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The Filtration of Ragweed Pollen Using Glass Fibrous Media

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INTRODUCTION

With the increased focus on air cleanliness and environmental control, the need for more detailed data on particle removal systems is apparent. Specifically, information concerning the filtration of special particulates, such as pollens, is lacking. A contribution in this area of study would also be helpful in certain medical researches conducted in the field of allergenics. Ragweed pollen, one of the most common pollen grains, was selected as the filterable material as it is very nearly round, uniform in particle size, and readily available. The filter media was commercially available glass fiber mats because this is the most common material used in this field. Previous investigations over the past 35 years have been conducted by Hughes, Drinker, Silvermann, and Annis, but the pertinent efficiency and pressure drop data are considered very meager (*1–4*). However, adequate test equipment development has been one of the significant results of these studies and some of these have been incorporated in the present work. The hazardous nature of using pollens as test materials has undoubtedly discouraged investigations of this type.

In contrast to the paucity of studies on pollen, there is an abundance of investigative work available on aerosols or small particle filtration. These studies are primarily concerned with fibrous media with the theoretical

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analysis being based almost exclusively on the "single fiber theory." Significant contributors to the literature have been Langmuir, Blodgett, Davies, Ranz, Thomas, and Lapple (*5–9*). All of this work concerns itself primarily with particles that will "stick" to the fibers, and their results fit the theoretical considerations very well. The particle bounce or blow-off phenomena is that exhibited by ragweed pollen when filtered through glass fibrous media. This mechanism has been previously considered but not in the detail required to describe a suitable mechanism (*10*). It is one of the purposes of this work to develop a modified single fiber theory that would be applicable to ragweed pollen filtration.

The variables studied were efficiency as a function of fiber density/unit area using fiber size air velocity across the filter as parameters. Gravitational, electrostatic, and thermal effects were justifiably neglected. Selected glass fiber mats, mildly resin impregnated for mechanical stability and high temperature baked to minimize surface effects, served as the media. A specific variety of giant ragweed (*Ambrosia Elatior*), whose diameter was 20 μ, was the pollen selected.

This investigation determines the filtration characteristics of giant ragweed pollen using glass fibrous media. A broad range of filter densities (0.02 to 0.40 lb/ft^2), fiber size (1.4 to 113 μ), and air velocities (450 to 1800 ft/min) were employed. A straight-through filter circuit was used where a minimum Reynolds number of 5000 was maintained to insure proper mixing of the pollen in the air stream. In addition, in order to avoid excessive pressure drop in the system, the maximum experimental air velocity was fixed at 2000 ft/min. These restrictions, in addition to fan characteristic limitations, required an air system whose duct size was 6 in.

THEORETICAL DEVELOPMENT

Filtering a particulate, such as pollen, through a glass fibrous media involves a mechanism considerably different from that of a sieving action or conventional cake theory encountered in solid–liquid filtration. In a physical sense the filter consists of a mat of heterogeneously sized fibers in which the interstices are bonded or loose and subject to localized fiber density variation. The fiber mat is relatively open and, in the case of the roughing filters studied in this investigation, the relative volume occupied by the fibers is 1.5% or less. The particle must follow a tortuous path through the mat and the particle filtration characteristics are determined by the variable combinations of fiber density, particle inertial effects, and

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air flow patterns around the fibers. In the case of liquid droplets (or with adhesive coated fibers and solid particles) the particle has very little ability to rebound, and its initial contact with the fiber usually results in complete adherence. The theoretical treatment of this phenomena is known as the classical "single fiber efficiency theory" (*5*, *11*). However, in the case where particles bounce off the fiber surface one or more times before being intercepted, this concept cannot be applied as such; pollen over glass fibers is in this class of exceptions.

The possible mechanisms that have been developed are inertial, interception, and diffusion (*12*). Since the particles are relatively large and would not necessarily follow velocity streamlines around a hypothetical isolated fiber or cylinder, the mechanism that applies in this case is "inertial." Several investigations in working with particles and filter media in the same size range have verified this situation (*6*, *7*, *9*, *13*). A schematic diagram of this is shown in Fig. 1. Equations have been developed by Langmuir, Blodgett, and Davies which describe an overall filtration efficiency in terms of a single fiber efficiency and the various parameters.

Referring to Fig. 1, the single fiber efficiency η_i will be defined equal to $2y/2r_f$ or, in terms of flow, η_i is the ratio of air volume filtered to the air volume passing an area equivalent to that of the planar fiber projection. This also states that all particles in a layer $2y$ thick, well upstream of an isolated fiber of radius r_f, will be removed. This definition and mechanism assumes no particle bounce or deflection along a streamline. By using

$$v_0 = \frac{Q}{(1-\alpha)A} \text{ ft/sec} \qquad \text{and} \qquad X = \frac{\alpha V}{\pi r_f^2} \text{ ft} \tag{1}$$

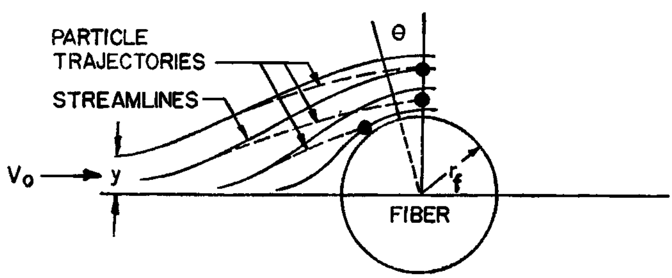

FIG. 1. Particle trajectories across a single fiber of a fibrous media for the filtration mechanism of inertial impaction.

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where v_0 = average velocity through the filter and X = total fiber length of the filter, a differential mass balance across the filter shows that

$$CQ - (C + dC)Q = C2yv_0\left(\frac{\alpha}{\pi r_f^2}\right) dV \qquad (2)$$

This simplifies to:

$$-Q\, dC = C(2yv_0)\left(\frac{\alpha}{\pi r_f^2}\right) dV \qquad (3)$$

By rearrangement and substitution

$$\frac{-dC}{C} = \frac{2y\,\alpha\, dL}{(1 - \alpha)\pi r_f^2} \qquad (4)$$

By investigation and insertion of proper limits, it can readily be shown that

$$\frac{C}{C_0} = \exp\left[\frac{4\alpha L\eta_i}{\pi(1 - \alpha)d_f}\right] \qquad (5)$$

By definition $P = C/C_0$ or $E = 1 - C/C_0$. Thus

$$P = 1 - E = \exp\left[\frac{4\alpha L\eta_i}{\pi(1 - \alpha)d_f}\right] \qquad (6)$$

This is the equation usually given for analyzing filtration data where inertial impaction is predominant.

Equation (6) can be further simplified as α is small, and $\alpha/(1 - \alpha)$ is approximately equal to α. An identity for α which may be used is

$$\alpha = W/\rho_f L \qquad (7)$$

After appropriate substitutions, one finds that

$$E = 1 - \exp\left(\frac{4W\eta_i}{\pi\rho_f d_f}\right) \qquad (8)$$

The fiber mat thickness has been eliminated as a variable. This is important since the actual fiber thickness would normally have to be measured dynamically or estimated from filter mat compression data.

The group $4W/\pi\rho_f d_f$ may be defined as S_f, a measure of mat solidarity (*13*). Equation (8) then becomes simply

$$E = 1 - e^{-S_f\eta_i} \qquad (9)$$

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It is seen that the mat efficiency, E, is a function of two dimensionless groups, one a measure of fiber properties and the other an arbitrary measure of single fiber efficiency which must include other factors such as film orientation and mat nonuniformities. Since S_f is readily measurable, it remains to correlate η_i to the specific parameters applicable to pollen filtration.

Lapple in his work with dye particle filtration successfully used dimensional analysis to describe single fiber efficiency when both particle diffusion and inertial impaction were the predominant mechanisms (*9*). Similarly, the same technique can be used to show that η_i, the single fiber efficiency, is a function of R, the ratio of the particle diameter to the fiber diameter, ψ, an inertial parameter, and the Reynolds number, or:

$$\eta_i = f(R, \psi, \text{Re}) \tag{10}$$

where

$$R = \frac{d_p}{d_f}; \qquad \psi = \frac{C\rho_p d_p{}^2 v_0}{18\mu d_f}; \qquad \text{Re} = \frac{d_f v_0 \rho}{\mu}$$

The inertial parameter ψ is frequently used in analytically or graphically describing filtration efficiency when single fiber filter theory is utilized. It is defined physically as representing the ratio of the force necessary to stop a particle traveling at a velocity v_0 in a distance $d_f/2$ to the fluid resistance acting on the particle moving according to Stoke's law with a relative velocity v_0 (*10*).

In order to solve Eq. (9) the relationship of the dimensionless group to η_i must be experimentally determined. The graphical and numerical solutions to the functional equation $\eta_i = f(R, \psi, \text{Re})$ for ragweed pollen filtration are given in this study. Pressure drop, although of considerable importance in a filtration study, is not analyzed in this investigation. The filter resistance was accurately measured and graphically represented as ΔP vs W, the fiber weight/unit area (*14*).

EXPERIMENTAL EQUIPMENT AND TEST PROCEDURES

Physical Properties of Filter Test Material

Ragweed Pollen

The pollen selected for the study was obtained from the Greer Drug and Chemical Co., the specific variety being short ragweed (*Ambrosia Elatior*). The particles were spherical within $\pm 2\%$ and very uniform in size. The average diameter, as measured optically, was determined as

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20.8 μ with a range of about ±2.4 μ. Small, sharp protrusions about 1 μ in height and 3 μ apart covered the surface. Details of the pollen shape configuration can be seen in Fig. 2. The density of the material was determined by a conventional pycnometer method using *n*-heptane which was found to be nonabsorbing. The average value obtained in this manner was 1.18 g/cc.

