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AEROSOL PENETRATION THROUGH 9 MIL HV-70 FILTER PAPER WITH AND WITHOUT PINHOLES

By
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August 1963

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New York City, New York
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J.W. Thomas
G.D. Crane

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U. S. ATOMIC ENERGY COMMISSION
HEALTH AND SAFETY LABORATORY
NEW YORK, NEW YORK
ABSTRACT

Studies were made of the penetration of two polydispersed dioctylphthalate aerosols of different particle size distribution through 9 mil HV-70 type filter paper with and without pinholes at several different air velocities.

It was found, as was expected from elementary considerations, that the penetrations of the two aerosols of different particle size differed greatly for an intact filter, but approached the same value for the filters containing pinholes. This result implies that in testing filters or filter installations for leaks, aerosol particle size is much less important than in evaluating filter materials per se.

To account for the pinhole effect, a generalized equation was developed which relates change of aerosol penetration through a filter to air linear velocity. This equation was confirmed within limits.
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INTRODUCTION

Basic theory predicts, and numerous experiments have shown, that the penetration of an aerosol through a filter is a strong function of aerosol particle size. This statement, of course, implicitly assumes an intact paper without pinholes. For filters with relatively large pinholes, a different situation exists; the aerosol penetration is due mainly to flow through the pinhole rather than flow through the filter per se. Hence, one would assume much less change in penetration with particle size.

The reason for this assumption can easily be visualized. Let us suppose for example that there was a hole 0.25 millimeters in diameter in a filter. Penetration of an 0.3 micron aerosol through such a hole would be about 100%, as would penetration of a 1 micron aerosol; in either case the hole is hundreds of times as large as the particle and there is no reason to believe that there would be any significant removal of either size aerosol in passing through the hole. Thus if the filter material itself is high grade but with a leak, one would expect, for example, about the same penetration for an 0.3 micron aerosol as for a 1.0 micron aerosol.

Experimental confirmation of this assumption would have great practical significance since (1) there is reason to believe that leaks or holes in filters or filter installations are the principal cause of poor filtration systems, and (2) questions have been raised as to whether it is valid to test filter installations with Naval Research Laboratory (NRL) air operated generators, which produce a polydisperse aerosol containing particles larger than the standard 0.3 micron aerosol used in the acceptance test of filters and filter units. If it could be shown that particle size is not critical in evaluating filters with holes, it would be a strong indication that polydispersed aerosols are acceptable for testing filtration systems.

This paper describes an investigation made of the assumed lack of sensitivity of aerosol penetration through pinholed filters to particle size differences. A generalized equation for the pinhole effect is also developed and experimentally confirmed.
THEORETICAL ANALYSIS OF PINHOLE EFFECT

A. Effect of Particle Size on Aerosol Penetration Through Leaky Filters

Let us assume that there exists a leaky filter so that due to holes or poor seals 1% of the incoming aerosol leaks through it. We can see no reason to believe that there would be any appreciable aerosol removal from the stream passing through the leak.

Suppose the fractional penetration of the intact filter is \( P'_s \) for a given small aerosol (s) and \( P'_\ell \) for a given large aerosol (\( \ell \)). Suppose \( P_s \) and \( P_\ell \) be the fractional penetrations of the small and large aerosol through a filter with leaks. Then if the fraction of air through the leak is small, as it normally would be, to a good approximation

\[
P_s = P'_s + 0.01
\]
\[
P_\ell = P'_\ell + 0.01
\]

If both \( P'_s \) and \( P'_\ell \) are very small, which would certainly be the case with an absolute type filter, then, very nearly,

\[
P_s = P_\ell = 0.01
\]

Hence aerosol particle size would make very little difference in the penetration of a filter with holes.

For the case of intact filters having appreciable penetrations, the equations may be written in a more general form

\[
P_s = P'_s + \left( \frac{Q_h}{Q_t} \right)
\]
\[
P_\ell = P'_\ell + \left( \frac{Q_h}{Q_t} \right)
\]

where \( Q_h \) and \( Q_t \) are the flows through the hole and entire filter respectively. Solving the two equations gives

\[
P_s = P_\ell + \left( P'_s - P'_\ell \right)
\]  

(1)
Equation (1) may be used to calculate the penetration of a leaky filter for one aerosol from data on the penetration of another aerosol, and penetrations of both aerosols on intact filters.

