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Expedient Methods of Respiratory Protection: III. Submicron Particle Tests and Summary of Quality Factors

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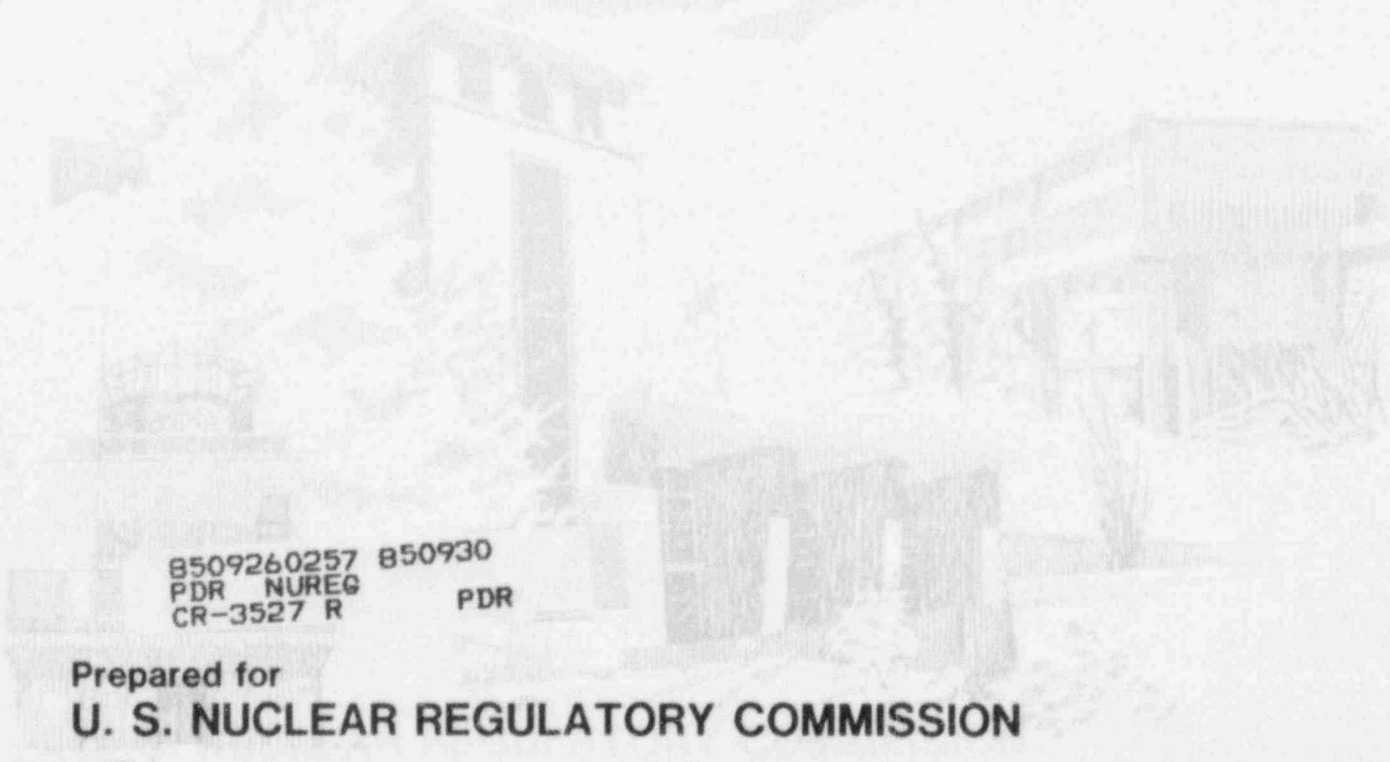

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III. Submicron Particle Tests and Summary of Quality Factors

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Previous Reports in Series

1. Cooper, D. W., W. C. Hinds, and J. M. Price, "Expedient Methods of Respiratory Protection," SAND81-7143, NUREG/CR-2272, prepared for Sandia National Laboratories, Albuquerque, NM (Nov. 1981).

2. Cooper, D. W., W. C. Hinds, J. M. Price, R. Weker, and H. S. Yee, "Expedient Methods of Respiratory Protection II: Leakage Tests," SAND82-7084, NUREG/CR-2958, prepared for Sandia National Laboratories, Albuquerque, NM (Mar. 1982).

Abstract

The efficacy of readily available materials, such as cotton fabrics, toweling, a surgical mask, and a single-use respirator, for providing emergency respiratory protection was evaluated by determining the filtration efficiency as a function of aerosol particle size over the size range of 0.001 to 5.0 µm and as a function of filtration face velocity. Filtration face velocity was set at 1.5, 5.0, and 15.0 cm/s. This report describes the equipment and procedures used to obtain efficiency measurements for particles 0.5 µm in diameter and smaller, and summarizes the results of all three phases of this research. Particles with diameters from 0.10 to 0.50 µm proved to be the most difficult sizes of particles to remove. Particles smaller than 0.10 µm were removed due to diffusion while particles larger than 0.50 µm were removed due to inertia and gravitational settling. Deposition of the smallest particles was favored by the use of low face velocities. A fractional efficiency curve was determined for each material at each velocity for comparison. Values of the quality factor, [-ln(penetration]/(pressure drop), were calculated. Quality factors were less for wet materials than for dry; less at high velocities rather than low; and best for the single-use respirator mask, next best for the surgical mask and often third best for the toweling (washcloth).

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Introduction

Testing of six materials has been continued from earlier work [1], where the efficiency of each material for removing aerosol particles as a function of particle size and face velocity was measured for aerosol particles 0.40 to 5.0 μm in diameter. The present work was carried out in two parts. The first part involved the use of a forward-light-scattering laser instrument (Particle Measuring Systems Inc., Boulder, Colorado), similar to the instrument used in the earlier work, but capable of sizing aerosol particles over the range of 0.10 to 1.0 μm in diameter. In the second part, particles 0.001 to 0.10 μm in diameter had their size distributions and concentrations determined by using a diffusion battery device in conjunction with a condensation nuclei counter.

The earlier two phases of this project included investigation of the effect of humidification on aerosol removal for several materials. However, due to time constraints this effect was only investigated in the first part of the present work.

A description of each material tested is shown in Table I. The lower-quality toweling reported in the earlier work was replaced by use of the Johnson & Johnson surgical mask in the present work. Thus, the data for particles from 0.40 to 5.0 μm in diameter were collected at this time for the surgical mask.

Experimental Apparatus

Part I: Particle diameters from 0.1 to 1.0 μm.

To determine the penetration of aerosol particles 0.10 to 1.0 μm in diameter through each material, the Dynamic Aerosol Test System (DATS) was used as done in the previous work. Shown in Figure 1, DATS consists of a main test chamber where the test aerosol flows past a 47-mm open-faced filter holder containing a test material. Total air flow through the DATS was monitored by a calibrated orifice meter, while separate exhaust and supply blowers along with a purge line provided means for running as a closed-loop system or exhausting up to 100% of the flow. By partially exhausting the system flow, one can maintain the test chamber at ambient

static pressure, thus preventing leakage of particle laden air into or out of the system. For experiments done at 95% relative humidity, the purge line provided a means to introduce steam generated by an electric steam generator (CHROMALOX, Wiegand Co., Pittsburgh, PA; 5 kg/hr capacity).

Upstream of the test chamber, a port directs the mineral oil aerosol (Arco Prime 200 oil) generated by a DeVilbiss #40 nebulizer into the clean air stream. A 90-degree sampling probe located parallel to the filter holder was used as the upstream sampler for monitoring the aerosol concentration in the test chamber. To determine aerosol penetration through the test materials, a downstream sample was taken from the air drawn through the filter holder and compared with the upstream sample. Samples were analyzed using the PMS Active Scattering Aerosol Spectrometer Probe (PMS model ASASP-X), which sized and counted particles 0.09 to 3.0 μm in optical equivalent diameter.

Each filtering material was cut into 47-mm diameter circles to fit inside the filter holder and enough layers were placed to give a resistance of about 0.40 inch of water (0.40 inch water = 1.0 cm water = 100 Pa) at a face velocity (volume air flow per unit filter face area) of 5 cm/s. The single-use 3M respirator and the Johnson & Johnson surgical mask were tested using only one layer, since a single layer would be the normal usage. The wash cloth (toweling) thickness prevented layering more than two layers in the filter holder. Pressure drop data for the materials at the three face velocities for the dry conditions are shown in Table II and for the wet conditions in Table XII. An experiment consisted of sampling for five one-minute periods, starting with the upstream sample and alternating with the downstream sample, to give a total of three upstream and two downstream measurements. This procedure was done to improve the precision of the penetration measurement by lessening the effects of changes in the challenge aerosol concentration during the duration of the experiment (approximately 20 minutes). Penetration is defined as the ratio of downstream to upstream concentration. Flow through the DATS was set at 160 cfm (0.075 m^3/sec) to provide adequate dilution of the aerosol generated. Air flow through the test materials was set at face velocities of 1.5, 5.0, and 15.0 cm/s using a calibrated rotameter. Pres-

sure drop across the filter material was measured using an inclined water manometer. A Wang 2200 computer system facilitated data storage and performed the computations for determining aerosol size distributions and fractional penetrations from the particle counting and sizing data.

For the high humidity conditions the DATS system air was raised to 97% ± 3% RH by injecting steam. After equilibrium was reached, testing of each material was done in the same manner as for the dry conditions.

Part 2: Particle diameters from 0.001 to 0.1 μm.

Penetration measurements for aerosol particles in the range 0.001 to 0.10 μm were performed by using a diffusion battery (In-Tox Products, Albuquerque, N.M., Model 02-1900) in conjunction with a manually operated condensation nuclei counter known as the Pollak counter. Figure 2 shows the set-up: room background aerosol was drawn from a 90-m^3 exposure chamber that was also being used in a study on the efficiency of various air cleaning devices for the removal of attached radon progeny found in atmospheric dust. Although the size distribution and concentration of the aerosol from the chamber changed week to week, due to the use of different air cleaning devices, sufficient concentrations of particles were present to challenge the test materials. The advantage in using the aerosol from the exposure chamber was that its concentration was found to be quite constant (±10%) during the course of an experiment; in contrast, the general room air aerosol in the laboratory was found to vary considerably.

The challenge aerosol was drawn through a charge neutralizer before entering the test filter holder, where a test material was placed. Since the diffusion battery was calibrated at 8.0 liters per minute, it was used at this flow rate and air was supplied to or exhausted from the aerosol stream in order to vary the total air flow rate through the filter holder (to vary the face velocity). A calibrated rotameter was used to monitor the addition or removal of air to insure that the total flow through the system was correct. Along the diffusion battery a series of sample ports were located to allow one to draw the air stream into the Pollak counters to measure the aerosol concentration. The diffusion battery stage configuration is described in Appendix A. The

mechanism of collection and penetration for each stage was described by Cheng and Yeh [2]. By measuring the particle concentration at each of the stages of the diffusion battery and applying the mathematical solutions available for determining the penetration of an aerosol flowing through the screens, one can determine a size distribution and number concentration. The test apparatus had a single diffusion battery, so it was necessary to run a set of measurements with the test material placed in the filter holder to determine a downstream size distribution and then remove the material from the filter holder to run another set of measurements to determine an upstream size distribution. To insure that the conditions did not change during the course of the experiment and to enhance the precision of the penetration measurement, a repeat of the downstream measurements was done. Each measurement was done using two Pollak counters operated in parallel, which gave paired measurements of the particle concentrations for determining the aerosol size distributions.

Data Analysis

Part I: Particle diameters from 0.1 to 1.0 μm.

For measuring the particle sizes from 0.12 to 0.50 μm, the PMS ASASP-X forward-light-scattering probe was used. The measuring system is capable of sizing particles of diameters from 0.09 to 3.0 μm in 45 non-overlapping channels. A problem was encountered in sizing the aerosol generated by the DeVilbiss #40 nebulizer (at 4 psig) operated under the same conditions as in the previous study of penetrations of particles 0.3 to 5.0 μm in optical diameter, sized using the PMS Classical Scattering Aerosol Spectrometer Probe (PMS CSASP-100). The aerosol concentration was found to be so high that a coincidence error was found to influence counting of the smaller particles. At high number concentrations small particles tend to be interpreted as larger particles due to limitations of the scattering collection optics. Hinds [3] calculated that the number concentration giving a 5% coincidence error is 2700 particles per cubic centimeter. The approach used here was to determine a concentration generated by the DeVilbiss nebulizer, operated at the same

pressure of 4 psig (so as to not to change the size distribution), which would not cause a coincidence error. This was achieved by drawing off a fraction of the nebulizer aerosol for use in challenging the materials. It was found that under the stated operating conditions, drawing off 7.0 liters per minute of the total output by use of a tee fitting located on the exit tube of the nebulizer, a particle concentration of 6250 particles per cubic centimeter was challenging the test materials. Higher concentrations demonstrated significant differences in the fractions of 0.12 and 0.25 μm present in the distribution, indicating coincidence problems. Lower concentrations did not demostrate significant differences.

For analysis of the data, only particles from narrow size intervals were selected. The basis of selection was to choose the smallest size particle from the PMS spectrum which had little influence from electronic noise from channel switching. Then this size was doubled for the next selected size and the resulting size doubled for the next. We selected three particle diameters (0.12, 0.25, and 0.50 μm). Therefore, on RANGE 3 of the PMS ASASP-X, channels 4 and 5 were combined to give an average diameter of 0.12 μm; the next size, 0.25 μm, was obtained from channels 10 and 11 of RANGE 2. Finally, channel 7 of RANGE 1 was selected, which gave a particle diameter of 0.50 μm. Above 0.50 μm the number distribution of the challenge aerosol was too low to give a useful count within the time limit of sampling. A typical upstream size distribution is given in Appendix B. From analyzing the data from the PMS ASASP-X unit, we concluded that the problem of electronic noise might have been present in the analysis of the earlier work done with the PMS Classical Scattering Aerosol Spectrometer Probe (CSASP-100) which sized and counted particles 0.32 to 20.0 μm in diameter. On this basis, the earlier data were re-analyzed: instead of combining many channels that might include problemmatic channels and then reporting a mid-point diameter value, we selected one or two channels that corresponded to the previous mid-point sizes. The re-analysis determined that the 0.51 size range was influenced by the first channel of RANGE 3 which contained spurious counts. By selecting channel 7 of RANGE 3 to give an average size of 0.51 μm, we believe that a better estimate is obtained for the counting of this size particle. Similar selections were done for 1.1, 2.1, and 4.4 μm diameter particles. A typical size distribution from the earlier work along with the two methods of analysis

are given in Appendices B and C.

For all of the data, sampling was done in a fashion where upstream sample and downstream samples were alternated until three upstream and two downstream samples had been collected for each material at each of the three face velocities. Background counting in the DATS before and after each test determined that only the mineral oil aerosol was present during a test. Several tests were done without a test material in the filter holder to determine any difference between the upstream and downstream sampling lines and whether the material support screen was removing a significant fraction of the aerosol. Results indicated agreement between the upstream and downstream particle counts. Once selected, the material was tested at each of the three face velocities, chosen to be random. This only partially random procedure was selected because great effort was needed to place a test material into the filter holder and determine that there was no leakage past the material. Replicate experiments were done for selected materials to obtain an estimate on the experimental variability.

From the PMS data, we combined counts from the selected particle diameter interval for the three upstream samples to determine an average upstream count and then the same technique was carried out for the two downstream samples. Penetration for each of the selected particle diameters was calculated by dividing the downstream average by the upstream average.

Part 2: Particle diameters from 0.001 to 0.1 μm

In sizing particles of diameters smaller than 0.12 μm, we used an eleven-stage diffusion battery device capable of classifying aerosol particles of 0.001 to 0.20 μm in diameter. By measuring the total number of particles penetrating each of the screened stages with the Pollak condensation nuclei (CN) counters and comparing the results with the theoretical penetration based on the geometry of the collecting stages, one can infer the size distribution of the aerosol. Cheng and Yeh [2] have developed a theory for the multiple-screen diffusion battery, and a detailed explanation that describes the experimentally determined characteristics for the device is available[4].

The diffusion battery does not separate particles perfectly into sharp diameter (mobility) categories, but the fraction (by number) of the aerosol found in a particular stage Y_i can be

approximately related to the true fraction X_i (by number) of the aerosol in a size range associated with that stage by use of an integral equation that can be approximated by a set of simultaneous linear equations:

$$Y_i = b_{i1}X_1 + b_{i2}X_2 + ...$$

or

$$Y_i = \sum_{j=1}^{N} b_{ij}X_j$$

The b_{ij} values are determined by calibration of the diffusion battery and by approximation of the integral equation. Calibration errors and these approximations, combined with errors in measurement of the Y_i, can cause problems when the set of simultaneous linear equations is solved to determine the X_j. Unphysical values ($X_j < 0$ or $X_j > 1$) for the size distribution components sometimes arise. There is a voluminous literature on the solution of such "ill-conditioned" inverse problems. The two major approaches (e.g., Cooper and Spielmans)[5] are 1.) to solve a slightly different set of equations, made different by the incorporation of an adjustable "smoothing" parameter of one sort or another, or 2.) to solve the equations through a search procedure that limits the search to acceptable values of X_j. The variant of smoothing that we employed was "ridge regression" (RR) (Draper and Smith)[6]. We were not able to find values of the smoothing parameter that were readily defensible beyond an appeal to the plausibility of the distributions that resulted, and we did not like the fact that the values that appeared best for the smoothing parameter ranged over an order of magnitude. We settled on the use of a non-negative least-squares search procedure (LSNN) that limited the search to physically possible values of the particle size distribution variables X_j. This gave answers that were generally plausible when used on our data and gave the correct answers when used on simulated data. See Appendix D.

For a typical experiment the size distribution was determined twice for a downstream sample and once for an upstream sample taken between the two downstream samples. The size distri-

bution was determined by using the Pollak CN counters to measure the particle number concentration after each of the eleven stages on the diffusion battery. Three total count samples of the particle concentration upstream from the diffusion battery were taken: as an initial measurement, as a repeat after the 5th stage (mid-way), and as a final sample, to give an indication as to the consistency of the particle concentration during the measurement period (45 minutes). For determining the three size distributions for an experiment the total elapsed time was approximately 2.5 hours. Analysis for the size distribution resulted in a number concentration in four particle size ranges, the mid-points of which are reported : 0.0015, 0.0059, 0.023, and 0.10 μm.

Results

Penetration measurements have been combined from the three phases of experiments (see also our earlier reports)[1] to determine a penetration-versus-particle-diameter (fractional penetration) curve for each material at the three face velocities. Tables III through VIII detail the penetration measurements for various particle diameter and face velocities for each of the six test materials listed in Table I. Figures 3 through 20 are fractional penetration curves corresponding to the results outlined in Tables III through VIII. For example, Table III outlines penetration measurements for the handkerchief material, and the data are plotted for each face velocity in Figures 3, 4, and 5 respectively.

Tables XIII through XVI detail the penetration measurements for three face velocities for four materials listed in Table XII tested under wet conditions (95% relative humidity). Figures 3 through 8 and 12 through 17 are the corresponding fractional penetration curves for each face velocity, plotted along with the dry condition data for comparison.

Discussion

The influence of face velocity is seen for three selected particle size ranges in the test results. From aerosol physics theory, particles 0.001 to 0.10 μm are largely removed by diffusion,

which effect decreases as the face velocity increases. Particles 1.0 to 4.4 μm in diameter were collected due to impaction, interception, and gravitation, primarily. As velocity increases, impaction increases, interception changes little, and sedimentation decreases. Particles 0.10 to 0.50 μm are collected most inefficiently since diffusion, impaction, and gravitation are not strong in this particle size range. Here interception is the major method of particle removal that would be relatively independent of face velocity. The trend of decreasing penetration as velocity increases for particles 0.10 to 0.50 μm is probably due to the increase in impaction. Other forces contributing to particle collection, such as electrostatic forces, we believe not to have had a significant role.

Handkerchief:

Table III details the penetration results for the 10 layers of the handkerchief tested under dry conditions (normal humidity: 20 to 40% RH) for particle diameters 0.0015 to 4.4 μm at the three face velocities 1.5, 5.0, and 15.0 cm/s. Here and elsewhere, the use of many decimal places does not indicate that there are many significant digits; more likely, there are two. Plots of these data are given in Figures 3, 4, and 5 respectively. In general, for each of the velocities tested, particle penetration is relatively low for particles 0.0015 to 0.023 μm, increases to a maximum for particle diameters from 0.10 to 0.50 μm, and then decreases again for particle diameters from 1.0 to 4.4 μm.

In detail (from Table III), penetration of particles 0.0059 μm in diameter was fairly stable, from 0.0190 to 0.0296, while penetration for 0.023 μm particles increased from 0.0203 to 0.1668 as face velocity increased. The same trend was noted for particles of diameters 0.12 and 0.25 μm, where penetration increased from 0.5371 and 0.5600 to 0.7532 and 0.7549 respectively as face velocity increased from 1.5 to 15.0 cm/s. Insufficient data were collected to determine a penetration trend for particle diameter as a function of face velocity for particle diameters 0.0015 and 0.10 μm.

