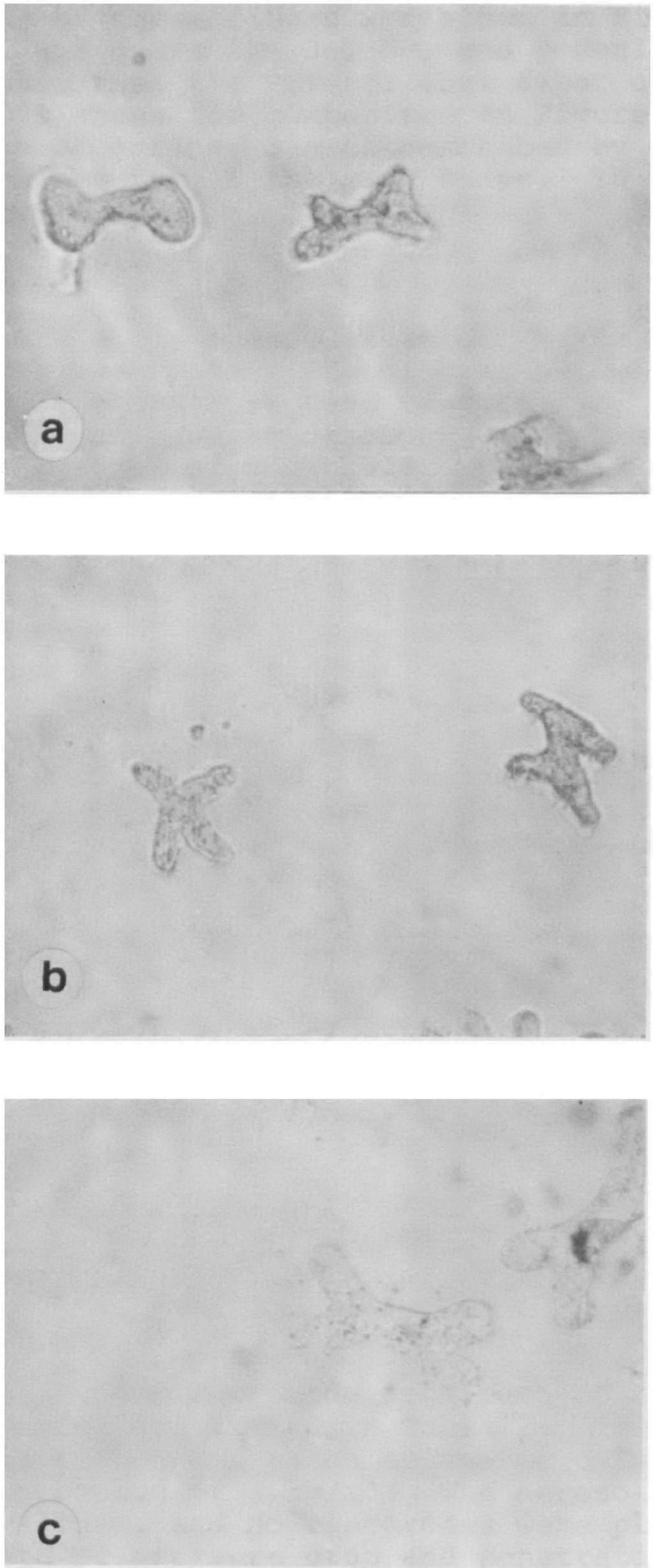


Figure 18. SEM cross sections of acetate fibers: a) 3-den I; b) 5-den X; c) 8-den I.

significantly lower than that for the PET trilobal. In Figure 20 the penetration is lower for the Y fibers than for the PET trilobal. The position in this performance scale taken by the X and I fibers is less clear since, while they produce higher pressure drops, they also give lower penetrations. It is not known how much the differences are due to the different chemical compositions of the fibers. However, cellulosic fibers should have a higher electrical conductivity. This tends to dissipate electric charges and to lead to poorer performance. The differences seen in Figures 19-21 are therefore unlikely to be due to the different compositions of the fibers.