B. Effect of Flow Rate on Penetration of Leaky Filters

Derivations of the equation for change of penetration with flow rate for a filter with pinholes or leaks have been given by Knudson and White\(^1\) and recently by Parrish and Schneider.\(^2\) The derivation of Knudson and White uses the assumption that the penetration of an intact filter is directly proportional to the flow rate. This assumption is generally not true, which makes the Knudson and White derivation of little use.

The Parrish and Schneider derivation is correct, granting their assumption that the flow through the hole is negligible compared to the flow through the main body of the filter. Their final equation however, is not given in an explicit form which may be readily used. The authors have developed a generalized derivation which is more direct and readily useful. The following assumptions are made in this derivation:

1. The hole is sufficiently small so that the air linear velocity through the main body of the filter is the same as if the hole were not present,

2. The aerosol that passes through the hole does not undergo any absorption by the hole edges,

3. Flow rate through the hole is proportional to the square root of the pressure drop through the hole,

4. Flow through the main body of the filter is proportional to the flow rate.

The following nomenclature is used:

\[ P = \text{penetration of a filter, with holes, at flow rate } Q, \]

\[ P' = \text{penetration of the filter, without holes, at the same flow rate } Q, \]
\[ P_1 = \text{penetration of the filter, with holes, at flow rate } Q_1, \]
\[ P_{1}^\prime = \text{penetration of the filter, without holes, at flow rate } Q_1, \]
\[ \Delta p = \text{pressure drop of filter at flow rate } Q, \]
\[ \Delta p_{1}^\prime = \text{pressure drop of filter at flow rate } Q_1, \]
\[ Q = \text{any flow rate,} \]
\[ Q_1 = \text{some flow rate at which } P \text{ and } P' \text{ values are known}, \]
\[ Q_h = \text{flow through the hole at total flow rate } Q, \]
\[ Q_{h1} = \text{flow through the hole at total flow rate } Q_1. \]

It is desired to write a general equation for \( P \), as a function of \( Q \), using the known quantities \( P', P_1', \) and \( Q_1 \), without using the unknown quantities \( \Delta p, \Delta p_1, Q_h, \) and \( Q_{h1} \). From assumptions 1 and 2, two equations may be written expressing that the total penetration is the sum of the penetrations through the main body of the filter and the hole:

\[ P = P' \left(1 - \frac{Q_h}{Q}\right) + \frac{Q_h}{Q} \]  \hspace{1cm} (2)

\[ P_1 = P_{1}^\prime \left(1 - \frac{Q_{h1}}{Q_1}\right) + \frac{Q_{h1}}{Q_1} \]  \hspace{1cm} (3)

From assumptions 1, 3, and 4, the following equations may be written:

\[ \frac{Q}{Q_1} = \frac{\Delta p}{\Delta p_1} \]  \hspace{1cm} (4)

\[ \frac{Q_h}{Q_{h1}} = \sqrt{\frac{\Delta p}{\Delta p_1}} \]  \hspace{1cm} (5)

The principal problem of the derivation is to eliminate the unknown quantity \( Q_h \) from equation (2).
From Eqs. (4) and (5),
\[ Q_h = Q_{hl} \sqrt{\frac{\Delta P}{\Delta P_1}} = Q_{hl} \sqrt{\frac{Q}{Q_1}} \]  
(6)

From Eq. (3)
\[ Q_{hl} = Q_{1} \left( \frac{P_1 - P_{1'}'}{1 - P_{1'}} \right) \]  
(7)

Substituting Eq. (7) into Eq. (6),
\[ Q_h = Q_{1} \left( \frac{P_1 - P_{1'}}{1 - P_{1'}} \right) \sqrt{\frac{Q}{Q_1}} \]  
(8)

Substituting Eq. (8) into Eq. (2),
\[ P = P' + (P_1 - P_{1'}) \left( \frac{1 - P_{1'}}{1 - P_1} \right) \sqrt{Q_1} \]  
(9)

which is the desired relationship. The penetrations \( P' \) and \( P_{1'} \) are usually very small compared to unity, so a very good approximation of Eq. (9) is:
\[ P = P' + (P_1 - P_{1'}) \sqrt{\frac{Q_1}{Q}} \]  
(10)

It is of interest to compare Eq. (10) with an equation that may be obtained from the work of Parrish and Schneider\(^2\) (P&S). Their equation: for the penetration \( P \) as a function of \( Q \) may be written:
\[ 1 - P = (1 - P') - \sqrt{\frac{A}{Q_1}} \]  
(9, P&S)

where \( A/B \) is a proportionality constant and is obtained from
\[ 1 - P_1 = (1 - P_{1'}) - \sqrt{\frac{A/B}{Q_1}} \]  
(7, P&S)

