NUREG/CR--2958

DE84 001184

NUREG/CR-2958
SAND82-7084
AN, CO, C3, C4, NL, 9R, 1S, 9U

# EXPEDIENT METHODS OF RESPIRATORY PROTECTION.
## II. Leakage Tests

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Final Report
30 March 1983

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Prepared for

Sandia National Laboratories
Albuquerque, New Mexico 87185
operated by
Sandia Corporation
for the
U.S. Department of Energy

Work performed under Sandia Contract No. 61-6824

Funded by
Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
Under Memorandum of Understanding DOE 40-550-75
NRC Fin No. A1042

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# ABSTRACT

The following readily-available materials were tested on a manikin connected to a breathing simulator to determine the fraction of an approximately 2-$\mu$m-diameter aerosol that would leak around the seal of the materials to the manikin's face: cotton/polyester shirt material, cotton handkerchief material, toweling (a wash cloth), a surgical mask (Johnson & Johnson Co., model HRI 8137), and a NIOSH-approved disposable face mask (3M, model #8710). The leakage tests were performed to supplement the measurements of penetration through the materials, conducted as the first phase of this investigation. The leakage tests were performed with the materials held on to the face by three methods, leakage fractions being determined from comparisons with the penetration of the same aerosol for the materials fully taped to the face. At a breathing rate of 37 liters per minute, mean leakages ranged from 0.0 percent to 63 percent. Mean penetrations exclusive of leakage ranged from 0.6 percent to 39 percent. Use of nylon hosiery material ("panty hose") to hold the handkerchief material or the disposable face mask to the face was found to be very effective in preventing leakage. Such a combination could be expected to reduce leakage around the handkerchief to about ten percent or less in practice, and around the mask to less than one percent, offering substantial protection from accidentally generated aerosols. The reduction in leakage around the mask provided by the hosiery material suggests the adaptation and use of such an approach in regular industrial hygiene practice. The third and final phase of this investigation is underway, in which the penetration of the materials by particles with diameters between 0.05 and 0.5 $\mu$m is being measured and the effectiveness of the methods for dose reduction in the presence of radioactive aerosols is being modeled.

# CONTENTS

# FIGURES

# TABLES

## ACKNOWLEDGMENTS

We appreciated the encouragement and support of Drs. David C. Aldrich and Daniel J. Alpert of Sandia National Laboratories, the useful comments of our colleagues at the School of Public Health (especially from Prof. Dade W. Moeller), and the suggestions of James A. Martin, Jr. of the U.S. Nuclear Regulatory Commission, especially the suggestion that nylon hosiery should be tested as a means of holding the household materials to the face.

## INTRODUCTION

This is a continuation of our previous work (1) on evaluating readily available materials for use in providing expedient respiratory protection in case of the accidental release of aerosols, due to such situations as fires, explosions, chemical spills, nuclear reactor malfunctions, etc.

Earlier investigations on expedient respiratory protection (2,3) used polydisperse aerosols of bacterial spores to determine the average penetration plus leakage measured by particle number count. Penetration plus leakage is the total fraction of the aerosol number concentration outside the mask that reaches the inside of the mask two ways: penetration is the fraction of particles of a given size which pass through the material; leakage is the fraction of the flow which passes not through the material but around it, through gaps in the seal between the mask and the face. Our previous study (1) determined penetration of these materials (those in Table I, except for the surgeon's mask and including a lower-quality towel material) at three face velocities (1.5, 5.0, 15 cm/s) as functions of particle (aerodynamic) diameter. The results were also presented in terms of the quality factor, q, the reciprocal of the pressure drop across the material multiplied by the natural logarithm of the penetration:

$$q=(1/\Delta P)ln(Pn) \tag{1}$$

in which Pn is the ratio of the number concentration downstream from the material to that upstream. Extrapolated to a pressure drop deemed acceptable (50 Pa, 0.2 inches of water, 0.5 cm of water), the materials tested gave, at 1.5 cm/s, penetrations of particles of 1 $\mu$m diameter ranging from .004 to .88.

In practice, the concentration within the face mask would be more than the penetration times the concentration outside the mask, because of leakage around the seal of the mask to the face. The distribution of such leakage values for a set of face masks (half-mask respirators) was summarized by Leidel (4). The goal of the present study was to determine the leakage for the materials studied in Phase 1, with the addition of the surgeon's mask (Johnson & Johnson Co. Model # HRI 8137), readily available at drugstores, and the deletion of the sheet material, which was less effective than the other materials tested.

## EXPERIMENTAL APPARATUS AND PROCEDURE

### Apparatus

Figure 1 shows the experimental set-up schematically. A Thermo Systems Incorporated (TSI) model 3050 vibrating orifice generator was used to generate a monodisperse (diameter of 1.8 $\mu$m) di-octylphthalate (DOP) aerosol for challenging the test respirators. The DOP aerosol, tagged with 5 percent by weight fluorescein, passed through a TSI model 3054 charge neutralizer before entering the exposure chamber. Flow in the chamber passed through a diffuser panel past a paddle wheel circulating fan to ensure that the aerosol was evenly distributed throughout the exposure chamber before exiting through the bottom diffuser panel to an exhaust line and high efficiency particulate air (HEPA) filter. A manikin head was placed in the center of the exposure chamber to provide a fairly realistic method of holding the test respirators (Figure 2). The materials tested are listed in Table I. The methods of holding test respirator material on the manikin face (Figure 3) were: a) completely seal all the edges with plastic (PVC) tape over the nose, around the cheeks, and under the chin (Figure 4); b) loosely hold the material on with four pieces of PVC tape on the corners of the mask (one on each cheek and one under each side of the chin (Figure 5) or hold by the straps provided on the commercial respirators; and c) hold to the face by a nylon support hosiery material ("panty hose") covering the entire manikin head (Figure 6). The manikin was of an U.S. Army design, used in testing military respirators, such that the facial features are based upon an average, clean-shaven, male. In addition, we covered the painted plaster material of the manikin by painting a thin film of PVC plastisol to provide a more skin-like surface for the test respirators to seal against.

The manikin was connected to an apparatus which mechanically simulated the breathing of a worker during a moderate level of activity. The volume of air inhaled in a minute ("minute volume") was 37.3 L; the respirator rate was 23 cycles per minute, having a breathing rate profile closely approximating that indicated by Silverman et al. (5) for a work rate of 622 kg-m/min.
The breathing machine drew the air through the manikin mouth, through a downstream absolute filter, and then through a check valve system into the breathing machine double-piston system. On exhalation, the air was pushed out of the pistons through the outlet side of the check valve system through a humidification system, where the air temperature was raised to 37°C ± 1°C with relative humidity of 97% ± 3%. The air exited the manikin mouth through a separate tube that encircled the inhalation tube, then flowed back out through the mask.

An upstream filter sampler was located in the chamber wall perpendicular to the axis of the manikin's mouth 13.3 cm above the mouth, 27.3 cm from the axis. Figure 2 includes a side view of the chamber.

## Test Procedure

The manikin inhalation and exhalation tubes as well as the face area were washed with distilled water to remove any fluorescein material left from previous tests. A fresh test respirator was applied to the manikin and the manikin was placed inside the exposure chamber and then attached to the breathing machine. The aerosol generator was started and fifteen minutes allowed to pass to bring the chamber aerosol concentration to equilibrium. Absolute filters were placed into the pre-washed upstream and downstream filter holders. Then the breathing machine and upstream sampler were run simultaneously for thirty minutes. After sampling was completed, the aerosol generator was shut off, and the sample filters removed for fluorescein analysis to determine DOP mass concentration upstream and downstream of the test respirator. For subsequent tests the used test respirator was removed, the washing procedure completed, and a fresh test respirator applied to the manikin for testing.

To determine the pressure drop across each test respirator, the test respirator was applied to the manikin and the resistance measured at a constant flow rate of 37.3 liters per minute (L/min), with a U-tube manometer. The measurements were corrected for the manikin resistance without a test respirator applied.

A stock solution of DOP and fluorescein in a 20-to-1 ratio by mass was prepared in 2-propanol. This solution was used to generate the test aerosol and also to prepare a standard curve. Samples of the test aerosol were collected on filters and then extracted. Because the fluorescence of fluorescein is maximum and the variability is minimum at pH values near 10.6, an appropriately buffered alkaline solution was used to extract the filters and to prepare the diluted standards. Concentrations of DOP aerosol were calculated by determining the concentration of the fluorescent tracer. Before being placed in the filter holders, as noted above, the 47-mm-diameter filters were formed by cutting them with a steel die from sheet stock of Mine Safety Appliances (Pittsburgh, PA) 1106-B all-glass filter paper with organic binder. To minimize contamination, the filters were pretreated with ethyl alcohol using a Buchner funnel-filtering flask set-up, then allowed to air dry. The extraction was done as follows: Ten ml of extracting-diluting solution ($NaOH/NaHCO_3$ buffer and water) were added and the solutions "ultrasonicated" for 2 to 5 minutes. Each solution was filtered through a new 0.2-$\mu$m Nuclepore filter to remove glass fibers dislodged during the "ultrasonication." The filtrate was collected directly in the cuvette for fluorescence measurement, the first ml being used to rinse the cuvette, then discarded. The fluorescence of the extract was measured and the fluorescein concentration determined by comparison with a standard curve. The latter was prepared by measuring the fluorescence of serial dilutions of the stock solution. Linear regression analysis was performed for standards ranging from zero (buffer extraction solution) to 100 ppb fluorescein. This method can detect as little as 0.1 ng fluorescein in 1 ml of solution and is linear up to about 1000 ng fluorescein in 1 ml.

## RESULTS

Table II shows the results of the measurements of chamber concentrations during five days of successful operation of the system, during which the penetrations were measured. The columns give the date, the number of assessments of chamber (upstream) concentration, the mean concentrations, the standard deviations of the measurements, and the coefficients of variation (the fractional standard deviations). As the table shows, the concentrations were measured typically with a standard deviation of about 4 percent of the mean concentration. The standard deviation of the ratio of two such concentration measurements would be about 6 percent of the mean of such ratios.

