In presenting this dissertation as a partial fulfillment of the requirements for an advanced degree from the Georgia Institute ot Technology, I agree that the Library of the Institution shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish from, this dissertation may be granted by the professor under whose direction it was written, when such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this dissertation which involves potential financial gain will not be allowed without written permission.

Winston C. Boteler

A STUDY OF THE FLOW OF AIR THROUGH FABRICS AT HIGH DIFFERENTIAL PRESSURES

A THESIS

Presented to
the Faculty of the Graduate Division

By
Winston Currie Boteler

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Mechanical Engineering

Georgia Institute of Technology
June 1956

3P
12T

A STUDY OF THE FLOW OF AIR THROUGH FABRICS AT HIGH DIFFERENTIAL PRESSURES

Approved:

Date Approved by Chairman: 31 May 1956

ACKNOWLEDGMENTS

The author gratefully appreciates the counsel and assistance of Mr. H. W. S. LaVier, formerly Associate Professor of Aeronautical Engineering, under whose guidance the investigation was accomplished. Dr. M. J. Goglia offered many helpful suggestions as Thesis Advisor. Professor Frank A. Thomas and Professor J. W. McCarty were helpful in serving on the reading committee.

The research reported herein was conducted at the Engineering Experiment Station of the Georgia Institute of Technology, sponsored by the Textile Branch of the Materials Laboratory, Wright Air Development Center.

TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS ii

LIST OF TABLES iv

LIST OF FIGURES v

SUMMARY vi

CHAPTER

I. INTRODUCTION 1

A Brief History of the Problem
Objective

II. THEORY 5

III. EXPERIMENTAL PROCEDURE 9

Apparatus
Instrumentation
Fabric Selection
Sample Mounting Procedure
Test Procedure
Handling of Data

IV. TEST RESULTS 14

Data and Results
Discussion and Results

V. CONCLUSIONS 15

LITERATURE CITED 16

APPENDIX A--Summary of Results 17

APPENDIX B--Sample Calculations 37

NOMENCLATURE 40

LIST OF TABLES

Table Page

1. Physical and Textile Properties of Test Fabrics 18
2. Experimental Data 20
3. Area Increase Factors 25
4. Calculated Effective Open Area 28

LIST OF FIGURES

Figure | Page

1. Schematic Diagram of Permeability Tester 10
2. Total Effective Open Area Versus Differential Pressure 31
3. Total Effective Open Area Versus Differential Pressure 32
4. Permeability Versus Differential Pressure 33
5. Permeability Versus Differential Pressure 34
6. Orifice Differential Pressure Versus Fabric Differential Pressure 35
7. Area Increase Factor Versus Pressure Differential 36
8. Master Data and Result Sheet 38

SUMMARY

The air permeability of fourteen experimental nylon parachute type fabrics was determined using a sample four inches square in an orifice meter whose capacity permitted testing at differential pressures across the cloth as high as 1900 inches of water. The test fabrics are divided into two groups; one group in which seven identical fabrics were subjected to different calender pressures during the finishing process, and another group of seven fabrics with varied warp and filling twists. The permeability, P , at pressures above 100 inches of water cannot be expressed as $P = C\,(\nabla p)^n$ as can the permeability below 50 inches of water.

Upon assuming that isentropic flow exists up to the point of minimum area in the fabric interstice, the increase in effective flow area for pressures above the critical pressure is calculated using the upstream properties of the air. The experimental data indicate that the total effective open area of the fabric may be expressed as a function of the differential pressure across the cloth, i.e., $A^* = C(\nabla p)^n$, where the constant, C, and the exponent, n, depend on the physical and textile properties of the cloth.

CHAPTER I

INTRODUCTION

The increasing need for the recovery of personnel and equipment from supersonic aircraft has motivated a research program to determine more precisely the parameters relating the flow of air through fabrics and their physical properties. In supersonic operations, the parachute must inflate rapidly to avoid fatigue destruction of uninflated or loose sections. The supersonic velocity must be reduced rapidly to avoid weakening of the parachute structure from aerodynamic heating. A decrease in the opening time, however, produces an increase in the opening shock.

The magnitude of opening shock, inflation time, critical or squidding speed, rate of descent, and stability of the parachute are all affected by, or are functions of, the air permeability of the parachute fabric. The common definition of permeability is the volume rate of flow per unit area ($ft^3/min.-ft^2$) under a specified differential pressure at some standard temperature and pressure.

The effect of increasing or decreasing the air permeability of parachute fabric on the performance of the parachute is significant. For example, a parachute made from a loosely woven fabric may have a higher descent velocity than one made from a tightly woven fabric. Decreasing the fabric permeability will result in greater oscillation or pendulation of the parachute and its cargo.

Since the parachute design is affected by the air permeability of the fabric, the designer would like to be able to choose a particular value of air permeability at a given pressure differential across the cloth. This in turn necessitates providing the weaver with instructions about the number and denier of warp yarns, the number and denier of filling threads, and the weave pattern. The cloth finisher must be instructed as to the desired air permeability of the cloth after finishing. Obtaining cloth of uniform permeability throughout the entire process requires the use of very careful quality control.

A Brief History of the Problem.--A survey was made of all available existing literature pertinent to air permeability of parachute and other types of fabric. Very little information on this subject was found in the literature. This is indicative that very little fabric air permeability research has been conducted in the United States or Europe. Research in this field heretofore has involved the study of the mechanics of air flow through the cloth at pressure differential of 50 inches of water and under.

At low differential pressures (50 inches of water and under), the flow may be compared to that of a liquid flowing through a porous media. At higher differential pressures, the mechanics of flow may be compared to the flow through a porous non-homogeneous elastic membrane. At higher differential pressures, the effects of compressibility must be taken into account in addition to those effects due to stretching of the fabric.

The flow through porous media has been investigated analytically. Green and Duwez (1) have developed formulae for use in analytical treatment of such flows. For flow of a compressible fluid through a porous media, the pressure gradient may be expressed as:

$$-\frac{dp}{dx} = \alpha\mu V + \beta\rho V^2 \qquad (1)$$

For isothermal flow of a gas through a porous bed the pressure-square gradient becomes from equation (1):

$$\frac{P_1^2 - P_2^2}{L} = \alpha(2RT\frac{\mu}{g_c})\ G + \beta(\frac{2RT}{g_c})\ G^2 \qquad (2)$$

They define a characteristic β/α as a characteristic length to describe the geometry of the bed.

Goglia (2) and Brown (3) developed a method of presenting the flow data in a general dimensionless form over a limited range of flow. Under the assumption that the pressure-square gradient in the flow through a fabric is the arithmetic sum of the viscous $(2\alpha RT\mu\frac{G}{g_c})$ and the inertial $(2\beta\frac{RT}{g_c}G^2)$ contribution, they infer the existence of a characteristic length β/α. They show that the relationship between the flow-through drag coefficient, C_f, and the Reynolds number, Re, based on this characteristic length is common to all fabrics so that $C_f = 2/Re + 2$. The parameters α and β may be estimated from physical measurements of the cloth, thus permitting an estimate of the permeability of the fabric.

There is no literature available concerning the flow of air through fabrics at high pressures up to the rupture point, other than the data obtained during the course of this project.

Objective.--The objective of this study was threefold:

1. To measure the permeability of a number of fabrics at pressures up to the rupture point.
2. To correlate the high pressure flow data with similar data

obtained at low pressures.

3. To determine the fabric properties which influence the permeability.

CHAPTER II

THEORY

In classical flow problems the quantity of flow is usually expressed as a function of the orifice area and the differential pressure, modified by some correcting factor such as the orifice discharge coefficient. In the case of rigid orifices, the orifice discharge coefficient changes very little with changes in pressure, and the orifice area remains the same, regardless of pressure. Thus the volume rate of flow becomes directly functional with the square root of the differential pressure. On the other hand, in the case of textile fabrics with potentially expanding orifices, the flow appears to be proportional to the differential pressure raised to the power n for low differential pressures, the numerical value of n being greater than one half.