Solving (Eq. 7, P&S) for the quantity \( A/B \) and inserting in (Eq. 9, P&S), the authors obtained:
\[ P = P' + (P_1 - P_{1'}) \sqrt{\frac{Q_1}{Q}} \]  
which is Eq. (10) of this report.
EXPERIMENTAL PROCEDURE

Figure 1 is a schematic of the filter test apparatus. Aerosol from an air operated generator is diluted to a useable range with room air and pulled by the blower through the large 2' x 2' x 1' clean up filter. A sample of aerosol is removed and filter penetration determined by alternately pulling the aerosol at a known linear velocity through the filter contained in the filter holder and through the by-pass line to the photometer. Details of the apparatus follow.

Aerosol Generators - The two NRL type, air-operated DOP generators include the small generator specified in NRL drawing D3356 and the large generator specified as NRL drawing F3609. The small generator consists of two one quart cans, the first containing an atomizer head having four #60 drill (0.040") atomizing jets, and the second containing an impactor. The impactor slit is 0.36 inches by 0.031 inches. Aerosol flowing through the slit impacts on a plate 0.072 inches distant. The large generator consists of a five gallon can containing six atomizing heads, each head having four #60 drill (0.040) atomizing jets. No impactor is used with this generator. The size of the two different polydispersed aerosols produced was not determined. It was known from other work that the aerosols from both generators were in the 0.1 to 1.0 micron range, and that the large generator produced larger particles than the small generator.

Filter Holder - Figure 2 shows an exploded view of the filter holder. Several sets of area-defining metal plates are provided so that different filter areas can be used.

Flowmeters - The accurate capillary type flowmeters used consist of a fine capillary and a water manometer. The flow through the capillaries is measured as a function of pressure drop by use of an accurate wet type gas meter. An accuracy of ± 1% in flow may be obtained.

Photometer - The photometer, NYAEC 7219, was manufactured by National Instrument Laboratories, Washington, D.C. It is equipped with a light leak and light shield.

Essentially, the procedure was to (1) test an intact
filter paper sample with two different aerosols having different size distributions, and (2) retest the same filter paper, but with a hole, with the two different aerosols. If the test with the intact paper showed great differences in penetration, it was evidence that the particle sizes of the two aerosols were substantially different.

It was necessary to have readily available sources of two different aerosols so that the input to the filter paper under test could be rapidly switched from one aerosol to another without changing other test conditions, which might introduce errors. The small generator and large generator, previously described, were used for this purpose.

The comparison of filter penetration with the two different generators was done as follows. First, the photometer was warmed up and zeroed with respect to "meter zero" and stray light with clean air in the smoke cell. The flowmeter was adjusted to the proper flow rate. The blower was turned on, one of the generators placed at the duct inlet, and the generator air pressure adjusted to a standard value (5.0 ± 0.2" of mercury for the large generator, 8 1/2 ± 1 lb/in² for the small generator). The resulting aerosol was then pulled through the by-pass line for a sufficient time to sweep out the volume of the system, and the photometer reading noted. Then the connections were switched to the filter holder, and the filter penetration noted. This procedure was repeated several times to complete one test at one flow rate on one of the aerosols. The generator was then removed, and the other generator placed at the duct inlet, and the test repeated. In most cases, after completing the filter paper test on both of the aerosols, the first aerosol tested was again used to insure that no change had occurred in the apparatus or filter paper with time. The following other routine checks were made during the test.

Aerosol Stability - A sample of input aerosol was isolated in the smoke cell and the rate of change of the photometer reading with time noted (no flow in the cell). This change was always found to be slow, less than 5% per minute.

Leaks - The filter holder, photometer smoke cell, etc. were closed off and a vacuum applied. The rate of decrease of the vacuum, after removal of the vacuum source, gave an indication of magnitude of leakage, which was always found to be negligible.
RESULTS AND DISCUSSION

In the first set of experiments for determining penetration with and without pinholes, Table I, seven different samples of HV-70 paper were evaluated at linear air velocities from 0.17 to 15.0 cm/sec.

The results of Table I are compared in Table III to equation (1) which states that

\[ P_s = P_I + (P_{s'} - P_{I'}) \]  

or that the penetration of a pinholed filter is the same for two different aerosols, except for the differences in penetration of the intact filters. Agreement is considered to be fair. The three figures (Figs. 3, 4 and 5) graphically present the data from Table I. Figure 3 confirms that the pressure drop of 9 mil HV-70 paper is proportional to the flow rate over the range of flows studied. This verifies assumption 4 used in deriving the equation for change in penetration with flow rate of pinholed filters (Eq. 10). Figure 4 shows penetration of the two aerosols through intact 9 mil HV-70 paper versus air velocity, and shows that the two aerosols were of different particle size.