Glass Fiber Filters

The filter material, which was obtained from the Product Development Laboratory of the Owens Corning Fiberglas Corp., was especially selected

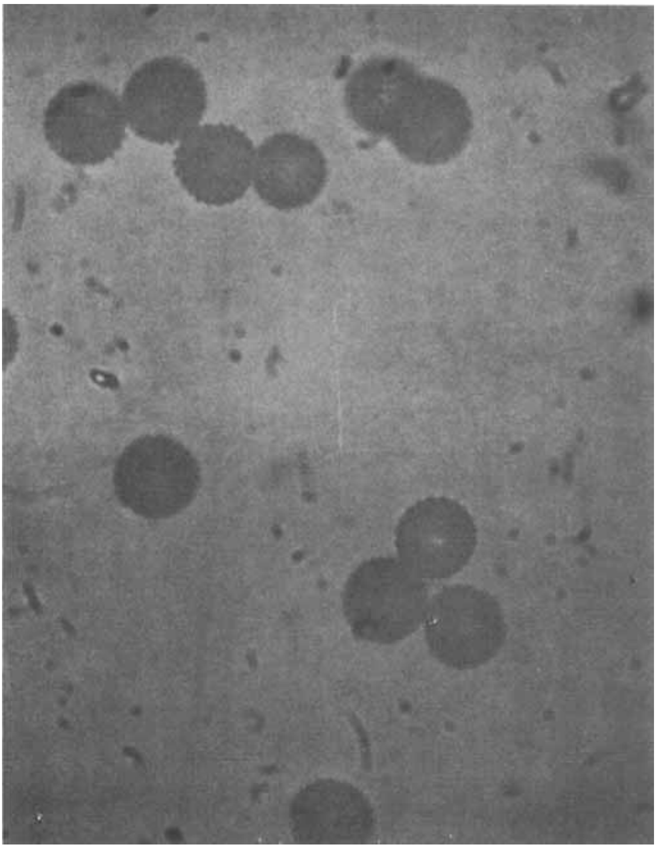

FIG. 2. Electron microscope photograph showing surface detail of ragweed pollen. 500×.

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for fiber size and orientation uniformity. All of the fiber mats were impregnated to some degree with a resinous binder with a very small amount of mineral oil being present on the fiber surface. In order to eliminate the effects of these extraneous materials on filtration efficiencies, the glass fibers were baked at 500°F for 15–30 min. Weight loss curves verified that the resin and the oil were satisfactorily removed. The fiber sizes of the mats ranged from 1.4 to 113 μ. The distribution of the fiber size for each material tested was fairly wide. The method for determining the sizes was optical and, with the exception of the smallest size, was done by measuring 400 fibers. The 1.0-μ size was determined by using an electron microscope and viewing 172 fibers. The properties of the fiber mats are presented in Tables 1 and 2. Electron microscopy revealed that the surface

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TABLE 1

Nominal Density and Thickness of Filter Materials Supplied by Fiberglas Corp.

Nominal filter size (μ)	Density (lb/ft^3)	Thickness (in.)
110	2.25	0.50
36	0.5	1.0
10	3.0	1.5–2.0
7	2.0	0.50
5	0.6	0.50
1	1.1	0.25

TABLE 2

Average Fiber Size and Distribution of the Fiber Materials

Filter size nominal (μ)	Average filter size actual (μ)	Distribution range (μ)
110	113.0	85 –210
36	36.3	12 – 58
10	10.77	2.5– 25
7[a]	6.98	1 – 17
5	5.20	0.5– 29
1[b]	1.40	0.1– 6.2
1[c]	1.17	—

[a] 1/2 in. thick sample.
[b] Electron microscope.
[c] Fiberglas porosity method.

variation of the fibers was 0.2 μ maximum while the cylindrical uniformity was exceptional, regardless of whether they contained resin or not.

A representative value of glass fiber density was obtained by liquid displacement using a Weld pyconometer. The higher resin containing fibers was found to have a density of 1.88 g/cc while the 10-μ low resin size was 2.04 g/cc.

It was concluded that the baked filter media would simulate raw fiber glass surface behavior. It was postulated that the very thin layer of resin present would not significantly affect the resilience of the glass fiber underneath. Furthermore, the pollen grain structure, being much softer than either the resin or the glass, would control the degree of particle rebound in a filtration process where inertial impaction is predominant.

The Test Filter Apparatus

The circuit chosen for filter testing was similar to that used by other investigators (*3*, ,*4* *15*). The primary differences are the use of a small circular duct instead of a larger square or rectangular one and the lengthened approach section to the filter. Capacity requirements necessitated the use of a smaller duct, and the longer pipe section aided in providing a higher degree of particle dispersibility. A sketch of the equipment is shown in Fig. 3.

The dispersing chamber consisted of a pollen mixing section 2 ft long with a perforated plate baffle arrangement at one end and another perforated plate at the other. This portion of the apparatus was followed by a straight run approach section 10 ft long, next the filter section, and finally 8 additional feet of straight pipe. All piping was 6 in. circular galvanized steel with a "tile clad" epoxy paint coating on the inside surface. An air flow measuring circuit using standard ASME orifice plates was incorporated further downstream, along with a 1800/3600 rpm high pressure (18 in. H_2O) 1000 cfm capacity blower (*16*).

The filter holder consisted of 12 in.^{2}, 1/2 in. and 3/4 in. thick "tile clad" epoxy painted plywood pieces with 6 or 8 in. round holes cut from the center. The filter retainers were standard 2 mesh galvanized screens. An exploded view of this portion of the test apparatus is shown in Fig. 4. An S-shaped 4 mm glass tube pollen generator similar to the one used by Annis (*4*) was utilized. In order to insure uniform pollen dispersion, the nozzle of the generator was placed and used in the same position at the point of injection.

In order to measure the filtration characteristics or efficiencies of pollen

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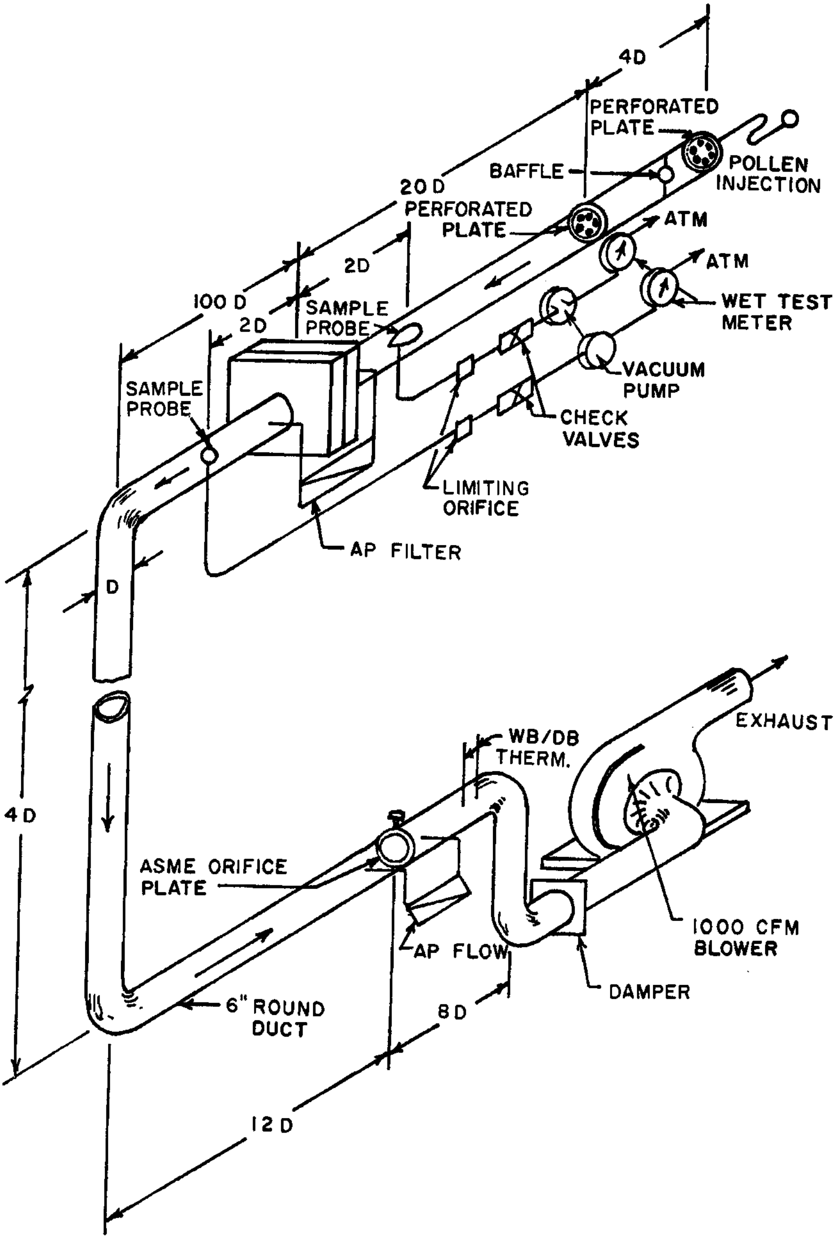

FIG. 3. Schematic diagram of filter apparatus.