The work accomplished thus far indicates that the tighter the weave, the greater the deviation of n from the value one half.

Those fabrics of lowest permeability at low differential pressures change most rapidly with increases in pressure drop. An empirical analysis of the air permeability data measured at the Georgia Institute of Technology disclosed that the line showing air permeability versus differential pressure was straight when plotted on full logarithmic graph paper. Data for two hundred fabric samples have been plotted and the results consistently bear out the relationship:

$$\text{Permeability} = C(\nabla p)^n.$$

This variation is very closely followed by fabrics in the range from one inch to 55 inches of water differential pressure.

In the range from 100 inches of water differential pressure to the rupture pressure of the fabric, the above proportionality does not express the relationship of differential pressure versus permeability. Throughout the subject research it had been hoped that a theory might be developed for describing the flow of air through the parachute type fabrics at high differential pressures. However, the many variables and the difficulty involved in measuring the cloth thickness and increase in area combine to prevent a precise analytical solution of the flow problem.

The measurement of the air flow through fabrics at differential pressures up to 1500 inches of water permits the determination of the effective open area of the fabric sample. The assumption is made that isentropic flow exists from upstream conditions to the minimum area in the pore opening. Also, the Mach number is one at that position when the pressure ratio is less than the so-called critical pressure ratio, based on initial conditions. The author recognizes that the foregoing assumption may be neither necessary nor sufficient.

In order to determine the velocity of sound in the interstice it is first necessary to determine the stagnation conditions for the flow ahead of the fabric. The upstream Mach number must also be determined and is derived in the following equations. The velocity of sound in a perfect gas may be expressed as

$$c = \sqrt{kRT} \quad \text{ft/sec}$$

and for air this becomes (3)

$$c = 49.02\sqrt{T} \text{ ft/sec.}$$

The equation of state gives the relationship between pressure, density, and temperature as

$$p = \rho RT.$$

Then, since the Mach number, M, is equal to V/c, the mass flow rate may be related to the Mach number as follows:

$$\rho V/p = Mk/c.$$

Solving the equation for M, we get

$$M = \frac{c}{k}\,(\rho V/p) = \frac{49.02\,\rho V/p}{k}\sqrt{T.}$$

Having determined the Mach number in the flow ahead of the fabric, the stagnation pressure and temperature are obtained by use of the isentropic tables as follows:

$$\rho_o \text{ from } M \text{ and } \rho/\rho_o$$

$$T_o \text{ from } M \text{ and } T/T.$$

The conditions in the interstices for M = 1 may be computed as follows:

$$P^* = 0.528\ P_o$$

$$T^* = 0.833\ T_o$$

$$V^* = 49.02\ T^*$$

$$\rho^* = 2.70\ P^*/T^*.$$

(The subscript o denotes stagnation conditions and the superscript * denotes conditions when M = 1.)

The mass rate of flow, w, expressed in lb_m/sec is taken from the calculation sheet and then the effective flow area or effective open area of the fabric samples is calculated from the following equation:

$$A^* = \frac{w}{\rho^* V^*}.$$

By use of the above formula and gas dynamics tables and the properties determined experimentally, it is therefore possible to calculate the effective open area of the fabric sample at differential pressures ranging from the critical pressure ratio up to the rupture pressure.

Since all the calculations are based on the total open area necessary to accelerate the mass flow in the pipe to Mach 1, the area of the fabric cannot be determined. In the absence of observed deformation data, the permeability (cfm/ft^2) is determined by utilizing the load-elongation characteristics for the fabrics under biaxial tension.

A review of the biaxial tension data by Boteler (6) indicates the load-elongation curves for parachute type fabrics may be approximated closely by straight lines drawn from the origin to the point of rupture elongation and pressure. Since the elongation at rupture is an indication of the maximum possible increase of the fabric sample area, this load-elongation point is common to both the plane biaxial and the hydrostatic case. The assumed fabric sample area at rupture of the cloth in the permeability tester is assumed to be the original area plus the additional area indicated by the measured elongations. It is then assumed that the fabric sample area increases linearly under air load from the original size at no load to the maximum possible area at rupture. The area so determined is used as the sample area in calculating the permeability.

CHAPTER III

EXPERIMENTAL PROCEDURE

Apparatus.--The high pressure permeability tester was designed to provide a pressure differential across the fabric sample up to 1500 inches of water. The tester consists essentially of an air supply system, an orifice meter, fabric sample holder, and recording equipment.

A 12 x 13 inch Worthington air compressor driven by a seventy-five horsepower electric motor provides compressed air up to a maximum of 125 pounds per square inch pressure. The air from the compressor is cooled in a water-cooled aftercooler to a temperature of 100 degrees Fahrenheit, then passed through a C. D. Kemp single tower adsorption dryer, where it dried to a dew point of -8 degrees Fahrenheit. The air is stored after drying in a 1000 cubic foot capacity reservoir. The air for testing is reduced to the desired pressure through a pressure regulator, then passed through a 100 cubic foot capacity stilling chamber to the test section. The air supply to the test section is controlled by a gate type valve upstream of the orifice meter.

The air flows from the gate valve through a four inch pipe to a flange tap type orifice meter, installed in accordance with the American Society of Mechanical Engineers Special Research Committee on Fluid Meters (7), and through the fabric sample to the atmosphere. A sample holder having a 16 square inch (4" x 4") opening is used in these tests. It consists of two aluminum plates with a rubber seal between them. A schematic diagram of the permeability tester is shown in Figure 1.

