EVALUATION OF NAPPED FABRICS FOR AEROSOLIZED CHEMICAL AGENT PROTECTION

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The Navy Clothing and Textile Research Facility subjected various outershell fabrics from existing chemical protective suits to four levels of napping. The napped fabrics were then evaluated for potential increase in protection to aerosolized chemical agents. Based on laboratory testing, napping had little or no effect on the filtration efficiency, physical or insulation properties of the fabrics tested.

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TABLE OF CONTENTS

LIST OF TABLES

EVALUATION OF NAPPED FABRICS FOR AEROSOLIZED CHEMICAL AGENT PROTECTION

INTRODUCTION

In September 1991, the Navy Clothing and Textile Research Facility (NCTRF) was tasked by the Marine Corps Research, Development and Acquisition Center, Quantico, VA, to evaluate the potential of enhancing aerosol protection of existing chemical protective suits by napping the back side of the outershell fabric layer. The program was established as a two phase approach; Phase I of the program was to be conducted as a validation of concept, and Phase II would act as a continuance of the program if Phase I provided supporting data. The information reported herein provides the findings of Phase I only.

Candidate fabrics representing existing and developmental outershell layers from various Department of Defense chemical protective suits were napped at different levels of densities. The napped and unnapped candidate fabrics were subsequently subjected to in-house testing to evaluate the effects of napping on each material's thermal insulation and physical properties. Small scale liquid aerosol fabric swatch testing for filtration efficiency data was conducted on all candidate fabrics at the Research Triangle Institute (RTI), Research Triangle Park, North Carolina. RTI's report is attached as Appendix A, and will be referenced throughout this report.

Overall results of this evaluation determined:

1. Napping does not appear to provide a significant increase in aerosol protection of the candidate fabrics.

2. Napping does not significantly increase the insulation properties of the candidate fabrics.

3. With the exception of increased air permeability and shrinkage, the napping had an insignificant effect on the physical properties of the candidate fabrics.

BACKGROUND

Napping is a mechanical process by which individual fibers are raised from the fabric yarn structure to create surface cover (e.g., flannel). It has been theorized by NCTRF that by napping a fabric, aerosolized particles may become entrapped with the surface fibers, thus increasing the protection provided to the wearer of the napped garment. Since napping is a fairly simple and inexpensive process, it was the intent of this program to investigate the possibility of improving the protection of the Marine Corps Protective Overgarment with minimal increase to cost and heat stress.

Emerging technologies in chemical agent dissemination has increased awareness of the aerosol threat, thereby warranting the necessity for specialized protection. An aerosol may be defined as a suspension of solid or liquid particles in the air.(1) Aerosols, in the sense of posing a chemical warfare threat, can be thought of as being in the range of 0.1 to 10 microns in diameter, which is intermediate in size between droplets and vapors. Particles in this size range tend to penetrate permeable protective fabrics to a higher degree than do either droplets or vapor. This is because, on the one hand, the particles are sufficiently large that they do not have the high diffusion rates to be efficiently absorbed by carbon as are the smaller vapor molecules (diffusion rates are inversely proportional to particle, or molecule size). On the other hand, the particles are sufficiently small that, unlike the larger droplets, they tend to follow the flow steamlines as air flows through a garment and are not collected efficiently by the threads of a protective garment.(2)

To date, the Navy is the only branch of service that has established an aerosol requirement for chemical protective clothing. This aerosol requirement only applies to the Navy's experimental Advanced Chemical Protective Garment program.

MATERIAL DESCRIPTION

Four candidate fabrics, which represent existing or experimental outershell layers from Navy, Army and Marine Corps chemical protective clothing, were procured and napped. The actual degree to which each fabric was napped was not quantified. Rather, the degree of napping was expressed as the number of times the base fabric was passed through the napping machine.(3) Each candidate fabric was subjected to 1, 2, 3, and 4 napping passes, which the exception of the nylon/cotton woodland twill. The strength of the nylon fiber required that this fabric be subjected to twice as many napping passes in order to achieve the same "cover" or density as all the other candidate fabrics. As was expected, each candidate fabric responded differently to the napping process, due to the varying constructions, weaves and weights. Fabrics were napped on a Woonsocket napper at Galey & Lord, Society Hill, South Carolina.

The candidate fabrics consisted of the following:

Fabric A - 100% cotton ripstop, quarpel water repellent treated, 6 ounces per square yard, desert camouflage, conforming to MIL-C-43468.

Fabric B - 50/50 polyester/cotton twill, fire retardant/water repellent teated, 6 ounces per square yard, navy blue.

Fabric C - 100% cotton twill, fire retardant/water repellent treated, 6 ounces per square yard, navy blue.

Fabric D - 70/30 cotton/polyester twill, fire retardant/water repellent, 6.5 ounces per square yard, navy blue.*

Fabric E - 50/50 nylon/cotton, quarpel water repellent treated, 7 ounces per square yard, woodland camouflage, conforming to MIL-C-44031.

A full description of the candidate fabrics can be found in Table I.

*Fabric D was not an existing or experimental fabric for any of the service chemical protective suits, but was specifically engineered by Galey & Lord for the napping procedure. Since napping is considered a "filling phenomenom", whereby the process digs into the filling yarns to produce a cover, Fabric D was designed to possess a high filling construction with low twist yarns. It was necessary to evaluate a fabric designed uniquely for napping, in order to investigate any potential differences or improvements Fabric D may offer over the other candidate fabrics which were not specifically created for napping. Due to technical difficulties experienced by Galey & Lord, the quantities of Fabric D necessary to produce the four levels of napping were unavailable. It was also questionable as to whether or not the unnapped materials possessed a water repellent treatment. As a result, Fabric D could not be fully evaluated.

TABLE - I

NAPPED CANDIDATE FABRICS

Material	Suit	DOD Branch
A - WR treated 100% cotton ripstop desert camouflage	Saratoga chemical protective overgarment	Marine Corps
B - FR/WR treated, 50/50 polyester/cotton twill, navy blue	Interim chemical protective suit (experimental)	Navy
C - FR/WR treated, 100% cotton twill, navy blue	Interim chemical protective suit (experimental)	Navy
D - FR/WR treated, 70/30 cotton/polyester twill, navy blue	N/A	N/A
E - WR treated 50/50 nylon/cotton twill, woodland camouflage	Battle dress overgarment	Army

WR - water repellent
FR - Fire retardant
N/A - Not applicable

TEST PROCEDURES

All of the candidate fabrics were subjected to physical, thermal insulation and aerosol penetration testing. With the exception of aerosol penetration, the test methods that were performed on the candidate fabrics are listed in Table II.

Physical Characteristics

The physical characteristics were obtained (break and tear strengths, air permeability, colorfastness, etc.) by testing the candidate materials in accordance with the test methods listed in Table II.

Dimensional Stability

The dimensional stability for all of the candidate fabrics was determined using the test methods listed in Table II. Wash wheel results were recorded after one and ten cycles. Home laundering results were recorded after one and five cycles.

Flame Resistance

Vertical flammability testing was performed only on the candidate fabrics (B & C) containing a flame retardant treatment. Testing was conducted before and after ten launderings in accordance with Federal Test Method 5903. This method judges the ability of a material to self-extinguish after removal of the flame source and the degree of material degradation caused by the flame exposure. Since Fabrics B and C are being proposed for use in chemical protective garments which are not laundered, the repeated launderings normally conducted to evaluate the durability of a fabric's finish were not required. However, the testing of the candidate fabrics after ten cycles was still performed in order to investigate potential trends resulting from napping.

Guarded Hot Plate

Since the insulation properties of a fabric could potentially be altered by napping, guarded hot plate testing was conducted in accordance with the test procedure cited in Table II. Guarded hot plate testing measures the thermal insulation (clo) and water vapor permeability (i_m) values of material. To minimize heat stress, the material in a chemical protective garment should have low thermal resistance and high water vapor permeability. To rank candidate garments, the ratio of i_m to clo is calculated. The lighter the i_m/clo ratio, the greater the rate of heat loss through the material, resulting in less thermal stress to the wearer.

The total clo for each material was determined by using ASTM D-1518. Since there are no applicable standards for i_m testing. Conditions for clo and i_m measurements were as follows:

clo:	Ambient temperature	- 20°C
	Dewpoint temperature	- 10°C
	Relative humidity	- 50%
	Plate temperature	- 33-36°C

im: Ambient temperature - 27°C
Dewpoint temperature - 15°C
Relative Humidity - 48%
Plate temperature - 33-36°C

Aerosol Penetration Testing

Aerosol penetration testing of all candidate napped fabrics was conducted by RTI, and is reported in its entirety in Appendix A. RTI's test procedure is summarized as follows:

Both a polydispersed challenge aerosol and size discriminating aerosol analyzer were used to measure the filtration efficiency of each sample (in triplicate) at a 0.3 to 6.5 micron particle size range. A Collision-type nebulizer generated a liquid oleic acid aerosol challenge. The aerosol was passed through an aerosol neutralizer to eliminate any possible electrostatic charge. An airstream was set to generate a standard airflow rate of 5 cm/sec through all candidate fabrics during aerosol testing. This rate roughly corresponds to the airflow encountered in a 10 mph wind. A Climet 226/8040 High Resolution Optical Counter performed upstream and downstream aerosol concentration measurements through 16 sizing channels, from which filtration efficiencies were computed.(4) For each size channel, the ratio of the average of six downstream concentration measurements to the average of six upstream concentration measurements yielded the Aerosol Penetration for that channel. The aerosol penetration is a measure of how much aerosol passes through the fabric.(5) The aerosol penetration was a function of both particle size and air permeability.

RESULTS/DISCUSSION

Physical Properties

The physical properties for candidate fabrics A, B, C, and E are provided in Table III through VI, respectively. (As previously discussed in the Material Description section of this report, Fabric D will not be discussed as a result of the unavailable napping levels required for comparison. Additionally, the water resistance data reported in Table VII, indicates that the unnapped sample was not water repellent treated and the 1 napping pass was. Since the consistency of water repellency of the only two Fabric D samples are questionable, a comparison cannot be conducted on the available data to draw valid conclusions.) Results are provided for the unnapped, as well as for each of the four napping levels of each candidate fabric. Since there was very little difference in properties measured within each of the candidate fabrics from one nap level to the next, discussion of results will be limited to comparing the unnapped sample and the sample with four nap passes.

Napping had little or no effect on any of the candidate fabrics with respect to weight, stiffness, hydrostatic resistance (before and after laundering). With the exception of Fabric B, napping tended to increase the air permeability of the samples. With exception of Fabric A, napping had little effect on dimensional stability. The thickness of Fabrics C

TABLE - II

Laboratory Test Methods

Characteristic	Test Method*
Weight	5041
Yarns per inch	5050
Air permeability	5450
Break strength	5100
Tear strength	D1424, ASTM**
Abrasion resistance	5302
Stiffness	5202
Thickness	5030
Hydrostatic resistance	5514
After 3 launderings	5556 & 5514
Water resistance	5526
After 3 launderings	5556 & 5526
Dimensional stability	5556
Dimensional stability	AATCC-135***
Flame resistance	5903
After 10 launderings	5556 & 5903
Guarded hot plate (Insulation)	D1518, ASTM**

* Federal Standard for Textile Test Methods No. 191A, except where noted:
** ASTM - American Standard Test Methods
*** AATCC - American Association of Textile Chemists and Colorists

and E were slightly increased by the napping process. Fabric C experienced significant increase in both hydrostatic resistance and water resistance after laundering. Based on the 4 percent shrinkage Fabric C experienced after ten cycles of TM5556, the only explanation that may be provided for the increased hydrostatic and water resistance is that the construction tightened after multiple launderings. Abrasion resistance decreased significantly for Fabrics B and C (28% and 16%, respectively). Of the two candidate fabrics possessing fire retardant treatments, only Fabric B experienced a slight increase in char length in the unlaundered state as a result of napping. This increase was still within acceptable levels. The strength properties varied from one candidate sample to the next, with no predictable trends.

Insulation

The results for clo and i_m are summarized in Table VIII. The clo, i_m and i_m/clo rations were statistically analyzed and summarized as follows:

clo: Compared to the initial fabric, Fabrics A, C, and E showed a significant increase in clo after the first nap pass. For Fabrics A, and E, there was little further increase in insulation as nap passes increased. Three and four nap passes significantly increased the clo value of Fabric C compared to the one and two nap passes. Napping appeared to have little effect on the clo value of Fabric B.

i_m: Napping had no effect on the i_m values on Fabrics A and B. However, napping did increase the water vapor permeability of Fabrics C and E. As with clo values, one and two nap passes had similar results; greater number of passes showed significantly increased i_m values.

i_m/clo Ratio: There were no significant differences in the i_m/clo ration due to napping of the fabrics. Therefore, it would be expected that napping the fabrics would not increase heat stress.

Aerosol Penetration

The results for the aerosol penetration measurements and standard deviations for each nap level of the candidate fabrics are attached as Appendix A of this report. It was reported that each aerosol penetration curve represents the average of three replicate runs for that particular fabric/napping combination.(6) RTI noted that there appeared to be two sources which contributed to variability in test results: a. drift within the challenge aerosol concentration; and b. differences which resulted in significant pressure drops within a given fabric/napping sample.

