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EPA Fabric Filtration Studies: 6. Influence of Dust Properties on Particle Penetration

Interagency Energy/Environment R&D Program Report

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EPA REVIEW NOTICE

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EPA Fabric Filtration Studies: 6. Influence of Dust Properties on Particle Penetration

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ABSTRACT

This report examines the importance of dust properties in determining dust penetration through a fabric filter. The major property considered is the size distribution of the dust which is an important dust property for dust penetration. Most other important variables of dust penetration depend more on the dust/fabric combination than on the dust alone.

The report begins by reviewing dust penetration mechanisms and relating them to dust and dust/fabric properties. These interactions are illustrated using data generated in the EPA in-house laboratory as well as data published in the open literature. Both shaker baghouse data and pulse-jet baghouse data are used in an attempt to identify commonality in dust penetration independent of fabric cleaning technique.

PREFACE

This report is the sixth in a series of reports, entitled EPA Fabric Filtration Studies, which summarize the results of EPA laboratory testing of new baghouse fabric materials and present the conclusions of specialized research studies in fabric filtration. These tests have been carried out over the past 5 years by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, N. C. and previously by predecessor agencies. The purpose of these investigations was to evaluate the potential of various new fabrics as baghouse filters and to obtain data for use by the fabric filtration community.

The testing consisted of simulating a baghouse operation in a carefully controlled laboratory setting that allowed measurement and comparison of bag performance and endurance. The simulations discussed in this report cover only a very narrow range of operating conditions: room temperature filtration with an inlet dust loading of about 3 gr/ft^3.*

Extreme caution should be used in extrapolating the results reported here to the substantially different conditions that occur in field applications. The usefulness of the present results is primarily either as an initial screen of candidate fabrics for baghouse applications or as an exploration of baghouse phenomena.

Author Donovan's efforts in this report are represented by EPA Contract 68-02-2612, Task 42 with Research Triangle Institute, Research Triangle Park, N.C. 27709.

*EPA policy is to use metric units. For convenience and consistency with existing baghouse conventions, British units are used in this report. Readers more faimilar with the metric system may use the factors listed elsewhere in this report to convert to that system.

The EPA Fabric Filtration Studies series now consists of the following reports:

1) Turner, J. H. Performance of Non-woven Nylon Filter Bags, EPA-600/2-76-168a (NTIS PB 266271), December 1976.
2) Ramsey, G. H. et al. Performance of Non-woven Polyester Filter Bags, EPA-600/2-76-168b (NTIS PB 258025), June 1976.
3) Donovan, R. P., B. E. Daniel, and J. H. Turner. Performance of Filter Bags Made from Expanded PTFE Laminate, EPA-600/2-76-168c (NTIS PB 263132), December 1976.
4) Donovan, R. P., B. E. Daniel, and J. H. Turner. Bag Aging Effects, EPA-600/7-77-095a (NTIS PB 271966), August 1977.
5) Daniel, B. E., R. P. Donovan, and J. H. Turner. Bag Cleaning Technology High Temperature Tests, EPA-600/7-77-095b (NTIS PB 274922), November 1977.
6) Donovan, R. P., B. E. Daniel, and J. H. Turner. The Influence of Dust Properties on Particle Penetration (this report).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

A = filtration area of fabric (ft^2)
C_o = mass outlet concentration (gr/1000 ft^3)
E = mass collection efficiency (percent)
K_2 = true value of specific cake resistance (in. H_2O/fpm)/(lb/ft^2)
K_2' = measured value of specific cake resistance (in. H_2O/fpm)/(lb/ft^2)
ΔP_E = pressure drop across bag extrapolated to time zero of filtration cycle (in. H_2O)
ΔP_T = pressure drop across bag at end of filtration cycle (in. H_2O)
S_E = effective drag (in. H_2O/fpm)
S_T = terminal drag (in. H_2O/fpm)
A/C = air/cloth ratio (fpm)

METRIC CONVERSION FACTORS

Non-metric	Times	Yields Metric
ft	0.30	m
ft^2	0.09	m^2
ft^3	28.3	ℓ
gr	0.06	g
in.	2.54	cm
lb	0.45	kg
oz	28.3	g
yd^2	0.84	m^2

SECTION 1
INTRODUCTION

Physical properties of the particles making up a dust source influence the rates at which the dust penetrates through a fabric filter. Previous studies reported in this series [Refs. 1-5] and the 1977 annual report [Ref. 6] have emphasized the importance of the fabric properties in the dust/fabric interaction. This report emphasizes primarily the importance of the dust properties.

A primary physical property of a dust source is its size distribution. Reports in the literature disagree as to the importance of this property. Early workers argued that there should be a mimimum in the plot of collection efficiency vs. particle size (conversely a maximum in particle penetration vs. particle size), since large particles (3.5 μm and larger) are efficiently removed by mechanisms such as sieving, interception, and impaction and since small molecular-sized particles (0.05 μm and smaller) are captured because of diffusion processes. Between these extremes are the intermediate respirable particulates (0.05 to 3.5 μm) which penetrate the fabric more readily than the larger or smaller particles. Dust penetration through a fabric filter should therefore vary according to particle size distribution. And early measurements of fractional efficiency seemed to support this prediction [Refs. 7-9].

More recent works [Refs. 10-12], however, describe dust/fabric systems in which dust penetration is relatively independent of particle size and, if anything, increases as particle size changes from the respirable range to the larger range. Various mechanisms have been postulated to explain this size-independent particle penetration. Depending upon the dominant mechanism in a given dust/fabric system, the effect of dust size distribution on penetration seems to vary.

Fabric cleaning technique may be an important parameter in understanding particle penetration through a fabric filter [Ref. 13]. This report emphasizes the unity of particle penetration, regardless of cleaning technique, rather than the differences: distinctions between the various cleaning mechanisms are subordinated to the similarities. Fabric cleaning technique is explicitly specified for all data cited, however. The importance of cleaning parameters during pulse-jet operation has been forcefully presented by Leith, et al. [Ref. 14].

This paper presents the results of further study of the dependence of particle penetration on dust properties including: size distribution (Section 4.1) and other properties (Section 4.2).

SECTION 2
CONCLUSIONS

Particles penetrating through a fabric filter are classified as either prompt or delayed. Prompt penetrating particles follow straight-through trajectories without colliding with the fibers or dust cake of the fabric/dust cake composite. Their transit time through the fabric filter is the same as that of the gas flow in which they are entrained. These prompt penetrating particles are fractionated in size according to classical fiber filtration mechanisms: typically, they decrease in concentration as the dust cake grows.

Delayed penetrating particles are removed from the gas flow, no matter how briefly, but subsequently become reentrained and are emitted from the clean-air side of the fabric. Delayed penetration particles are further subdivided into two subclasses: those with the same size distribution as the inlet dust; and those which penetrate by some size-dependent mechanism.

The mechanisms by which particles penetrate a fabric filter vary in importance from one dust/fabric system to another and can vary in importance as a function of time during filtration. The dominant mechanism depends on the dust, the fabric, their interaction, and time. Examples in this paper, illustrating different penetrating mechanisms and behavior, are drawn from data based on:

1) Flyash filtered by woven polyester, spunbonded polyster, Gore Tex/ Nomex, polyester felt, and Nomex fabrics (shake-cleaned baghouse).
2) Rock dust filtered by polyester felt and Nomex fabric (pulse-jet).
3) Other published work in the open or U.S. Government literature (shake-cleaned, reverse-air-cleaned, and pulse-jet).

These data sources generally support the physical model that favors delayed, non-fractionating particle penetration when the filtration is carried out at high (≥10 fpm) air-to-cloth ratios (such as the pinhole plug mechanism described by Leith _et al_., [Ref. 11]) and fractionating delayed particle penetration when filtration is carried out at low (1-4 fpm) air-to-cloth ratios (such as Dennis' rear-face slough-off [Ref. 12]). Prompt straight-through processes dominate at the beginning of filtration cycles in which the filtering action depends primarily upon dust cake filtration. Fabric cleaning technique (pulse-jet vs. shake-cleaning or reverse-air-cleaning) may also influence particle penetration [Refs. 13,14].

The size distribution of a dust source can therefore be an important filtration property both because of its influence on particle penetration mechanisms and also because of its effect on dust-cake growth and properties.

Other dust properties, such as affinity for water, and particle adhesion and cohesion, could also have major influences on dust cake formation and particle penetration. In this report, comparisons between rock dust and flyash penetration of certain fabric filters show that the major filtration performance parameters depend more on the properties of the dust/fabric system than on the properties of the dust alone.

SECTION 3
EXPERIMENTAL WORK

The apparatus used in gathering the data presented in this paper consisted of both a shake-cleaned baghouse and a pulse-jet unit. The dusty air source is the same for both units and the analytical taps in the outlet, while not identically the same line, are similar. Outlet air measurements included total mass over a 20 minute sampling period (the Millipore filter technique), optical counter determination of outlet particle size distribution, and impactor analysis of inlet particle size distribution. The first two techniques are the same as has been used in the work previously described [Refs. 1-5]. The impactor data have not previously been reported in this series. They were gathered using either a 7-stage MRI impactor or an Andersen impactor preceded by a 3-stage cyclone. The purpose of the impactor data was to determine the size distribution and density of dust particles in the inlet air. Originally the plan was to sample the outlet dust with an impactor also but this plan was abandoned because of the impractically lengthy sampling times and/or system modifications required for statistically significant data. The only direct size-distribution measurements of the outlet dust were carried out with the Climet optical counter.

Figure 1 compares impactor analysis of the size distribution of two inlet dusts with those determined by a Coulter counter. The two dusts are power plant flyash (the same Detroit Edison flyash used in all previous experimental work reported in this series) and asphalt plant rock dust. The two analytical methods agree reasonably well for the rock dust; less well for the flyash. Both sets of measurements, however, show that the rock dust is composed of smaller particles than the flyash--the cumulative percentage of particles smaller than any given size is greater for the rock dust than for the flyash. This observation will be recalled later to establish a difference between the penetration of rock dust particles and the penetration of flyash particles.