A discrepancy exists in the penetration measurements for particle diameters 0.50 and 0.51 μm. These measurements represent the overlap of the two PMS laser probes. An explanation of the disagreement would be a lack of sensitivity for counting 0.50 μm particles by the ASASP-X

probe due to low number concentrations. Both the ASASP-X and the CSASP-100 probe were calibrated at several points by generating single-size particles (polystyrene latex spheres) and found to be within ±10% for sizing. The results from both probes demonstrated an increase in penetration as face velocity increased from 1.5 to 5.0 cm/s but a decrease in penetration as velocity increased from 5.0 to 15.0 cm/s. Since the change in penetration as the face velocity is changed is on the order of 10%, 0.5121 to 0.5679 and 0.7667 to 0.8294, an argument could be made that the penetration did not statistically have significant change. Perhaps, the actual penetration for this size particle is between the two extreme measurements, from 0.512 to 0.829, as the increased penetration with increasing face velocity and the disagreement between the two instruments cannot be explained easily.

For particle diameters from 1.0 to 4.4 μm, penetration decreased as face velocity increased and particle diameter increased. An exception is the 5.0 cm/s measurement of 0.6179 for 1.0 μm which is greater than the 0.5776 penetration for the 1.5 cm/s measurement, but perhaps identical within the experimental error.

Sheet:

The penetration results for the sheet material are presented in Table IV and Figures 6 through 8. The same trends for particle size removal as a function of velocity are noted here as for the handkerchief. The penetration values reported for the 0.10-μm diameter, 1.873 and 2.386, were unrealistic since penetration > 1.0 is not possible and thus were excluded from the graph shown in Figure 7. The particle counts for the upstream and downstream measurements were found to be low, which could give higher downstream counts than upstream counts due to either counting errors or a change in the challenge particle concentration during the period between the upstream and downstream measurements. Experiments without materials in the filter holder and no aerosol demostrated that particles forming from condensation was not occuring.

3M Respirator:

The single-use 3M respirator results shown in Table V, Figures 9 through 11 demonstrated the lowest penetration for all particles at all face velocities for the materials tested. Again, the same trends are evident including the discrepancy between the 0.50 and 0.51 μm measurements. Even this NIOSH-approved respirator did not effectively remove particles between 0.10 and 0.51 μm. Penetrations were as high as 0.6659 for 0.12 μm particles at 15.0 cm/s.

Shirt:

Penetration results for the shirt material are presented in Table VI and Figures 12 through 14. These results are in line with results for the handkerchief and the sheet.

Wash Cloth:

Results for the wash cloth shown in Table VII and Figures 15 through 17 show that the penetrations for this material were lower than the other fabric materials for the majority of the measurements. An unrealistic measurement, 6.121 penetration for 0.0234 μm at 5.0 cm/s, is reported but is excluded from the graph shown in Figure 16. Again low counts are assumed to have given such results.

Surgical Mask:

The last material reported on is the surgical mask respirator have results shown in Table VII and Figures 18 through 20. Although it can be classified as a type of respirator, it is not designed to be as high a quality respirator as the (NIOSH-approved) 3M respirator. Penetration results are lower than those for the wash cloth material as well as for those for the other fabric materials but significantly higher than the single-use 3M respirator.

Quality Factor:

To compare effectively each of the tested materials from the results of the penetration measurements for each particle size and face velocity is a difficult task. Lower face velocities favor small particle removal due to diffusion while higher velocities favor large particle removal. Pressure drop across the material is a factor to consider, since a benefit of decreased particle penetration at high velocities is offset by a penalty of increased resistance to flow. The number of layers

of material used must also be taken into consideration, since pressure drop would increase as the number of layers used increases. A measure that incorporates these factors must be used so that an overall comparison of each material can be done: a "quality factor" has been calculated for each material for each particle size at each face velocity. The quality factor, as defined, by Fuchs[7] is

$$q = \frac{-ln(c/c_o)}{\Delta P}$$

where:

q = quality factor, Pa^{-1}

c/c_o = ratio of downstream to upstream particle concentration

ΔP = pressure drop across material, Pa

The rationale for this calculation is as follows: the penetration for n layers of the same material would decrease as $(c/c_o)^n$ while the pressure drop would increase as n times the pressure drop of one layer.The quality factor depends on the material, the particle size, and the face velocity, but not on the number of layers. Tables IX through XI detail the calculation results for the quality factors for the materials tested under dry conditions. These quality factors can be used to predict the penetration of the materials at any chosen pressure drop for the particle diameter and the velocity tested. The higher the quality factor, the less penetration at a given pressure drop or, equivalently, the less pressure drop for a given penetration. Where penetration was measured as zero the quality factor is reported as an asterisk, since the logarithm of zero is ill-defined. A penetration of 1.0 would result in a quality factor of zero. The quality factors have been plotted in Figures 21 through 23 for the three velocities as a function of particle diameter for all materials. Clearly the NIOSH-approved, single-use 3M respirator performed best followed by the surgical mask and then the wash cloth. The remaining fabric materials were quite similar in comparison to each other but significantly lower in quality factor than the wash cloth.

For a given face velocity (thus pressure drop), the quality factors follow qualitatively the same particle size dependence as does collection efficiency. At a given particle size, the quality factors tend to diminish as velocity increases, in agreement with predictions (Cooper)[8]. This means that the use of large-area masks is favored over the use of small-area masks, if the leakages are the same and the number of layers is adjusted to give the same pressure drop. In practice, however, it may be found that holding the material over the mouth and breathing only through the mouth may give a better seal to the face than trying to cover both mouth and nose.

Wet Materials:

Each of the fabric materials were also tested under wet conditions where the test material was wetted and the test air flow was kept above 95% RH to prevent drying to determine if particle collection could be enhanced. The single-use 3M respirator and the surgical n ask were not tested wet, as the pressure drop would be excessive. Penetration measurements were done for particle diameters from 0.12 to 4.4 μm using the two PMS laser probes. Penetration measurements for the handkerchief are shown in Table XIII and plotted in Figures 3 through 5 for each of the face velocities and include the data from the dry condition experiments to facilitate comparison. In general, the penetration results are lower for the wet conditions for particle diameter greater than 1.0 μm. However, note that for particle diameters from 0.10 to 0.50 μm penetration is higher under the wet conditions. Results for the sheet, shirt, and wash cloth are similar, in that the wet penetrations are higher for the 0.10 to 0.50 μm and lower for the particles greater than 1.0 μm as compared to the dry condition penetrations. Penetration decreases with increasing face velocity for particles larger in diameter than 0.50 μm, as was also seen in the dry condition results. The highest penetration values were found for particles 0.12 μm in diameter, and there is evidence that penetration of these particles increases with increasing face velocity. Particles 0.25 μm in diameter seem not to have been influenced by face velocity. Calculated quality factors are shown in Tables XVII through XIX for the wet condition tests and plotted in Figures 24 through 26.

Table XX shows some details of the calculation of the mass fraction of a hypothetical aerosol expected to penetrate face masks made of toweling. (This material is presented to illustrate

the calculational technique and should not be relied on as an example of predicted performance.) The aerosol is assumed to have a lognormal particle size distribution, with a mass median diameter of 2 μm equal to its aerodynamic mass median aerodynamic diameter (the particle density was chosen to be that of water, 1 g/cm^3), and with a geometric standard deviation of 2.0. The masks are assumed to be held to the face with nylon hosiery and thus have a leakage fraction of 5%, comparable with that found for handkerchief material held onto the face of a manikin with nylon hosiery [9]. It is assumed that the number of thicknesses are adjusted by the wearer to give substantial but not uncomfortably high flow resistance, taken to be a pressure drop of 50 Pa. It is assumed that the area of the mask is chosen large enough to cover nose and mouth and that the breathing rate is appropriate for moderate exertion or less, giving a face velocity between 1.5 and 5.0 cm/s, so penetrations are calculated for both these values. Mass penetration is determined by finding the aerosol fraction by mass in a size interval and multiplying this fraction by the average of the penetrations calculated for the upper and lower size limits of the size interval, then summing these products. (This is equivalent to "trapezoidal rule" numerical integration of the product of penetration and aerosol mass size distribution.) The penetrations are determined from the quality factors by raising the base of the natural logarithms, e, to the negative power of the product of the quality factors and the pressure drops:

$$Pn = \exp(-q\ \Delta P)$$

The total penetration for the wash cloth at 1.5 cm/s is calculated to be 0.15 and for the wash cloth at 5.0 cm/s it is calculated to be 0.54. Thus, between about one-sixth and about one-half of the aerosol would be expected to penetrate. Other conditions can be explored similarly, and any such predictions should take into account the range of pressure drops and face velocities (and particle size distributions) likely to be encountered in practice.

Summary

The material presented in this report allows calculation of fabric penetration from the quality factors. Combined with the leakage test results from the Phase II report, these results can be used to estimate the effectiveness of such materials for use as expedient methods of respiratory protection in accident situations.

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TABLE I

Materials Tested For This Report

Material	Composition	Thread Count	Manuf. Code
Wash Cloth	88% cotton, 12% polyester dacron		Lady Pepperell Grandeur
Handkerchief	100% cotton	57/in X 64/in ($121/in^2$)	RN#16810
Shirt	40% fortrel polyester, 60% cotton	46/in X 45/in ($91/in^2$)	
Sheet	100% cotton	87/in X 74/in ($161/in^2$)	50030 3
3M Respirator			#8710
Johnson&Johnson Surgical Mask	Non-glass		HRI 8137-00 Barrier-Surgikos

TABLE II

Pressure Drop of Dry Materials, Pa

MATERIAL	Face Velocity (cm/s)		
	1.5	5.0	15.0
3M Respirator(1)*	11	37	120
Sheet(12)	37	123	420
Shirt(8)	26	89	321
Wash Cloth(2)	15	47	159
Handkerchief (10)	35	119	418
Surgical Mask (1)	10	32	109

* Number of layers in parenthesis

TABLE III

Penetrations for Handkerchief , Dry Condition

	Face Velocity (cm/s)		
Diameter (μm)	1.5	5.0	15.0
.0015	.0006 .0020	***** *****	***** *****
.0059	.0268 .0190	.0107 .0126	.0284 .0296
.023	.0203 .0229	.0880 .0831	.1668 .1534
.10	.5448 .5700	***** *****	***** *****
.12	.5371	.7032	.7532
.25	.5600	.7019	.7549
.50	.5121	.5679	.5262
.51	.7667	.8294	.8182
1.0	.5776	.6179	.3972
2.1	.5263	.1852	.0000
4.4	.1333	.0000	.0000

* Upstream concentration negligible

TABLE IV

Penetrations for Sheet , Dry Condition

	Face Velocity (cm/s)		
Diameter (μm)	1.5	5.0	15.0
.0015	.0092 .0057	.0000 .0000	.0000 .0095
.0059	.0000 .0008	.0013 .0050	.0161 .0000
.023	.1136 .0640	.0609 .0492	.4653 .2932
.10	.3006 .3314	1.873 2.386	.3960 .6399
.12	.5237	.6731	.8266
.25	.5648	.6709	.7326
.50	.5180	.6300	.5042
.51	1.000	.8560	.7701
1.0	.7091	.6281	.5598
2.1	.5000	.3200	.0000
4.4	.1000	.0000	.0000

TABLE V

Penetrations for 3M Respirator #8710 , Dry Condition

Diameter (μm)	Face Velocity (cm/s) 1.5	5.0	15.0
.0015	***** *****	***** *****	.0030 *****
.0059	.0002 .0002	.0000 .0000	.0014 .0000
.023	.0000 .0027	.0038 .0030	.0741 .0718
.10	***** *****	***** *****	.3826 .4051
.12	.1665	.4127	.6659
.25	.1468	.3036	.5009
.50	.0542	.1257	.2203
.51	.1475	.2513	.2897
1.0	.0403	.0692	.0549
2.1	.0000	.0000	.0000
4.4	.0000	.0000	.0000

* Upstream concentration negligible

TABLE VI

Penetrations for Shirt , Dry Condition

	Face Velocity (cm/s)		
Diameter (μm)	1.5	5.0	15.0
.0015	.0078 .0080	***** .0709	.0000 *****
.0059	.0000 .0000	.0091 .0083	***** *****
.023	.0000 .0098	.1430 .1464	.2474 .2396
.10	.5169 .5027	.6077 .5051	.5994 .5858
.12	.5817	.6536	.8013
.25	.6191	.6834	.7551
.50	.5653	.6395	.5469
.51	.6990	.8182	.9381
1.0	.7094	.6574	.4342
2.1	.3000	.2000	.0000
4.4	.2778	.0455	.0000

* Upstream concentration negligible

TABLE VII

Penetrations for Wash Cloth , Dry Condition

	Face Velocity (cm/s)		
Diameter (μm)	1.5	5.0	15.0
.0015	.0781 .0519	.0006 .0038	.0259 .0272
.0059	.0000 .0000	.0000 .0000	.0105 .0000
.023	.0861 .0976	6.121 .7102	.5224 .4782
.10	.3812 .3553	.3296 .3584	.5874 .6022
.12	.5644	.6610	.7932
.25	.6528	.7466	.7830
.50	.6155	.6924	.6802
.51	.6316	.8232	.8477
1.0	.4734	.6129	.5144
2.1	.2308	.1833	.0508
4.4	.0455	.0000	.0000

TABLE VIII

Penetrations for Surgical Mask Respirator , Dry Condition

	Face Velocity (cm/s)		
Diameter (μm)	1.5	5.0	15.0
.0015	.0000 .0038	***** *****	***** .0000
.0059	.0045 .0000	.0001 .0000	.0056 .0079
.023	.0228 .0252	.0014 .0027	.1173 .1144
.10	.3780 .3729	***** *****	***** *****
.12	.4790	.7170	.8291
.25	.5395	.7049	.6985
.50	.4272	.4383	.4664
.51	.4138	.6290	.6388
1.0	.2788	.3747	.2924
2.1	.0811	.0526	.0000
4.4	.0250	.0000	.0000

* Upstream concentration negligible

TABLE IX

Quality Factors for 1.5 cm/s Face Velocity

Diameter (μm)	Materials					
	Handk	Sheet	3M Resp	Shirt	Wash Cloth	Surg Mask
.0015	0.1899	0.1324	------	0.1862	0.1822	0.6266
.0059	0.1079	0.2115	0.7743	******	******	0.6097
.0234	0.1096	0.0654	0.6007	0.2046	0.1592	0.3730
.1027	0.0167	0.0311	------	0.0259	0.0666	0.0980
.12	0.0178	0.0175	0.1630	0.0208	0.0381	0.0736
.25	0.0166	0.0154	0.1744	0.0184	0.0284	0.0617
.50	0.0191	0.0178	0.2650	0.0219	0.0324	0.0851
.51	0.0076	0.000	0.1740	0.0138	0.0306	0.0882
1.0	0.0157	0.0093	0.2919	0.0132	0.0499	0.1277
2.1	0.0183	0.0187	******	0.0463	0.0977	0.2512
4.4	0.0576	0.0622	******	0.0493	0.2060	0.3689

- Upstream concentration negligible

* Penetration measured as zero

TABLE X

Quality Factors for 5.0 cm/s Face Velocity

	Materials					
Diameter (μm)	Handk	Sheet	3M Resp	Shirt	Wash Cloth	Surg Mask
.0015	------	******	------	0.0297	0.1302	------
.0059	0.0374	0.0468	******	0.0533	******	0.3095
.0234	0.0207	0.0236	0.1536	0.0217	0.0073	0.1934
.1027	------	-0.0061	------	0.0066	0.0227	------
.12	0.0030	0.0032	0.0239	0.0048	0.0088	0.0104
.25	0.0030	0.0032	0.0322	0.0043	0.0062	0.0109
.50	0.0048	0.0038	0.0561	0.0050	0.0078	0.0258
.51	0.0016	0.0013	0.0373	0.0023	0.0041	0.0145
1.0	0.0040	0.0038	0.0722	0.0047	0.0104	0.0307
2.1	0.0142	0.0093	******	0.0181	0.0361	0.0920
4.4	******	******	******	0.0347	******	******

- Upstream concentration negligible

* Penetration measured as zero

TABLE XI

Quality Factors for 15.0 cm/s Face Velocity

Diameter (μm)	Materials					
	Handk	Sheet	3M Resp	Shirt	Wash Cloth	Surg Mask
.0015	-----	0.0127	0.0484	------	0.0228	------
.0059	0.0085	0.0115	0.0605	------	0.0330	0.0459
.0234	0.0044	0.0023	0.0218	0.0044	0.0044	0.0198
.1027	------	0.0016	0.0078	0.0016	0.0033	------
.12	0.0007	0.0005	0.0034	0.0007	0.0015	0.0017
.25	0.0007	0.0007	0.0058	0.0009	0.0015	0.0033
.50	0.0015	0.0016	0.0126	0.0019	0.0024	0.0070
.51	0.0005	0.0006	0.0103	0.0002	0.0010	0.0041
1.0	0.0022	0.0014	0.0242	0.0026	0.0042	0.0113
2.1	******	******	******	******	0.0187	******
4.4	******	******	******	******	******	******

- Upstream concentration negligible

* Penetration measured as zero

TABLE XII

Pressure Drop of Wet Materials, Pa

MATERIAL	Face Velocity (cm/s)		
	1.5	5.0	15.0
Sheet(12)*	3535 - 3559	4032 - 4132	4456 - 5152
Shirt(8)	597 - 1817	2489 - 2589	2688 - 3360
Handkerchief (10)	3037 - 3136	3933 - 4306	5078 - 6571
Wash Cloth(2)	2514 - 2788	2315 - 4107	1170 - 4729

* Number of layers in parenthesis

TABLE XIII

Penetrations for Handkerchief, Wet Condition

Diameter (μm)	Face Velocity (cm/s) 1.5	5.0	15.0
0.12	.7626	.8514	.8537
0.25	.8100	.8301	.5185
0.50	.8020	.7096	.0140
0.51	.9508	.9891	.3898
1.00	.7914	.4106	.0149
2.10	.3333	.0000	.0000
4.40	.0714	.0000	.0000

TABLE XIV

Penetrations for Wash Cloth , Wet Condition

Diameter (μm)	Face Velocity(cm/s) 1.5	5.0	15.0
0.12	.9067	.9410	.9205 .9370
0.25	.7580	.7333	.6353 .8358
0.50	.1905	.1749	.1202 .2496
0.51	.3333	.2018	.1565
1.00	.0473	.0358	.0179
2.10	.0000	.0000	.0000
4.40	.0000	.0000	.0000

TABLE XV

Penetrations for Shirt , Wet Condition

Diameter (μm)	Face Velocity(cm/s)		
	1.5	5.0	15.0
0.12	.9384	.9387	.9949
0.25	1.036	.8271	.8785
0.50	.7090	.2505	.3460
0.51	1.077	.7480	.6151
1.00	.2374	.2007	.0707
2.10	.0000	.0000	.0000
4.40	.0000	.0000	.0000

TABLE XVI

Penetrations for Sheet , Wet Condition

	Face Velocity(cm/s)		
Diameter (μm)	1.5	5.0	15.0
0.12	.8121	.9455	1.007
0.25	.7298	.9220	.8777
0.50	.3381	.4272	.1799
0.51	.8271	.8453	.9827
1.00	.7343	.3576	.1930
2.10	.1667	.0000	.0000
4.40	.0667	.0000	.0000

TABLE XVII

Quality Factors for 1.5 cm/s Face Velocity (wet)

Diameter (μm)	Materials			
	Handk	Sheet	Shirt	Wash Cloth
0.12	0.00009	0.00006	0.00005	0.00004
0.25	0.00007	0.00009	-0.00003	0.00010
0.50	0.00007	0.00031	0.00028	0.00063
0.51	0.00002	0.00005	-0.00006	0.00041
1.00	0.00008	0.00009	0.00119	0.00115
2.10	0.00036	0.00051	*******	*******
4.40	0.00087	0.00076	*******	*******

* Penetration measured as zero

TABLE XVIII

Quality Factors for 5.0 cm/s Face Velocity (wet)

Diameter (μm)	Materials			
	Handk	Sheet	Shirt	Wash Cloth
0.12	0.00004	0.00001	0.00002	0.00002
0.25	0.00005	0.00002	0.00007	0.00010
0.50	0.00009	0.00021	0.00055	0.00054
0.51	0.00000	0.00004	0.00011	0.00050
1.00	0.00023	0.00026	0.00063	0.00104
2.10	*******	*******	*******	*******
4.40	*******	*******	*******	*******

* Penetration measured as zero

TABLE XIX

Quality Factors for 15.0 cm/s Face Velocity (wet)

Diameter (μm)	Materials			
	Handk	She- t	Shirt	Wash Cloth
0.12	0.00003	-0.00000	0.00000	0.00003
0.25	0.00011	0.00003	0.00004	0.00010
0.50	0.00073	0.00036	0.00035	0.00057
0.51	0.00016	0.00001	0.00016	0.00063
1.00	0.00072	0.00034	0.00088	0.00136
2.10	*******	*******	*******	*******
4.40	*******	*******	*******	*******

* Penetration measured as zero

TABLE XX

Predicted Penetrations for Toweling at 50 Pa Pressure Drop and with a 5% Leakage

Particle Diameter (μm)	Quality Factor		Fabric Penetration		Total Penetration[a]	
	1.5 cm/s	5.0 cm/s	1.5 cm/s	5.0 cm/s	1.5 cm/s	5.0 cm/s
0.0015	0.182	0.130	0.000	0.002	0.500	0.052
0.0059	-----	-----	0.000	0.000	0.050	0.050
0.02	0.159	0.007	0.000	0.704	0.050	0.754
0.10	0.067	0.023	0.035	0.317	0.085	0.367
0.12	0.038	0.009	0.150	0.638	0.200	0.688
0.25	0.028	0.006	0.247	0.740	0.297	0.790
0.50	0.031	0.006	0.212	0.740	0.262	0.790
1.0	0.050	0.010	0.082	0.607	0.132	0.657
2.1	0.098	0.036	0.007	0.165	0.057	0.215
4.4	0.206	----	0.000	0.000	0.050	0.050

Assumes that leakage would be 5% of flow, comparable to that found for the handkerchief held to manikin face with nylon hosiery material.