Table III summarizes the most important results. The first column indicates the mask or material used. The second indicates how many layers thick the mask or material was. The third column shows the manner in which the mask or material was attached to the manikin. The next several columns give the leakage plus penetration values measured (the ratios of the downstream to upstream concentrations). The penetration values were calculated after correcting for about 5% loss of particles when there is no mask present. These are followed by their means and standard errors of the mean (the standard deviations divided by the square roots of the number of measurements making up the mean). Finally, pressure drop means (in $Pa=N/m^2$) and standard errors are presented. Of the fully-taped conditions, only the 3M mask and the Johnson and Johnson mask allowed less than 20 percent of the 1.8 $\mu$m-diameter particles to penetrate. The leakages plus penetrations for the masks and materials, when not fully taped nor held on with the nylon hosiery, ranged from a mean of 19 percent to 74 percent. While the panty hose material was readily penetrated (98 percent) by these particles, when used with the 3M mask and with the handkerchief it succeeded in reducing leakage by holding the material more snugly to the face. This is discussed below.

The mean pressure drops for the fully taped materials ranged from 19 N/m$^2$ to 42 N/m$^2$, in comparison with the level of 50 N/m$^2$ (0.5 cm of water) selected as an upper limit for comfortable use. (However, Federal regulations for respirators, published in the *Federal Register* for 25 March 1972, allow resistances at 85 L/min to be as high as 500 N/m$^2$, 5 cm of water.) The lower pressure drops for conditions in which the materials are not fully taped are due to the flow through leakage paths, reducing the resistance. Such low resistance could alert the wearer to the lack of protection and produce some compensating adjustment of the material to reduce the leakage.

Table IV condenses the information on leakage plus penetration, giving the materials, the number of layers, the mean total penetration plus leakage, the standard deviation, and the coefficient of variation. From the coefficients of variation for the cotton shirt and the toweling, one notes that errors in concentration determination were probably dominant, as these coefficients of variation are not far from the 0.06 value predicted by error analysis for the concentration determinations alone. The coefficient of variation for the handkerchief fully taped is higher than expected, suggesting that some of the variation came from the material itself. The fully taped masks also gave higher coefficients of variation than expected, but this could indicate that the lower concentration (due to their low penetrations) was measured with greater inaccuracy, in percentage terms. Those situations for which the corners were taped only or where the mask was held on with the strap(s) provided had coefficients of variation not greatly different from the corresponding fully taped condition values.

One goal of these measurements was to estimate leakages. Table V gives the material, the number of layers, the mean penetrations for the conditions in which the materials were held on with tape at the corners or by the straps provided, the mean penetration for the fully taped condition, and the estimates of the leakages and the confidence intervals for the leakages.

The calculation of leakages was done using a formula developed as follows. The mass collected on the downstream filter (corrected for a few percent loss due to traversal through the manikin) is the product of the concentration ($c$) downstream, the total volume rate of flow ($Q_T$) and the time ($t$) and is equal to the indicated combination of upstream concentration ($c_0$), mean penetration ($\overline{Pn}$) and leakage flow rate ($Q_L$):

$$c\,Q_T t = c_0[\overline{Pn}(Q_T - Q_L) + Q_L]t \tag{3}$$

which can be shown to give a ratio of leakage flow to total flow of:

$$Q_L/\,Q_T = [(c\,/\,c_0) - \overline{Pn}]/(1 - \overline{Pn}). \tag{4}$$

Eq. (4) indicates that the inferred leakage ($\overline{c\,/\,c_0 - Pn}$) must be corrected by one minus the penetration of the material itself ($1 - \overline{Pn}$). This assumes that the penetration of the fabric itself under these conditions is the same as under the fully taped conditions, an assumption that is only approximately true. The leakage estimates were calculated by using Eq. (4). They are shown in Table V as the mean leakage values. The confidence intervals were first determined for the difference $c/c_0 - \overline{Pn}$ using standard statistical techniques that do not assume that both means have the same variance. The confidence intervals thus determined were then expanded by the factor $1/(1-\overline{Pn})$, and these values are given in the last column of the table. The mean leakages for the household materials ranged from 18 percent to 63 percent, for the conditions in which these were held to the face by having the corners only taped. The masks when strapped on gave mean leakages of 17 percent and 33 percent. The nylon hosiery material held the handkerchief well enough to the face to reduce the leakage to about 5 percent. Most significantly, the panty hose material held the commercial mask to the face so well that its leakage was reduced from about 17 percent to 0 percent, suggesting the incorporation of such nylon material in commercial masks to form a particularly effective combination for respiratory protection.

From the pressure drops measured with the masks on the manikin at 37 L/min flow and from the measurements made in our earlier study, one can infer the filter area of the masks and materials. The earlier measurements were interpreted by using a linear fit to the values of drag (pressure drop per unit face velocity) versus face velocity. Table VI gives the materials, the number of layers, the condition, the mean pressure drop, the two coefficients from the regressions, the inferred face velocity (V) and inferred area (A). V was obtained by solving a quadratic equation and A is the ratio of the volume flow rate to V.

A measurement of the assumed effective breathing area of the material was done for the white handkerchief and Oxford shirt material by the following procedure: The respective masks were fully taped to the manikin's face. An assumed effective breathing zone was traced out with a marker. The areas marked with superscript "b" in Table VII were areas of the mask which were not in contact with the face of the manikin. The other measurement, marked with superscript "a", are the areas that were not covered by the tape but do include the regions where the mask came into contact with the face of the manikin. The measurements marked with the superscript "a" can be taken as the possible effective breathing areas because it is arguable that air flow can also occur where the mask, not covered by taping, comes into contact with the face. The mean value for both types of area estimates was 0.0127 $m^2$ with a range of .0095 to .0142 $m^2$.

The values inferred from the flow resistance ranged from 0.0071 to 0.0247 $m^2$. The effective surface area measurement of the 3M mask #8710 was conducted in a slightly different fashion. Due to the hemispherical form of the 3M mask it was not possible to trace out and measure an effective surface area. The problem was alleviated by making a weight-by-weight to an area-by-area ratio. A square of approximately 2 cm x 2 cm was taken. The area of the "2 x 2 cm" square was 425 $mm^2$ as measured by an image analyzer system. From the ratio of the weight of this piece to the weight of the mask, the surface area of the mask was calculated to be 0.0213 $m^2$, which agrees rather well with the area calculated from the pressure drop data.

Table VIII shows values which can be used for a comparison between the tests with the manikin and the tests done earlier, using the materials in filter holders in an aerosol test loop, as the first phase of this project. The first column lists the materials. The second indicates the number of layers. The third gives the measured pressure drop (manikin tests). The fourth gives the inferred velocity (see Table VI). The fifth lists the measured penetration (manikin tests). Next are given the penetrations expected from the previous set of measurements, which determined the quality factor [Eq. (1)] for the materials. The quality factors change as face velocity and particle size change. They were determined previously at a particle diameter of 1.9 $\mu$m, a close approximation to the 1.8 $\mu$m droplets used in the manikin tests, and at 0.015, 0.05, and 0.15 m/s face velocities. The expected penetrations are calculated at the one velocity immediately above and below the inferred face velocity. The penetration measured on the manikin was between the two estimates for the 3M mask and the toweling, but it fell below both estimates for the shirt material and the handkerchief. (The estimates are made for the dry material; penetration estimates based on the wet material values from the earlier work would have been higher still for the shirt and the handkerchief.)

## DISCUSSION

### Experimental Conditions Versus Usage Conditions

The breathing cycle and the temperature and humidity of the air we used closely match those of humans and the differences should not introduce appreciable error into the results. Taping the masks to the face should have succeeded in reducing the leakage through the seals to zero, as results for large particles for the commercial mask demonstrated. Holding the mask to the face with tape at the corners only seems likely to produce more leakage than would be expected for a person who is still and not talking. Activity and conversation would be expected to increase leakage, though not necessarily above that measured with only the corners taped. Covering the materials with the nylon material has to be done carefully. If the materials collapse and cover the mouth and nose separately, the air flow resistance will increase, improving filtration efficiency for particles larger than a micrometer but making breathing more difficult. The flow resistance chosen was low in comparison with the upper limits allowed for respiratory protection devices; higher flow resistances would produce decreased penetrations of the material, somewhat offset by greater leakages. We chose our conditions to give representative to slightly conservative results, with regard to respiratory protection.

### Comparison With Results of Other Investigators

The fabrics tested by Guyton et al. (3) were worn by volunteers exposed to aerosols of bacterial spores *(bacillus globigii)* having, they reported, count median diameter of 1.3 $\mu$m and geometric standard deviation of 1.5. The penetration for these particles would be expected to be somewhat greater than that for the larger (diameter = 1.8 $\mu$m) particles we used. They tested the resistance to flow by measuring the pressure drop (as mm $H_2O$ = 9.8 N/m$^2$) for a constant flow of 10 liters per minute through 12.5 cm$^2$ of the materials. Our sheet, handkerchief and towel were similar to the ones they used. Table IX shows the pressure drop ($\Delta P$) and penetration (Pn) values measured by Guyton et al. and the pressure drop and penetration extrapolated from their measurements to single-layer values, $\Delta P/n$, and $Pn^{1/n}$. Also shown are our results, put in comparable terms. Our single-layer pressure drops tended to be higher by 50% or less than those measured by Guyton et al. Our single-layer penetrations are given as ranges, the lower end being the value with the material fully taped to the manikin, the upper end being the penetration plus leakage for the partially taped condition. The penetration results for the towel and the handkerchief showed good agreement with those obtained by Guyton et al. Our results with the cotton shirt showed somewhat higher penetrations than they had measured, and this is surprising given our larger particle size. The comparison is not clear-cut because of the range of particle sizes in the work of Guyton et al. and the likelihood of leakage around the seals the volunteers were trying to maintain (1).

The manufacturers of the disposable mask (3M Corporation) do not have data on penetration versus particle size for the mask, since the NIOSH approval required a different kind of test, 99% collection efficiency (by mass) on a silica dust having a number median diameter near 0.5 $\mu$m, and their experience has shown more leakage when a mask is tested on a manikin than when tested on a person, because of the tendency for skin to yield more and provide a better seal (6).

Extrapolation to Other Conditions

In designing respirators for emergency use, one may want to aim for a pressure drop of about 50 N/m$^2$ for comfortable use. Designing for pressure drops toward the high end of the acceptable range is desirable because collection efficiency increases with pressure drop, other things being equal. The designed mask's behavior would be more accurately predicted if the face velocity were within the range studied (0.015 to 0.15 m/s). Adjusting the thickness of the material (and to a lesser extent the area) allows one to achieve the design pressure drop. A flow rate near 37 L/min might well be used. We discuss next how our data can be extrapolated to aid in such a design.