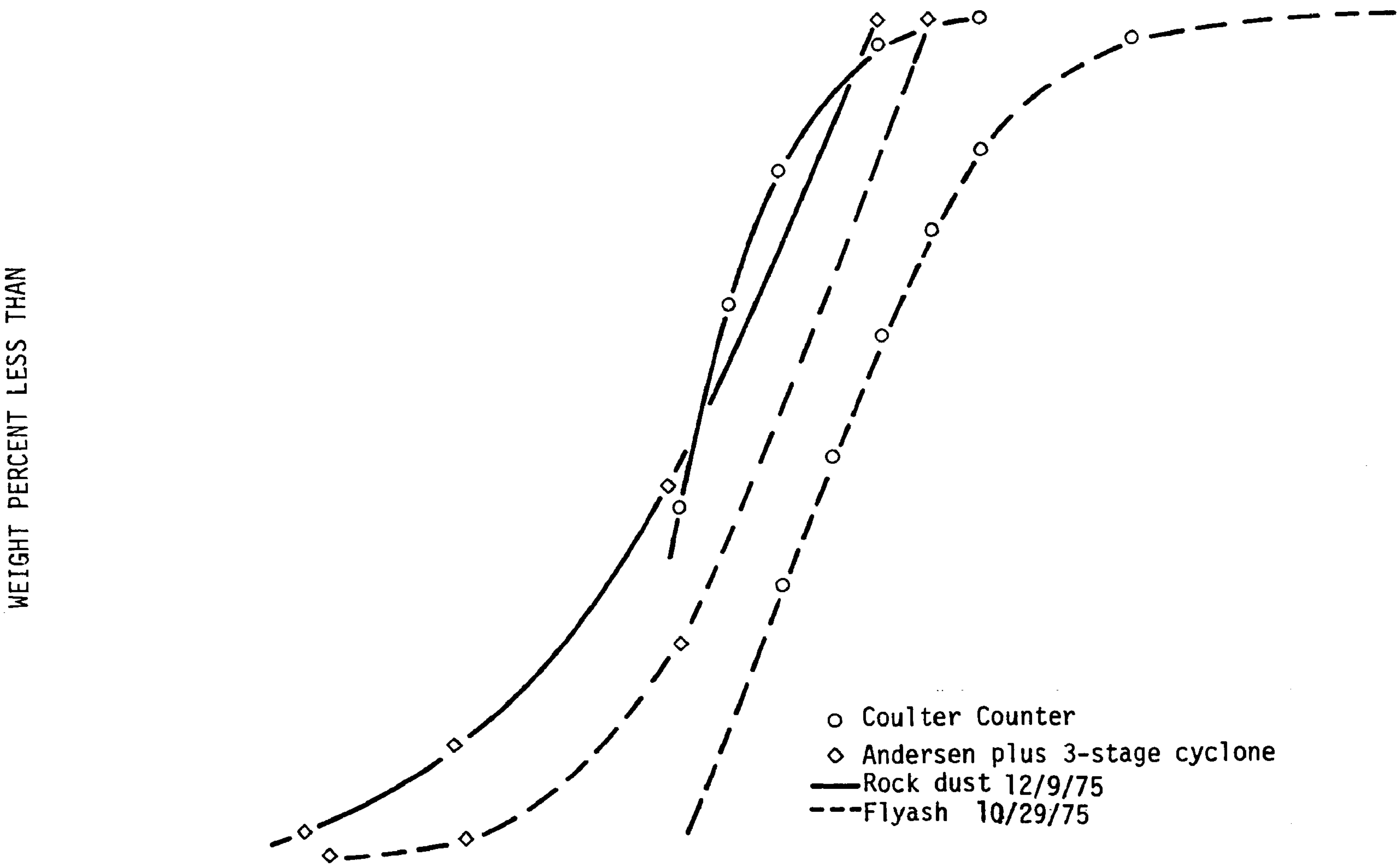

Figure 1. Size distribution of inlet dusts.

The test dust recovered in the collection hopper of the baghouse is reused over and over again. With some addition for losses, the same flyash has been recycled through the baghouse and back to the dust feeder hundreds of times over a period of years. That the size distribution of this dust has not changed appreciably over the years (Figure 2) shows that the particle penetration through all (or at least most) of the many fabrics tested is essentially independent of size. This absence of fractionation is not true for all flyash/fabric systems, however, and Figure 2 also includes a size distribution curve for the dust collected in the hopper when using spunbonded polyester to filter flyash [Ref. 2]. For this dust/fabric system the filtration appears size-dependent, since the size distribution of the collected particles shifts significantly to the larger particles when compared with the size distribution of the inlet dust. This shift says that a proportionally larger number of small particles are penetrating the fabric; their absence in the collected dust gives rise to the changed size distribution.

This shift is atypical: it was not observed for the flyash/fabric systems to be reported here. The size distribution of the rock dust was not checked before and after filtration but, as reported in Section 4.2, other evidence suggests that the rock dust filtration would also be size-dependent when filtered by the fabrics used in these experiments.

Shifts in the opposite direction (the dust becomes enriched in small particles because the filtration process removes a proportionally greater number of the large particles) are also common, especially when the initial dust contains many large dust particles and has a mass median diameter (D_{50}) in excess of 20 to 30 μm. Many of these large dust particles simply settle out in unrecoverable regions of the flow systems and are lost to the dust recycling action. Cement dust, exhibiting a D_{50} of about 50 μm before filtration, lost a sufficient number of large particles after 19 hours of operation in the high temperature baghouse [Ref. 6] to have its D_{50} value reduced to about 15 μm. This shift was the largest observed; other checks of the cement dust size distribution showed similar shifts with time but of reduced magnitude.

The observation is that it is possible for the outlet size distribution of a dust source to remain the same as the inlet distribution

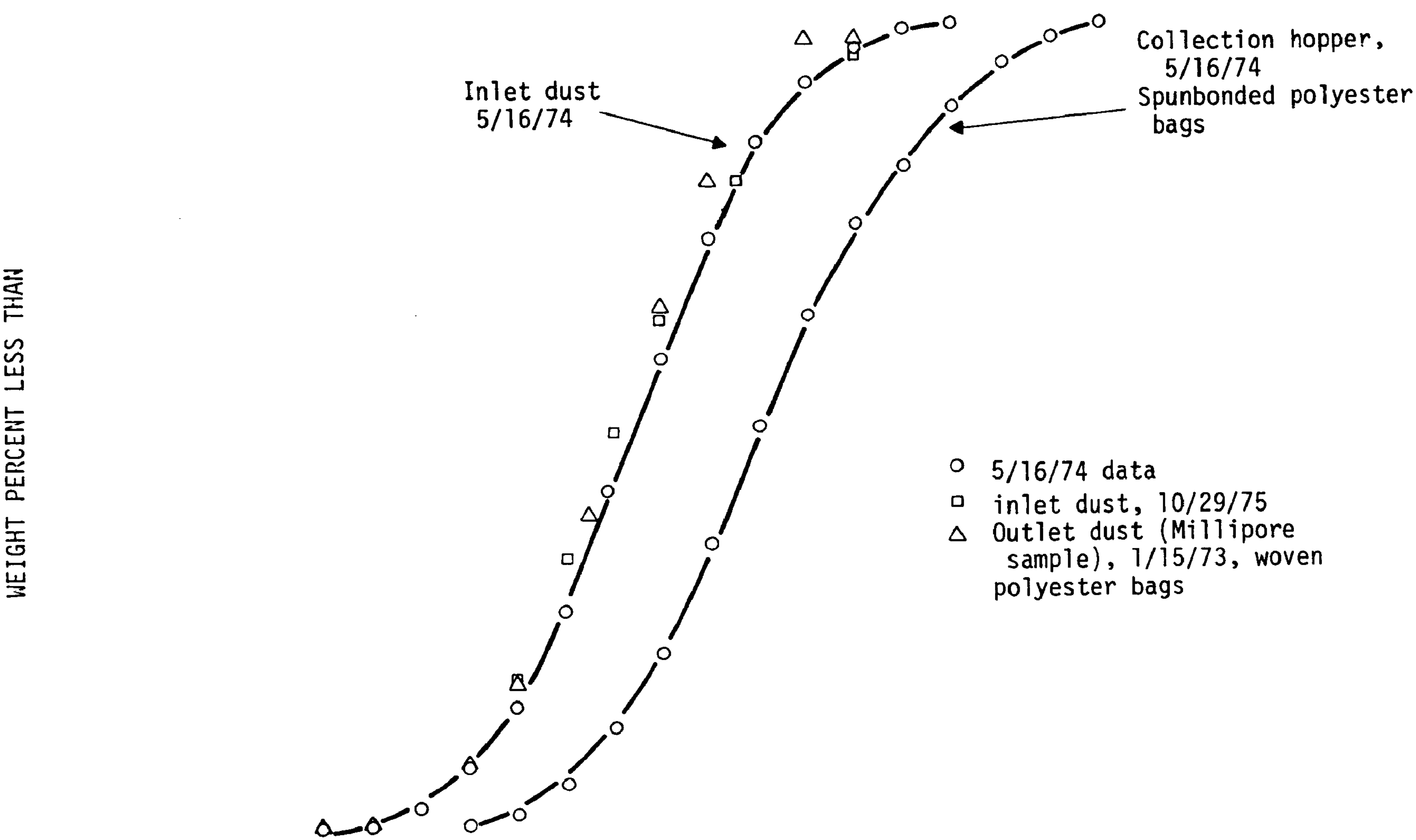

Figure 2. Stability of flyash size distribution.

during filtration or to shift toward either larger or smaller particles, depending on baghouse properties and the mechanisms of dust penetration. A recycled dust can go either way because of the possibility of large particle loss to the system (rather than penetration of the fabric). That is, a baghouse divides an inlet dust into two fractions: the outlet dust and the dust collected in the hopper. The dust quantity collected in the hopper is generally about 2 to 3 orders of magnitude greater than that passed through the fabric to the outlet. Consequently, fractionation during fabric filtration is more rapidly detected in the size distribution of the outlet dust. Conversely, however, changes detected in the hopper dust are major effects. Hopper dust analysis by a Coulter counter is primarily what was carried out here (Figure 2, however, did present a Coulter counter analysis of the dust collected on a Millipore filter in the outlet). The outlet dust size distribution should show simply the small difference between the inlet dust and the hopper dust. For the original work reported here, some supplementary analyses of the size distribution of the outlet dust were carried out with the optical detector. The number data generated by the optical detector are not directly comparable with the inlet dust size distributions generated by either an impactor or the Coulter counter and no such comparisons are made.

The shake-cleaned baghouse used in this work is described in prior reports of this series [Refs. 1-5]. The pulse-jet is a commercially available, nine-bag MikroPul binvent baghouse, described in the most recent annual report [Ref. 6].

SECTION 4

RESULTS AND DISCUSSION

This section is divided into two topics: size distribution effects and other dust property effects. The first section draws only on data collected using the classified flyash that has been the primary dust used in the previously reported work [Refs. 1-5]. The second section compares rock dust filtration with flyash filtration under identical laboratory conditions.