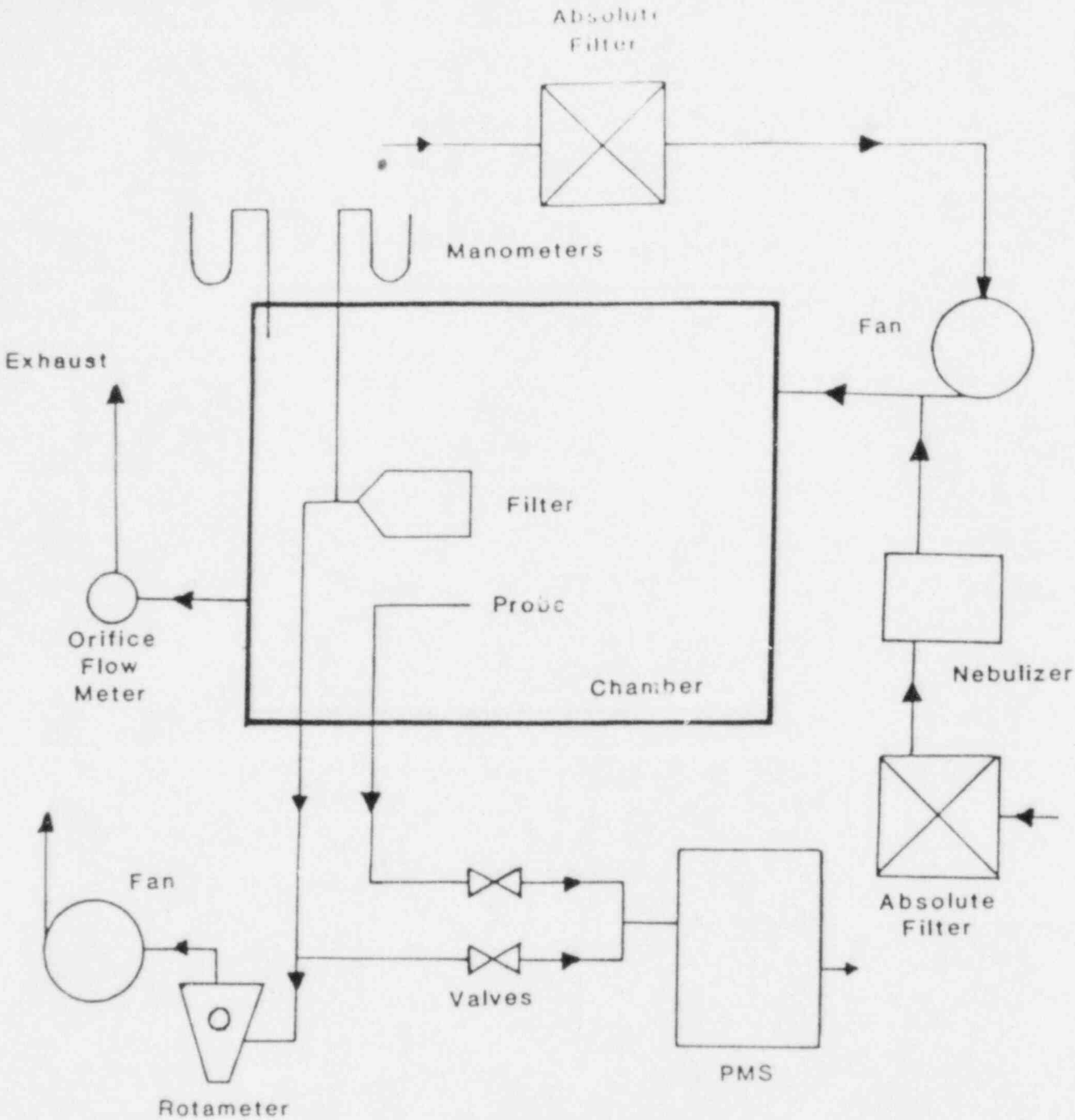


FIGURE 1: AEROSOL TEST SYSTEM

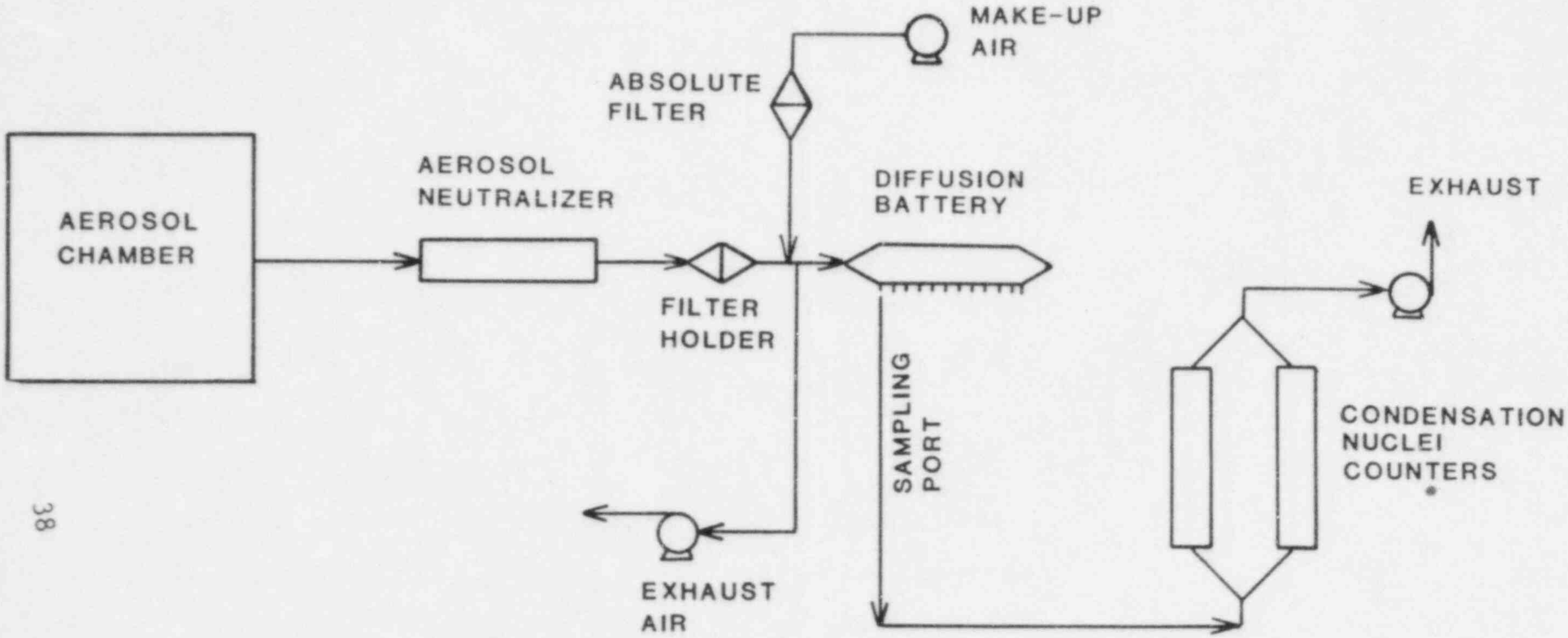


FIGURE 2 : 0.001-0.10 MICROMETER PARTICLE DIAMETER MEASUREMENT SYSTEM

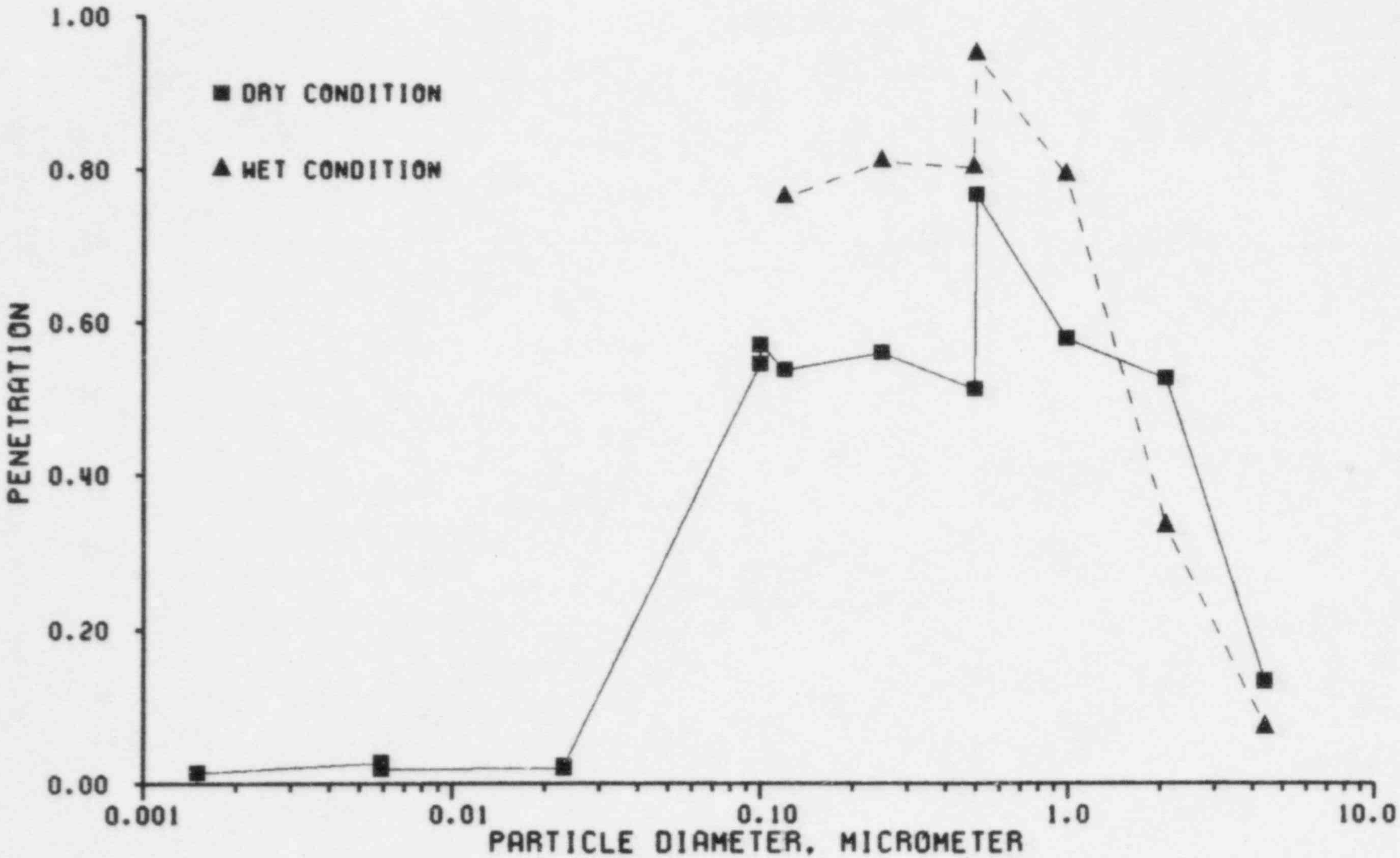


FIGURE 3 : PENETRATION VERSUS PARTICLE DIAMETER FOR HANDKERCHIEF(10) 1.5 CM/S

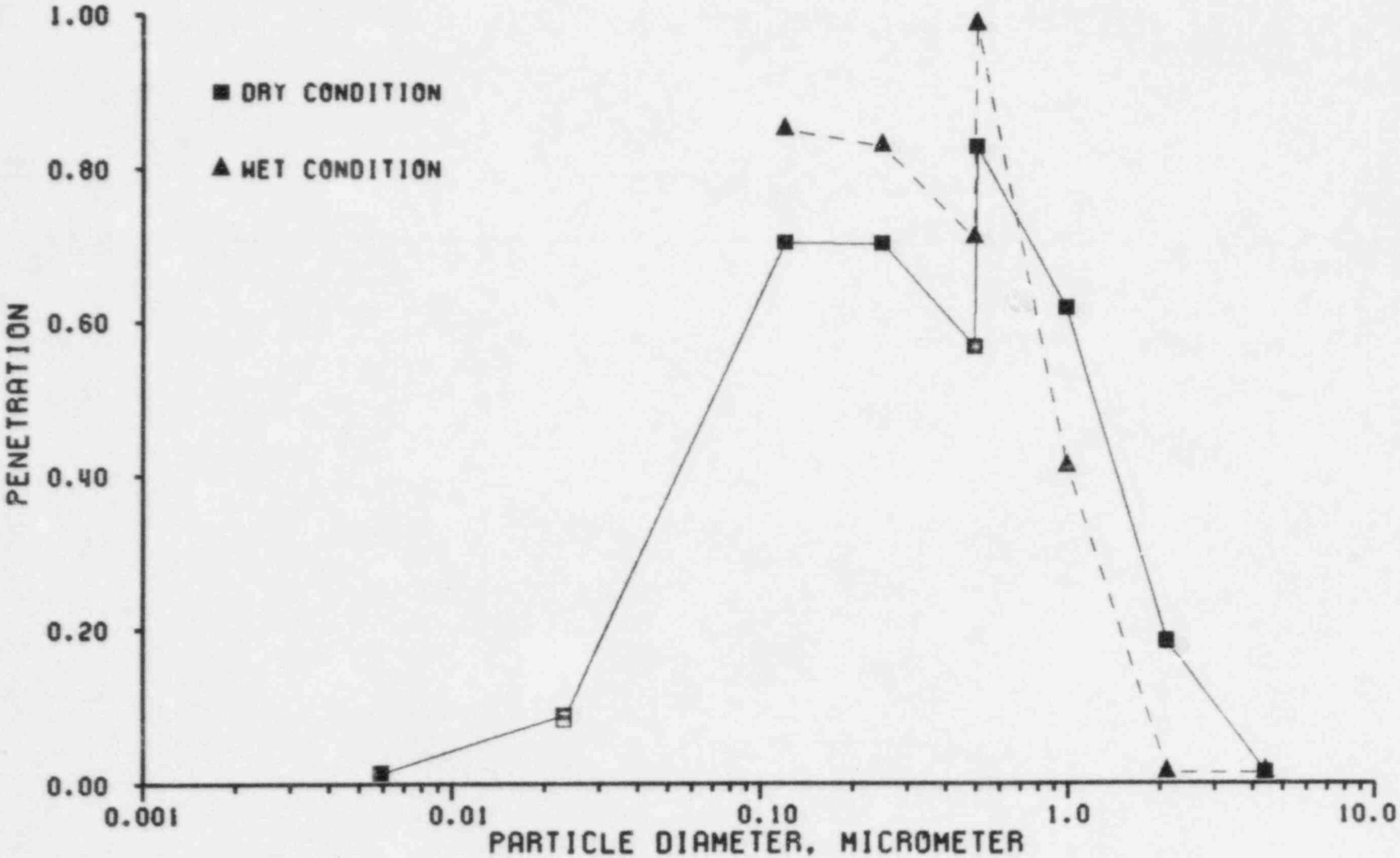


FIGURE 4 : PENETRATION VERSUS PARTICLE DIAMETER FOR HANDKERCHIEF(10) 5.0 CM/S

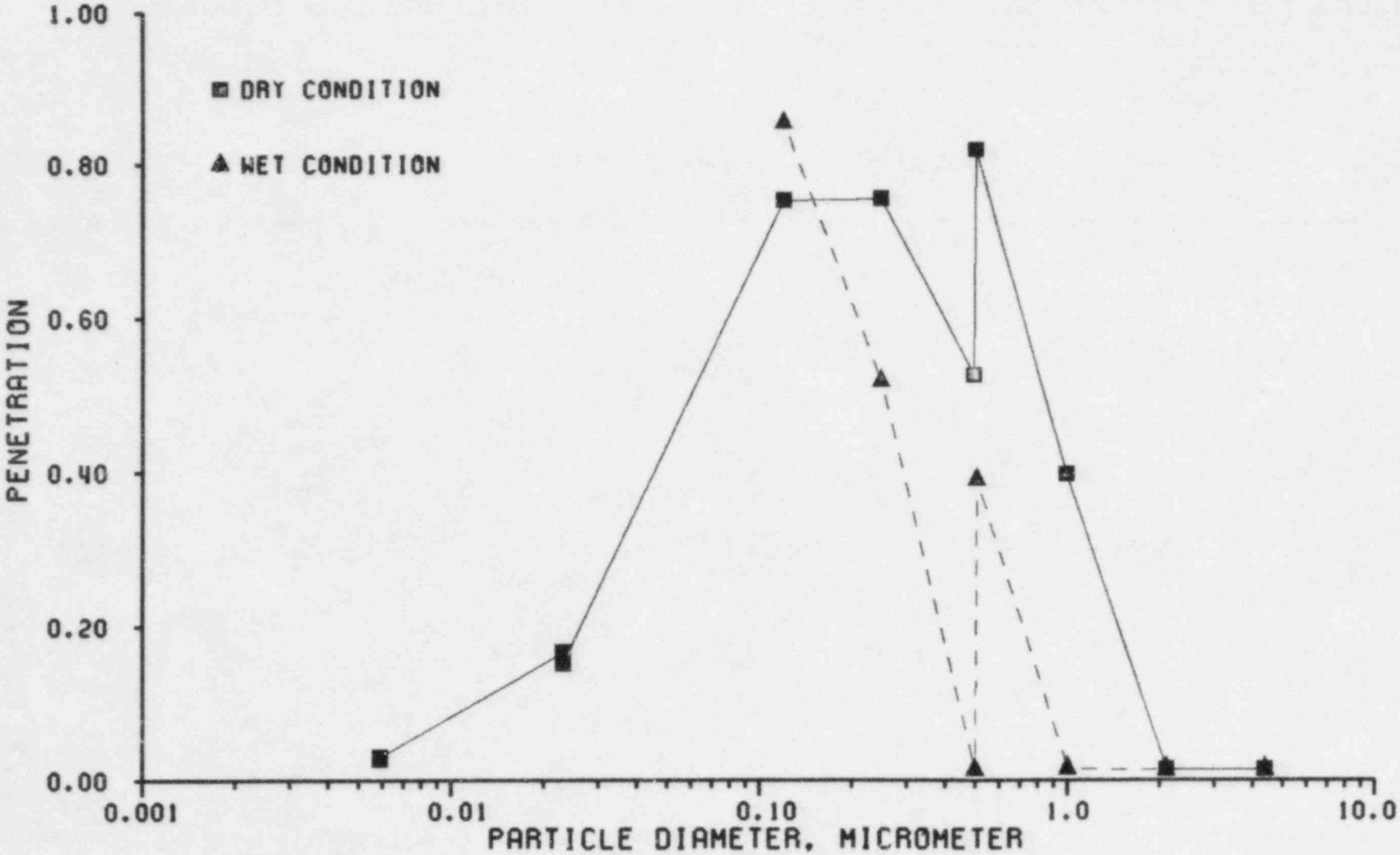


FIGURE 5 : PENETRATION VERSUS PARTICLE DIAMETER FOR HANDKERCHIEF (10) 15.0 CM/S

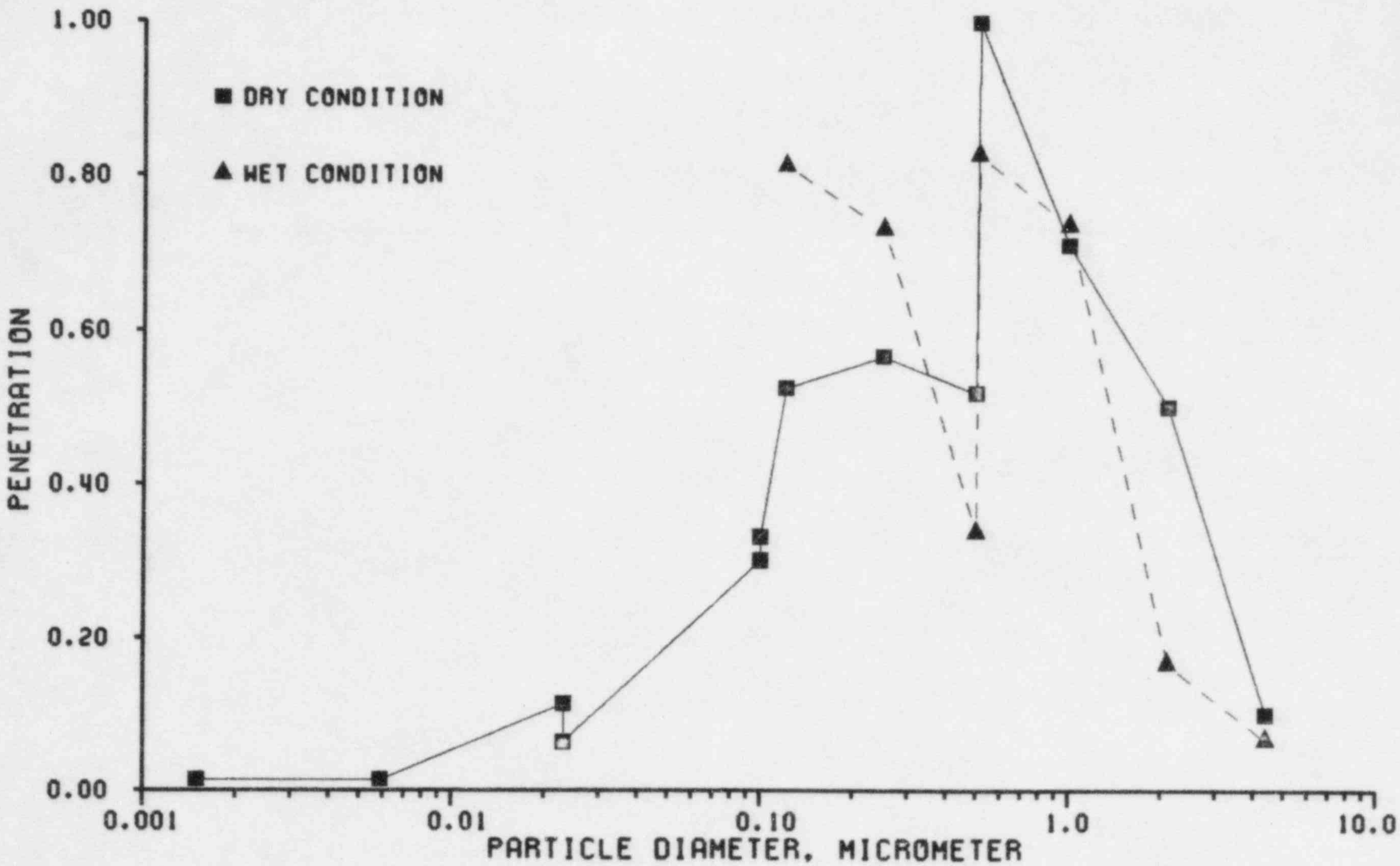


