

Viledon Industrial  
Products Division



October 15 1987

Mr. Murray Cohen, Acting Director  
Division of Safety Research  
NIOSH 944  
Chestnut Ridge Road  
Morgantown, West Virginia 26505

Reference: New Proposed NIOSH Standard 42 CFR Part 84

Dear Mr. Cohen:

We would like to voice our objection to the newly proposed NIOSH standard published in the Federal Register on August 27, 1987, and in particular to the points listed below. At the same time we would like to offer our suggestions for a new NIOSH Standard for your consideration.

Subpart V, 84273:

- a) "Filters of particulate respirators shall be tested for instantaneous penetration filter efficiency against both solid and oil liquid particles in the following manner"

Under (d):

"Filters shall be tested, each at a continuous airflow rate of 32 and 85 liters per minute."

- b) Under (h) and (i):

"If filter penetration is increasing when the  $100 \pm 5$  mg challenge point is reached, the test shall be continued until there is no further increase in penetration.

Throughout the entire test the instantaneous penetration shall never exceed the level specified by the applicant."

Our comments to the above cited points are as follows:

1. Test Aerosols

Aerosols of different chemical composition will penetrate certain filter media at different levels even though their particle size and particle size distribution are the same. Therefore it is absolutely necessary to specify the chemical nature of the aerosol.

It is our opinion that NIOSH should only consider aerosols which can be generated at a given particle size distribution and are chemically and physically inert.

10-20-87

## Comparison of Respirator Filter Penetration by Dioctyl Phthalate and Sodium Chloride

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Ⓢ The penetration of all types of particulate respirator filters by a polydisperse solid sodium chloride aerosol and a monodisperse liquid dioctyl phthalate (DOP) aerosol is compared and corrected. The NaCl aerosol penetration ( $0.3 \mu\text{m}$ ) was measured with a British-manufactured EEL Respirator Tester. This instrument and its calibration are described. High-efficiency particulate respirator filters are tested against DOP in the United States and against NaCl in Great Britain. The DOP test is faster, but impractical for a degradable filter such as resin-impregnated wool batt. The feasibility of using a NaCl aerosol to test all types of particulate respirator filters is discussed. The results indicate that filter penetration by DOP and NaCl test aerosols does not differ significantly.

### Introduction

THIS TESTING PROGRAM was initiated to compare the filter penetration of all types of half-mask particulate respirator filters by a liquid and a solid aerosol. Comparison of various investigations<sup>1-4</sup> indicated significant differences in filter penetration measured using solid and liquid aerosols. In the United States, the U. S. Bureau of Mines Approval Schedule 21B<sup>5</sup> specifies a monodisperse  $0.3\text{-}\mu\text{m}$  liquid dioctyl phthalate (DOP) as the standard test aerosol for high-efficiency respirator filters. For lower-efficiency dust respirators, the Bureau of Mines uses several test aerosols of various sizes such as silica dust, chromic acid mist, and lead dust and fume.

There is considerable interest in adopting a single test aerosol, preferably a polydisperse solid with a test unit capable of rapidly measuring penetrations of as low as 0.01%.

In the United Kingdom, a polydisperse sodium chloride (NaCl) (count median diameter =  $0.6 \mu\text{m}$ ,  $\sigma_g = 2.0$ ) is the standard<sup>6</sup> aerosol used to measure the efficiency of respirator filters. The use of flame photom-

etry for filter testing in the United Kingdom was first reported by Thomas<sup>7</sup> in 1952. Improved sodium flame penetrometers for respirator filter testing have been described by Dorman<sup>8</sup> and by Dymnt and Thomason.<sup>9</sup> They report that penetrations of as low as 0.001% can be measured. In 1966, Dorman<sup>10</sup> recommended that the sodium flame penetrometer be considered the prime method to test both high- and low-efficiency respirator filters because it can accurately measure high penetrations.

If one aerosol is to have wide general application for testing many types of filters, it must not affect the filter media. For example, a liquid aerosol such as DOP rapidly degrades respirator filters made of resin-impregnated felt or wool batting. In Figure 1, the percent of penetration of a U.S.-made resin-impregnated felt filter is plotted against time. The DOP penetration increases rapidly because the liquid aerosol removes the electrostatic charge on the felt. This type of medium is also degraded in industrial atmospheres containing oil mists or solvents. Our tests with both felt and wool batt filters against radon daughters in uranium mines indicated wide variations in penetration among filters from

<sup>1</sup>Work performed under the auspices of the U. S. Atomic Energy Commission.

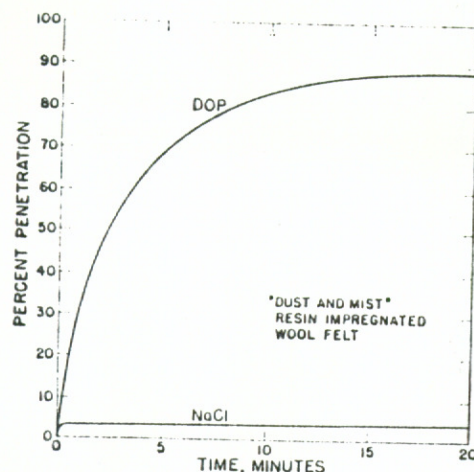


FIGURE 1. DOP and NaCl penetration of wool felt filter versus time.

various manufacturers. The DOP is useful to screen this type of filter.

There are few data comparing the penetration of filters by DOP and NaCl. Dorman<sup>11</sup> has reported that tests on small areas of high-efficiency filter media (100 cm<sup>2</sup>) indicate that DOP penetration is three times as great as that of NaCl at a velocity of 2.5 cm/sec, and that they are equal at 12 cm/sec, after which NaCl is more penetrating. In our laboratory, Ettinger *et al.*<sup>12</sup> compared NaCl tests on Whatman 41 filters with DOP tests on the same medium, by other investigators. The comparison shows DOP penetrations considerably higher than those of NaCl in filtering velocities ranging from 5 to 50 cm/sec.

#### Equipment and Methods

##### DOP Respirator Filter Tester

The DOP filter tester is a TD Associates Model Q127 built in accordance with the specifications for the Army Chemical Corps' Model E 27 filter tester. As shown in the flow diagram (Figure 2), the vapor from the heated DOP is swept out of the heating pot with 20 liters/min of heated air. This air-vapor mixture is then diluted with 80 liters/min of cooler air, condensing the DOP vapor into a nominally monodisperse 0.3- $\mu$ m-

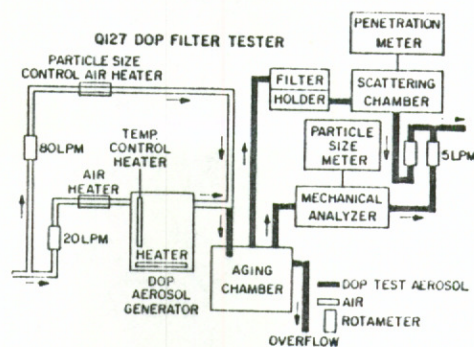


FIGURE 2. Flow diagram of Model Q127 respirator filter tester.

diameter aerosol. The aerosol concentration entering the aging chamber is  $\approx 100$  mg/m<sup>3</sup>.

A flow of 5 liters/min from the aging chamber is passed through the mechanical analyzer which monitors the aerosol particle size by measuring the polarization ratio of light scattered at 90° by the aerosol.<sup>13</sup> The particle size is regulated by controlling the temperature of the 80 liters/min of diluting air.

The penetration of a filter is measured by a forward light-scattering photometer. The penetration meter has scales of 100%, 1.0%, and 0.1% which can be changed to 25%, 0.25%, and 0.025%, respectively, by an optional circuit that increases meter deflection by a factor of 4.

##### DOP Test Method

The penetration meter is adjusted to read 100% when aerosol from the aging chamber is pulled through the empty filter holder and the scattering chamber. The most sensitive scale is adjusted to zero while filtered room air is passed through the scattering chamber.

The filter to be tested, mounted in a connector in the same manner as in a respirator, is secured in the filter holder. The filter holder is closed, and the challenge aerosol is admitted. The aerosol passing the filter is indicated by the penetration meter. Following the procedures of Bureau of Mines Schedule 21B, we recorded the penetration of the degradable resin-wool filters 10 seconds after the aerosol was admitted to the filter holder.

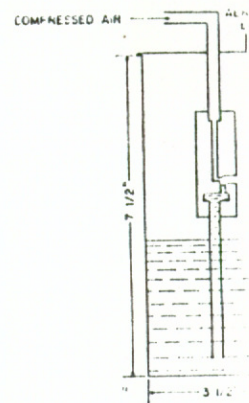


FIGURE 3. NaCl generator.

##### NaCl Respirator Filter Tester

The NaCl respirator filter tester consists of an aerosol flame penetrometer, an calibration system. The generator or atomizer (Figure 4) design developed by the Experimental Establishment, and detailed by the generator has three nozzles at 120° apart. The operating pressure with 2% NaCl solution through the generator produced a NaCl aerosol with a mean diameter of  $\approx 100$  mg/m<sup>3</sup>. An elevation view (Figure 4) shows NaCl aerosol entering the filter with a Zeiss compound microscope (CM 2.22, and a mass median diameter of 0.35  $\mu$ m).

The sodium flame respirator tester) was built in accordance with the guidance of Evans Electrochemical Instrument Co. The schematic of the EF 27 filter tester is shown in Figure 5. The test procedure is as follows: Propane gas is introduced into the instrument by the impeller through the Venturi injection air from the 4-lb. The gas and air mixture

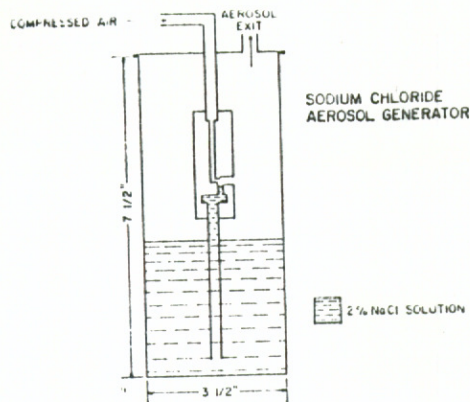


FIGURE 3. NaCl aerosol generator.

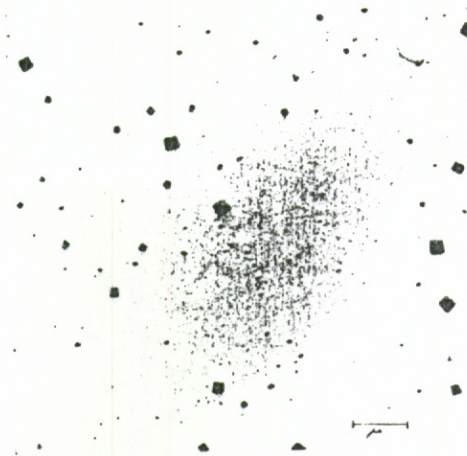


FIGURE 4. Electron micrograph of NaCl aerosol.