4.1 SIZE DISTRIBUTION EFFECTS

For a large class of dust/fabric systems, particle penetration with time is of the form shown in Figure 3--the maximum in penetration occurs immediately after the cleaning cycle (or very shortly into the new filtration cycle). Most of the particles that penetrate through the fabric do so in the first half of the filtration cycle. In this model the primary filtration media is the dust cake itself; the fabric serves mainly as an initiating and supporting lattice on which the dust cake forms and to which it remains affixed, as shown in Figure 4. The high rates of particle penetration occuring in the initial time period of the filtration cycle correspond to the time period in which the dust cake is of minimum thickness and is being rebuilt (repaired) following the cleaning cycle. Partial destruction and removal of the dust cake is necessary in order to recover tolerable pressure drop and drag so that the optimum cleaning cycle is a compromise between the restoration of low pressure drop and the loss of filtration efficiency.

Of particular interest is the time dependence of the size distribution that is reflected in the plots of Figure 3. During the first half of the filtration cycle (zero to 10 min) the size distribution of the outlet dust changes dramatically. Over the second half of the filtration cycle, it remains much more constant. To take the Millipore filter catch and analyze it in a Coulter counter or, alternatively, to take impactor samples from the outlet would, of course, average these time dependencies and give an average size distribution. In dust cake

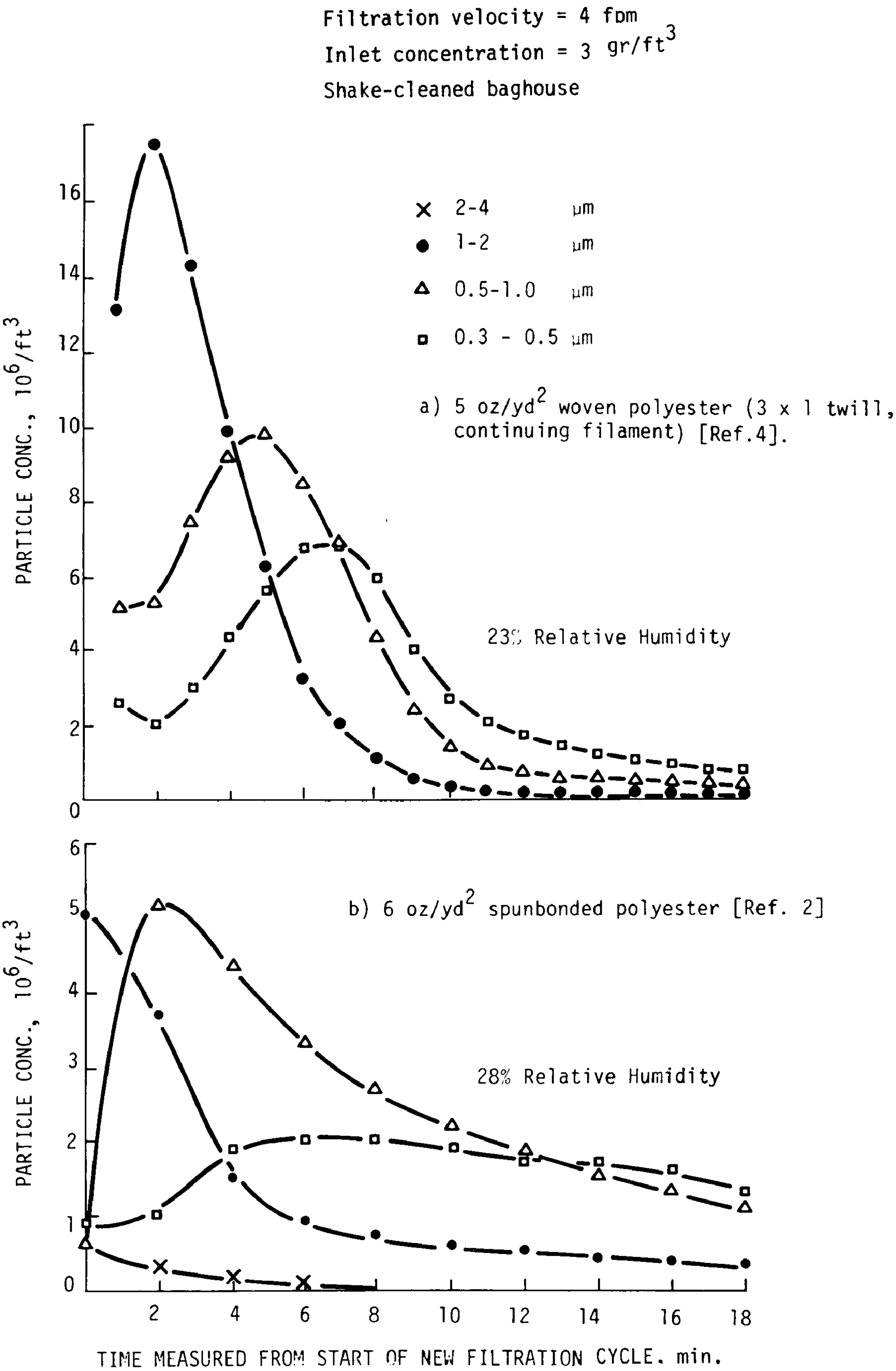

Figure 3. Flyash penetration in classical dust cake filtration.

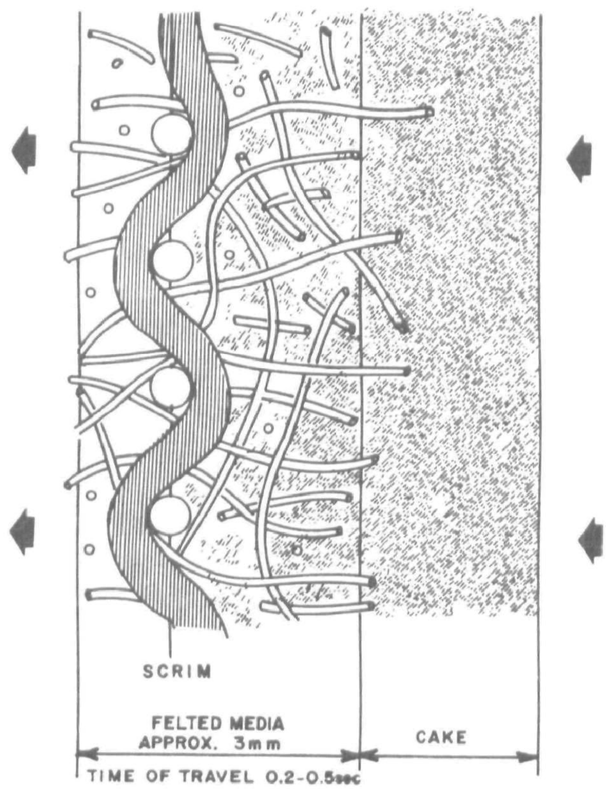

Figure 4. Section through felted filter media showing distribution of dust [Ref. 9].

filtration the dust cake/filter composite is a dynamic structure: it changes rapidly with time during the initial growth of the dust cake. Its properties as a filter and the mechanisms of particle penetration through it also change with dust cake growth [Ref. 11].

Penetration mechanisms and their dependence on dust cake thickness have been described for penetration through a pulse-jet filter by Leith et al. [Ref. 11] in terms of straight-through passages, seepage processes, and pinhole plug bursts.

The straight-through component is that which penetrates without ever being captured; seepage is that component which is captured one or more times but is released after each capture and eventually works its way through the filter; and pinhole plugs are those particles which are captured and clustered about a pore and then released in a single penetrating burst. Leith et al. state that both the seepage component of penetrating particles and that attributable to pinhole plugs should have the same size distribution as the inlet dust. To interpret their experimental data, they assume that seepage, in keeping with its size independence, is a queuing process in which the first particles to arrive at the filter face are also the first particles to leave the rear face of the filter--there is no way one particle can pass another in traversing the bulk of the filter.

These mechanisms were investigated experimentally by Leith et al. [Ref. 11] with chemically tagged flyash and quantitatively evaluated for a specific flyash (from an electrostatic precipitator)/polyester needled felt in a pulse-jet bag filter. Based on these physical concepts and experimental measurements, they deduced a plot, reproduced in Figure 5, to describe particle penetration mechanisms as a function of dust cake thickness (hence, filtration time).

The data taken in our experiments cannot be analyzed quantitatively as could Leith et al.'s data (Leith used chemically tagged flyash to follow groups of flyash and particles through the filter). Some qualitative comparisons can be made, however.

Figure 3 shows that the time of maximum particle penetration varies with particle size: the smaller particles peak later in the filtration cycle than the larger. In Figure 3a, for example, peak penetration of the 1-2 μm particles occurs 2 min into the new filtration cycle; peak