FIGURE 6 : PENETRATION VERSUS PARTICLE DIAMETER FOR SHEET(12) 1.5 CM/S

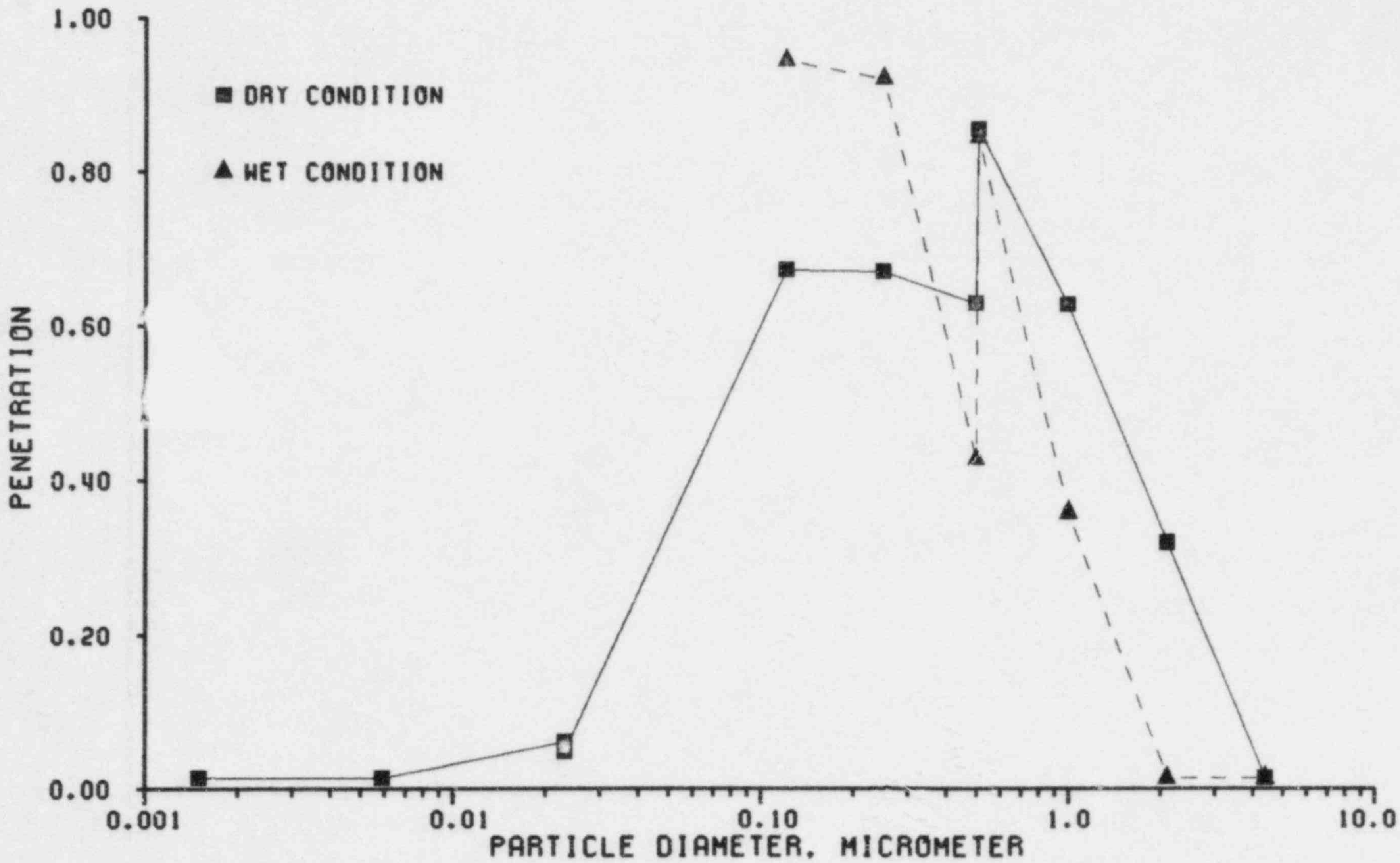


FIGURE 7 : PENETRATION VERSUS PARTICLE DIAMETER FOR SHEET(12) 5.0 CM/S

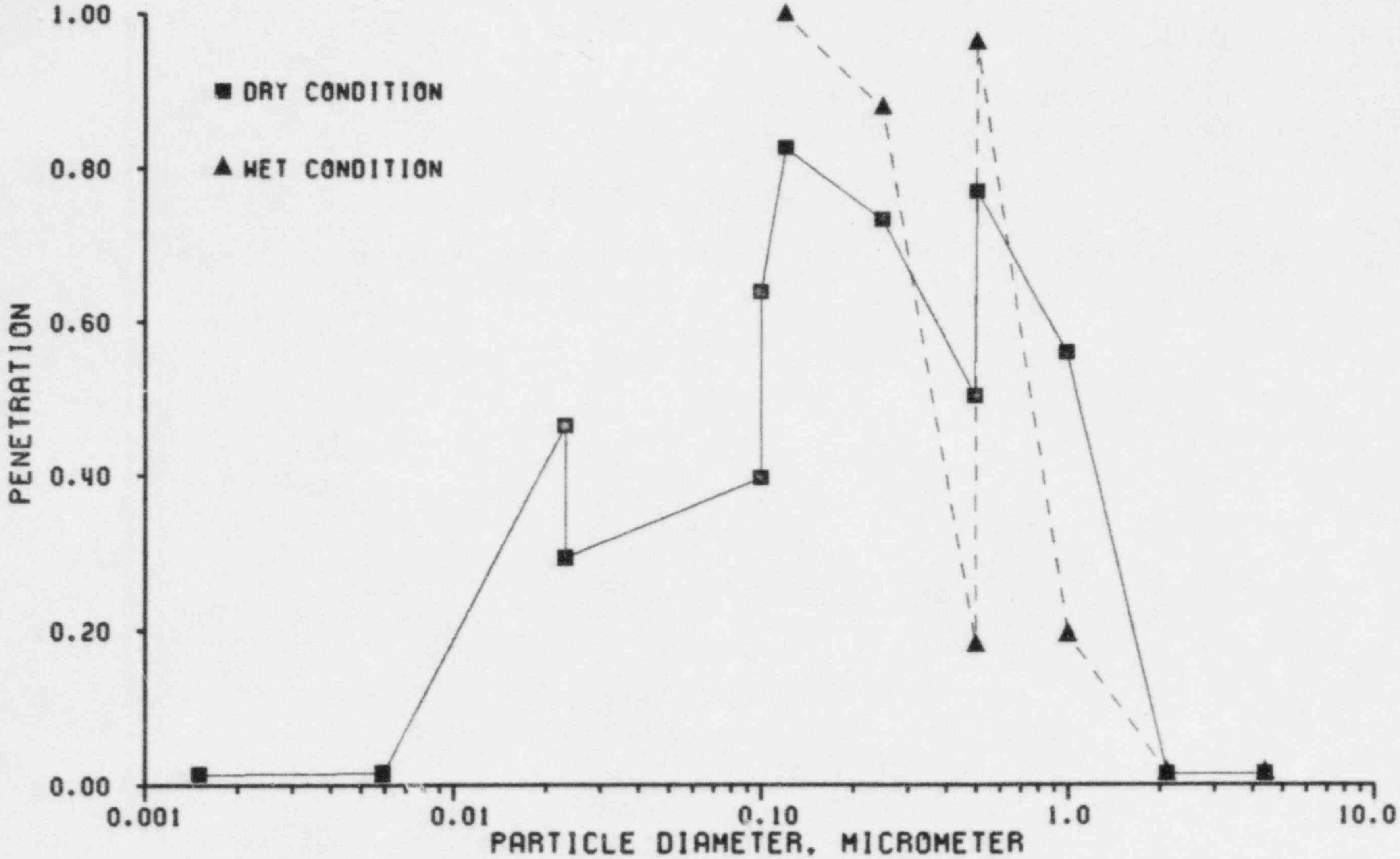


FIGURE 8 : PENETRATION VERSUS PARTICLE DIAMETER FOR SHEET(12) 15.0 CM/S

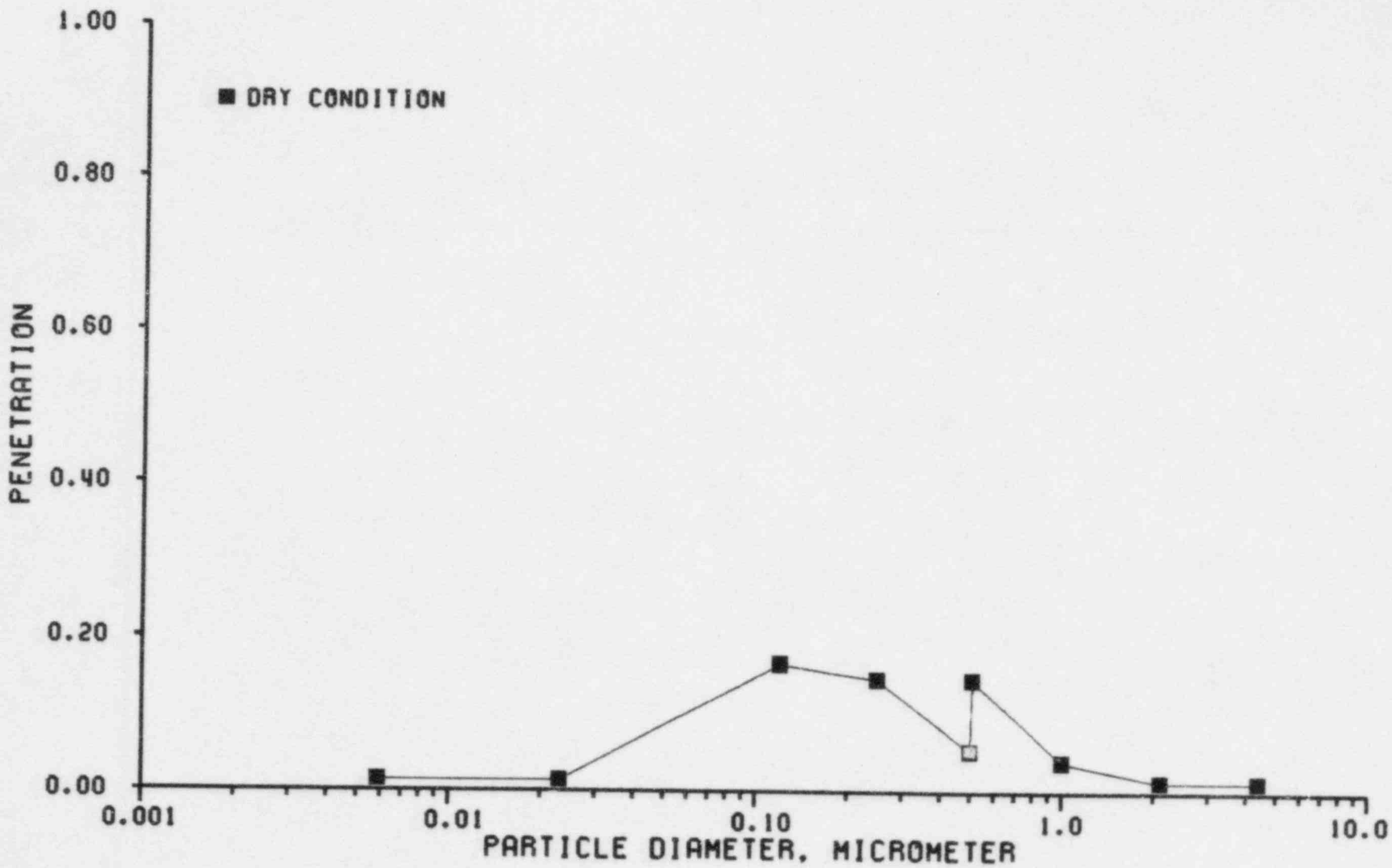


FIGURE 9 : PENETRATION VERSUS PARTICLE DIAMETER FOR 3M RESPIRATOR(1) 1.5 CM/S

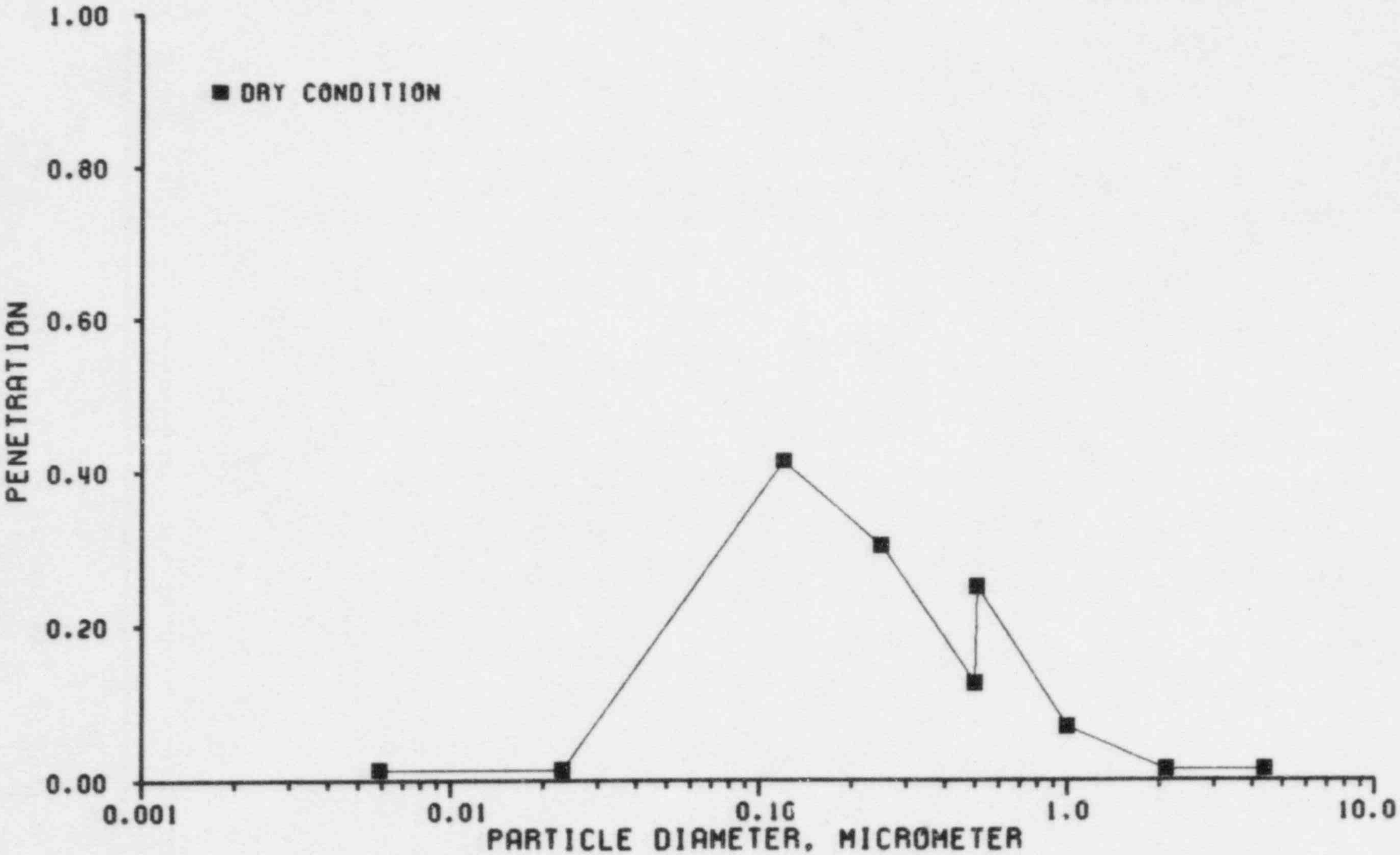


FIGURE 10 : PENETRATION VERSUS PARTICLE DIAMETER FOR 3M RESPIRATOR(1) 5.0 CM/S