Two limits for the relationship between the leakage and the pressure drop are that the flow in the leak is nearly laminar and depends proportionately on the pressure drop:

$$Q_L = k'(\Delta P) \tag{5}$$

or that the flow in the leak and its vicinity is nearly potential flow, with the velocity and thus volume rate of flow depending on the square root of the pressure drop:

$$Q_L = k''(\Delta P)^{1/2} \tag{6}$$

In the first case, as pressure drop increases, the leakage flow ratio ($Q_L / Q_T$) will stay constant, because the fabric flow is also proportional to pressure drop. In the second case, as pressure drop increases, the leakage flow ratio will decrease. In the analysis that follows, we chose a design pressure drop of 50 Pa and used the pessimistic assumption that the leakage is proportional to pressure drop.

To estimate the penetration of the fabrics/materials we used the quality factors determined in our previous study, using those for 0.015 and 0.05 m/s, as the velocities inferred from our current work were between these two values.

Penetration is estimated from the quality factors using:

$$Pn = exp(-q\Delta P) \tag{7}$$

and the quality factor values used are shown in Table X. We set ΔP=50 Pa. If L* is the leakage fraction ($Q_L / Q_T$), then the total of leakage plus penetration is

$$(1-L^*)exp(-50q)+L^* \tag{8}$$

The results of these analyses are shown in Figures 7 through 11. The values obtained by assuming the quality factors for 0.015 m/s are marked "A" and those for 0.05 m/s are marked "B".

The first of these figures, Figure 7, shows the results for the 3M mask #8710 according to this extrapolation. As the mask gets quite efficient, for the larger particles, the penetration is almost equal to the leakage, 0.17. The second figure, Figure 8, shows that the shirt material is expected to offer little protection, largely due to the leakage around the seal to the face. The towel, as shown in Figure 9, is expected to do somewhat better; however, its performance is also seriously limited by leakage. The handkerchief alone also did poorly at providing respiratory protection, but the handkerchief held on with the nylon hoisery material performed better, as shown in Figure 10. Even so, the reduction of concentration of 1-$\mu$m-diameter particles is not impressive, being roughly a reduction of 20 to 60 percent. Very significant reductions are shown in Figure 11, where the expected behavior of the 3M #8710 mask held with the nylon hosiery is shown. Twenty percent or less of 1-$\mu$m-diameter particles would be expected to reach an individual wearing this combination, the leakage having been reduced essentially to zero.

## Implications for Improved Designs

The measurements indicated that the nylon hosiery did not itself collect particles, but it served to reduce dramatically the leakage through the seal of the other materials to the face, especially for the commercial mask. Clearly, the incorporation of material such as panty hose to fix the mask to the face would be an improvement on the strap now used, and this applies whether the mask is used routinely or only in emergency situations.

It is important to note that under conditions in which the panty hose pulled the fabrics against the lips of the manikin, the filtration area was greatly reduced and the flow resistance became unacceptably high (10 to 100 times higher).

Having reduced the leakage to nearly zero percent with the use of the panty hose material as the method of holding the mask to the face, the limiting factor becomes the penetration of the material. The commercial materials tested showed appreciable penetration of particles of 1 $\mu$m diameter and smaller. However, glass fiber filters are available commercially that allow much less than one percent penetration of the most penetrating particle size (near 0.3 $\mu$m diameter). Such filters could be used instead of, or as a supplementary layer for, the commercial mask material. If they were used as the front layer, then the second layer would assure that the glass fibers themselves, if dislodged, would not reach the wearer. If the flow resistance were too high with such a design, it could be reduced by increasing the filter area (through making it cover a larger fraction of the face or through pleating) and by reducing the thickness of the layers used, given the extremely high efficiency of the glass fiber filter material. In practice, the glass fiber material might be placed as the central layer in a three-layer combination, to keep the glass fiber filter from being damaged. The design would also incorporate a mechanism for holding the filter to the face much like the panty hose.

## CONCLUSIONS

The leakage around the seals of the materials to the face of the manikin was so substantial as to compromise appreciably the effectiveness of the household fabrics studied as means of expedient respiratory protection: cotton/polyester shirt material, toweling, handkerchief material. Leakage around the commercial respirator mask and around the surgeon's mask was estimated to be about 1/6 of the flow for the first and about 1/3 of the flow for the second. The combination of the nylon stocking material (panty hose) and the handkerchief should reduce concentrations by a factor of two or more for particles larger than about 2 $\mu$m in diameter. The use of the nylon stocking material with the commercial respirator mask studied would reduce concentrations of 2-$\mu$m particles to about 2 percent or less of their original values, and perform even better for larger particles. The nylon stocking material would also allow the surgeon's mask studied to approach the efficiency it had when fully taped to the manikin's face, allowing only a few percent of particles near 2 $\mu$m in diameter to penetrate. Thus, some expedient methods of respiratory protection can be expected to produce substantial decreases in the amount of particulate material inhaled during emergency situations. Further, the modifications suggested for commercial masks now used routinely in industrial hygiene offer the promise of reducing to a few percent or less the amount of particulate material inhaled by workers wearing such masks.

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# APPENDIX: DETERMINATION OF FLUORESCEIN

## Introduction

This presents the methodology in greater detail than in the body of the report.

Concentrations of DOP aerosol were calculated after determining the concentration of a proportionately coexistent fluorescent tracer, fluorescein. A stock solution of DOP and fluorescein in a 20-to-1 ratio by mass was prepared in 2-propanol. This solution was used to generate the test aerosol and also to prepare a standard curve. Samples of the test aerosol were collected on filters and then extracted. The fluorescence of the extract was measured and the fluorescein concentration determined by comparison with a standard curve, prepared by measuring the fluorescence of serial dilutions of the stock solution. An appropriately buffered alkaline solution, having pH values near 10.6, was used to extract the filters and to prepare the diluted standards. The method can detect as little as 0.1 ng fluorescein in 1 ml of solution and is linear up to about 1000 ng fluorescein in 1 ml.

## Fluorescence Photometer

A Photovolt Model 540 fluorescence photometer was used for this study. The mercury vapor lamp output is directed through a primary broad band filter of 454 nm to narrow the wavelength range impinging on the sample. The sample fluorescence was filtered by a 520-nm broad-band secondary filter before impacting on the photomultiplier tube, set at a 90° angle to the incident beam. The spectral response curve of the tube peaks at about 400 nm and is approximately 50% peak at 520 nm. A special 1-cm path length quartz cell was used.

## Standard Curve

The stock solution was prepared by accurately weighing sufficient DOP and fluorescein, which, when dissolved in 2-propanol, became 100 ppm and 5 ppm respectively. The DOP was conveniently transferred to the weighing container with an automatic micropipette. Both ultrasonication and sufficient solvent (approximately 150 ml) were necessary to dissolve the fluorescein (approximately 20 mg.) rapidly.

Approximately 200 ml of 2-propanol (of especially low particulate content) from a newly opened bottle were placed in each of two 400-ml beakers, the first used for dissolving the previously weighed analytes then returning the resulting solution to the bottle, the second used to rinse the first beaker, quantitatively transferring all rinses to the bottle.

An extraction-dilution buffer solvent was prepared by dissolving 1.26 gm of sodium bicarbonate and 7 ml of 10 N NaOH in 500 ml $H_2O$ in a mixing cylinder and diluting to the mark with $H_2O$. (The sodium hydroxide solution was transferred by automatic pipette, while a 4-ml polystyrene vial was used for rough weighing the $NaHCO_3$; the latter can be approximated by marking the vial at the $NaHCO_3$ level and then for future use refilling to this mark.)

Working standards of 300, 100, 10, and 1 ppb were prepared by serial dilution of the 5-ppm stock solution using automatic pipettes and 100-ml mixing cylinders. All standards were made to the mark with the extracting-dilution solution.

The fluorescence of each working standard was determined while the extraction buffer served as the zero, and a standard curve was plotted on log-log paper.

## Sample Analysis

47 mm filters were cut with a steel die from sheet stock of 1106-B all-glass filter which contains a small percentage of acrylic binder. The filters were pretreated with ethyl alcohol using a Buchner funnel-filtering flask set-up, and allowed to air dry.

Using tweezers, exposed filters were transferred to a 150-ml (or larger) beakers, exposed side facing up. Ten ml of extracting-diluting solution were added with a Brinkmann Dispensette, and the solutions ultrasonicated 2 to 5 minutes.

In order, each solution was filtered through a new 0.2-$\mu$m Nuclepore filter to remove glass fibers dislodged during the ultrasonication. About 4 ml of solution was withdrawn into a disposable 5-ml plastic syring, which was then attached to a 13-mm Nuclepore "pop-top" holder; sufficient pressure was applied to the plunger to force the solution through the enclosed 2.0-$\mu$m Nuclepore membrane. This removed particulate matter, especially the dislodged glass fibers. The filtrate was collected directly in the cuvette for fluorescence measurement, the initial few drops of filtrate being used to rinse the cuvette walls, then discarded. A filtering flask-vacuum line setup was used along with a $H_2O$ wash bottle to clean the cuvette after each use.

The Photovolt fluorometer had a satisfactory 4-decade range but the zero needed occasional adjustments, particularly on the more sensitive settings. The more worrisome problem was inter-range agreement, which even after adjustment was apparently dependent on needle friction and direction of needle travel.

## Calculations

Linear regression analysis was performed for standards ranging from zero (buffer extraction solution) to 100 ppb fluorescein. A log-log plot was also constructed to obtain values between 100 and 300 ppb fluorescein because a slight degree of non-linearity was present beyond 100 ppb. These became the calibration charts.