Based on RTI's results, it appears that napping the fabrics had little or no effect on aerosol penetration. Differences between test runs for a given fabric at the various level of napping fall within the measure of error.(7)

TABLE - III
FABRIC A - PHYSICAL PROPERTIES
100% COTTON RIPSTOP, DESERT CAMOUFLAGE

Characteristic	Initial	1 Pass	2 Passes	3 Passes	4 Passes
Weight, finished (oz/sq yd)	6.2	6.2	6.2	6.2	6.2
Yarns/inch					
Warp	108	108	107	108	108
Filling	55	55	55	55	55
Air Permeability (ft3/sec/ft2)	13.3	16.8	18.5	17.4	17.9
Break Strength (lbs)					
Warp	155	154	154	153	151
Filling	78	83	85	80	83
Tear Strength (lbs)					
Warp	8.1	8.7	7.5	7.2	7.9
Filling	7.2	8.0	6.7	8.0	7.6
Abrasion Resistance (cycles)	620	690	710	660	653
Stiffness (lbs)					
Warp	.001	.001	.001	.002	.001
Filling	.001	.001	.001	.001	.001
Thickness (inch)	.015	.015	.015	.015	.015
Hydrostatic Resistance (cm)					
Initial	20.5	19.4	19.4	20.4	20.9
After 3 launderings	24.2	24.8	24.6	25.3	26.8
Water Resistance (average)					
Initial	100	100	100	100	100
After 3 launderings	100	100	100	100	100

TABLE - III (cont'd)
FABRIC A - PHYSICAL PROPERTIES
100% COTTON RIPSTOP, DESERT CAMOUFLAGE

Characteristic	Initial	1 Pass	2 Passes	3 Passes	4 Passes
Shrinkage (%)					
TM 5556					
Initial					
Warp	2.6	4.9	4.2	4.3	5.0
Filling	1.1	0.8	0.9	0.7	1.0
After 10 cycles					
Warp	4.7	6.7	5.6	6.1	6.8
Filling	1.1	0.8	0.6	0.6	0.6
Shrinkage (%)					
AATCC-135					
Initial					
Warp	2.3	5.1	4.3	5.2	4.3
Filling	0.7	1.0	0.6	0.7	0.6
After 5 cycles					
Warp	3.1	6.0	5.6	6.8	6.1
Filling	1.0	0.8	0.7	1.2	0.3

TABLE - IV
FABRIC B - PHYSICAL PROPERTIES
50/50 POLYESTER/COTTON TWILL, FRT/WRT

Characteristic	Initial	1 Pass	2 Passes	3 Passes	4 Passes
Weight, finished (oz/sq yd)	5.9	6.0	6.0	6.0	6.0
Yarns/inch					
Warp	109	108	108	108	108
Filling	43	43	43	43	43
Air Permeability (ft3/sec/ft2)	80.2	73.4	71.1	74.9	83.0
Break Strength (lbs)					
Warp	125	129	122	126	120
Filling	63	66	63	65	56
Tear Strength (lbs)					
Warp	3.3	3.7	3.7	4.0	4.1
Filling	2.9	3.4	3.4	3.2	3.2
Abrasion Resistance (cycles)	1180	1040	700	660	850
Stiffness (lbs)					
Warp	.005	.005	.004	.004	.004
Filling	.001	.002	.001	.001	.001
Thickness (inch)	.015	.015	.015	.015	.015
Hydrostatic Resistance (cm)					
Initial	16.8	17.1	17.6	16.5	17.0
After 3 launderings	18.0	19.0	19.4	18.1	18.3
Water Resistance (average)					
Initial	100	100	100	100	100
After 3 launderings	100	100	100	100	100

TABLE - IV (cont'd)
FABRIC B - PHYSICAL PROPERTIES
50/50 POLYESTER/COTTON TWILL, FRT/WRT

Characteristic	Initial	1 Pass	2 Passes	3 Passes	4 Passes
Shrinkage (%)					
TM 5556					
Initial					
Warp	1.0	1.0	1.1	1.2	1.3
Filling	0.5	0.6	0.5	0.3	0.6
After 10 cycles					
Warp	3.1	3.6	3.6	3.7	3.7
Filling	1.5	1.6	1.4	1.4	1.4
Shrinkage (%)					
AATCC-135					
Initial					
Warp	0	0	0.3	0.4	0.3
Filling	0	0	0.2	0	0.1
After 5 cycles					
Warp	1.4	1.7	1.6	1.7	1.6
Filling	0.2	0.2	0.2	0	0.8
Flame Resistance					
Initial					
Warp					
After Flame (sec)	0	0	0	0	0
After Glow (sec)	1.8	1.6	1.2	1.8	1.9
Char length (inch)	4.8	4.4	4.5	5.1	5.1
Filling					
After Flame (sec)	0	0	0	0	0
After Glow (sec)	1.7	1.6	1.5	1.7	1.9
Char length (inch)	3.8	3.5	3.8	4.6	4.7
After 10 launderings					
Warp					
After Flame (sec)	0	0	0	0	0
After Glow (sec)	1.7	1.5	1.8	1.8	1.7
Char length (inch)	3.1	3.6	3.6	3.7	3.7
Filling					
After Flame (sec)	0	0	0	0	0
After glow (sec)	1.7	1.8	1.9	1.8	1.7
Char length (inch)	4.8	4.4	4.2	4.3	4.5

TABLE - V
FABRIC C - PHYSICAL PROPERTIES
100% COTTON TWILL, FRT/WRT

Characteristic	Initial	1 Pass	2 Passes	3 Passes	4 Passes
Weight, finished (oz/sq yd)	6.2	6.1	6.1	6.3	6.3
Yarns/inch					
Warp	102	101	101	102	1[illegible]
Filling	75	76	76	76	
Air Permeability (ft3/sec/ft2)	47.3	45.0	48	54.1	53.6
Break Strength (lbs)					
Warp	114	111	111	110	106
Filling	71	62	67	62	62
Tear Strength (lbs)					
Warp	8.0	8.1	8.5	7.8	8.1
Filling	6.4	4.8	6.1	5.7	4.7
Abrasion Resistance (cycles)	510	550	400	440	430
Stiffness (lbs)					
Warp	.002	.001	.002	.002	.002
Filling	.001	.001	.001	.001	.001
Thickness (inch)	.016	.015	.016	.017	.020
Hydrostatic Resistance (cm)					
Initial	11.4	11.5	11.4	11.7	11.1
After 3 launderings	20.7	20.7	20.1	19.6	20.0
Water Resistance (average)					
Initial	0	0	0	0	0
After 3 launderings	50	50	50	50	50

TABLE - V (cont'd)
FABRIC C - PHYSICAL PROPERTIES
100% COTTON TWILL, FRT/WRT

Characteristic	Initial	1 Pass	2 Passes	3 Passes	4 Passes
Shrinkage (%)					
TM5556					
Initial					
Warp	1.1	2.5	2.5	2.0	2.3
Filling	1.2	2.0	1.8	1.9	2.3
After 10 cycles					
Warp	4.6	5.7	5.8	5.6	5.3
Filling	1.7	2.1	2.1	1.9	1.9
Shrinkage (%)					
AATCC-135					
Initial					
Warp	0	0.2	1.2	0.4	0.3
Filling	-0.3	0.2	0.7	-0.3	0.8
After 5 cycles					
Warp	-0.5	1.4	1.4	1.0	1.6
Filling	-0.1	0.6	-0.1	0.1	-0.7
Flame Resistance					
Initial					
Warp					
After Flame (sec)	0	0	0	0	0
After Glow (sec)	1.6	1.6	1.8	1.7	1.6
Char length (inch)	3.5	4.0	4.0	3.6	3.7
Filling					
After Flame (sec)	0	0	0	0	0
After Glow (sec)	1.8	1.9	1.8	1.5	1.8
Char length (inch)	3.7	4.0	3.5	3.7	3.6
After 10 launderings					
Warp					
After Flame (sec)	0	0	0	0	0
After Glow (sec)	1.9	1.9	2.1	1.7	2.0
Char length (inch)	3.4	3.8	3.6	3.5	3.8
Filling					
After Flame (sec)	0	0	0	0	0
After glow (sec)	2.0	2.4	2.3	2.1	2.0
Char length (inch)	4.0	3.9	3.5	3.3	3.9

TABLE - VI
FABRIC D - PHYSICAL PROPERTIES
70/30 COTTON/POLYESTER TWILL, FRT/WRT

Characteristic	Initial	1 Pass
Weight, finished (oz/sq yd)	7.0	6.8
Yarns/inch		
Warp	107	108
Filling	40	40
Air Permeability (ft3/sec/ft2)	44.5	60.3
Break Strength (lbs)		
Warp	131	121
Filling	39	44
Tear Strength (lbs)		
Warp	NT	NT
Filling	4	2.5
Abrasion Resistance (cycles)	1170	1020
Stiffness (lbs)		
Warp	.002	.002
Filling	.003	.003
Thickness (inch)	.015	.015
Hydrostatic Resistance (cm)		
Initial	10.8	12.9
After 3 launderings	16.5	18.5
Water Resistance (average)		
Initial	0	100
After 3 launderings	70	100

TABLE - VI
FABRIC D - PHYSICAL PROPERTIES
70/30 COTTON/POLYESTER TWILL, FRT/WRT

Characteristic	Initial	1 Pass
Shrinkage (%)		
TM5556		
Initial		
Warp	1.2	1.4
Filling	0.7	3.5
After 10 cycles		
Warp	4.0	4.3
Filling	1.2	4.4
Shrinkage (%)		
AATCC-135		
Initial		
Warp	0	1.1
Filling	-0.6	2.3
After 5 cycles		
Warp	1.3	1.9
Filling	-1.0	2.7
Flame Resistance		
Initial		
Warp		
After Flame (sec)	0	0
After Glow (sec)	1.5	1.3
Char length (inch)	3.9	4.0
Filling		
After Flame (sec)	0	0
After Glow (sec)	1.2	1.7
Char length (inch)	4.1	4.2
After 10 launderings		
Warp		
After Flame (sec)	0	0
After Glow (sec)	1.8	1.9
Char length (inch)	4.8	4.6
Filling		
After Flame (sec)	0	0
After glow (sec)	1.7	2.0
Char length (inch)	5.1	4.9

TABLE - VII
FABRIC E - PHYSICAL PROPERTIES
50/50 NYLON/COTTON TWILL, WRT

Characteristic	Initial	2 Pass	4 Passes	6 Passes	8 Passes
Weight, finished (oz/sq yd)	7.8	7.8	7.6	8.5	7.9
Yarns/inch					
Warp	90	92	92	90	91
Filling	56	57	57	57	57
Air Permeability (ft3/sec/ft2)	9.0	10.7	11.9	12.8	12.1
Break Strength (lbs)					
Warp	271	272	272	273	264
Filling	160	168	155	150	146
Tear Strength (lbs)					
Warp	14.4	14.4	15.0	13.6	14.8
Filling	10.8	11.0	10.9	12.2	8.7
Abrasion Resistance (cycles)	5880	5660	6120	5980	5580
Stiffness (lbs)					
Warp	.002	.002	.002	.002	.002
Filling	.002	.001	.001	.001	.002
Thickness (inch)	.016	.017	.019	.020	.021
Hydrostatic Resistance (cm)					
Initial	30.4	30.0	29.2	29.9	30.1
After 3 launderings	31.9	29.8	30.6	30.9	30.9
Water Resistance (average)					
Initial	100	100	100	100	100
After 3 launderings	100	100	100	100	100

TABLE - VII (cont'd)
FABRIC E - PHYSICAL PROPERTIES
50/50 NYLON/COTTON TWILL, WRT

Characteristic	Initial	2 Pass	4 Passes	6 Passes	8 Passes
Shrinkage (%)					
TM5556					
Initial					
Warp	2.0	3.3	3.1	3.3	3.4
Filling	0.4	0.1	0.2	0.3	0
After 10 cycles					
Warp	3.5	5.1	4.3	4.9	4.7
Filling	0.5	0.2	0.3	0.5	-0.5
Shrinkage (%)					
AATCC-135					
Initial					
Warp	0.8	2.6	1.7	2.2	2.2
Filling	-0.6	-0.9	-0.7	-1.1	-1.3
After 5 cycles					
Warp	0.9	2.4	2.0	2.7	2.2
Filling	-1.0	-0.8	-0.8	-1.5	-2.1

TABLE - VIII
GUARDED HOT PLATE RESULTS

Fabrics i_m/clo	clo (+/-Std Dev)	i_m (+/-Std Dev)	Average i_m/clo
A initial	0.55 (+/-0.01)	0.41 (+/-0.02)	0.75
1 pass	0.57 (+/-0.01)	0.43 (+/-0.06)	0.76
2 passes	0.57 (+/-0.01)	0.40 (+/-0.01)	0.69
3 passes	0.59 (+/-0.02)	0.44 (+/-0.02)	0.75
4 passes	0.60 (+/-0.01)	0.43 (+/-0.02)	0.72
B initial	0.58 (+/-0.01)	0.44 (+/-0.03)	0.75
1 pass	0.55 (+/-0.01)	0.42 (+/-0.02)	0.77
2 passes	0.55 (+/-0.01)	0.45 (+/-0.04)	0.82
3 passes	0.57 (+/-0.01)	0.44 (+/-0.02)	0.77
4 passes	0.57 (+/-0.01)	0.44 (+/-0.05)	0.77
C initial	0.57 (+/-0.01)	0.34 (+/-0.02)	0.60
1 pass	0.61 (+/-0.02)	0.42 (+/-0.06)	0.70
2 passes	0.63 (+/-0.02)	0.43 (+/-0.02)	0.68
3 passes	0.68 (+/-0.02)	0.47 (+0.02)	0.70
4 passes	0.69 (+/-0.01)	0.48 (+/-0.01)	0.70
E initial	0.54 (+/-0.01)	0.30 (+/-0.04)	0.56
1 pass	0.62 (+/-0.02)	0.34 (+/-0.01)	0.55
2 passes	0.59 (+/-0.02)	0.35 (+/-0.02)	0.60
3 passes	0.61 (+/-0.01)	0.35 (+/-0.00)	0.57
4 passes	0.62 (+/-0.02)	0.36 (+/-0.03)	0.58

Results are the + mean ± S.D. for 3 replicate tests.

CONCLUSIONS

Although the intent of napping the outershell fabric of chemical protective garments was to possibly enhance the entrapment of aerosolized particles within the raised surface fibers, napping actually resulted with little or no effect on the degree of aerosol penetration.

In general, the napping process did not appear to have an adverse effect on the physical properties of the candidate fabrics tested, with exception of slight increases to air permeability and shrinkage.

As indicated by the statistical analysis of the I_m/Clo ratios, the napping of candidate fabrics indicates that it would not produce any additional thermal stress to the wearer.

RECOMMENDATION

Since none of the napped fabrics provided enhanced aerosol protection, it is this Facility's recommendation to terminate this project.

ACKNOWLEDGMENTS

Appreciation is extended to Ms. Debbie Peppenelli, Ms. Marie Dobachesky, and Mr. Ronald Hall of the Navy Clothing and Textile Research Facility, for their performance of extensive physical testing on the candidate napped fabrics.