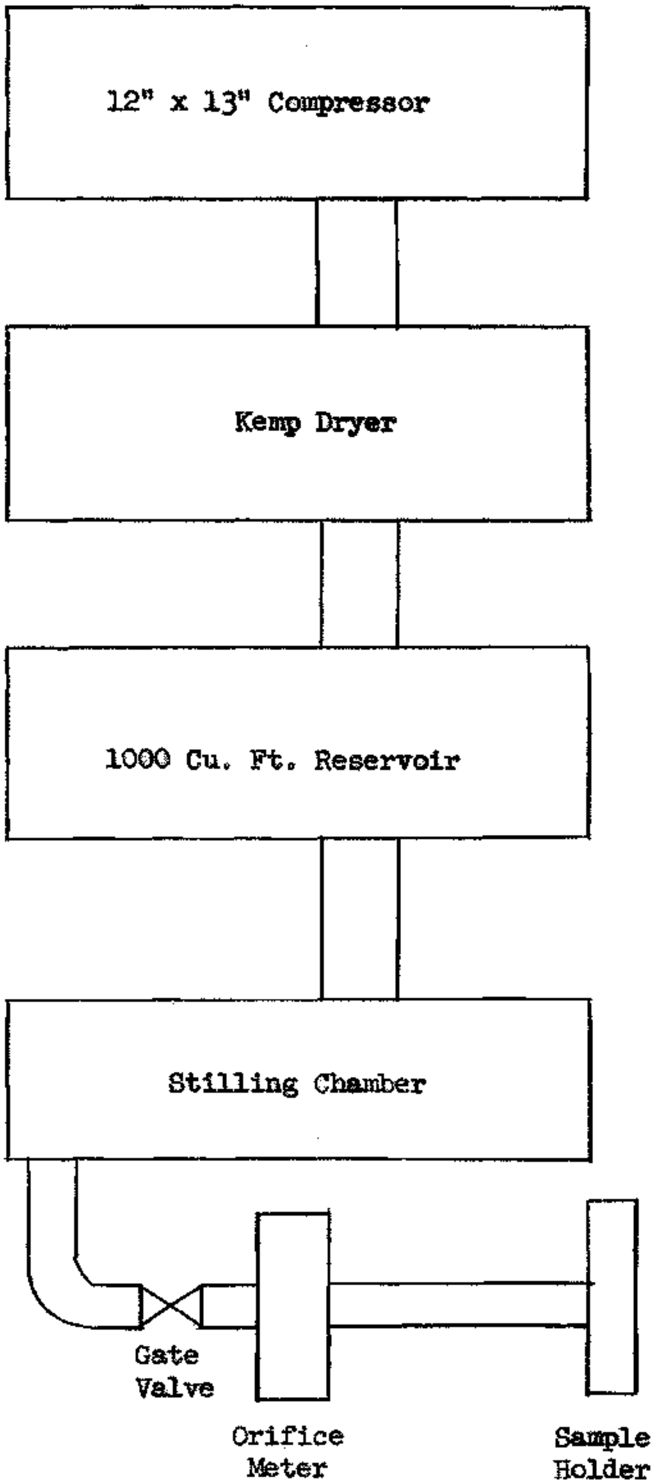

Figure 1. Schematic Diagram of Permeability Tester

Instrumentation.--Because the air capacity provides a constant pressure flow of only sixty seconds at high fabric differential pressures, the pressures and temperatures are recorded on an oscillograph. The upstream static pressure, the cloth static pressure, and the orifice differential pressure are sensed by Ceco Type 7 pressure transducers. The air temperature is sensed with an iron-constantan thermocouple inserted in the air stream.

A Ceco Type 1-118 Carrier Amplifier supplies a carrier voltage to the transducers and amplifies the response signal to any desired value. The amplified signals are recorded by a Ceco Type 5-116 recording oscillograph.

Fabric Selection.--The fourteen experimental fabrics selected for the tests reported here were woven by the Cheney Brothers Company. The fabrics are divided into two groups. Seven fabrics were obtained from a piece of MIL-C-7020, Type I, nylon ripstop parachute fabric woven from the same warp on one loom and totaling approximately 330 yards. All the samples were cut from this original piece. The cloth was sewed together after grey calendering, and all finishing and dyeing operations thereafter were performed on the sewed piece. The other seven fabrics are of plain weave and nominal 130 x 80 construction, with variable filling twist and finishing. The physical and textile properties of these fabrics are presented in Table I of Appendix A.

Sample Mounting Procedure.--A fabric sample is cut one inch oversize to permit the secure clamping of the sample between the two halves of the sample holder. The cloth is oriented so that the warp and filling threads are mutually perpendicular to the edges of the aperture. The cloth is drawn taut with the fingers, eliminating any slack. After the fabric sample is clamped, the holder is bolted securely to the end of the permeability tester.

Test Procedure.--Preliminary test runs are made to determine approximately the bursting differential pressure of the fabric under test. Then the test pressure range is divided into ten increments below the rupture pressure. The fabric sample is subjected to each of the pressures by means of varying the pressure in the stilling chamber with the pressure regulator. As the air flows through the fabric sample, the pressures and temperatures are recorded on the oscillograph. Nine samples of each fabric are tested, and these samples are selected so that no two samples contain the same warp and filling threads.

Handling of Data.--The pressure differential across the sample, pressure upstream of the orifice, pressure differential across the orifice, and the air temperatures are obtained from the oscillograph record. Figure 6 is an example of the test data obtained from the oscillograph record for the nine samples. This data is averaged for use in subsequent steps. The curves are cut off at the average rupture pressure differential. A fabric area increase factor, I, is computed from elongation measurements obtained during biaxial tension tests. The elongations of the warp and filling threads are equal at the rupture point; therefore, a sample of area L^2 at zero pressure has an area of $(L + \nabla L)^2$ at the rupture point, thus at this point $I = \frac{(L + \nabla L)^2}{L^2}$. A graph of area increase factor versus differential pressure across the sample is constructed, using the calculated value at the rupture point and assuming a linear variation for the area between zero pressure and the rupture pressure. A typical plot of the area increase factor versus pressure differential is shown in Figure 7. Figure 8 demonstrates the Master Data and Result Sheet used in computing the permeability.

CHAPTER IV

TEST RESULTS

Data and Results.--The test results for these fabrics are presented in summary form in Tables 1 through 4. Typical curves of static pressure versus total effective open area are shown in Figures 2 and 3. The effective open areas for one inch of water static pressure were obtained by measurements from photomicrographs. The curves for permeability versus static pressures are shown on Figures 4 and 5.

Discussion of Results.--A study of the air flow versus differential pressure characteristics of the fabrics tested indicates that the flow cannot be characterized by the simple relationship which has been established for flow at low differential pressures. The calculations for effective open area indicate that the effective flow area change above the critical pressure may be expressed as a power function of the differential pressure. This relationship may be extended to low pressures for fabrics with open weaves, such as the high twist fabrics tested here. Since the total fabric area increase versus static pressure was necessarily estimated due to lack of observed data, no quantitative conclusions can be drawn from the permeability calculations. The calculated values for permeability may not hold for larger fabric samples at the higher pressures because the edge effect of the sample holder becomes more significant.

CHAPTER V

CONCLUSIONS

The following conclusions may be drawn from this study:

1. The total effective open area may be expressed as

$$A = C(\nabla p)^n$$

for pressures above the critical pressure.

2. The permeability at high pressure may be controlled by varying twist and calender pressure.

LITERATURE CITED

1. Green, Leon and Duwez, Pol, "Fluid Flow through Porous Media." Journal of Applied Mechanics, 18, No. 1, 39-45 (March 1951).

2. Goglia, M. J., Air Permeability of Parachute Cloth, Technical Report No. 1, Project No. 170-117, Georgia Institute of Technology, Atlanta, 1952, pp. 9-10.

3. Brown, C. D., A Study of the Laws of the Flow of Fluids through Fabrics. M.S. Thesis, Georgia Institute of Technology, November 1952.

4. Shapiro, Ascher, The Dynamics and Thermodynamics of Compressible Fluid Flow, Volume I, Ronald Press, New York, 1953, p. 47.

5. Shapiro, op. cit., p 614.

6. Boteler, Winston C., An Apparatus for Determining Biaxial Strength Properties of Cloth and Supporting Test Data, WADC Technical Report 55-485, Wright Air Development Center, January 1956. pp. 18-35

7. American Society of Mechanical Engineers, Fluid Meters Report, Fourth Edition, New York, 1947.

APPENDIX A

SUMMARY OF RESULTS

Table 1. Physical and Textile Properties of Test Fabrics

Fabric Number	7C35	7C1/2	10N35	10N7	7N35	7N1/2	7N7
Fiber Content	Nylon	Nylon	Nylon	Nylon	Nylon	Nylon	Nylon
Construction:	Plain	Plain	Plain	Plain	Plain	Plain	Plain
Finished	130x78	130x79	124x78	130x77	126x76	131x77	128x78
Warp Yarns:							
Denier	40	40	40	40	40	40	40
Filaments	13	13	13	13	13	13	13
Filling Yarns:							
Denier	70	70	70	70	70	70	70
Filaments	34	34	34	34	34	34	34
Twist:							
Filling	39.6	1.0	38.6	7.4	39.3	1.2	7.8
Warp	7.8	7.7	10.3	10.6	7.7	7.9	8.0
Elongation (%):							
Filling	47.3	31.1	44.3	41.1	43.0	39.0	40.7
Warp	33.4	32.2	31.4	33.7	30.1	32.0	31.3

Table 1 (Cont'd). Physical and Textile Properties of Test Fabrics

Fabric Number	Width	Construction	Warp Yarns	Filling Yarns	Weight	Twist		Elongation		Tensile Strength	
						Filling	Warp	Filling	Warp	Filling	Warp
	(Inches)		(Denier/ Filament)	(Denier/ Filament)	(Oz/Sq.Yd.)			(%)	(%)		
1	36-1/8	126x119	30/10	30/10	1.11	1.5	9.0	44	34	45	47
2	36-5/8	124x119	30/10	30/10	1.09	1.5	9.0	39	32	40	47
3	36-1/8	126x119	30/10	30/10	1.10	1.5	9.0	44	32	42	47
4	36-1/2	125x118	30/10	30/10	1.08	1.5	9.0	40	33	42	46
5	36-1/4	126x119	30/10	30/10	1.08	1.5	9.0	39	31	42	45
6	36-3/4	124x118	30/10	30/10	1.07	1.5	9.0	33	34	43	47
7	36-1/2	116x115	30/10	30/10	.98	1.5	9.0	36	30	41	42

(1) No grey calendering, no heat treat, finished.
(2) Hot calendered in grey, 19 tons, no heat treat.
(3) Hot calendered in grey, 25 tons, no heat treat.
(4) Hot calendered in grey, 50 tons, no heat treat.
(5) Hot calendered in grey, 100 tons, no heat treat.
(6) a.Hot calendered in grey, 19 tons, no heat treat.
b.Heat treat on tenter frame at 420°F, 7.1/2 sec.
c.Heat set on Morrison at 420°F, 9 sec.
(7) Grey sample, no finish or heat treat - as woven.