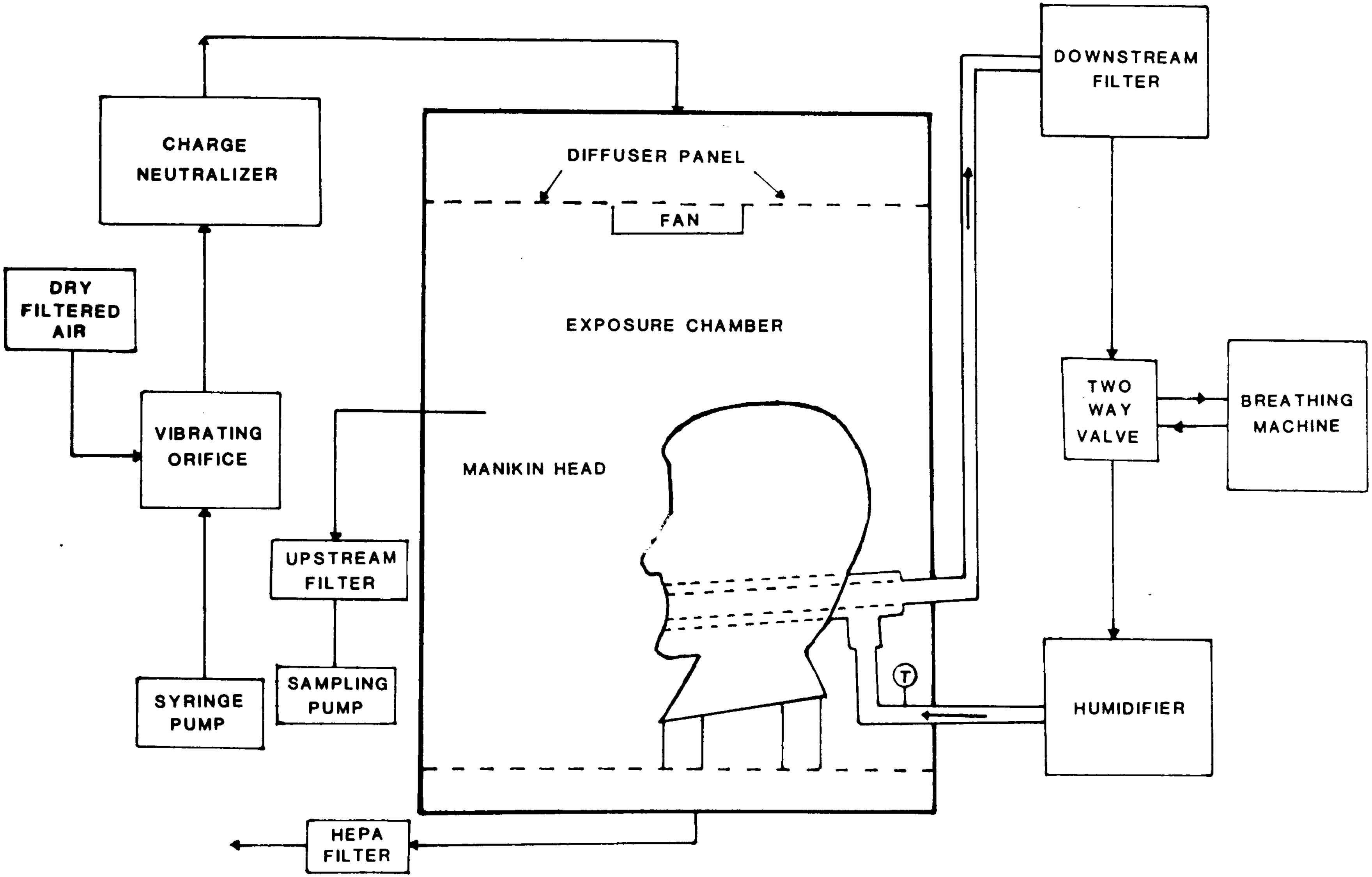

Figure 1 - Schematic flow diagram.

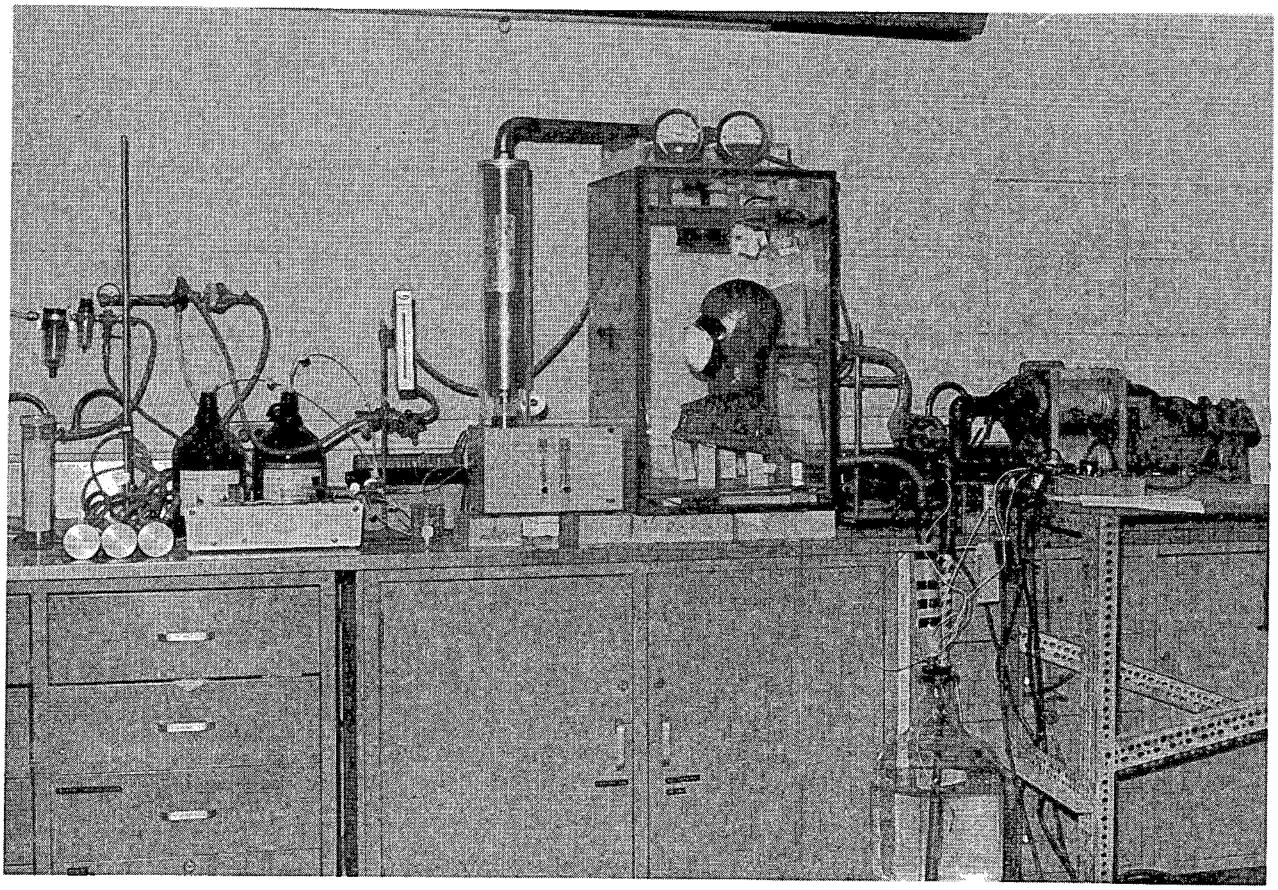

Figure 2 - Photograph of test equipment.

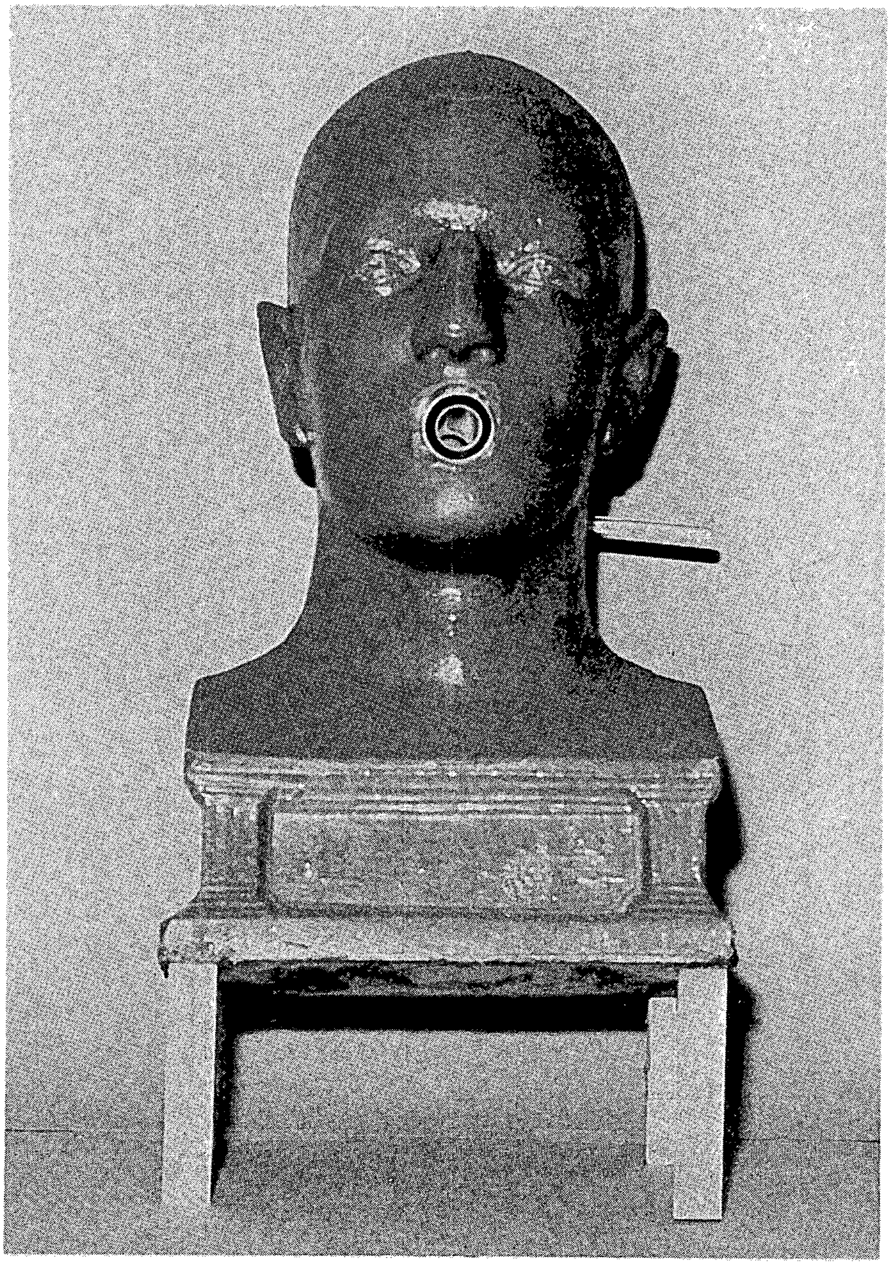

Figure 3 - Photograph of manikin from front.