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6. Ibid

7. Ibid

APPENDIX A

RESEARCH TRIANGLE INSTITUTE

AEROSOL PENETRATION TESTING OF NAPPED FABRICS

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RTI PROJECT NO. 95U-5068

SEPTEMBER 1991

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TABLE OF CONTENTS

FIGURES

TABLES

1.0 INTRODUCTION

Under contract with the US Navy Clothing and Textile Research Facility (Contract No. N00189-91-P-BG47), the Research Triangle Institute (RTI) investigated the efficacy of using fabric napping as a means to enhance a fabric's resistance to aerosol penetration. Napping of a fabric has the potential to alter the degree of aerosol penetration (either for better or for worse) by altering the interaction of the aerosol particles with the fabric fibers. The tests were performed using 5-inch diameter fabric swatches mounted in an aerosol penetration test apparatus. An optical particle counter was used to measure aerosol concentrations, over the particle size range of 0.3 to 6.5 μm diameter, upstream and downstream of the fabric swatches. The size-dependent aerosol penetration of the fabrics was calculated from these measurements.

The tests examined the effect of napping on five different base (un-napped) fabrics identified as Fabrics A through E. The fabrics provided by the Navy for the tests were:

Fabric A: 100% cotton 6 oz/yd^2 ripstop, quarpel treated, woodland camouflage.

Fabric B: 50/50 polyester/cotton twill, fire retardant/water repellent treated, 6 oz/yd^2, blue.

Fabric C: 100% cotton twill, fire retardant/water repellent treated, 6 oz/yd^2, navy blue.

Fabric D: 70/30 cotton/polyester twill, fire retardant/water repellent treated, 6.5 oz/yd^2, navy blue.

Fabric E: 50/50 Nylon/cotton twill, quarpel treated, 7.0 oz/yd^2, woodland camouflage.

Section 2 describes the processes that occur as aerosol particles interact with a permeable fabric. Section 3 outlines the test matrix. Procedures used to perform the aerosol penetration measurements are described in Section 4. Test results are presented in Section 5 with a summary presented in Section 6. The Appendix contains results from each individual test run.

2.0 THE PROCESS OF AEROSOL PENETRATION THROUGH PERMEABLE FABRICS

2.1 INTRODUCTION

An aerosol can be defined as a suspension of solid or liquid particles in the air. The size of individual aerosol particles can range from near molecular size on up to raindrop size (Figure 1). Generally, particles smaller than about 10 microns have sufficiently low terminal velocities that they have a long residence time in the atmosphere. On this program, we examined the degree to which particles in the 0.3 to 6.5 micron size range penetrated the test fabrics. As can be seen in Figure 1, this size range roughly corresponds to that of the ambient aerosol. Particles in this size range are too small to be seen individually with the unaided eye though their collective effect is readily observed in, for example, cigarette smoke and atmospheric haze. Realizing that there are typically more than 100,000 micron-sized particles per cubic foot of ambient air attests to the small size of these particles.

2.2 AEROSOL COLLECTION MECHANISMS

There are several mechanisms which can lead to the collection of aerosol particles in permeable fabrics. These include the processes of sieving, inertial impaction, interception, and diffusion. Other collection mechanisms for aerosols include electrostatic attraction and gravitational settling. These processes are shown schematically in Figure 2.

Sieving is the straightforward collection of particles whose diameter is greater than the "pore size" of the fabric. Thus, for the test fabrics, the sieving mechanism is responsible for the collection of particles greater than about 100 microns. For particles smaller than the pore size, the aerosol can still be collected by the fabric by one of the other collection mechanisms.

Inertial impaction occurs when the inertia of the particle prevents it from following the airflow as the flow deviates around the fabric fibers. In general, inertial impaction is important for particles greater than about 1 micron. For smaller particles (less than 0.1 micron), inertial impaction is insignificant due to the small mass of the particles.

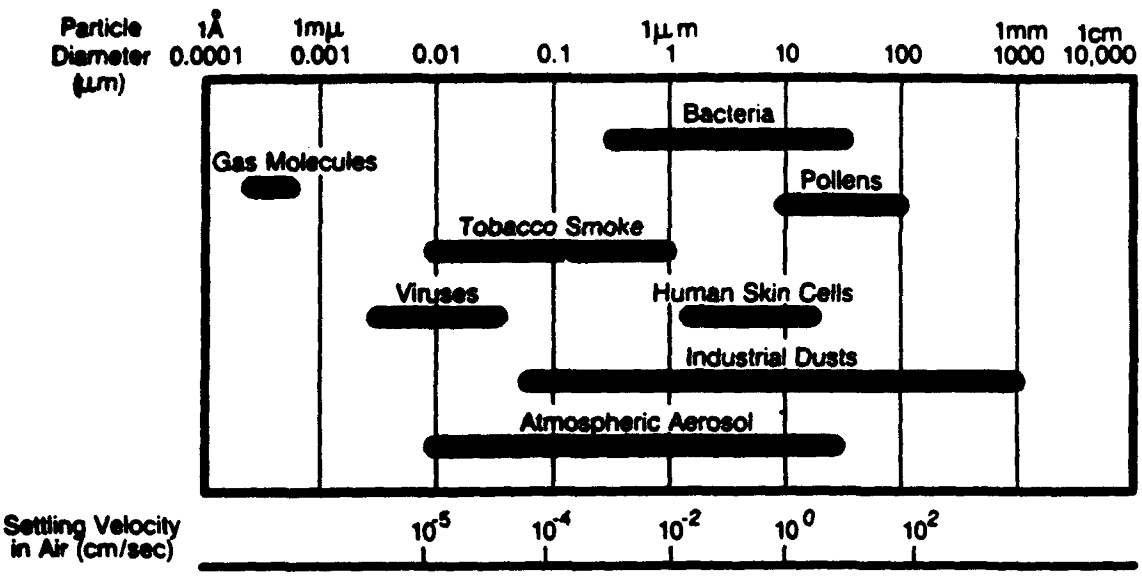

Figure 1. An overview of the size range and settling velocities of several common aerosols.

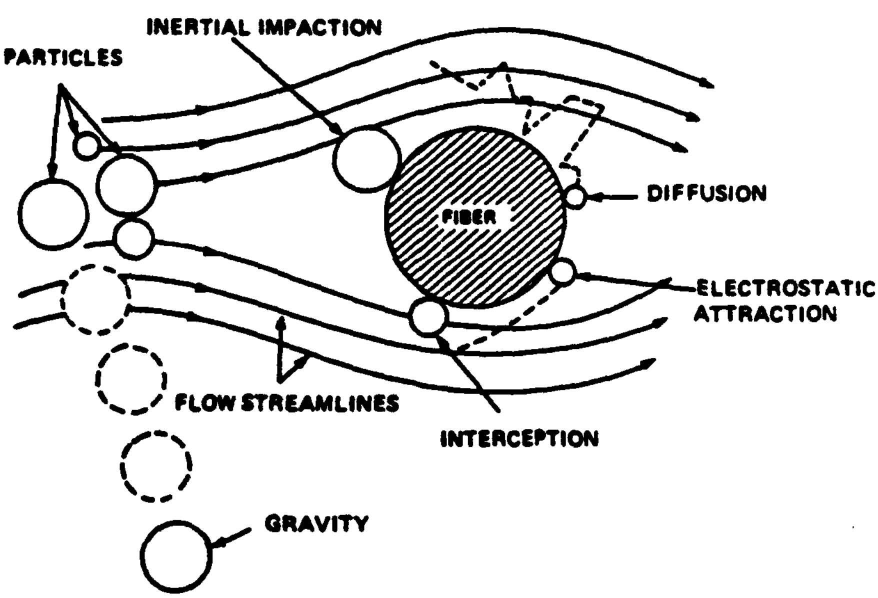

Figure 2. Classical mechanisms of aerosol capture by a fiber.

Interception occurs when the streamline a particle is following comes within one particle radius of an obstacle. For the test fabrics, this mechanism would be most significant for particles in the 1 to 10 micron size range.

For particles smaller than about 0.5 microns diameter, collection resulting from diffusion can be significant. Particle diffusion is the result of the Brownian motion small particles undergo due to collision with gas molecules. Diffusion is a small-particle phenomenon; larger particles (greater than about 0.5 microns) are too massive to have their trajectories significantly altered by collision with gas molecules. The particle diffusion coefficient increases sharply with decreasing size. Thus, the smaller the particle the greater its diffusion coefficient will be. Taken one step further, the diffusion coefficient of gas molecules (about 0.001 microns in size) is about 100,000 times greater than for a 1 micron diameter particle. This fact explains how activated carbon filters, which rely on the diffusion process, can be highly efficient for the removal of toxic gases, yet be poor filters for aerosol particles.

To summarize, the mechanisms responsible for aerosol collection in the permeable fabrics include sieving for the collection of particle larger than about 100 microns, inertial impaction and interception for particles greater than about 1 micron, and diffusional collection for particle smaller than about 0.5 microns diameter. This is, of course, a somewhat simplified view as the size ranges over which the mechanisms operate tend to overlap substantially. It should also be noted that only the screening process, involving particles larger than the pore size of the fabric, can be considered to be 100% efficient. The other processes, involving particles smaller than the pore size, will have efficiencies below 100%. Thus, some degree of penetration by aerosol particles smaller than the fabric pore size would be expected.

3.0 THE TEST MATRIX

The base and napped fabrics were provided as outlined in Table 1. The actual degree to which each base fabric was napped was not quantified. Rather, the degree of napping was expressed as the number of times the base fabric was passed through a napping machine. Because the base fabrics were of different construction, each responded differently to the napping machine. After 4 passes through the machine, Fabrics A and C appeared to have the greatest degree of napping, while Fabrics B and E appeared to have the least. Note that Fabric D was supplied in only its base fabric and after 1 pass through the napping machine. Also note that fabric E had double the number of passes through the napping machine due to its inherent resistance to napping.

TABLE 1. THE TEST FABRICS

Fabric A	Fabric B	Fabric C	Fabric D	Fabric E
Initial	Initial	Initial	Initial	Initial
1 Pass	1 Pass	1 Pass	1 Pass	2 Passes
2 Passes	2 Passes	2 Passes		4 Passes
3 Passes	3 Passes	3 Passes		6 Passes
4 Passes	4 Passes	4 Passes		8 Passes

Each fabric/napping combination was tested in triplicate yielding a total of 66 runs. The airflow rate through the fabrics was set at 5 cm/sec for all tests. This flowrate was selected based on prior measurements (1, 2) that showed that the airflow rate through permeable fabrics is approximately 1% of the incident windspeed. While this relationship will vary depending upon the permeability of the fabric, it was used to select a reasonable airflow for the tests. Thus, an airflow of 5 cm/sec (0.1 mph) was chosen so as to be roughly equivalent (i.e., within an order of magnitude) to the airflow that would be expected to occur in a 10 mph wind.

4.0 TEST PROCEDURES

The tests were performed with the apparatus illustrated in Figure 3. The challenge aerosol particles were composed of oleic acid -- a non-toxic, low volatility, DOP-like liquid. A syringe pump was used to meter the oleic acid at a rate of 0.3 cc/min into a collison-type nebulizer (similar in design to the TSI Model 3076 Constant Output Aerosol Atomizer). Air pressure to the nebulizer was set at 0.4 psi (300 cc/min). This pressure is well below the nebulizer's normal operating pressure but was used to keep the resultant aerosol concentration below the saturation limit of the optical particle counter. After exiting the nebulizer, 24.3 l/m of additional air was added through a porous-tube diluter to achieve the desired 5 cm/sec face velocity through the fabric. The aerosol was passed through a charge neutralizer (TSI Model 3054) to neutralize any electrostatic charge that have been present on the aerosol (electrostatic charging is a natural consequence of the nebulization process).

Aerosol concentrations upstream and downstream of the fabric were measured with a Climet 226/8040 High Resolution Optical Particle Counter (OPC). The OPC measures particle concentrations in 16 sizing channels between 0.3 and 10 microns. The sampling rate of the OPC was 0.25 cfm (7.1 lpm).

The concentration measurements consisted of a 3 upstream - 6 downstream - 3 upstream sampling sequence. The measurements began by taking 3 consecutive upstream 1-minute samples. Then, the OPC sample line was switched to the downstream sample line. After waiting 2- minutes, 6 consecutive 1-minute downstream samples were obtained. The two minute period between the downstream and upstream samples is provided to allow the OPC'c sample line and optical chamber time to "flush out" the old sample and get the new one. The OPC was then switched back to the upstream sample line and, after waiting 2-minutes, 3 consecutive 1- minute samples were obtained.