Table 2. Experimental Data

Static Pressure Upstream of Cloth	Air Density Upstream of Cloth	Mass Velocity of Air Upstream of Cloth	Permeability
(Inches of Water)	(lbm ft.$^{-3}$)	(lbm sec.$^{-1}$ft.$^{-2}$)	(cfm ft.$^{-2}$)
7N 7			
64	0.0837	6.29	4,760
134	0.0964	8.76	6,180
204	0.109	10.6	7,010
274	0.122	12.1	7,610
344	0.135	13.5	8,030
413	0.147	14.8	8,430
483	0.160	16.1	8,810
553	0.173	17.2	9,150
623	0.186	18.5	9,380
693	0.199	19.5	9,580
723	0.204	19.9	9,650
7N 35			
35	0.0764	7.21	5,710
93	0.0866	11.1	8,250
151	0.0970	13.5	8,250
209	0.107	15.4	9,520
238	0.112	16.1	10,520
296	0.123	17.4	10,870
354	0.133	18.5	11,110
412	0.143	19.6	11,300
470	0.154	20.6	11,490
528	0.164	21.4	11,550
10N			
96	0.0874	7.36	5,460
168	0.100	10.0	6,910
241	0.113	12.1	7,880
314	0.126	13.8	8,510
386	0.139	15.4	9,020
459	0.152	16.8	9,430
531	0.165	18.0	9,700
604	0.179	19.3	10,020
676	0.191	20.5	10,280
649	0.204	21.7	10,530
790	0.211	22.4	10,700

Table 2 (Cont'd). Experimental Data

Static Pressure Upstream of Cloth	Air Density Upstream of Cloth	Mass Velocity of Air Upstream of Cloth	Permeability
(Inches of Water)	(lbm ft.$^{-3}$)	(lbm sec.$^{-1}$ft.$^{-2}$)	(cfm ft.$^{-2}$)
7C 1/2			
91	0.0890	5.44	4,000
176	0.105	6.35	4,300
260	0.120	7.13	4,510
344	0.135	7.93	4,720
428	0.151	8.61	4,860
512	0.166	9.24	4,970
596	0.181	9.92	5,100
680	0.197	10.5	5,190
764	0.212	11.2	5,310
848	0.227	11.9	5,380
881	0.234	12.0	5,440
7C 35			
96	0.0870	7.54	5,600
139	0.0947	9.79	6,960
183	0.102	11.8	8,100
226	0.110	13.4	8,840
270	0.118	14.7	9,360
328	0.128	16.4	10,000
386	0.138	17.9	10,570
444	0.149	19.4	11,000
488	0.156	20.3	11,260
531	0.164	21.4	11,550
10N 35			
22	0.0749	6.82	5,460
64	0.0825	10.8	8,260
120	0.0925	13.6	9.820
176	0.103	15.6	10,680
232	0.113	17.1	11,180
287	0.123	18.4	11,480
343	0.133	19.4	11,660
399	0.143	20.3	11,750
455	0.153	21.0	11,750

Table 2 (Cont'd). Experimental Data

Static Pressure Upstream of Cloth	Air Density Upstream of Cloth	Mass Velocity of Air Upstream of Cloth	Permeability
(Inches of Water)	(lbm ft.$^{-3}$)	(lbm sec.$^{-1}$ft.$^{-2}$)	(cfm ft.$^{-2}$)
7N 1/2			
117	0.0921	6.11	4,410
229	0.112	7.89	5,160
341	0.132	9.39	5,650
397	0.143	10.2	5,890
509	0.163	11.2	6,110
565	0.173	11.8	6,210
621	0.183	12.4	6,340
677	0.193	13.0	6,470
789	0.213	14.4	6,860
845	0.223	15.3	7,080
901	0.233	16.3	7,390
1			
72	0.0862	6.14	4,580
135	0.0973	8.14	5,720
197	0.109	9.70	6,440
260	0.120	11.0	6,960
321	0.132	12.2	7,360
385	0.144	13.4	7,720
449	0.155	14.2	7,890
510	0.166	15.1	8,130
587	0.587	16.3	8,400
2			
72	0.0849	5.73	4,210
134	0.0962	7.57	5,350
197	0.108	9.26	6,160
260	0.119	10.6	6,700
322	0.130	11.8	7,160
385	0.141	12.9	7,510
447	0.153	13.9	7,780
510	0.164	14.8	8,020
572	0.175	15.7	8,250
619	0.184	16.5	8,400
641	0.188	16.9	8,530

Table 2 (Cont'd). Experimental Data

Static Pressure Upstream of Cloth (Inches of Water)	Air Density Upstream of Cloth (lbm ft.$^{-3}$)	Mass Velocity of Air Upstream of Cloth (lbm sec.$^{-1}$ft.$^{-2}$)	Permeability (cfm ft.$^{-2}$)
3			
103	0.0904	6.65	4,740
166	0.102	8.24	5,660
228	0.113	9.75	6,350
291	0.124	10.9	6,780
353	0.136	12.2	7,240
416	0.147	13.2	7,550
478	0.158	14.1	7,780
541	0.169	15.2	8,100
604	0.181	16.2	8,350
4			
75.1	0.0851	5.52	4,140
138	0.0964	7.33	5,170
200	0.108	8.85	5,900
263	0.119	10.0	6,360
325	0.130	11.2	6,770
388	0.141	12.1	7,100
450	0.153	13.1	7,340
573	0.164	13.1	7,520
576	0.175	14.7	7,700
622	0.184	15.4	7,850
5			
106	0.0909	6.11	4,450
169	0.102	7.65	5,250
231	0.114	9.04	5,860
294	0.125	10.1	6,250
357	0.136	11.2	6,650
418	0.147	12.0	6,860
482	0.159	13.0	7,140
543	0.170	13.8	7,330
607	0.181	14.7	7,570

Table 2 (Cont'd). Experimental Data

Static Pressure Upstream of Cloth	Air Density Upstream of Cloth	Mass Velocity of Air Upstream of Cloth	Permeability
(Inches of Water)	(lbm ft.$^{-3}$)	(lbm sec.$^{-1}$ft.$^{-2}$)	(cfm ft.$^{-2}$)
6			
106	0.0897	7.37	5,390
200	0.106	9.46	6,360
294	0.123	11.4	7,120
388	0.140	13.0	7,610
479	0.156	14.6	8,090
573	0.173	15.9	8,370
668	0.190	17.3	8,690
762	0.206	18.8	9,070
7			
65.7	0.0835	7.07	5,360
128	0.0945	9.47	6,760
191	0.106	11.3	7,590
254	0.118	12.8	8,150
316	0.129	14.0	8,540
380	0.140	15.0	8,780
440	0.151	16.0	9,010
504	0.163	17.0	9,220
535	0.168	17.6	9,400