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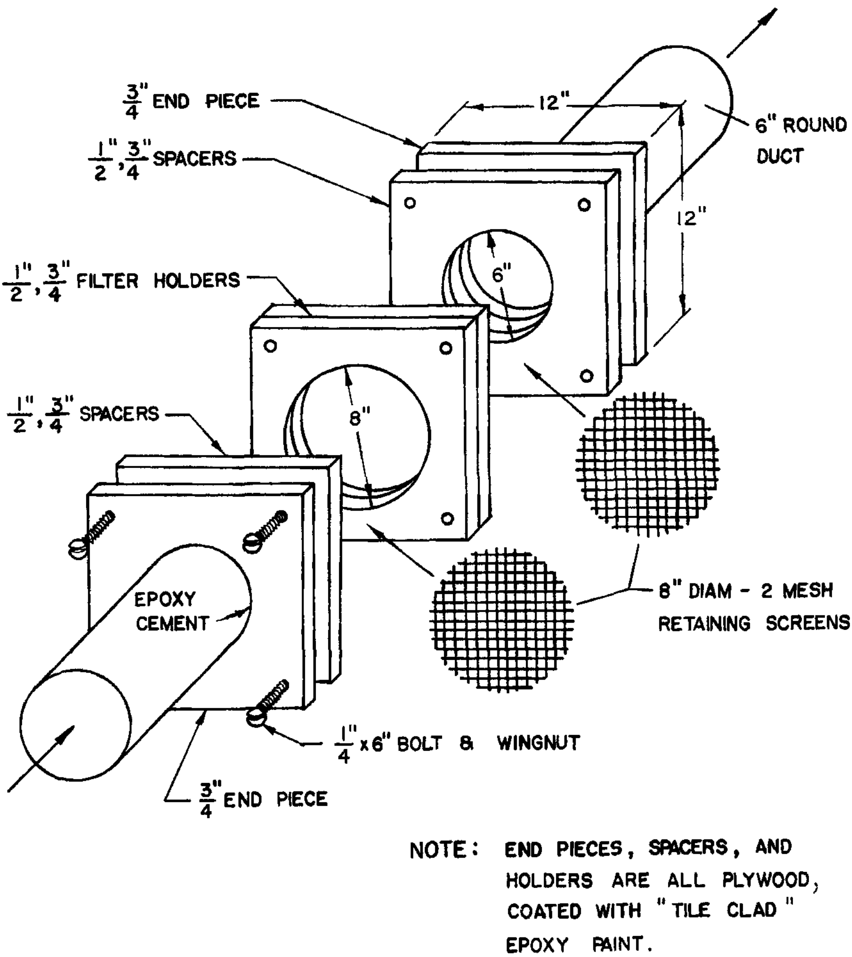

FIG. 4. Section view of filter holder arrangement.

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passing through glass fiber media, the instantaneous particle concentration must be available before and after the filter. This consists of collection or sampling probes, gas flow metering equipment, and a particle detector. In the case of this study, direct impaction was employed using probes very similar to that developed by Annis and Whitby (*4*, *15*). The pollen concentration measuring equipment consisted of special sampling probes, 0.1 ft^3/rev, wet test meters, limiting orifices, and 20 in. Hg capacity vacuum pumps. The pollen particles were collected by impaction on a Millipore 3.10 mm^2, black gridded membranes (0.80 ± 0.05 μ pore size) mounted in a modified 25 mm Swinnex filter holder. Although isokinetic sampling is recommended for this type of measuring equipment, it was found that these probes could be used with a high degree of precision at duct to probe air velocity ratios of as high as 15–20: 1 (*14*). The schematic diagram of the probes and the mounting arrangement can be found in Figs. 5 and 6.

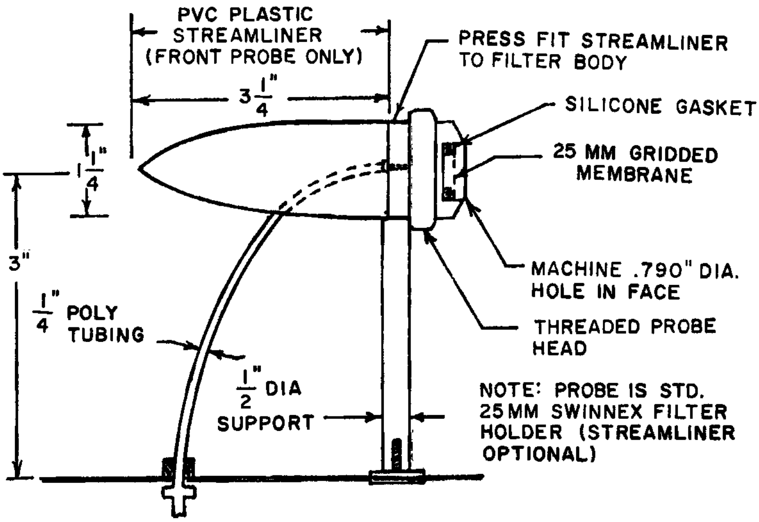

FIG. 5. Detail sketch of the experimental sampling probe.

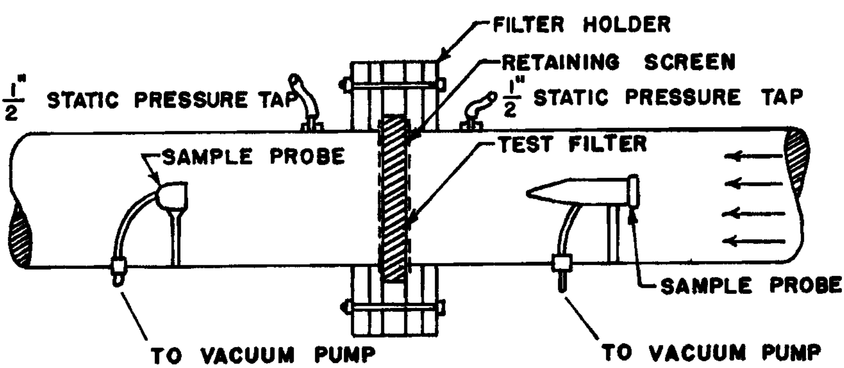

FIG. 6. Schematic diagram of sampling probe arrangement.

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The wide range of air stream velocities and the limited size of the equipment necessitated the development of this arrangement.

Test Procedure

A standard procedure was used for testing all filters. After securing the filter in place, the fan was turned on about 1 min prior to each run. The vacuum pumps were then switched on and allowed to run for 30 sec, at which time the pollen was injected for approximately 1 sec into the duct at the dispersion chamber entrance. The pumps were then allowed to run for an additional 170 sec which made a standard time cycle of 200 sec. The pollen load was varied from 0.1 to 1.0 mg depending on the concentration requirement. This procedure minimized air volume sampling errors and insured complete pollen pickup.

After the pollen was collected on the gridded membrane, the unit was removed from the filter circuit, placed in a plastic petrislide, and the particles counted optically using a low power binolcular microscope at 24 or 36 ×. A total count method was found to be the most acceptable, and consequently the one used in this investigation. Whenever possible the particle count was maintained in the range of 500–1500 as this was the level that gave the most reproducible results. Considerable effort was expended in determining the most applicable count method for this type of sample probe. It was concluded that total count measurement was the most precise method of determining relative pollen concentration for this type of study (*14*).

Each filter was precut to fit the 8-in. diameter wooden holder and weighed to 0.01 g. The filters were checked for mechanical disintegration by observations and weight loss after each test. The pressure drop across the filter was measured using appropriate water manometers, and is reported elsewhere (*14*).

Air flow was determined using standard orifice plates as recommended in the 1940 ASME Power Test Code (*16*). The temperature and humidity of the test room and filtered air stream were controlled by two 1½ ton window air conditioners and a 4000-W electric thermostatically controlled space heater. During the course of the test work the room air temperature was maintained at 74 ± 4°F at 40 to 60% relative humidity. The nominal filter sizes tested were 1, 5, 7, 10, 36, and 110 μ. Filter efficiencies were determined in most cases at three or more filter densities. Air flow was varied from 150–1800 ft/min. Each filter mat was tested two to four times to minimize error. The testing schedule is shown in Table 3.

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TABLE 3

Experimental Program for Testing Filter Media with Ragweed Pollen

Filter size (μ)	Fiber density level (lb/ft^2)	Airflow nominal (ft/min)	Remarks
1	0.02	300	Baked at 500°F
5	0.02, 0.04, 0.08, 0.10	150, 300, 1000, 1800	"
7	0.1, 0.2, 0.3	300	"
10	0.1, 0.2, 0.4	150, 300, 1000, 1800	"
36	0.05, 0.10, 0.15, 0.25	150, 300, 1000	"
110	0.1, 0.2, 0.4	150, 300, 1000	"
5	0.02, 0.05, 0.10	300	As received
36	0.04, 0.10, 0.12	300	"

FILTRATION CHARACTERISTICS OF GLASS FILTERS

Filtration experiments performed over a wide range of air velocities using various fiber size media yielded results that permitted penetration or efficiency to be correlated to the basic parameters studied. The majority of investigations was conducted using oil-free baked fibers while a few selected runs were made with "as received" material.

An exponential relationship of penetration vs fiber weight/unit area was found which was expected from theory but generally not given in the literature. Graphical representations are shown in Figs. 7–12, at various air velocities for each fiber size. In order to more clearly demonstrate fiber size as a variable, a cross plot of two of the graphs as penetration vs weight/unit area for all the sizes at one given velocity are shown. This is given in Figs. 13 and 14.