#### NaCl Respirator Filter Test Apparatus

The NaCl respirator filter test apparatus consists of an aerosol generator, a sodium flame penetrometer, and a dilution board and calibration system. The NaCl aerosol generator or atomizer (Figure 3) was based on a design developed by the Chemical Defence Experimental Establishment, Porton, England, and detailed by Vokes, Ltd.<sup>14</sup> The generator has three atomizing jets spaced 120° apart. The operating air pressure was 75 psi with 2% NaCl solution. The airflow through the generator was 1.3 cfm, which produced a NaCl aerosol concentration of  $\approx 100$  mg/m<sup>3</sup>. An electron micrograph (Figure 4) shows NaCl aerosol representative of that entering the filter holder. Particle sizing with a Zeiss comparator showed a count median diameter (CMD) of 0.05  $\mu$ m,  $\sigma_g = 2.22$ , and a mass median diameter (MMD) of 0.35  $\mu$ m.

The sodium flame penetrometer (EEL respirator tester) was manufactured by Evans Electroelenium, Ltd. (England), with the guidance of Houtman and Walsh.<sup>15</sup> A schematic of the EEL respirator tester is shown in Figure 5. The instrument operates as follows: Propane gas is injected into the instrument by the injector (1). Gas flowing through the Venturi tube (2) draws combustion air from the 1-liter sampling cavity (3). The gas and air mix in the mixing chamber

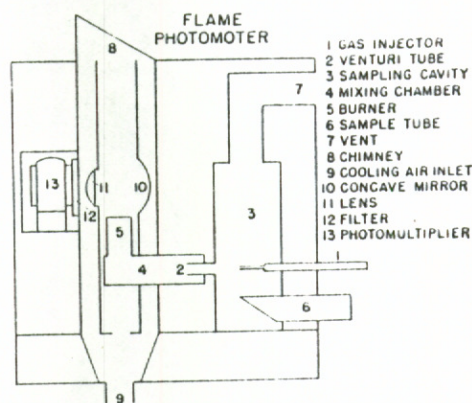


FIGURE 5. Schematic of EEL flame photometer.

(4) and burn on the single row of holes on the burner (5). The sample is injected through the tube (6) into the sampling cavity (3), and excess sample is vented through the vent (7). The chimney (8) is two concentric tubes; the flame burns in the inner tube, while the outer tube is purged with air for cooling. A very small amount of air is bled into the inner chimney. The air is supplied (9) through high-efficiency filters. The light from the flame caused by ionization of the NaCl aerosol is collected by a concave mirror (10) and focused by the lens (11) onto the filter (12). The filter selects

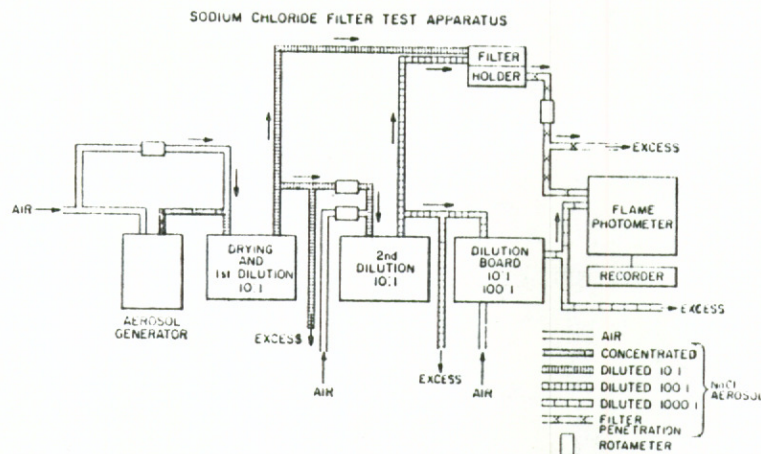


FIGURE 6. Flow diagram of NaCl respirator filter test apparatus.

the characteristic wavelength of the sodium emission from the flame. The light from the filter is seen by the photomultiplier (13). The amplified photomultiplier signal is displayed on the meter and recorder. The instrument has three scales—100%, 10%, and 1.0%.

Figure 6 is a flow diagram of the NaCl respirator filter test apparatus. A dilution board and calibration system was built to determine the optimum operating conditions and to check the linearity of response of the unit because the EEL operating instructions did not include information on meter deflection versus salt concentration.

The first dilution system tested consisted of two 10-1 dilutions of the aerosol from the generator after it had passed through the 30-gallon drum. We found that the photomultiplier was swamped by the higher concentrations, and only with the 100:1 dilution as the maximum concentration could the unit be calibrated and have linear response on each scale and between the scales. To provide enough dilute aerosol for calibration and testing, more air was added to the 30-gallon drum and another 10:1 dilution step was incorporated. The unit was calibrated, and the optimum operating conditions were found to be as follows.

1. A 0.28-liter/min propane gas flow gave a steady flame with maximum sensitivity.

Higher gas flow extinguished the flame, and lower flows reduced the sensitivity.

2. Full-scale reading on the 100% scale could be obtained with an aerosol concentration of 1 mg/m<sup>3</sup>, and the linearity was maintained on each scale and between scales.

3. A 10-liter/min sample flow into the sample cavity caused minimum disturbance of the flame, gave reproducible calibration and penetration results, and permitted the sample cavity to be brought to equilibrium in  $\approx$  1 minute.

4. The dilution system operated best at 1.0 to 1.25 psi in the 30-gallon drum. This pressure keeps the whole dilution and test system positive, thus eliminating the need for pumps or blowers to inject calibration or test aerosol into the sample cavity.

#### NaCl Test Method

After the sample cavity is purged and the three scales are adjusted to zero, the calibration aerosol is injected into the sample cavity and the 100% scale is adjusted to a full-scale reading with the sensitivity control. The sample cavity is again purged, and the zero settings are rechecked. The filter is placed in the holder, and the challenge atmosphere is admitted. A challenge atmosphere with a NaCl concentration of 1 mg/m<sup>3</sup> is used for a filter with a penetration of 1% or greater. The lower penetration filters are tested against

an aerosol concentration. The flow rate of air passing the filter is injected into the sample cavity at 10 liters/minute. A flow rate of 10 liters/minute is required for the sample cavity to reach equilibrium. The meter reading to reach the penetration.

#### Comparison of DOP and NaCl

The following comparison of the characteristics of the NaCl apparatus points out some of the advantages and disadvantages of a respirator filter penetration control tests.

1. *Start-up Time.* The NaCl tester requires about 45 minutes to reach operating temperature and before filter testing can begin. The DOP system reaches a steady state after 15 minutes. Testing can begin immediately for the 100% calibration on each scale.

2. *Filter Test Time.* The NaCl test with the Q127 requires 10 or 15 seconds. The DOP test is indicated in 10 seconds. The NaCl test requires purging the filter, and the penetration is zero by the time the next test is begun.

The NaCl tester requires a filter penetration test to be performed before the aerosol is required to bring the sample cavity to equilibrium and to purge after the test.

It may not seem fair to compare the experimental NaCl test system with a \$8000 DOP unit, but the DOP system were more sophisticated than the NaCl system. The time required for the type of equipment is shortened.

3. *Flow Control.* The NaCl test has one inherent advantage over the DOP test. The filter holder, the sample cavity, and the photometer form a closed system during the test. In this arrangement, the flow rate of the flow and the flow rate are located beyond the penet-

an aerosol concentration of 10 mg/m<sup>3</sup>. Air passing the filter is injected into the sample cavity at 10 liters/min. Approximately 1 minute is required for the concentration in the sample cavity to reach equilibrium and the meter reading to level out and indicate the penetration.

#### Comparison of DOP and NaCl Filter Testing

The following comparison of the operating characteristics of the DOP and NaCl test apparatus points out some of the advantages and disadvantages of each for testing respirator filter penetration and for quality control tests.

1. *Start-up Time.* The Q127 DOP filter tester requires about 45 minutes to heat to operating temperature and reach equilibrium before filter testing can start. The NaCl system reaches a steady state very quickly, and testing can begin immediately after adjusting for the 100% calibration and setting the zero on each scale.

2. *Filter Test Time.* A filter penetration test with the Q127 requires no more than 10 or 15 seconds. The penetration in most cases is indicated in 10 seconds, the scattering chamber purges quickly on removal of the filter, and the penetration meter is at zero by the time the next filter is ready for testing.

The NaCl tester requires  $\approx 2$  minutes for a filter penetration test because of the time required to bring the concentration of the aerosol in the 1-liter sampling cavity to equilibrium and to purge the sampling cavity after the test.

It may not seem fair to compare our experimental NaCl test system to a sophisticated \$8000 DOP unit, but even if the NaCl system were more sophisticated it does not seem that the time required for a test using this type of equipment could be significantly shortened.

3. *Flow Control.* The DOP filter tester has one inherent advantage. The aerosol generator, the filter holder, and the penetrometer form a closed system during a filter test. With this arrangement, the rotameter measuring the flow and the flow-regulating valve can be located beyond the penetrometer and thus not

TABLE I  
DOP and NaCl Penetration of High-Efficiency Respirator Filters

Filter	Flow Rate (liters/min)	DOP (% penetration)	NaCl (% penetration)
A	16.0	<0.001	<0.002
	42.5	0.002	0.002
B	16.0	<0.001	<0.002
	42.5	0.004	0.007
C	16.0	<0.001	<0.002
	42.5	0.003	0.003
D	16.0	<0.002	<0.002
	42.5	0.009	0.015
E	16.0	<0.001	<0.002
	42.5	0.003	0.004

TABLE II  
DOP and NaCl Penetration of Fume\* Respirator Filters

Filter Type	Flow Rate (liters/min)	DOP (% penetration)	NaCl (% penetration)
Fiberglass	16.0	4.0	3.1
	42.5	7.5	6.5
Treated "paper"	16.0	8.3	7.5
	42.5	14.8	12.5
Organic and asbestos fibers	16.0	19.7	17.0
	42.5	25.0	24.5

\*Complete respirator tested against lead fume and approved by U. S. Bureau of Mines.

alter the aerosol before it encounters the filter being tested.

The detection unit in the NaCl system, on the other hand, is at the end of the system because the sample cavity and burner must operate at atmospheric pressure and with a free discharge. Very slight changes in pressure can have a large effect on the amount of aerosol that is drawn from the sample cavity into the burner. Therefore, all the flow-measuring devices and flow-regulating valves are between the aerosol generator and the sample cavity. Deposit of NaCl in the devices can alter the aerosol concentration and necessitates frequent cleaning to maintain accurate flow measurement and control.

## Discussion of Results

### High-Efficiency Filters

A comparison of the results of DOP and NaCl penetration tests on high-efficiency res-

TABLE III  
DOP and NaCl Penetration of Dust and Mist\*  
Respirator Filters

Filter <sup>b</sup>	Flow Rate (liters/min)	DOP (% penetration)	NaCl (% penetration)
A	16.0	2.5	0.8
	42.5	21.3	3.8
B	16.0	30.0	29.0
	42.5	40.0	40.0
C	16.0	46.0	24.5
	42.5	68.0	44.0

\*Complete respirator tested against silica dust and chromic acid mist and approved by U. S. Bureau of Mines.

<sup>b</sup>The filters listed contain resin-impregnated wool felt media.

pirator filters is shown in Table I. The Bureau of Mines Schedule 21B specifies that the total DOP leakage for the filter and connector shall not exceed 0.03% at 16 or 42.5 liters/min when testing single cartridges used in pairs on the half-mask facepiece. We obtained reproducible DOP penetration readings down to 0.001% and estimated penetrations as low as 0.0005%. The NaCl penetration can be accurately read down to 0.002%. Because the penetrations are so low for both DOP and NaCl, we cannot compare the penetrations and flow rate of 16 liters/min; however, we can compare the penetrations and the flow rate of 42.5 liters/min. At this flow rate the NaCl penetration is slightly higher, ranging from 0 to 2.0 times the DOP penetration of the same filter.