Table 3. Area Increase Factors

Static Pressure Upstream of Cloth	Elongation	Area Increase Factor
(Inches of Water)	(Inches/inch)	$(1 + \text{Elongation})^2$
7N 1/2		
117	0.039	1.08
229	0.077	1.16
341	0.109	1.23
397	0.127	1.27
509	0.162	1.35
565	0.179	1.39
621	0.096	1.43
677	0.208	1.46
789	0.237	1.54
845	0.257	1.58
901	0.273	1.62
7N 7		
64	0.025	1.05
134	0.049	1.10
204	0.082	1.17
274	0.105	1.22
344	0.131	1.28
413	0.158	1.34
483	0.183	1.40
553	0.204	1.45
623	0.229	1.51
693	0.253	1.57
723	0.261	1.59
7N 35		
35	0.020	1.04
93	0.054	1.11
151	0.082	1.17
209	0.114	1.24
238	0.127	1.27
296	0.158	1.34
354	0.187	1.41
412	0.212	1.47
470	0.241	1.54
528	0.265	1.60

Table 3 (Cont'd). Area Increase Factors

Static Pressure Upstream of Cloth	Elongation	Area Increase Factor
(Inches of Water)	(Inches/inch)	$(1 + \text{Elongation})^2$
10N 7		
96	0.034	1.07
168	0.063	1.13
241	0.086	1.18
314	0.114	1.24
386	0.140	1.30
459	0.162	1.35
531	0.187	1.41
604	0.208	1.46
676	0.233	1.52
749	0.253	1.57
790	0.265	1.60
10N 35		
22	0.015	1.03
64	0.044	1.09
120	0.082	1.17
176	0.114	1.24
232	0.149	1.32
287	0.183	1.40
343	0.217	1.48
399	0.245	1.55
455	0.277	1.63
7C 1/2		
91	0.034	1.07
176	0.063	1.13
260	0.095	1.20
344	0.123	1.26
428	0.153	1.33
512	0.179	1.39
596	0.204	1.45
680	0.233	1.52
764	0.257	1.58
848	0.285	1.65
881	0.311	1.72

Table 3 (Cont'd). Area Increase Factors

Static Pressure Upstream of Cloth	Elongation	Area Increase Factor
(Inches of Water)	(Inches/inch)	$(1 + \text{Elongation})^2$
7C 35		
96	0.044	1.09
139	0.063	1.13
183	0.082	1.17
226	0.100	1.21
270	0.118	1.25
328	0.145	1.31
386	0.166	1.36
444	0.196	1.43
488	0.208	1.46
531	0.225	1.50

Table 4. Calculated Effective Open Area

Static Pressure (Inches of Water)	Total Effective Open Area (ft.^{2})
1	
385	0.0229
449	0.0238
510	0.0246
587	0.0258
2	
385	0.0215
447	0.0222
510	0.0229
572	0.0238
614	0.0247
641	0.0250
3	
353	0.0208
416	0.0219
478	0.0227
541	0.0238
604	0.0246
4	
388	0.0207
450	0.0217
513	0.0224
576	0.0233
622	0.0241
5	
357	0.0196
418	0.0204
482	0.0216
543	0.0224
607	0.0234

Table 4 (Cont'd). Calculated Effective Open Area

Static Pressure (Inches of Water)	Total Effective Open Area (ft.^{2})
6	
388	0.0208
479	0.0223
573	0.0231
668	0.0242
762	0.0253
7	
380	0.0258
440	0.0266
504	0.0275
535	0.0281
7N 1/2	
397	0.0152
509	0.0156
565	0.0158
621	0.0162
677	0.0166
789	0.0175
845	0.0181
901	0.0189
7N 7	
413	0.0225
483	0.0236
553	0.0244
623	0.0251
693	0.0258
723	0.0259

Table 4 (Cont'd). Calculated Effective Open Area

Static Pressure (Inches of Water)	Total Effective Open Area (ft.^{2})
7N 35	
354	0.0320
412	0.0328
470	0.0337
528	0.0339
7C 1/2	
344	0.0126
428	0.0130
512	0.0132
596	0.0136
680	0.0139
764	0.0142
848	0.0147
881	0.0151
7C 35	
386	0.0289
444	0.0304
488	0.0311
531	0.0318
10N 7	
386	0.0238
459	0.0247
531	0.0256
604	0.0261
676	0.0270
749	0.0277
790	0.0282
10N 35	
343	0.0354
399	0.0362
455	0.0369