TABLE 2. PROPERTIES OF FELTS MADE FROM ACETATE FIBERS WITH VARIOUS CROSS SECTIONS

Fiber cross-sectional shape	Fiber linear density (den)	Fabric weight (kg/m^2)	Fabric density (g/cm^3)
I	2.62	0.257	0.142
Y	2.67	0.255	0.134
X	6.03	0.256	0.150
Y	5.31	0.258	0.151
I	8.24	0.257	0.146
Y	8.35	0.256	0.147
Trilobal (PET)	3	0.251	0.134
Round (PET)	3	0.253	0.138

So-called "performance curves" have been plotted in the past [6] to allow for the trade-off between pressure drop and penetration as fiber linear density changes. These curves are developed by plotting penetration vs. pressure drop (or some equivalent parameter), as in Figure 21, and ideal performance is represented by a point at the origin. Performance points for felts made of fibers with a particular cross-sectional shape but of different linear densities will fall on a characteristic curve. The distance of the curves from the origin can be taken as a measure of the performance associated with that fiber. This criterion applied to the results in Figure 21 shows that, in fact, the Y fibers produce a curve which is closer to the origin than the PET trilobal fibers. The points in Figure 21 represent an incomplete collection, which will be filled in the future. In addition, the performance curves show that the Y fibers make for slightly better performance than the I fibers. From the cross sections shown in Figure 18 it would appear that the X fibers should give performance very similar to that of I fibers since they all approximate irregular tetralobal shapes. The results in Figure 21, however, show that the X fibers are slightly better, though it is impossible to identify a feature of their cross section to which this better performance may be attributed.

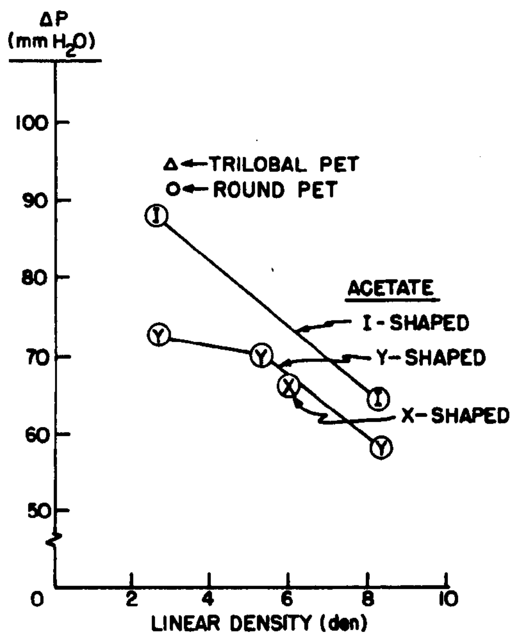


Figure 19. Comparison of pressure drop with fabrics made of I, Y, and X-shaped acetate, trilobal PET (Δ), and round PET (o) fibers.