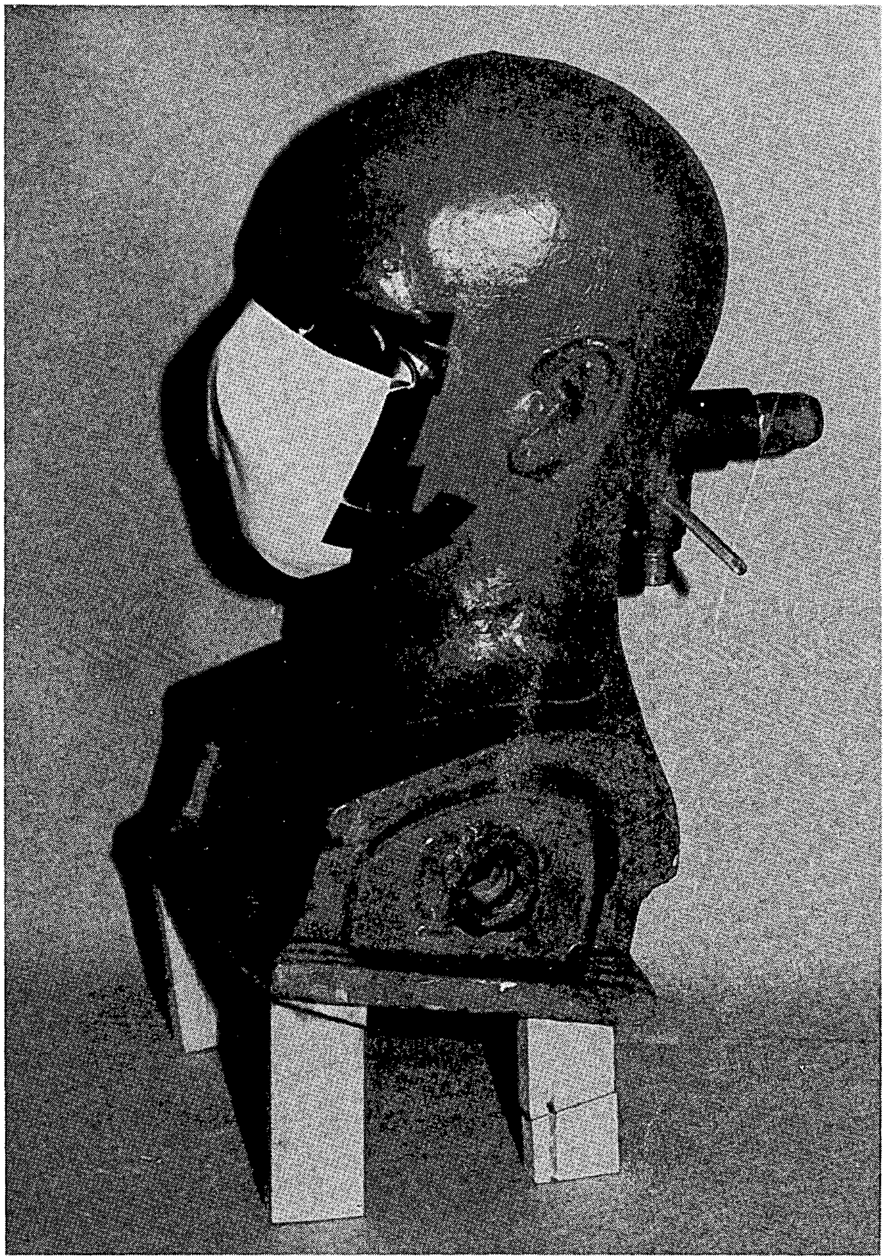

Figure 4 - Photograph of manikin with fabric fully taped to face.

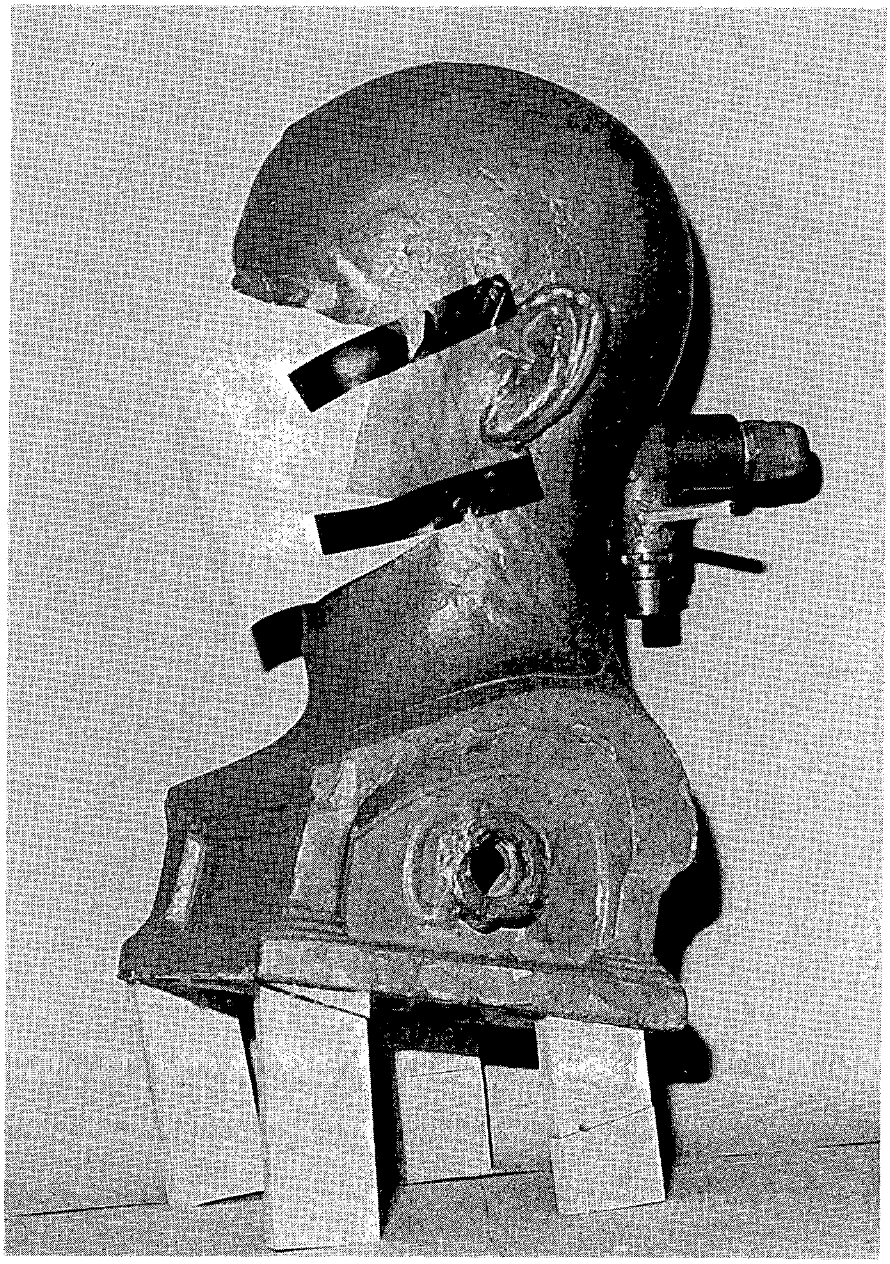

Figure 5 - Photograph of manikin with fabric corners taped to face.