For each size channel, the ratio of the average of the six downstream concentration measurements to the average of the six upstream measurements yielded the Aerosol Penetration for that channel:

$$\text{Aerosol Penetration} = \frac{\text{Avg. of six downstream measurements}}{\text{Avg. of six upstream measurements}}.$$

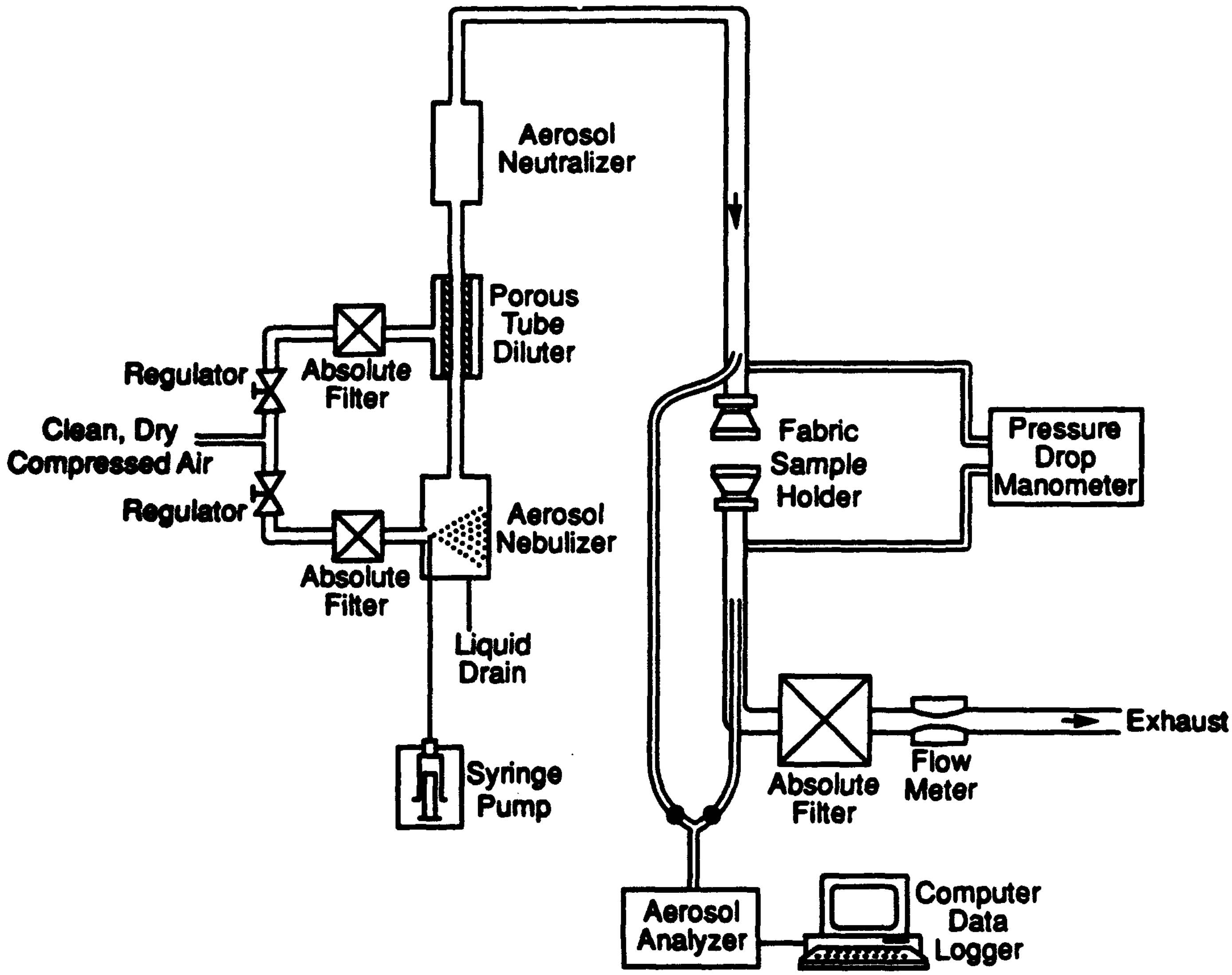

Figure 3. Schematic diagram of test apparatus for measuring the aerosol penetration of the fabric samples.

The Aerosol Penetration is a measure of how much aerosol passes through the fabric. The amount of aerosol retained in the fabric is simply:

$$\text{Aerosol Retention} = 1 - \text{Aerosol Penetration}$$

The pressure drop across the fabrics was measured with an inclined manometer. System flow rate was measured with a Meriam Laminar Flow Element Model 50MW20-1.

5.0 TEST RESULTS

Particle counts (counts per minute) for each sizing channel for the upstream and downstream measurements for a typical test are shown in Table 2. The upstream counts were approximately the same during all the tests. The downstream counts varied depending upon the filtration efficiency of the particular fabric under test. Due to the low concentration of particles above 7 μm in the upstream airstream, the upper size limit for the penetration measurements was 6.5 μm (i.e., the 6 to 7 μm channel of the particle counter).

The results of the aerosol penetration measurements for each level of napping for fabrics A through E are shown in Figures 4 through 8, respectively. Each curve in these figures represents the average of the three replicate runs for that particular fabric/napping combination. The penetration values measured for each of the 66 individual test runs are presented in the Appendix. Also presented in the Appendix is the pressure drop measured across each fabric at the test flow rate of 5 cm/sec.

Figures 9 through 13 show the estimated error (+/- 1 standard deviation) associated with the measurements for the various fabrics. These curves are based on the average of the means and standard deviations for the triplicate runs (tabulated in the appendix) within each fabric group.

There were two general sources of variability in the test data. One source was differences between individual samples taken from the same fabric/napping bolt. While samples from the same bolt visually appeared identical, undetected differences would lead to variability in the measured penetration. In some instances, significantly different pressure drops (tabulated in the Appendix) were measured across the three samples for a given fabric/napping combination indicating that the samples were not always as identical as they appeared to be visually. The second source of variability was drift in the challenge aerosol concentration. The drift was greatest at the larger particle sizes (from about 2 to 6 microns diameter). Combined with the high penetration at these sizes for some of the fabrics (particularly fabrics B and D), aerosol drift would lead to greater variability in those tests.

Table 2. Upstream and downstream particle counts from a typical test (Fabric E, 2 passes, Test No. 71). Upstream counts for other tests were similar. Downstream counts varied depending upon the fabric filtration efficiency. The particle counts are based on an OPC sampling rate of 7.1 lpm and a 1-minute sample duration.

	Mean Particle Diameter (microns)															
	0.35	0.45	0.55	0.7	0.9	1.25	1.75	2.5	3.5	4.75	5.75	6.5	7.5	8.5	9.5	10
downstream	40850	44640	38540	50200	22620	31840	15890	467	34	7	1	0	0	0	0	2
downstream	40120	43820	37640	48960	22200	31270	15590	493	47	7	0	0	0	0	0	0
downstream	39980	43390	37370	48830	21630	30700	15070	437	43	6	0	0	0	0	0	0
upstream	46680	53490	48660	62840	29750	48350	37470	4392	819	207	16	11	13	1	0	0
upstream	50890	59280	53760	68960	32450	53370	41030	4802	916	227	28	18	5	0	0	0
upstream	47040	54970	49590	63800	30110	48920	38190	4513	835	212	17	18	3	1	0	0
upstream	46730	54940	49240	64200	30450	49520	38350	4519	889	204	15	20	5	2	1	0
upstream	45990	53530	48410	62560	29550	48290	37820	4296	842	211	19	18	8	1	0	0
upstream	44420	51140	45910	60310	28560	46130	36530	4354	796	182	28	14	5	2	0	0
downstream	38620	42230	35970	47360	21180	29630	14870	456	41	3	1	0	0	0	0	0
downstream	40740	44910	38260	50230	22790	31880	15780	443	43	9	0	0	0	0	0	2
downstream	39870	43580	37100	48510	21570	30410	15120	435	56	10	0	0	1	0	0	0
Avg. up	46958	54558	49262	63778	30145	49097	38232	4479	850	207	21	17	7	1	0	0
Avg. down	40030	43762	37497	49015	21998	30955	15387	455	44	7	0	0	0	0	0	1
Penetration	0.85	0.80	0.76	0.77	0.73	0.63	0.40	0.10	0.05	0.03	0.02	0.00	0.03	0.0	0.0	0.0

Fabric A
Summary of Penetration Measurements

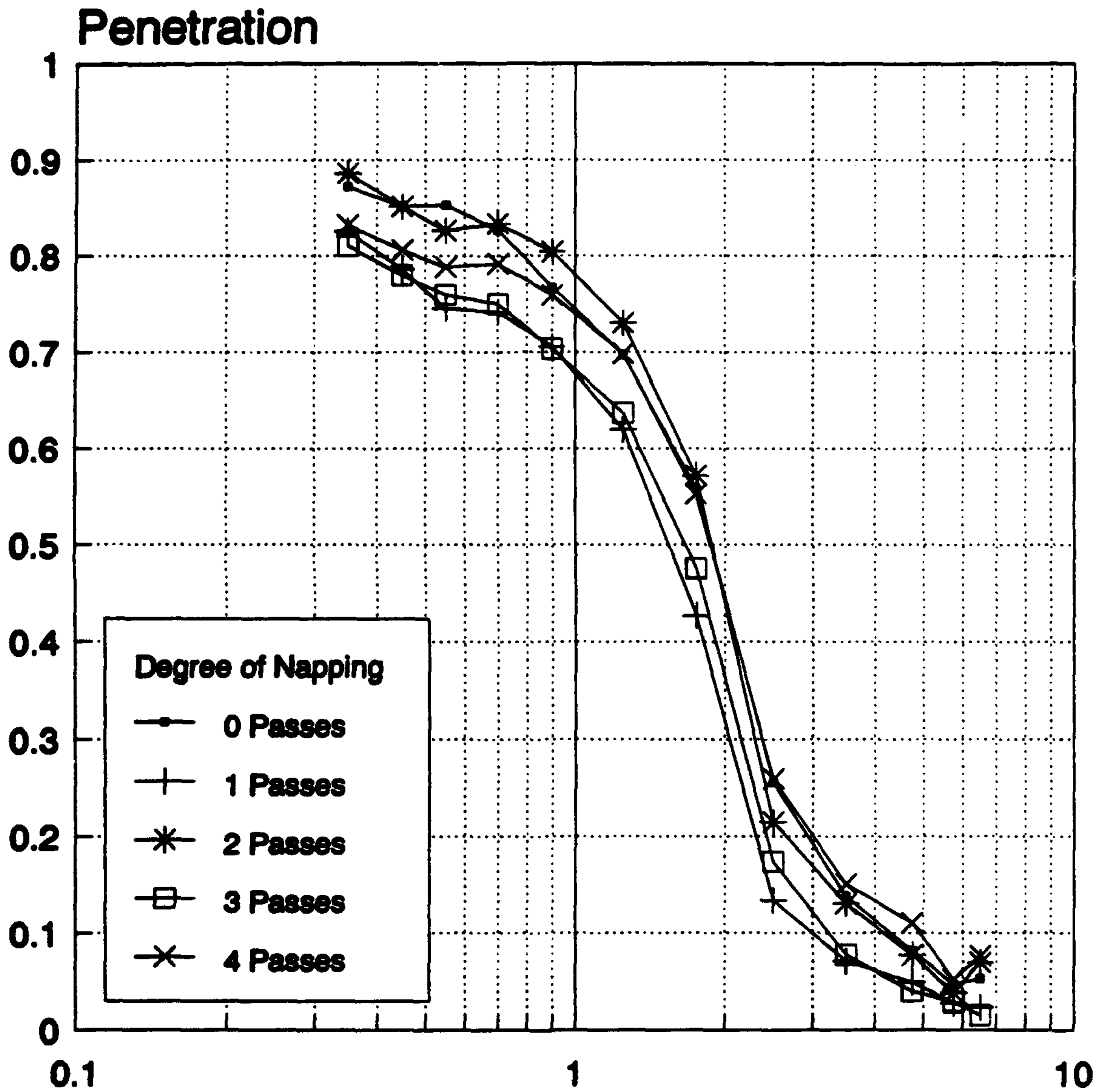

Figure 4. Average aerosol penetration curves for Fabric A. Each curve is the average of three replicate runs.

Fabric B
Summary of Penetration Measurements

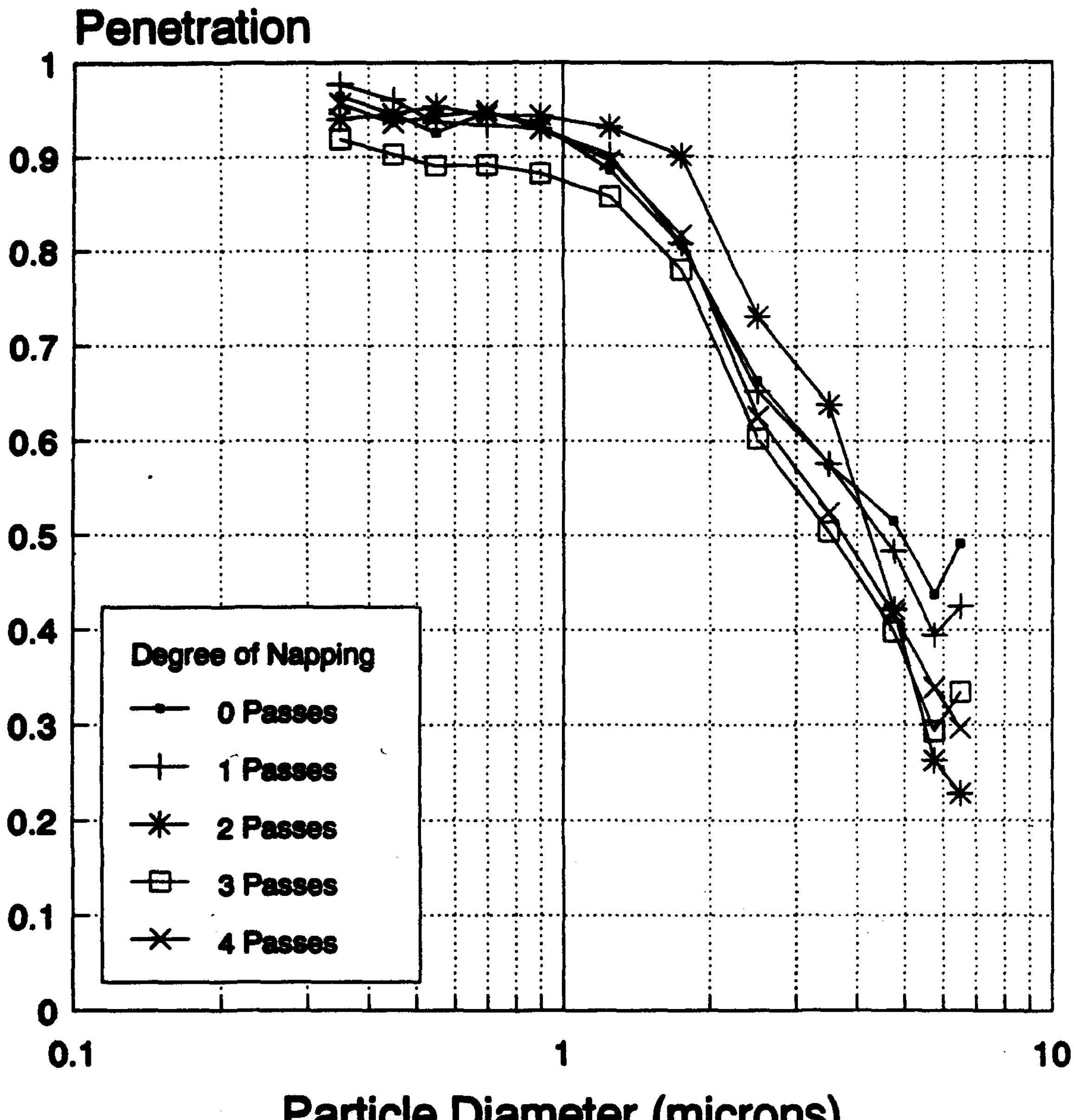

Figure 5. Average aerosol penetration curves for Fabric B. Each curve is the average of three replicate runs.