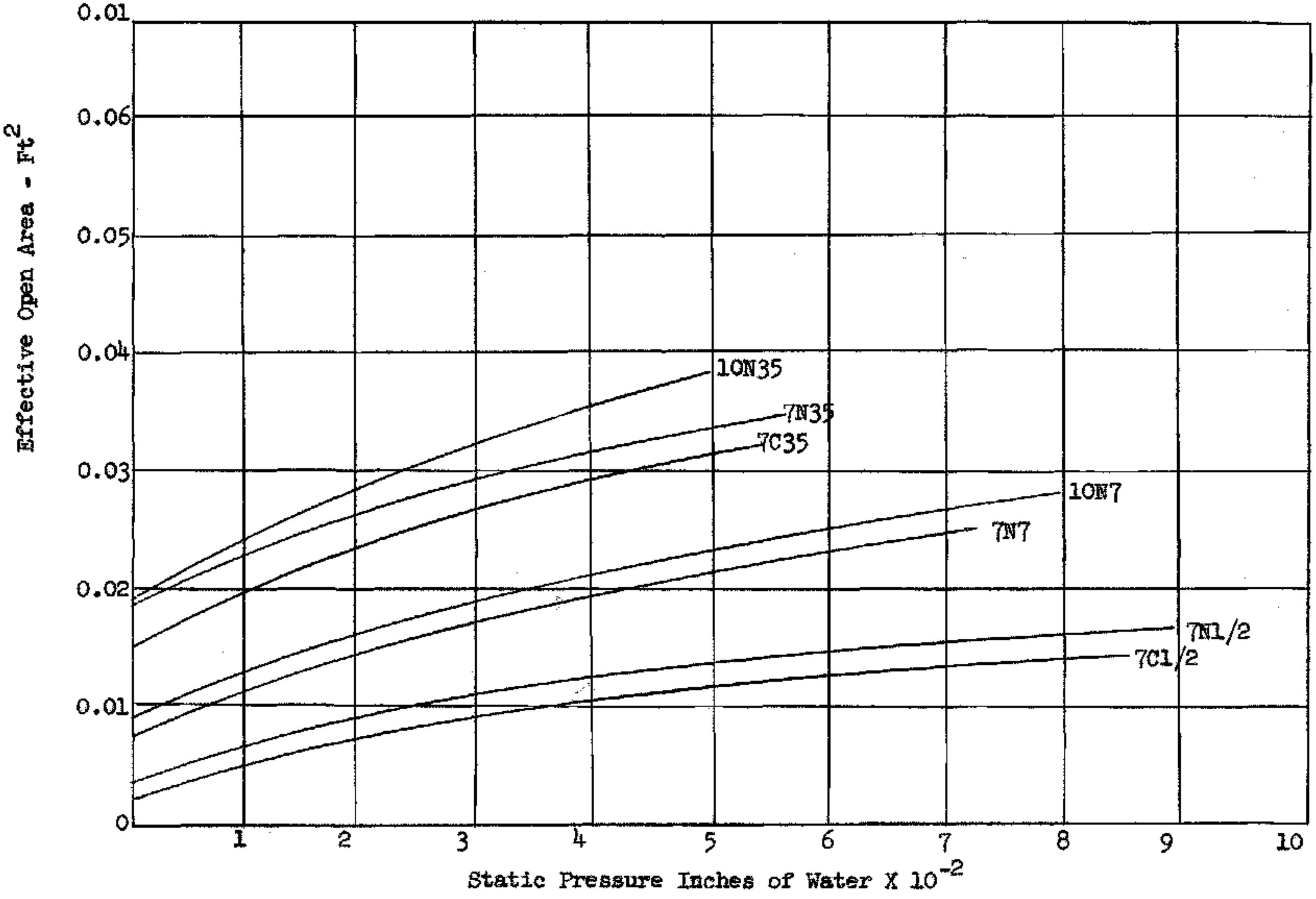

Figure 2. Total Effective Open Area Versus Differential Pressure

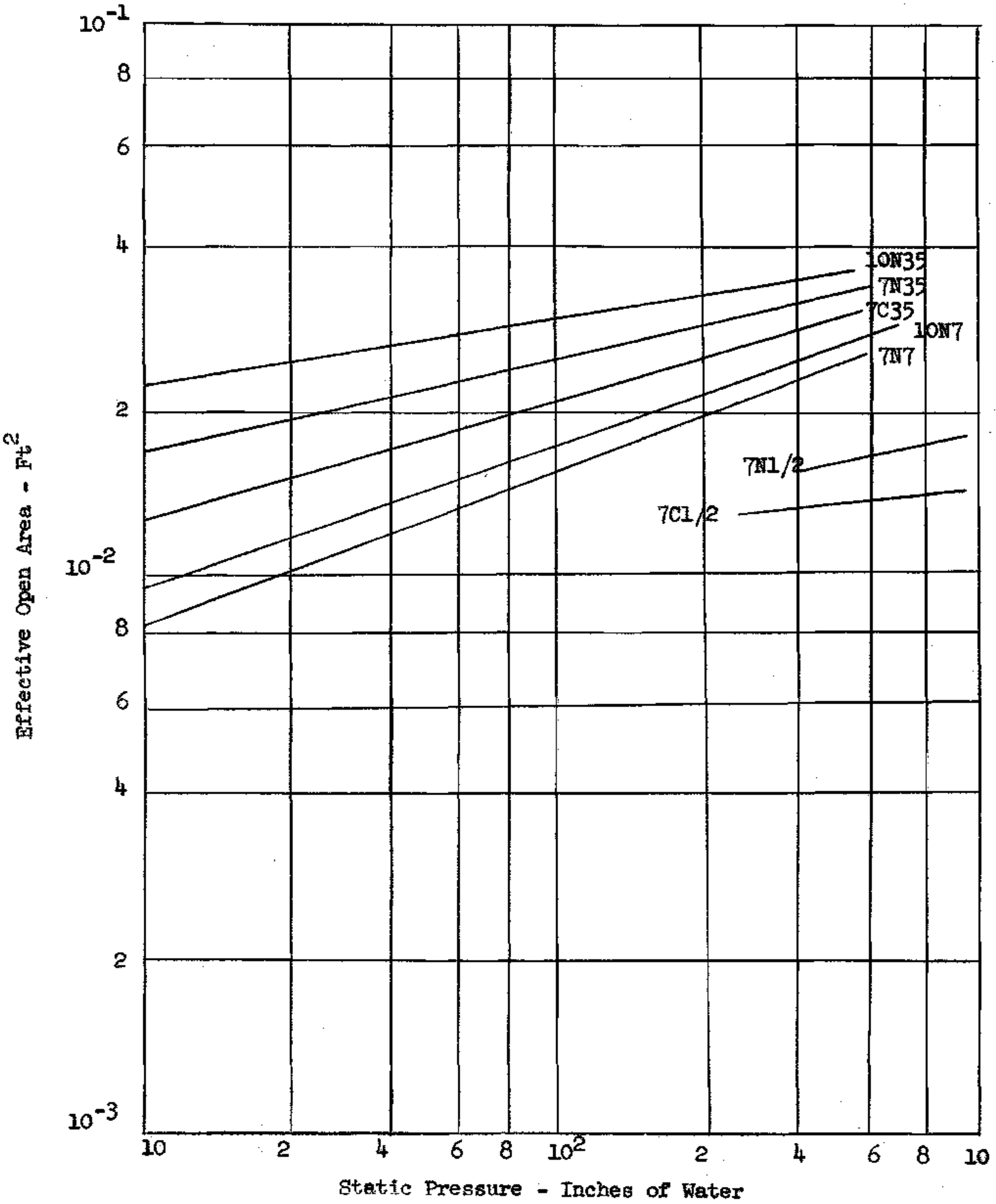

Figure 3. Total Effective Open Area Versus Differential Pressure

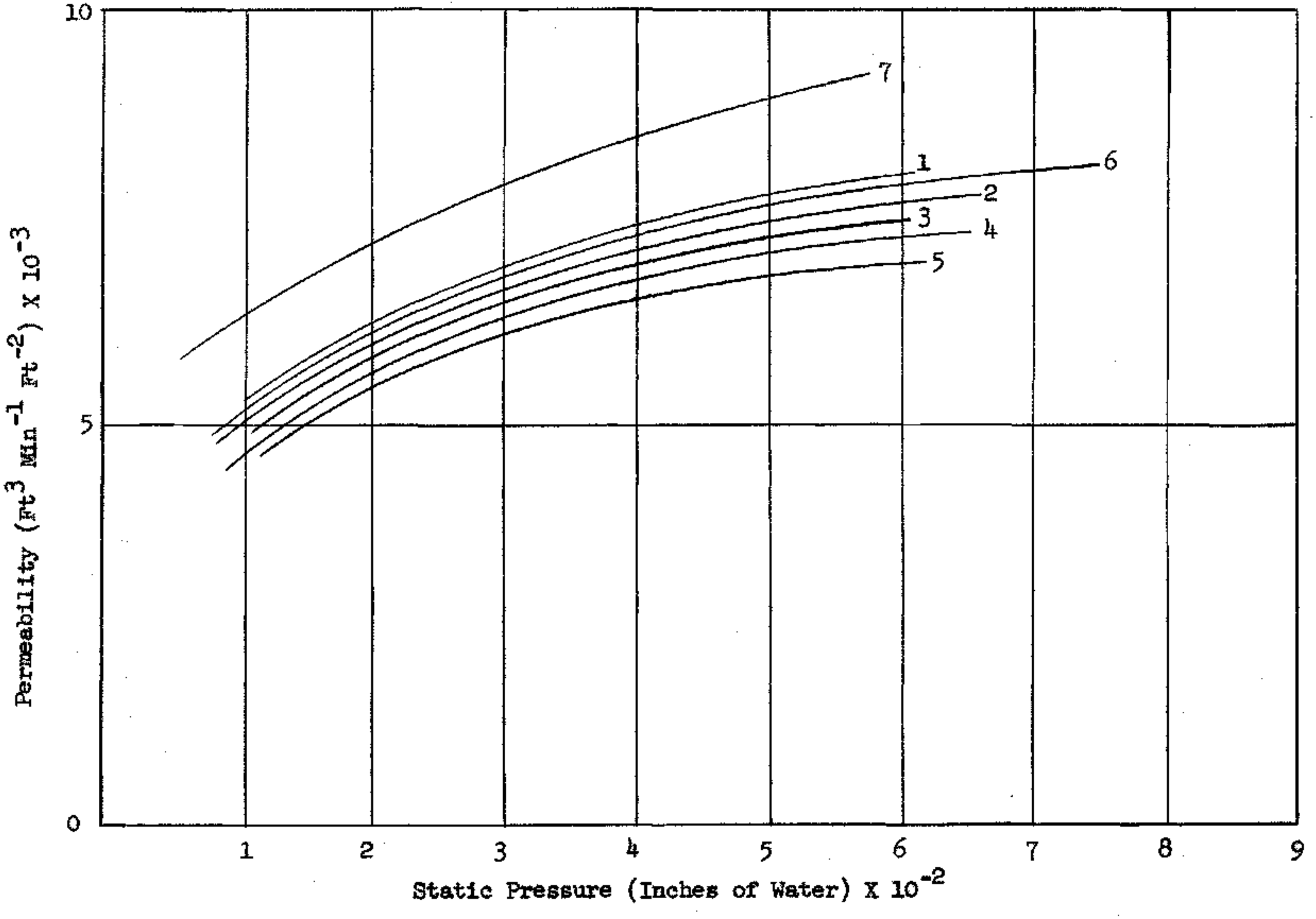

Figure 4. Permeability Versus Differential Pressure

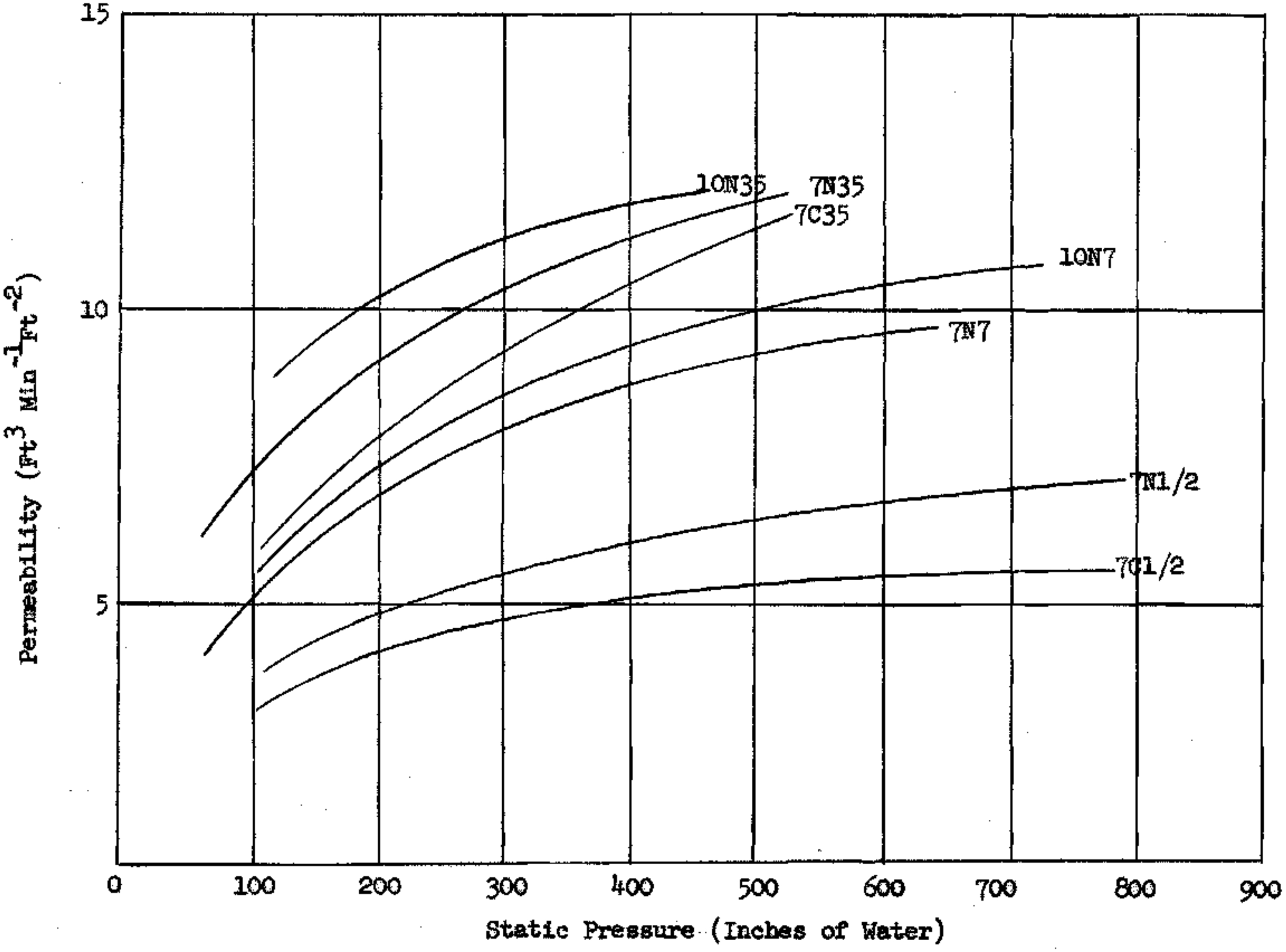

Figure 5. Permeability Versus Differential Pressure

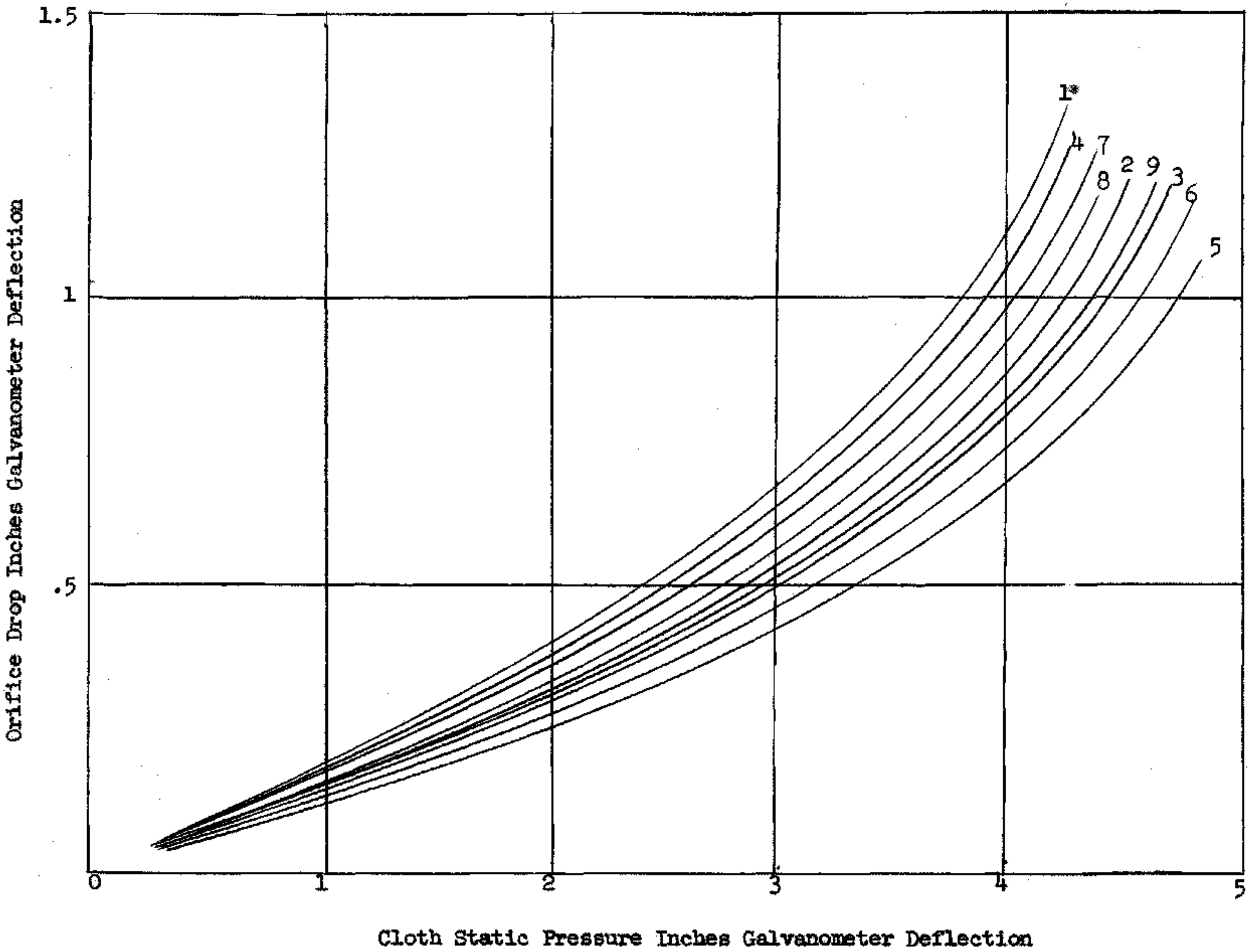

Figure 6. Orifice Differential Pressure Versus Fabric Differential Pressure

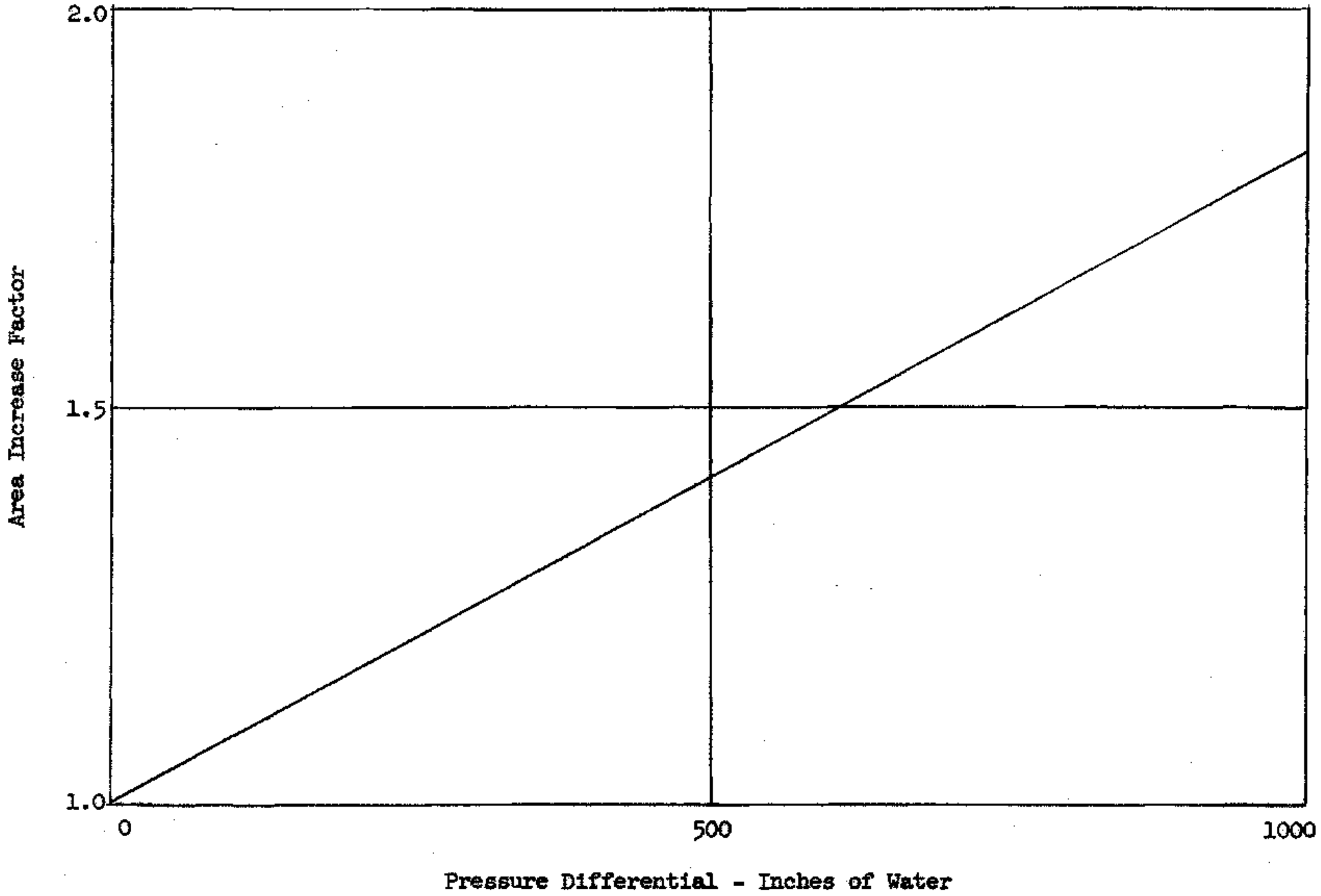

Figure 7. Area Increase Factor Versus Pressure Differential

APPENDIX B

SAMPLE CALCULATIONS

Item No.		Dimensions
1.	Barometer (Data)	in. Hg.
2.	Barometer (0.491 x item 1)	lb_f in^{-2}
3.	Cloth Static Pressure (Data)	psig
4.	Cloth Static Pressure (item 2 + item 3)	psia
5.	Cloth Static Pressure (item 3 x 27.7)	in. W.G.
6.	Temperature, T, (Data)	°F abs.
7.	2.70 ÷ T, (From Curve)	
8.	Air Density at cloth, ρ_c, (item 4 x item 7)	lb_m ft^{-3}