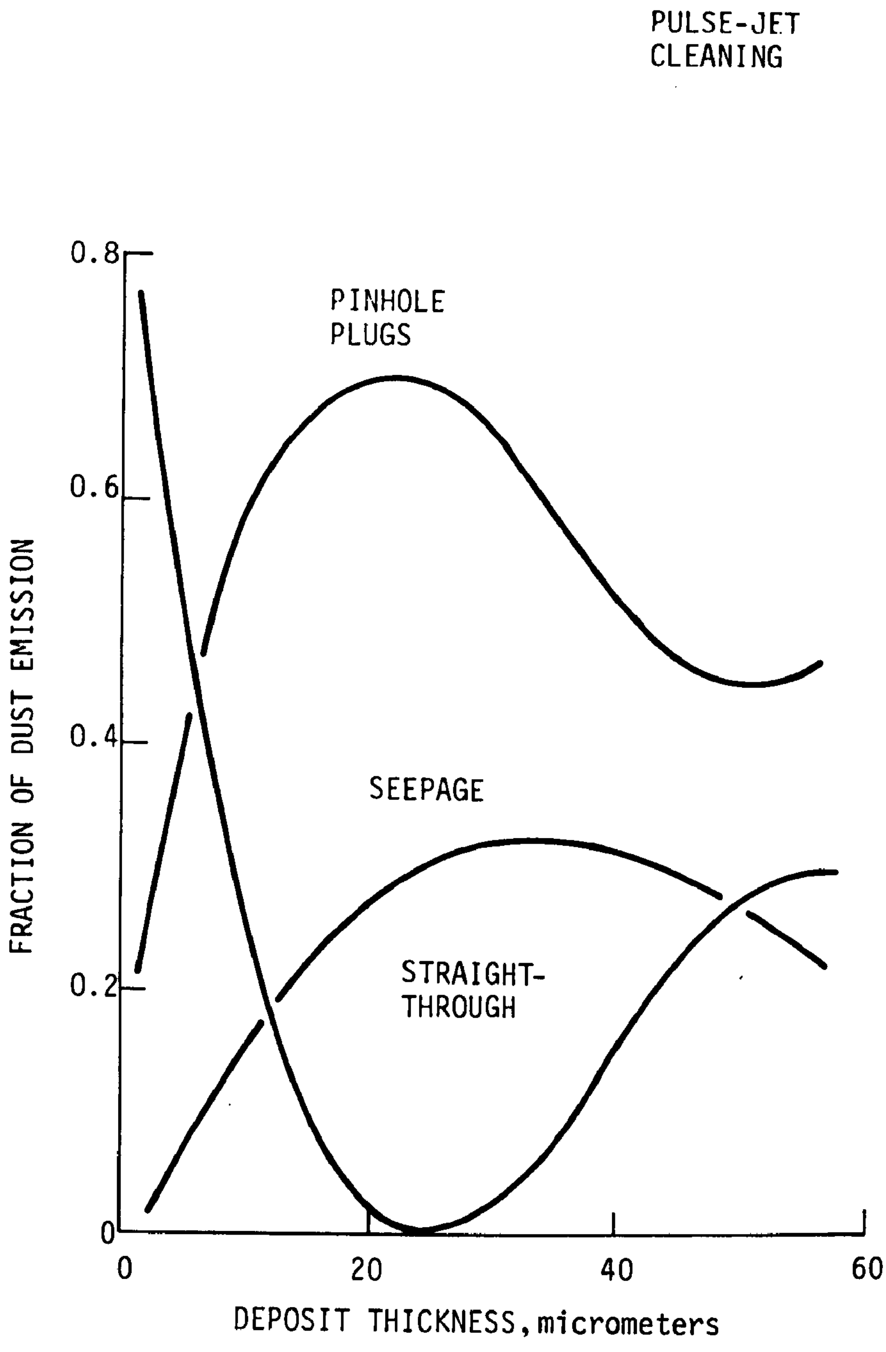

Figure 5. Fraction of total flyash emitted, which is accountable to indicated emission mechanism, versus deposit thickness [Ref. 11].

penetration of 0.5-1.0 μm particles occurs at 5 min; and peak penetration of 0.3-0.5 μm particles occurs at about 7 min. This observation suggests that the regrowing dust cake does not trap the smaller particles as efficiently as the larger particles and that, in the initial phase of the filtration cycle, the fabric/dust cake composite may actually lose particles that were previously trapped but which have been dislodged by the shake-cleaning, the forward air flow through the fabric freshly stripped of dust cake, or a combination of the two.

Similar observations apply to pulse-jet cleaning as well (the rock dust/polyester felt data in Figure 6). The 0.3 μm particle pulse peaks later in the filtration cycle (the filtration cycle is defined as beginning with the cleaning pulse, indicated by the solid arrows in Figure 6; the pulse peaks at the broken arrows) than the 0.5 μm particle pulse (which peaks later than the 1 μm particle pulse). The time scale for the traces of particle concentration shown in Figure 6 differs greatly from that of Figure 3: the time between pulses (Figure 6) is on the order of 60 secs. The same general time dependence of particle penetration seems to take place, however, in both cycles--at least for the rock dust/ polyester felt system.

The pinhole plug mechanism of particle penetration described by Leith et al. [Ref. 11] predicts an initial increase in particle penetration with dust cake thickness (Figure 5). Particle penetration attributable to pinhole plugs then peaks at some intermediate value of dust cake thickness, showing a time dependence similar to that of the particle penetration curves of Figure 3. The differentiation according to particle size evident in Figure 3 is not, however, accounted for by pinhole plugs--at least not by the Leith description in which the particle size distribution of the pinhole plug is assumed to be that of the incoming dust.

That one size range of penetrating particles decreases with time is not unusual--Leith's straight-through mechanism predicts this (Figure 5). What is not accounted for is the concurrent increase in the concentration of a smaller particle range. (In Figure 3, for example, the concentration of 1-2 μm particles decreases between minutes 2 and 4; yet, in this same time interval, the concentration of 0.3-0.5 μm

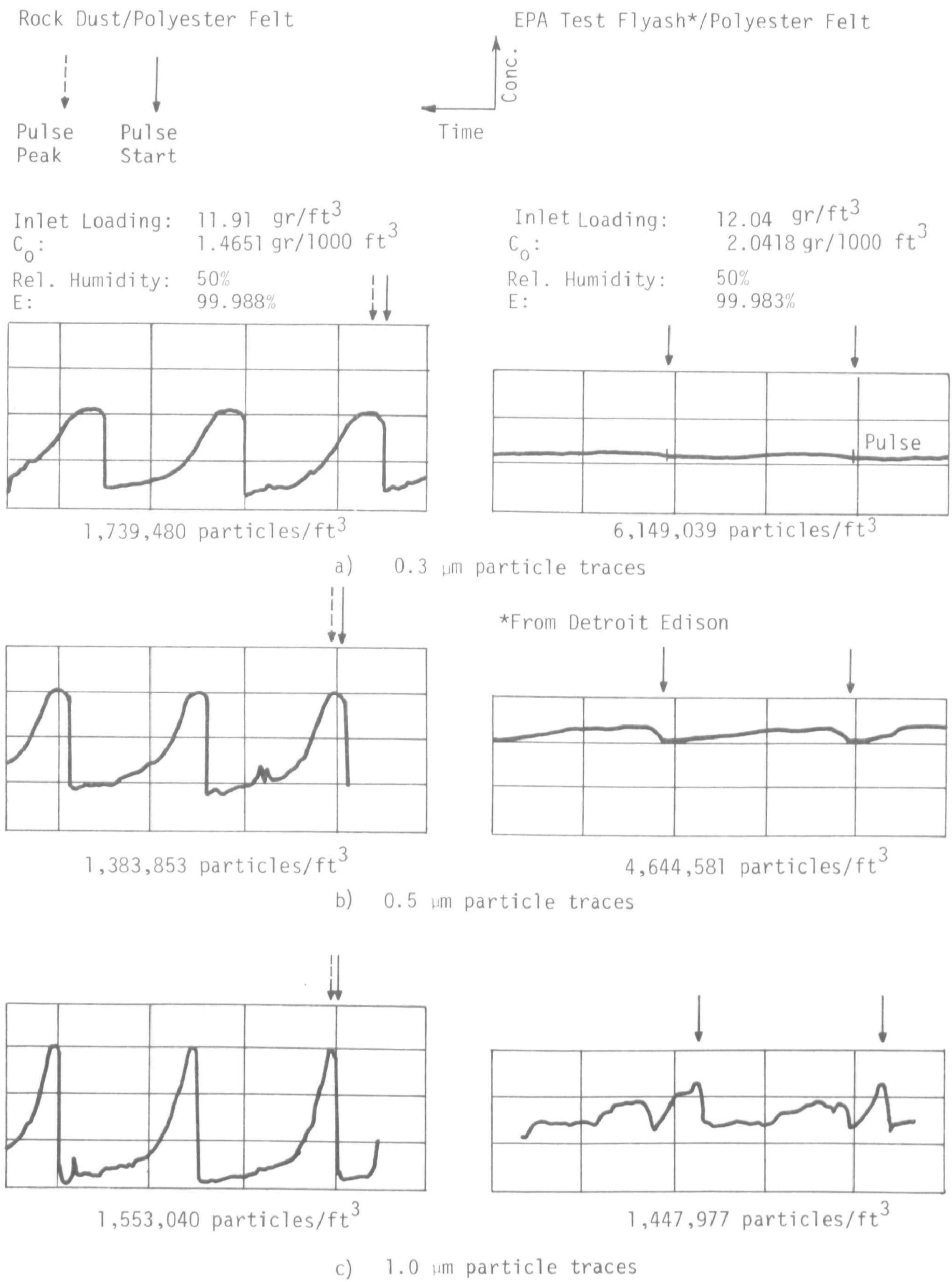

Figure 6. Optical counter traces in outlet of pulse-jet baghouses.

particles increases.) The conclusion would seem to be that different mechanisms of penetration dominate different size ranges or that the dominant mechanism of penetration has size and time dependence--perhaps similar to that shown for the straight-through mechanism in Figure 5.

A mechanism of delayed particle penetration in addition to pinhole plugs seems required. This component of delayed particle penetration is defined here simply as that which depends on size--it is a fractionating form of delayed particle penetration, complementing the non-fractionating mechanism of pinhole plugs. The physical description of seepage, given by Leith [Ref. 11], might well cover this mode of particle penetration if seepage is viewed as a particle diffusion or permeation through the fabric--a size-dependent process rather than size-independent as presented by Leith.

Regardless of the physical processes, the data presented in Figure 3 reflect a size-dependent penetration. Figure 7 shows additional optical counter data taken with the flyash/woven polyester system, but after the dust feed had been stopped. These data were collected in the shake-cleaned baghouse, filtering flyash with woven polyester fabric filters (with same experimental conditions as in Figure 3a). For these specific data, the dust feed was stopped after a standard cycle and the succeeding cycles (labeled No. 6 and succeeding) were run the same as before except for no dust feed. The particle count presented in Figure 7 is that accumulated during the first minute of the filtration cycles given. Since no dust feed was used, the emitted dust must be delayed penetration of the dust particles previously fed (air flow through the bag continues but with ambient dust load only--total particle concentration estimated to be less than $10^6/ft^3$). The property of the delayed particles emitted that is emphasized here is the change in their size distribution with time. Large particles dominate the first dust-off cycle but immediately decrease in concentration as the smaller sizes increase. This behavior is similar to that observed during dust-on filtration (Figure 3). The significant difference here is that the Figure 7 data are for the delayed component of particle penetration.