Fabric C
Summary of Penetration Measurements

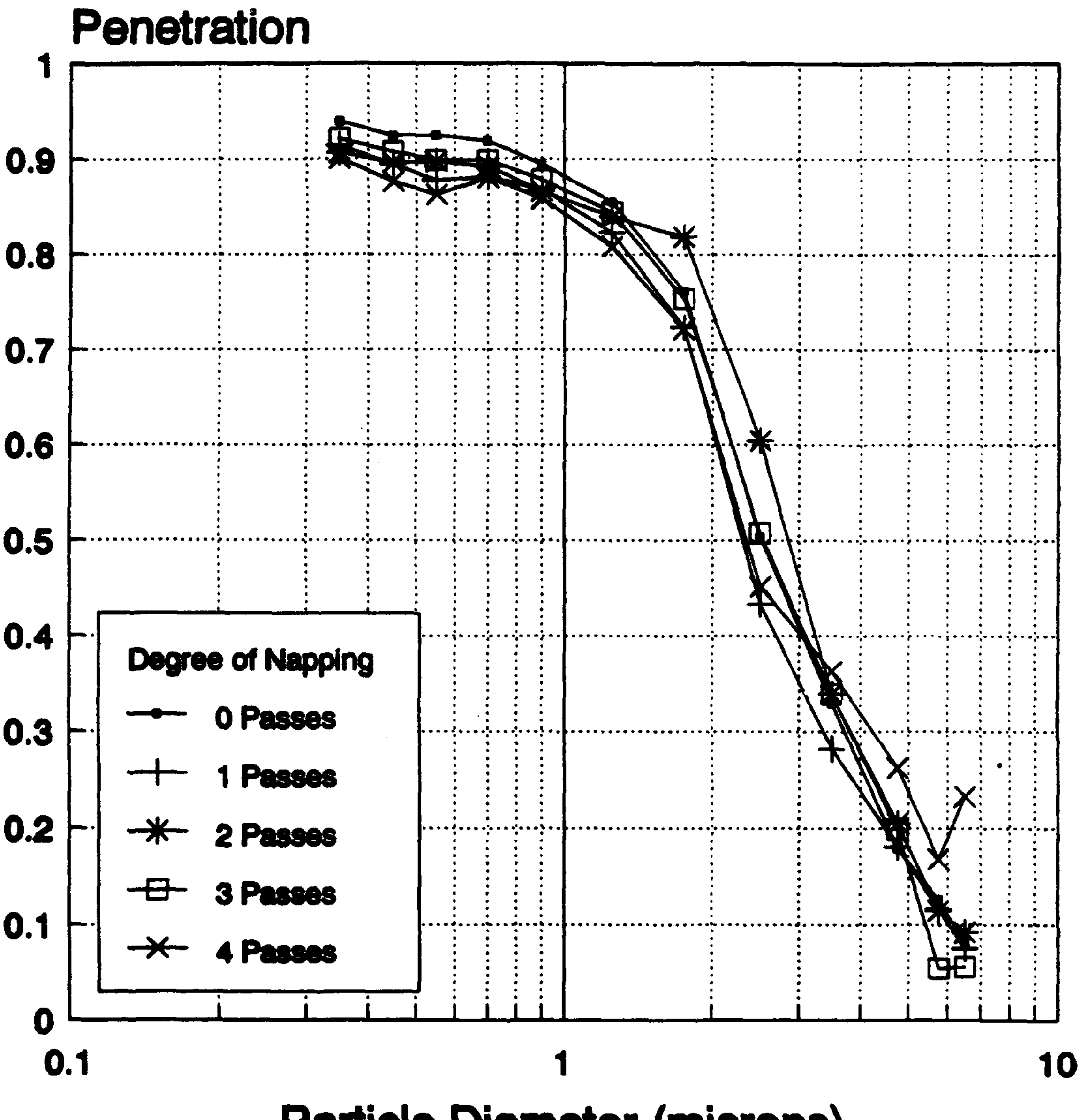

Figure 6. Average aerosol penetration curves for Fabric C. Each curve is the average of three replicate runs.

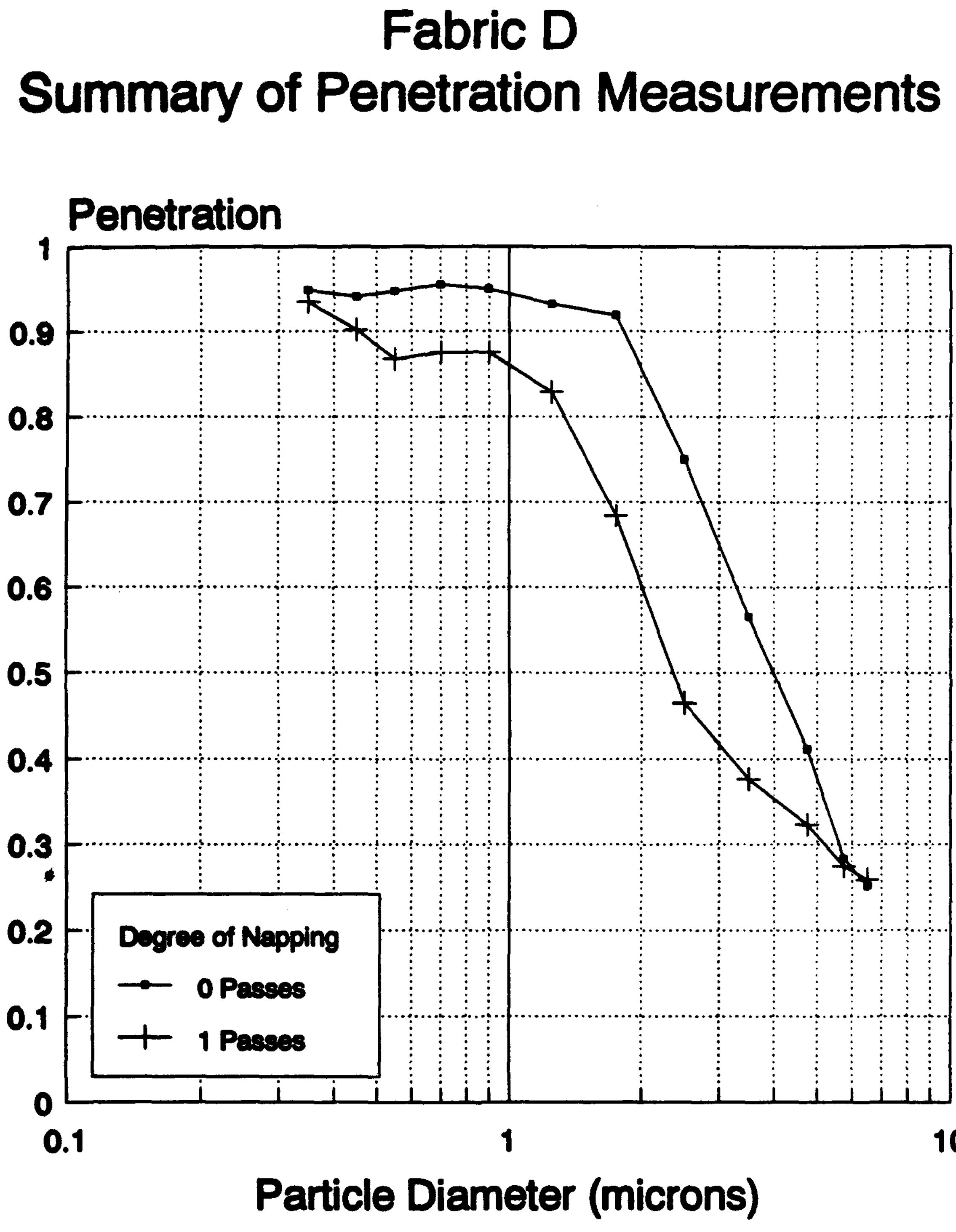

Figure 7. Average aerosol penetration curves for Fabric D. Each curve is the average of three replicate runs.

Fabric E
Summary of Penetration Measurements

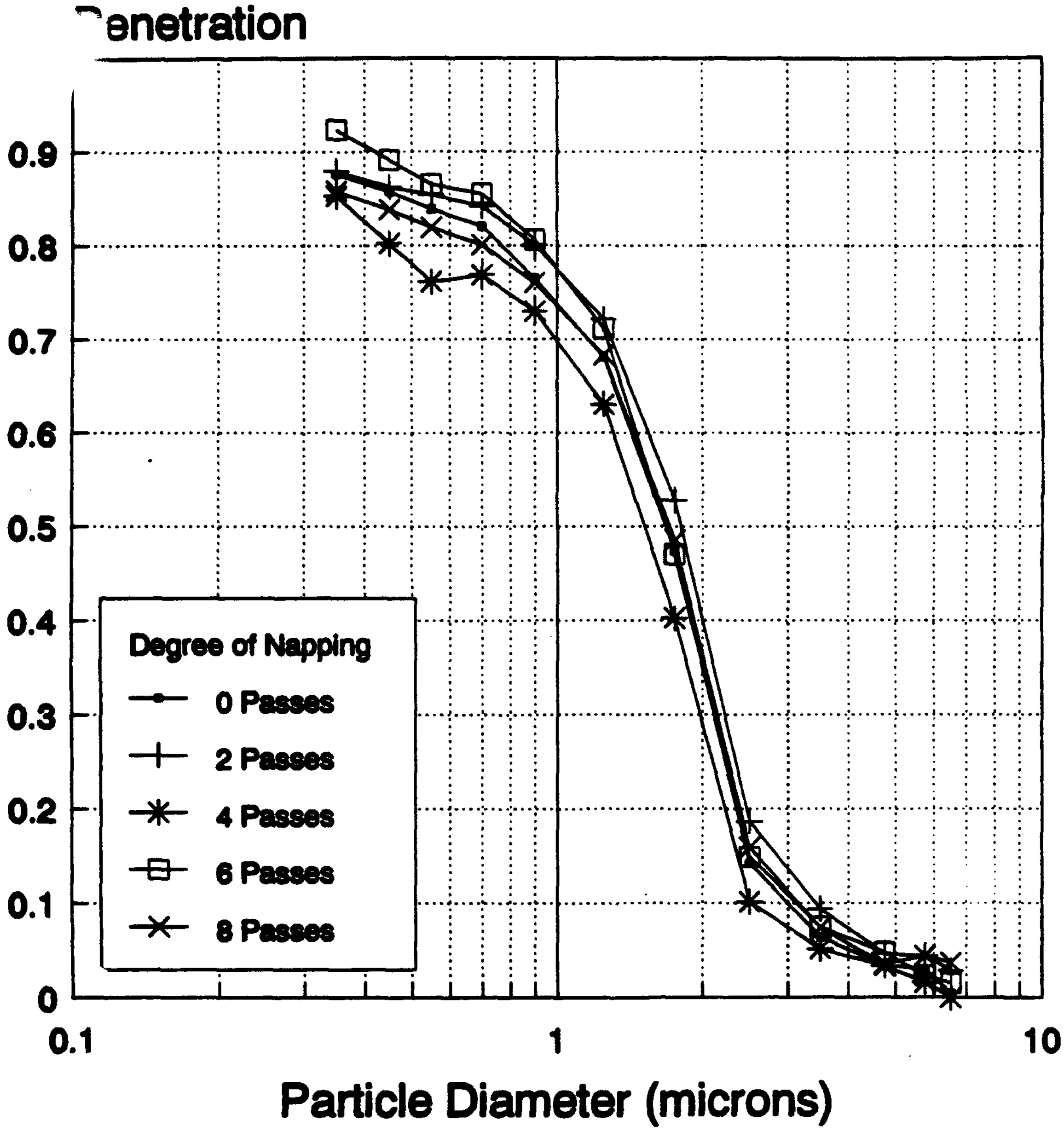

Figure 8. Average aerosol penetration curves for Fabric E. Each curve is the average of three replicate runs.