To estimate the filtering velocity at 42.5 liters/min for the five high-efficiency filters tested, we have measured the filtering area and calculated that the velocity ranges from 2.5 to 3.5 cm/sec for comparison with the results of other investigators testing high-efficiency filter media against DOP and NaCl. We noted above that Dorman<sup>13</sup> reported that DOP penetration is greater than that of NaCl by a factor of 3 at a velocity of 2.5 cm/sec. Dorman's NaCl aerosol had an MMD of 0.7 $\mu$ m. We believe the NaCl penetration was slightly higher than that of the DOP because our 0.3- $\mu$ m NaCl aerosol is smaller.

#### Fume Filters

Our test results on DOP and NaCl penetration of fume respirator filters are compared

in Table II. For convenience we call this type of filter cartridge a "fume" respirator filter because it has been tested against a lead fume on a complete half-mask respirator mounted on a test head in a test chamber. The Bureau of Mines does not test individual filters against lead fume. To be approved, the complete respirator must show a penetration of less than 0.1% by freshly formed lead fume. Obviously the penetration of the filter by lead fume would be less than 0.1%.

For our comparison we have tested only three basic types of fume respirator filters. The DOP penetration through fume filters is slightly higher than that of NaCl at both flow rates. There is considerable difference in the penetration by DOP and NaCl of the best fume filter made of fiberglass and the filter made of organic and asbestos fibers. Our results indicate that both test methods quickly and accurately rate various types of fume respirator filters. Although all these fume filters have been tested and approved for protection against lead fume, there is obviously a great difference in their efficiency. This difference in filtering efficiency was reported by Revoir and Yurgilos<sup>16</sup> in their tests of several Bureau of Mines approved dust respirators against various aerosols.

#### Dust Filters

A comparison of our test results on DOP and NaCl penetration of "dust and mist" respirator filters is shown in Table III. This table lists only three of the many types of commercially available "dust" and "dust and mist" respirator filters that have been approved by the Bureau of Mines by testing the complete respirator against silica dust and chromic acid mist. To be approved, a dust respirator must show less than 1.0% penetration by silica dust. The three filters listed contain resin-impregnated wool felt media whose filtering efficiency is based on an electrostatic charge created on the media by impregnation with approximately 15% resin. The DOP aerosol degrades this type of filter medium very rapidly, as illustrated in Figure 1 by a continuous DOP test on filter A. The DOP penetration readings were taken at exactly 10 seconds. The NaCl penetration results are considered reliable and are useful

to demonstrate the difference in the filter A as compared with filter B by the fact that the patented process by resin-impregnated wool electrostatic charge on Resin-Wool Batt Filter.

A comparison of the NaCl penetration test impregnated wool media used in the can manufactured in either Australia. The companies A, C, and E were supplied these two countries. A, C, and E were provided respirator manufacturer impregnated wool media manufacturers and standard filter cartridges face pieces.

We obtained several impregnated wool batts in 1967 to test attached to mine at mines in New Mexico filter was tested because criteria—low breathing dust loading character this study<sup>17</sup> indicated batt filters maintain >95% against radon hour continuous test many of the 15 types were degraded very collection efficiencies of hours. We learned of resin-impregnated they produce several based on weight, ounces per square yard using the NaCl filter the many types of were proposed by the ing against radon da

In Table IV, experimental weight of 62 oz/yd<sup>2</sup> penetration, and its efficiency of U. S.-made high

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to demonstrate the difference in efficiency of filter A as compared with filters B and C. The lower penetration of filter A can be explained by the fact that the manufacturer has a patented process by which he fractures the resin-impregnated wool to impart a greater electrostatic charge on the medium.

#### Resin-Wool Batt Filters

A comparison of the results of DOP and NaCl penetration tests on six types of resin-impregnated wool batt filter cartridges is shown in Table IV. All the resin-wool batt media used in the cartridges tested were manufactured in either the United Kingdom or Australia. The commercial cartridges B, D, and F were supplied by manufacturers from these two countries. Experimental cartridges A, C, and E were provided by three American respirator manufacturers who obtained resin-impregnated wool batt media from English manufacturers and mounted it in their standard filter cartridges to fit American-made face pieces.

We obtained several representative resin-impregnated wool batt respirator filter cartridges in 1967 to test against radon daughters attached to mine aerosols in the uranium mines in New Mexico. This type of respirator filter was tested because it met two of our criteria—low breathing resistance and good dust loading characteristics. The results of this study<sup>17</sup> indicated that some of the wool batt filters maintain collection efficiencies of >95% against radon daughters during a 24-hour continuous test at 85 liters/min, but many of the 15 types of wool batt filters tested were degraded very rapidly and showed collection efficiencies of less than 90% in a few hours. We learned from the manufacturers of resin-impregnated wool batt media that they produce several grades of these media based on weight, commonly expressed in ounces per square yard. In 1968, we started using the NaCl filter test method to screen the many types of wool batt cartridges that were proposed by the manufacturers for testing against radon daughters.

In Table IV, experimental filter A with a weight of 62 oz/yd<sup>2</sup> showed very little penetration, and its efficiency is equivalent to that of U. S.-made high-efficiency filters. This

TABLE IV  
DOP and NaCl Penetration of Resin-Wool Batt\*  
Respirator Filters

Filter No. and Medium Weight	Flow Rate (liters/min)	DOP (% penetration)	NaCl (% penetration)
A—Experimental 62 oz/yd <sup>2</sup>	16.0 42.5	<0.001 0.006	0.005 0.015
B—Commercial 52 oz/yd <sup>2</sup>	16.0 42.5	0.25 0.46	0.06 0.22
C—Experimental 48 oz/yd <sup>2</sup>	16.0 42.5	0.31 0.65	0.05 0.32
D—Commercial 36 oz/yd <sup>2</sup>	16.0 42.5	0.54 1.50	0.12 0.75
E—Experimental 24 oz/yd <sup>2</sup>	16.0 42.5	1.10 3.30	0.33 1.40
F—Commercial 18 oz/yd <sup>2</sup>	16.0 42.5	1.25 3.50	0.47 1.70

\*All wool batt media impregnated with ≈15% resin.

medium is not commercially available and has a pressure drop of approximately 1.5 inches w.g. which would make it unsuitable for use in low breathing resistance respirators. The DOP readings were taken at exactly 10 seconds because this type of medium is degraded very rapidly by a liquid DOP aerosol. Because of this, the DOP penetration tests would not be suitable as a quality control test on wool batt filter cartridges. Note that the DOP penetration of the six types of resin-wool batt media is lower by an order of magnitude than that of the resin-impregnated wool felt media reported in Table III.

#### Comparison of Two DOP Test Units

We have noted that we believe our NaCl penetration of high-efficiency filters is slightly higher than DOP penetration because our NaCl aerosol is smaller than the NaCl aerosol used in Great Britain. However, the question has been raised whether our DOP test unit will give penetration test data on high-efficiency filters comparable to that of other DOP respirator filter test units. Since the Bureau of Mines DOP respirator filter tester is used to test and approve high-efficiency filters, we asked Mr. Robert Schutz, Supervisor of the U. S. Bureau of Mines Respirator Approval and Testing, to test with DOP the same five high-efficiency filters that we had tested with both DOP and NaCl. The LASL and the Bureau of Mines DOP penetration tests on



TABLE V  
NaCl and Two DOP Tester Penetrations of  
High-Efficiency Filters

Filter	Penetration at 42.5 Liters/Min (%)		
	DOP		NaCl LASL
	Bureau of Mines	LASL	
A	0.008	0.002	0.002
B	0.068	0.004	0.007
C	0.004	0.003	0.003
D	0.018	0.009	0.015
E	0.028	0.003	0.004

identical filters, along with our NaCl penetration tests, are shown in Table V. Comparison of the DOP penetration tests of filters A, B, C, and D indicates that the Bureau of Mines penetration ranged from two to four times as high as the LASL penetration. We believe that we can explain the larger difference in penetration of filter E by the fact that we sometimes found higher penetrations with this filter and holder because it was more difficult to obtain a seal in this particular holder. Note that the Bureau of Mines DOP penetration test and our NaCl penetration test of filters B, C, and D gave almost identical results. If we accept the Bureau of Mines penetration test as a standard, comparison of our NaCl test and the Bureau of Mines DOP tests shows very little difference. It should be noted that our laboratory is at 7200 feet elevation while that of the Bureau of Mines in Pittsburgh is much nearer sea level. A possible explanation for the differences in DOP penetration reported may be that the air density and viscosity are different at the higher elevation.

### Conclusions

Our comparison of the penetration of high-efficiency and fume respirator filter cartridges by monodisperse 0.3- $\mu$ m DOP and polydisperse 0.3- $\mu$ m NaCl indicates no significant differences. The NaCl penetration ranges from 0 to 2.0 times as high as the DOP penetration of high-efficiency filters. For the fume filters, the DOP penetration is slightly greater (<25%). Tests of resin-impregnated wool felt and batt filters cannot be compared be-

cause the DOP degrades the media, even at our 10-second penetration reading.

Our comparative tests suggest that a NaCl aerosol used with a sodium flame penetrometer reliably tests all types of respirator filters and that DOP is reliable for all but degradable media. Comparison of existing DOP and NaCl testing units shows that DOP is faster for routine quality control. The results suggest methods for routine quality control of high penetration filters.

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### Introduction

AS INDICATE this laboratory effect of light irradiation on hydrocarbons in air. Evidence was presented that arenes decrease in concentration of a traverse of a laboratory reactor. Continuing interest in this transformation as that account for the doubt that transfer of the chemical conditions have been reported others.<sup>2,3</sup>

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## DEGRADATION OF ELECTROSTATIC FILTERS AT ELEVATED TEMPERATURE AND HUMIDITY

Mark W. Ackley  
Scott Aviation, Division of Figgie International Inc., Lancaster, New York

Measurements have been made to determine the degradation in aerosol collection efficiency of electrostatic filters from storage at elevated temperature and/or humidity. Three types of electrically charged filter media have been included in this study, i.e. resin wool, electret and an electrostatically-spun polymer. Short-term tests of fourteen-day duration have been conducted at conditions ranging from 21°C to 65°C, and 0% R.H. to 90% R.H. Tests at 42.5°C and 87.5% R.H. have been in progress for several months. In all tests, filter samples have been removed at specific intervals, and aerosol penetration measured. Several types of protective bags have been included in the long term tests. Both 0.3  $\mu\text{m}$  monodisperse DOP and 1.0  $\mu\text{m}$  MMAD polydisperse NaCl aerosols have been used to determine penetration. The degradation history of filters under a continuous challenge of DOP has also been measured.

INTRODUCTION

Electrostatic filters are a curiosity to much of the filtration industry. However, resin wool filters have filled an important application in respirators for many years. Other uses include vacuum cleaners for asbestos clean-up, room air-purifiers and pre-filters for HEPA filters. Degradation in collection efficiency due to certain types of liquid aerosols, and in high temperature and high relative humidity environments has been the primary disadvantage of these filters.

Concern has arisen over the loss of efficiency of resin wool filters during storage and use. Hyatt et al (1) and Douglas et al (2) conducted studies for NIOSH showing significant reduction in aerosol collection ability for filters subjected for short durations at conditions of 22°C, 100% R.H. and 32°C, 90% R.H., respectively. More recently, new types of electrostatic media and improved resin wool filters have been developed. The purpose of this study was to evaluate the performance of these various electrostatic materials - particularly in regard to degradation of collection efficiency at elevated temperature and humidity.