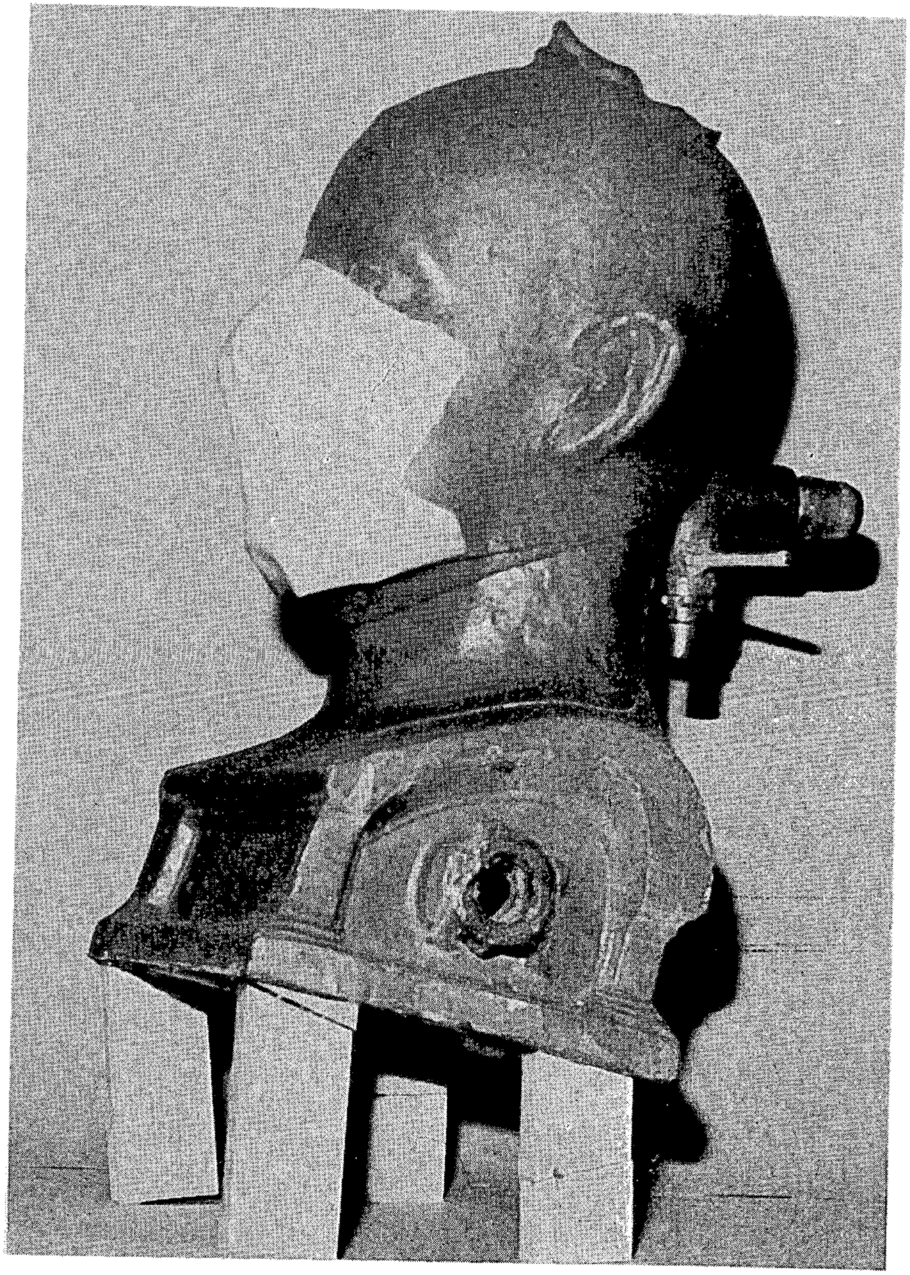

Figure 6 - Photograph of manikin with fabric held to face by nylon hosiery.

```
           1.00+
               -
Penetration    -
  Plus         -
 Leakage       -
            .80+
               -
               -
               -
               -
            .60+
               -
               -    B
               -      B
               -
            .40+
               -        B
               -
               -             B
               -
            .20+    A A            B            B
               -        A    A    A            A
               -
               -
               -
               -
            .00+
                +---------+---------+---------+---------+---------+
                .0       1.0       2.0       3.0       4.0       5.0
```

Particle Diameter, μm

Figure 7 - Estimated penetration plus leakage of 3M #8710 mask at 50 Pa pressure drop at (A) .015 and (B) .05 m/s face velocities versus particle diameter.

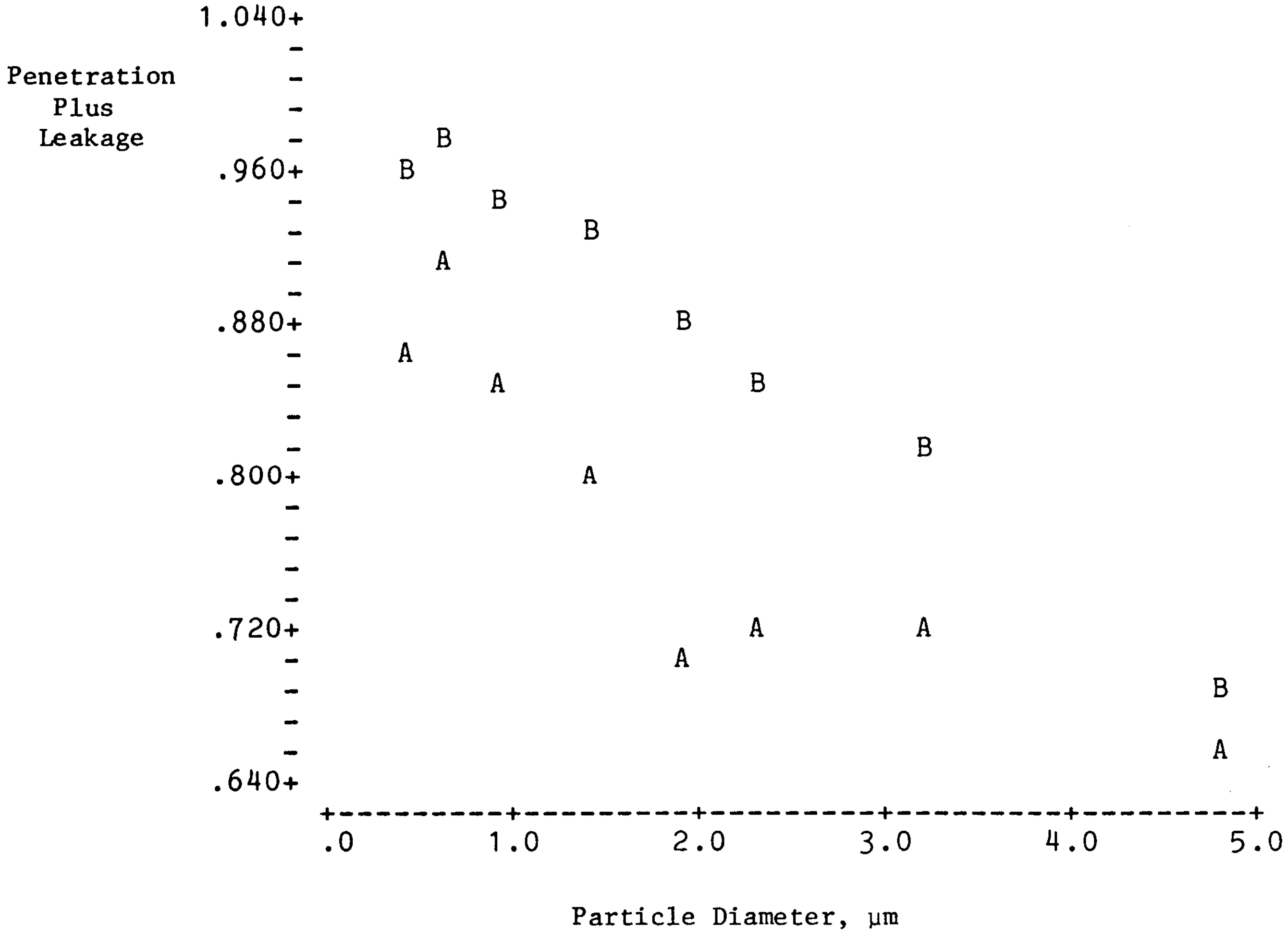

Figure 8 - Estimated penetration plus leakage of shirt (Oxford cloth) at 50 Pa pressure drop at (A) .015 and (B) .05 m/s face velocities versus particle diameter.

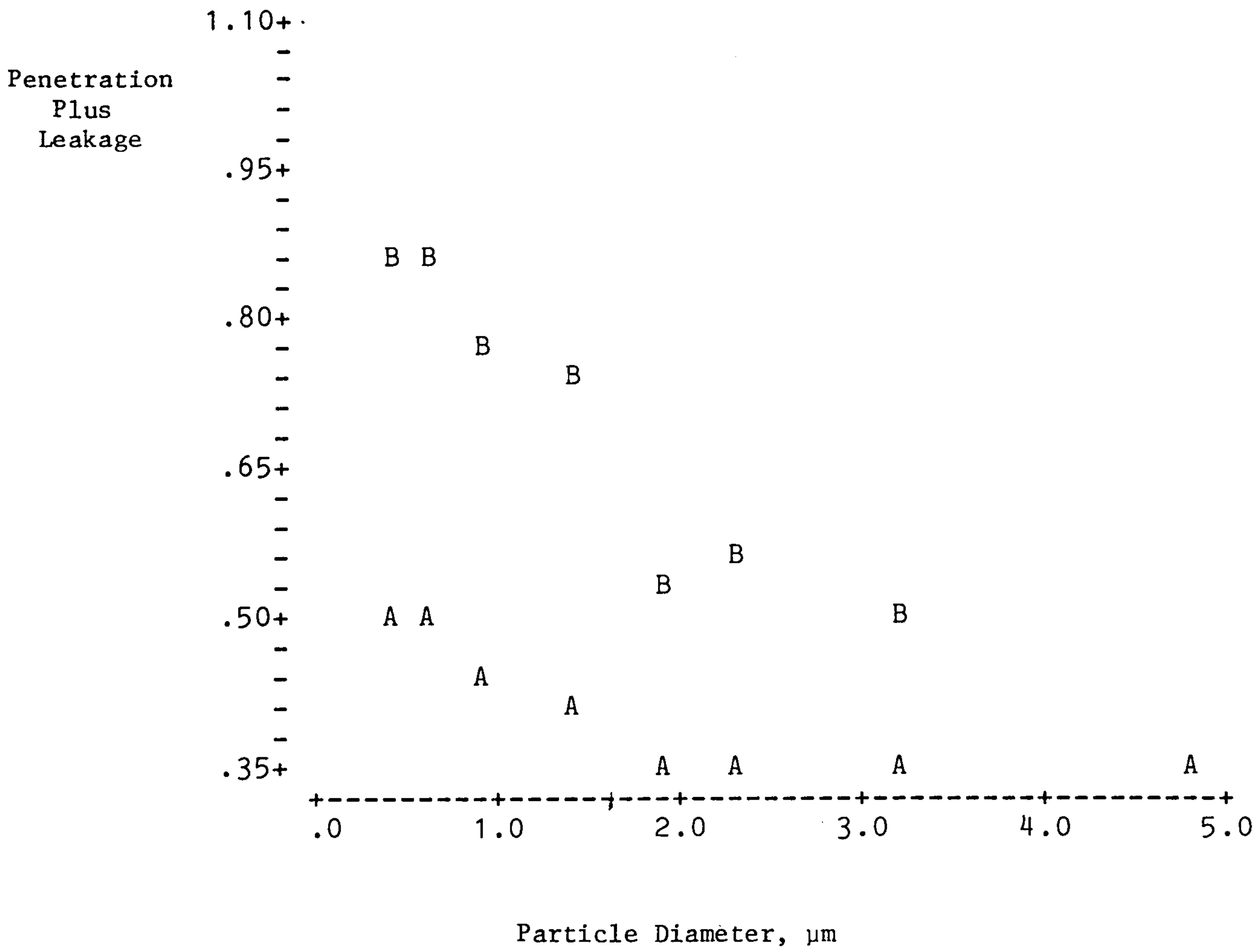

Figure 9 - Estimated penetration plus leakage of toweling material at 50 Pa pressure drop at (A) .015 and (B) .05 m/s face velocities versus particle diameter.