9.	Upstream Static Pressure, P_1, (Data)	psig
10.	Upstream Static Pressure, P_1, (Item 9 + Item 2)	psia
11.	Upstream Density, ρ_1, (Item 10 x Item 7)	lb_m ft^{-3}
12.	Orifice Pressure Drop, $\nabla P.$, (Data)	psi
13.	$\nabla P_o \times \rho_1$ (Item 12 x Item 11)	
14.	$\sqrt{\nabla P_o \times \rho_1}$ (Item 13)$^{1/2}$	
15.	Estimated flow, ω_e, $\beta = 0.60$ (2.03 x Item 14)	lb_m ft^{-3}
16.	$\frac{C}{\mu}$ (From Curve), C = 9335, μ = viscosity in C.P.	
17.	Reynolds number at orifice, (Item 16 x Item 15)	
18.	Corrected Orifice Coefficient, K_c, (From Curve)	
19.	kP_1, (1.4 x Item 18)	
20.	$\nabla P_o/kP_1$, (Item 12 ÷ Item 19)	
21.	Expansion Factor, Y_1, (From Curve)	

Figure 8. Master Data and Result Sheet

Item No.	Dimensions
22. $Y_1 \times W_e$ (Item 21 x Item 15)	
23. K_c/K (Item 18 ÷ 0.650)	
24. Corrected Flow, W_c, (Item 22 x Item 23)	$lb_m\ ft^{-3}$
25. Mass Velocity of Cloth, G, (9.00 x Item 24)	$lb_m sec^{-1} ft^{-2}$
26. $\sqrt{\rho_c}$, $(\text{Item } 8)^{1/2}$	
27. 219 x G (219 x Item 25)	