DESCRIPTION OF FILTER MEDIA

Three types of electrostatic filter media have been included in this investigation - resin wool, electret, and an electrostatically-sprayed polymer. All are briefly described below. An excellent review of the various types of electrostatic filters has also been presented by Brown (3).

Resin wool is the most common of the electrostatic filter media, having been developed for respirators by Hansen about 1930, Davies (4). Walton's (5) research is responsible for much of today's understanding of this filter. A thorough historical account has been given by Feltham (6). Typical media consists of wool and synthetic fibers, and resin particles. The resin constitutes 15%-20% of the total filter weight, while the balance is made up of approximately equal proportions of the wool and synthetic fiber. A photomicrograph of this structure is shown in Figure 1. Resin particles (1  $\mu\text{m}$  and larger) adhere to the wool fibers (15  $\mu\text{m}$ -20  $\mu\text{m}$  diameter) by strong electrostatic attraction. Friction generated during the filter carding process between the resin and the wool results in negatively-charged resin particles and positively-charged wool fibers. Due to this separation of charge, local non-uniform electrostatic fields develop throughout the filter. These electric fields are responsible for the enhanced aerosol collection ability of the filter. The high resistivity of the resin and the minute contact area between the resin and the fiber are primarily responsible for the long-term stability of the charge (5).

An electret is a material that is often described as the electric analog to the permanent magnet. Such materials contain a positive charge on one side and a negative charge of equal magnitude on the opposite side. The best known laboratory electret is that made

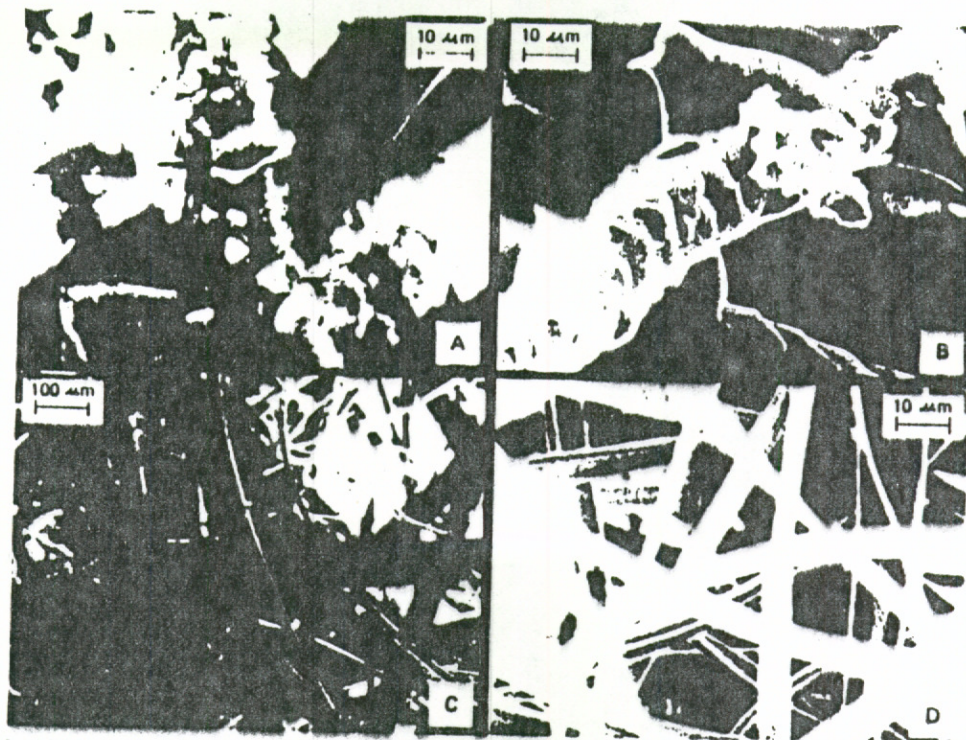


Figure 1 Scanning Electron Micrographs: (a) Resin wool, type B, (b) Resin wool, degraded with DOP, (c) Electret, (d) Electrostatically-spun polymer

from carnauba wax. However, modern day electrets are commonly made from thin-film plastics. Electret devices are not limited to filters, and typical applications are radiation detectors, humidity meters, electrostatic relays, etc. Jefimenko (7) describes the electrical characteristics of an electret in terms of dielectric absorption - which involves charge penetration and trapping by the dielectric material, accompanied by internal molecular polarization. The electret filter investigated in this study is also shown in Figure 1. Corona discharge is used to inject positive charges on one side and negative charges in an equal amount on the opposite side of thin polypropylene films, Turnhout et al (8). These thin sheets are then shredded into fibers of rectangular cross-section, with fiber widths varying from a few micrometers to one hundred micrometers. Fibers are carded and needled into fabric form.

Another type of filter is made from electrostatically-spun fibers. The process involves the distribution of a liquid polymer solution on a moving electrode, the formation of spinning threads of liquid film in the presence of a strong applied electric field, the subsequent detachment and precipitation of fibers as the solvent evaporates, and finally the deposition of the charged fibers on a precipitation electrode as described by Simm et al (9). Layers of alternately charged fibers are produced by alternating the polarity of the spray electrode. Polymers such as polystyrene, polycarbonate, polyvinyl chloride and polypropylene have been suggested. This process results in finer synthetic fibers than can be produced by conventional means. Fibers appear as bands approximately 1  $\mu\text{m}$  thick and 5  $\mu\text{m}$  to 10  $\mu\text{m}$  wide as shown in Figure 1.

In all three types of filters, enhanced aerosol collection efficiency is achieved due to localized, nonuniform electrostatic fields. Resin wool and electret filters are inherently neutral, while the overall charge on the spun synthetic is dependent upon the proportion of negatively and positively charged fibers. The degree and stability of the electrostatic enhancement of these materials is the subject of this investigation. Properties of these filters are summarized in Table 1 and in Figure 2.

#### TEST PROCEDURES AND APPARATUS

##### Aerosols

Monodisperse (0.3  $\mu\text{m}$  diameter) dioctyl phthalate (DOP), generated by an ATI model Q127 penetrometer, was employed for the majority of the degradation measurements. Filters are mounted in a test chuck on this apparatus and aerosol penetration is determined by a light scattering photometer. DOP concentration was controlled at  $100 \text{ mg/m}^3 \pm 10 \text{ mg/m}^3$ . Filter face velocities of 5.4 cm/sec and 6.5 cm/sec, corresponding to test filter areas of 83  $\text{cm}^2$  and 98  $\text{cm}^2$ , respectively, were used.

TABLE 1 - Filter Properties

FILTER DESIG.	FILTER TYPE	FIBER COMPOSITION	WEIGHT g/m <sup>2</sup>	THICKNESS mm	INITIAL DOP PERF.			
					P %	n	s	C <sub>v</sub> %
A	Resin Wool	45% Wool, 55% Acrylic	410	3.2	6.2	10	0.66	11.
B	Resin Wool	45% Wool, 55% Polypropylene	510	3.8	0.81	21	0.16	20.
C	Wool Felt	45% Wool, 55% Polypropylene	410	6.4	77.	31	2.7	4.
D	Electret	Polypropylene	305	5.7	0.08	17	0.03	38.
E	Spun Polymer	Polycarbonate	140	1.1	0.24	20	0.21	88.

Mitchell et al (10) has suggested that DOP is not a reliable test method for degradable media. The use of DOP in this study is justified by the penetration histories of a resin wool and a mechanical filter shown in Figure 3. The initial peaks in the response curves are due to residual DOP in the sampling lines. Although degradation of the resin wool is apparent during the first sixty seconds of the test, the change in penetration during the measuring period (five to twenty seconds) is negligible. Similar results were obtained for the other types of electrostatic filter materials. Since DOP is a reliable and discriminative test aerosol, its use is very appropriate for these degradation measurements. Since filters are not returned to the environmental chamber after a DOP measurement, there is no degradation due to DOP other than that occurring during the short measuring period.

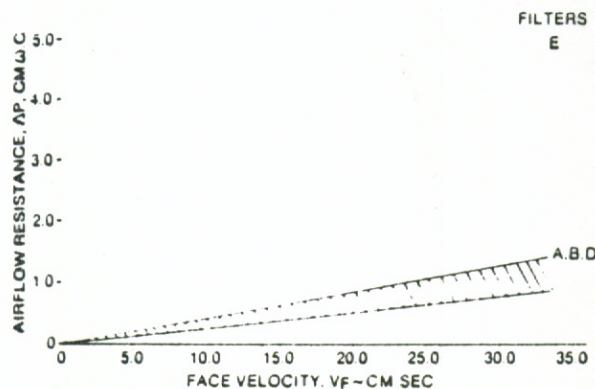


Figure 2 Filter Airflow Resistance Characteristics

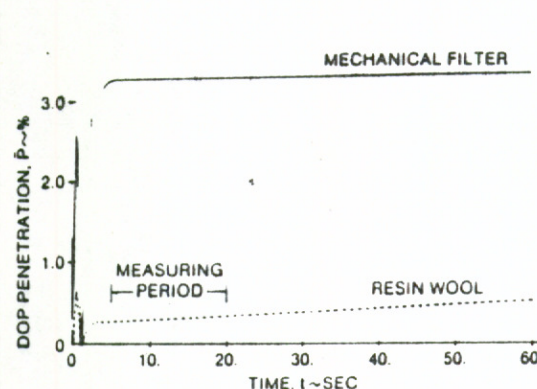


Figure 3 DOP Penetration Measuring Period

Sodium chloride (NaCl) was used to produce a polydisperse aerosol with a mass median aerodynamic diameter (MMAD) of 1.0  $\mu$ m and a geometric standard deviation of 1.9. A Dynatech-Frontier Corporation, model FE 560A sodium chloride test unit was used for these measurements. Aerosol concentration was controlled at approximately 10 mg/m<sup>3</sup>, and penetration was determined by a sodium flame photometer. Particle-size distributions were measured using an eight-stage Andersen impactor.

#### Environmental Testing

Short-term tests up to fourteen-day duration were performed in a Tenney environmental chamber. The Tenney chamber has variable relative humidity and temperature control. A rack was designed to support twenty filter samples in the chamber.

A single test condition (42.5°C, 87.5% R.H.) was chosen for long-term tests. This environment was perceived as an upper-limit storage and use condition for the majority of electrostatic respirator filter applications. The selected temperature and relative humidity were achieved using a saturated solution of potassium nitrate (KNO<sub>3</sub>). This technique has been described by Greenspan (11). Useful information on the control of the test conditions is also given in ASTM E104-51 (12).

A special chamber was constructed of polyethylene, and insulated on all sides to minimize heat transfer to the room. The KNO<sub>3</sub> solution temperature and the air temperature inside the chamber were thermostatically controlled. A small circulating fan mixed the air continuously. A total of one hundred thirty-six filters were attached to four equally-spaced racks. Temperature and relative humidity control were achieved within  $\pm 2.5^\circ\text{C}$  and  $\pm 2.5\%$  R.H., respectively.