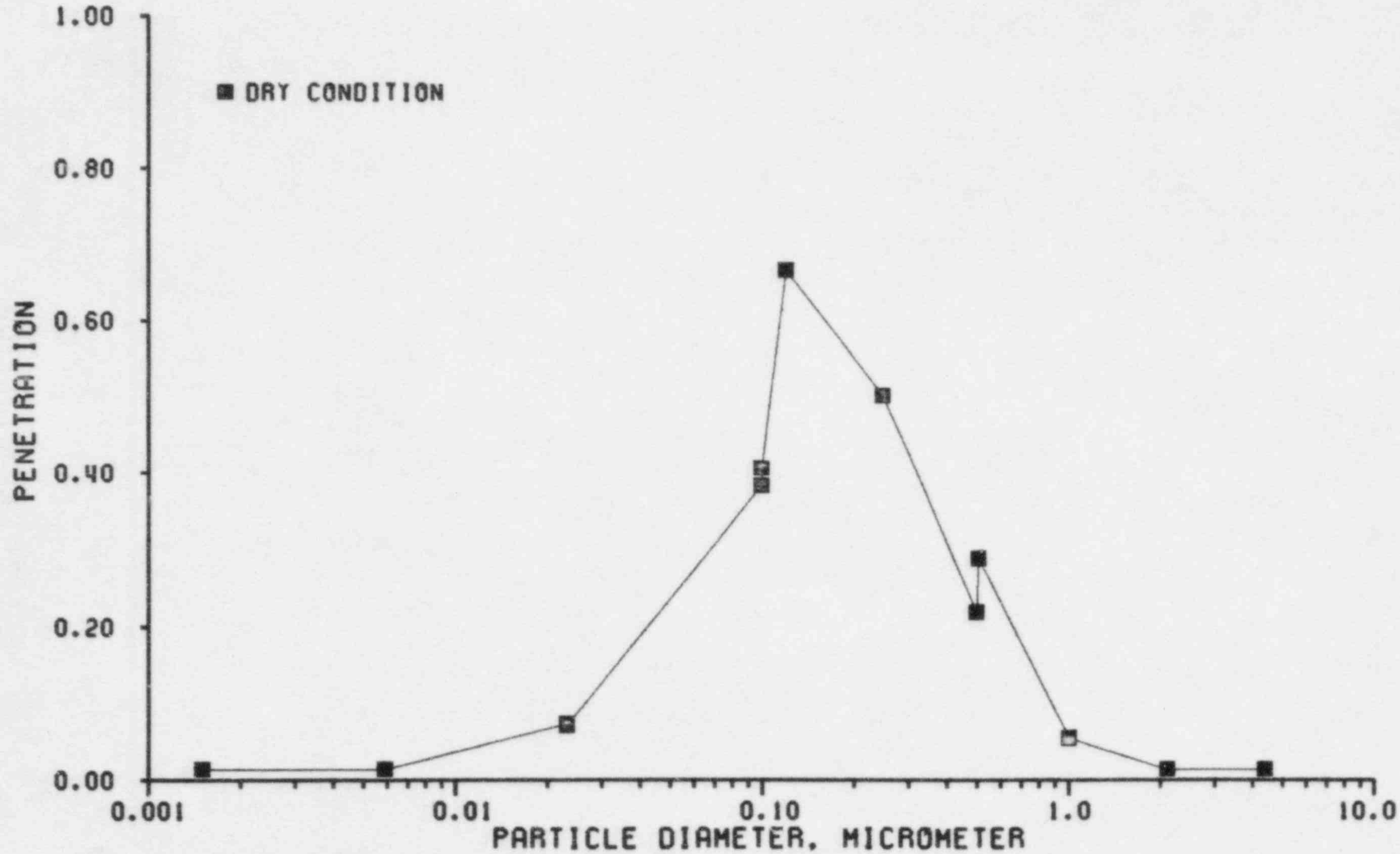


FIGURE 11 : PENETRATION VERSUS PARTICLE DIAMETER FOR 3M RESPIRATOR(1) 15.0 CM/S

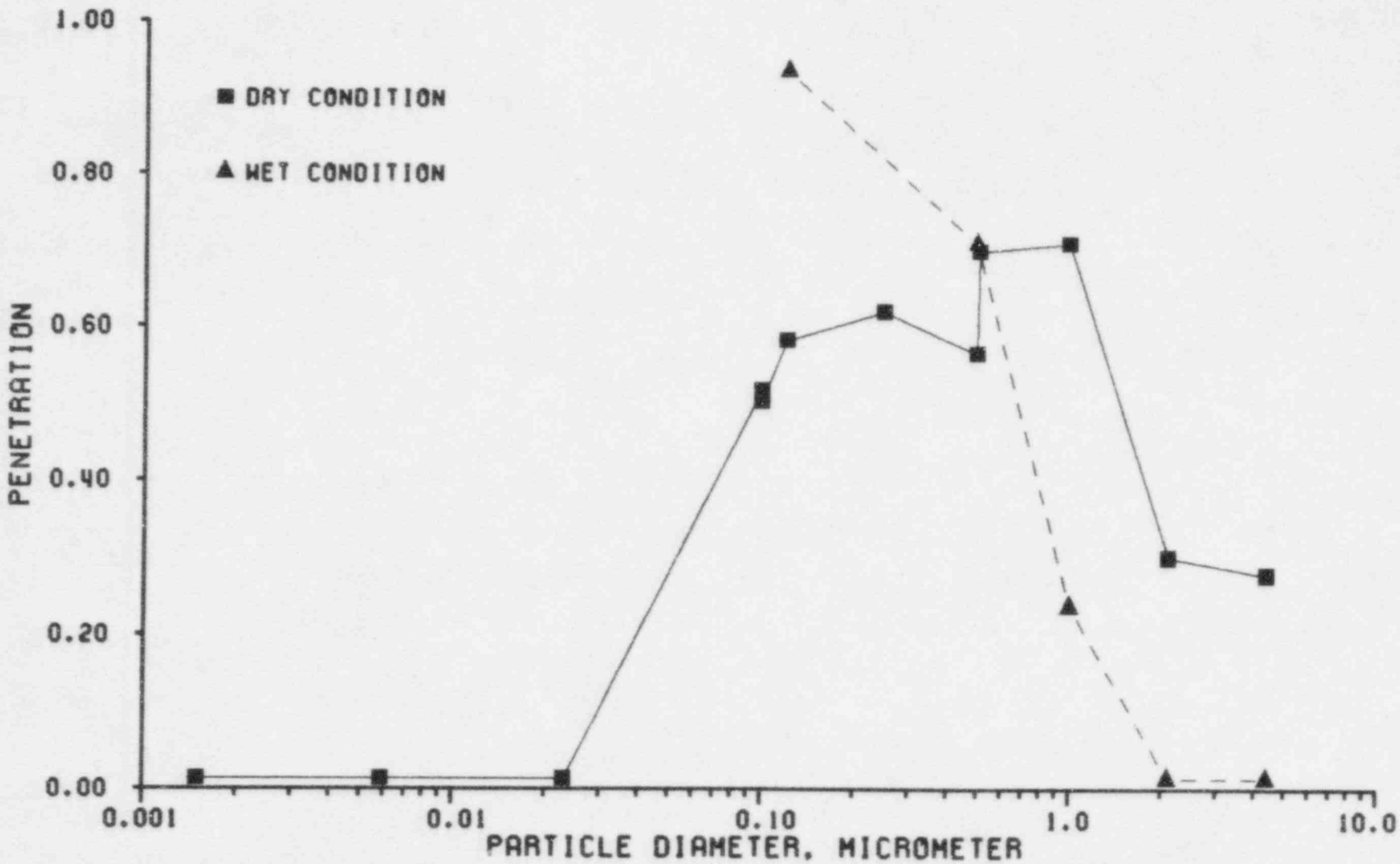


FIGURE 12 : PENETRATION VERSUS PARTICLE DIAMETER FOR SHIRT(8) 1.5 CM/S

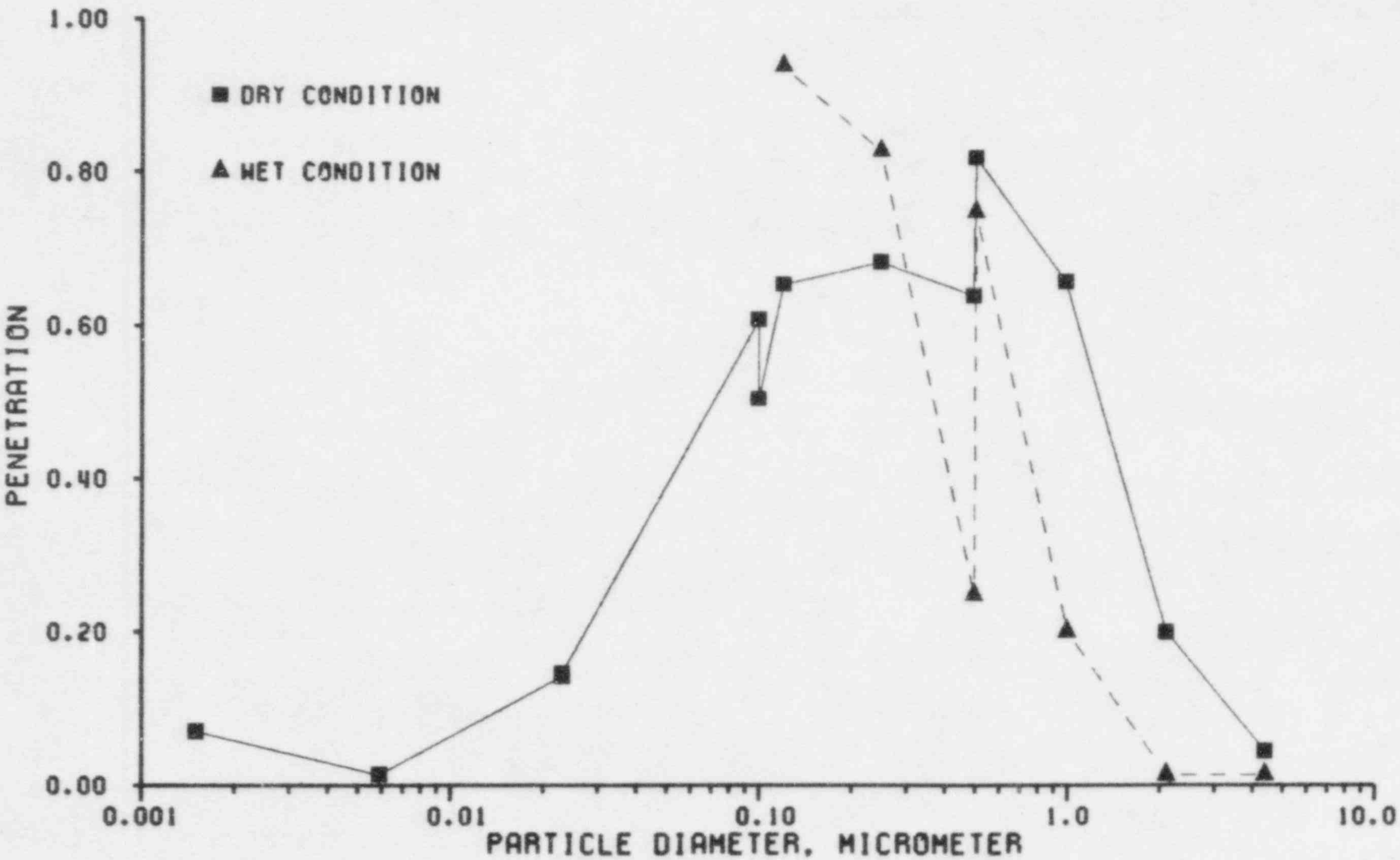


FIGURE 13 : PENETRATION VERSUS PARTICLE DIAMETER FOR SHIRT(8) 5.0 CM/S

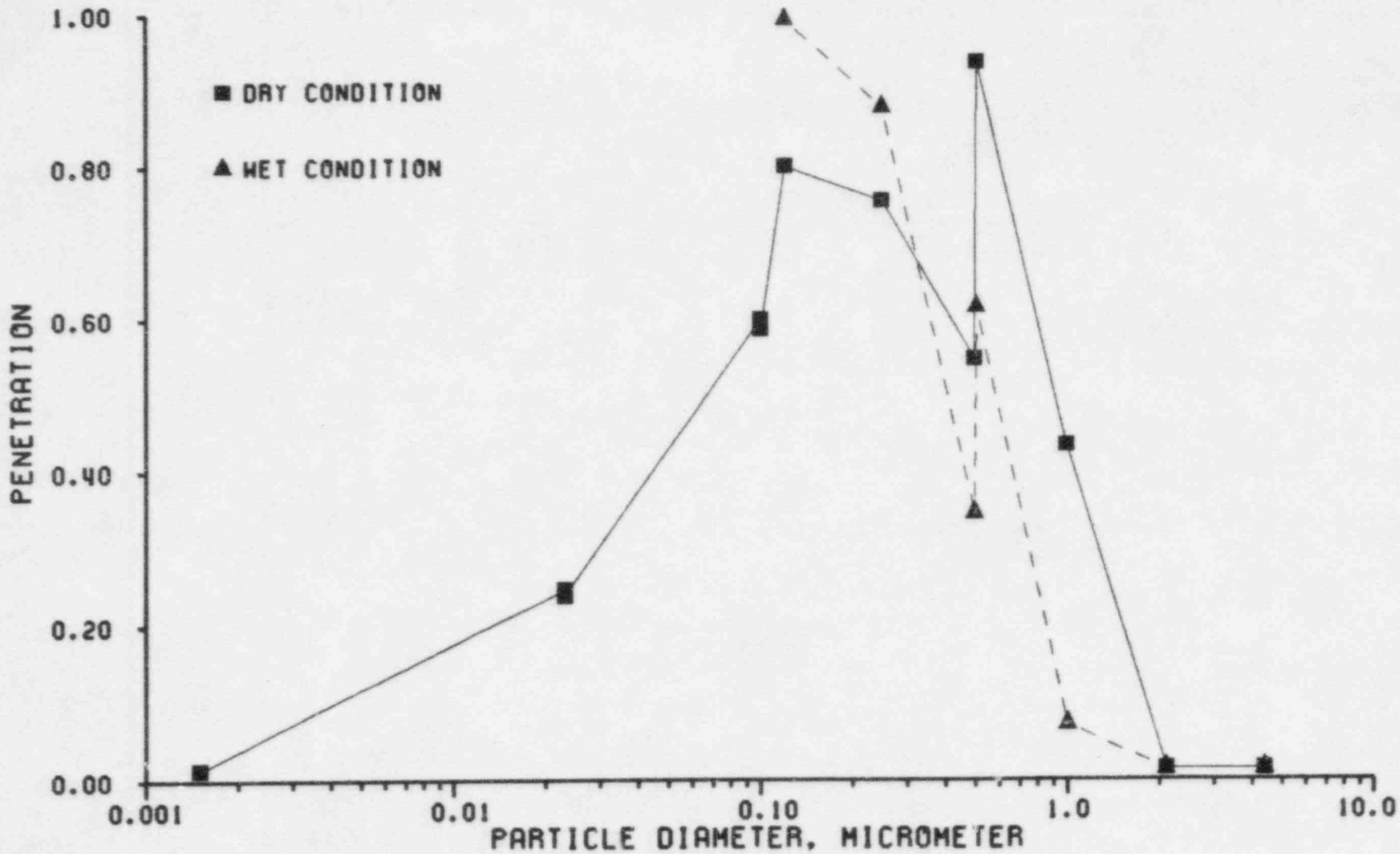


FIGURE 14 : PENETRATION VERSUS PARTICLE DIAMETER FOR SHIRT(8) 15.0 CM/S

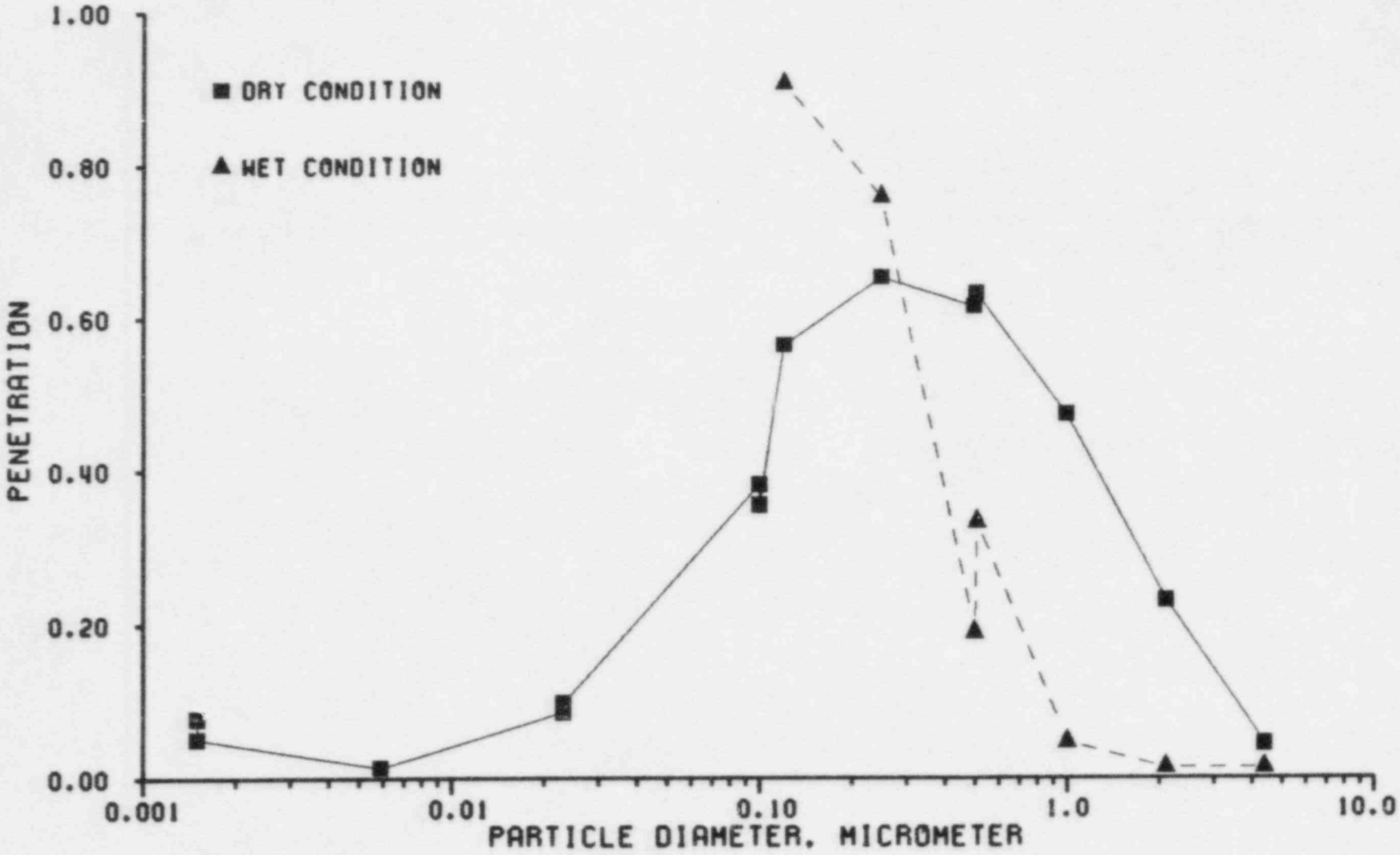


FIGURE 15 : PENETRATION VERSUS PARTICLE DIAMETER FOR WASH CLOTH(2) 1.5 CM/S