28. Permeability, $G/\sqrt{\rho_s \rho_c}$ (Item 27 ÷ Item 26)	$scfm.ft^{-2}$
29. Area Increase Factor, I, (From Curve)	
30. Permeability, based on corrected area, (Item 28 ÷ Item 29)	

Figure 8 (cont'd). Master Data and Result Sheet

NOMENCLATURE

Symbol	Quantity	Dimensions
A	Area	ft^2
C_f	Flow-Through-Drag-Coefficient	Nondimensional
C	Constant	Nondimensional
c	Sonic Velocity	ft/sec
G	Mass Velocity	$lb/sec\text{-}ft^2$
g_c	Dimensional Constant	$32.2\ (lb_m ft/lb_f sec^2)$
I	Area Increase Factor	Nondimensional
k	Ratio of Specific Heats	Nondimensional
L	Length	ft
M	Mach Number	Nondimensional
n	Constant	Nondimensional
P,p	Pressure	lb_f/ft^2
R	Gas Constant	$ft\ lb_f/lb_m\ °F$
Re	Reynold's Number	Nondimensional
T	Temperature	F Absolute
V,v	Velocity	ft/sec
W	Weight Rate of Flow	lb/sec
α	Viscous Coefficient	$1/ft^2$
β	Inertial Coefficient	1/ft.
μ	Viscosity	$lb_m/ft\text{-}hr$
ρ	Density	lb_m/ft^3

NOMENCLATURE (Cont'd)

Subscripts

1 -- Upstream of Cloth

2 -- Downstream of Cloth

0 -- Stagnation Conditions

Superscripts

* -- Conditions where $M = 1$