Figure 5 shows a plot of the ratio of penetration of the small aerosol to the large aerosol as a function of air linear velocity, for both intact and pinholed filters. This figure shows explicitly that while penetrations of intact filters might differ by a factor of about three with two different aerosols when pinholes (or leaks) are present the differences in penetration can fall to 50% or less. Had an absolute type paper been used instead of HV-70, theory indicates that the differences in penetration of pinholed absolute filters would have been much less. Figure 5 implies therefore that in testing filters or filter installations for leaks, particle size is much less important than in testing intact papers.

In the second set of experiments for confirming the pinhole equation, Table II, the same piece of filter paper, containing a 0.25 mm diameter hole, was evaluated at air linear velocities from 2.5 to 15.0 cm/sec using the two different
aerosols. Figure 6 is a plot of the data of this test, which also shows, for purposes of comparison, the penetration versus air velocity of the intact paper taken from Figure 4. Figure 6 shows in a striking manner the different behavior of an intact and a pinholed filter containing one 0.25 mm pinhole.

Results of Tables I and II show that aging effects were non-existent or negligible during the two sets of experiments. For example, in the test of the filter paper sample #4, Table I, the paper was tested (1) without holes, then (2) with holes, and (3) with holes sealed. The area of the holes, including the adjacent area covered by the rubber cement sealer was less than 0.1% of the area of the filter under test, therefore, the sealed filter was equivalent to an intact filter. If no aging effects existed, the penetration after sealing should be the same, within experimental error, as the penetration of the original intact filter. This was found to be the case. The lack of aging effects is confirmed by results of Table II, where the first and last tests on the paper at 2.5 cm/sec air velocity show essentially the same results.

Figure 7 is a comparison of values computed from the pinhole effect equation (Eq. 10) with the experimental results of Table II. The equation is written for linear velocity $V$ instead of volumetric flow rate $Q$,

$$P = P' + (P_1 - P_1') \sqrt{\frac{Q_1}{Q}} = P' + (P_1 - P_1') \sqrt{\frac{V_1}{V}}$$

(11)

In equation (11), a value of 5 cm/sec was selected for $V_1$. Corresponding values of $P_1$ and $P_1'$ were 1.29 and 0.27 for the small generator aerosol, 0.96 and 0.11 for the large generator aerosol, from Table III and Figure 4. Hence equation (11) became, for the small generator aerosol,

$$P = P' + 1.02 \sqrt{\frac{5}{V}}$$

(12)

and for the large generator aerosol,

$$P = P' + 0.85 \sqrt{\frac{5}{V}}$$

(13)

Values of $P'$ for the two aerosols were taken from Figure 4 which gave the theoretical curves in Figure 7. The figure shows fair agreement of theory and experiment. Parrish and
Schneider also made a test of equation (11), using a filter and an external synthetic leak combination having much lower penetrations, in the range 0.08 to 0.17%. Their results, also, confirm fairly well equation (11).

CONCLUSIONS

1. Particle size has much less effect on aerosol penetration through pinholed filters than it does on penetration through intact filters. This result implies that in testing filters or filter installations for leaks, aerosol particle size is less important than in evaluating filter materials per se.

2. A generalized pinhole effect equation

\[ P = P' + (P_1 - P_1') \sqrt{\frac{Q_1}{Q}} \]

where \( P \) and \( P' \) are the penetrations of pinholed and intact filters, respectively, at flow rate \( Q \), and \( P_1 \) and \( P_1' \) are the penetrations of pinholed and intact filters at some fixed flow-rate \( Q_1 \), has been developed.

