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AIR PERMEABILITY OF PARACHUTE CLOTHS

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WRIGHT AIR DEVELOPMENT CENTER

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AIR PERMEABILITY OF PARACHUTE CLOTHS

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State Engineering Experiment Station
Georgia Institute of Technology

November 1952

Materials Laboratory
Contract No. AF 33(038)-15624
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Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by the State Engineering Experiment Station of the Georgia Institute of Technology under Contract Number AF 33(038)-15624 and Research and Development Order No. 612-12, "Textiles for High Speed Parachutes." It was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. W. A. Corry and Mr. J. H. Ross acting as project engineers. This report is one of a series to be issued on this project.

Mr. H. W. S. LaVier, Research Associate Professor in the State Engineering Experiment Station of the Georgia Institute of Technology, and Professors J. L. Taylor and G. B. Fletcher of the Georgia Institute of Technology participated extensively in the study. Dr. J. J. Moder's assistance in the formulation of the statistical analysis is gratefully acknowledged.

ABSTRACT

The air permeability of eight standard nylon parachute cloths was determined using a sample 6.05 inches in diameter in a wind tunnel whose capacity permitted obtaining static pressure differentials across the cloth as high as 55 inches of water. Fifty-nine experimental nylon cloths manufactured by the Bally Ribbon Mills were subjected to the same test procedure, as were two experimental fabrics of orlon and dacron, respectively.

Upon assuming that the pressure gradient in the flow through a parachute fabric is proportional to the arithmetic sum of an inertial ($\beta\rho v^2$) and the viscous contribution ($\alpha\mu v$), one is able to infer the existence of a parameter, β/α, whose measure is length. This length can be employed to characterize the geometry of the cloth. Experimental work to date in the case of the eight standard cloths and the orlon and dacron fabrics has indicated a verification of the assumption; a high-pressure tunnel employing pressure differentials across the cloth approximating ten pounds per square inch was used for this purpose.

Employing the characteristic length so determined permits writing a single relation common to all cloths between a "flow-through-drag coefficient," C_f, and a Reynolds number based on the characteristic length; viz., $C_f = 2 + \frac{2}{N_{Re}}$.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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I. NOMENCLATURE*

Symbol	Quantity	Dimensions**
A	Area	L^2
C_f	Flow-Through-Drag Coefficient	Nondimensional
d	Dimensional Constant	12^4, (in $ft^{-1})^4$
G	Mass Velocity	$MT^{-1}L^{-2}$
g_o	Dimensional Constant	32.2, (lbm ft $lb_f^{-1} sec^{-2}$)
K	Orifice Coefficient	Nondimensional
L	Cloth Thickness	L
$\dot{m}$	Mass Flow	MT^{-1}
N_{Re}	Reynolds Number	Nondimensional
P,p	Pressure	FL^{-2}
R	Gas Constant	$FLM^{-1}\Theta^{-1}$
T	Temperature	Θ
V,v	Velocity	LT^{-1}
$\bar{x}$	Average Value of a Quantity	
α	Viscous Coefficient	L^{-2}
β	Inertial Coefficient	L^{-1}
α'	(See note in Table IV.)	
β'	(See note in Table IV.)	
μ	Viscosity	$ML^{-1}T^{-1}$
ρ	Density	ML^{-3}
σ	"Standard" Deviation from True Value	

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*Symbols used on Master Data and Result Sheet (Figure 13) are defined there.

**The force, F, mass, M, length, L, time, T, temperature, Θ, system is used. Units of quantities employed are indicated in illustrative instances of calculations, e.g., on Master Data and Result Sheet.

Subscripts

1--Upstream of Cloth Sample

2--Downstream of Cloth Sample

II. INTRODUCTION

A. Statement of the Problem

The study reported herein was an outgrowth of a Wright Air Development Center project established at the State Engineering Experiment Station of the Georgia Institute of Technology. It was concerned with the determination of the air permeability of nylon-type fabrics used in the manufacture of parachutes. The scope of the project included the experimental determination of the air flow through samples of the various fabrics under conditions of pressure differentials across the cloth up to 50 inches of water.

In order to permit the presentation of results in a general, non-dimensional manner, a characterization by means of a length parameter of the geometry of the fabric is required. A search of the literature indicated that little consideration (1,22) had been given to the characterization of fabrics from a point of view of the mechanism of air flow through them. Accordingly, an attempt was made, in the case of air flow through parachute fabric, to apply analysis similar to that employed in dealing with flow through porous media (2). A portion of this report deals, then, with the analysis and technique employed in the determination of the characteristic length for ten parachute cloths.

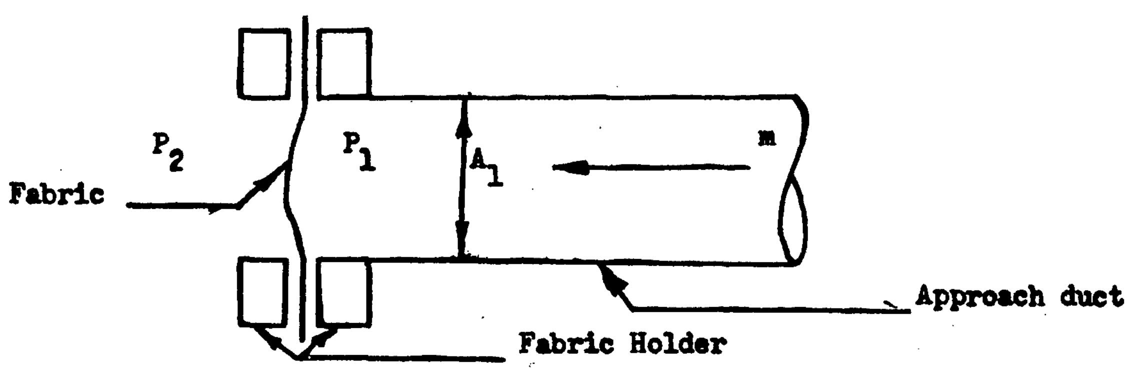
B. Definition of Terms

The literature indicates a lack of uniformity in the use of definitions concerned with permeability and porosity. For the sake of clarity the following terms are defined at this point and a comparison is given later (Appendix II) between their usage here and elsewhere.

Permeability: the time rate of mass flow of air per unit projected area of cloth.

Relative Porosity: arbitrarily defined as the ratio of the velocity of the air upstream of the cloth to the theoretical velocity attainable because of the pressure drop impressed across the cloth.

The illustrative sketch below and the symbols employed serve to implement these definitions. Subscripts 1 and 2 in the sketch indicate, respectively, the flow conditions upstream and downstream relative to the fabric.



$$\text{Permeability} = \frac{m}{A_1} = \frac{\rho_1 V_1 A_1}{A_1} = \rho_1 V_1 = G_1, \ \frac{\text{lbm}}{\text{sec ft}^2}$$

$$\text{Relative Porosity} = \frac{V_1}{\sqrt{2\,\frac{P_1 - P_2}{\rho_1}}} \quad \text{(dimensionless)}$$

In a more general sense, porosity would be measurable as the fraction representing void space within the volume of porous fabric under consideration; relative porosity is employed here as an index of porosity.

In the course of discussion this report will make reference to 10 WADC fabrics in contradistinction to the 59 Bally Ribbon cloths. The former are identified in Tables VIII and IX and the latter in Table X.

The WADC cloths will be referred to as fabrics numbered 1 through 10 and the Bally Ribbon cloths as fabrics BR-1, BR-2, etc.

Further reference will be made to a low-pressure tunnel and a high-pressure tunnel; all cloths were subjected to tests in the low-pressure tunnel, but only the 10 WADC cloths were tested in the high-pressure tunnel. Both tunnels are described completely in **Section IV, Apparatus.**

III. LITERATURE SURVEY

An extensive bibliography, including abstracts dealing with various phases of parachute design and performance as effected by permeability, is included as Appendix I. The following discussion is concerned with certain aspects of these references and their relation to the problem at hand.

A. Application of Permeability Data to Parachute Design

1. Increased Precision

Present-day military and civilian operations employing parachutes require a higher degree of precision than was possible in the past. In order to meet this demand in precision bombing and in dropping supplies or parachute troops, and to make parachuting safe for untrained passengers in general, accurate knowledge of the air permeability characteristics of the parachute fabric becomes necessary. The length of time for the opening of a parachute depends largely upon the rate at which the canopy permits air to pass through it. This knowledge, coupled with information on cross currents and initial velocity, allows a more exact prediction of the location of the chute and its cargo at any time after dropping. The effect of the least accurately known variables, the directions and velocities of cross currents, is directly dependent on the time of descent and, thus, on permeability.

2. Reduced Shock on Opening

At the instant that a parachute opens, the pressure developed under the canopy is quite high, and the shock is likewise high. It has been shown that this shock can be minimized by use of a panel of a highly permeable fabric around the central canopy vent (31). A strip of low-porosity fabric around the hem line has been recommended as beneficial to good opening characteristics (46).

3. Stable Opening

The spontaneous partial collapse of a parachute during descent, termed squidding, occurs when a certain critical velocity of descent is reached. This critical velocity is increased by the use of less permeable or porous canopies. (32,41,43,45,47)

4. Safe Loading

The maximum load which a canopy will support safely depends on the opening characteristics and on the drag during the uniform descent period. Both of these depend upon canopy permeability. (32,36)

5. Stable Uniform Descent

Parachutes of certain designs tend to pendulate and are dynamically unstable, even in uniform descent. This swinging and oscillating can be reduced by the use of high-permeability fabrics. (43,46)

B. Air Permeability of Parachute Fabrics

1. Approach to the Problem Previous to This Investigation

The first recorded air permeability data for fabrics appears to be that of Rubner in 1907 (26). Interest in the air permeability of fabrics for use in parachutes dates back to the World War I need for efficient chutes in large numbers. Permeability of cloth in general had been, and still is, of interest to the clothing manufacturer and to the lighter-than-air ship fabricator as well. Many machines and methods

(3,8,10,11,19,26,29,59), most of them as simplified as possible, were devised by weavers for measuring the tendency of a cloth to permit the passage of air or other gases. The calibration (9) and the interrelationship of readings from different machines (7) are carefully described in the literature. Most of these measuring devices utilize vacuum pumps to draw atmospheric air through the fabric at a low pressure drop across the cloth (about ten inches, or less, of water). To facilitate the measurement, the instrument is usually mounted downstream from the loom and the measurement made on the uncut cloth between the rolls as it leaves the loom under tension.

While this sort of data may be acceptable to the garment trade, a higher pressure drop and more carefully controlled conditions seemed necessary to the parachute manufacturer. (1,15,18,30,31,34,49,55,56)

2. Industrial Testing

Air permeability, defined as the volume of air which will flow through a unit area of a cloth under a given pressure head,* has been considered to be, principally, a function of the type and looseness of the weave and the yarn twist and diameter. It may also vary with texture, the amount of carding, extent of felting, etc. (6,14,19,25,27) The theory was advanced that fabric could be considered as a multiplicity of orifices (3,5,22,23,29), and emphasis was placed on the geometry of the cloth and its yarns (14,20,51,60). Presuming absolute uniformity of pore size, the theory of models was used to make data on the flow of a liquid through an idealized pore applicable to air flow through fabric. Other

- - - -

*This is a definition of air permeability employed by many; the air volume is measured at a prescribed temperature, pressure and relative humidity. Normally the pressure drop impressed across the cloth is 0.5 inch of water. An illustration of the conversion of data reported herein to this definition is given in sample calculations in Appendix II.

investigators theorized that fabrics are not uniform enough to allow only geometrical considerations in establishing orifice dimensions (4). Photomicrographic studies discussed in this report clearly indicate the random variation in the size and shape of pores.

3. Statistical Variation

The fact that randomness in pore dimensions is of such a nature that an average value of either porosity or permeability is not obtained from one sample from one piece of cloth is attested to by a report on the statistical variation in permeability from one location to another in one piece of cloth (16,17). This statistical variation, determined for several of the weaves employed on this project, is of such magnitude as to render any single permeability determination doubtful to the extent of plus or minus 15 per cent.

4. Geometric Concept and Theory of Models

The geometrical analogy used by some investigators assumes perfect symmetry, whereas it is almost universal practice in textiles to use yarns of different denier and twist in the warp and weft. A more logical approach appears to follow the theory of flow through porous media (2) where, obviously, the dimensions of the individual pores and cavities are unknown, and yet a characterization of geometry is required. Hoerner (1) has indicated that fabric permeability data are correlated by a method similar to Green's (2).

5. Cloth Deformation

This project has given some consideration to the deformation of the cloth matrix under the stress of applied pressure. Results indicate a greater cloth porosity with increased flow through the cloth and an attendant increase in pressure drop across the fabric.

6. Necessity for Aerodynamic Interpretation

It would seem necessary to conclude that the determination of the statistical variation of permeability in a fabric must precede interpretations of permeability data, and that aerodynamic, rather than geometrical, considerations must be followed in establishing the basis for prediction of flow properties of a cloth.

C. Methods and Apparatus for Air Permeability Determination

Three methods in general use for measuring the ability of a fabric to allow passage of air are (26): (1) measurement of the time required for the passage of a given volume of air through a given area of cloth, (2) measurement of the pressure differential required for passage of air at a given constant volume rate through a given area of cloth and (3) measurement of the volume rate of flow of air through a given area under a given pressure differential.

Of the commercially available instruments, the Densometer represents the first method; the Fabric Porosity Machine, the second method; and the third method, which is the one most generally employed in this country in the field of textiles, is followed by the Frazier, the Saxl and the Permeameter instruments.