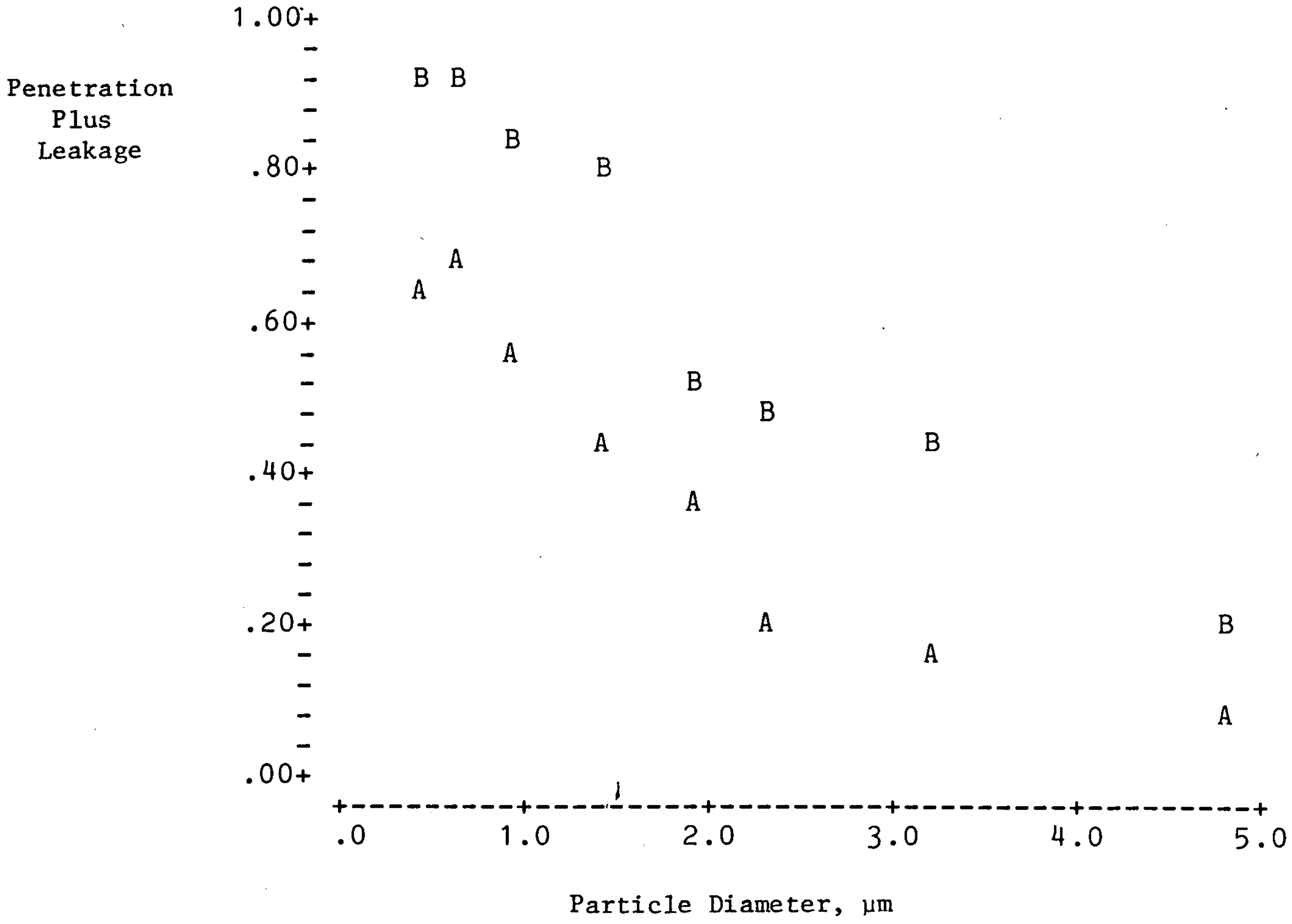

Figure 10- Estimated penetration plus leakage of handkerchief/nylon hosiery combination at 50 Pa pressure drop at (A) .015 and (B) .15 m/s face velocities versus particle diameter.

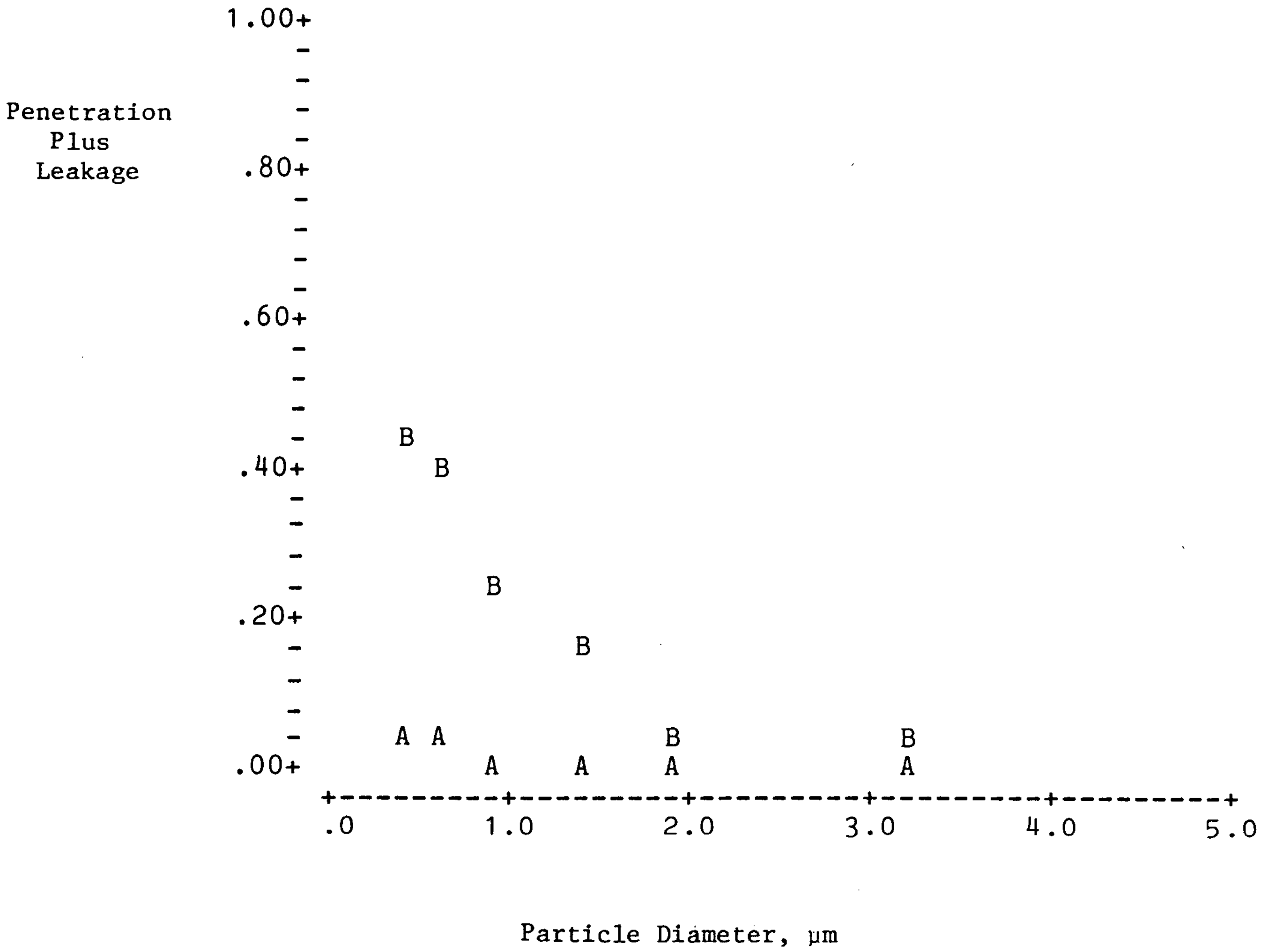

Figure 11 - Estimated penetration plus leakage of 3M #8710/nylon hosiery combination at 50 Pa pressure drop at (A) .015 and (B) .15 m/s face velocities versus particle diameter.

## TABLE I

### Test Materials

1. Single-use respirator mask, 3M corporation model #8710.
2. Handkerchief - white broadcloth 100% cotton 66/in by 58/in thread count.
3. Washcloth - terryweave 88% cotton, 12% dacron (RN-15964) polyester.
4. Oxford shirt material - 65% fortel polyester, 35% cotton, 46/in by 46/in thread count.
5. Surgeon's mask - disposable Johnson and Johnson model #HRI 8137.
6. Women's nylon hosiery ("panty hose").

## TABLE II

### Chamber Concentrations

| Date | Number of Measurements | Concentration, $\bar{c}$ (µg/L of DOP) | Standard Deviation, $s_c$ (µg/L of DOP) | $s_c/\bar{c}$ |
|---|---|---|---|---|
| 6/10/82 | 10 | .0595 | .00126 | .021 |
| 6/14/82 | 7 | .0695 | .00455 | .065 |
| 6/17/82 | 9 | .0679 | .00446 | .066 |
| 6/22/82 | 8 | .0673 | .00071 | .010 |
| 6/24/82 | 8 | .0603 | .00232 | .038 |
| means: |  | .0649 | .00266 | .041 |

## TABLE III

Penetrations (Corrected) and Pressure Drops

| Mask | # Layers | Condition | Leakage Plus Penetration (Pn, %) | | | | Mean $\overline{Pn}$ | Standard Error SE($\overline{Pn}$) | Pressure Drop at 37 L/min (N/m$^2$) $\overline{\Delta P}$ | SE($\overline{\Delta P}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 3M - #8710 | 1 | panty hose | 0.93 | 0.34 | 0.48 | | 0.58 | 0.18 | 41 | 0.8 |
| 3M - #8710 | 1 | fully taped | 1.8 | 1.0 | 1.8 | 1.3 | 1.5[a] | 0.24 | 42. | 0.8 |
| 3M - #8710 | 1 | strapped | 12.2 | 22.2 | 22.8 | 17.3 | 18.6 | 2.5 | 28. | 0.0 |
| J&J - HRI 8137 | 1 | fully taped | 5.7 | 3.5 | 3.4 | | 4.2[a] | 0.8 | 28. | 2.2 |
| J&J - HRI 8137 | 1 | tied | 27.9 | 44.9 | 35.6 | | 36.1 | 4.9 | 21. | 2.2 |
| Shirt (Oxford) | 4 | fully taped | 32.2 | 28.9 | 30.6 | | 30.6[a] | 1.0 | 27. | 3.0 |
| Shirt (Oxford) | 4 | corners taped | 84.5 | 68.7 | 70.1 | | 74.4 | 5.0 | 11. | 0.8 |
| Handkerchief | 4 | fully taped | 29.7 | 19.8 | 21.4 | | 23.6[a] | 3.1 | 35. | 3.8 |
| Handkerchief | 4 | corners taped | 61.6 | 64.8 | 76.5 | | 67.6 | 4.5 | 11. | 1.9 |
| Handkerchief | 4 | panty hose | 33.6 | 25.5 | 23.9 | | 27.7 | 3.0 | 34. | 2.2 |
| Toweling (Washcloth) | 1 | fully taped | 38.3 | 40.9 | 37.4 | | 38.9[a] | 1.0 | 19. | 3.0 |
| Toweling (Washcloth) | 1 | corners taped | 50.3 | 61.3 | 69.2 | | 60.3 | 5.5 | 8. | 0.8 |
| Toweling (Washcloth) | 2 | corners taped | 29.0 | 27.1 | 33.3 | | 29.8 | 1.8 | 18. | 4.4 |

[a] These tests involved taping the entire mask periphery to the manikin's face, which is not how the materials would be expected to be used in practice.