Recalling that $P = e^{-S_f \eta_i}$ and $S_f = 4W/\rho_f d_f$, plots of log P vs S_f at various air velocities reveal straight line relationships whose slope is equal to η_i, the single fiber efficiency.

A summary of η_i values for the various filter sizes, along with corresponding S_f, W, P, L, and α, is presented in Table 4. From these data the effect of fiber size d_f and air velocity v_0 on single fiber efficiency can be determined.

Inertial impaction theory predicts that the single fiber efficiency η_i approaches unity for the values of variables and parameters used in this investigation. However, calculations of η_i using actual experimental data show that the values range from approximately 0.01 to 0.10 or 1 to 10% of that predicted by theory. The low efficiencies are attributed to particle

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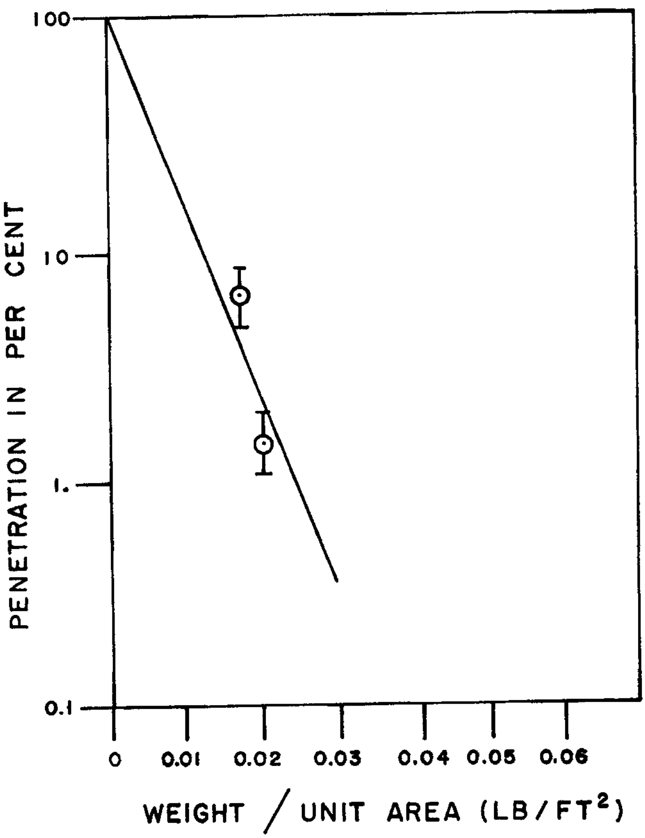

FIG. 7. Penetration vs weight/unit area at 300 ft/min air velocity for 1.40 μ filters.

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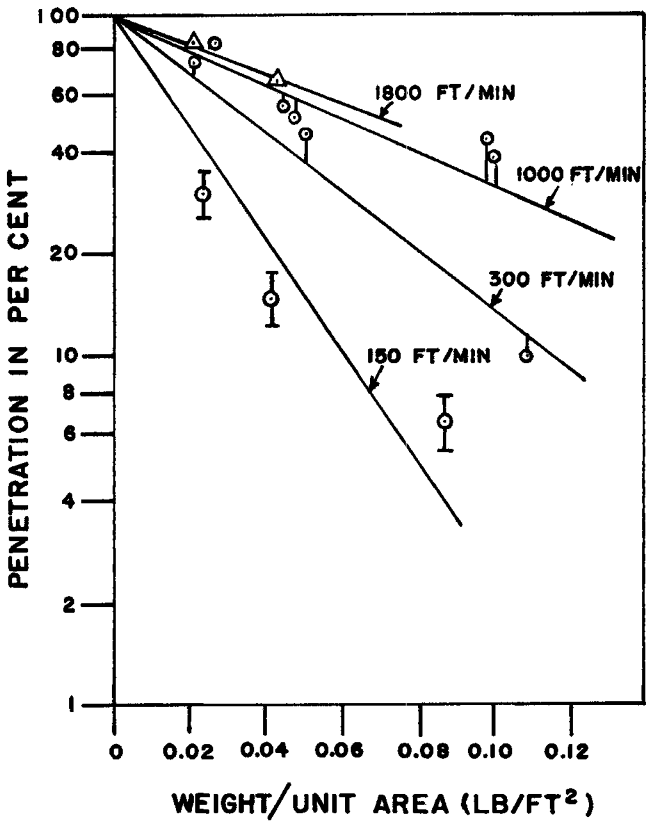

FIG. 8. Penetration vs weight/unit area at various air velocities for 5.20 μ filters.

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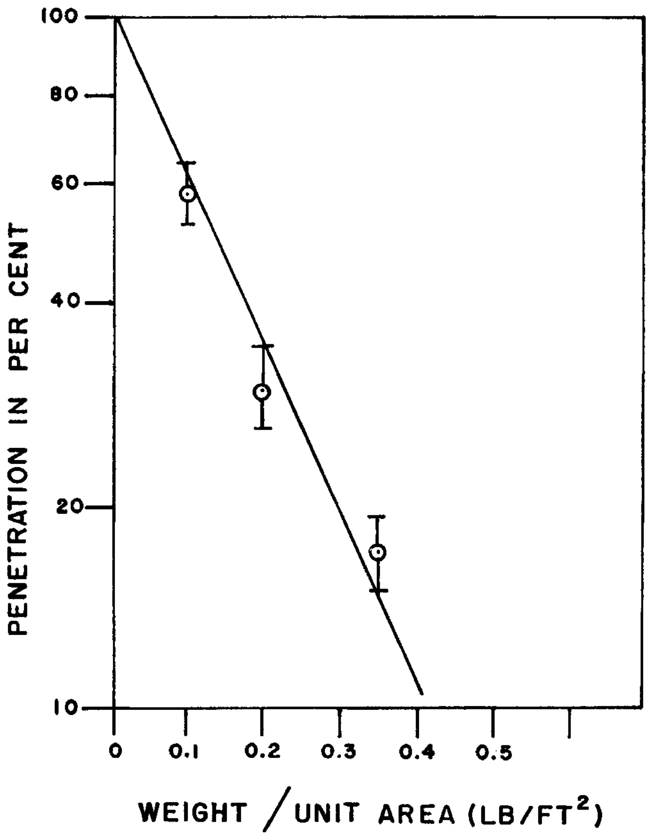

FIG. 9. Penetration vs weight/unit area at 300 ft/min air velocity for 6.98 μ filters.

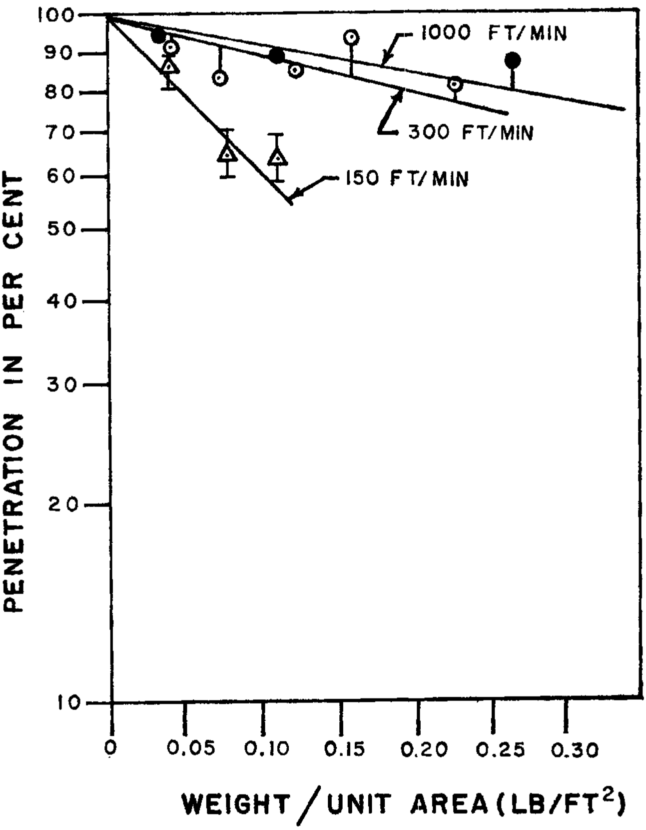

FIG. 10. Penetration vs weight/unit area at various air velocities for 10.77 μ filters.

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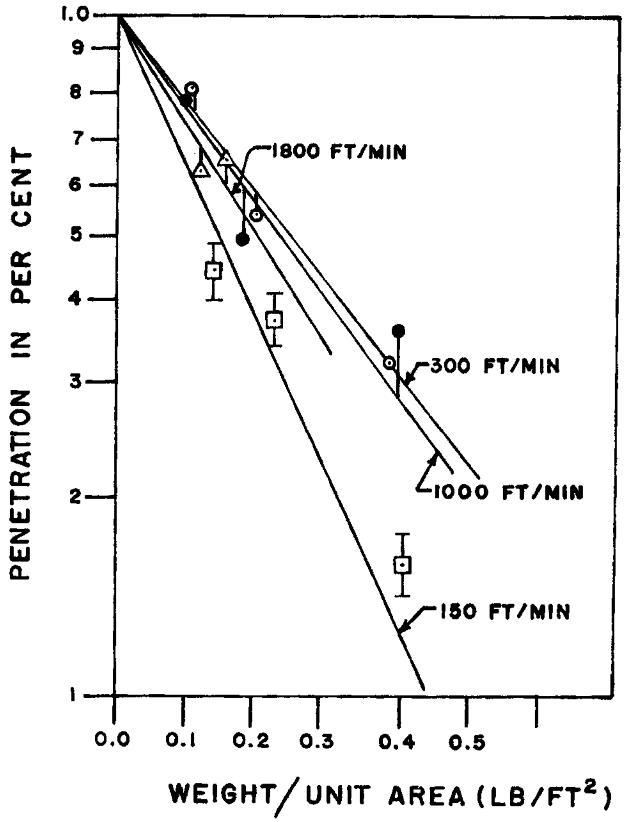

FIG. 11. Penetration vs weight/unit area at various air velocities for 36.3 μ filters.