1. Densometer (Gurley)

The Gurley Densometer consists of two self-aligning, coaxial, circular metal discs which have standard-sized (1.0 or 0.1 square inch) circular orifices at their centers. The cloth sample whose permeability is to be measured is clamped between these orifices. A capstan screw clamping device permits quick and efficient securing of the sample so that no leakage occurs along the face of either disc. The upper disc serves as the bottom of a vertical cylinder, 3-1/2 inches in diameter and 9-1/2 inches high, into which telescopes another cylinder closed at the top. This upper cylinder weighs 5.0 ounces, and its walls telescope into an oil-filled annulus which serves as a seal between the free-floating and the stationary cylinders. The air pressure exerted at the orifice at the bottom of the cylinder by the floating cylinder is equal to 1.22 inches of water, and, by noting the relative elevations of the floating cylinder before and after its descent, the amount of air expelled through the orifice is measured.

Permeability readings are expressed in terms of the time required for the passage of 300 cc of air through the standard orifice area under the constant head of 1.22 inches of water.

2. Fabric Porosity Machine

The Albany Felt Company holds a patent on what they call a "Fabric Porosity Machine" in which a low-pressure blower drives air through a small measuring orifice and then through the test fabric, which is held in pneumatic-powered jaws. The back pressure behind the cloth at a given flow rate is termed a "fair measure of the porosity of the goods to air flow." (29)

3. Saxl Apparatus

The Saxl Instrument Company produces a machine called the "New Porosity Tester" which consists of a blower to force air through the fabric into a rotameter to measure the rate of flow directly (29).

4. Bureau of Standards (Frazier) Apparatus

In the Frazier machine the cloth sample is held by a clamp horizontally over an orifice at the top of one of two airtight chambers, an upper and a lower chamber. Air is drawn through the sample into the upper chamber, through a standard measuring orifice into the lower chamber, and through a suction fan out into the atmosphere. Baffles just above the fan intake prevent the formation of a vortex at that point.

Pressure measurements by means of manometers in the upper and lower chambers permit a calculation of the rate of flow, and the results are expressed in cubic feet/min. of air at a prescribed temperature, pressure and humidity passing through a given area of cloth under a standard pressure head of 0.5 inch of water.

It has been shown on the basis of extensive data on many types of weaves that the results of the Frazier instrument and the Gurley densometer can be correlated. The relationship obtained was Frazier $= \frac{507.5}{\text{Gurley}}$. (7)

5. Permeameter (Gurley)

The principle of the Permeameter (29) is comparable to that of the electrical Wheatstone bridge in that pressures are balanced to give an accurate determination of permeability. The apparatus consists of two airtight chambers and a suction fan. Air is drawn through a fixed orifice into the first chamber and out through another fixed orifice, thus maintaining a fixed pressure in this chamber. The same fan draws air into the second chamber through a calibrated micrometer valve of the plug and orifice type. A tube connects each chamber to a variometer, and the pressures are adjusted to the same value by the proper setting of the micrometer valve. This setting indicates the air permeability when the instrument is properly calibrated against standard orifice plates. Air leakage between the fabric and the clamping rings is prevented by maintaining the same vacuum in an annular groove around the sample as that on the sample.

6. Other Types of Testing Machines

A practical apparatus, used in Britain and described in Engineering (London) in 1939, consists simply of a tube of standard cross section over the end of which the sample is held by rubber bands. Air is drawn through the cloth by a suction pump and the pressure drop required to cause a flow of air of one cubic foot per minute is measured and termed the "porosity," contrary to the usage of that term in this country to designate the percentage of void space in the volume occupied by a porous media.

The Apermeter developed at Lowell Textile Institute utilizes a hydrostatic head, developed by adjusting the elevation of a "leveling bottle" containing water, to draw atmospheric air through a cloth sample. No provision is made for maintaining a constant pressure differential across the fabric. The developers of the Apermeter have redefined air permeability as the ratio of the times required for a given volume of flow with and without a cloth sample over the inlet orifice.

An instrument for the measurement of air permeability of blankets was designed by Sale and Hedrich; in this the material is stretched across the top of a cylinder at a tension of one per cent of its breading load. Air drawn through the sample by an aspirator bottle arrangement is measured by a wet-gas meter, and the pressure drop, by a micromanometer.

IV. APPARATUS

A. Introduction

Two wind tunnels were employed during this investigation; one will be referred to as the low-pressure tunnel (0-55 inches of water) and the other as the high-pressure tunnel (0-15 pounds per square inch).

B. Low-Pressure Tunnel

The fabric sample, cut approximately as a circle at least nine inches in diameter, was clamped between two flanges of the sample holder. In turn, the sample holder was mounted in a vertical plane on the end of the wind tunnel (which is horizontal). A circle of fabric 0.2 square feet in area was exposed to a flow of air from the end of the tunnel; the downstream face of the cloth was subjected to atmospheric pressure at all times.

1. Fan

Air drawn from within the Research Building was blown into the upstream end of the tunnel through a Buffalo Forge Centrifugal Blower, Model 35-1CB, with a direct-coupled, constant-speed, 7-1/2 hp motor. A pressure drop as high as 53 inches of water was obtained across the fabric with some of the more dense cloth samples; the pressure drop was measured using vertical glass manometers filled with water. By throttling the fan intake with a conical plug valve, the pressure drop could be varied to any value down to less than one inch of water.

2. Wind Tunnel

The wind tunnel was made up of three sections of 5-3/4 inches in inside diameter plastic tubing totaling 10 feet in length. Temperature measurements were made by mercury thermometers installed at the fan inlet and the tunnel outlet. The rate of flow of air was measured by an appropriately sized orifice installed in the tunnel duct. These were standard sharp-edged orifices designed according to specifications of the ASME Special Research Committee on Fluid Meters (72). In each installation the orifice was preceded and followed by straightening vanes in accordance with the ASME specifications. One-fourth-inch upstream and downstream flange-type pressure taps led to a micromanometer containing alcohol (sp. gr. 0.790) in which the pressure was balanced against the alcohol head in a flexible (rubber) tube. The tube's altitude above the alcohol reservoir level was adjusted by means of a micrometer screw. Since no liquid flowed into or out of the tube or reservoir, no error was introduced by change in reservoir alcohol content.

Photographs of the test setup and instrument board are shown in Figures 1 and 2. A typical orifice installation is shown in Figure 3.

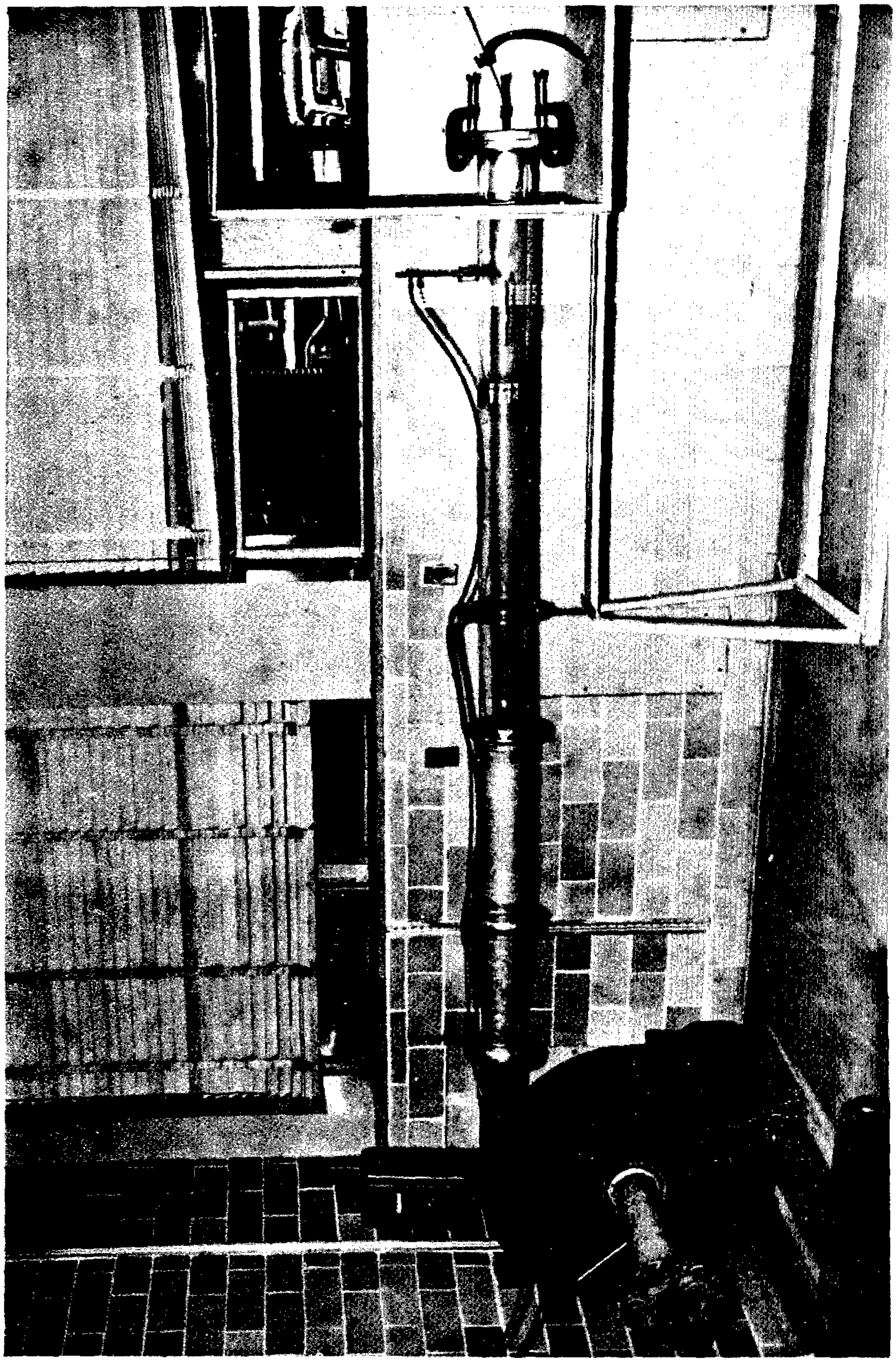


Figure 1. Test Setup.

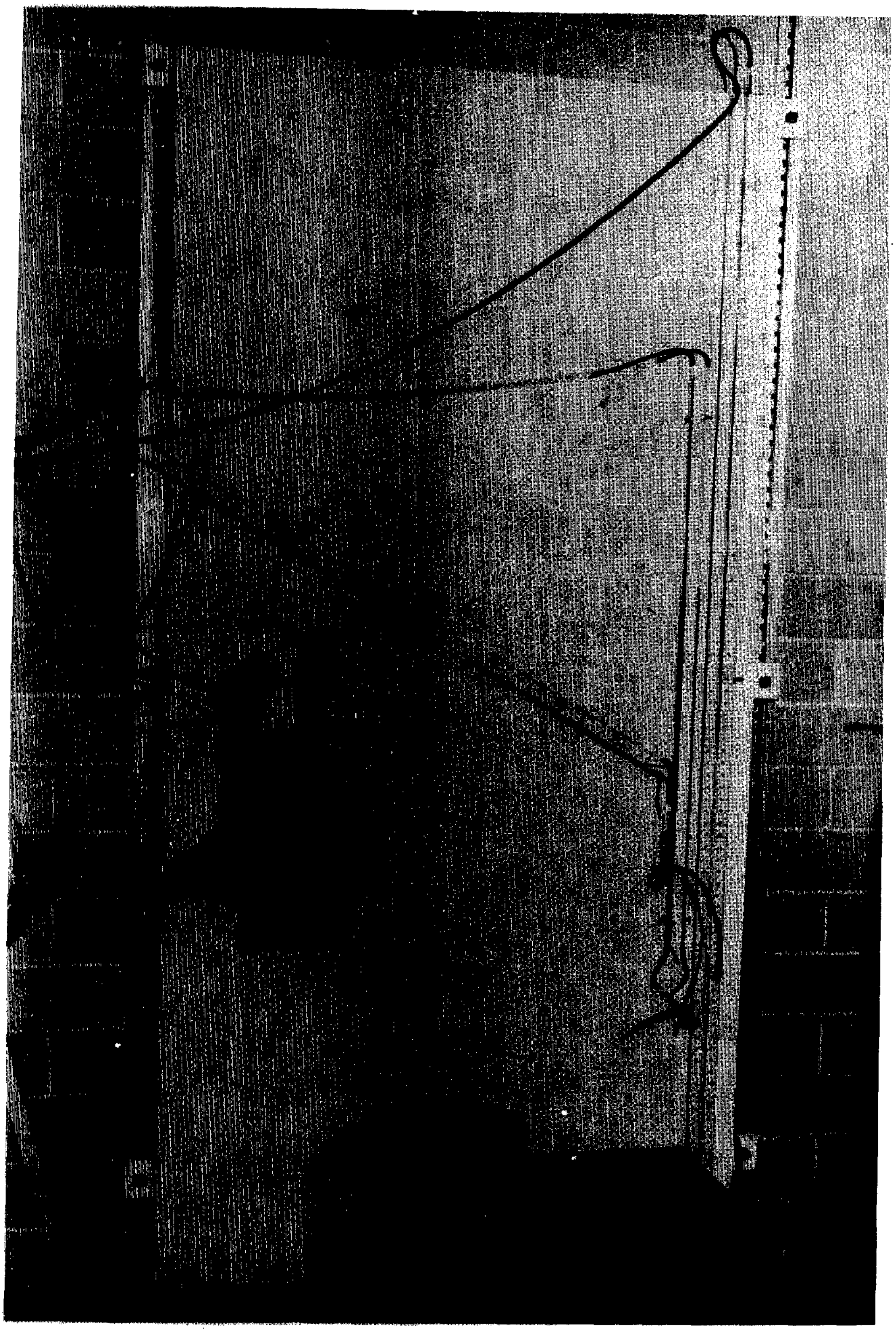


Figure 2. Gauge Board.