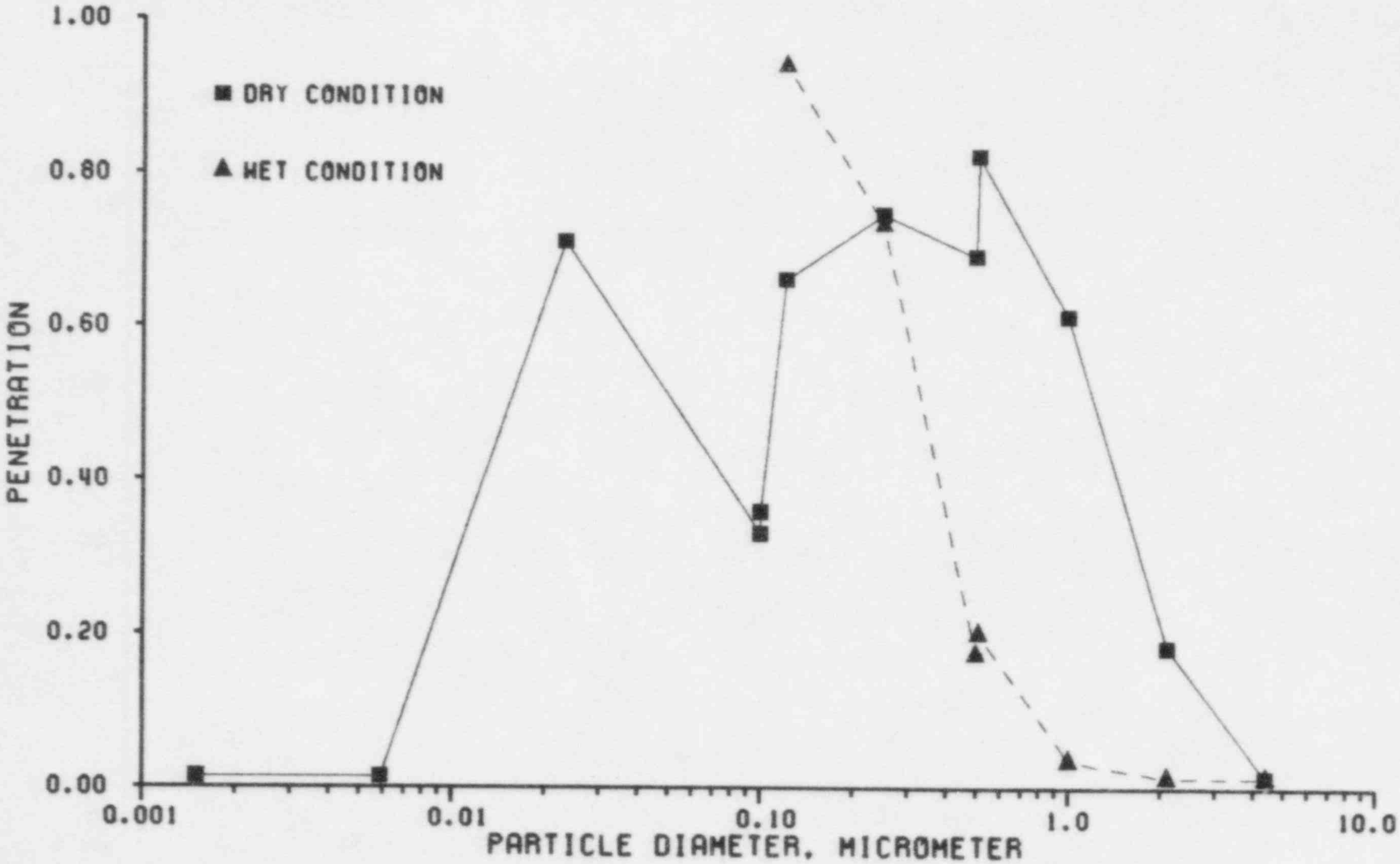


FIGURE 16 : PENETRATION VERSUS PARTICLE DIAMETER FOR WASH CLOTH(2) 5.0 CM/S

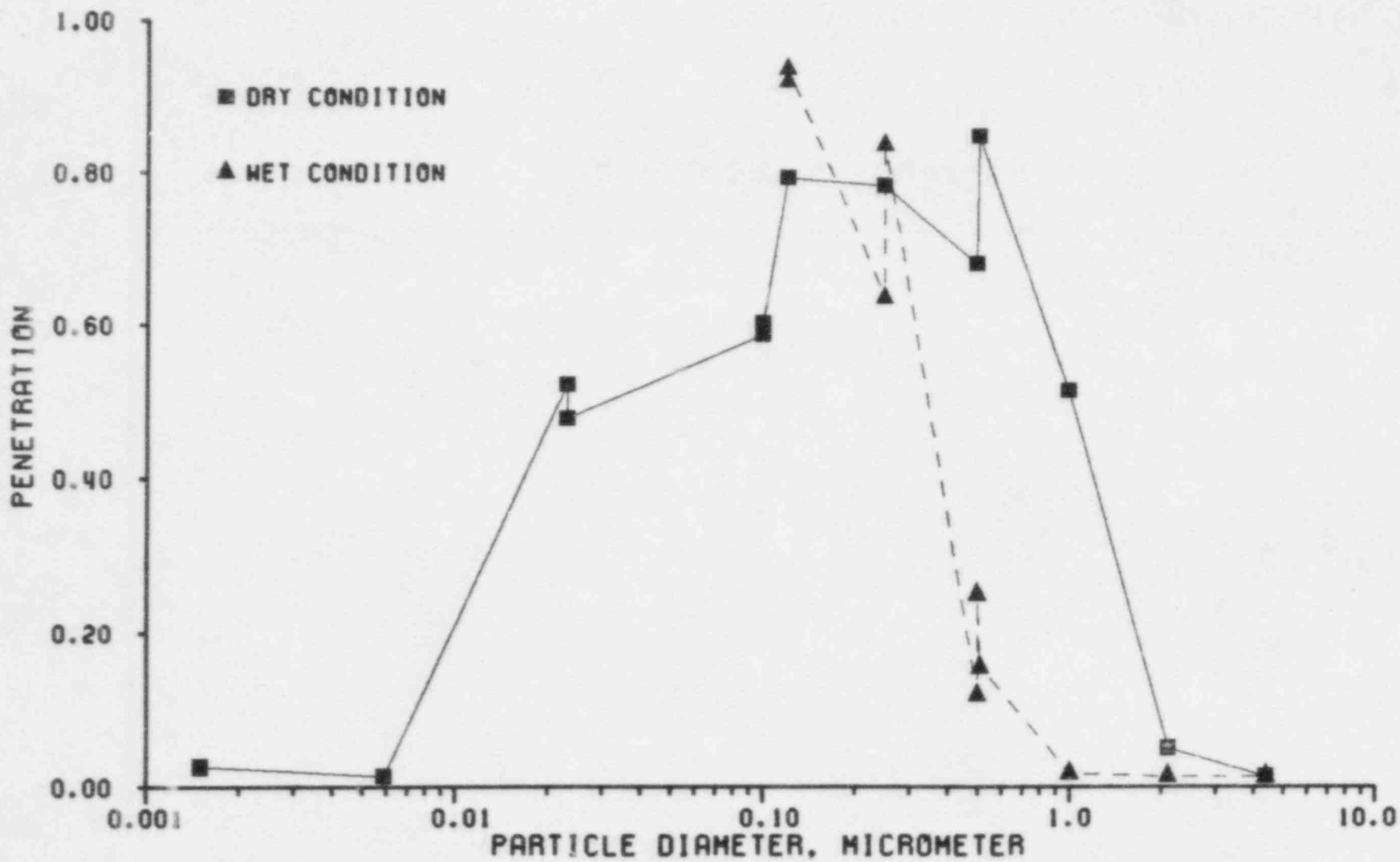


FIGURE 17 : PENETRATION VERSUS PARTICLE DIAMETER FOR WASH CLOTH(2) 15.0 CM/S

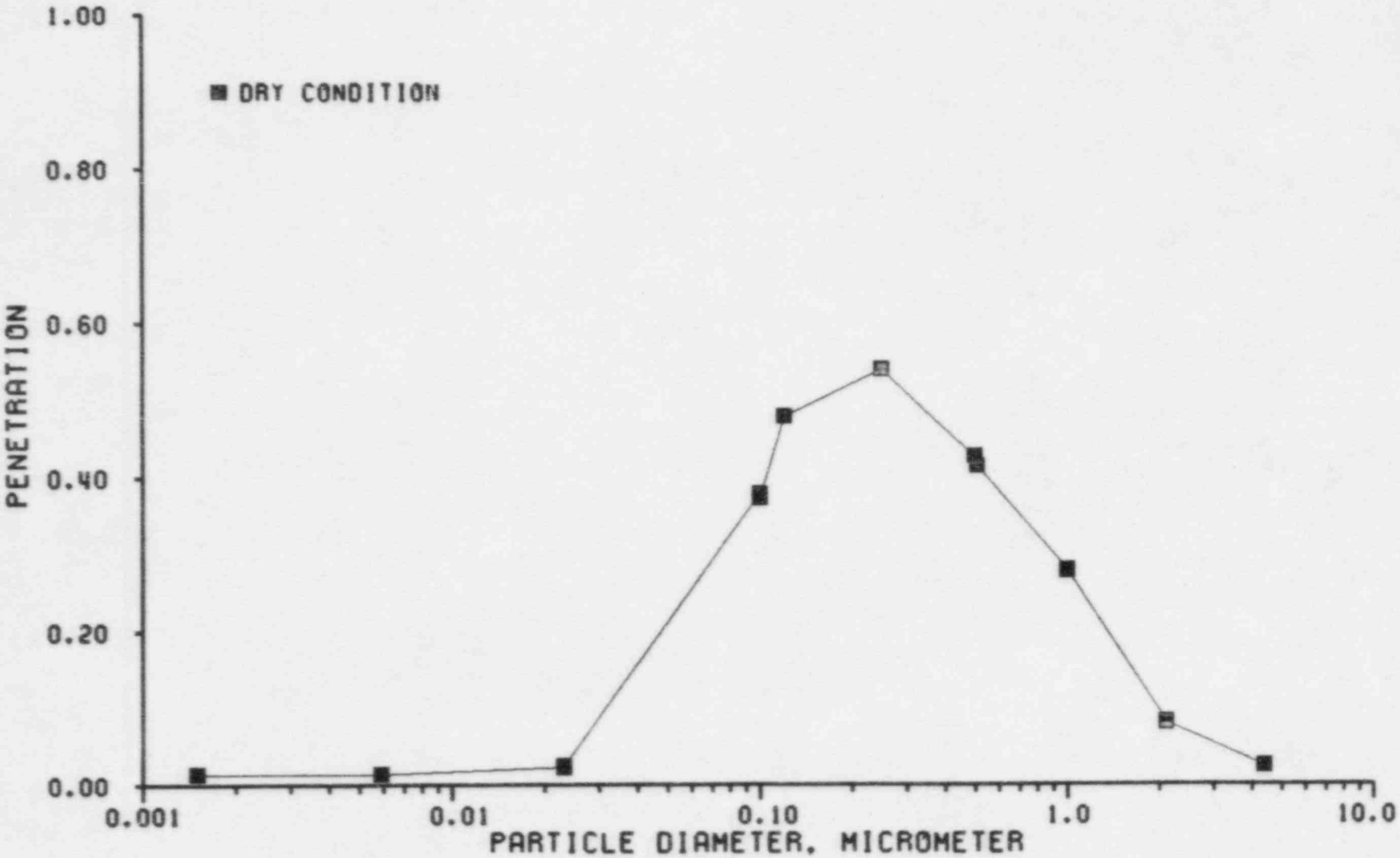


FIGURE 18 : PENETRATION VERSUS PARTICLE DIAMETER FOR SURGEON MASK(1) 1.5 CM/S

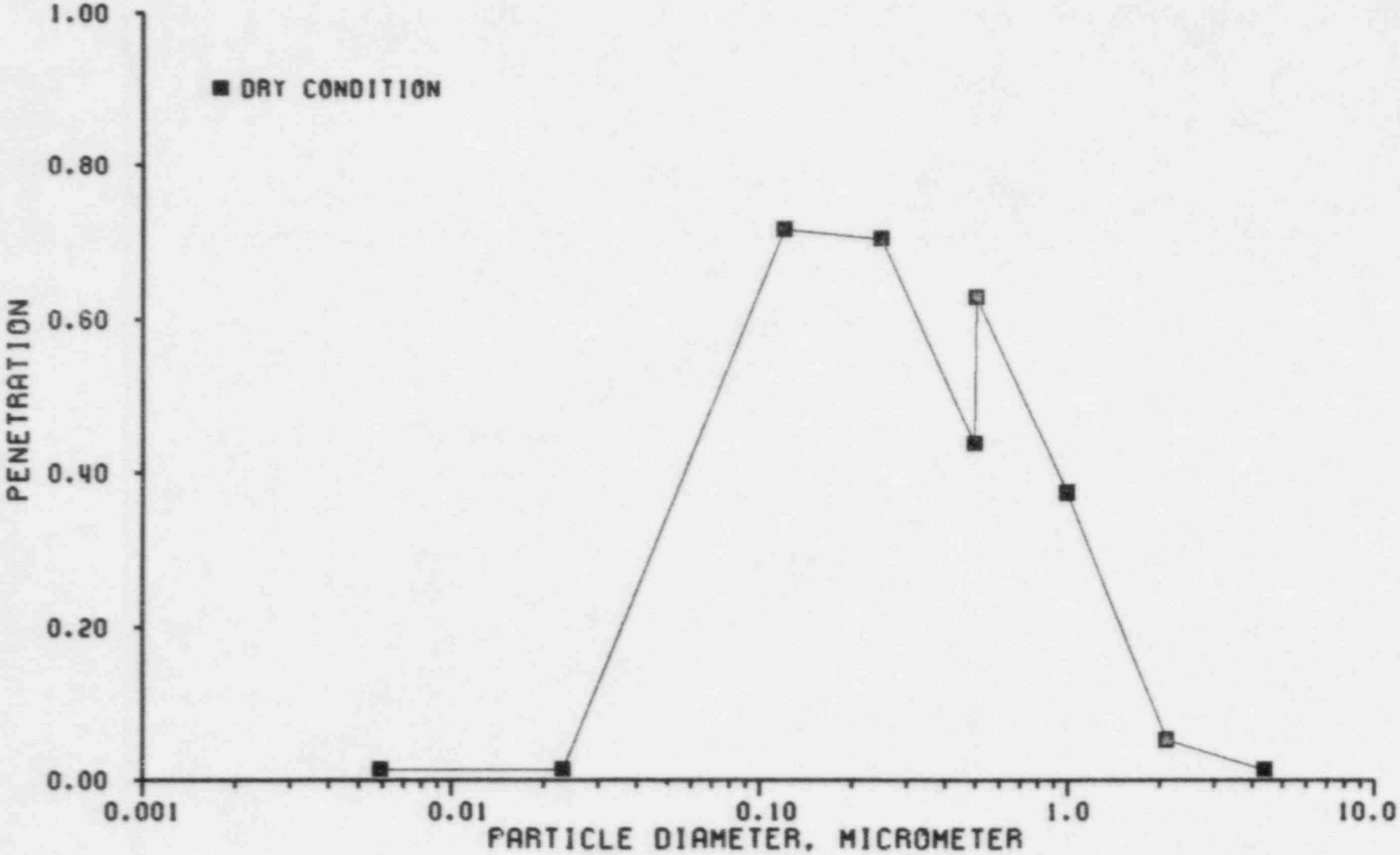


FIGURE 19 : PENETRATION VERSUS PARTICLE DIAMETER FOR SURGEON MASK(1) 5.0 CM/S

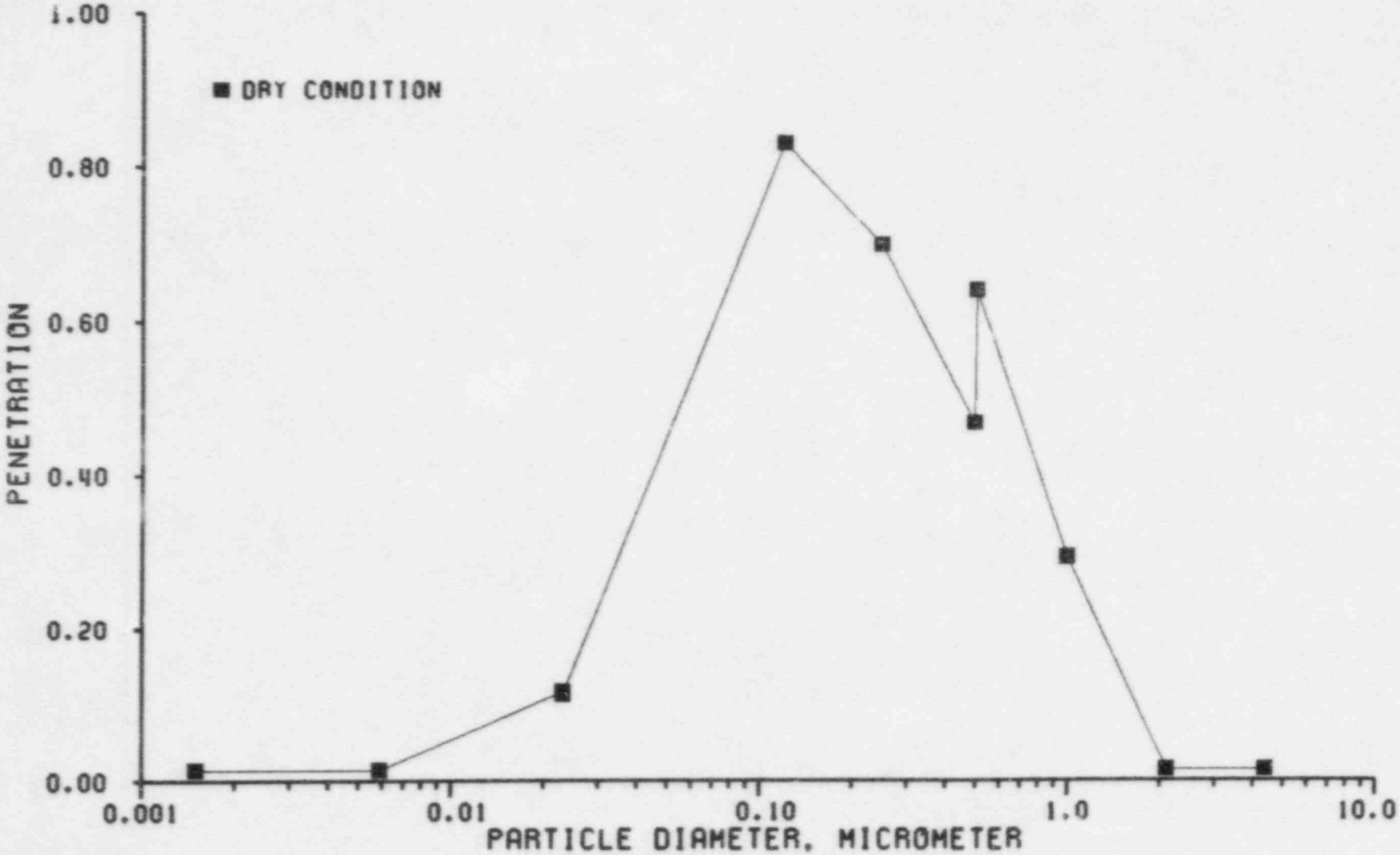


FIGURE 20 : PENETRATION VERSUS PARTICLE DIAMETER FOR SURGEON MASK(1) 15.0 CM/S