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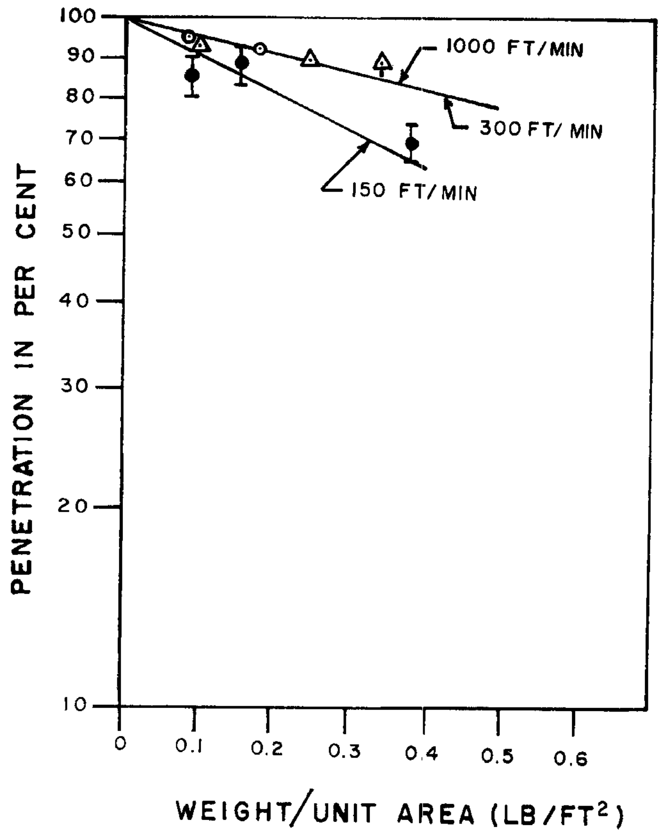

FIG. 12. Penetration vs weight/unit area at various air velocities for 113 μ filters.

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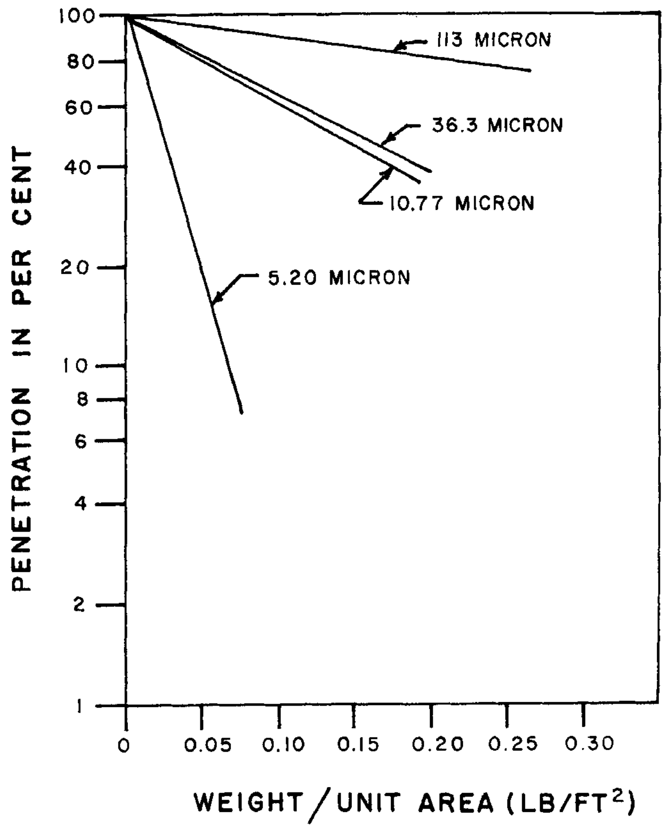

FIG. 13. Penetration vs weight/unit area for various filter fiber sizes at an air velocity of 150 ft/min.

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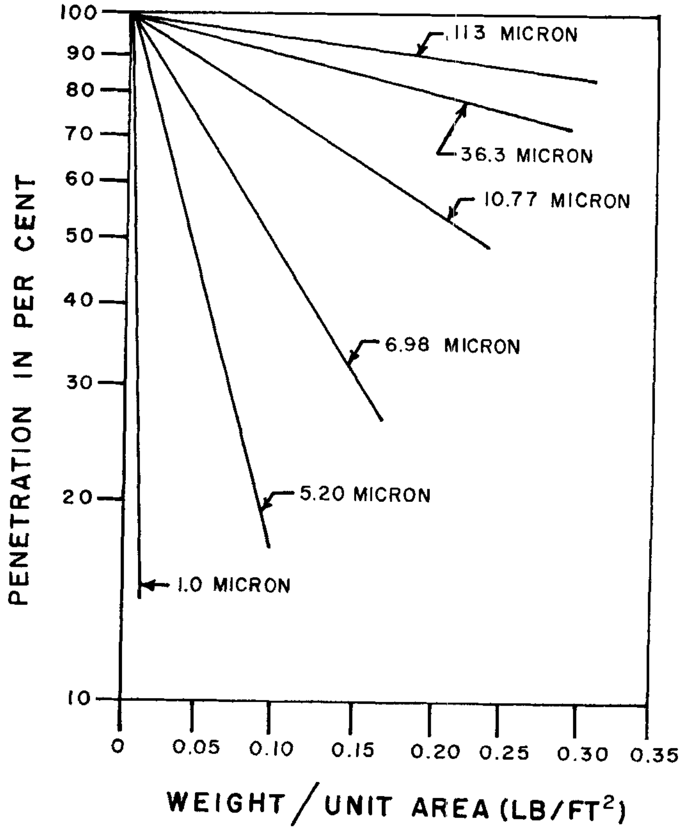

FIG. 14. Penetration vs weight/unit area for various filter fiber sizes at an air velocity of 300 ft/min.

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TABLE 4

Summary of Calculations for Filtration Data Showing Solidarity Factor, α, and Single Fiber Efficiency

Filter size (μ)	Penetration (1 − E)	W (lb/ft²)	Thickness (ft)	α	S_f	η_i	Av η_i (from graphs)
113	0.847	0.0785	0.0417	0.0161	2.30	0.0732	0.0411
	0.851	0.1560	0.0834	0.0160	4.58	0.0351	
	0.665	0.376	0.1668	0.0226	11.00	0.0372	
	0.923	0.0831	0.0417	0.0171	2.44	0.0330	0.01865
	0.883	0.238	0.0834	0.0244	6.96	0.0178	
	0.860	0.332	0.1668	0.0170	9.76	0.0151	
	0.938	0.0726	0.0417	0.0171	2.12	0.0305	0.01865
	0.874	0.1660	0.0834	0.0170	4.82	0.0286	
36.3	0.852	0.0385	0.0834	0.00396	3.53	0.0456	0.0494
	0.686	0.0716	0.1668	0.00367	6.60	0.0573	
	0.631	0.1112	0.2500	0.00381	10.20	0.0451	
	0.899	0.0436	0.0834	0.00448	4.01	0.0270	0.0134
	0.835	0.0762	0.1668	0.00392	7.01	0.0259	
	0.862	0.1204	0.2500	0.00412	10.10	0.0147	
	0.814	0.2240	0.1668	0.01156	20.20	0.0103	
	0.917	0.0403	0.0834	0.00414	3.71	0.00679	0.00896
	0.881	0.1125	0.2500	0.00384	10.37	0.01240	
	0.872	0.2607	0.1668	0.01340	24.00	0.00575	
10.77	0.435	0.132	0.0417	0.0250	37.4	0.0218	0.0176
	0.354	0.216	0.0834	0.0204	61.0	0.0172	
	0.484	0.402	0.1668	0.0190	113.2	0.0169	
	0.794	0.1021	0.0417	0.0193	28.8	0.00805	0.0103
	0.507	0.209	0.0834	0.0197	59.3	0.01142	
	0.322	0.390	0.1688	0.0184	110.0	0.0103	
	0.763	0.0920	0.0417	0.0174	26.2	0.0104	0.01087
	0.467	0.1953	0.0834	0.0184	55.6	0.0137	
	0.324	0.394	0.1668	0.0186	101.8	0.0111	
	0.627	0.1570	0.0834	0.0149	44.5	0.0105	0.0105
6.98	0.590	0.0915	0.0417	0.0188	43.1	0.0122	0.0118
	0.298	0.201	0.0834	0.0206	95.1	0.0127	
	0.174	0.341	0.1668	0.0175	161.5	0.0108	
5.20	0.316	0.0231	0.0417	0.00474	14.72	0.0783	0.0522
	0.1715	0.0444	0.0834	0.00454	28.2	0.0623	
	0.0743	0.0890	0.1668	0.00456	56.6	0.0458	
	0.755	0.0220	0.0417	0.00452	14.00	0.0202	0.0278
	0.449	0.0509	0.0834	0.00611	32.5	0.0246	
	0.1363	0.1090	0.1668	0.00560	69.5	0.0287	
	0.823	0.0258	0.0417	0.00528	16.5	0.01182	0.01565
	0.531	0.0466	0.0834	0.00478	29.8	0.0212	
	0.521	0.0476	0.0834	0.00489	30.5	0.0214	
	0.458	0.0705	0.1250	0.00482	44.8	0.0174	
	0.437	0.0995	0.1668	0.00510	63.4	0.0130	
	0.428	0.0995	0.1668	0.00510	63.4	0.0134	
	0.827	0.0215	0.0417	0.00440	13.70	0.0139	0.01375
	0.680	0.419	0.0834	0.00428	26.90	0.0144	
1.40	0.0454	0.0192	0.0208	0.00788	45.2	0.0685	0.0750
	0.0195	0.0217	0.0208	0.00892	51.1	0.0766	

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rebound, and it is apparent that an analysis based on direct particle trajectory interception of the fibers would be erroneous.