Relative humidity was monitored using an ion-exchange humidity element, while a platinum resistance thermometer was employed for temperature measurements. All aerosol penetration tests were considered destructive, so filters were discarded immediately afterwards. The average initial aerosol penetration of the raw media was obtained from a large sampling of the filter lot. Examples of initial penetration are given in Table 1. Each filter lot was periodically tested to verify uniformity and stability in collection efficiency. Both rectangular (15 cm x 15 cm) and circular (13.5 cm diameter) test samples were used in the test chamber. Samples were removed from the chamber on a rotating schedule, keeping all test positions filled at all times.

## RESULTS AND DISCUSSION

### Oil Mist Degradation

Filter types A, B, D and E were continuously challenged with DOP to determine the effect of the oil mist upon filter efficiency. The results are shown in Figure 4. All four types of filters degrade rapidly until only the mechanical collection ability of the filter remains. The efficiency of Filter C (Filter C is the foundation for Filter B prior to resin impregnation) corresponds well with that of Filter B after total DOP degradation. The two types of resin wool filters and the electret perform similarly, all having mechanical efficiencies between 20% and 30%. Filter E, however, displays a much higher mechanical efficiency (68%). This filter also degrades completely within eight minutes, and has a resistance to airflow three times that of the other filters. Its structure is noticeably different in that it is composed of finer fibers, weighs less and is thinner than the resin wools and electret. These factors, in combination with the lower dependence of efficiency upon electrostatics, account for the rapid degradation of the electrostatically-spun polymer filter.

A photomicrograph of the resin wool filter (type B) taken after complete DOP degradation is shown in Figure 1. Comparing the clean and degraded filters, it appears that DOP wets the wool fibers and resin particles, causing blockage or dissipation of the local electrostatic fields. A similar DOP film is not visually apparent in photomicrographs of the degraded electret and electrostatically-spun polymer. The rate of degradation is definitely a function of the aerosol concentration, and likely depends upon surface adsorption and wettability.

### Short-Term Degradation

Type B resin wool filters represent an improved design over the formerly developed Type A filters. The difference in performance of these two materials is readily apparent from the data in Figure 5. Type A filters degrade almost completely within four hours exposure at 65°C, 70% R.H. After twenty-four hours exposure to the same conditions, type B filters still perform well above their mechanical efficiency. These results can be interpreted to indicate the superior electrostatic charge stability of type B resin wool filters.

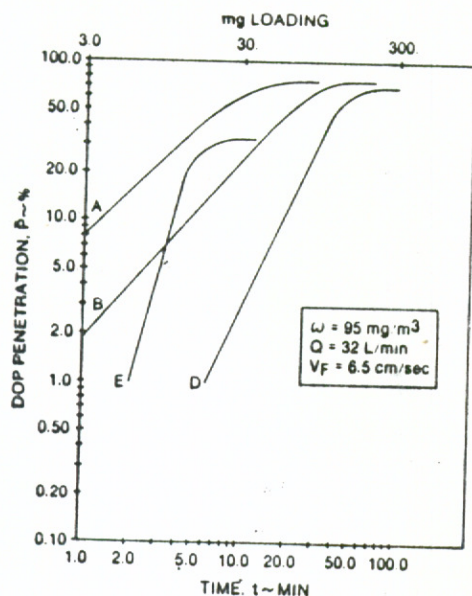


Figure 4 Electrostatic Filter Degradation Due to DOP

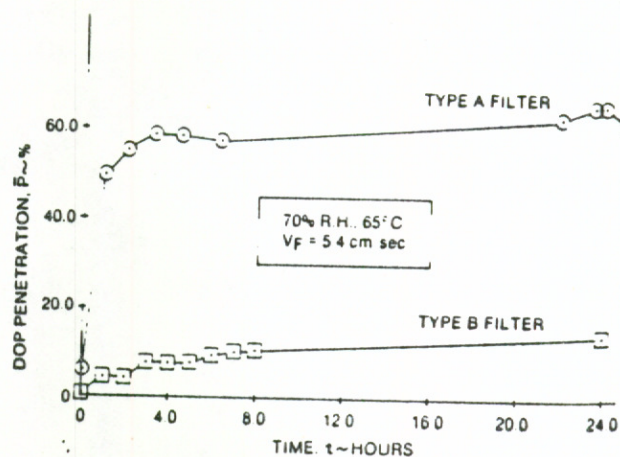


Figure 5 Comparison of Degradation of Type A and Type B Filters

Experiments were also conducted at various moisture levels and temperatures for durations up to fourteen days. Type B filters were subjected to absolute moisture conditions of zero, 0.014 and 0.107 grams of water vapor per gram of dry air ( $\text{g H}_2\text{O/g air}$ ). The corresponding temperatures and relative humidities are indicated in Figure 6 with the results of the degradation measurements. Aerosol penetrations were determined at the various chamber exposure times using DOP as described previously. Conditions of  $65^\circ\text{C}$ , 0% R.H. and  $21^\circ\text{C}$ , 90% R.H. appear to cause similar minor increases in aerosol penetration. However, exposure at conditions of  $65^\circ\text{C}$  and 70% R.H. resulted in a rapid increase in penetration in less than twelve hours, followed by continuous degradation throughout the duration of the test.

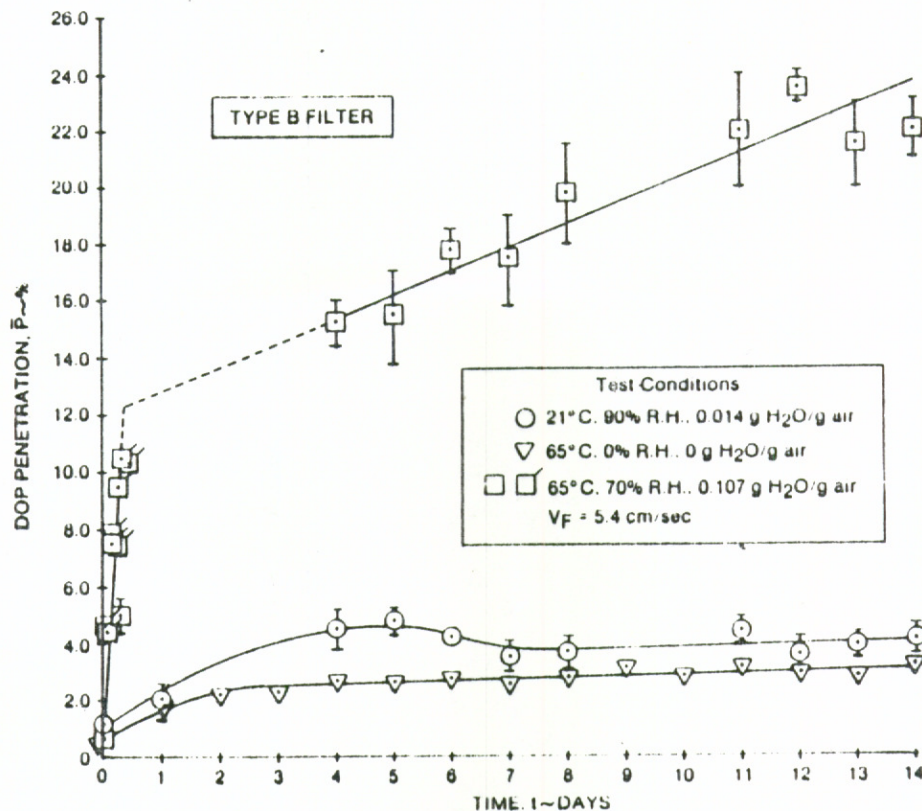


Figure 6 Short-term Degradation of Type B Filters

The effect of degradation upon collection efficiency depends upon the aerosol environment and the airflow through the filter. Tests were repeated with type B filters at  $65^\circ\text{C}$  and 70% R.H., and degradation was measured using NaCl aerosol. The data corresponding to  $V_F = 6.5$  cm/sec for NaCl in Figure 7 can be compared with that in Figure 6 for DOP. It is evident that the degree of degradation is relative to the type of aerosol. In this comparison, the DOP penetration of the filter is greater than the NaCl penetration for identical environmental exposure. This is primarily due to the larger size of the NaCl aerosol. DOP is more suitable for laboratory degradation studies because of the higher resolution in filter penetration changes. Increasing the face velocity of the NaCl aerosol to 12.8 cm/sec gives results similar to those obtained with DOP at 5.4 cm/sec, but the variation in the data is significantly greater.

Conditions for the short-term tests were chosen for initial filter performance screening, and for evaluation of degradation at various moisture levels. Long-term tests were not necessary in earlier studies (1,2) because of the rapid degradation rate. Because of the development of new types of electrostatic filters and improved resin wool filters, longer duration degradation results are now desired.

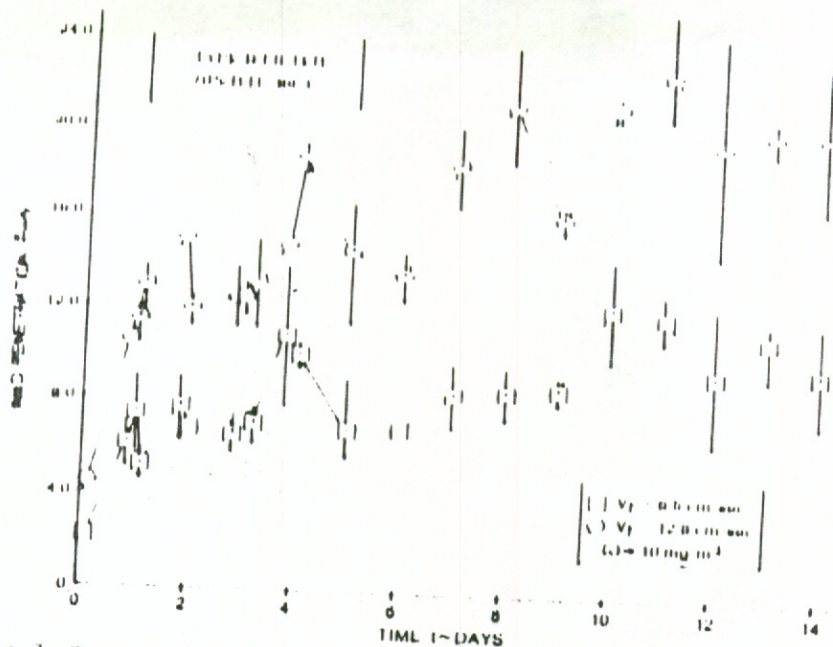


Figure 7 Degradation of Type D Filters - NaCl Penetration

#### Long-term Degradation

Filter types B, D and E were exposed at 42.5°C and 87.5% R.H. (0.045 g H<sub>2</sub>O/g air) in the specially constructed chamber described above. Average DOP penetration for each degradation time interval was computed from a sampling of two to six filters. Some of the filters in each time interval were typically from different calendar test periods. A fraction of the electret and resin wool samples were placed in bags to evaluate protection against degradation. Bags were constructed from two mil (0.05 mm) polyethylene and three mil (0.08 mm) Dow Chemical SARANEX® film. A type I Military Specification bag (13) was also used in the resin wool filter tests. Each bag containing a filter was heat-sealed prior to placing in the chamber. The SARANEX® bag had a nominal water vapor transmission rate (WVTR) of 2.33 g/m<sup>2</sup>·24h at 37.8°C, 90% R.H. The maximum WVTR allowed for the MIL SPEC bag is 0.47 g/m<sup>2</sup>·24 h.