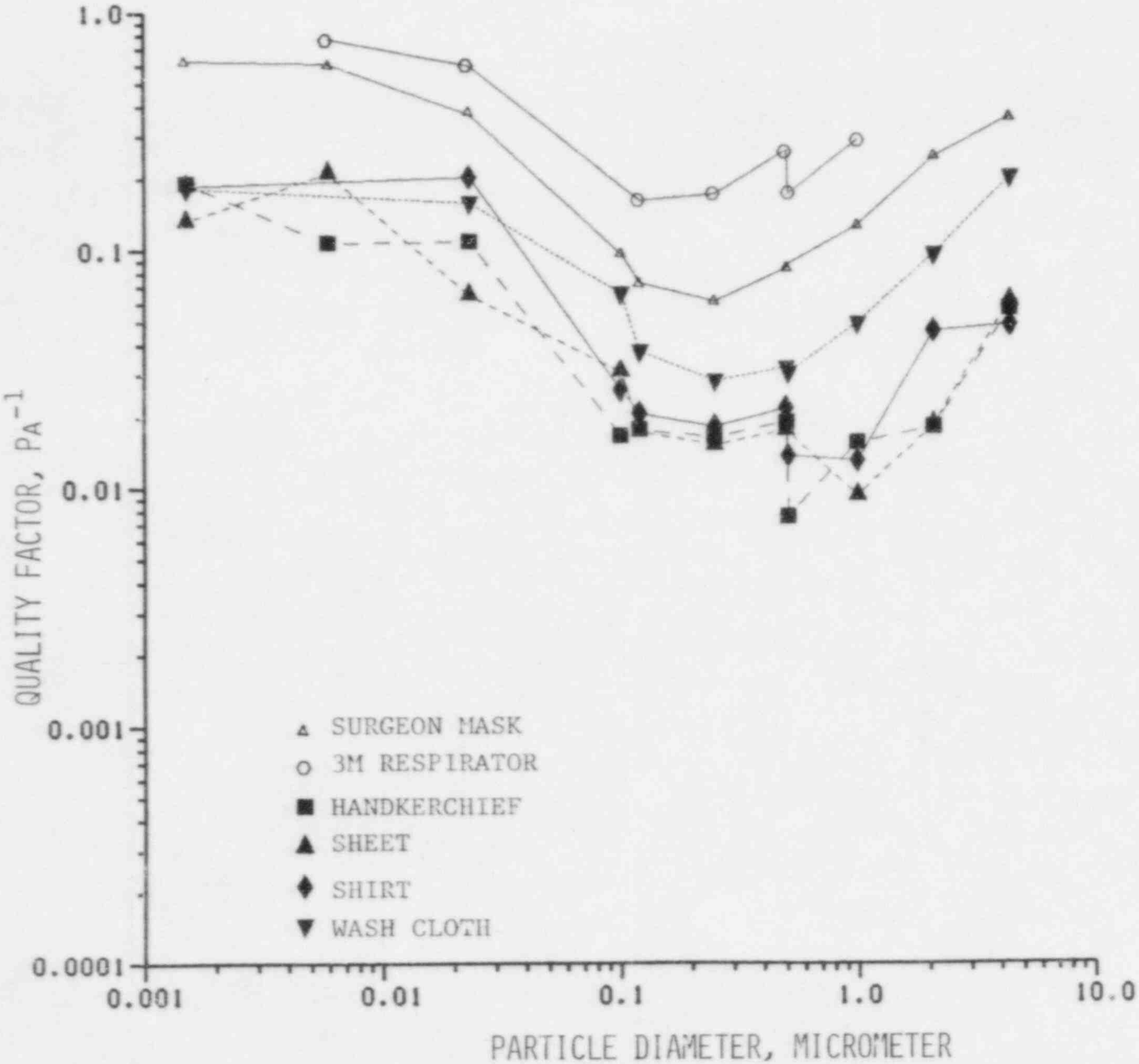


FIGURE 21 : QUALITY FACTORS. 1.5 CM/S

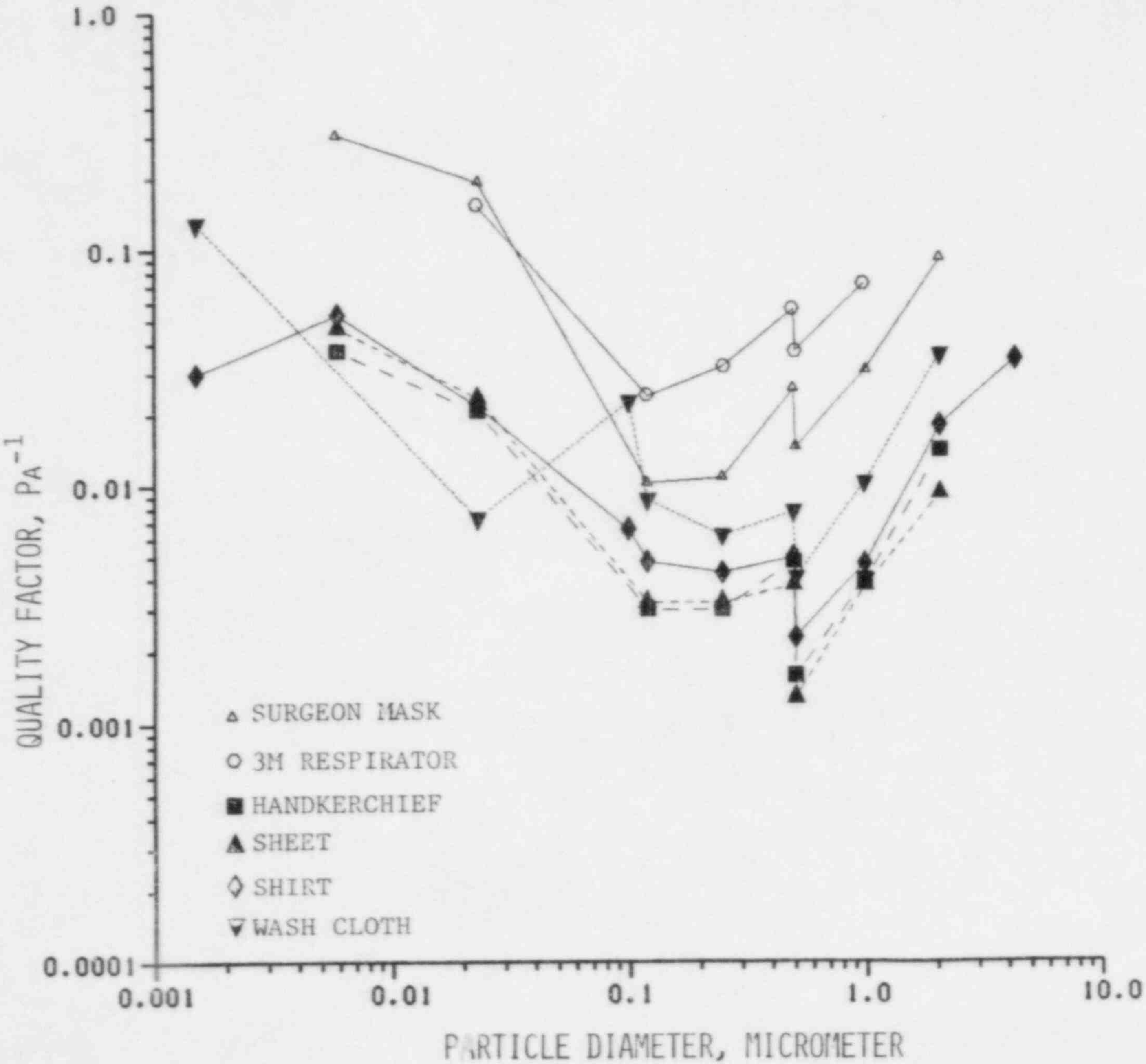


FIGURE 22 : QUALITY FACTORS, 5.0 CM/S

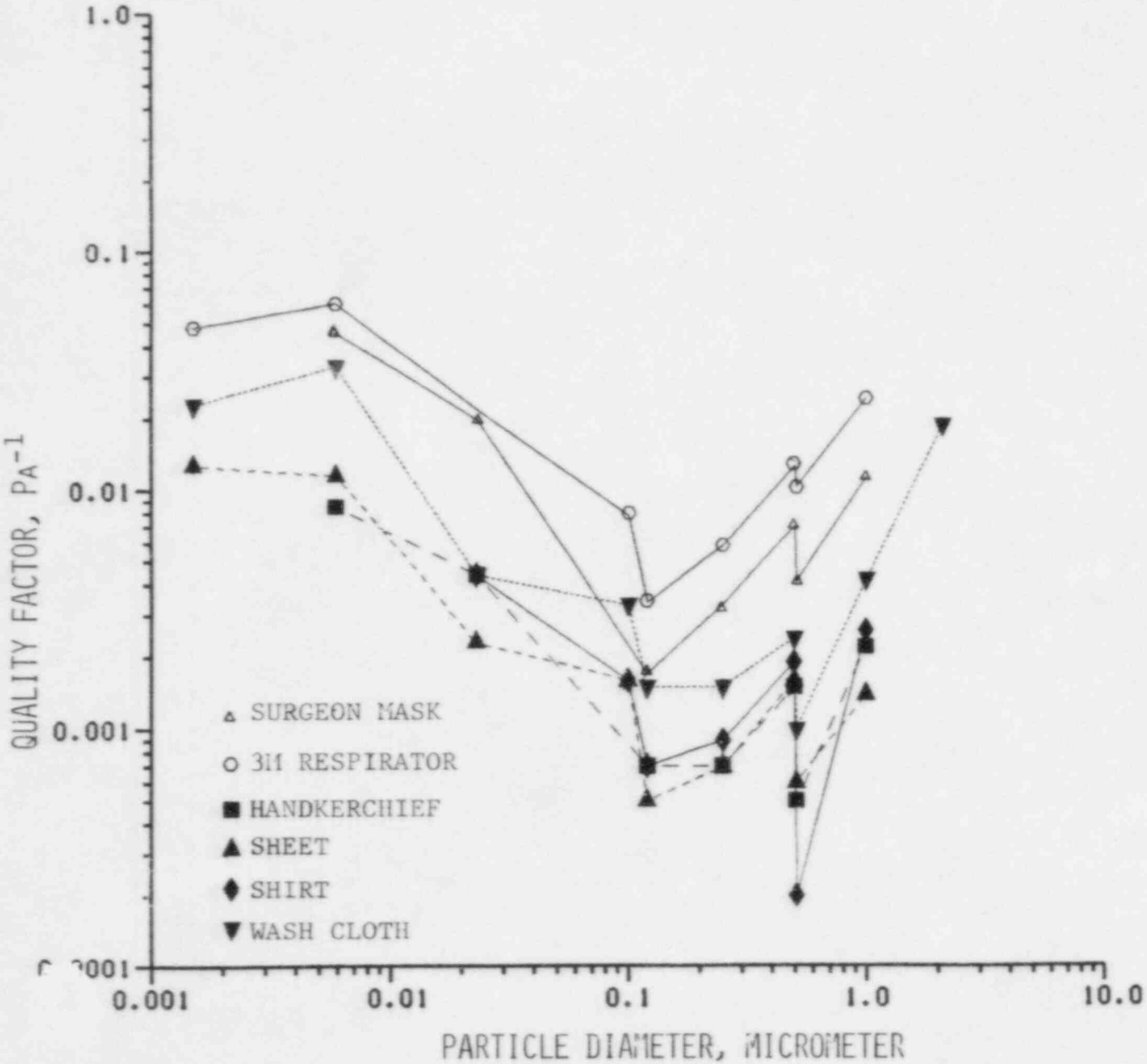


FIGURE 23 : QUALITY FACTORS. 15.0 CM/S

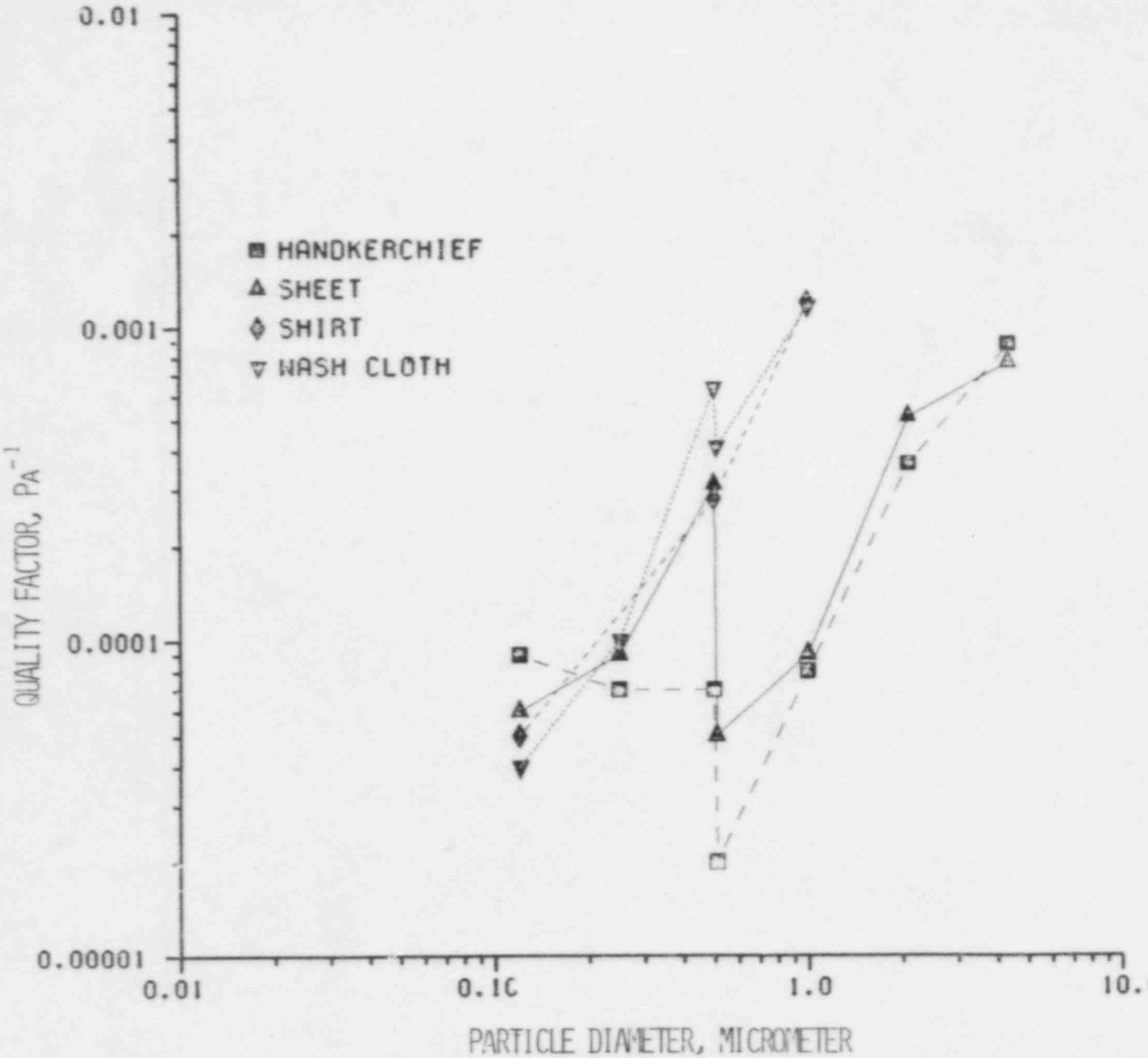


FIGURE 24 : WET QUALITY FACTORS. 1.5 CM/S

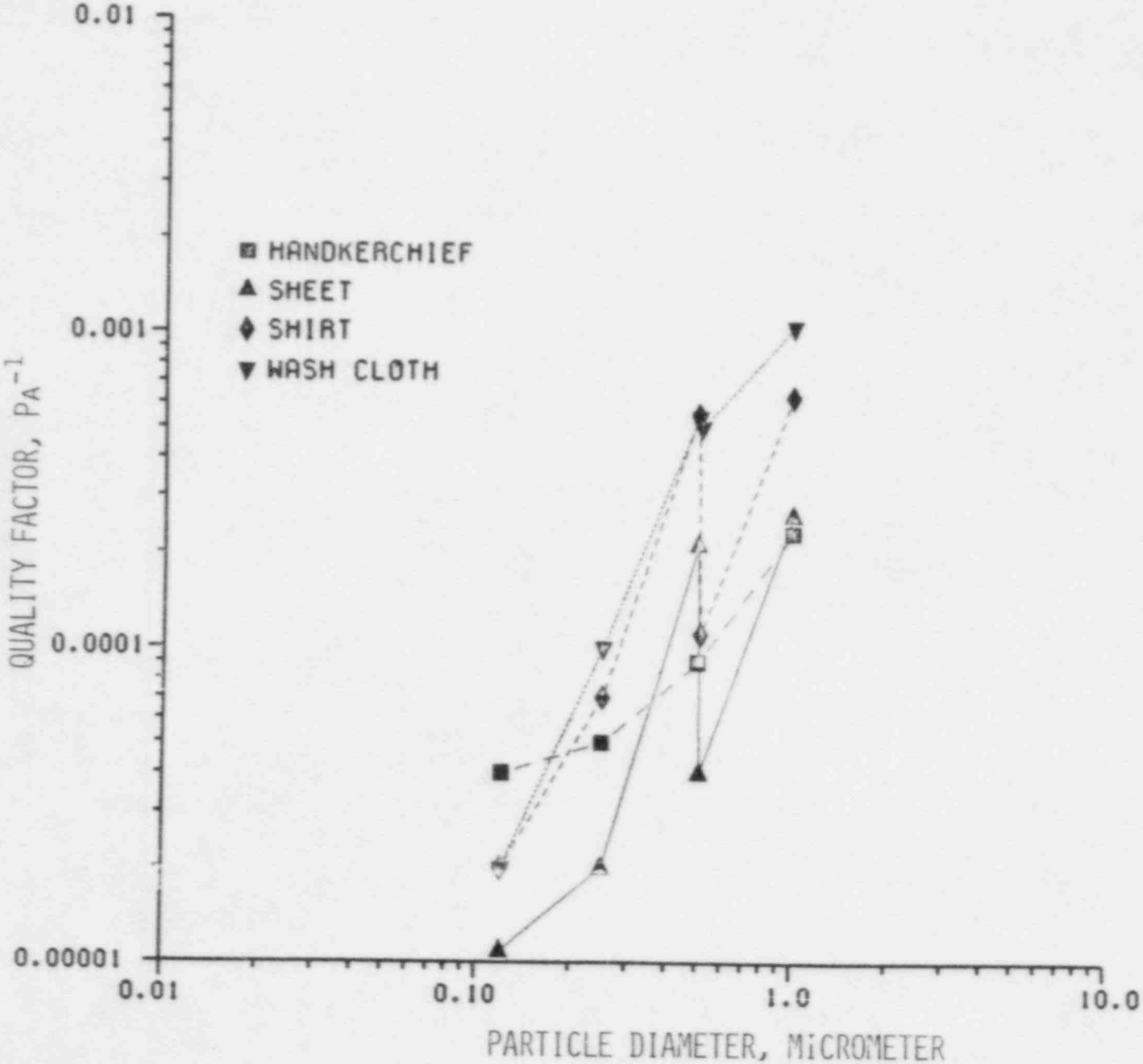


FIGURE 25 : NET QUALITY FACTORS. 5.0 CM/S

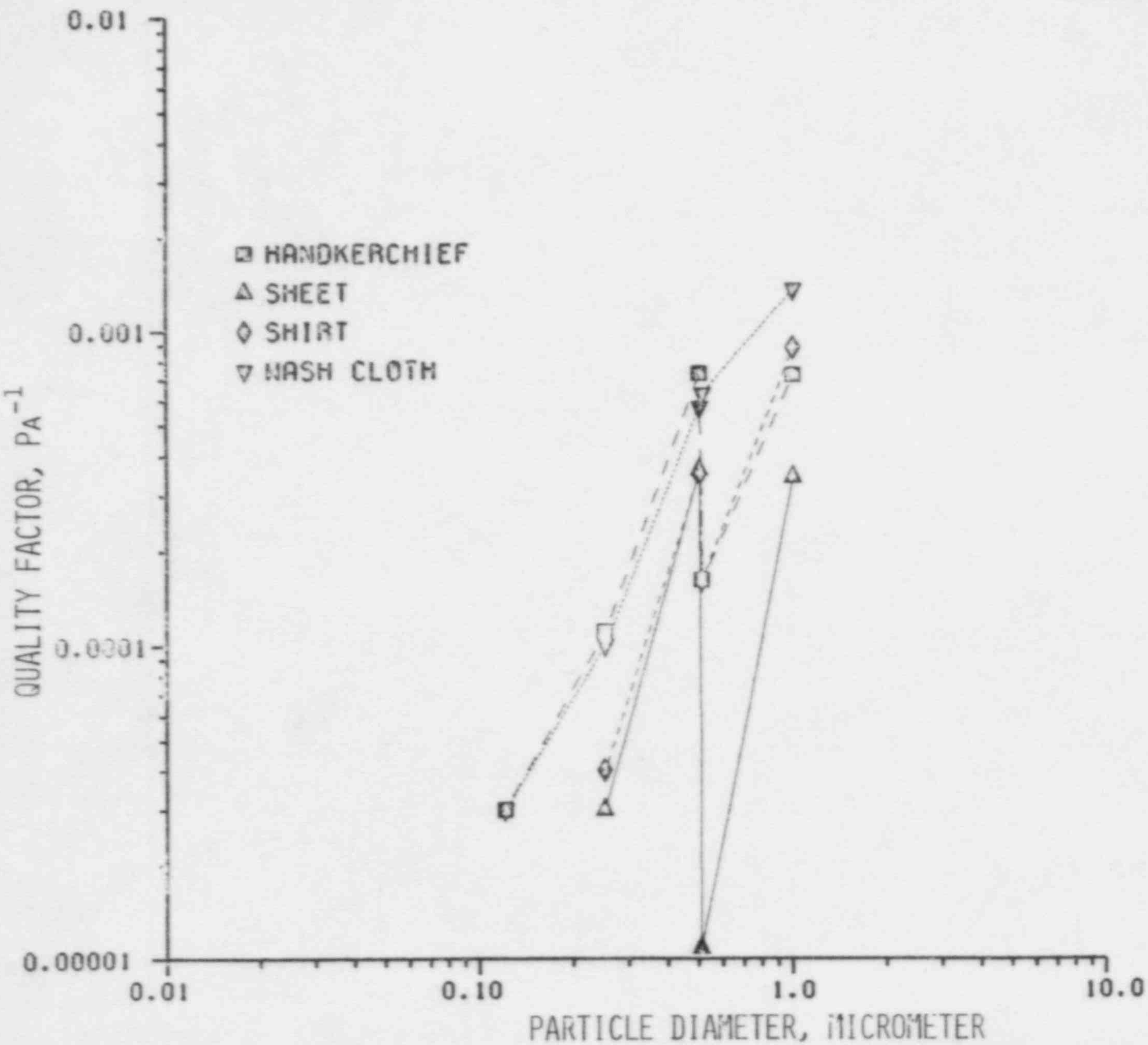
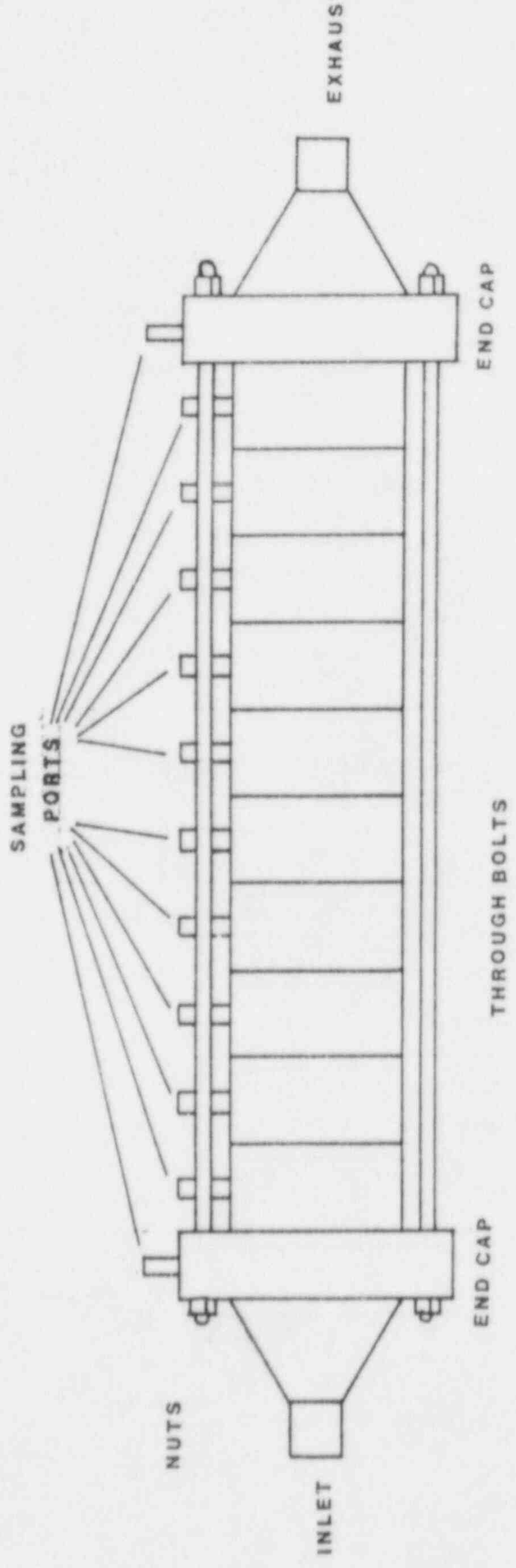
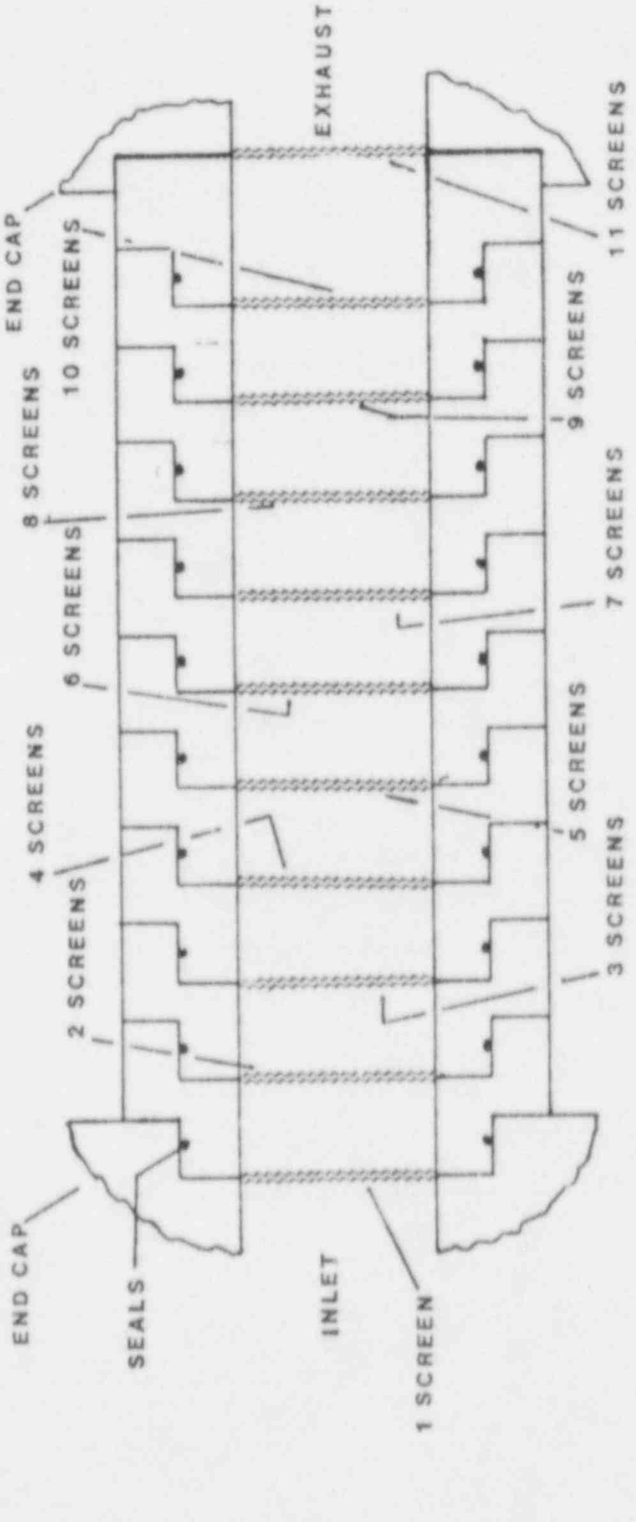