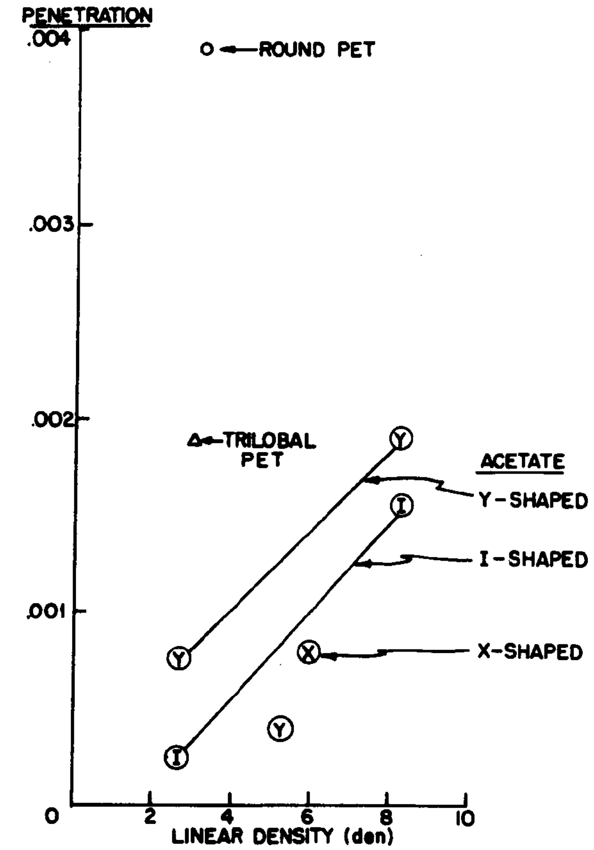


Figure 20. Comparison of penetration (1 - efficiency) with fabrics made of I, Y, and X-shaped acetate, trilobal PET (Δ), and round PET (o) fibers.

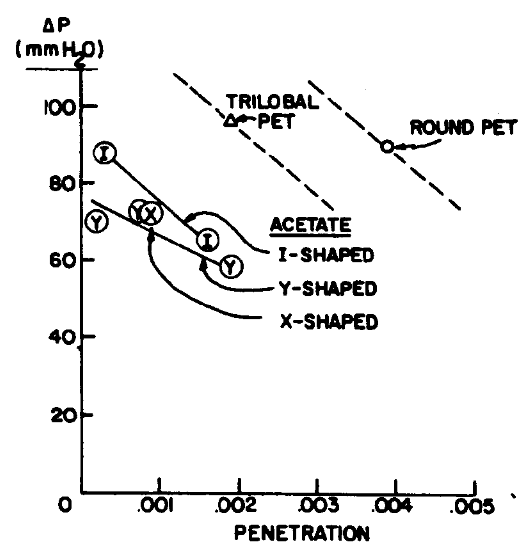


Figure 21. Performance curves for the fabrics in Figures 19 and 20.

A previous report [4] gave results of calculations of single fiber efficiencies in electric fields for fibers with different lobe depths. The results indicated a strong direct dependence of capture efficiency on lobe depth. These results have suggested the possibility that the better performance of lobed-fiber filters may be due to the better capture behavior of these fibers in localized electric fields due to deposited charged aerosol particles. No experimental verification of the hypothesis has been made, but the better performance with deep-lobed fibers reported above appears to support it.

C. COMPOSITE FILTERS

1. Initial Cycles

The last report [4] described measurements on filters made by pressing together layers of vinyon-bonded nonwovens made with different fibers. The fibers used at that time were 3-denier trilobal and 3-denier round cross section polyester. It was found that the upstream layers appeared to control the behavior of the filter.

Measurements of this type were repeated with layers differing in fiber fineness, namely with 3 and 6-denier trilobal polyester. Table 3 describes the combinations used; just as in the first study, two filters had all layers composed of either 3 or 6-denier fibers, the other two had a top layer of one fiber and the remaining 5 layers of the other. Trial conditions were identical with the first study. At the twentieth cycle of conditioning, the trials were terminated and measurements recorded.

TABLE 3. COMPOSITE FILTERS MADE OF 3 AND 6-DENIER TRILOBAL POLYESTER FIBERS

Upstream layer	Downstream layer
All 6 denier ($0.25\ kg/m^2$)	
All 3 denier ($0.25\ kg/m^2$)	
6 denier ($0.04\ kg/m^2$)	3 denier ($0.21\ kg/m^2$)
3 denier ($0.04\ kg/m^2$)	6 denier ($0.21\ kg/m^2$)

Figure 22 shows an unexpected trend in pressure drop behavior for the four fabrics during conditioning. In the first 10 cycles, the upstream layers dominate the behavior, just as in the study of cross-sectional shape. Thereafter, a reversal in the trend appears, with pressure drop now being determined by the downstream fibers. A similar crossover occurs in the pressure drop rise within one cycle (the 20th) shown in Figure 23.