By replotting the data in terms of log η_i vs log d_f using v_0 as a parameter, it can be seen that a fiber efficiency minimum of $\eta_i = 0.008$ to 0.017 exists in the range of $d_p/d_f = 1$. This is graphically shown in Fig. 15. Two mechanisms apparently exist, one for filter fiber sizes greater than 20 μ and the other for sizes less than this value. Air velocity v_0, on the other hand, decreases the efficiency at an exponential rate as high particle blow-off is apparent. Figures 16 and 17 demonstrate this relationship.

A dimensional analysis of the problem as given in the theoretical section shows that

$$\eta_i = f(R, \psi, \mathrm{Re})$$

Furthermore, in the case of the larger fiber sizes where $d_p/d_f < 1$, it was concluded that R would not be a prime variable since the particles would not stick to the fiber readily. Far more important would be the inertial parameter ψ, where both the particle dynamics $d_p^2 v_0 \rho_p$ and the fiber size d_f

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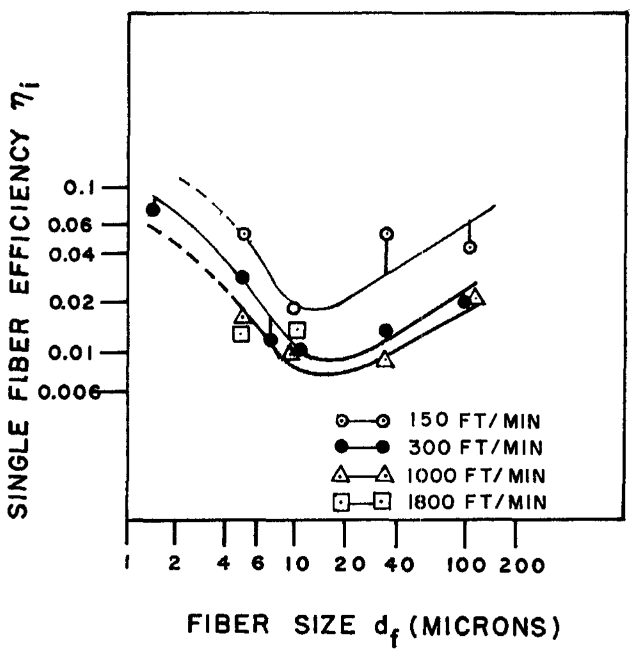

FIG. 15. Single fiber efficiency vs filter fiber size at various air velocities.

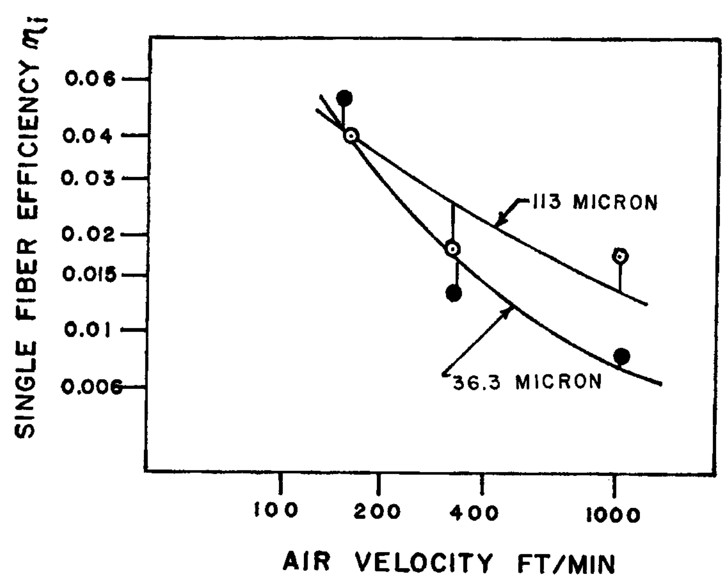

FIG. 16. Effect of air velocity on single fiber efficiency for 36.3 and 113 μ filter sizes.

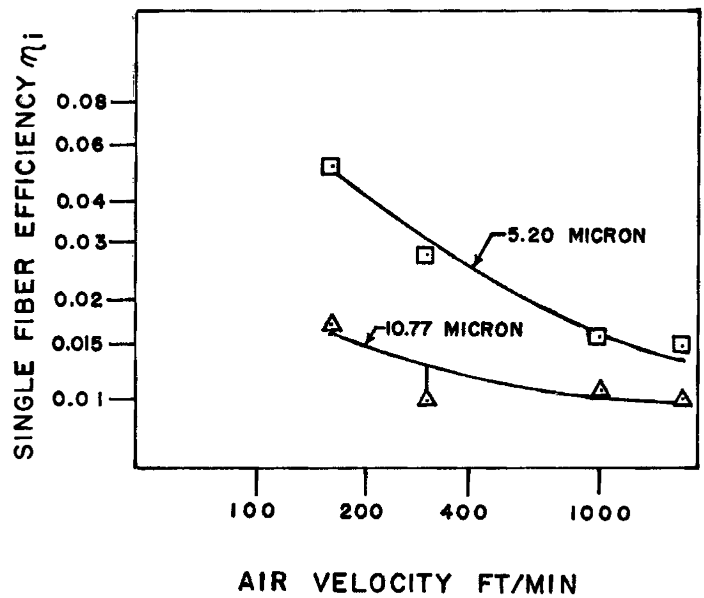

FIG. 17. Effect of air velocity on single fiber efficiency for 5.20 and 10.77 μ filter sizes.

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are incorporated. In addition, the Reynolds number should have an influence on the particle path, particularly in the distortion of streamline flow at high velocities. The relationship for η_i now reduces to $\eta_i = K\psi^a \mathrm{Re}^b$, where a, b, and K are constants that can be readily determined from a computer program based on a linear regression analysis of Eq. (10):

$$\log \eta_i = \log K + a \log \psi + b \log \mathrm{Re}$$

The resulting equation is $\eta_i = 0.15\psi^{-0.42}\mathrm{Re}^{-0.19}$. Using the experimental data, a plot of this correlation is shown in Fig. 18. The final equation for the 36 and 110 μ filters is then

$$\ln (1 - E) = \ln P = -0.15 S_f \psi^{-0.42} \mathrm{Re}^{-0.19}$$

Similarly, the data for the smaller filter sizes, 1 through 10 μ, were correlated with the dimensional groups R and ψ. It was concluded that

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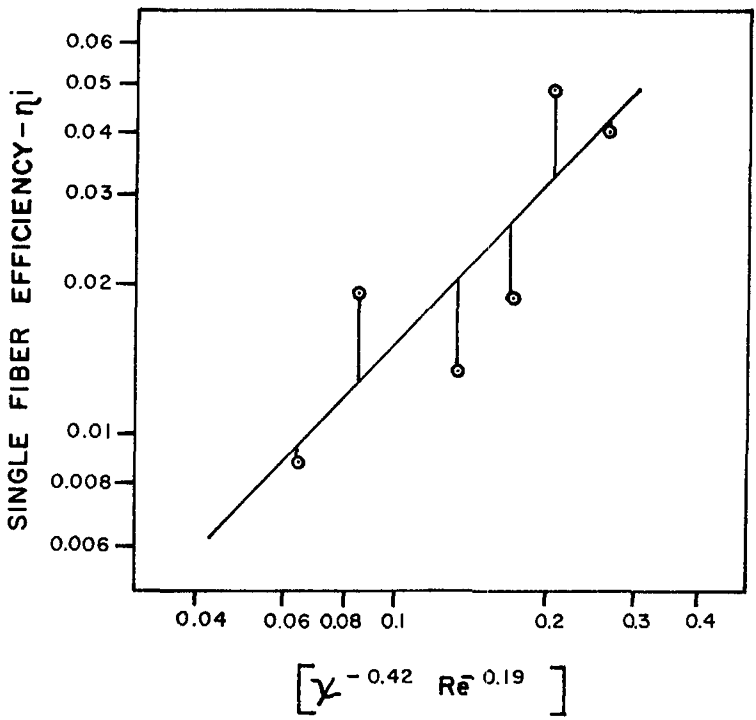

FIG. 18. Relationship of single fiber efficiency to the dimensionless groups Re and ψ $(d_p/d_f < 1.0)$.

the Reynolds number could be eliminated as it would have little or no effect on the particle striking the fiber since the d_p/d_f ratio was greater than 1.0. The resulting equation for filtration when $d_p/d_f > 1$ was found to be

$$\ln (1 - E) = \ln P = -0.035 S_f R^{1.15} \psi^{-0.30}$$

A plot of η_i vs $R^{1.15}\psi^{-0.30}$ using experimentally determined values is shown in Fig. 19.