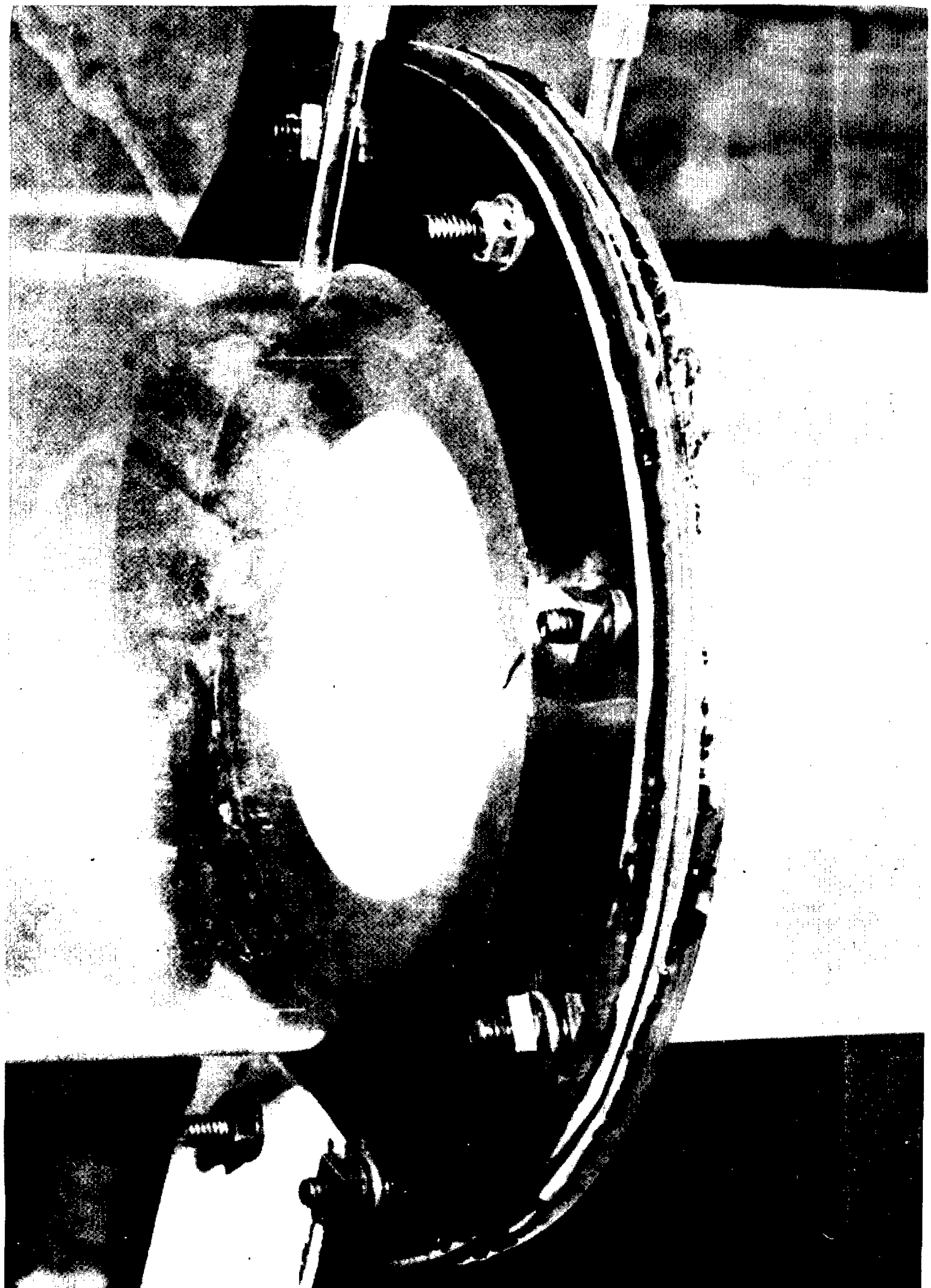


Figure 3. Typical Orifice Installation.

3. Sample Holder

The sample holder, designed for this project, consisted of two round flat flanges of one-inch aluminum, 12 inches in diameter, and is shown in Figures 4, 5 and 6. A hole six inches in diameter was cut in the center of the upstream flange so that the holder fitted over the end of the tunnel tube. A hole 5-3/4 inches in diameter was cut in the center of the downstream flange; thus the actual area of cloth exposed to flow of air was 0.2 square foot. A groove of 1/8 inch radius was provided, forming a concentric circle with the hole in the center. When clamped between the flanges, the fabric is forced into this groove by a ring of 1/4-inch rubber tubing, thus preventing any slippage of fabric when the stress of pressure is applied to it. With the sample thus mounted, the flanges were held together by seven bolts; the whole holder assembly is clamped in place on a flange on the end of the tunnel.

The low-pressure tunnel was employed to determine the air permeability of the parachute fabrics with pressure drop across the cloth not exceeding approximately 55 inches of water. The high-pressure tunnel was required in order to determine the characteristic length for the ten samples.

C. High-Pressure Tunnel

In describing the high-pressure tunnel, reference will be made to Figure 7 which is a photograph of the experimental setup. A service air line (upper right hand portion of photograph) supplies air to the wind tunnel. The air passes in turn through an oil and water strainer, through a spring-loaded pressure-regulating valve, through either or both of two manually controlled pressure-regulating valves, through either of two orifice meter installations, and, finally, through the fabric sample and into the atmosphere. Measurements of the air flow through the cloth

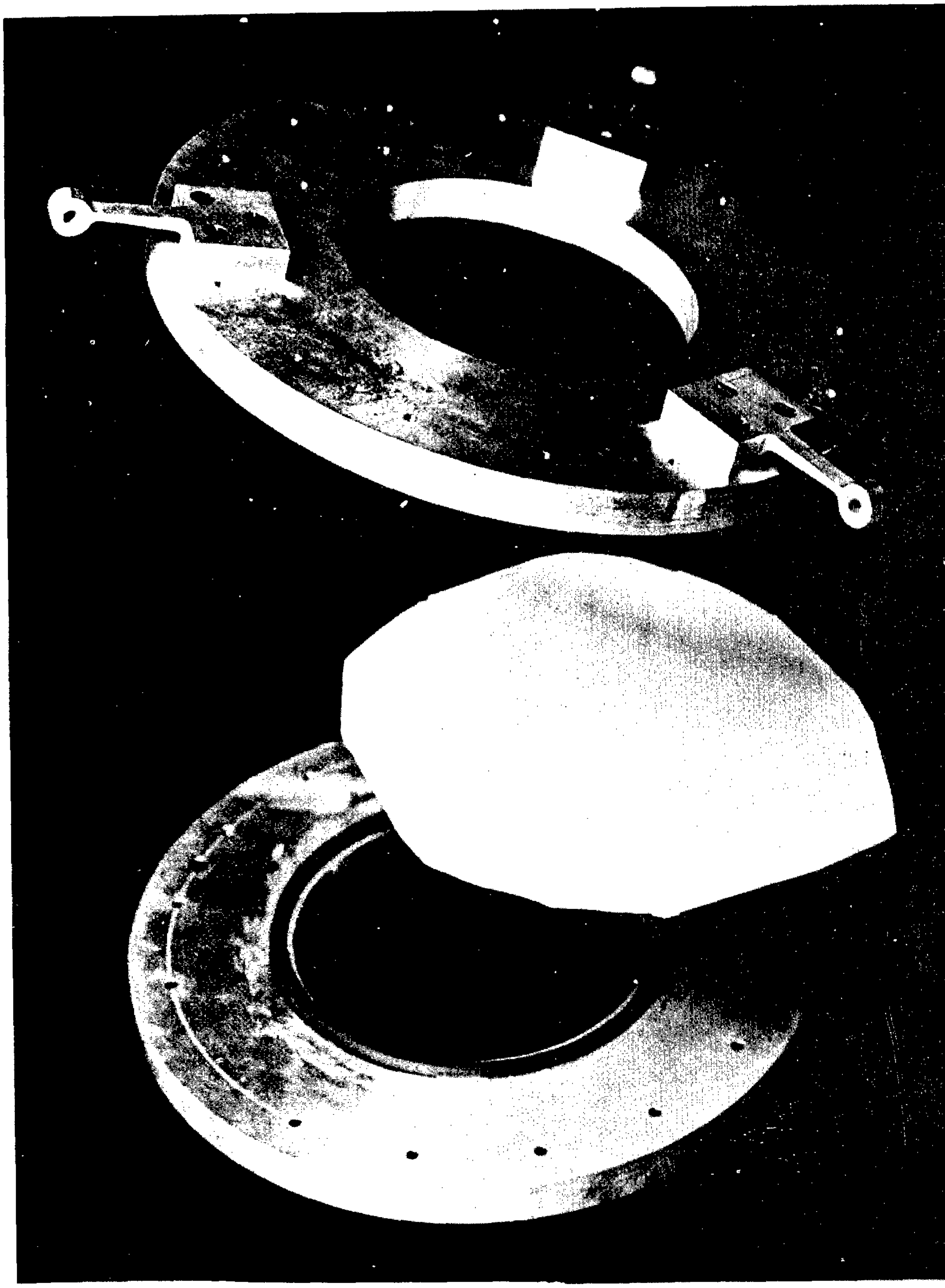


Figure 4. Exploded View of Low-Pressure Sample Holder.

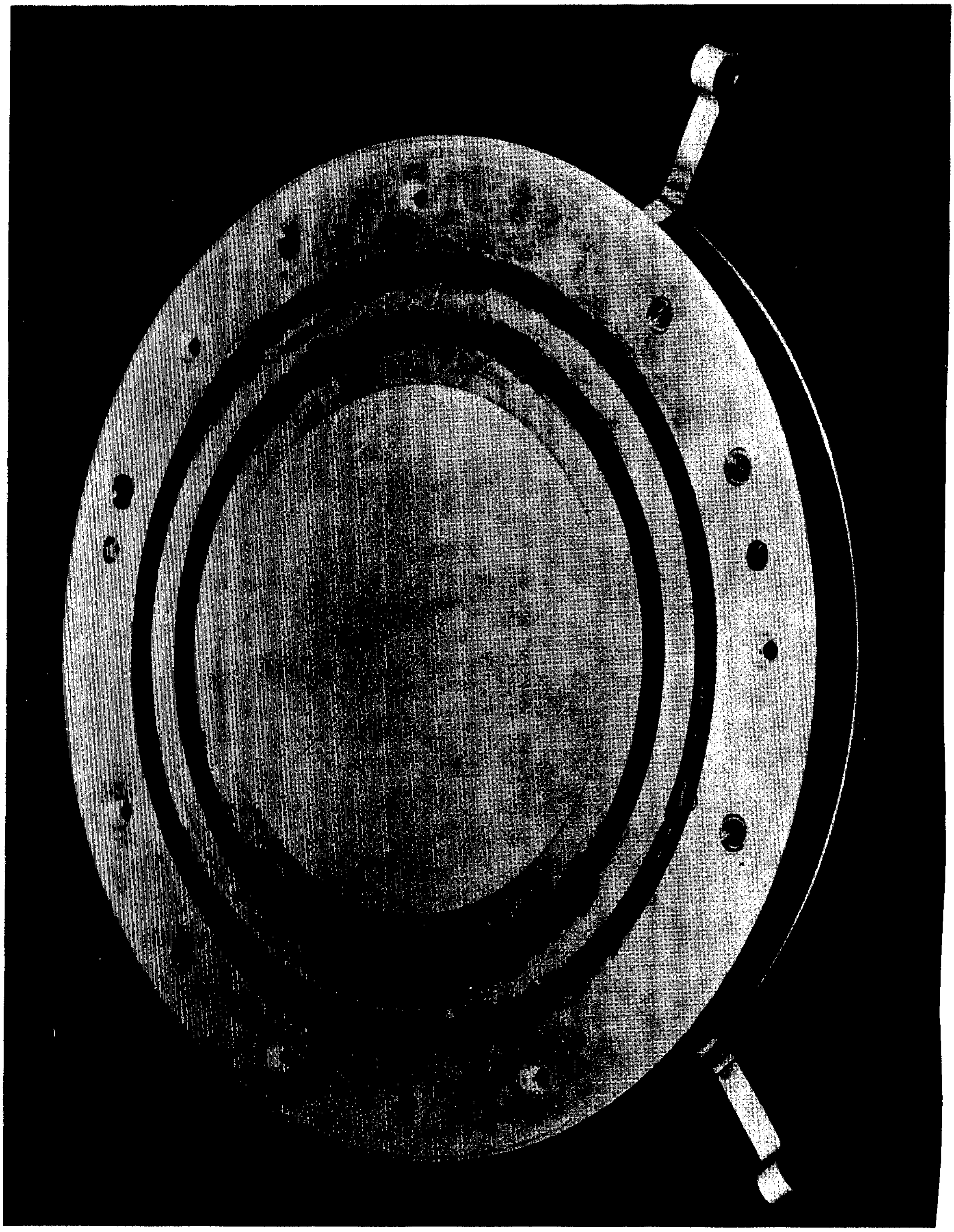


Figure 5. Upstream Face of Sample Holder.