These phenomena are assumed to be the result of dust seepage past the upstream layer, so that as the dust deposit advances, responses characteristic of the downstream layers appear. Since these data showed evidence that behavior had not yet stabilized, it was difficult to make any additional conclusions concerning fine/coarse composites. A new trial was initiated.

2. Conditioned Fabrics

A second study of fine/coarse composites was carried out using the following series of samples:

Upstream	/	Downstream
0% 6d		100% 3d
17% 6d		83% 3d
50% 6d		50% 3d
83% 6d		17% 3d
0% 3d		100% 6d
17% 3d		83% 6d
50% 3d		50% 6d
83% 3d		17% 6d

The samples were vinyon-bonded at a higher temperature than had previously been used (121°C instead of 99°C), thereby achieving a more stable fabric density. Measurements were made after a longer conditioning than reported previously (30 to 40 cycles instead of 20 cycles). Each data point is the average of from 2 to 5 measurements using replicate samples or vacuum-cleaned samples. The above steps were intended to further increase the reliability of the results. Experimental conditions were as follows:

Fabric weight	:	0.25 kg/m^2 (7.3 oz/yd^2)
Fabric density	:	0.130 g/cm^3
Fiber type	:	PET
Face velocity	:	60 mm/s (12 ft/min)
Inlet concentration	:	3.5 g/m^3
Cycle time	:	5 min
Pressure in reverse air cleaning	:	209 kPa (30 psi)

Measurements were made not only of the penetration and the pressure drop of these filters, but also of the residual dust after cleaning (expressed as a fraction of the base filter mass). Figures 24, 25, and 26 show these measurements as a function of composition

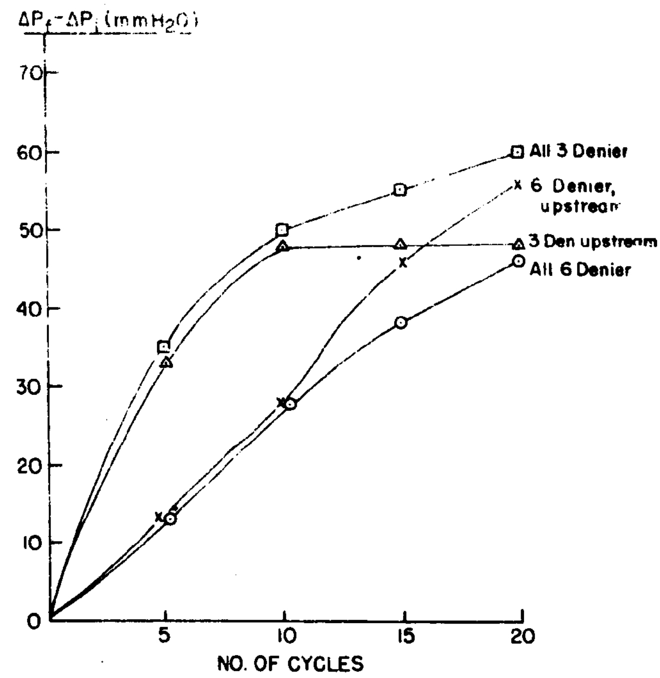


Figure 22. Changes in pressure drop during conditioning of composite PET filters.