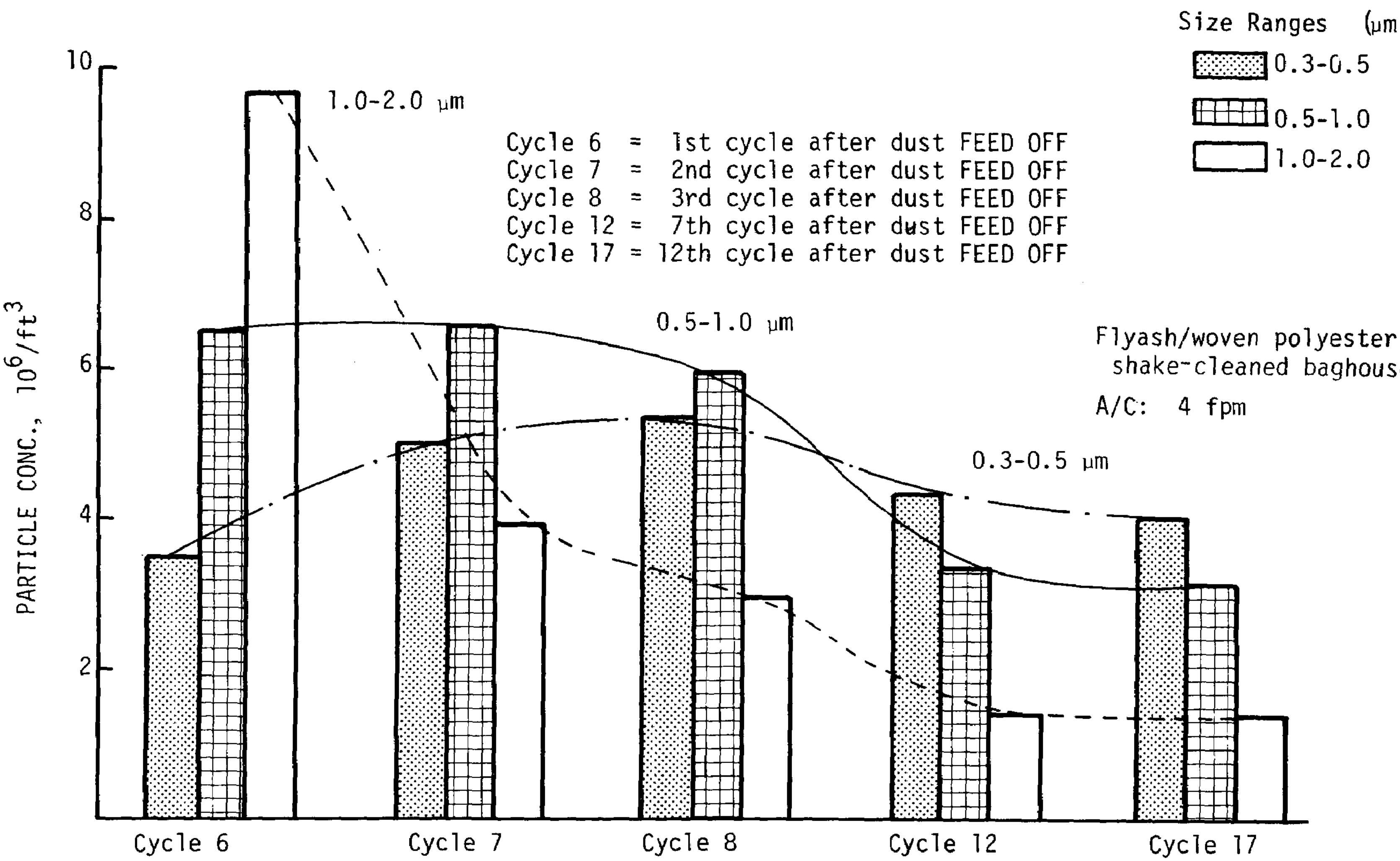

Figure 7. Size distribution of particles in the first minute of various cycles following the termination of dust feed [Ref. 4].

The classification of penetrating particles that is consistent with these experimental observations is therefore slightly altered from Leith's:

1) Prompt penetration (same as Leith's straight-through).
2) Delayed penetration.
   a) With same size distribution as the inlet dust (same as Leith's pinhole plugs).
   b) With size distribtuion differing from the inlet (modified from Leith's description of seepage; similar to Dennis' rear-face slough-off [Ref. 12]).

Further support of the dust cake model of filtration comes from fabrics constructed so as to minimize the role and presence of dust cake. Such a fabric is the Gore Tex/Nomex laminate [Ref. 3] which consists of a fine fibrillated film of PTFE (polytetrafluoroethylene) supported by a Nomex backing. Figure 8 shows a cross section of Gore Tex/Nomex at 215X. The wispy web-like network on the left is the PTFE film. The much coarser Nomex fibers are on the right and dominate the bulk of the fabric. In a sense the PTFE film simulates a dust cake but is a controlled, permanently affixed film that remains in place throughout the filtering and cleaning cycles--unlike the conventional dust cake which must be continually rebuilt. Flyash does not adhere to the PTFE surface very well; consequently, very little conventional dust cake builds up. Particle penetration during the filtration cycle is quite different under these conditions than under those previously described. Figure 9 is a plot of flyash penetration through shake-cleaned Gore Tex/Nomex fabric. Very little lessening of penetration is evident at A/C = 4 fpm. Penetration actually increases with time for A/C = 9. At both air-to-cloth ratios the size distribution of the outlet particles remains constant with time--unlike the behavior depicted in Figure 3 for a shake-cleaned woven fabric. These observations are consistent with sieving as the primary mechanism of filtration, increased penetration, and peaks at A/C = 9 being due to pressure-induced stretching and pulsing.

A comparison of the penetration curves shown in Figures 3 and 9 illustrates the importance of particle size distribution with respect to the properties of the fabric filter. The dust used to gather the data

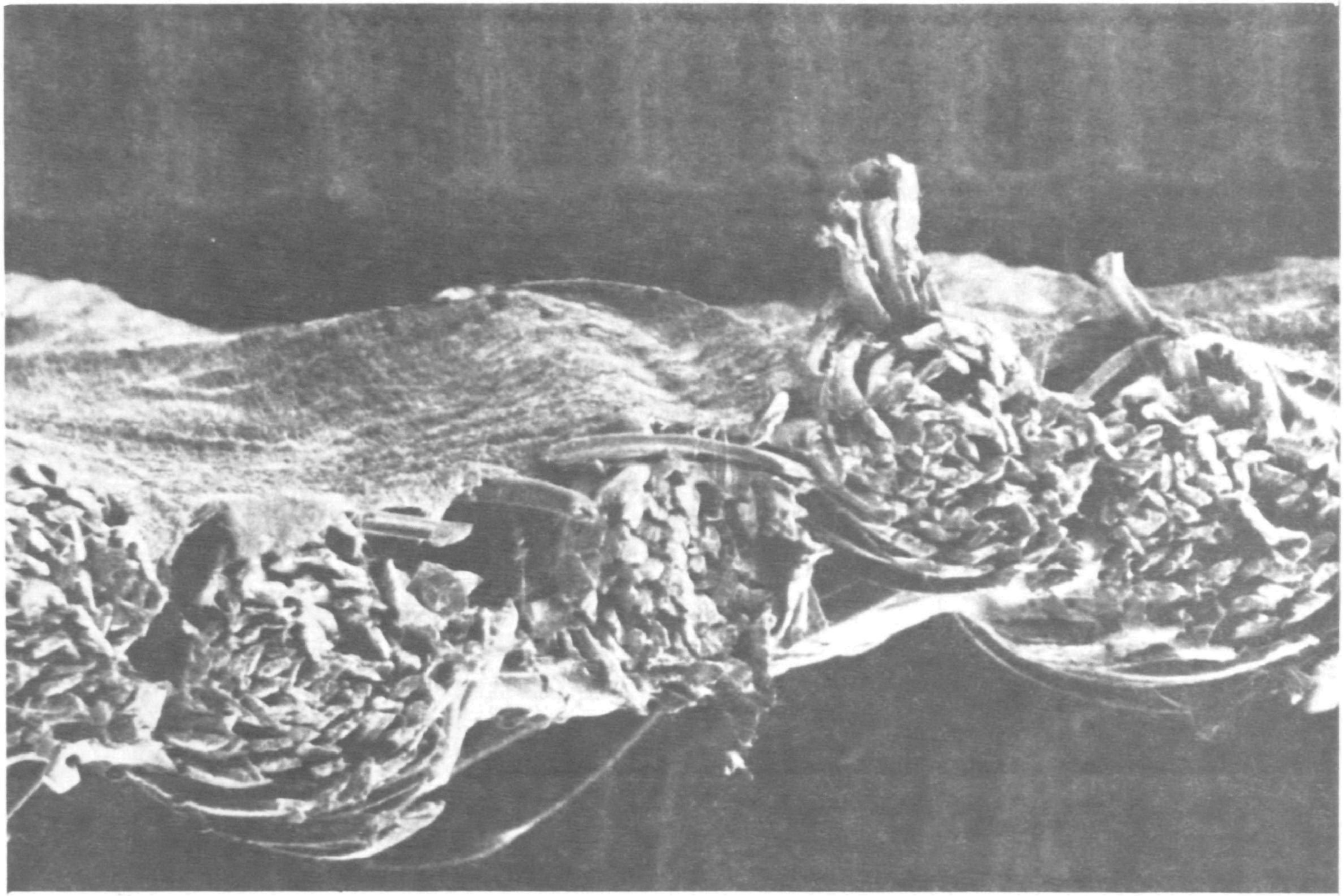

Figure 8. Cross section of Gore Tex/Nomex fabric (215X) [Ref. 3].