3. The generalized pinhole effect equation has been confirmed within limits.
REFERENCES


<table>
<thead>
<tr>
<th>Filter Paper Number</th>
<th>Filter Paper Condition</th>
<th>Flow Rate (liters/min)</th>
<th>Pressure Drop (cm H2O)</th>
<th>Flow Rate (liters/min)</th>
<th>Pressure Drop (cm H2O)</th>
<th>Flow Rate (liters/min)</th>
<th>Pressure Drop (cm H2O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No holes</td>
<td>0.17</td>
<td>0.1</td>
<td>0.4</td>
<td>0.059</td>
<td>0.4</td>
<td>0.028</td>
</tr>
<tr>
<td>2</td>
<td>No holes, #80 drill</td>
<td>0.15</td>
<td>0.3</td>
<td>0.4</td>
<td>0.095</td>
<td>0.4</td>
<td>0.054</td>
</tr>
<tr>
<td>3</td>
<td>No holes</td>
<td>0.16</td>
<td>0.8</td>
<td>1.0</td>
<td>0.064</td>
<td>1.0</td>
<td>0.050</td>
</tr>
<tr>
<td>4</td>
<td>4 holes, #73 drill</td>
<td>0.17</td>
<td>0.8</td>
<td>1.0</td>
<td>0.057</td>
<td>0.8</td>
<td>0.057</td>
</tr>
<tr>
<td>5</td>
<td>No holes, #73 drill</td>
<td>0.17</td>
<td>0.8</td>
<td>1.0</td>
<td>0.057</td>
<td>0.8</td>
<td>0.057</td>
</tr>
<tr>
<td>6</td>
<td>No holes, #80 drill</td>
<td>0.17</td>
<td>0.8</td>
<td>1.0</td>
<td>0.057</td>
<td>0.8</td>
<td>0.057</td>
</tr>
<tr>
<td>7</td>
<td>No holes</td>
<td>0.17</td>
<td>0.8</td>
<td>1.0</td>
<td>0.057</td>
<td>0.8</td>
<td>0.057</td>
</tr>
</tbody>
</table>

Note: "Penetration, Large Generator" and "Penetration, Small Generator" are not shown in the table.
## TABLE II

**PENETRATION OF A FILTER WITH 0.25 MM. DIAMETER HOLE**

<table>
<thead>
<tr>
<th>Linear Velocity (cm/sec)</th>
<th>% Penetration, 9 mil HV-70 Paper</th>
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<tr>
<td></td>
<td>Small Generator</td>
</tr>
<tr>
<td>2.5</td>
<td>1.71</td>
</tr>
<tr>
<td>5.0</td>
<td>1.29</td>
</tr>
<tr>
<td>10.0</td>
<td>0.84</td>
</tr>
<tr>
<td>15.0</td>
<td>0.65</td>
</tr>
<tr>
<td>2.5</td>
<td>1.71</td>
</tr>
</tbody>
</table>
TABLE III
CALCULATED AND OBSERVED VALUES OF PENETRATION OF SMALL AEROSOL, $P_s$

<table>
<thead>
<tr>
<th>Filter Paper Number</th>
<th>Air Velocity (cm/sec)</th>
<th>Calculated $P_f + (P_s' - P_f') = P_s$</th>
<th>Observed $P_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.4</td>
<td>0.76 + (0.15 - 0.05) = 0.86</td>
<td>0.95</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>0.46 + (0.16 - 0.05) = 0.57</td>
<td>0.64</td>
</tr>
<tr>
<td>4</td>
<td>2.65</td>
<td>0.25 + (0.126 - 0.10) = 0.41</td>
<td>0.43</td>
</tr>
<tr>
<td>4</td>
<td>2.65</td>
<td>0.54 + (0.26 - 0.10) = 0.70</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>2.65</td>
<td>0.76 + (0.26 - 0.10) = 0.92</td>
<td>1.18</td>
</tr>
<tr>
<td>5</td>
<td>2.65</td>
<td>0.58 + (0.25 - 0.10) = 0.73</td>
<td>0.90</td>
</tr>
<tr>
<td>6</td>
<td>8.3</td>
<td>0.76 + (0.26 - 0.10) = 0.92</td>
<td>1.03</td>
</tr>
<tr>
<td>6</td>
<td>12.4</td>
<td>0.48 + (0.20 - 0.07) = 0.61</td>
<td>0.78</td>
</tr>
</tbody>
</table>
Figure 1. Filter Test Arrangement
1 - Rubber Gasket
2 - Metal Plate
3 - Filter Paper
4 - Backing Screen
5 - Indicated Air Flow

Figure 2. Filter Holder
Figure 3. Pressure Drop of 9 mil HV-70 Paper
Figure 4. Aerosol Penetration Through Intact 9 mil HV-70 Paper
Figure 5. Aerosol Penetration Ratios

Air Linear Velocity, cm/sec

$R = \frac{\text{Penetration, Large Generator Aerosol}}{\text{Penetration, Small Generator Aerosol}}$

(From Figure 4)
Figure 6. Aerosol Penetration of 9 mil HV-70 Paper, With and Without a Pinhole, as a Function of Air Linear Velocity
Figure 7. Test of Pinhole Effect Equation