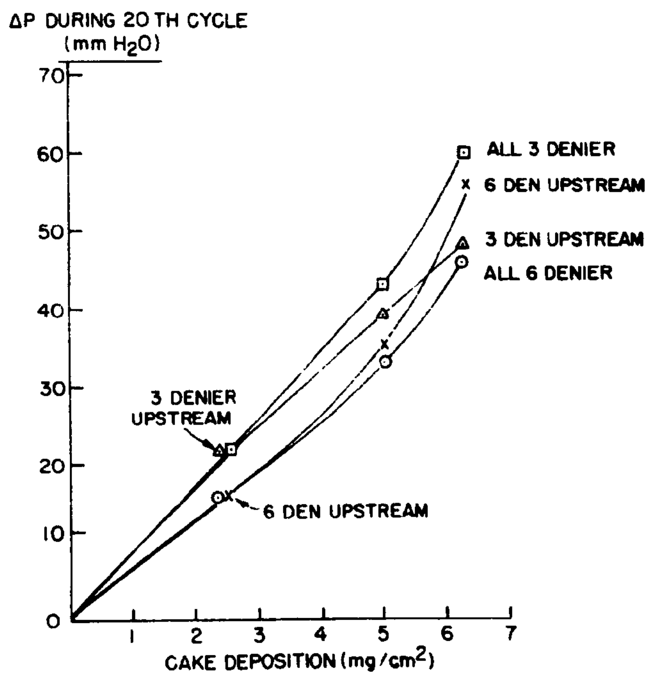


Figure 23. Changes in pressure drop during the 20th cycle for composite PET filters.

by weight (% 6d/% 3d) of the two-layer composite filters. In these graphs, percentage of 6-denier fibers upstream increases to the right, whereas percentage of 3-denier fibers upstream increases to the left. It can be seen now that a composite with 3-denier fibers upstream allows less penetration and also exhibits a lower pressure drop than one with 6-denier fibers upstream or one with 100% 3-denier fibers. The 17% 3d upstream/83% 6d downstream composite appears to be optimum.

These effects may be explainable by the correlation between the curves of Figures 24 and 25 with those of Figure 26. It appears generally that penetration and pressure drop are directly related to the amount of dust retained after cleaning. Finer (3-denier) fibers upstream prevent dust from lodging deeper into the filter where it cannot be blown back. This in turn keeps the penetration lower, and since unremovable dust increases resistance, also keeps the pressure drop lower. The slightly upward turn of the pressure drop curve at 100% 6d may also be due to increased residual dust. Although 17% 3d/83% 6d appears to be optimum, further studies with commercial-weight filters should be conducted to verify these findings.

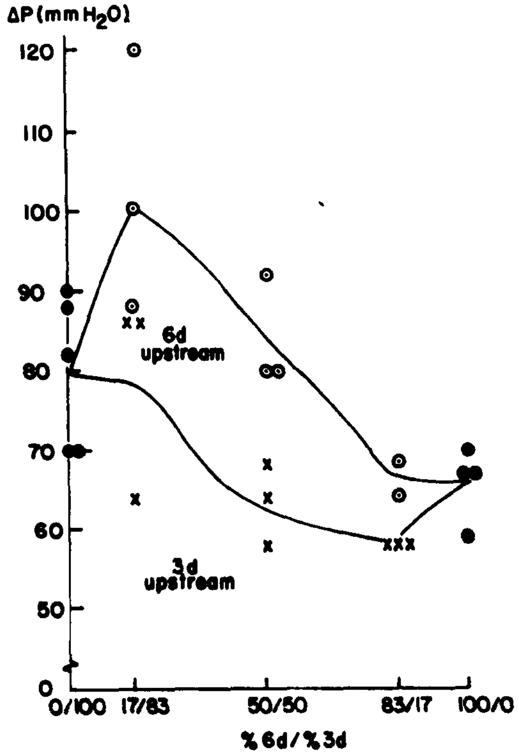


Figure 24. Pressure drop across composite vinyon-bonded PET filters having varying proportions of 3 and 6-denier fibers in two layers.