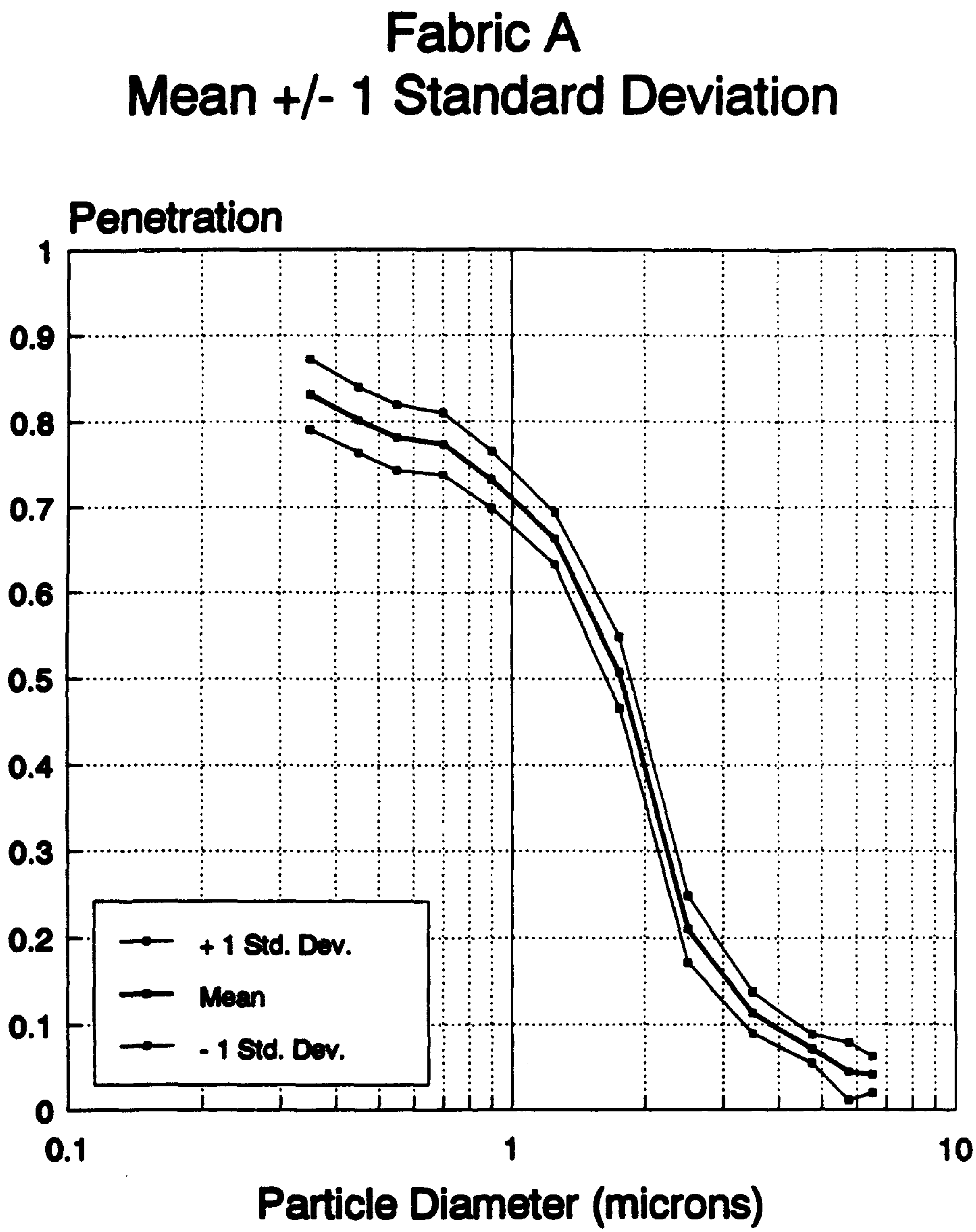

Figure 9. Mean and +/- 1 standard deviation penetration curves for Fabric A.

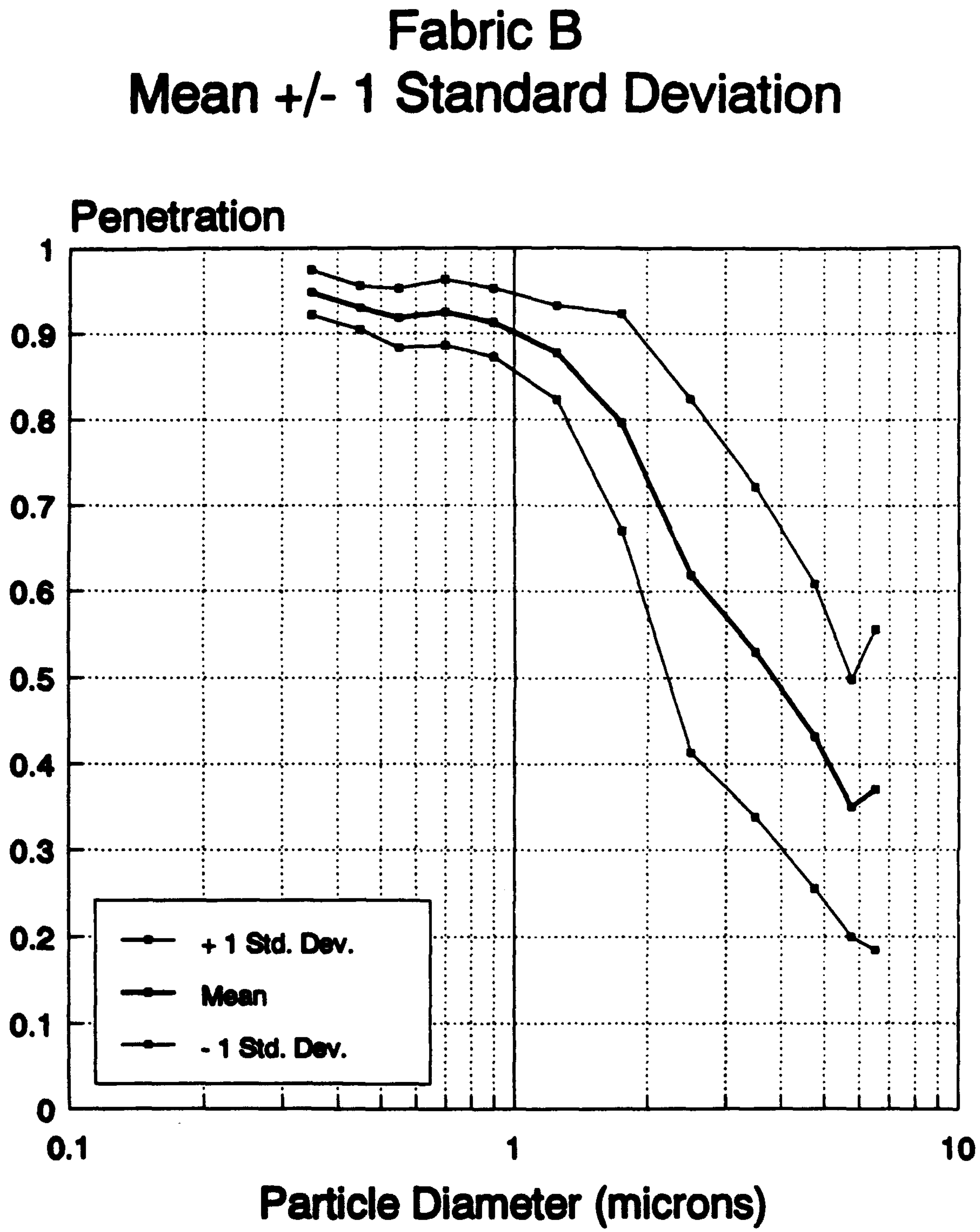

Figure 10. Mean and +/- 1 standard deviation penetration curves for Fabric B.

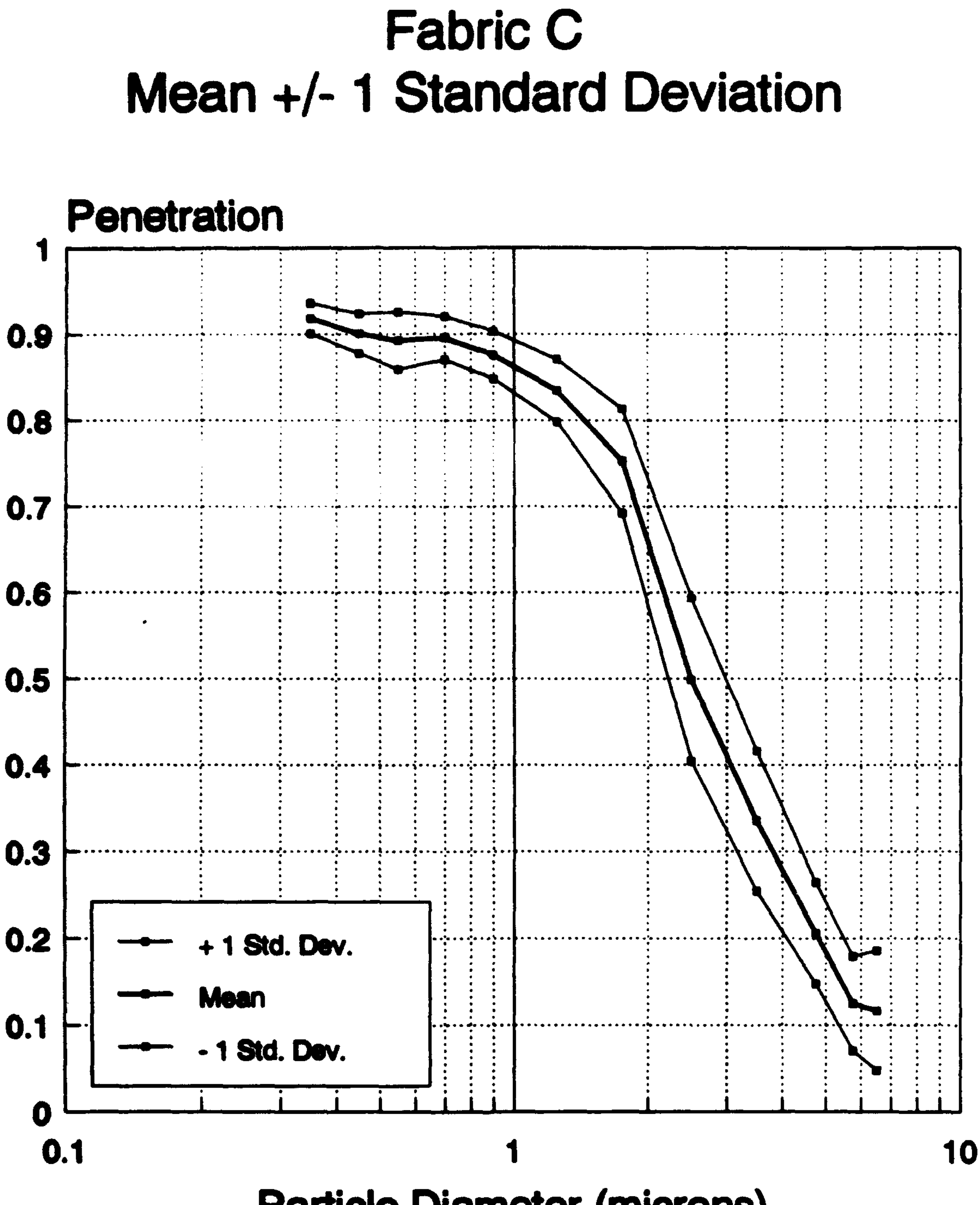

Figure 11. Mean and +/- 1 standard deviation penetration curves for Fabric C.

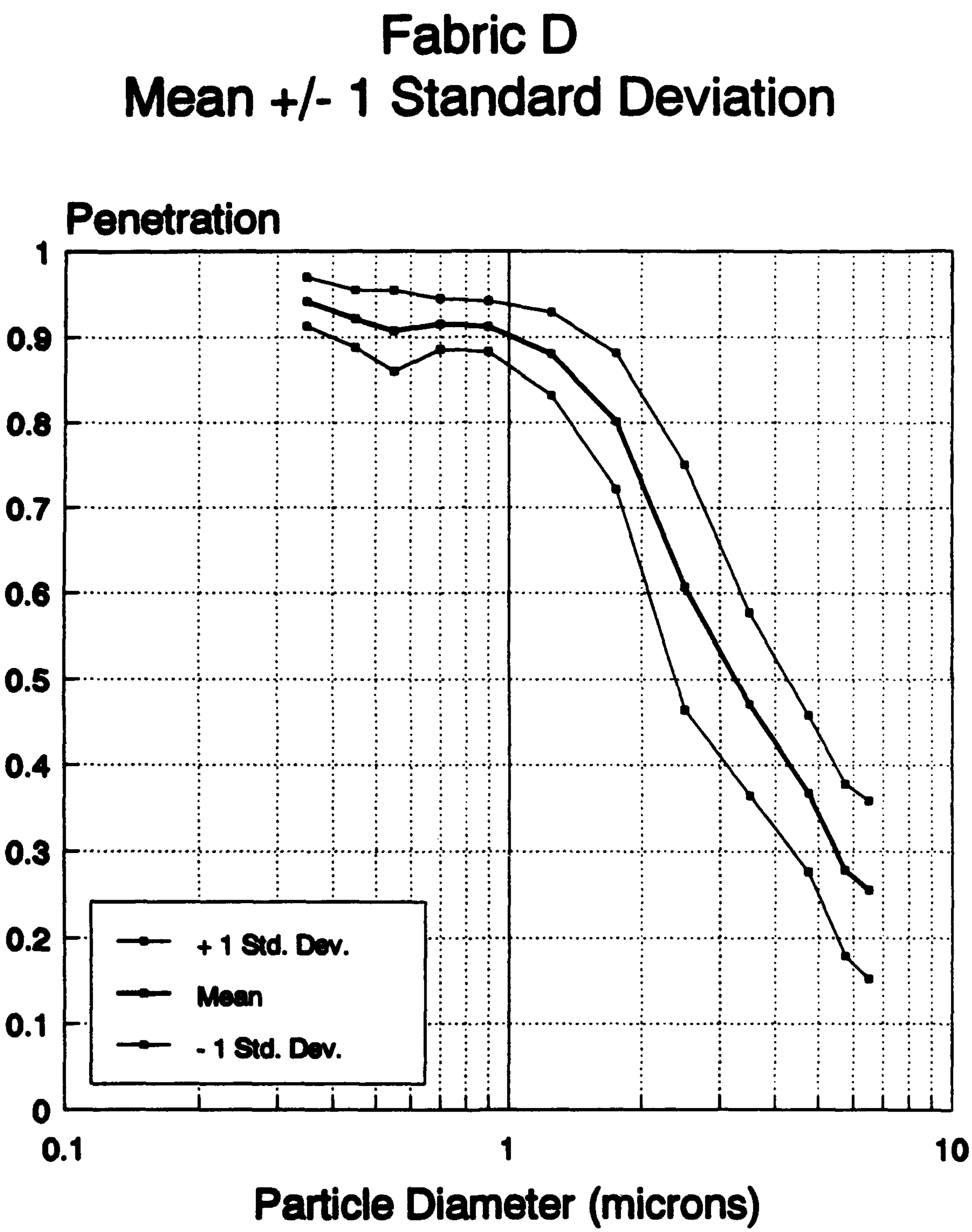

Figure 12. Mean and +/- 1 standard deviation penetration curves for Fabric D.