The electrostatically-spun polymer filter (type E) was tested for durations up to 91 days in the chamber. Protective bagging was not used with this filter. Samples were removed at seven-day intervals, and DOP penetration was measured. The results are shown in Figure 8. Most of the average penetrations were only slightly greater than the average initial DOP penetration of 0.24%. However, individual DOP penetration measurements of the exposed test samples varied from 0.09% to 1.5%. Although degradation is suggested by these results, the data are inconclusive because the changes in penetration due to environmental exposure are not significantly greater than the inherent performance variability of the filter (C<sub>v</sub>=88%).

The effect of the test environment upon the performance of type D electret filters is also shown in Figure 8. Average DOP penetration increases steadily from an initial value of 0.08% to 0.18% during the first 28 days of the experiment. Subsequent average penetrations fluctuated about a mean of 0.14% for the remainder of the 154-day test. The use of the polyethylene bag appeared to suppress degradation for a period of 91 days, as did the SARANEX® bag for the full 154 days.

The degradation history of the resin wool filter (type B) has been included in Figure 8 along with that of the electret and electrostatically-spun polymer. The initial increase in penetration at this moisture level (0.045 g H<sub>2</sub>O/g air) is similar to that at zero and 0.014 g H<sub>2</sub>O/g air shown in Figure 6. The comparative data in Figure 8 indicates that the resin wool is more susceptible to degradation at these conditions than the other two types of electrostatic filters. After 154 days, the unprotected resin wool has a DOP penetration of 9.0%. Since resin wool filters similar to type A filters degraded almost completely within 28 days at 32°C, 90% R.H. (2), the performance of the type B filter represents a significant improvement in resin wool material.

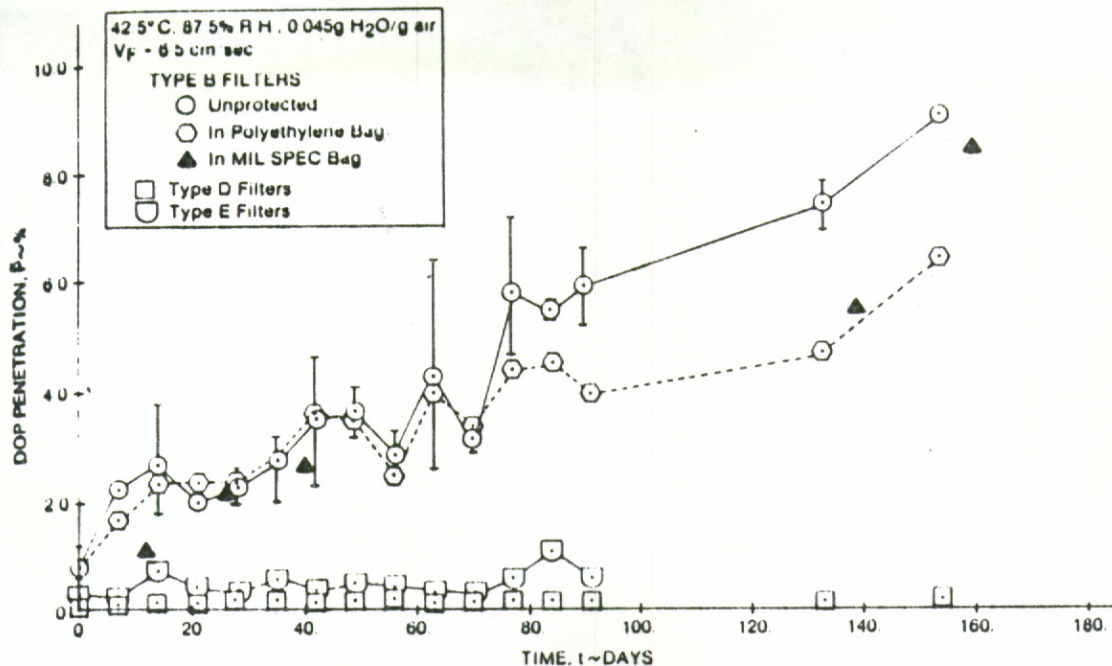


Figure 8 Long-term Degradation of Electrostatic Filters

All three types of bags were employed in the tests of type B filters. Results for the polyethylene and MIL SPEC bags are shown in Figure 8. Filters sealed in SARANEX® bags performed nearly the same as the unprotected samples over the complete duration of the test. After 90 days, the polyethylene bag appeared to suppress degradation. This is somewhat puzzling since polyethylene film of this type has a relatively high moisture permeability. There is no apparent reason why any significant reduction in filter degradation should occur with this bag. A continuation of these tests should determine if this is a sustained effect.

Surprisingly, the protection offered by the moisture barrier MIL SPEC bag against degradation is very minor. It is possible that the bags were not properly heat-sealed, although this is unlikely. Either the moisture barrier provided is insufficient in this application, or the thermal degradation effects are as important as those due to moisture. In either case, bagging the filters provides minimum protection.

In both short-term and long-term tests, it was found that unprotected resin wool materials adsorbed moisture within the first several hours in the test chamber. After this period, the moisture content of the filters remained nearly constant as degradation continued. Thus, degradation rate appears to be independent of moisture adsorption rate. Type B filters generally gained less than three percent of the filter weight at 42.5°C, 87.5% R.H. This quantity of moisture would permeate the MIL SPEC bag in approximately 45 days at a WVTR rate of 0.15 g/m<sup>2</sup>.24h (approximately one-third the maximum allowable WVTR).

The non-uniform electric field responsible for the enhanced aerosol collection ability of the resin wool filter decays as the charge equalizes in the filter. The time constant for this dielectric relaxation process is a function of the resistivity of the dielectric, Pohl (14). For materials of high resistivity at normal conditions, this decay process may take several years. The transfer of electrical charge from the resin particles is accelerated at elevated temperature and humidity. Walton (5) studied the material charge decay process in resin wool filters, but was hampered by the inability to accurately determine the resistivity of the resin. Both Silverman et al (15) and Vonnegut (16) indicate that moisture adsorption on the surface of a dielectric lowers its resistivity. Elevated temperature has a similar effect. Although wool has a substantial moisture adsorption capability, its resistivity is low compared to that of the resin, i.e. the wool fiber is electrically conductive relative to the resin particle. Thus, it appears that the resistivity of the resin and the effective "interface resistivity" at the charge-transfer boundary establish the charge relaxation time.



The accelerated degradation of filter efficiency is the result of these reduced resistivities - caused by elevated temperature and the formation of surface-conductive films. The experimental evidence obtained in this study is consistent with this physical description of the degradation process. Quantitative expression of this phenomena would require the functional relationship between resistivity, moisture and temperature. Additionally, the single fiber efficiency parameter for the electrostatic collection mechanism must be determined for the filter. Such electrostatic single fiber efficiencies have not been well-defined for real filters. As a result, no attempt was made in this study to mathematically describe degradation of aerosol collection efficiency of resin wool filters.

#### CONCLUSIONS

Three types of electrostatic filters have been evaluated for degradation after exposures to an oil mist and at conditions of elevated temperature and relative humidity. All three types of filters degraded rapidly during continuous DOP exposure, and use of these filters should be avoided in such environments. A resin wool with greatly improved electrostatic charge stability (type B filter) is more susceptible to degradation at 42.5°C, 87.5% R.H. than are the electret and electrostatically-spun polymer. The use of moisture barrier bags did not have an appreciable effect upon the resin wool degradation. Thus, storage of resin wool filters at or below room temperature and 50% R.H. is advisable.

Electrostatic respirator filters are primarily used for protection against nuisance dusts, for which both the electret and resin wool are applicable. The electrostatically-spun polymer has a higher mechanical efficiency than these other electrostatic filters, but its characteristically high airflow resistance disallows comparable use. Although the electret is less susceptible to moisture and thermal degradation, it has disadvantages in requiring a cover scrim to maintain filter surface integrity, and in being considerably more costly than resin wool material. The degree and effect of degradation depends upon the aerosol application-as evidenced by the comparison of DOP and NaCl aerosol penetrations presented.

#### ACKNOWLEDGEMENTS

The author wishes to thank Michele Utgenannt and Charles Zeh for their assistance in the experimental program and Hank Filipiak for his help in preparing this paper.

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#### SYMBOLS

$C_V$  = coefficient of variation, (%)  
 $n$  = number of samples  
 $P$  = average penetration, (%)  
 $Q$  = airflow rate, (L/min)  
 $R.H.$  = relative humidity, (%)  
 $s$  = sample standard deviation

$t$  = time, (min, h, d)  
 $V$  = filter face velocity, (cm/sec)  
 $WVTR$  = water vapor transmission rate, (g/m<sup>2</sup>.24h)  
 $\omega$  = aerosol concentration, (mg/m<sup>3</sup>)  
 $\Delta P$  = airflow resistance, (cm w.c.)

# Aerosols

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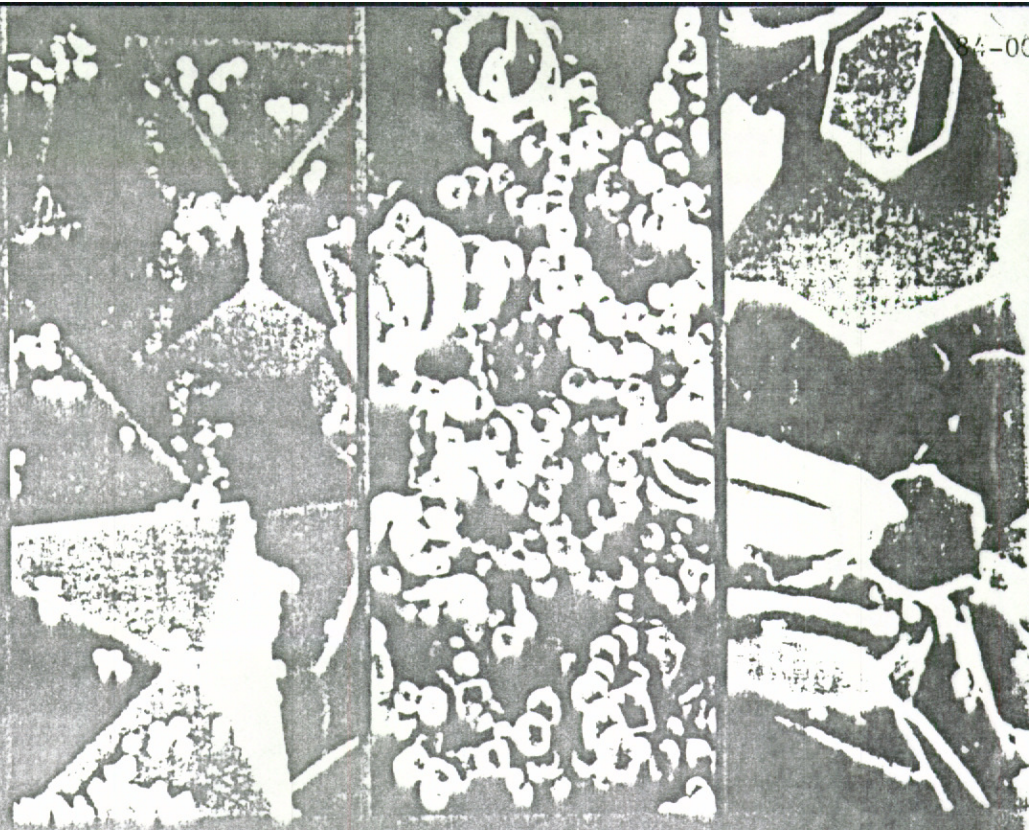
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# Aerosols

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## ELECTROSTATIC ENHANCED FILTRATION

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### EXTENDED ABSTRACT

#### Introduction

The requirements for clean air are becoming increasingly stringent. Small, submicron particles at low concentrations often must be eliminated, because even small particles can cause damage to products in clean rooms or to humans in nuclear power plants.