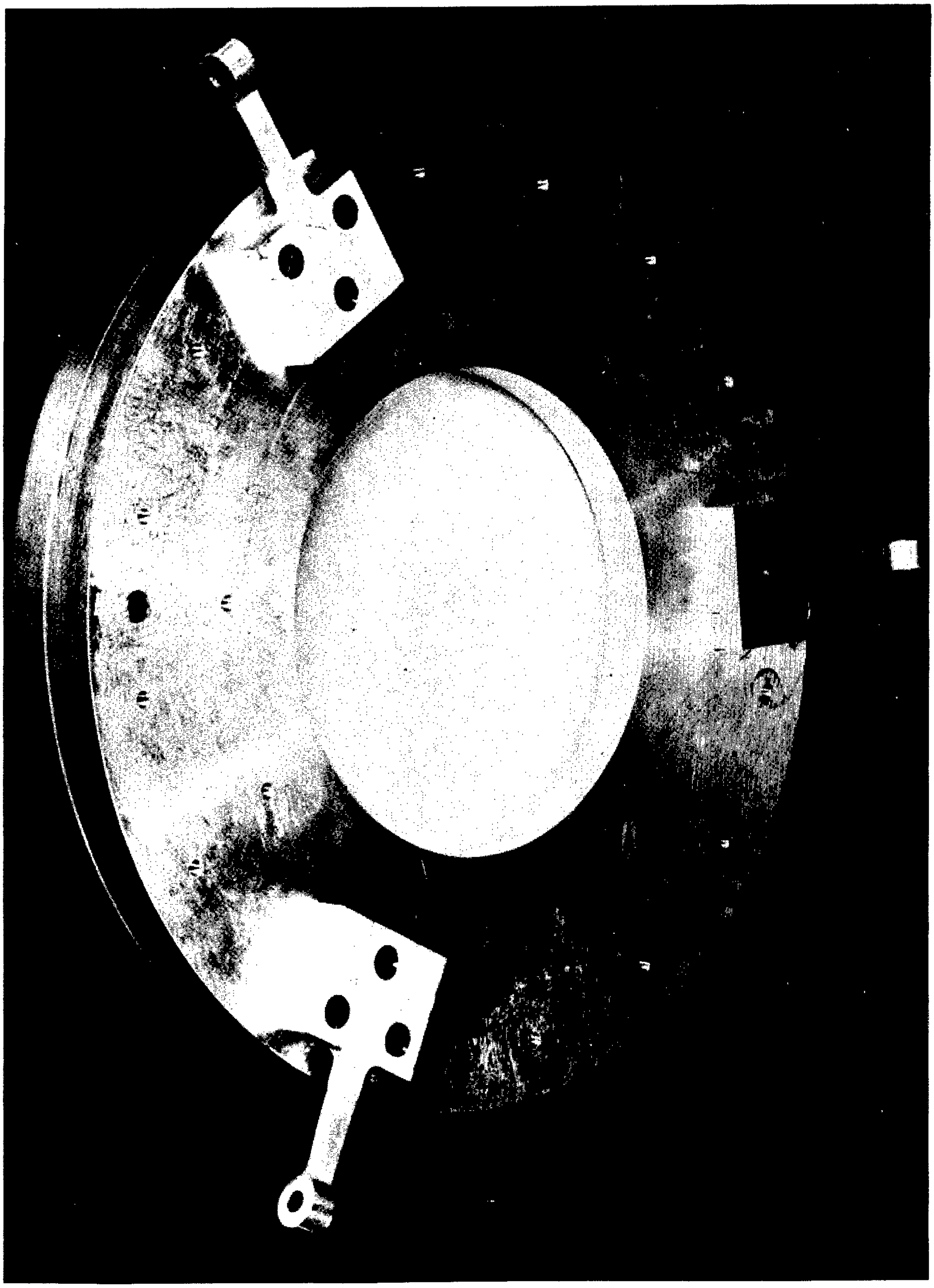


Figure 6. Downstream Face of Sample Holder.

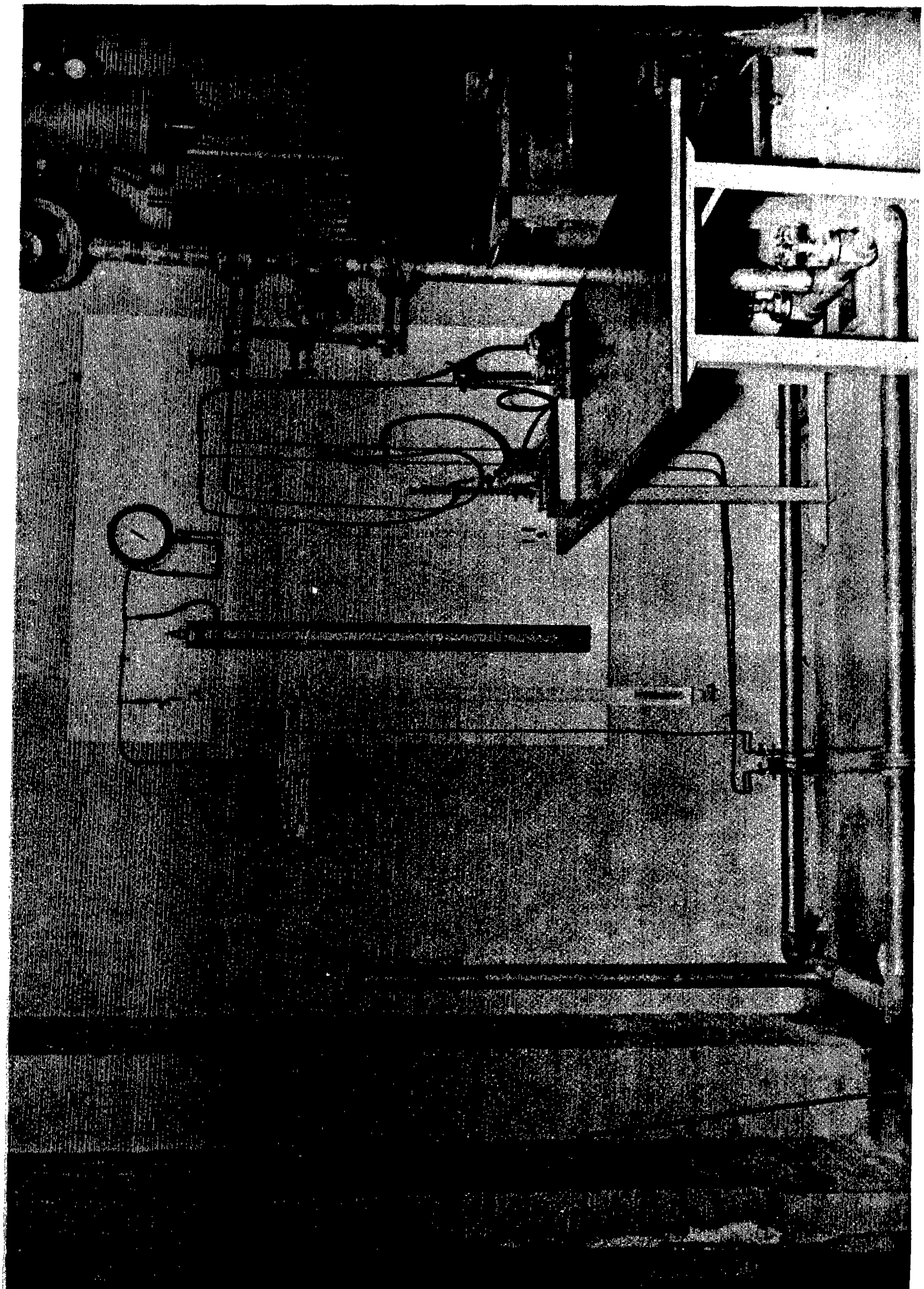


Figure 7. High-Pressure Tunnel.

and of the pressure upstream of the cloth were made with different instruments, depending upon the range of variables involved. Diagrammatic sketches showing design features of the piping and sample holder are included as Figure 8 and Figure 9, respectively. A photograph of the sample holder is Figure 10.

V. TEST PROCEDURE AND METHOD OF HANDLING DATA

A. Selection of Cloth Sample

The position on the cloth yardage from which each sample was cut was selected as dictated by statistical considerations described in Chapter VII of this report, Statistical Analysis. The same procedure for selecting the sample was employed for both the low-pressure and high-pressure wind tunnels.

B. Test Procedure for Low-Pressure Tunnel

1. Sample Mounting Procedure

The sample was cut with a pair of hand shears and laid flat on the face of the upstream flange of the sample holder, which was described in the section on apparatus and is shown in the photograph of Figure 4. A removable circle of plywood placed in the center hole provided a flat stage for the cloth during mounting. A ring of 1/4-inch rubber tubing was laid on the cloth over the groove in the flange face. The downstream flange was carefully placed over the other, allowing the 3/8-inch taper pins attached to it to center the aligning holes in the other flange. The faces of the flanges were then pressed together, and, while in this horizontal position, the two flanges were fastened together with seven bolts which passed through the upper flange and threaded into the lower one.

The fabric was securely held by the pressure of the ring of rubber tubing, and there was no noticeable stress applied to the cloth. The

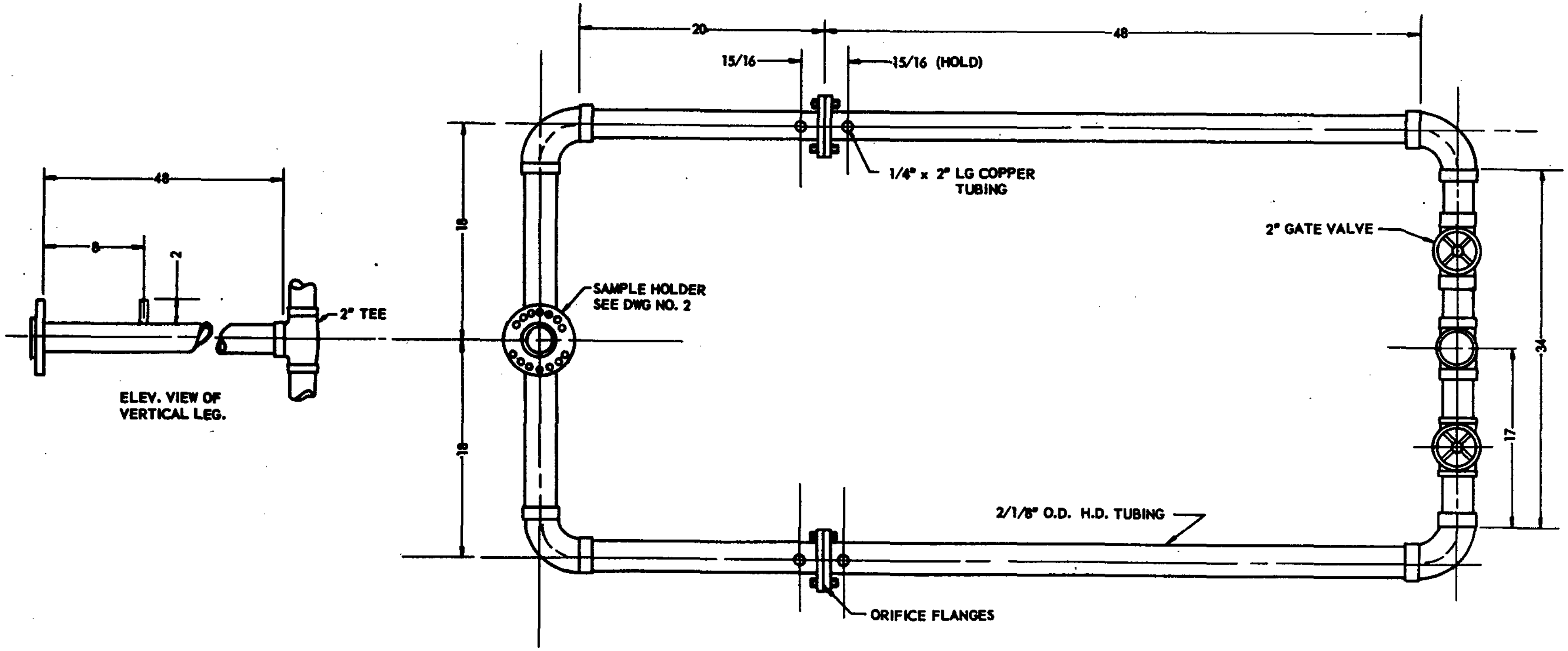


Figure 8. Piping Assembly of High-Pressure Tunnel.

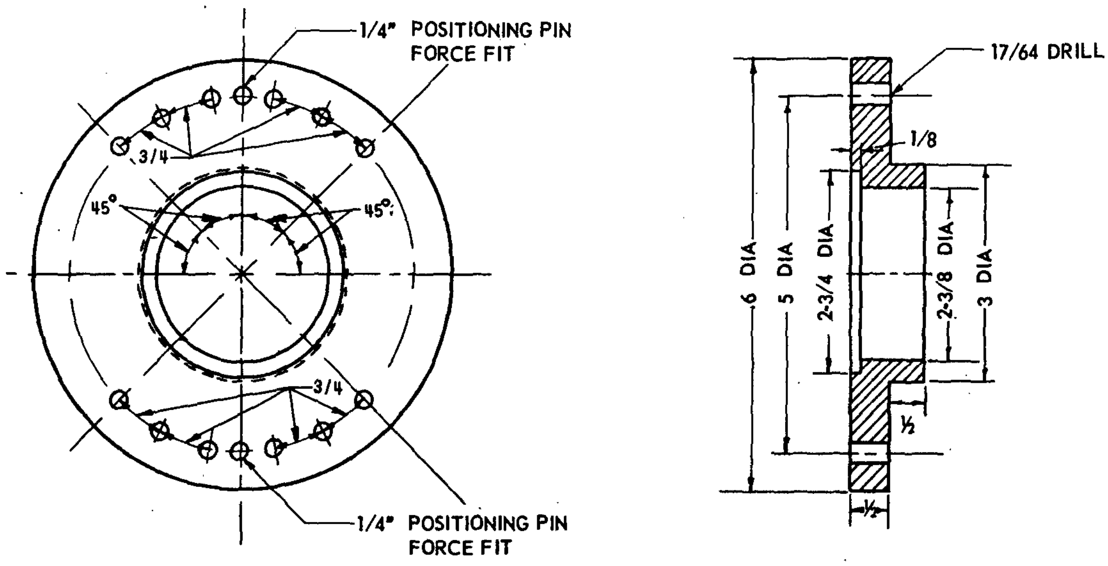


Figure 9. A. Upstream Flange of High-Pressure Sample Holder.