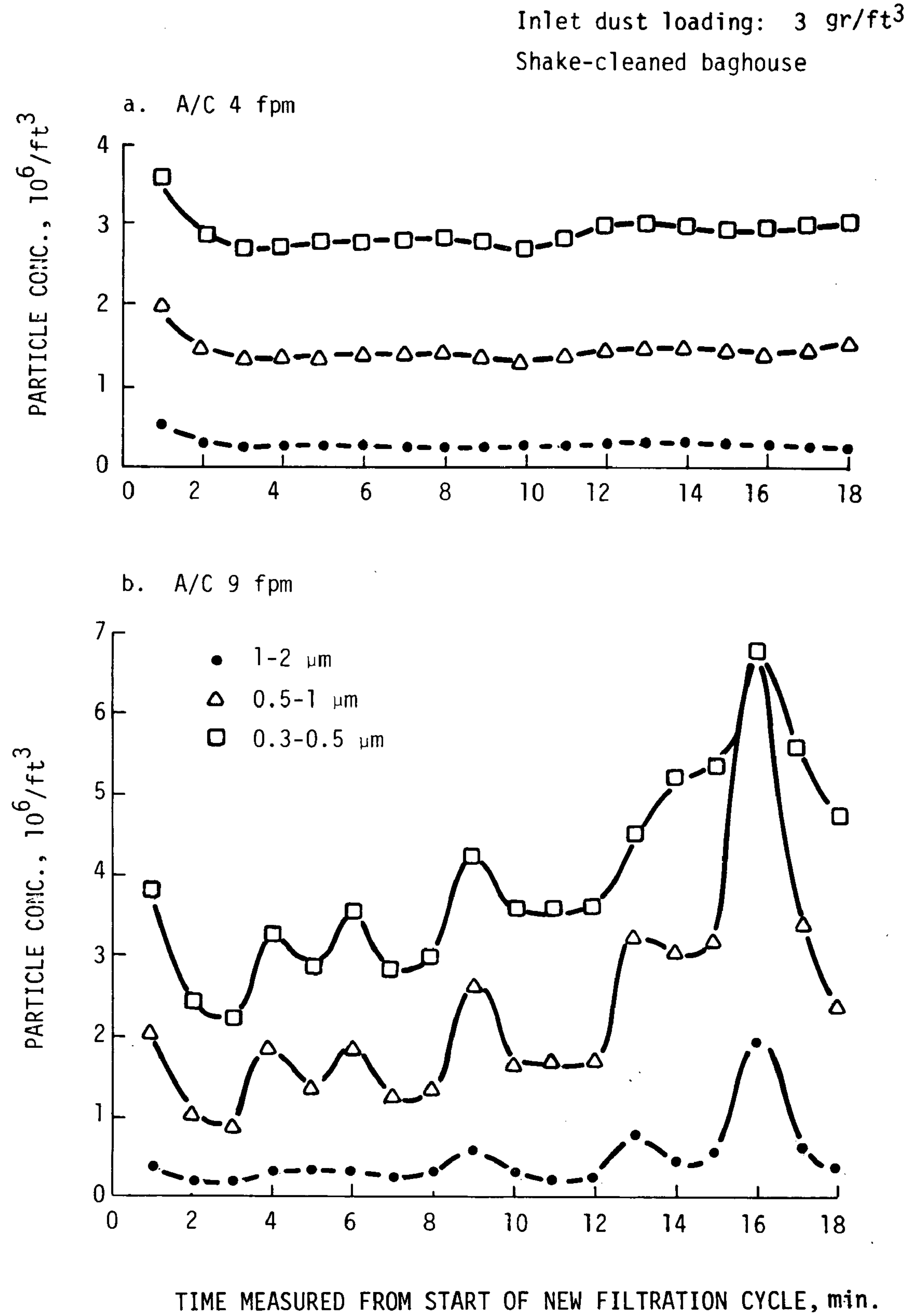

Figure 9. Time dependence of flyash particles penetrating Gore Tex/Nomex bags [Ref. 3].

for both figures was the same and presumably had the same size distribution. The method of fabric cleaning was the same. The mass median diameter of the dust was small compared to the pores of the woven polyester (Figure 3) but large with respect to the openings of the Gore Tex/Nomex (Figure 8). The difference in the time dependence of particle penetration for these two dust/fabric systems is dramatic.

An additional key difference is the stability of the size distribution with time that characterizes the outlet dust penetrating the Gore Tex/Nomex (Figure 9). This observation indicates that the concentration ratios of the three particle size ranges are relatively constant throughout the filtration period, including many periods when pulses of particles are emitted. This time behavior is quite different from that displayed by the optical counter data illustrated in Figure 3 and is an essential part of the evidence used to distinguish between the dust cake filtration reflected in Figure 3 and the sieving (or perhaps pinhole plug) penetration reflected in Figure 9.

These optical counter data cover only a small mass portion of the complete size spectrum of the inlet dust. They do not, therefore, allow size distribution comparisons between inlet and outlet dusts. They do, however, allow comparisons between different outlet dusts. For example, comparisons of Figures 3 and 9 show that the Gore Tex/Nomex fabric allows more penetration of the small particles once a quasi-steady state is reached (time measured from start of filtration cycle > 10 min). This observation does not necessarily mean that the polyester fabrics are better filters for fine particulates.

When the fine particulate penetration is averaged over the entire filtration cycle, the polyesters, including the spunbonded, may not be better, for fine particles, for this particular flyash source. The data in Figures 3 and 9 do show that the fine particle penetration behavior is quite different for polyester fabrics and Gore Tex/Nomex and that changes in the dust properties, such as size distribution, might well affect one system differently than the other. Size distribution directly affects penetration by sieving. It influences dust cake filtration both directly and indirectly. The indirect dependence is through the dependence of the growth of the dust cake and its properties on the size distribution of the dust (among other variables).

Recognizing the dependence of dust cake growth on the particle size distribution of the dust alerts one to the dangers of studying respirable particle behavior by using a dust source, such as flyash, in which the respirable particles are in the minority by mass (though not by number). Dust cake growth depends on the full spectrum of particle sizes in any dust. Without the large particles, different dust cake structure and growth rates result but, in dust cake filtration, the dust cake captures the small particles. Concluding that polyester fabrics would be more effective in filtering small particles could be misleading because, from Figures 3 and 9, the steady state small particles concentrations in the outlet are less than for the polyester fabrics. If the dust source were a classified flyash, containing nothing but 2 μm particles or smaller, fine particulate penetration through the polyester fabrics could increase much more than it would through the Gore Tex/Nomex because the reduced dust cake growth on the polyester fabrics could adversely affect their ability to collect fine particulates. Gore Tex/Nomex fabric, on the other hand, does not depend on dust cake growth for filtration efficiency and would therefore be unaffected.

4.2 EFFECTS OF OTHER DUST PROPERTIES

4.2.1 Polyester Felt Fabric

Changing dusts but keeping the fabric the same can also influence particle penetration. Compare the differences in flyash penetration through polyester felt with those of rock dust through the same fabric (Figure 6). Both dust sources have approximately log-normal size distributions: the D_{50} of the rock dust is about 2.25 μm and that of flyash, about 4.0 μm (see Figures 1 and 2). Much more fine (0.3 - 0.5 μm) flyash penetrates the polyester felt fabric than rock dust, even though Coulter counter and Andersen impactor analyses show that the concentration of this size particle in the inlet is much higher for the rock dust than the flyash (see Figures 1 and 2).

The rate of dust cake buildup is much more rapid for the rock dust/polyester felt system than for the flyash/polyester felt system, thereby reestablishing high efficiency filtration more rapidly following a cleaning pulse. This behavior is consistent: specific cake resistance, K_2', is significantly higher for the rock dust/polyester felt system. Obviously from Figure 6, the concentration of penetrating particles lessens more rapidly following cleaning when filtering rock dust than flyash. More rapid buildup of the dust cake would be expected to produce higher pressure drops; indeed, the rock dust/polyester felt system exhibits much higher pressure drops and drags than the flyash/polyester felt system (Table 1).

That the dust types interact differently with the polyester felt can also be seen by noting the humidity dependence of the outlet concentration and the collection efficiency. With flyash, the highest outlet concentration occurs at the lowest humidity for all inlet grain loadings. As relative humidity increases from 50 to 70 percent, however, the results are mixed--down for one of the grain loadings, up for the other two.

The dependence of collection efficiency on relative humidity listed in Table 1 for the flyash/polyester felt system is consistent with that found by Durham and Harrington [Ref. 15] who reported that various shake-cleaned flyash/woven fabric systems showed dramatic increases in collection efficiency as the relative humidity increased from 20 to 60 percent. Other dust/woven fabric systems investigated by Durham and Harrington did not show this sensitivity to relative humidity: Durham and Harrington interpreted this observation to be evidence illustrating the importance of dust properties.

Pressure drops generally increase with humidity, but not always. It's a mixed picture here, too, as it was in the work reported by Durham and Harrington [Ref. 15].

For rock dust filtration, humidity dependencies are much clearer. Outlet concentration always decreases with increasing humidity and so do the pressure drops. The rock dust/polyester system is better in two

Table 1. PULSE-JET FILTRATION USING 16 OZ/YD^2 POLYESTER FELT FABRIC

(9 bags; total cloth area, 41.94 ft^2; A/C, 6 fpm; total flow, 250 cfm)

Inlet Loading gr/ft^3	Relative Humidity %	Outlet Concentration gr/ft^3	Efficiency %	Penetration %	Bag ΔP In. H_2O	Slope K_2'	Effective Drag	Residual Drag	Run Time hrs.	Sample Time min.
a) Flyash (90 psi pulse, 60 sec interval)										
4.07	25	1.0443	99.9744	0.0256	0.71	3.3853	0.1067	0.1183	8.0	45
3.92	50	0.7975	99.9797	0.0203	1.00	3.5186	0.1550	0.1667	7.3	45
4.16	70	0.8364	99.9799	0.0201	1.11	3.0782	0.1742	0.1850	8.2	45
7.05	25	1.6106	99.9772	0.0228	1.03	2.5155	0.1559	0.1709	8.3	45
6.91	50	1.0445	99.9849	0.0151	1.39	2.8499	0.2150	0.2317	8.3	45
7.05	70	1.8314	99.9741	0.0259	1.38	2.5155	0.2142	0.2292	7.8	45
12.10	25	2.6107	99.9785	0.0215	1.68	2.4428	0.2550	0.2800	7.5	45
12.04	50	2.0418	99.9830	0.0170	1.81	2.6190	0.2750	0.3017	7.8	45
12.22	70	1.5508	99.9874	0.0126	1.61	1.9345	0.2484	0.2684	9.4	45
b) Rock Dust (90 psi pulse, 45 sec interval)										
4.15	20	3.8263	99.9078	0.0922	7.39	24.3825	1.1675	1.2317	7.3	30
3.81	50	2.4970	99.9345	0.0655	4.90	30.3497	0.7433	0.8167	8.4	30
3.99	70	1.7109	99.9572	0.0428	3.80	21.7069	0.5775	0.6325	8.0	30
6.91	20	4.7966	99.9307	0.0693	9.34	20.1393	1.4683	1.5567	7.0	30
6.97	50	1.7534	99.9749	0.0251	6.41	26.3637	0.9517	1.0684	6.5	30
7.04	70	0.9144	99.9871	0.0129	5.38	25.5725	0.7817	0.8958	7.5	45
11.94	20	6.3747	99.9466	0.0534	11.13	19.6949	1.7050	1.8542	7.5	30
11.91	50	1.4651	99.9877	0.0123	8.38	22.0510	1.2300	1.3967	7.7	30
11.85	70	0.7481	99.9937	0.0063	6.97	21.5009	0.9984	1.1617	7.8	60

ways at higher humidity: collection efficiencies are higher, and pressure drops across the bag (and the associated drags) are lower. Note, however, that the absolute values of the pressure drops and drags are still much higher than those of the flyash/polyester felt system, regardless of humidity effects.

With rock dust, the lowest outlet concentration occurs at the combination of the highest inlet grain loading and the highest relative humidity. Significantly less dust penetrates the bag under these conditions than when the inlet grain loading is, say a third as much at the same relative humidity. Lowering the humidity at constant inlet grain loading increases particle penetration even more.

This behavior is plausible if the effect of humidity is to enhance particle agglomeration of the rock dust (perhaps through Kelvin condensation), before the filter and at the filter surface. Agglomeration would cause the dust cake to consist more of discrete clumps or clusters of deposits around which the air streamlines pass. This clustering pattern is one which minimizes increases in air resistance per unit of dust collected--hence the observed low pressure drops at high relative humidity.