TABLE IV

Penetration Means, Standard Deviations, and Coefficients of Variation

| Material (layers) | Condition | Number of Measurements | Mean Leakage Plus Penetration, $\overline{Pn}$, % | Standard Deviation, $s_{Pn}$, % | Coefficient of Variation, $s_{Pn}/\overline{Pn}$ |
|---|---|---|---|---|---|
| 3M - #8710 (1) | h[d] | 3 | 0.58 | .31 | .53 |
| 3M - #8710 (1) | ft[a] | 4 | 1.5 | .35 | .23 |
| 3M - #8710 (1) | s[b] | 4 | 19. | 5.1 | .27 |
| J&J (1) - HRI 8137 | ft | 3 | 4.2 | 1.3 | .31 |
| J&J (1) - HRI 8137 | s[b] | 3 | 36. | 8.5 | .24 |
| Shirt-Oxford (4) | ft | 3 | 31. | 1.6 | .05 |
| Shirt-Oxford (4) | ct[c] | 3 | 74. | 8.8 | .12 |
| Handkerchief (4) | ft | 3 | 24. | 5.3 | .22 |
| Handkerchief (4) | ct | 3 | 68. | 7.8 | .11 |
| Handkerchief (4) | h[d] | 3 | 28. | 5.2 | .19 |
| Toweling (Washcloth) (1) | ft | 3 | 39. | 1.8 | .05 |
| Toweling (Washcloth) (1) | ct | 3 | 60. | 9.5 | .16 |
| Toweling (Washcloth) (2) | ct | 3 | 30. | 3.2 | .11 |
| Nylon Hosiery (1) |  | 3 | 98. | 8.3 | .08 |

a. fully taped b. strapped c. corners taped d. nylon hosiery

## TABLE V

### Leakage Estimates

| Material | Number of Layers | Mean Penetration Plus Leakage (%) |  | Leakage (%) |  |
|---|---|---|---|---|---|
|  |  | Not Fully Taped | Fully Taped | Mean[a] | 95% C.I.[b] |
| 3M - #8710 + Nylon Hosiery | 1 | 0.6 | 1.5 | -1. | -1.6, -0.2 |
| 3M - #8710 | 1 | 19. | 1.5 | 17. | 9, 25 |
| J&J - HRI 8137 | 1 | 36. | 4.2 | 33. | 11, 56 |
| Shirt (Oxford) | 4 | 74. | 31. | 63. | 31, 95 |
| Handkerchief | 4 | 68. | 24. | 58. | 35, 80 |
| Handkerchief + Nylon Hosiery | 4 | 28. | 24.[c] | 5.4 | -13, 23 |
| Toweling (Washcloth) | 1 | 60. | 39. | 34. | -4, 74 |
| Toweling (Washcloth) | 2 | 30. | 15.[d] | 18. |  |

a. Corrected difference in penetrations. See text.
b. Corrected confidence intervals for differences in mean penetrations. See text.
c. Assumed to be the same as without nylon hosiery.
d. Assumed to be the square of the penetration (0.39) of the single-layer when fully taped.

## TABLE VI

Data for Calculation of Mask Effective Area
(Assuming Material To Be Dry
for 37 L/min)

| Material | (# Layers) | Condition | $\Delta P$ (N/m$^2$) | n | a $\frac{(N/m^2)}{(m/s)}$ | b $\frac{(N/m^2)}{(m/s)}$ | V (m/s) | A (m$^2$) |
|---|---|---|---|---|---|---|---|---|
| 3M - #8710 | 1 | ft[a] | 42 | 1 | 1647 | -516 | .026 | .0241 |
| | | h[b] | 41 | | | | .025 | .0247 |
| Shirt | 4 | ft[a] | 27 | 4 | 223 | 125 | .030 | .0208 |
| | | h[b] | 37 | | | | .041 | .0153 |
| Handkerchief | 4 | ft | 35 | 4 | 231 | 200 | .037 | .0167 |
| | | h | 34 | | | | .036 | .0174 |
| Toweling (Washcloth) | 1 | ft | 19 | 1 | 577 | 361 | .032 | .0192 |
| | | h | 53 | | | | .087 | .0071 |

a. fully taped

b. nylon hosiery

## TABLE VII

Results of Measurements of Effective Breathing Areas

| Filter Type | Area Measurement ($m^2$) |
|---|---|
| Handkerchief | 0.0141[a] |
| Handkerchief | 0.0137[a] |
| Handkerchief | 0.0111[b] |
| Handkerchief | 0.0120[b] |
| Handkerchief | 0.0141[a] |
| Shirt-Oxford cloth | 0.0096[b] |
| Shirt-Oxford cloth | 0.0142[a] |

[a] Area includes portions touching cheeks.

[b] Area does not include portions touching cheeks.

## TABLE VIII

Comparison Between Manikin Tests and Previous Tests

| Material | Number of Layers | $\Delta P$ ($N/m^2$) | V (m/s) | Measured Penetration | Expected Penetration[a] at V=.015 m/s | at V=.05 m/s |
|---|---|---|---|---|---|---|
| 3M #8710 | 1 | 42 | .025 | .015 | .0005 | .088 |
| Shirt | 4 | 27 | .030 | .31 | .43 | .80 |
| Handkerchief | 4 | 35 | .037 | .24 | .47 | .61 |
| Toweling (Washcloth) | 1 | 19 | .032 | .39 | .18 | .62 |

a. $Pn = \exp(-q\Delta P)$, where q is a quality factor, determined in the previous work.

## TABLE IX

### Pressure Drop and Penetration Comparisons with Guyton et al. ( 3 ) Data

| Item | Thicknesses, n | Pressure drop, $\Delta P$ (mm $H_2O$) | $\Delta P/n$ (mm $H_2O$) | Penetration, Pn | $Pn^{1/n}$ |
|---|---|---|---|---|---|
| Handkerchief, cotton, man's | 16 | 36 | 2.3 | .06 | .84 |
| Handkerchief, cotton, man's | 8 | 18 | 2.3 | .11 | .76 |
| Handkerchief, cotton, man's | 1 | 2 | 2.0 | .72 | .72 |
| Handkerchief, cotton, man's | 4[a] | 12[b] | 3.1 | .24 - .68 | .70 - .91 |
| Handkerchief, cotton, woman's | 4 | 2 | 0.5 | .44 | .81 |
| Shirt, cotton | 2 | 7 | 3.5 | .34 | .58 |
| Shirt, cotton | 1 | 3 | 3.0 | .65 | .65 |
| Shirt, cotton | 4[a] | 13[b] | 3.3 | .31 - .74 | .75 - .93 |
| Towel, bath | 2 | 11 | 5.5 | .15 | .39 |
| Towel, bath | 1 | 5 | 5.0 | .26 | .26 |
| Towel, bath | 1[a] | 8[b] | 8.5 | .34 - .60 | .34 - .60 |
| Towel, bath | 2[a] | 17[b] | 8.5 | .15 - .30 | .39 - .55 |

a. Data in these rows are from this study.

b. Our measurements are extrapolated to the conditions used by Guyton et al.: $10^4$ $cm^3/(60s)(12.5\ cm^2) = 13.3$ cm/s; 1 mm $H_2O$ = 9.8 $N/m^2$; they were extrapolated using a and b from Table VI.

TABLE X

Quality Factors ($m^3/J$) at 0.015 m/s and 0.05 m/s for 3M #8710, Shirt Material, Toweling, and Handkerchief

| Particle Diameter, μm | 3M #8710 .015 m/s | 3M #8710 .05 m/s |
|---|---|---|
| .4 | .071 | .017 |
| .6 | .078 | .019 |
| .9 | .110 | .029 |
| 1.4 | .144 | .039 |
| 1.9 | .181 | .058 |
| 2.3 | .000 | - |
| 3.2 | .250 | .064 |
| 4.8 | - | - |

| Particle Diameter, μm | Shirt .015 m/s | Shirt .05 m/s |
|---|---|---|
| .4 | .009 | .0027 |
| .6 | .0052 | .0018 |
| .9 | .011 | .0037 |
| 1.4 | .015 | .0038 |
| 1.9 | .031 | .0084 |
| 2.3 | .028 | .011 |
| 3.2 | .029 | .014 |
| 4.8 | .053 | .036 |

| Particle Diameter, μm | Toweling .015 m/s | Toweling .05 m/s |
|---|---|---|
| .4 | .028 | .0054 |
| .6 | .029 | .0048 |
| .9 | .041 | .0083 |
| 1.4 | .051 | .011 |
| 1.9 | .090 | .025 |
| 2.3 | .091 | .023 |
| 3.2 | .091 | .028 |
| 4.8 | .173 | - |

| Particle Diameter, μm | Handkerchief .015 m/s | Handkerchief .05 m/s |
|---|---|---|
| .4 | .010 | .0019 |
| .6 | .0085 | .0015 |
| .9 | .012 | .0034 |
| 1.4 | .017 | .0047 |
| 1.9 | .022 | .014 |
| 2.3 | .040 | .016 |
| 3.2 | .041 | .018 |
| 4.8 | .069 | .036 |

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