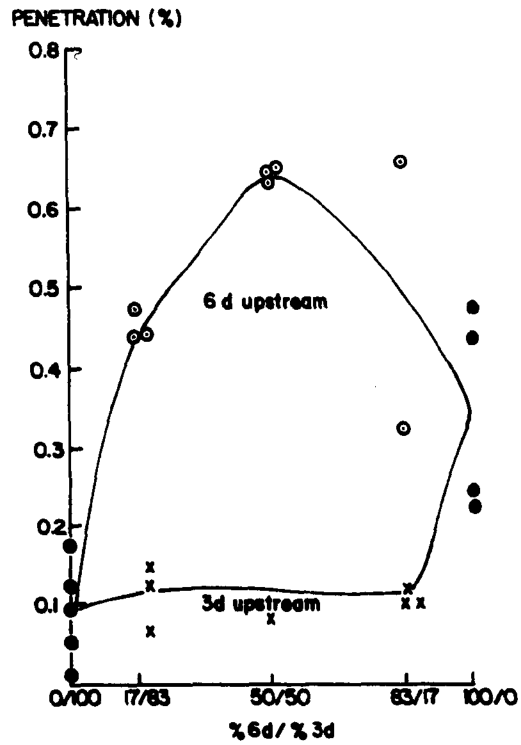


Figure 25. Penetration through the composite filters of Figure 24. Solid circles are points for all 3 or all 6-denier filters.

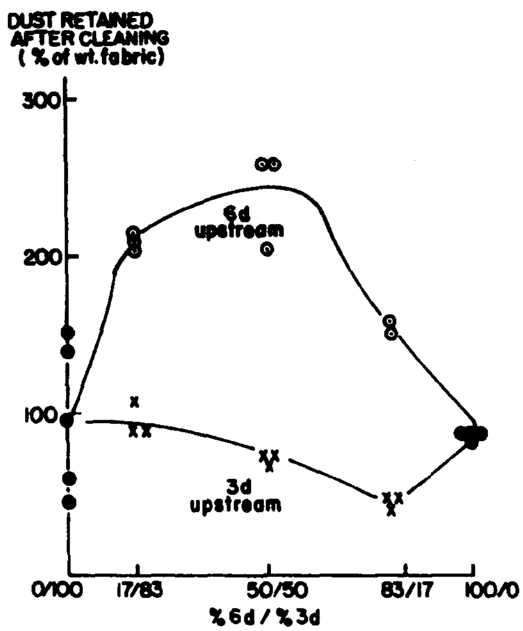


Figure 26. Residual dust after cleaning the filters of Figure 24.

SECTION V

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TECHNICAL REPORT DATA
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1. REPORT NO. EPA-600/7-79-108	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Studies of Dust Cake Formation and Structure in Fabric Filtration: Second Year		5. REPORT DATE April 1979
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Bernard Miller, George Lamb, Peter Costanza, George Harriott, Janet Dunbar, and Michael Mokricki		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Textile Research Institute P.O. Box 625 Princeton, New Jersey 08540		10. PROGRAM ELEMENT NO. EHE624A
		11. CONTRACT/GRANT NO. Grant R804926
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED 12/77 - 12/78
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is James H. Turner, MD-61, 919/541-2925. Report EPA-600/7-78-095 covers the first year's work.

16. ABSTRACT The report describes experiments to improve fabric filter efficiency and pressure drop by use of electric fields near the filter surface. Modified fiber geometries and fabric construction are also investigated. Tests with patch filters showed pressure drops reduced to about 13 mm H2O from about 36 mm H2O upon the application of a 6 kV/cm electric field. Total fractional particle penetration was reduced to about 0.001 from 0.170 under the influence of the same field. The electric field was more effective when applied to filters having loose fibers at the surface. Deeply lobed fibers produced filters with higher efficiency, lower pressure drop, and better cleanability than filters made from round fibers. The effects were attributed to induced localized fields at the lobed surfaces. The fields were produced from collection of naturally charged particles. Fabric structure that promotes particle collection near the upstream surface of the filter gave the best performance.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Fibers	Pollution Control	13B	
Gas Filters	Shape	Stationary Sources	13K	12A
Fabrics		Fabric Filters	11E	
Dust		Particulate	11G	
Caking			07A,13H	
Electric Fields			20C	

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 45
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)