Because of their small size (with respect to the fiber dimensions) and non-aerodynamic shape, the growing clumps become even more efficient sites for removal of dust and dust agglomerates by impaction than the initial fibers of the fabric--hence the observed high collection eficiencies at high relative humidity.

If the effect of high relative humidity is to enhance particle agglomeration and if this property depends only on the dust, then the data in Table 1 suggest that the properties of rock dust (because of the observed greater sensitivity of their filtration parameters to relative humidity) are more humidity dependent than those of flyash. That the primary interaction of relative humidity is through particle agglomeration is not proven however. Data presented in Ref. 15 show that the effect of relative humidity varies considerably from fabric to fabric when filtering flyash. Those observations, plus those presented in Section 4.2.2, show that knowing only the dust type is not sufficient information for predicting the effects of relative humidity on filtration performance. Humidity dependence during fabric filtration varies with the dust/fabric system rather than either the dust or the fabric alone. Any mechanism purporting to explain the humidity interaction must depend on the properties of the dust/fabric system.

4.2.2 Nomex Fabric

A second pair of dust/fabric systems was used to explore these effects--a rock dust/Nomex system and a flyash/Nomex system. Nomex is a commercial nylon fabric used in baghouses; it ranks at or near the top of varous published triboelectric series classifying fabrics according to electrostatic behavior [Ref. 16].

Measurements similar to those listed in Table 1 are reported in Table 2 for the Nomex systems. As with the polyester felt, the dependence of the flyash outlet concentration (C_0) on relative humidity is mixed: the highest humidity always corresponds to the lowest C_0, but the highest C_0 occurs at 50 percent relative humidity, the mid-range value of humidity. Pressure drops at any given inlet loading are lowest when the humidity is highest, but the intermediate humidities have mixed C_0 with respect to the lowest humidities.

The rock dust/Nomex data show an even stronger lowering effect of high relative humidity on outlet concentration than observed with the rock dust/polyester felt system.

The difference in C_0 between 50 and 70 percent relative humidity is at least 1 order of magnitude at the highest inlet loading. The C_0 decreases by over 2 orders of magnitude as the relative humidity increases from 50 to 70 percent. The lowest values of C_0 observed in these series (Tables 1 and 2) were measured at 70 percent relative humidity in the rock dust/Nomex system, regardless of inlet loading. Again, somewhat unexpectedly, the C_0 decreased as the inlet grain loading increased. For the rock dust/Nomex system at fixed inlet loading, however, the pressure drops increased with increasing relative humidity (unlike for the rock dust/polyester felt system). The ranges of pressure drops observed with the rock dust/Nomex system are not dramatically higher than those of the flyash/Nomex system.

TABLE 2. PULSE-JET FILTRATION USING 16 OZ/YD^2 NOMEX

(9 bags; total cloth area, 41.94 ft^3; A/C, 6 fpm; total flow, 250 cfm)

Inlet Loading gr/ft^3	Relative Humidity %	Outlet Concentration gr/ft^3	Efficiency %	Penetration %	Bag ΔP In. H_2O	Slope K_2'	Effective Drag	Residual Drag	Run Time hrs.	Sample Time min.
a) Flyash (90 psi pulse, 60 sec interval)										
4.18	25	0.4676	99.9888	0.0112	1.21	4.0046	0.1867	0.2009	8.4	30
3.83	50	1.3482	99.9648	0.0352	1.77	5.1482	0.2950	0.2950	7.7	30
3.98	70	0.5845	99.9853	0.0147	1.46	3.9589	0.2300	0.2433	8.5	30
6.91	25	0.9469	99.9864	0.0136	2.18	5.2723	0.3325	0.3634	8.0	30
6.97	50	1.0911	99.9844	0.0156	2.34	5.3669	0.3600	0.3917	6.8	30
7.16	70	0.5105	99.9929	0.0071	1.65	2.8893	0.2575	0.2750	8.1	30
12.34	25	1.0498	99.9915	0.0085	5.25	5.5060	0.8192	0.8767	7.5	30
12.22	50	1.0832	99.9912	0.0088	3.04	4.6750	0.4575	0.5059	6.0	30
12.22	70	0.4286	99.9965	0.0034	2.12	3.2241	0.3200	0.3533	6.7	30
b) Rock Dust (90 psi pulse, 60 sec interval[a])										
3.76	20	11.2023	99.7025	0.2975	1.92	21.7154	0.2509	0.3200	5.0	30
3.78	50	2.9887	99.9210	0.0790	2.18	27.7707	0.2967	0.3633	6.0	30
3.93	70	0.2156	99.9946	0.0054	3.23	22.7992	0.4625	0.5383	6.7	45
6.70	20	9.1372	99.8636	0.1364	3.44	22.0636	0.4484	0.5734	3.0	30
6.73	50	4.6173	99.9315	0.0685	3.23	19.1631	0.4292	0.5383	6.5	30
6.97	70	0.0805	99.9989	0.0011	6.02	17.7955	0.8983	1.0033	7.0	45
12.82	20	6.5532	99.9493	0.0507	5.33	15.8288	0.7158	0.8875	3.7	30
11.76	50	3.2029	99.9526	0.0474	5.50	17.7607	0.7400	0.9167	5.5	30
11.67	70	0.0130	99.9999	0.0001	8.72	19.5351	1.2667	1.4525	7.0	45

[a] Except the 3.78 inlet loading data (row 2) for which the pulse interval was 45 secs.

Specific cake resistance during the filtering of rock dust continues to be much higher than when filtering flyash.

4.2.3 Summary

Table 3 summarizes trends for the two dusts and the two fabrics. The key dust-related effect is probably the difference in humidity dependence reflected in the C_0 trends of flyash and rock dust in both systems. The C_0 of rock dust decreases with increasing relative humidity regardless of the fabric, while flyash C_0 does not. That this trend occurs in both fabric systems suggests that it could be a dust effect. That it is so much more pronounced in the rock dust/polyester felt system shows that it also depends on the dust/fabric system rather than on the dust alone.

Mixed dust/fabric dependencies--those that depend on both the dust and the fabric--dominate Table 3. They can be identified by a conflicting trend when switching either fabric or filter. For example, with felted polyester, flyash C_0 increases with increasing inlet concentrations, but rock dust C_0 decreases. With Nomex fabric, both C_0's decrease with increasing inlet loading.

Alternatively the mixed dependence could be a conflicting trend that occurs for the one dust and the two fabrics but not for the other dust and the same two fabrics. An example of this mixed dependence is humidity-dependence of pressure drop. Using rock dust, the trends differ for the Nomex fabric and the polyester felt; using flyash as the dust, the trends are similar. Leith et al. [Ref. 14] speculate that the stronger particle-to-particle and particle-to-fiber bonds brought about by higher relative humidity could cause pressure drop to either decrease or increase with increasing relative humidity, depending on whether the increased particle-to-fiber bond strength dominates (and causes higher areal dust cake loadings and higher pressure drops) or the particle-to-particle bond strength dominates (and causes a more porous dust cake structure and reduced pressure drops).

The trends in K_2' reflect only small changes and do not justify any general qualitative conclusions, especially in view of the effective nature of the slope measurements that constitute K_2'.

Table 3. SUMMARY OF TRENDS IN THE PULSE-JET FILTRATION OF FLYASH AND ROCK DUST

With Respect to Increasing:	Polyester Felt (from Table 1) C_o	ΔP	K_2'	Nomex (from Table 2) C_o	ΔP	K_2'
FLYASH:						
Inlet Loading (constant humidity,	↑ [a]	↑	↓	↓ [a]	↑	→ [b]
Humidity (constant inlet loading)	↘ ↗ [a]	↗ ↘ [a]	↗ ↘	↗ ↘	↗ ↘ [a]	↗ ↘ [a]
ROCK DUST:						
Inlet Loading (constant humidity)	↓ [a]	↑	↓ [a]	↓ [a]	↑	→ [b]
Humidity (constant inlet loading)	↓	↓	↗ ↘	↓ ↓	↑ [a]	→ [b]

[a] Mixed results; majority trend shown (see Tables 1 and 2).

[b] Mixed results; no majority trend.

SECTION 5

RELATIONSHIP TO EXISTING FABRIC FILTRATION LITERATURE

5.1 FRACTIONATING EFFECTS DURING FILTRATION

As discussed in Section 1, fabric filtration literature seems to contain conflicting conclusions regarding the fractionating effects of fabric filtration. Data presented here are evidence that fabric filtration can be either fractionating or non-fractionating, depending on the dominant mechanism of particle penetration. Knowing whether fractionation occurs or not is very useful in understanding the physics of particle penetration. For example, if the size distribution of the outlet dust is identical to that of the inlet, the straight-through processes of particle penetration are not dominant, but rather some non-fractionating mechanism such as pinhole plugs [Ref.11].

Because of the experimental decisions made early in the work and their consequent limitations, as discussed in Section 3, few direct measurements of the size distribution of the outlet dust were made. Indirect evidence (the size distribution of dust in the collection hopper during specific experiments and the size distribution of the feed dust sampled over long periods of time) was presented to support the conclusion that both fractionating and non-fractionating filtration exists. Data in the literature also support this position. For example, non-fractionating filtration has been analyzed by Leith et al. [Ref.11]. As mentioned in Section 4, Leith et al. assign non-fractionating properties to their two delayed components of particle penetration (seepage and pinhole plugs). Leith's dissertation [Ref.17] documents the many experimental measurements and analyses supporting the non-fractionating property of his filtration work.

Also from contemporary literature, however, are the data plotted in Figure 10. These curves show the size distribution of the inlet flyash to a fibrous glass filter (the dashed curve) and the outlet dust from that dust filter after the inlet gas was switched to unloaded ambient air. The dust in the outlet under these latter conditions is presumably primarily delayed dust penetrating the fabric--Dennis calls it rear-face slough-off [Ref.12]. Since the data in Figure 10 clearly show this dust to be of a different size distribution than the inlet flyash, it cannot be penetrating by the seepage/pinhole plug mechanisms of Leith et al. An alternative explanation is that seepage and pinhole plugs may fractionate by size after all.

Highly significant in this experimental work is the air-to-cloth ratio at which the filtration is carried out. In all of Leith's work for pulse-jet filters [Refs.11, 17] the A/C is 10 fpm or higher. His analysis predicts pinhole plug penetration to increase with velocity. Dennis' data in Figure 10 for woven cloth filters cleaned by hand-shaking is based on filtration at about 2 fpm, a more common operating value in field installations.

The implied correlation between face velocity and penetration mechanism appears in the Gore Tex/Nomex data of Figure 9. At the higher A/C (Figure 9b) one can almost see the pinhole plugs bursting through the fabric and producing the pulses of particles reflected in the data. Little evidence exists for such bursts at the lower A/C of 4 fpm (Figure 9a).