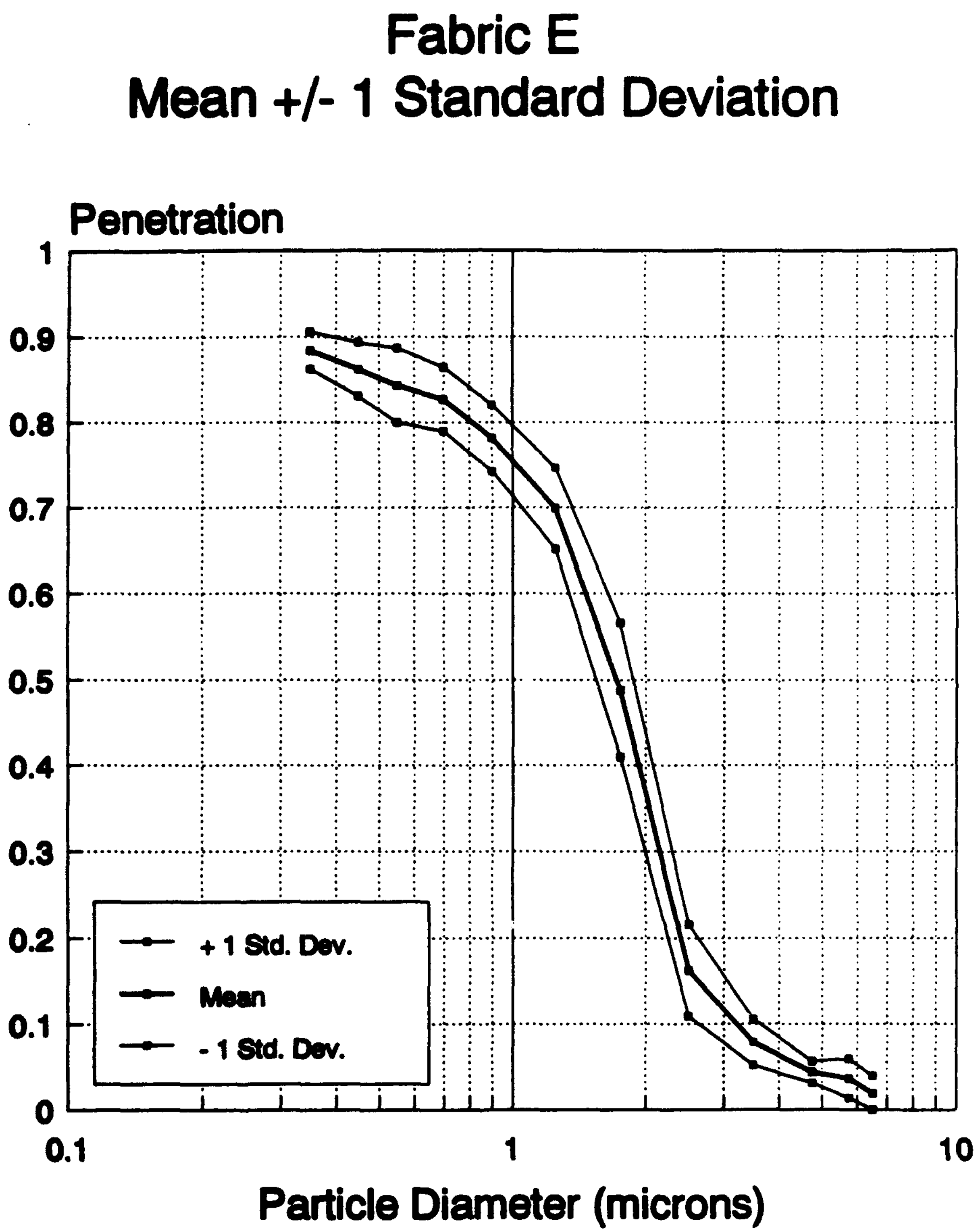

Figure 13. Mean and +/- 1 standard deviation penetration curves for Fabric E.

6.0 SUMMARY

From the results, it appears that napping the fabrics had little or no effect on aerosol penetration. Differences between test runs for a given fabric at the various levels of napping fall within the measurement error. The physical appearance of the fabric samples intuitively supports this finding in that, overall, napping had only a slight affect on the fabrics outward physical appearance. Theoretically, napping could alter (either for better or for worse) the degree of aerosol penetration though a fabric by altering the way the aerosol particles interact with the fabric fibers. However, the degree of napping given the fabrics on this program was insufficient to significantly alter the degree of aerosol penetration.

7.0 REFERENCES

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APPENDIX

AEROSOL PENETRATION AND PRESSURE DROP FOR EACH TEST RUN

Summary of Aerosol Pentration Data for Fabric A

	Test #	Delta P (in. H2O)	0.35	0.45	0.55	0.7	0.9	1.25	1.75	2.5	3.5	4.75	5.75	6.5
			Particle Diameter (microns)											
Initial	1	0.41	95.7%	92.0%	92.4%	88.1%	78.6%	68.3%	49.5%	18.0%	9.7%	5.9%	1.8%	2.6%
Initial	18	0.39	85.7%	83.9%	82.3%	81.7%	77.8%	71.4%	57.3%	25.4%	14.6%	7.4%	10.7%	8.3%
Initial	31	0.39	80.1%	79.5%	81.0%	78.1%	73.8%	69.5%	60.5%	33.3%	17.1%	11.2%	1.7%	4.9%
Initial	Mean		87.1%	85.1%	85.2%	82.7%	76.7%	69.7%	55.8%	25.6%	13.8%	8.2%	4.7%	5.3%
Initial	Std. Dev.		7.9%	6.3%	6.2%	5.0%	2.6%	1.6%	5.7%	7.6%	3.6%	2.8%	5.2%	2.9%
1 Pass	43	0.38	83.1%	79.6%	75.7%	75.2%	70.8%	62.5%	42.2%	12.2%	5.8%	4.1%	1.3%	4.6%
1 Pass	44	0.38	84.0%	79.7%	75.7%	75.4%	72.2%	63.3%	4'.6%	13.9%	7.7%	5.8%	4.9%	2.5%
1 Pass	45	0.38	80.4%	76.2%	72.2%	72.0%	68.6%	60.1%	42.2%	14.1%	7.9%	5.0%	2.3%	0.0%
1 Pass	Mean		82.5%	78.5%	74.5%	74.2%	70.6%	62.0%	42.7%	13.4%	7.1%	5.0%	2.8%	2.4%
1 Pass	Std. Dev.		1.9%	2.0%	2.1%	1.9%	1.8%	1.7%	0.8%	1.0%	1.2%	0.9%	1.9%	2.3%
2 Passes	56	0.30	88.6%	85.1%	82.6%	83.3%	80.4%	73.0%	57.2%	21.5%	13.1%	7.7%	3.8%	6.9%
2 Passes	57	0.32	75.7%	72.9%	72.3%	70.5%	66.3%	61.5%	49.5%	22.4%	12.6%	6.0%	10.8%	0.0%
2 Passes	91	0.31	82.5%	78.4%	73.8%	74.3%	70.9%	64.2%	50.5%	24.8%	14.1%	10.0%	6.1%	5.1%
2 Passes	Mean		82.3%	78.8%	76.2%	76.0%	72.5%	66.2%	52.4%	22.9%	13.3%	7.9%	6.9%	4.0%
2 Passes	Std. Dev.		6.4%	6.1%	5.6%	6.6%	7.2%	6.0%	4.2%	1.7%	0.8%	2.0%	3.6%	3.6%
3 Passes	60	0.33	81.2%	77.1%	73.6%	73.1%	68.2%	60.6%	42.0%	13.6%	6.2%	3.7%	2.6%	0.6%
3 Passes	61	0.34	81.3%	77.8%	75.7%	75.7%	71.0%	63.8%	47.5%	16.4%	7.4%	4.5%	2.9%	1.4%
3 Passes	62	0.35	80.4%	79.0%	78.6%	76.3%	71.7%	66.6%	53.2%	22.2%	9.7%	3.8%	3.3%	2.6%
3 Passes	Mean		81.0%	78.0%	76.0%	75.0%	70.3%	63.7%	47.6%	17.4%	7.7%	4.0%	2.9%	1.5%
3 Passes	Std. Dev.		0.5%	0.9%	2.5%	1.7%	1.9%	3.0%	5.6%	4.4%	1.8%	0.5%	0.3%	1.0%
4 Passes	6	0.35	78.8%	76.5%	76.0%	76.2%	72.9%	67.1%	50.6%	21.3%	9.9%	9.0%	0.0%	6.9%
4 Passes	20	0.31	88.1%	83.7%	81.7%	81.8%	79.3%	73.0%	59.3%	29.7%	17.2%	10.6%	3.8%	7.3%
4 Passes	32	0.29	84.4%	81.5%	78.7%	79.5%	75.6%	69.5%	55.7%	26.9%	18.1%	13.6%	11.8%	8.6%
4 Passes	Mean		83.1%	80.5%	78.8%	79.2%	75.9%	69.8%	55.2%	26.0%	15.1%	11.1%	5.2%	7.6%
4 Passes	Std. Dev.		3.8%	3.7%	2.9%	2.8%	3.2%	3.0%	4.4%	4.3%	4.5%	2.4%	6.0%	0.9%
Summary of Error Estimation:														
Average of Means			83.2%	80.2%	78.1%	77.4%	73.2%	66.3%	50.7%	21.0%	11.4%	7.2%	4.5%	4.2%
Average of Std. Dev.			4.1%	3.8%	3.8%	3.6%	3.3%	3.1%	4.1%	3.8%	2.4%	1.7%	3.4%	2.1%
Mean + 1 Std. Dev.			87.3%	84.0%	82.0%	81.0%	76.5%	69.3%	54.9%	24.9%	13.8%	8.9%	7.9%	6.3%
Mean - 1 Std. Dev.			79.1%	76.4%	74.3%	73.8%	69.9%	63.2%	46.6%	17.2%	9.0%	5.5%	1.1%	2.0%

Summary of Aerosol Pentration Data for Fabric B

	Test #	Delta P (in. H20)	0.35	0.45	0.55	0.7	0.9	1.25	1.75	2.5	3.5	4.75	5.75	6.5
			Particle Diameter (microns)											
Initial	7	0.08	95.2%	92.5%	89.8%	88.8%	86.7%	81.7%	61.0%	45.1%	38.8%	24.2%	19.5%	19.0%
Initial	23	0.04	99.8%	96.8%	93.3%	99.7%	97.4%	89.0%	81.2%	56.7%	54.4%	52.5%	41.1%	45.8%
Initial	33	0.04	94.3%	94.5%	94.7%	95.9%	96.2%	95.1%	99.7%	97.1%	81.3%	77.9%	70.6%	82.6%
Initial	Mean		96.4%	94.6%	92.6%	94.8%	93.4%	88.6%	80.6%	66.3%	57.5%	51.5%	43.7%	49.1%
Initial	Std. Dev.		3.0%	2.1%	2.5%	5.6%	5.9%	6.7%	19.3%	27.3%	22.4%	26.9%	25.7%	31.9%
1 Pass	97	0.04	101.0%	98.5%	94.0%	93.9%	94.1%	89.8%	71.9%	45.1%	37.8%	36.2%	41.9%	28.9%
1 Pass	48	0.04	95.8%	93.7%	91.5%	91.9%	91.3%	87.9%	79.5%	66.8%	61.6%	51.1%	33.1%	44.3%
1 Pass	49	0.04	96.3%	98.0%	95.7%	94.5%	93.6%	93.1%	91.1%	83.8%	73.3%	57.7%	43.3%	54.3%
1 Pass	Mean		97.7%	96.0%	93.7%	93.4%	93.0%	90.2%	80.8%	65.2%	57.6%	48.3%	39.4%	42.5%
1 Pass	Std. Dev.		2.9%	2.4%	2.1%	1.4%	1.5%	2.6%	9.7%	19.4%	18.1%	11.0%	5.5%	12.8%
2 Passes	93	0.05	94.0%	94.5%	95.4%	94.4%	94.4%	93.2%	90.1%	73.1%	63.8%	42.1%	26.3%	22.8%
2 Passes	64	0.04	94.0%	91.6%	90.0%	92.2%	91.0%	87.4%	84.3%	70.6%	64.4%	55.2%	54.7%	61.6%
2 Passes	65	0.04	88.6%	85.1%	82.6%	83.3%	80.4%	73.0%	57.2%	21.5%	13.1%	7.7%	3.8%	6.9%
2 Passes	Mean		92.2%	90.4%	89.3%	90.0%	88.6%	84.5%	77.2%	55.1%	47.1%	35.0%	28.3%	30.5%
2 Passes	Std. Dev.		3.1%	4.8%	6.4%	5.9%	7.3%	10.4%	17.6%	29.1%	29.5%	24.5%	25.5%	28.1%
3 Passes	78	0.05	88.8%	86.8%	84.3%	85.1%	84.6%	80.9%	69.7%	47.1%	41.1%	35.9%	28.0%	32.8%
3 Passes	79	0.05	92.9%	92.2%	92.2%	92.2%	90.7%	89.5%	87.4%	74.1%	61.1%	47.2%	28.4%	31.1%
3 Passes	80	0.05	93.9%	91.8%	90.6%	90.2%	89.4%	86.7%	77.0%	59.5%	48.9%	36.3%	31.7%	36.5%
3 Passes	Mean		91.9%	90.3%	89.0%	89.2%	88.2%	85.7%	78.0%	60.2%	50.4%	39.8%	29.4%	33.4%
3 Passes	Std. Dev.		2.7%	3.0%	4.2%	3.6%	3.2%	4.4%	8.9%	13.5%	10.1%	6.4%	2.1%	2.7%
4 Passes	2	0.05	97.4%	94.0%	96.4%	97.7%	94.1%	87.8%	77.9%	56.8%	49.0%	46.6%	39.3%	37.1%
4 Passes	24	0.04	94.8%	93.7%	94.3%	94.8%	94.3%	93.5%	90.6%	77.8%	69.7%	57.9%	46.3%	41.9%
4 Passes	35	0.05	94.9%	93.2%	92.3%	92.1%	90.5%	87.6%	76.6%	53.0%	38.6%	20.2%	16.2%	10.0%
4 Passes	Mean		95.7%	93.6%	94.3%	94.9%	93.0%	89.6%	81.7%	62.6%	52.4%	41.6%	33.9%	29.7%
4 Passes	Std. Dev.		1.5%	0.4%	2.1%	2.8%	2.1%	3.3%	7.8%	13.4%	15.9%	19.4%	15.8%	17.2%
Summary of Error Estimation:														
Average of Means			94.8%	93.0%	91.8%	92.4%	91.3%	87.7%	79.7%	61.9%	53.0%	43.3%	35.0%	37.0%
Average of Std. Dev.			2.8%	2.6%	3.5%	3.9%	4.0%	5.5%	12.6%	20.5%	19.2%	17.6%	14.9%	18.6%
Mean + 1 Std. Dev.			97.4%	95.5%	95.3%	96.3%	95.3%	93.2%	92.3%	82.4%	72.2%	60.9%	49.9%	55.6%
Mean - 1 Std. Dev.			92.1%	90.4%	88.3%	88.6%	87.2%	82.3%	67.0%	41.3%	33.8%	25.6%	20.0%	18.5%