FIGURE 26 : WET QUALITY FACTORS, 15.0 CM/S

APPENDIX A : DIFFUSION BATTERY




END CAP
4 SCREENS
8 SCREENS
END CAP
2 SCREENS
6 SCREENS
10 SCREENS
SEALS
INLET
EXHAUST
1 SCREEN
5 SCREENS
9 SCREENS
3 SCREENS
7 SCREENS
11 SCREENS

CUMULATIVE FREQUENCY
NON-OVERLAPPING A
TIME 35 : 29
DATA RATE 2
5 CYCLES

A R C	MIN	MAX	MID	COUNT	FREQ/UM	FRAC/UM	CUM CNT	CUM FRAC
A 3 1	0.090	0.097	0.0935	1408	201142.85	0.0357	1408	0.0357
A 3 2	0.097	0.104	0.1005	575	82142.85	0.0145	1983	0.0502
A 3 3	0.104	0.111	0.1075	505	72142.85	0.0128	2488	0.0631
A 3 4	0.111	0.118	0.1145	478	68285.71	0.0121	2966	0.0752
A 3 5	0.118	0.125	0.1215	527	75285.71	0.0133	3493	0.0886
A 3 6	0.125	0.132	0.1285	464	66285.71	0.0117	3957	0.1004
A 3 7	0.132	0.139	0.1355	516	73714.28	0.0130	4473	0.1135
A 3 8	0.139	0.146	0.1425	589	84142.85	0.0149	5062	0.1285
A 3 9	0.146	0.153	0.1495	639	91285.71	0.0162	5701	0.1447
A 3 10	0.153	0.160	0.1565	629	89857.14	0.0159	6330	0.1607
A 2 2	0.160	0.170	0.1650	1067	106700.00	0.0270	7397	0.1877
A 2 3	0.170	0.180	0.1750	1248	124800.00	0.0316	8645	0.2194
A 2 4	0.180	0.190	0.1850	1272	127200.00	0.0322	9917	0.2517
A 2 5	0.190	0.200	0.1950	1456	145600.00	0.0369	11373	0.2887
A 2 6	0.200	0.210	0.2050	1351	135100.00	0.0342	12724	0.3230
A 2 7	0.210	0.220	0.2150	1316	131600.00	0.0334	14040	0.3564
A 2 8	0.220	0.230	0.2250	1343	134300.00	0.0340	15383	0.3905
A 2 9	0.230	0.240	0.2350	1219	121900.00	0.0309	16602	0.4214
A 2 10	0.240	0.250	0.2450	1121	112100.00	0.0284	17723	0.4499
A 2 11	0.250	0.260	0.2550	1136	113600.00	0.0288	18859	0.4787
A 2 12	0.260	0.270	0.2650	1001	100100.00	0.0254	19860	0.5041
A 2 13	0.270	0.280	0.2750	877	87700.00	0.0222	20737	0.5264
A 1 2	0.280	0.320	0.3000	3335	83375.00	0.0846	24072	0.6111
A 1 3	0.320	0.360	0.3400	3042	76050.00	0.0772	27114	0.6883
A 1 4	0.360	0.400	0.3800	2935	73375.00	0.0745	30049	0.7628
A 1 5	0.400	0.440	0.4200	1480	37000.00	0.0375	31529	0.8004
A 1 6	0.440	0.480	0.4600	1122	28050.00	0.0284	32651	0.8289
A 1 7	0.480	0.520	0.5000	711	17775.00	0.0180	33362	0.8469
A 1 8	0.520	0.560	0.5400	639	15975.00	0.0162	34001	0.8631
A 1 9	0.560	0.600	0.5800	633	15825.00	0.0160	34634	0.8792
A 1 10	0.600	0.640	0.6200	570	14250.00	0.0144	35204	0.8937
A 1 11	0.640	0.680	0.6600	455	11375.00	0.0115	35659	0.9052
A 1 12	0.680	0.720	0.7000	344	8600.00	0.0087	36003	0.9140
A 1 13	0.720	0.760	0.7400	312	7800.00	0.0079	36315	0.9219
A 0 2	0.760	0.920	0.8400	1162	7262.50	0.0294	37477	0.9514
A 0 3	0.920	1.080	1.0000	595	3718.75	0.0151	38072	0.9665
A 0 4	1.080	1.240	1.1600	401	2506.25	0.0101	38473	0.9767
A 0 5	1.240	1.400	1.3200	257	1606.25	0.0065	38730	0.9832
A 0 6	1.400	1.560	1.4800	203	1268.75	0.0051	38933	0.9883
A 0 7	1.560	1.720	1.6400	160	1000.00	0.0040	39093	0.9924
A 0 8	1.720	1.880	1.8000	97	606.25	0.0024	39190	0.9949
A 0 9	1.880	2.040	1.9600	72	450.00	0.0018	39262	0.9967
A 0 10	2.040	2.200	2.1200	50	312.50	0.0012	39312	0.9980
A 0 11	2.200	2.360	2.2800	25	156.25	0.0006	39337	0.9986
A 0 12	2.360	2.520	2.4400	13	81.25	0.0003	39350	0.9989
A 0 13	2.520	2.680	2.6000	15	93.75	0.0003	39365	0.9993
A 0 14	2.680	2.840	2.7600	13	81.25	0.0003	39378	0.9996
A 0 15	2.840	3.000	2.9200	12	75.00	0.0003	39390	1.0000

Appendix B (con't)

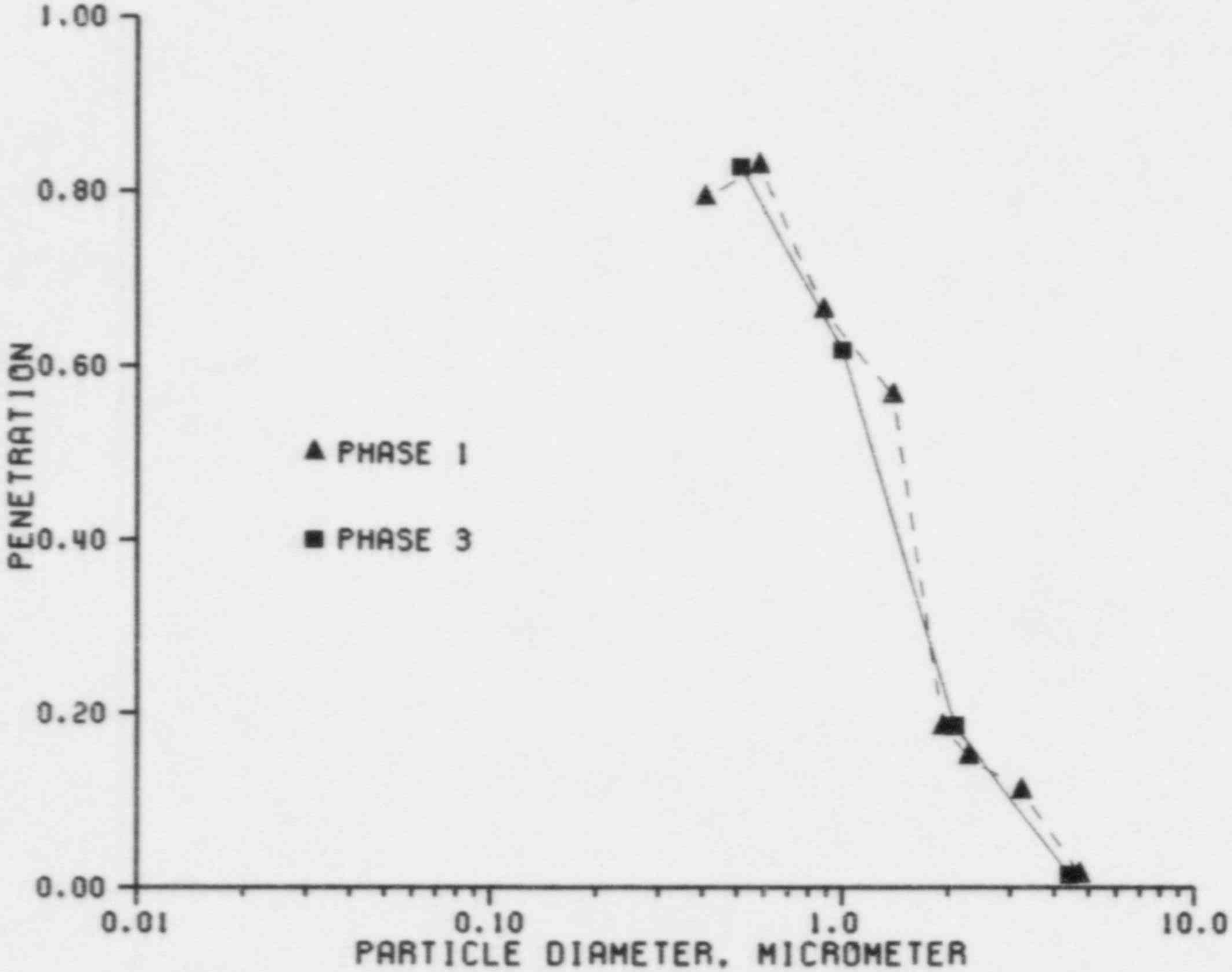
FREQUENCY PER CHANNEL
NON-OVERLAPPING B
TIME 8 : 25
DATA RATE 2
3 CYCLES

P	R	C		MIN	MAX	COUNT	FREQ/WDTH
B	3	1		0.320	0.349	1029	35482.75
B	3	2		0.349	0.378	633	21827.58
B	3	3		0.378	0.407	588	20275.86
B	3	4		0.407	0.436	375	12931.03
B	3	5		0.436	0.465	419	14448.27
B	3	6		0.465	0.494	378	13034.48
B	3	7		0.494	0.523	346	11931.03
B	3	8		0.523	0.552	283	9758.62
B	3	9		0.552	0.581	198	6827.58
B	3	10		0.581	0.610	174	6000.00
B	3	11		0.610	0.639	169	5827.58
B	3	12	*	0.639	0.668	193	6655.17
B	2	2		0.650	0.800	995	6633.33
B	2	3		0.800	0.950	832	5546.66
B	2	4		0.950	1.100	988	6586.66
B	2	5		1.100	1.250	785	5233.33
B	2	6		1.250	1.400	200	1333.33
B	2	7		1.400	1.550	58	386.66
B	2	8		1.550	1.700	41	273.33
B	2	9		1.700	1.850	30	200.00
B	2	10		1.850	2.000	33	220.00
B	2	11		2.000	2.150	52	346.66
B	2	12		2.150	2.300	50	333.33
B	2	13		2.300	2.450	73	486.66
B	2	14	*	2.450	2.600	67	446.66
B	1	3		2.500	3.250	209	278.66
B	1	4		3.250	4.000	56	74.66
B	1	5		4.000	4.750	16	21.33
B	1	6		4.750	5.500	4	5.33
B	1	7		5.500	6.250	0	0.00
B	1	8		6.250	7.000	0	0.00
B	1	9		7.000	7.750	0	0.00
B	1	10		7.750	8.500	0	0.00
B	1	11		8.500	9.250	0	0.00
B	1	12		9.250	10.000	0	0.00
B	1	13		10.000	10.750	0	0.00
B	1	14		10.750	11.500	0	0.00
B	1	15	*	11.500	12.250	0	0.00
B	0	9		11.600	12.800	0	0.00
B	0	10		12.800	14.000	0	0.00
B	0	11		14.000	15.200	0	0.00
B	0	12		15.200	16.400	0	0.00
B	0	13		16.400	17.600	0	0.00
B	0	14		17.600	18.800	0	0.00
B	0	15		18.800	20.000	0	0.00

TOTAL COUNT IS 9274

Appendix C: Phase I vs. Phase III
(Handkerchief, 5.0 cm/s, Dry Condition)

Particle Diameter (μm)	Phase I	Particle Diameter (μm)	Phase III
0.4070	.7930	0.51	.8294
0.5810	.8300	1.0	.6179
0.8840	.6630	2.1	.1852
1.4000	.5650	4.4	.0000
1.9300	.1840		
2.3000	.1500		
3.2300	.1110		
4.7500	.0130		



APPENDIX C : HANDKERCHIEF, 5.0 CM/S

Appendix D: Comparison of Data Inversion Methods RR and LSNN

Surgical Mask

	Face Velocity(cm/s)					
Diameter	1.5		5.0		15.0	
(μm)	LSNN	RR	LSNN	RR	LSNN	RR
.0015	.0000 .0038	.0000 .0030	***** *****	.0000 .0000	***** .0000	.0001 .0016
.0059	.0045 .0000	.0070 .0000	.0001 .0000	.0002 .0002	.0056 .0079	.0194 .0218
.0234	.0228 .0252	.0410 .0430	.0014 .0027	.0021 .0024	.1173 .1144	.0531 .0536
.1027	.3780 .3729	.3130 .3160	***** *****	***** *****	***** *****	***** *****

3M Respirator

	Face Velocity(cm/s)					
Diameter	1.5		5.0		15.0	
(μm)	LSNN	RR	LSNN	RR	LSNN	RR
.0015	***** *****	***** *****	***** *****	.0054 .0086	.0030 *****	.0000 .0028
.0059	.0002 .0002	.0002 .0003	.0000 .0000	.0008 .0003	.0014 .0000	.0106 .0099
.0234	.0000 .0027	.0001 .0012	.0038 .0030	.0032 .0031	.0741 .0718	.0475 .0482
.1027	***** *****	***** *****	***** *****	.1116 .1081	.3826 .4051	.3256 .3228

Handkerchief

	Face Velocity(cm/s)					
Diameter	1.5		5.0		15.0	
(μm)	LSNN	RR	LSNN	RR	LSNN	RR
.0015	.0006 .0020	.0021 .0027	***** *****	.0804 .0284	***** *****	.0177 .0184
.0059	.0268 .0190	.0070 .0059	.0107 .0126	.0257 .0267	.0284 .0296	.0399 .0413
.0234	.0203 .0229	.0383 .0386	.0860 .0831	.0651 .0648	.1668 .1534	.0695 .0686
.1027	.5448 .5700	.3472 .3489	***** *****	.4216 .3868	***** *****	***** *****

Appendix D (cont'd)

Sheet

Diameter (μm)	Face Velocity(cm/s) 1.5 LSNN	1.5 RR	5.0 LSNN	5.0 RR	15.0 LSNN	15.0 RR
.0015	.0092 .0057	.0011 .0013	.0000 .0000	.0000 .0000	.0000 .0095	.0000 .0225
.0059	.0000 .0008	.0009 .0020	.0013 .0050	.0090 .0120	.0161 .0000	.2142 .0414
.0234	.1136 .0640	.0165 .0185	.0609 .0492	.0368 .0335	.4653 .2932	.4510 .3071
.1027	.3006 .3314	2.305 1.170	1.873 2.386	.7376 .6643	.3960 .6399	.4043 .5934

Shirt

Diameter (μm)	Face Velocity(cm/s) 1.5 LSNN	1.5 RR	5.0 LSNN	5.0 RR	15.0 LSNN	15.0 RR
.0015	.0078 .0080	.0050 .0047	***** .0709	.0037 .0123	.0000 *****	.0000 *****
.0059	.0000 .0000	.0004 .0004	.0091 .0083	.0309 .0318	***** *****	.0000 2.053
.0234	.0000 .0098	.0057 .0133	.1430 .1464	.0946 .0964	.2474 .2396	.4345 .3949
.1027	.5169 .5027	1.803 1.446	.6077 .5051	.4418 .4097	.5994 .5858	.5863 .5737

Wash Cloth

Diameter (μm)	Face Velocity(cm/s) 1.5 LSNN	1.5 RR	5.0 LSNN	5.0 RR	15.0 LSNN	15.0 RR
.0015	.0781 .0519	.0097 .0105	.0006 .0038	.0018 .0033	.0259 .0272	.0170 .0145
.0059	.0000 .0000	.0142 .0151	.0000 .0000	.0052 .0079	.0105 .0000	.0206 .0164
.0234	.0861 .0976	.0718 .0826	6.121 .7102	.1339 .1310	.5224 .4782	.2155 .2408
.1027	.3812 .3553	.3376 .3170	.3296 .3584	.5368 .5199	.5874 .6022	.6507 .6543

Appendix D

Program Test Data Analysis with Hypothetical Aerosol Distributions

Diameter (μm)	Actual	LSNN	RR
.0015	2500	2501	2495
.0059	2500	2498	2497
.0234	2500	2501	2500
.1027	2500	2500	2500

Appendix D

Program Test Data Analysis with Hypothetical Aerosol Distributions

Diameter (μm)	Actual	LSNN	RR
.0015	36	35	35
.0059	2264	2266	2265
.0234	6600	6599	6599
.1027	1100	1100	1099

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13. ABSTRACT (200 words or less)

The efficacy of readily available materials, such as cotton fabrics, toweling, a surgical mask, and a single-use respirator, for providing emergency respiratory protection was evaluated by determining the filtration efficiency as a function of aerosol particle size over the size range of 0.001 to 5.0 μm and as a function of filtration face velocity. Filtration face velocity was set at 1.5, 5.0, and 15.0 cm/s. This report describes the equipment and procedures used to obtain efficiency measurements for particles 0.5 μm in diameter and smaller, and summarizes the results of all three phases of this reaearch. Particles with diameters from 0.10 to 0.50 μm proved to be the most difficult sizes of particles to remove. Particles smaller than 0.10 μm were removed due to diffusion while particles larger than 0.50 μm were removed due to inertia and gravitational settling. Deposition of the smallest particles was favored by the use of low face velocities. A fractional efficiency curve was determined for each material at each velocity for comparison. Values of the quality factor, [-ln(penetration)]/(pressure drop), were calculated. Quality factors were less for wet materials than for dry; less at high velocities rather than low; and best for the single-use respirator mask, next best for the surgical mask and often third best for the toweling.

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