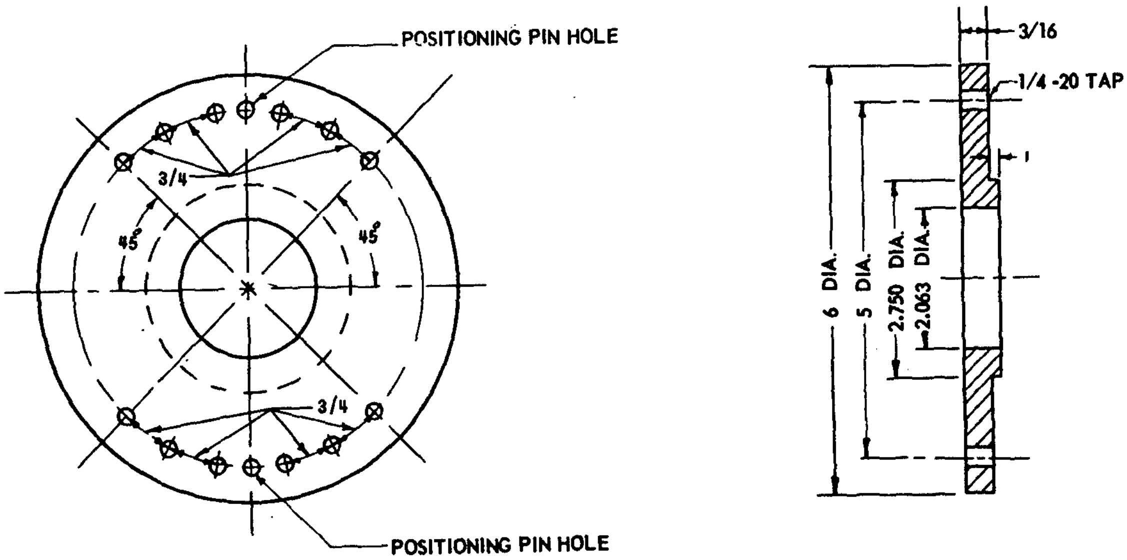


Figure 9. B. Downstream Flange of High-Pressure Sample Holder.

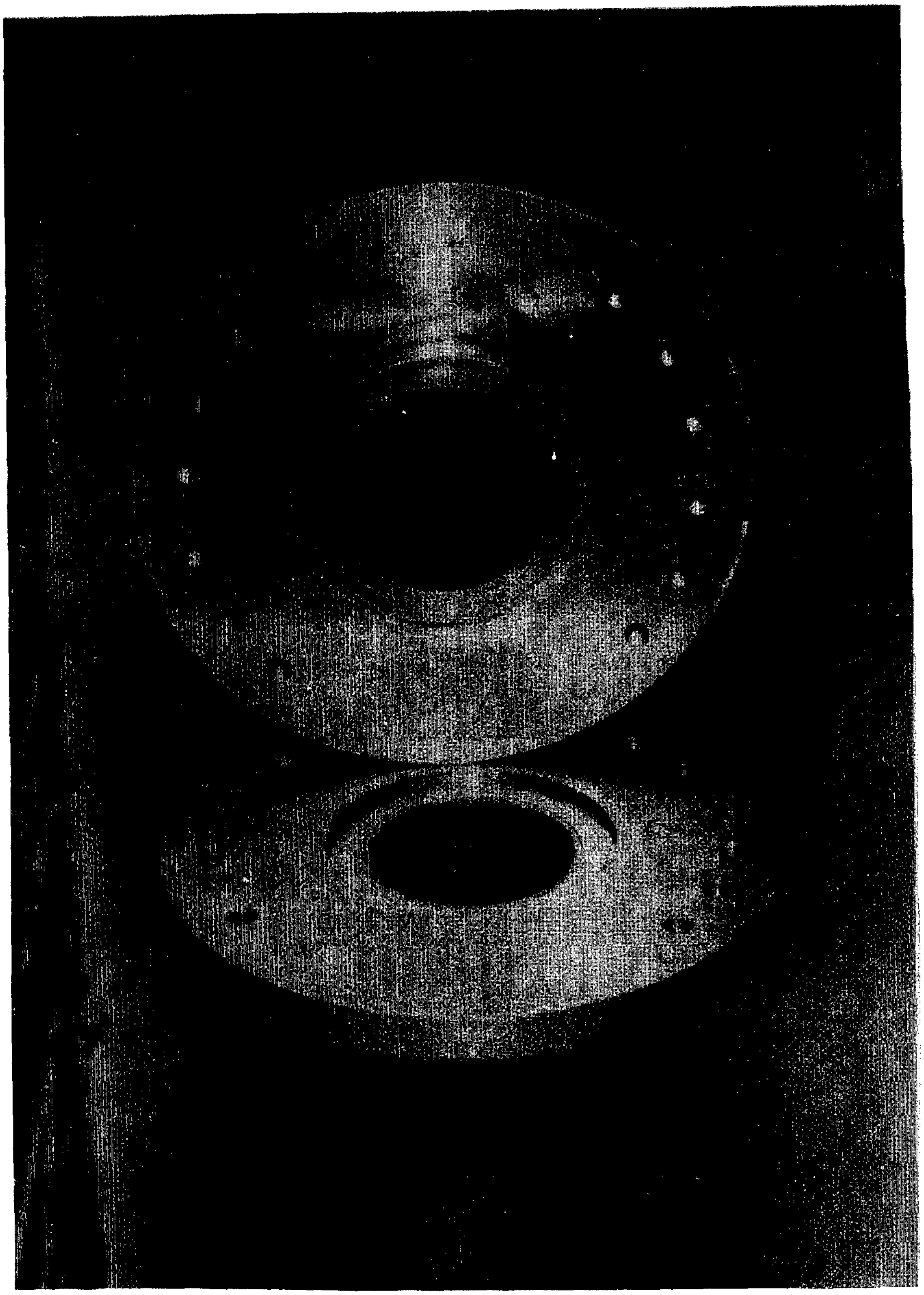


Figure 10. High-Pressure Sample Holder.

statistical analysis showed that any effect on the results which was due to this technique of mounting, when reasonable tarefully executed, was negligible.

2. Preliminary Operations

After completing of the operational procedure of placing the sample in its holder, the assemblage was mounted over the discharge end of the tunnel. Zero readings were taken from the manometers and the thermometers. With the plug valve closed, the fan was started and allowed to come up to speed. The plug valve was then opened quickly, thus simulating the shock of opening the parachute.

3. Data Obtained

When the flow had become steady, as indicated by the constancy of the static pressure upstream of the sample (a steady temperature, approximately 125° F, usually obtained downstream of the cloth), a record was made on the log sheets of this static pressure and the orifice pressure drop, along with the inlet and outlet air temperatures. The relative humidity of the air in the laboratory was determined by a sling psychrometer. The laboratory room was served by the building air conditioning system; tunnel inlet air at a constant condition was not available.

Similar readings were taken at about twelve different static pressures distributed over the possible range; the entering of the complete sample identification, the date and the psychrometer data completed the log sheet. The barometric pressure was recorded twice daily.

Eight more samples from the same piece of fabric, the locations of which were so selected that the statistical variation of the fabric permeability would be represented, were treated in the same fashion as the first sample. Figure 11, a sample log sheet for test ES-1, dated 29 August 1951, is attached. The test designation ES-1 refers to WADC Fabric No. 3, USAF plain weave white, Table VII.

Run No. ES-1 Page No. 1

LOG SHEET

Project 170-117

Cloth Identification
Style No. 000/100
Fiber Content Nylon
Weave Pattern Plain - 131461A
Color Style White

Date 29 August 51

Room Temperatures
Dry Bulb ______
Wet Bulb ______

Remarks: U. S. Air Force

Baro 29.23

Test Number	Static Pressure in. W.G.	Orifice Pressure Drop in. W.G.	Temperatures °F	
			Inlet	Outlet
Zero Readings	0.03	0.00	83	83
I	43.02	4.112	90	118
II	40.57	3.826	90	120
III	31.23	3.047	90	120
IV	25.82	2.288	89	121
V	18.52	1.549	88	121
VI	14.97	1.218	89	121
VII	9.87	0.759	89	122
VIII	5.87	0.406	89	122
IX	2.97	0.170	91	124
X	2.37	0.138	95	124
XI	9.65	0.619	88	125
XII	18.60	1.300	89	125
XIII	30.55	2.353	89	124
XIV	43.65	3.546	91	123

Figure 11. Sample Log Sheet For Low-Pressure Study.

4. Averaging of Data

From the data for each of these nine samples nine curves were plotted of the static pressure versus orifice pressure drop. (A sample plot for test ES-1 is shown as Figure 12.) The nine values for orifice pressure drop read at various values of static pressure were then averaged. This manipulation gave a set of smoothed data which was presumed to represent the fabric statistically. A table giving the results of this averaging process for test ES-1 is included as Table I.

5. Calculations

These statistically corrected data were used in a series of calculations described in detail by an itemized list of 28 operations in the Master Data and Result Sheet, which is included herewith as Figure 13. Table II is a record of the results obtained upon applying the calculation procedure to the statistically smoothed data shown in Table I. In the course of these calculations the density of the air flowing was obtained, the rate of flow through the ASME standard orifice was calculated, and the velocity pressure upstream of the fabric was obtained.

6. Correlation of Calculated Values

The square root of the ratio of velocity pressure upstream of the fabric to the static pressure upstream was termed the "relative porosity" and its variation plotted versus the mass velocity, $\frac{\text{lbm}}{\text{sec ft}^2}$, of the air upstream of the cloth to give a curve characteristic of the fabric permeability. The curve in Figure 14 represents this result for the sample ES-1. Table III includes the numerical values used in constructing Figure 14.

The following comments serve to illustrate the manner of application of the Master Data and Result Sheet, Figure 13.

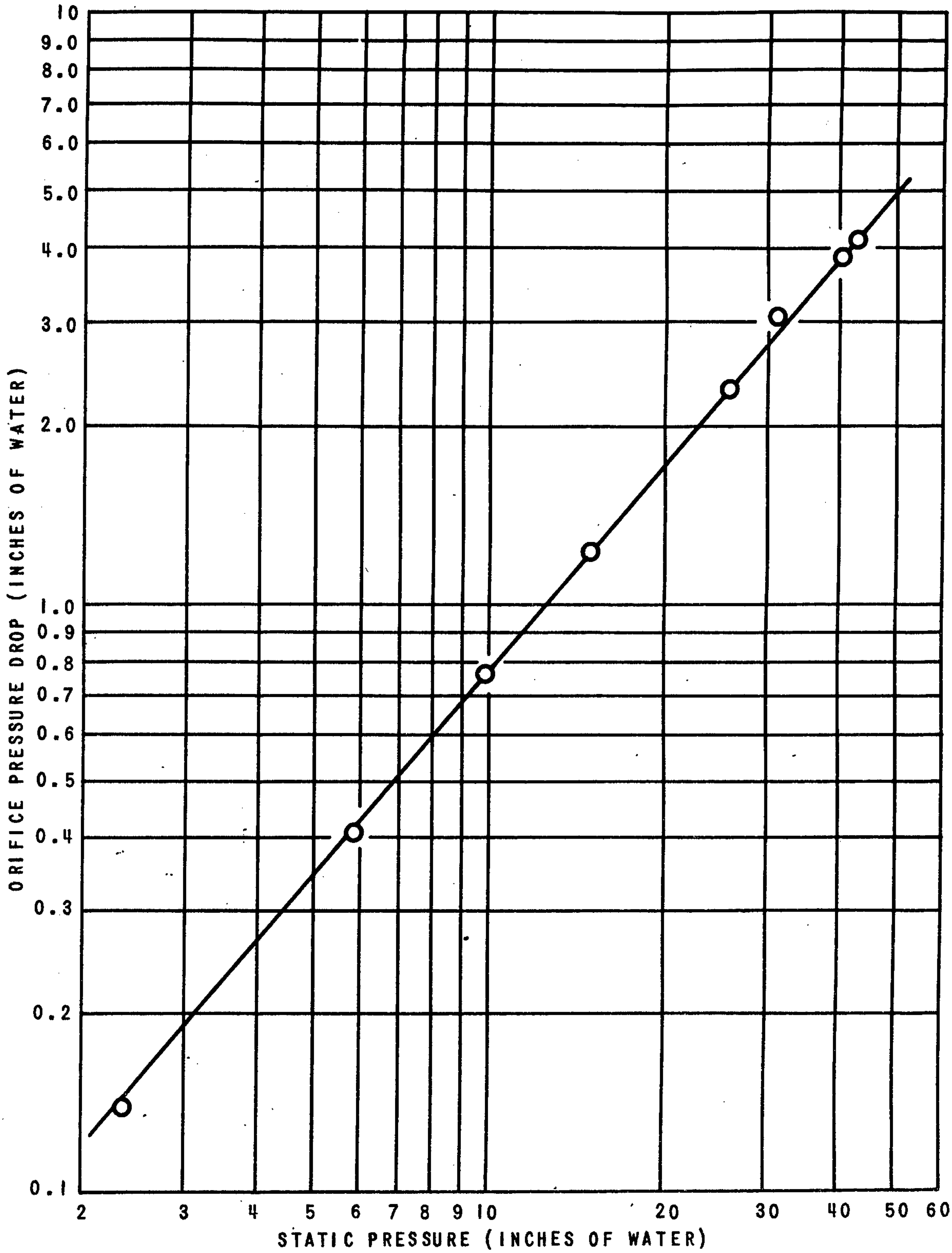


Figure 12. Relation of Static Pressure to Orifice Pressure Drop.