Summary of Aerosol Pentration Data for Fabric C

	Test #	Delta P (in. H20)	0.35	0.45	0.55	0.7	0.9	1.25	1.75	2.5	3.5	4.75	5.75	6.5
			Particle Diameter (microns)											
Initial	3	0.12	96.3%	95.4%	97.5%	96.1%	92.0%	86.9%	78.9%	51.4%	30.9%	15.9%	8.0%	6.5%
Initial	25	0.10	94.9%	93.2%	92.3%	92.1%	90.5%	87.6%	76.6%	53.0%	38.6%	20.2%	16.2%	10.0%
Initial	36	0.12	90.7%	88.6%	87.5%	87.5%	85.7%	81.9%	72.9%	46.8%	29.3%	17.6%	14.0%	8.0%
Initial	Mean		93.9%	92.4%	92.5%	91.9%	89.4%	85.5%	76.1%	50.4%	32.9%	17.9%	12.7%	8.1%
Initial	Std. Dev.		2.9%	3.5%	5.0%	4.3%	3.3%	3.1%	3.0%	3.2%	5.0%	2.2%	4.2%	1.8%
1 Pass	50	0.11	91.7%	89.5%	87.3%	88.5%	88.1%	82.7%	73.8%	41.8%	26.1%	15.2%	11.6%	5.9%
1 Pass	51	0.11	92.1%	89.3%	88.1%	88.4%	87.3%	83.3%	73.0%	47.0%	31.8%	22.0%	15.0%	11.1%
1 Pass	52	0.12	90.5%	89.3%	87.7%	87.3%	85.0%	80.8%	70.2%	41.2%	26.7%	17.2%	8.4%	5.7%
1 Pass	Mean		91.4%	89.4%	87.7%	88.1%	86.8%	82.3%	72.3%	43.4%	28.2%	18.1%	11.7%	7.6%
1 Pass	Std. Dev.		0.8%	0.1%	0.4%	0.7%	1.6%	1.3%	1.9%	3.2%	3.1%	3.5%	3.3%	3.1%
2 Passes	66	0.11	90.6%	89.6%	89.7%	89.2%	86.6%	83.9%	81.8%	60.4%	33.9%	20.5%	11.5%	9.3%
2 Passes	67	0.10	92.6%	92.6%	94.6%	94.4%	92.8%	91.1%	96.4%	85.3%	54.8%	30.2%	26.4%	24.6%
2 Passes	69	0.11	91.3%	88.1%	85.2%	85.7%	84.0%	77.8%	62.5%	33.3%	20.7%	12.0%	10.2%	7.7%
2 Passes	Mean		91.5%	90.1%	89.8%	89.8%	87.8%	84.3%	80.2%	59.7%	36.5%	20.9%	16.0%	13.8%
2 Passes	Std. Dev.		1.0%	2.3%	4.7%	4.4%	4.5%	6.6%	17.0%	26.0%	17.2%	9.1%	9.0%	9.3%
3 Passes	81	0.11	93.4%	91.8%	90.1%	89.4%	87.1%	82.8%	70.9%	47.3%	30.6%	18.0%	4.0%	8.3%
3 Passes	82	0.11	89.6%	88.4%	87.4%	87.2%	85.1%	82.6%	74.0%	50.4%	35.1%	19.5%	3.0%	2.6%
3 Passes	83	0.11	93.4%	92.0%	92.1%	92.9%	91.1%	87.8%	81.1%	54.6%	35.9%	22.2%	9.5%	6.1%
3 Passes	Mean		92.1%	90.7%	89.8%	89.8%	87.8%	84.4%	75.4%	50.8%	33.9%	19.9%	5.5%	5.7%
3 Passes	Std. Dev.		2.2%	2.0%	2.3%	2.9%	3.1%	3.0%	5.2%	3.7%	2.8%	2.1%	3.5%	2.9%
4 Passes	94	0.07	90.3%	89.9%	89.5%	87.9%	86.9%	84.1%	75.5%	52.7%	41.0%	27.7%	15.0%	12.2%
4 Passes	26	0.09	88.0%	83.5%	81.5%	88.4%	84.5%	76.1%	69.3%	32.4%	22.3%	13.3%	10.7%	14.3%
4 Passes	37	0.08	91.8%	89.3%	87.7%	87.8%	86.0%	82.1%	71.7%	50.4%	45.6%	37.8%	24.7%	43.4%
4 Passes	Mean		90.0%	87.6%	86.2%	88.0%	85.8%	80.8%	72.2%	45.2%	36.3%	26.3%	16.8%	23.3%
4 Passes	Std. Dev.		1.9%	3.5%	4.2%	0.3%	1.2%	4.1%	3.1%	11.1%	12.3%	12.3%	7.2%	17.4%
Summary of Error Estimation:														
Average of Means			91.8%	90.0%	89.2%	89.5%	87.5%	83.4%	75.2%	49.9%	33.6%	20.6%	12.5%	11.7%
Average of Std. Dev.			1.8%	2.3%	3.3%	2.5%	2.7%	3.6%	6.1%	9.5%	8.1%	5.8%	5.4%	6.9%
Mean + 1 Std. Dev.			93.6%	92.3%	92.5%	92.0%	90.3%	87.1%	81.3%	59.3%	41.6%	26.5%	18.0%	18.6%
Mean - 1 Std. Dev.			90.0%	87.8%	85.9%	87.0%	84.8%	79.8%	69.2%	40.4%	25.5%	14.8%	7.1%	4.8%

Summary of Aerosol Pentration Data for Fabric D

	Test #	Delta P (in. H2O)	0.35	0.45	0.55	0.7	0.9	1.25	1.75	2.5	3.5	4.75	5.75	6.5
			Particle Diameter (microns)											
Initial	90	0.07	95.9%	95.8%	97.7%	97.6%	96.9%	96.8%	94.4%	79.1%	67.4%	52.6%	49.2%	39.6%
Initial	27	0.08	91.7%	90.0%	87.7%	90.7%	90.5%	85.2%	79.5%	51.4%	35.7%	25.9%	14.8%	10.0%
Initial	96	0.05	96.9%	96.4%	98.7%	98.4%	97.6%	97.5%	101.7%	94.6%	66.5%	44.9%	21.1%	25.9%
Initial	Mean		94.9%	94.1%	94.7%	95.5%	95.0%	93.2%	91.9%	75.0%	56.5%	41.2%	28.4%	25.2%
Initial	Std. Dev.		2.7%	3.5%	6.1%	4.2%	3.9%	6.9%	11.3%	21.9%	18.1%	13.8%	18.3%	14.9%
1 Pass	9	0.08	90.6%	87.2%	84.4%	87.3%	88.9%	85.2%	73.6%	51.8%	40.3%	35.6%	29.2%	32.2%
1 Pass	28	0.05	93.2%	89.8%	85.2%	85.9%	85.2%	79.8%	64.4%	38.9%	34.1%	33.9%	26.9%	24.2%
1 Pass	40	0.05	96.5%	93.5%	90.5%	89.3%	88.4%	83.6%	67.1%	48.7%	38.6%	27.5%	26.3%	21.3%
1 Pass	Mean		93.4%	90.2%	86.7%	87.5%	87.5%	82.9%	68.4%	46.5%	37.7%	32.3%	27.5%	25.9%
1 Pass	Std. Dev.		3.0%	3.1%	3.3%	1.7%	2.0%	2.8%	4.7%	6.7%	3.2%	4.3%	1.6%	5.6%

Summary of Error Estimation:

	0.35	0.45	0.55	0.7	0.9	1.25	1.75	2.5	3.5	4.75	5.75	6.5
Average of Means	94.1%	92.1%	90.7%	91.5%	91.2%	88.0%	80.1%	60.8%	47.1%	36.8%	27.9%	25.6%
Average of Std. Dev.	2.8%	3.3%	4.7%	3.0%	2.9%	4.9%	8.0%	14.3%	10.6%	9.1%	9.9%	10.3%
Mean + 1 Std. Dev.	97.0%	95.5%	95.4%	94.5%	94.2%	92.9%	88.1%	75.1%	57.7%	45.8%	37.8%	35.9%
Mean - 1 Std. Dev.	91.3%	88.8%	86.0%	88.6%	88.3%	83.2%	72.1%	46.4%	36.5%	27.7%	18.0%	15.3%

Summary of Aerosol Pentration Data for Fabric E

	Test #	Delta P (in. H2O)	0.35	0.45	0.55	0.7	0.9	1.25	1.75	2.5	3.5	4.75	5.75	6.5
			Particle Diameter (microns)											
Initial	17	0.63	88.9%	87.8%	86.3%	83.1%	78.1%	68.4%	47.6%	14.1%	5.3%	2.8%	0.0%	0.0%
Initial	29	0.59	86.3%	83.5%	80.6%	80.3%	75.9%	66.9%	43.0%	12.3%	6.1%	4.8%	4.0%	1.4%
Initial	39	0.58	87.5%	85.8%	84.6%	82.7%	77.5%	68.9%	51.5%	16.2%	7.8%	2.8%	5.1%	0.0%
Initial	Mean		87.6%	85.7%	83.8%	82.0%	76.5%	68.1%	47.4%	14.2%	6.4%	3.5%	3.0%	0.5%
Initial	Std. Dev.		1.3%	2.1%	2.9%	1.5%	0.9%	1.0%	4.3%	2.0%	1.3%	1.2%	2.7%	0.8%
2 Passes	53	0.51	88.8%	86.9%	85.0%	83.7%	79.0%	71.0%	48.6%	15.0%	7.4%	4.8%	3.6%	4.5%
2 Passes	54	0.53	85.9%	82.2%	78.9%	78.3%	73.9%	64.3%	40.7%	10.4%	5.3%	3.3%	1.6%	1.6%
2 Passes	55	0.47	89.1%	89.4%	92.2%	90.4%	87.3%	81.1%	69.1%	30.6%	15.5%	6.0%	8.1%	2.5%
2 Passes	Mean		87.9%	86.2%	85.4%	84.1%	80.1%	72.2%	52.8%	18.7%	9.4%	4.7%	4.4%	2.9%
2 Passes	Std. Dev.		1.7%	3.7%	6.7%	6.1%	6.8%	8.5%	14.7%	10.6%	5.4%	1.3%	3.3%	1.5%
4 Passes	71	0.48	85.2%	80.2%	78.1%	78.9%	73.0%	63.0%	40.2%	10.2%	5.2%	3.4%	1.6%	0.0%
4 Passes	72	0.47	89.3%	89.0%	89.0%	87.0%	81.9%	76.5%	62.1%	27.4%	13.0%	7.4%	8.1%	2.8%
4 Passes	73	0.46	90.6%	89.6%	87.1%	81.7%	77.8%	70.0%	42.4%	15.7%	7.9%	5.0%	1.9%	0.0%
4 Passes	Mean		88.4%	86.3%	84.1%	81.9%	77.6%	69.9%	48.2%	17.8%	8.7%	5.3%	3.9%	0.9%
4 Passes	Std. Dev.		2.8%	5.3%	7.0%	5.1%	4.5%	6.7%	12.1%	8.8%	4.0%	2.0%	3.7%	1.6%
6 Passes	74	0.48	95.2%	91.7%	88.5%	87.4%	82.2%	72.5%	46.4%	15.0%	7.8%	5.6%	3.1%	1.8%
6 Passes	75	0.46	92.0%	90.2%	89.2%	88.2%	83.8%	75.6%	54.2%	18.9%	9.4%	5.1%	2.5%	2.2%
6 Passes	76	0.55	89.9%	85.4%	81.7%	80.7%	75.8%	65.3%	40.5%	10.9%	5.3%	3.7%	1.3%	0.7%
6 Passes	Mean		92.3%	89.1%	86.5%	85.5%	80.6%	71.1%	47.0%	14.9%	7.5%	4.8%	2.3%	1.5%
6 Passes	Std. Dev.		2.7%	3.3%	4.2%	4.1%	4.2%	5.3%	6.9%	4.0%	2.1%	1.0%	0.9%	0.8%
8 Passes	5	0.49	83.2%	82.3%	81.0%	77.8%	72.4%	65.7%	49.1%	17.3%	8.1%	2.6%	5.1%	0.0%
8 Passes	30	0.47	86.6%	84.3%	81.7%	80.7%	78.2%	69.7%	47.3%	14.6%	6.4%	3.9%	4.7%	9.9%
8 Passes	41	0.45	87.6%	84.7%	83.0%	81.6%	77.4%	69.5%	49.4%	15.8%	7.7%	4.2%	3.6%	1.2%
8 Passes	Mean		85.8%	83.8%	81.9%	80.0%	76.0%	68.3%	48.6%	15.9%	7.4%	3.6%	4.4%	3.7%
8 Passes	Std. Dev.		2.3%	1.3%	1.0%	2.0%	3.2%	2.3%	1.1%	1.3%	0.9%	0.8%	0.8%	5.4%
Summary of Error Estimation:														
Average of Means			88.4%	86.2%	84.3%	82.7%	78.2%	69.9%	48.8%	16.3%	7.9%	4.4%	3.6%	1.9%
Average of Std. Dev.			2.2%	3.1%	4.3%	3.8%	3.9%	4.8%	7.8%	5.3%	2.7%	1.3%	2.3%	2.0%
Mean + 1 Std. Dev.			90.6%	89.3%	88.7%	86.5%	82.1%	74.7%	56.6%	21.6%	10.6%	5.6%	5.9%	3.9%
Mean - 1 Std. Dev.			86.2%	83.1%	80.0%	79.0%	74.2%	65.2%	41.0%	11.0%	5.2%	3.1%	1.4%	-0.1%