A more convenient method of expressing the filtration efficiency relationships would be in terms of the more commonly used parameters W (lb/ft^2), d_f (μ), and v_0 (ft/min). By proper substitution and rearrangement the equations are

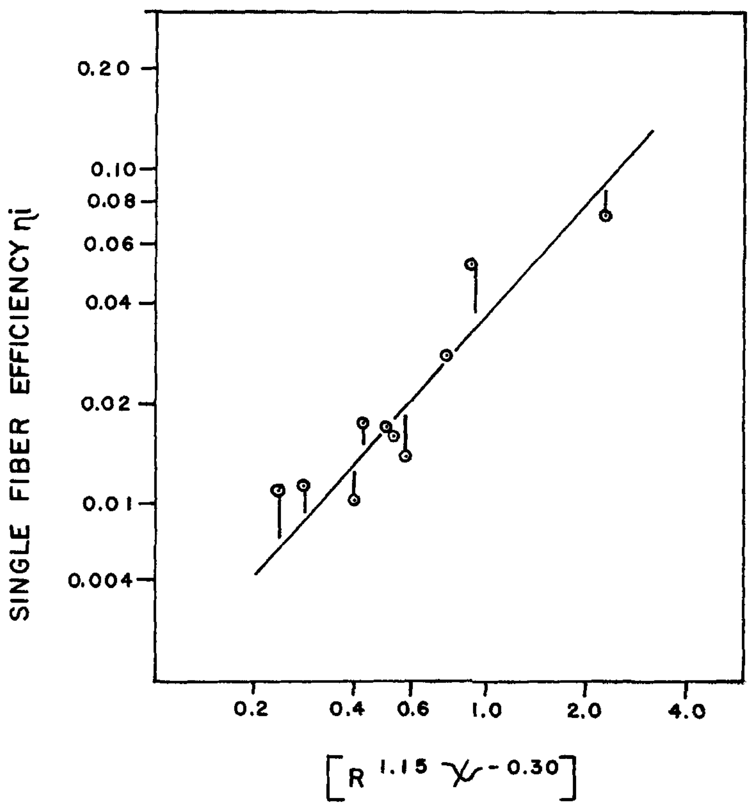

FIG. 19. Relationship of single fiber efficiency to the dimensionless groups R and ψ ($d_p/d_f > 1.0$).

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$$\ln(1 - E) = \ln P = -1215 W d_f^{-0.77} v_0^{-0.61}$$

for the 36 and 110 μ filters and

$$\ln(1 - E) = \ln P = -1875 W d_f^{-1.85} v_0^{-3.0}$$

for the 1 through 10 μ sizes. A graphical presentation of these equations is shown in Figs. 20 and 21 using a plot of overall efficiency vs the group $[W d_f^{a'} v_0^{b'}]$.

As previously stated, pollen filtration using fibrous media does not correlate completely with any existing accepted theory. The reasons for this are that pollen grains exhibit a certain amount of bounce or rebound and the theory applies to d_p/d_f ratios whose values are less than one

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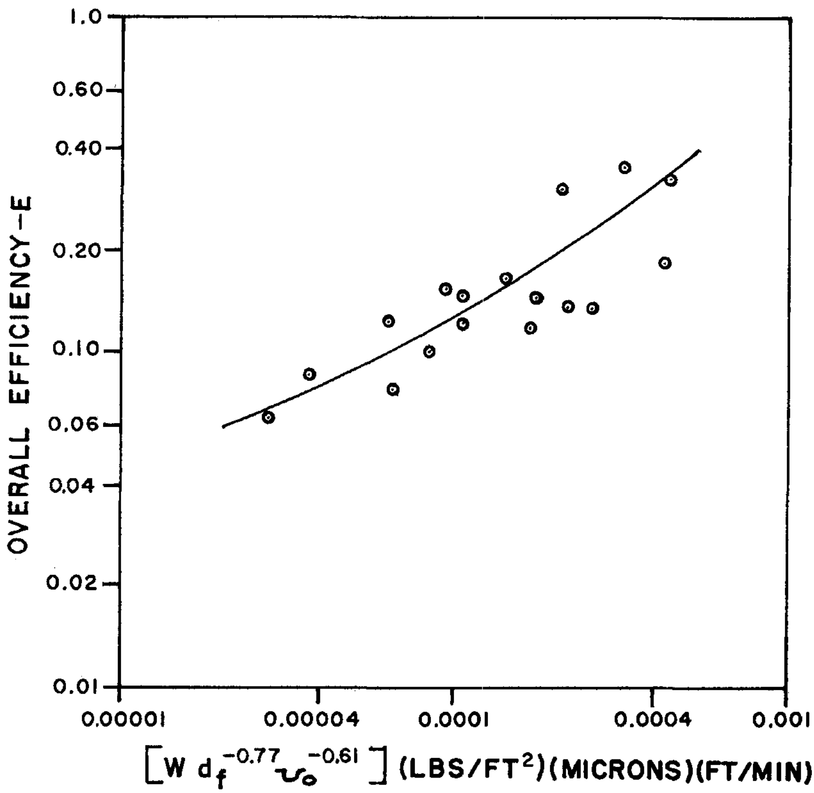

FIG. 20. Relationship of overall efficiency with correlation groups $W d_f^{a'} v_0^{b'}$ ($d_p/d_f < 1.0$).

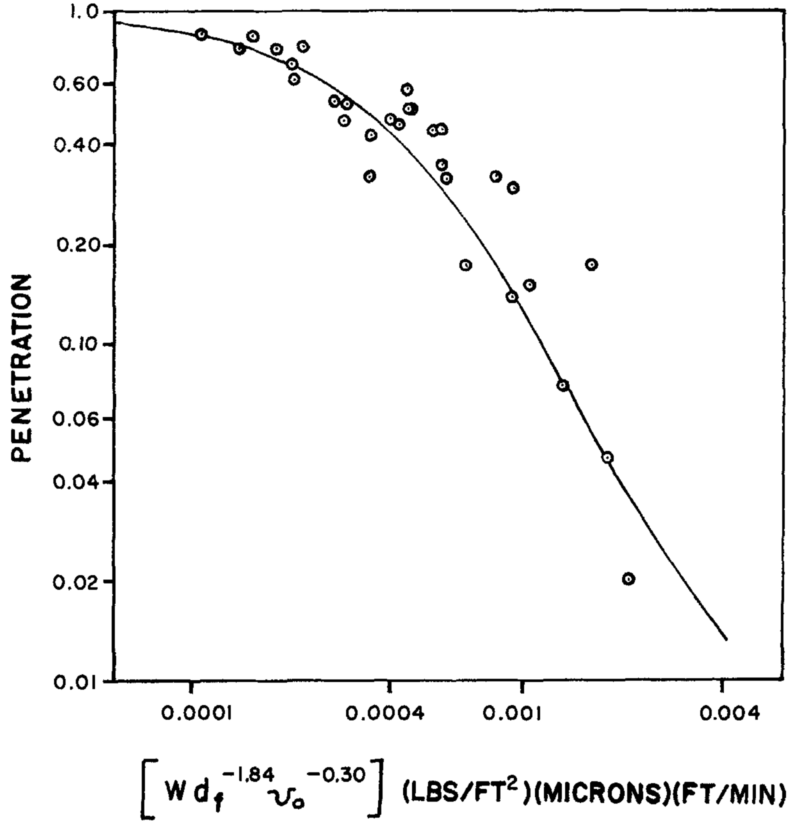

FIG. 21. Relationship of penetration to the correlation groups $Wd_f^{c'}v_0^{d'}(d_pd_f > 1.0)$.

combined with the use of low inertial parameter values. A comparison of the applicable experimental data to single fiber theory is shown in Fig. 22. Results obtained by Lundgren and Whitby (*17*) using 1-μ methylene blue crystals and 10-μ silver plated glass fiber filters at 10–80 ft/min air velocities show very low single fiber efficiencies (0.04 range), which is comparable to the values for the pollen data. Lapple (*9*) also reported filtering 1.2-μ ammonium bromide crystals at high velocities (up to 1800 ft/min) through 30 μ glass fibers and obtained single fiber efficiencies of 0.04 to 0.08. These values are also in the range of the experimental data and are also shown in Fig. 22. Whitby (*15*) tested atmospheric dust and powdered