Fiber filters are often used for the collection of submicron particles. The collection of particles is caused by diffusion, interception and inertia. As a result of these overlapping effects one finds a maximum of particle penetration in the submicron size range.

One way of decreasing the particle penetration through a filter is to reduce the fiber diameter, but this has the disadvantage of causing an increase in pressure drop. Another possibility is to make use of electrostatic effects which can reduce the particle penetration without causing an increase in pressure drop. This is the case with electret filters.

In this paper we report on the investigations of electrostatic effects in commercially available fiber filters (1) carrying charges from the production process.

#### Experiments

##### Generation and Characterization of Aerosols

The fractional penetration was determined using DOP-particles and NaCl-particles in the size range,  $0.035 \mu\text{m} < D_p < 0.7 \mu\text{m}$ . The aerosol generator consists of an atomizer followed by different types of conditioners (2). Nearly monodisperse DOP-aerosols ( $\sigma_g = 1.3$ ) were produced. The geometric standard deviation of NaCl-particles was  $\sigma_g = 1.8$ . The aerosols differed with respect to particle size and charge. The particle number concentration of DOP-particles upstream and downstream of the filter was determined with an electrical aerosol detector. The NaCl-particle number concentration was measured with a continuous flow condensation nuclei counter.

##### Description of filters

Three different fibrous filters (Freudenberg/Germany) were investigated (table 1).

Filter	Fiber Diameter $D_f$ [ $\mu$ m]	Solidity $\alpha$ [-]	Filter Thickness $L$ [cm]	Velocity $V_a$ [cm/s]	Pressure Drop $\Delta p$ [pa]	Reynold-Number $Re$ [-]	Knudsen-Number $Kn$ [-]
Filter / carbonate	1,8	0,03	0,06	2 5	16 35	0,024 0,006	0,087
Filter / carbonate	1,5	0,067	0,07	2 5	130 350	0,002 0,005	0,073
Filter / SS Fiber	1,3	0,17	0,08	2 5	175 430	0,00173 0,00433	0,1

1. Dimensions, Pressure Drop and Flow Regime of Investigated Filters

-filter is made of polycarbonate fibers with diameter  $D_f = 1.8 \mu m$ . This filter layer of which further data are given in Fig. 1 is supported by another filter layer of fibers with diameter  $D_f = 20 \mu m$ , which does not contribute to the collection of submicron particles. To eliminate large particles a third filter layer with fiber diameter  $D_f = 10.5 \mu m$  is placed in front of the main filter layer. The FA-filter which again does not contribute to the collection of submicron particles. The FB-filter has the same three layer structure. The main layer differs with respect to fiber diameter and solidity. Both filters carry charges as a result of the electrostatic process. The charge of the fibers is in the range of  $0.12 C/m$  to  $8 \cdot 10^{-11} C/m$  (3). The VS-filter consists of charged glass fibers with diameter  $D_f = 1.3 \mu m$ . It is a layer filter. The penetration was determined for two face filters and the corresponding pressure drops are given also in Fig. 1. Also included are the Reynold- and Knudsen numbers.

Penetration of the Results

Fig. 1 the fractional penetration  $P$  of the FA-filter is shown for different charge conditions of filter and particles. Results shown refer to a face velocity of  $5 \text{ cm/sec}$ . The upper curve refers to the case where no electrostatic effects are involved. The shape of this curve is determined by mechanical effects of diffusion and interception. The penetration decreases slightly for neutralized aerosols because of electrostatic effects. A strong decrease in penetration is observed, if the fibers are charged. For uncharged particles the penetration is caused by dielectrophoretic forces. The rapidly decreasing penetration with increasing particle diameter occurs, as a consequence of the dielectrophoretic force, which increases with the square of particle diameter. In the case of charged and neutralized aerosol the penetration is further decreased because of Coulomb effects. The Coulomb forces for a particle with a certain charge decreases with increasing particle diameter, but on the other hand, the bigger particles carry more

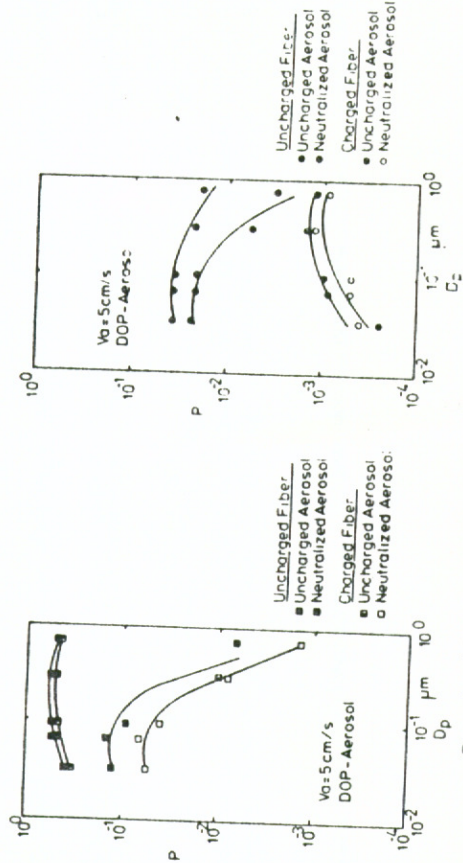


Figure 1. FA-Filter

Fig. 2 shows the corresponding fractional penetrations of the FB-filter. The reduction of fiber diameter and the increase of solidity results in a considerable decrease of fractional penetration by a factor of ten. The reduction in penetration caused by electrostatic effects are comparable to those of the FA-filter (Fig. 1). The reduction of the face velocity reduces the fractional penetration of all the investigated filters under all conditions.

In fig. 3 the fractional penetrations of the three filters for a face velocity of  $5 \text{ cm/sec}$  and neutralized DOP-particles are compared. For small particles the penetration of the FB-filter is smaller than that for the VS-filter, in spite of the fact that the pressure drop is higher in the case of the VS-filter. In the case of the VS-filter the collection of particles is only caused by mechanical forces, whereas in the case of the FB-filter, electrostatic effects are also involved.

For practical applications the dynamic behavior of a filter is most important. Thus far the particle loading of the filter was negligible. In order to determine the changes in filter behavior with loading, the FA-filter was loaded with liquid DOP-particles and solid NaCl-particles. The particle mass in the filter has been calculated from the measured number of collected particles and their size. The results are shown in fig. 4. In the case of DOP-particles the penetration increases with increasing particle mass loading. The penetration of neutralized aerosol is shifted to lower values because of the strong Coulomb forces acting on the particles. We believe that the increase in penetration is caused by a change in the charge loading of the fibers by particle deposition. Also changes in the structure may also occur.

ELECTRIC STIMULATED HEPA-FILTER FOR PARTICLES 0.1 μm

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EXTENDED ABSTRACT

Introduction

This paper presents the results and conclusions following the researches on an electric stimulated HEPA-Filter. Depending on the utilized filtering media and on the electric configuration, it has been obtained an efficiency between 99,99 % up to 99,99995 % for 0.1 μm particles, with a pressure loss dramatically smaller than that resulted by using mechanical HEPA-Filters without electric stimulation. Achieving a Super-HEPA-Filter for 0.1 μm level particles or smaller ones and, at the same time, reducing Δp are, in fact, two contradictory requirements for a mechanical filter. More than that, in the near future it will be surely necessary to filter particles under 0.1 μm very efficiently, for example about 0.04 - 0.05 μm and this performance is impossible for a mechanical filter with a reasonable Δp.

The answer to these special requirements can be given only by the electrically stimulated Super-HEPA-Filters.

Working Principle

By passing through the first stage, the ionizer, the particles are electrically charged. Together with the air that flows through the filter, the dust particles will pass from the ionizer to the second stage, called collector. At here, the in the first stage already electrically charged particles lie in an electrical field, that favours the arrest of the particles (due to the Coulomb Forces) on the separators and in the filtering medium on fibres. The filtering medium lies, in fact, in the electrical field of the separators which are connected to a power supply. Under these circumstances the dielectric material fibres will polarize very strongly. Between the electrically charged particles and the polarized fibres very strong attraction forces will appear, so that the particles will be attracted to and fixed to the fibres with an efficiency which depends on the applied electrical value and on the filter geometry.

The Collector seen as a Condenser

The collector of the Electro-HEPA-Filter is, actually, a multiple condenser containing several dielectric sheets. In fact, to simplify the problem we can consider the filtering medium to be a first dielectric sheet and the insulating material of the separators to be a second dielectric sheet. Under these circumstances the dielectric permittivity will be different in the space between the electrodes. The system considered above changes in the course of time with the increase of the aerosol quantity retained in the medium and on the separators. Accordingly, the permittivities and the intensities of the electric field in the two sheets will change also. Theoretically, the problem of this "dynamic" condenser is much more complicated and this paper does not deal with it.

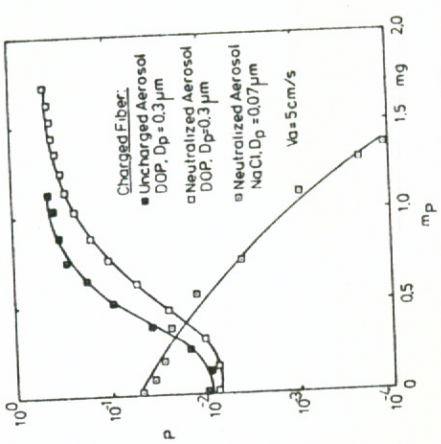


Figure 4. Penetration for FA-Filter against Mass Loading of Liquid and Solid Particles