TABLE I

DATA ON AVERAGED ORIFICE PRESSURE DROPS VS. STATIC PRESSURE USED FOR FIGURE 12

Cloth Identification
Style No. 000/100 Color Style White
Fiber Content Nylon Piece No. U.S. Air Force
Weave Pattern Plain - 131461A

Ref: Log Sheet
Run No. ES-1 to 10
Page No. 1
Computed by

S.P. (In. of Water)	Orifice Pressure (Inches of Alcohol) 3	4	5	6	7	8	9	10	15	20	30	40	50
1	0.189	0.262	0.340	0.420	0.565	0.587	0.673	0.760	1.22	1.70	2.72	3.80	4.90
2	0.178	0.249	0.323	0.400	0.478	0.560	0.643	0.725	1.16	1.64	2.64	3.68	4.78
3	0.228	0.317	0.410	0.503	0.600	0.700	0.800	0.900	1.44	2.00	3.18	4.40	5.68
4	0.224	0.310	0.400	0.492	0.586	0.685	0.785	0.885	1.40	1.95	3.10	4.32	5.55
5	0.188	0.265	0.344	0.423	0.510	0.595	0.682	0.773	1.25	1.75	2.80	3.92	5.12
6	0.215	0.298	0.384	0.473	0.565	0.655	0.755	0.850	1.35	1.88	2.98	4.15	5.35
7	0.194	0.270	0.350	0.430	0.515	0.600	0.685	0.775	1.23	1.72	2.75	3.83	4.98
8	0.235	0.326	0.420	0.515	0.615	0.715	0.815	0.920	1.45	2.01	3.20	4.43	5.70
9	0.227	0.315	0.408	0.500	0.598	0.695	0.795	0.895	1.43	1.98	3.18	4.41	5.70
10	0.204	0.284	0.365	0.450	0.575	0.625	0.720	0.810	1.29	1.80	2.85	3.97	5.15
Ave.	0.208	0.290	0.374	0.461	0.561	0.642	0.735	0.829	1.32	1.84	2.94	4.09	5.29
Corrected In. Water	0.164	0.229	0.295	0.364	---	0.507	---	0.655	1.04	1.45	2.32	3.23	4.17

Figure 13. Master Data and Result Sheet

Item No.		Dimension
1.	Barometer	in. Hg
2.	Barometer (0.491 x item 1)	$lb_f\ in^{-2}$
3.	Static pressure (S.P.)	inches of water
4.	Static pressure (0.0362 x item 3)	$lb_f\ in^{-2}$
5.	Static pressure, P, (item 2 + item 4)	$lb_f\ in^{-2}$ abs.
6.	Inlet air temperature	°F abs.
7.	Outlet air temperature, T,	°F abs.
8.	Psychrometer Data	
	Dry bulb temperature	°F
	Wet bulb temperature	°F
	Relative humidity	%
9.	Orifice pressure drop, h_w,	inches of water
10.	$\frac{P}{T}$, (item 5 ÷ item 7)	
11.	Air density at cloth, ρ, (0.004672 x item 5)	$lb_m\ ft^{-3}$
12.	$h_w\rho$, (item 9 x item 11)	
13.	$\sqrt{h_w\rho}$, (item 12)$^{1/2}$	
14.	Estimated air flow, M (0.894 x item 13)	$lb_m\ sec^{-1}$
15.	Air viscosity, μ, at temperature of item 7	cp
16.	$M \div \mu$ (item 14 ÷ item 15)	
17.	Reynolds number at throat, N_{Re} (6179 x $\frac{1}{\mu}$ x item 14)	
18.	Corrected orifice coefficient, K,	
19.	Correct flow, M_c (item 14 x $\frac{\text{item 18}}{0.662}$)	$lb_m\ sec^{-1}$
20.	Mass velocity at cloth, G, ($\frac{\text{item 19}}{0.2*}$)	$lb_m\ sec^{-1} ft^{-2}$
21.	Reynolds number in tube, N_{Re}, (0.64 x item 17)	

Figure 13. Master Data and Result Sheet (Continued)

22. $\frac{Mc}{\rho}$ (item 19 ÷ item 11)

23. Velocity in duct, V (item 22 ÷ 0.179**) ft sec^{-1}

24. ρV^2 [item 11 x (item 23)^2]

25. Velocity pressure, V.P., (0.00299 x item 24) in W.G.

26. Item 25 ÷ item 3

27. Relative porosity (item 26)$^{1/2}$

*0.2 ft^2 projected area of cloth sample.

**0.179 ft^2 wind tunnel area.

TABLE II

SAMPLE DATA AND RESULT SHEET

Cloth Identification

Style No. 000/100 Color Style White
Fiber Content Nylon Piece No. ES-1
Weave Pattern Plain - 131461A USAF

Ref: Log Sheet
Run No. ______
Page No. ______
Computed by ______

Item Number*	Test Number										
1	29.22	29.22	29.22	29.22	29.22	29.22	29.22	29.22	29.22	29.22	29.22
2	14.33	14.33	14.33	14.33	14.33	14.33	14.33	14.33	14.33	14.33	14.33
3	3	4	5	6	8	10	15	20	30	40	50
4	.109	.145	.181	.217	.290	.362	.543	.724	1.086	1.448	1.81
5	14.4	14.5	14.5	14.6	14.6	14.7	14.9	15.1	15.4	15.8	16.1
9	.164	.229	.295	.364	.507	.655	1.04	1.45	2.32	3.23	4.17
10	.0248	.0249	.0249	.0251	.025	.025	.0256	.026	.0265	.0271	.028
11	.0671	.0675	.0675	.068	.068	.068	.0694	.0704	.0718	.0734	.075
12	.0110	.01545	.0184	.0247	.0345	.045	.0721	.102	.1665	.237	.313
13	.105	.125	.136	.158	.186	.212	.268	.319	.408	.486	.56
14	.0940	.112	.121	.141	.166	.189	.240	.285	.365	.434	.50
15	.0195	.0195	--	--	--	.0195	--	--	--	--	--
17	29800	35500	38300	44600	52600	60000	76000	90300	116000	138000	158000
18	.700	.694	.692	.687	.683	.680	.676	.674	.672	.671	.67
19	.0996	.118	.127	.147	.1715	.195	.245	.291	.370	.438	.51
20	.498	.59	.635	.735	.857	.975	1.23	1.45	1.85	2.19	2.5
21	19100	22700	24500	28600	33600	38400	48600	57800	74200	88300	101000
22	1.485	1.75	1.885	2.16	2.52	2.84	3.54	4.14	5.16	5.98	6.75
23	8.30	9.78	10.9	12.1	14.1	15.9	19.8	23.15	28.85	33.45	37.8
24	4.62	6.46	8.04	9.92	13.5	17.3	27.2	37.7	59.8	82.0	108
25	.0138	.0193	.0240	.0296	.040	.0517	.08	.112	.179	.245	.32
26	.0046	.00481	.0048	.0049	.005	.00517	.00534	.0056	.0059	.00612	.0065
27	.0678	.0693	.0693	.0702	.0711	.0719	.0731	.0748	.0773	.078	.08

*Item 6, 7 and 8 data were not recorded.
Machine calculation eliminated need for recording Item 16.

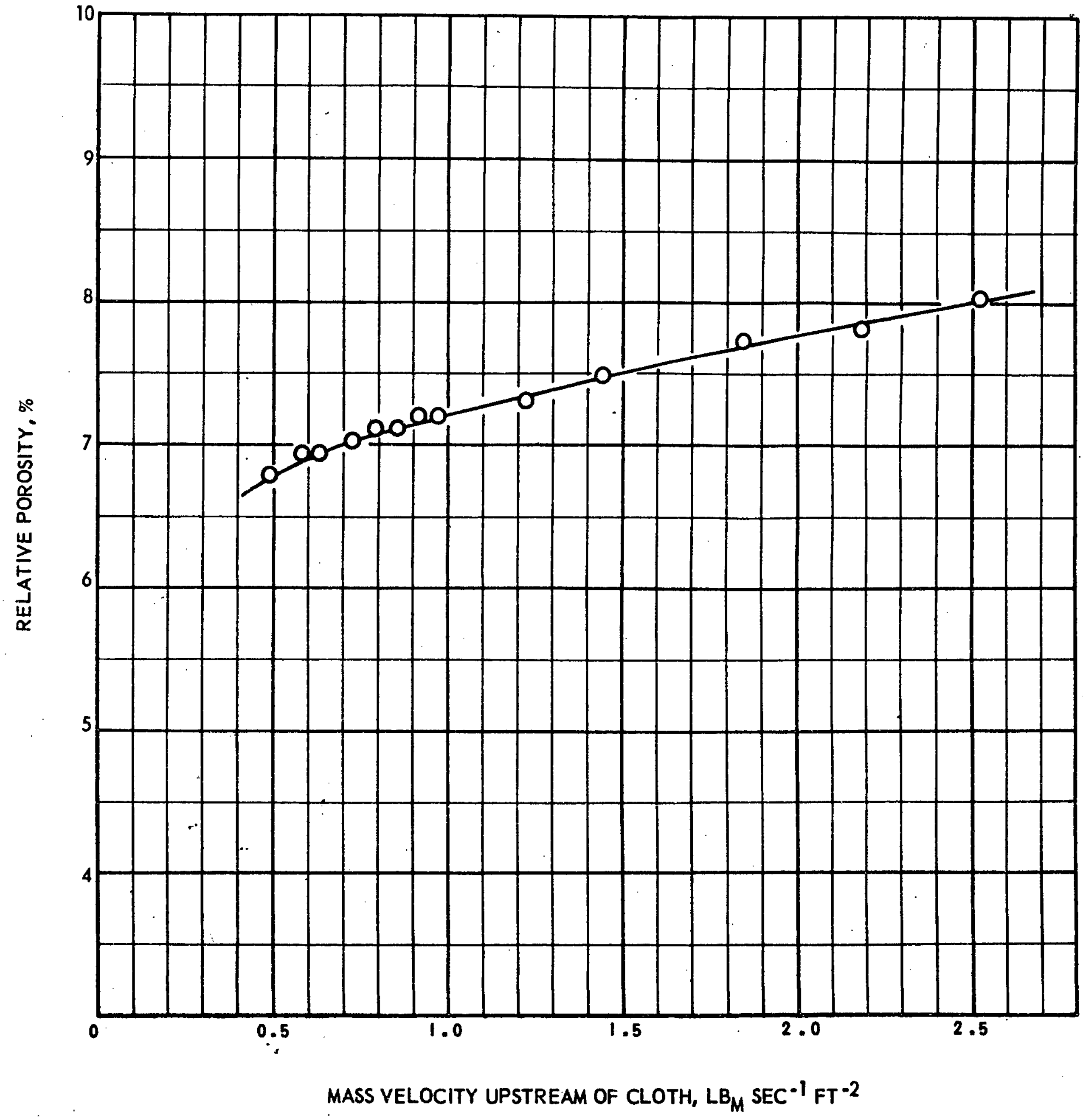


Figure 14. Porosity-Permeability Characteristics.

TABLE III

EXPERIMENTAL DATA USED IN FIGURE 14

G (Item 20, Figure 13) (lbs sec^{-1} ft^{-2})	Relative Porosity (Item 27, Figure 13)
0.498	0.0678
0.590	0.0693
0.635	0.0693
0.735	0.0702
0.800	0.0710
0.857	0.0711
--	--
0.975	0.0719
1.235	0.0731
1.450	0.0748
1.85	0.0773
2.19	0.078
2.5	0.080

Items 1 through 8 are self explanatory. Items 9 through 19 indicate the procedure employed to calculate the air flow through the fabric sample from measurements relating to air density and orifice pressure drops. The procedure is a standard one wherein the appropriate orifice coefficient, K, is selected, and an estimate is made of the flow through the orifice; a Reynolds number at the orifice is now calculable and a corrected value of K obtainable; in turn the correct air flow is calculated. A typical Reynolds number vs. orifice coefficient curve is shown in Figure 15. The mass velocity at the cloth is obtained in item 20 as the ratio of the mass flow through the cloth to the total cloth area subject to the flow; the latter is fixed at 0.2 square foot. Items 22, 23, 24 and 25 serve to illustrate the manner of arriving at velocity pressure upstream of the cloth. Items 26 and 27 show the application of the arbitrary definition of relative porosity to the sample data.

C. Test Procedure for High-Pressure Tunnel

1. Introduction

Based on the experience of operating the low-pressure tunnel, the air requirements at a 15 psi pressure drop for a 0.2-square-foot sample were estimated as greatly exceeding any service air supply available at test facilities. Accordingly the sample size for the high-pressure tunnel was reduced to an effective circular section 2.06 inches in diameter. In view of this reduced sample size, the sample holder design was changed in accordance with the description reported in the section on apparatus. This portion of the study was restricted to the eight standard cloths and to the orlon and dacron fabrics. None of the Bally Ribbon cloths was subjected to the high-pressure study.