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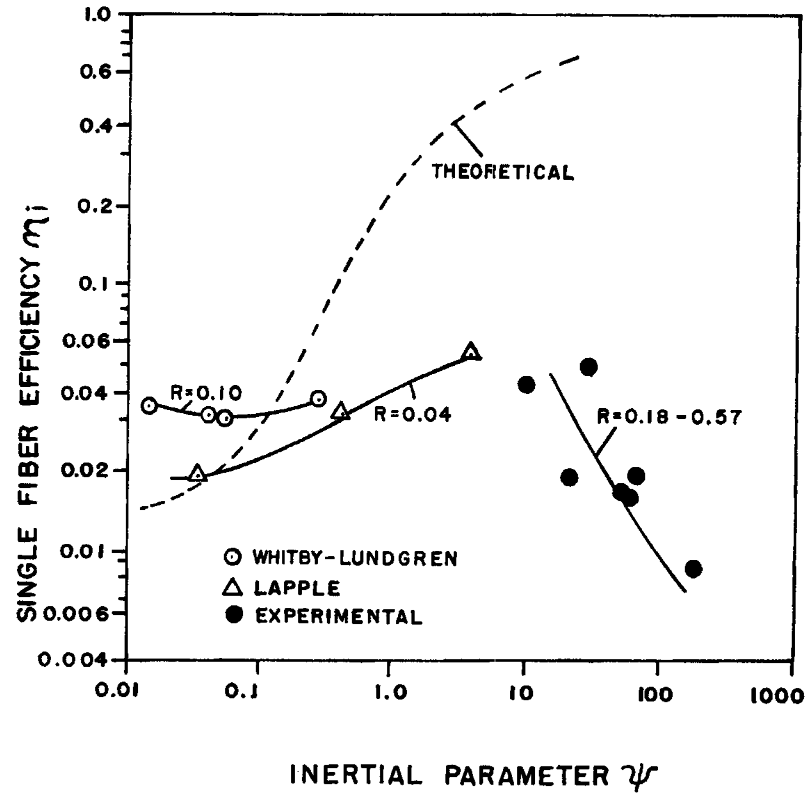

FIG. 22. Comparison of experimental data to literature for solid particle filtration.

coal containing particles from 0.1 to 20 μ and reported overall efficiency E vs $S_f d_f^{-1/2}$ for a large variety of filters. For explanatory purposes, $S_f d_f^{-1/2}$ is a property group used by Whitby that represents the combination of filter solidarity and particle inertia if v_0, the air velocity, is constant. The literature values for $v_0 = 300$ to 600 ft/min are compared to the experimental data at $v_0 = 300$ ft/min in Fig. 23. A reasonable comparison is shown.

Since the glass fibers tested were all baked at 500°F and the oily substances removed, the efficiency values were representative of natural glass fiber filters. In order to prove the filter's sensitivity to surface stickiness, the 5 and 36 μ filter sizes were retested on an "as received" basis at a

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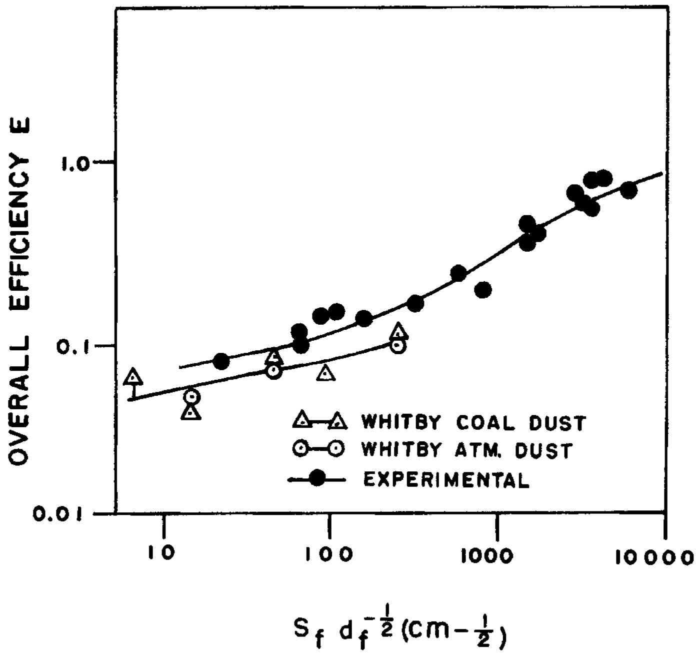

FIG. 23. Comparison of experimental data with fibrous filters tested by Whitby et al.

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300-ft/min air velocity. These filters had previously been found to contain a certain amount of residual mineral oil (3.5%). Results showed a substantial improvement in filtration as can be seen in Figs. 24 and 25. In addition, an overall comparison of the filters tested by Silverman (*3*) and Annis (*4*) are also shown in Fig. 24. It should be noted that Silverman's data were collected using well-lubricated filters that possessed a higher degree of uniform fiber orientation. This accounts for efficiency results that were far superior to the 36-μ fiber mats used in this study. It is evident from this work that fiber surface effects are a prime factor in filtration.

SYMBOLS

Capital Letters

A area, ft^2

C Cunningham correction factor

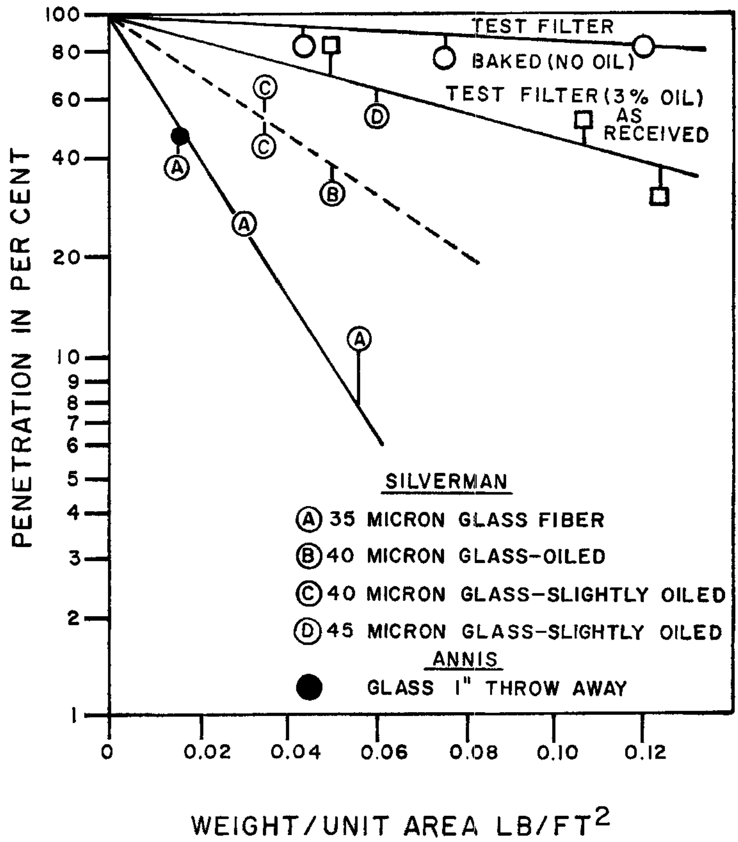

FIG. 24. Comparisons of test filter data with published values.

C	particle concentration, lb/ft^3
C_0	initial particle concentration, lb/ft^3
E	overall filter efficiency
K	a constant
L	filter thickness, ft
P	penetration or $(1 - E)$
P	pressure, in. water
Q	air flow rate, ft^3/sec
R	particle to fiber diameter ratio (d_p/d_f)
Re	Reynolds number
S_f	solidarity factor

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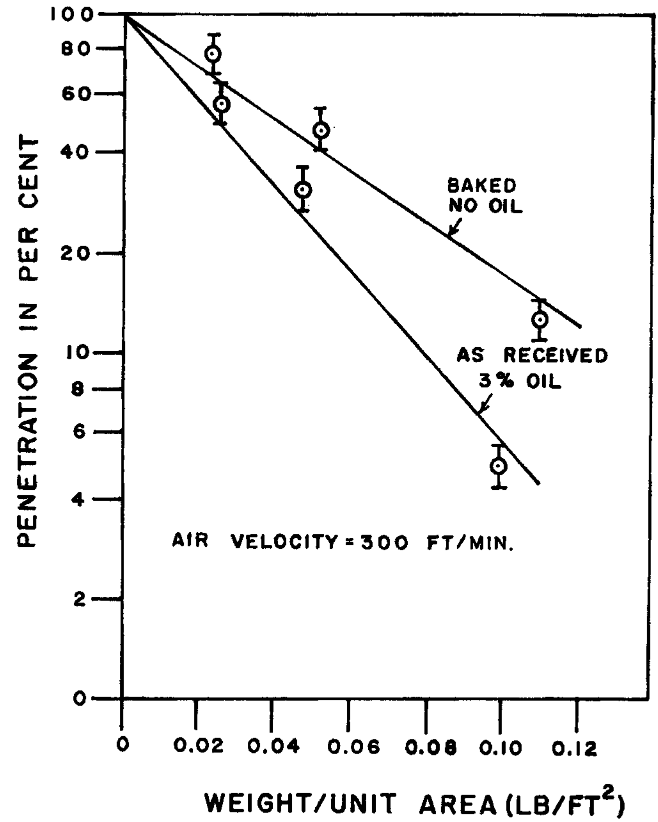

FIG. 25. Comparison of filtration characteristics of baked (no oil) and as-received 5.20 μ size mats.

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V	filter volume, ft^3
W	fiber weight per unit area, lb/ft^2
X	equivalent filter fiber length, ft

Small Letters

a,b,a',b'	exponents
d_p	particle diameter, microns, cm, ft
d_f	particle diameter, microns, cm, ft
e	base of natural logarithms
r_p	particle diameter, microns, cm, ft

r_f particle diameter, microns, cm, ft
v_0 free stream or air velocity, ft/sec
y, y_0 vertical displacement, ft

Greek Letters

α fractional volume of filter
Δ Incremental change
η_i single fiber efficiency—inertial impaction
μ gas or air viscosity, lb/ft-sec
μ particle or fiber size, microns
π pi (3.1416)
ψ inertial parameter
ρ gas or air density, lb/ft^3
ρ_f fiber density, lb/ft^3
ρ_p particle density, lb/ft^3

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