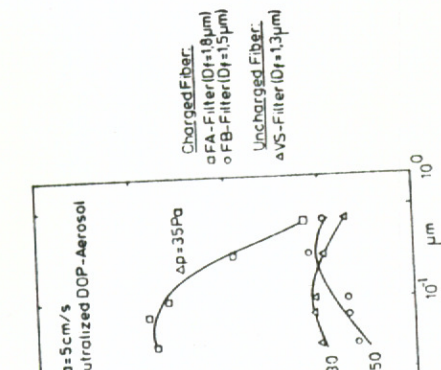
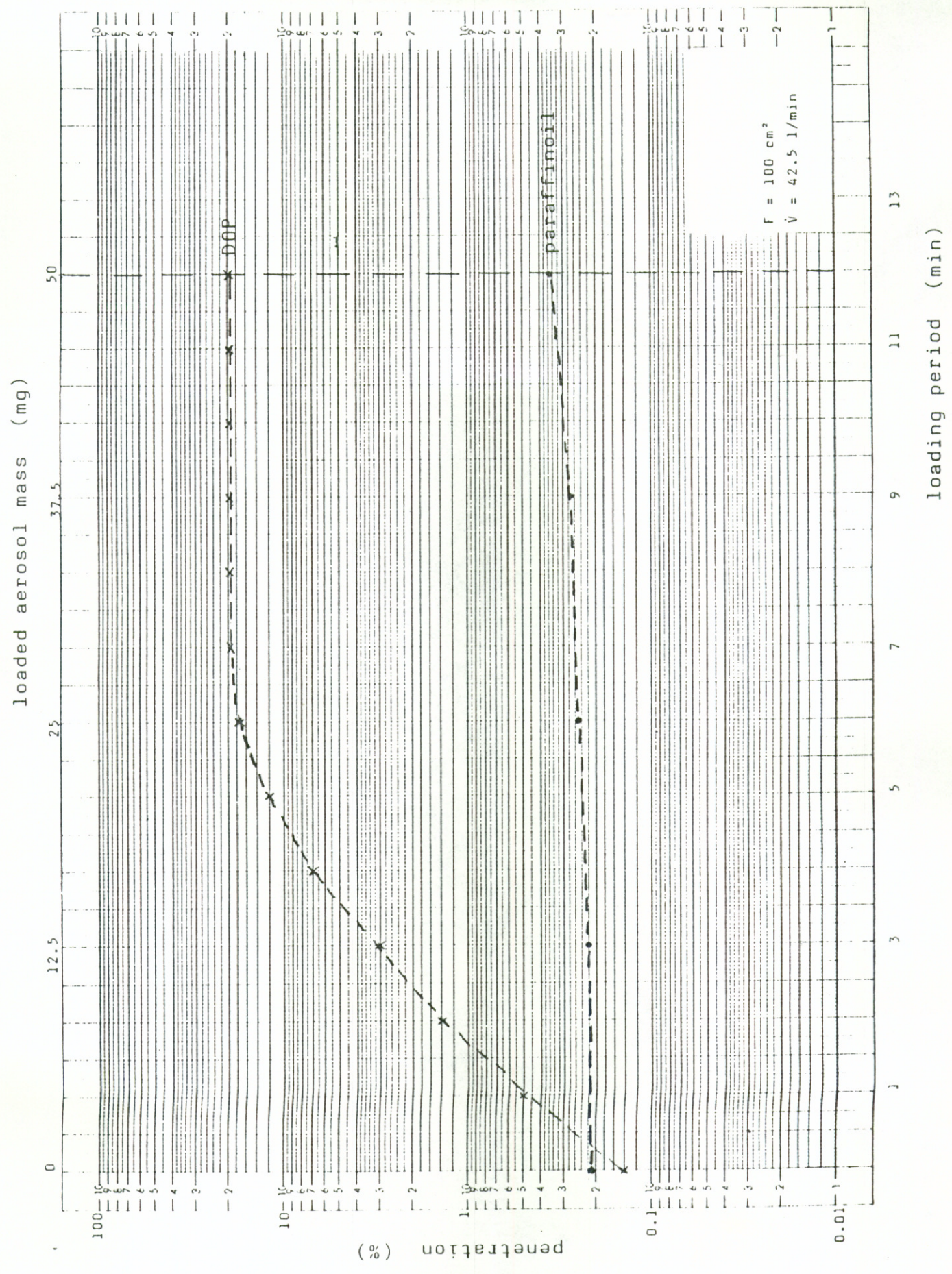


Figure 3. Penetration against Particle Diameter of Different Filters

The NaCl-particles show a totally different behavior. The penetration drops drastically with particle mass loading. We believe that this effect is mainly caused by structural changes in the filter by the deposition of solid particles.

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TIME DEPENDENCY OF COLLECTION PERFORMANCE OF ELECTRET FILTER

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EXTENDED ABSTRACT

Introduction

Electret filter is composed of "permanently" charged electret fibers and is capable of collecting fine particles at a high efficiency in the beginning of the filtration because of strong electrostatic effects, but its collection performance is reported to decrease with time. However, the time dependency of the collection performance and the reason of the decrease in collection efficiency are not well understood yet.

In this study, the stability of charges in the fiber was first tested by measuring the collection performances of chemically treated electret filters. Then the evolution of collection efficiency and pressure drop of an electret filter was measured using solid and liquid particles. Finally, a countermeasure for the decrease in the collection efficiency was discussed.

Property of electret filter

An electret filter used in this experiment is composed of polypropylene fibers with rectangular cross section. They carry positive and negative charges inside each fiber as shown in Figure 1. Its charging density is reported to be 34.2 nC/m-fiber. However, it is unknown that all charges stay stably inside the fiber. Furthermore, the value of charge density itself is still uncertain. Other relevant properties are listed in Table 1.

Collection performance of treated electret filter

To prepare the filters with different charging states, electret filters were treated by dipping for 24 hours into distilled water or 1N-NaCl solution or C<sub>2</sub>H<sub>5</sub>OH, and then their collection performances were measured using 0.5 μm PSL particles at various filtration velocities. Penetration of the filter was determined from the concentrations at filter inlet and outlet. They were measured by light scattering photometers. Figure 2 shows the experimental penetration at the initial stage as a function of filtration velocity. In the same figure, an estimated penetration of a fibrous filter composed of uncharged cylindrical fibers and with the same structure as the test filter is also shown by a solid line. As seen from the figure, the penetrations increase, i.e., the collection efficiency decreases, as filtration velocity increases. However, the penetration of electret filter is lower than that of estimated at any filtration velocities. Among the electret filters, the penetration decreases in the order of the treated filter with C<sub>2</sub>H<sub>5</sub>OH, the treated filters with H<sub>2</sub>O and NaCl, and the untreated filter. The penetration does not change by the chemical treatment of the filter, if charges were firmly attached in the fibers. The experimental result shows that some charges on electret fibers are removed by chemical treatment, especially it seems that most of charges are removed from the filter by the C<sub>2</sub>H<sub>5</sub>OH treatment, since the penetration

becomes comparably large as uncharged filter. This is probably caused by the difference in the affinity of of chemicals to the filter material.

Time dependency of filter performance

With proceeding of the filtration, the captured particles accumulate on fibers in the filter and the electrostatic effect becomes weaker so that the collection efficiency of the filter decreases with time. However, its decreasing trend is quite different depending on whether solid or liquid particles are filtrated. Figures 3 and 4 show the time dependancies of collection performances of the electret filters by the collections of solid stearic acid and liquid DOP particles. For the case of solid particles, the collection efficiency of the untreated filter gradually decreases with time in the early stage of the filtration because captured particles form dendritic agglomerates and cover the fiber surface so as to weaken the electrostatic effect of the fiber. After a certain period of time, the collection efficiency of the filter increased again, because the effect of the agglomerates on the collection of particles prevails the degradation of electrostatic effect. On the other hand, the collection efficiency of the treated filter increases with time and finally reaches to 100%, because the previously captured particles always positively contributes to the collection of upcoming particles.

For the case of liquid particles, the collection efficiency of the untreated filter decreases but that of C<sub>2</sub>H<sub>5</sub>OH treated filter increases somewhat with time in the early stage of the filtration. On the contrary to the solid particles, the collection efficiencies of both filters finally reach to the almost same asymptotic efficiency, because captured particles never form dendritic agglomerates unlike solid particles but cover the fiber surface with droplets so that electrostatic effect decreases with time but mechanical collection dose not increase so much with time. If electrostatic effect is proportional to the uncovered area with liquid particles and collection efficiency in covered area is given by the mechanical collection efficiency, a collection efficiency of a mist laden fiber is approximated by the following equation.

$$\eta = \eta_a - (\eta_a - \eta_k) \frac{m}{m_0} \quad (0 \leq m \leq m_0) \quad (1)$$

where,  $\eta$  and  $\eta_k$  denote the single fiber collection efficiencies due to electrostatic effect and mechanical effect respectively.  $m$  expresses the value of the mass of captured mist per unit filter volume,  $m_0$  when mist covers the whole fiber surface. Broken line in the Figure 4 shows the solution of a unsteady filtration equation using the above relation. It agrees very well with the experimental collection efficiency.

Decrease of the collection efficiency is unfavorable for the filter performance. Hence it is desirable for its practical use to find some countermeasure, which can prevent the decrease or decreasing rate of the filter efficiency with time. Applying the external electric field is considered to be one of the methods. Figure 5 shows the time dependency of the filter performances for untreated and treated filters. As seen from the figure, both efficiencies dose not change so much with time in compared with the efficiencies shown in Figure 4.

Table 1 Properties of electret filter

filter material	density of fiber $\rho$ (g/cm <sup>3</sup> )	width of fiber $d_{fw}$ ( $\mu$ m)	thickness of fiber $d_{ft}$ ( $\mu$ m)	packing density $\alpha$ [-]	filter thickness $L$ (mm)	charge density $Q$ (nC/m)
polypropylene	0.91	38	10	0.075	5.0	34.2

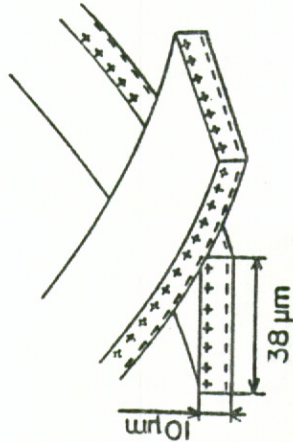


Figure 1 Schematic of an electret fiber

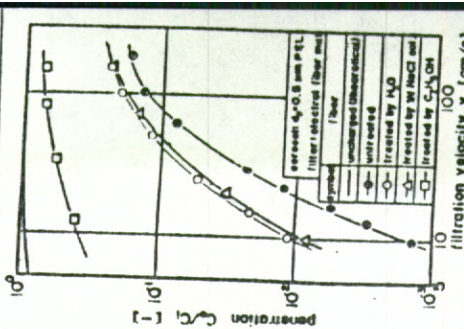


Figure 2 Penetration of variously treated electret filter

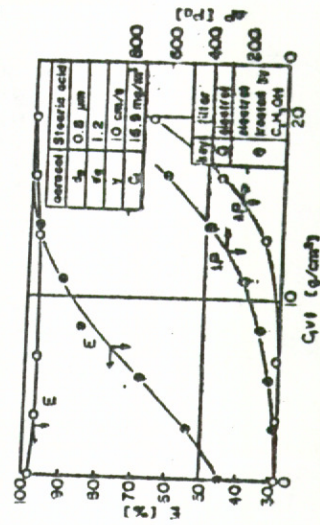


Figure 3 Time dependency of collection efficiency and pressure drop of an electret filter, when solid stearic acid particles are filtered



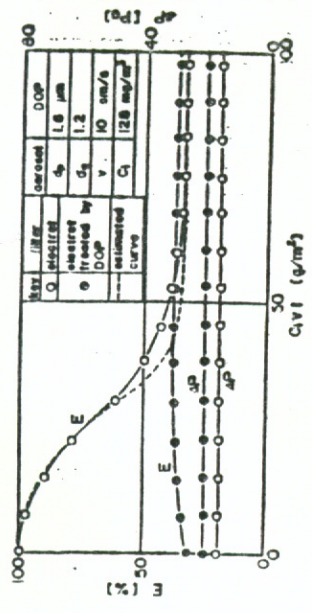


Figure 4 Time dependency of collection efficiency and pressure drop of an electret filter, when liquid DOP particles filtered.

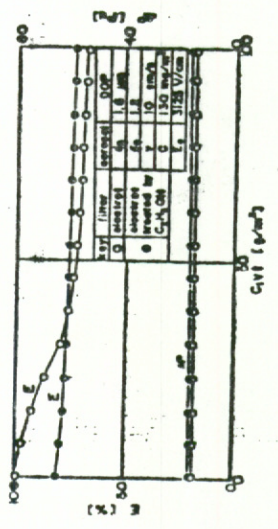


Figure 5 Time dependency of collection efficiency and pressure drop of an electret filter with external electrical field, when liquid DOP particles are filtered.