2. Preliminary Operations

The specimen fabric, a strip approximately 4 inches by 10 inches, was cut from the cloth yardage in accordance with the technique described

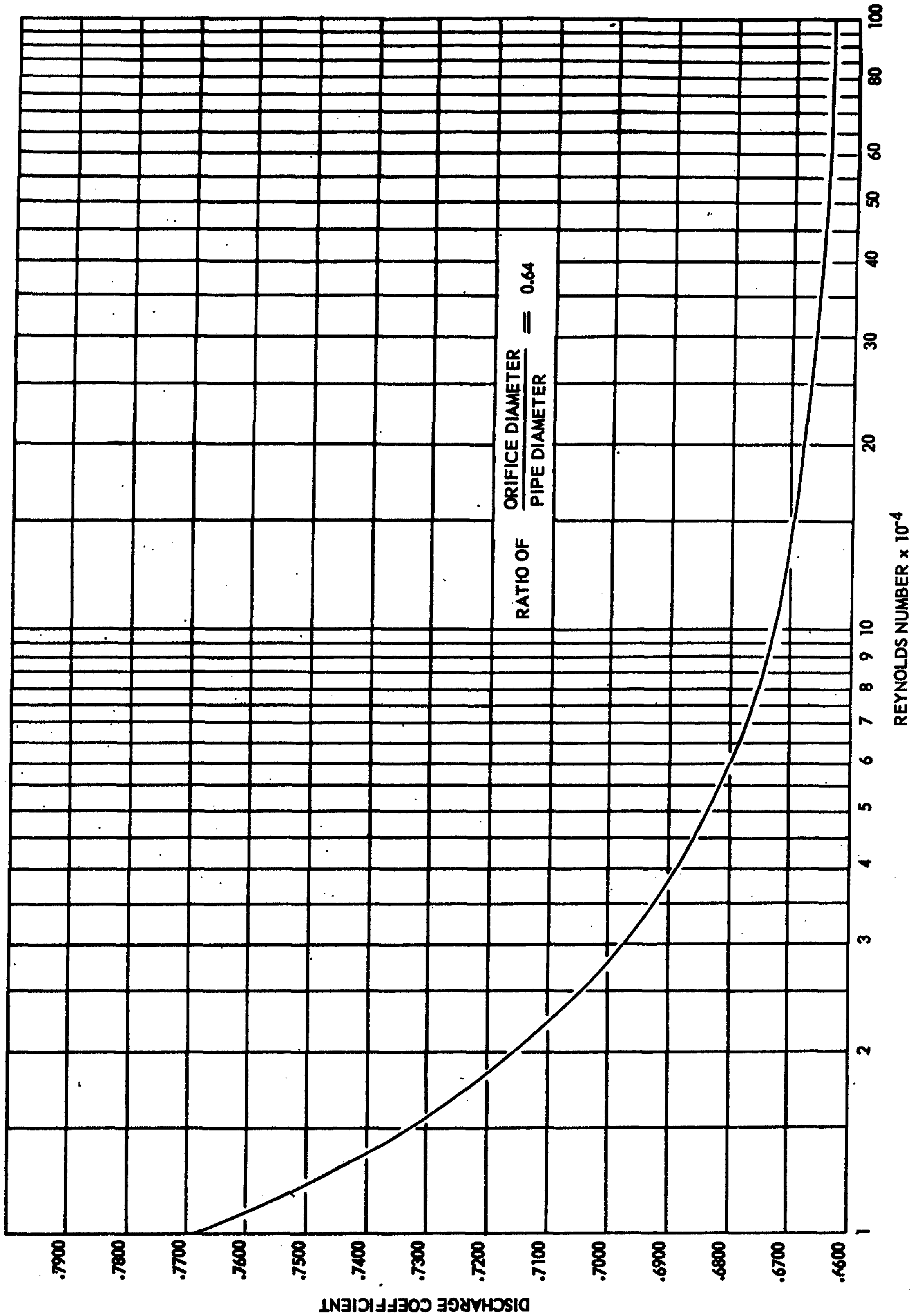


Figure 15. Orifice Coefficient Curve.

under statistical considerations. It was placed over the upstream flange of the sample holder (this flange was fixed to the tunnel), and the downstream flange was lowered and fixed in place, giving an installation wherein essentially uniform tension could be expected from sample to sample. No quantitative measure could be put on the small tension to which the samples were subjected. As in the case of the low-pressure tunnel, zero readings of instruments were observed and recorded. Once the air flow to the apparatus was established, its control was possible by manipulation of either of the manual control valves or of the spring-loaded regulating valve or by any combination. The air flow was increased to permit establishment of desired static pressures upstream of the cloth, starting with the lowest pressure setting, being based upon the readability of the indication of the micromanometer filled with alcohol as the manometric fluid. Thus, this series of tests was carried out without placing a simulated shock load on the sample, as was the case in the low-pressure tunnel.

3. Data Obtained

Measurements of air flow and static pressure upstream of the cloth, as well as air temperature, were the quantities required. In order to measure air flow, three flow-measuring units were employed; for the low flows a calibrated gas meter (obtained from the Atlanta Gas Company) was used, for intermediate flows, a 0.488-inch orifice plate meter, and for high flows, a 0.978-inch orifice meter. These meters were installed in parallel in 1.96 i.d. brass tubes.

The gas meter, when in use, was installed in parallel with the manifold of two manual control valves which, of course, were closed when the gas meter was totalizing flow. (The gas meter was known to indicate within $\pm$ 1.5 per cent on measured flows 0.5 ft^3 or greater; gas meters of this type are sensitive to the small gas flows required for the pilot light on common home appliances.) When flow reached predetermined values, assuring applicability of standard orifice coefficients, its measurement was switched in turn to the two orifice plate meters. Pressure differentials across the orifices were observed using in turn, as required, an alcohol micromanometer and a vertical water manometer.

Static pressure readings upstream of the cloth were observed by using in turn an alcohol micromanometer, a vertical water manometer and a vertical mercury manometer.

Nine samples from each bolt of cloth were again employed in order that the statistical variation of the fabric would be represented. For practical reasons, as well as limitations of time, the statistical analysis employed for the low-pressure tunnel was assumed to be valid in principle for the high-pressure tunnel.

4. Handling of Data

From the data obtained for each sample calculations were carried out, resulting in a set of points depicting the interrelation between the pressure square gradient across the sample versus the mass velocity upstream of the cloth. The significance of these two terms and the theoretical interrelation involved are discussed in Section IX of this report, High-Pressure Tunnel Characteristic Length Study.

The pressure square gradient-mass velocity results for the nine samples of each fabric were plotted on a single log log graph; from this set of results an equation of the form $\frac{\nabla P^2}{L} = \alpha' G + \beta' G^2$ was fitted analytically. In view of the range of variables three techniques were employed in establishing the fit: (1) least squares, (2) by eye in the high G range and least squares in the low G range and (3) method of averages throughout. The results for the three methods are shown in Appendix IV in Table IV and in the corresponding graphical presentations, Figures 36 through 45.

Rather than submit a detailed set of data resulting from the high-pressure tunnel study, the recommended values of α and β are given in Table IV. Figures 36 through 45 show the extent of variation of the experimental points from the recommended fit.

VI. PHOTOMICROGRAPHIC STUDIES

A. Appearance

1. Plain Weave

Photomicrographs at 100 diameters were taken of each of the four fabrics supplied by the Air Force, of the four Cheyney fabrics and of the orlon and dacron fabrics manufactured by the Duplon Corporation. These are shown as Figures 16 through 25.

The plain weave (white or camouflage-printed) appeared to have quite evenly spaced warp and filling, with interstices being generally rectangular in shape and varying considerably in size. The warp showed much less twist than the filling. (The Georgia Tech Textile Laboratory reported the warp to be 7 to 8 turns/inch and the filling to be 1 to 2 turns/inch.) The filling in the finished cloth was flattened to approximately twice the projected width of that of the warp and the interstices were about 1-1/2 times as long as they were in width.

2. Rip-Stop

The white and the orange rip-stop cloths were also similar in appearance. Except in those photographs in which the dense rip-stop lines were shown, the appearance of the rip-stop was similar to that of the plain weave as would be expected.

Twist appeared in the threads of both white and orange cloth as an occasional crossing of adjacent pairs of filaments rather than an actual twisting together of all filaments in one thread.

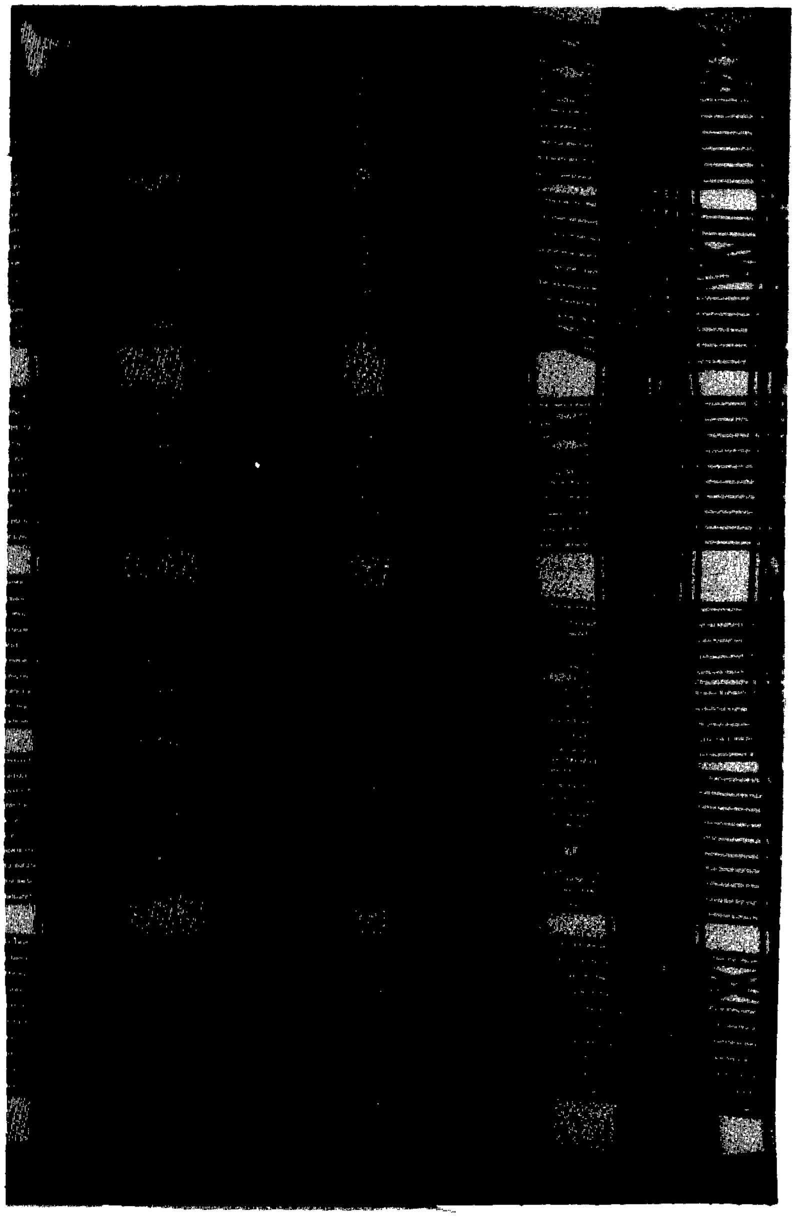


Figure 16. Photomicrograph of WADC Fabric No. 1 (USAF White Rip Stop).

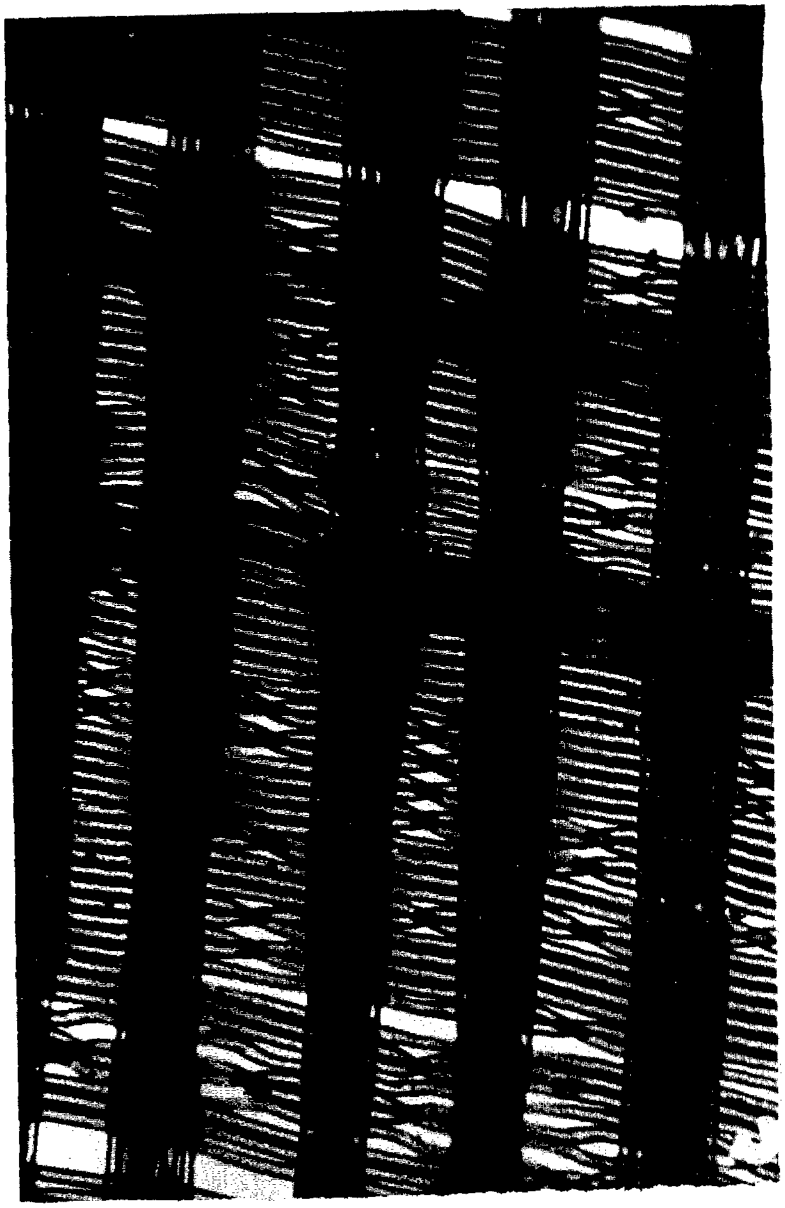


Figure 17. Photomicrograph of WADC Fabric No. 2 (USAF Orange Rip Stop).