Optical counter analysis of the outlet dusts penetrating through the Gore Tex/Nomex fabric is inconclusive. The results given in Reference 3 show a small dependence of size distribution on air-to-cloth ratio: the smallest particles (0.3 - 0.5 μm) fall from 66 percent of the total number measured at A/C = 4 fpm to 57 percent at A/C = 10 fpm. Similar small A/C dependencies of the size distribution of outlet dusts were found by McKenna et al. [Ref.7] in their filtration of coal-fired boiler flyash with Gore Tex/Nomex. McKenna's analysis of the outlet dust showed classical fractionation effects--particle penetration increased as particle size decreased below 10 μm, on down to about 0.5 μm. Below 0.5 μm, particle penetration decreased sharply.

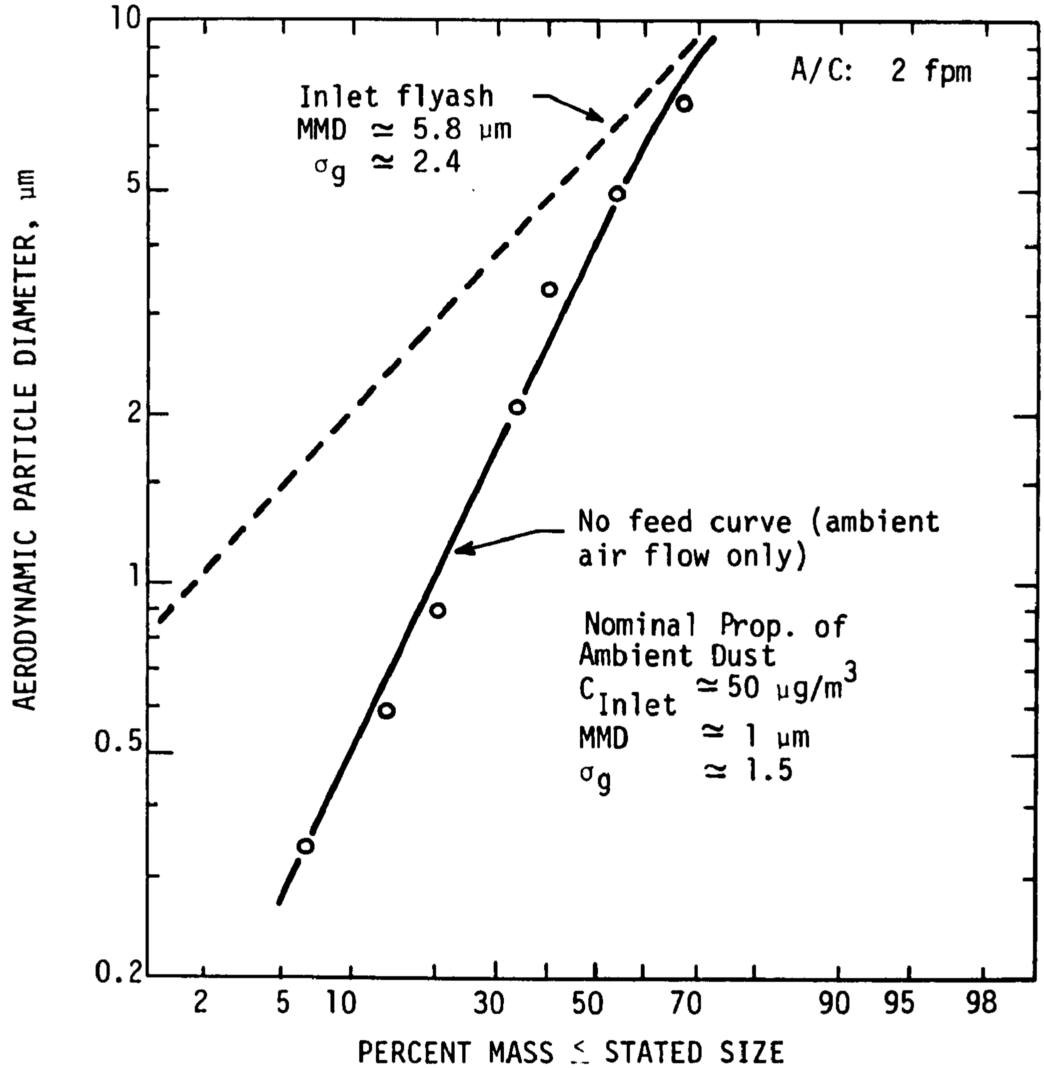

Figure 10. Comparison of the size distribution of the delayed component of particle penetration (solid curve) with that of the previously fed inlet flyash [Ref. 12].

The conclusion is not firm: fractionating effects during fabric filtration occur sometimes, but not always. Evidence from the literature supports the view that the different, seemingly conflicting conclusions regarding fractionation during filtration could well be consistent, being simply different extremes of a complex interaction. Air-to-cloth ratio is an important variable in determining the dominant penetration mechanism.

5.2 THE ROLE OF DUST PROPERTIES IN FABRIC FILTRATION

Some of the dependencies reported in Sections 4.1 and 4.2 are neither unique nor original. Figure 11, reproduced from Dennis et al. [Ref.12], shows the influence of size distribution on the filtration performance of woven glass bags. The two granite dusts differ only in size distribution. The other curves also reflect performance differences, possibly due in part to differences in size distribution but perhaps also due in part to other dust property differences, since the flyashes are from different sources. Regardless of the interpretation of the exact mechanism, these data are included to demonstrate the importance of dust properties in typical or simulated field installations.

The importance of dust properties, particularly with respect to humidity effects, has been recognized and documented previously [Refs.5, 18]. For many dusts, but not all, higher relative humidity has been shown to produce higher collection efficiency at lower pressure drop--like the data shown in Table 2 for the rock dust/Nomex system. Such humidity dependence, while not fully understood, is commonplace and reproducible and would seem to possess the potential for providing more competitive fabric filtration.

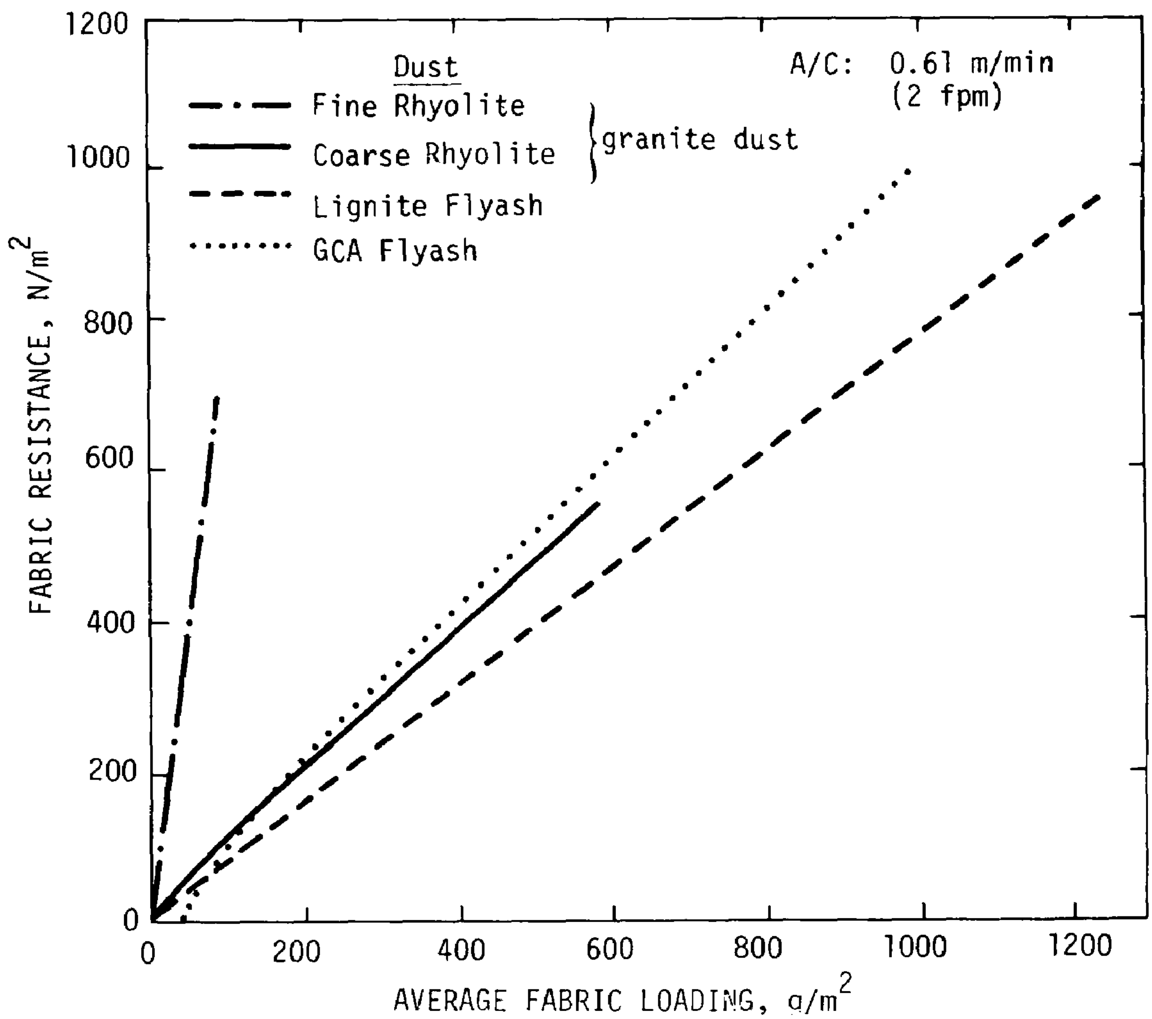

Figure 11. Dependence of pressure drop buildup across woven glass fabric on dust properties (from Dennis [Ref.12]).

SECTION 6

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16. ABSTRACT The report examines the importance of dust properties in determining dust penetration through a fabric filter. The major property considered is the size distribution of the dust, which is an important dust property for dust penetration. Most other important variables of dust penetration depend more on the dust/fabric combination than on the dust alone. The report reviews dust penetration mechanisms and relates them to dust and dust/fabric properties. It illustrates these interactions, using data both generated in EPA's inhouse laboratory and published in the open literature. Shaker and pulse-jet baghouse data are used in an attempt to identify commonality in dust penetration independent of fabric cleaning technique.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Cleaning	Air Pollution Control	13B	13H
Filtration		Stationary Sources	07D	
Fabrics		Fabric Filtration	11E	
Dust		Particulate	11G	
Penetration		Baghouses		
Properties		Shake Cleaning		
Particle Size Distribution		Pulse-jet Cleaning		

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