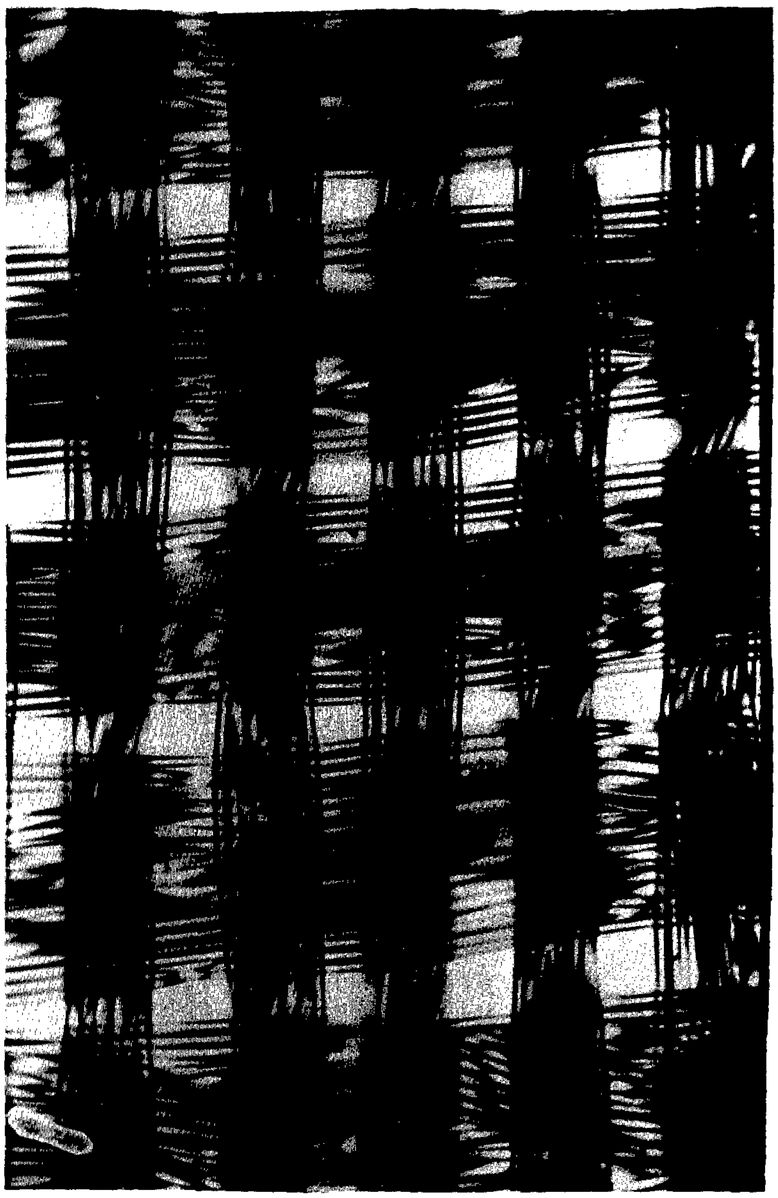


Figure 18. Photomicrograph of WADC Fabric No. 3 (USAF White Twill).

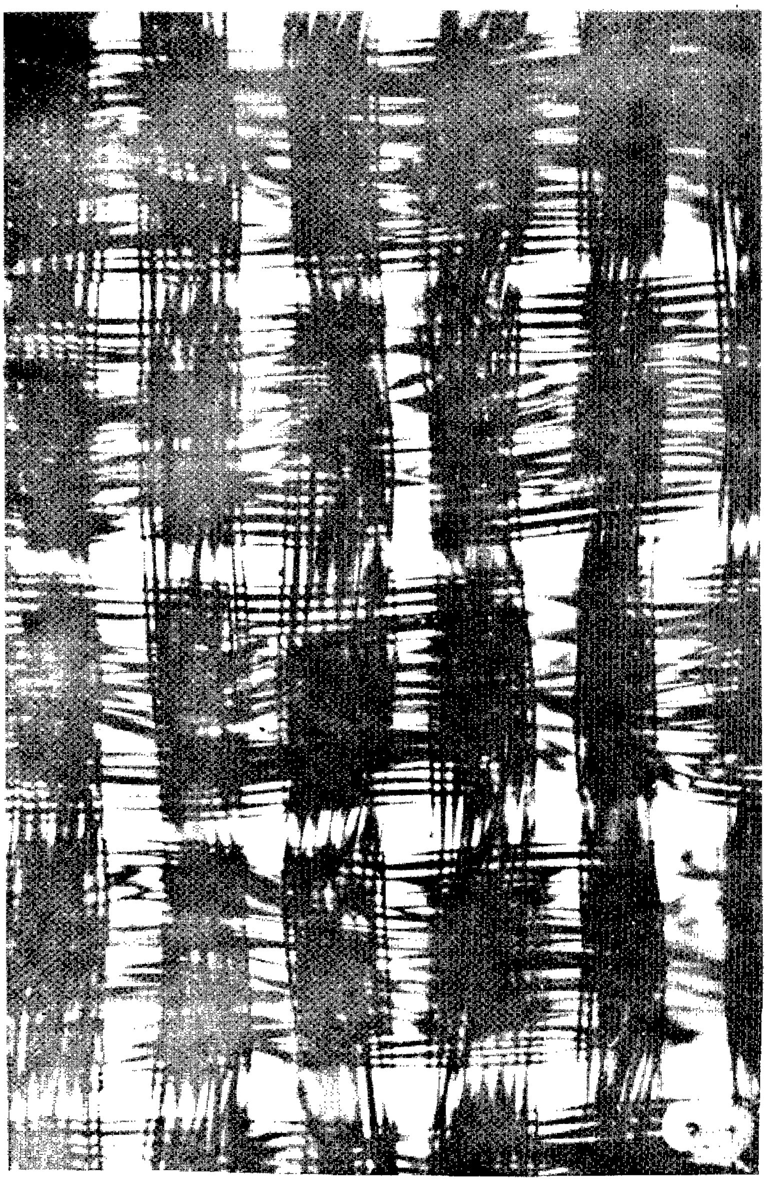


Figure 19. Photomicrograph of WADC Fabric No. 4 (USAF Camouflage Twill).

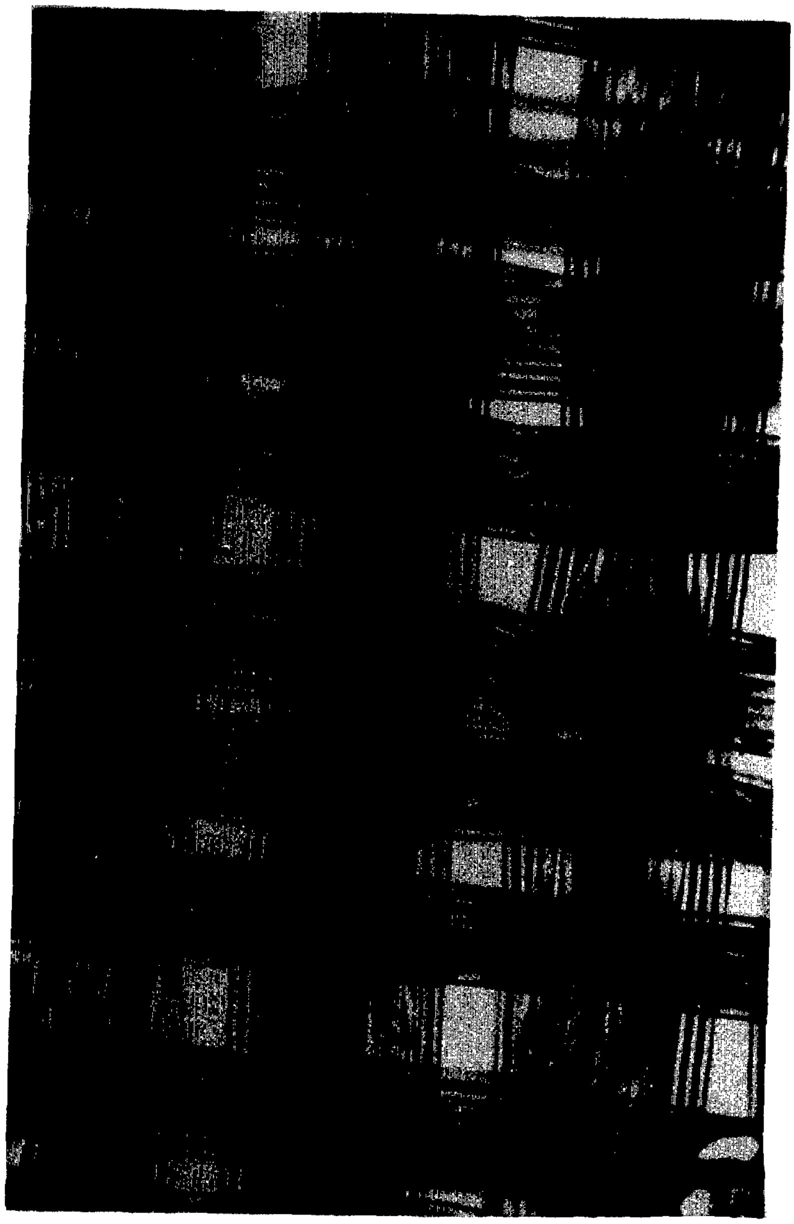


Figure 20. Photomicrograph of WADC Fabric No. 5 (Cheney Bros. White Finished).

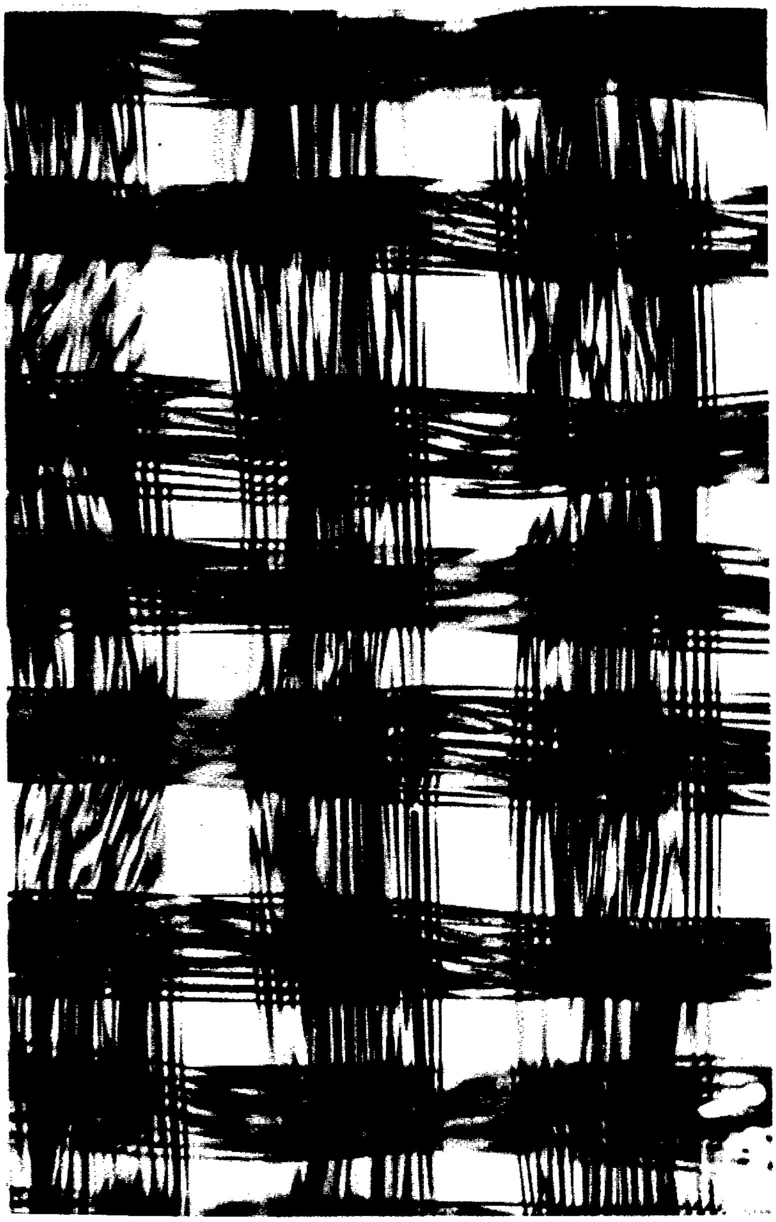


Figure 21. Photomicrograph of WADC Fabric No. 6 (Cheney Bros. White Greige).

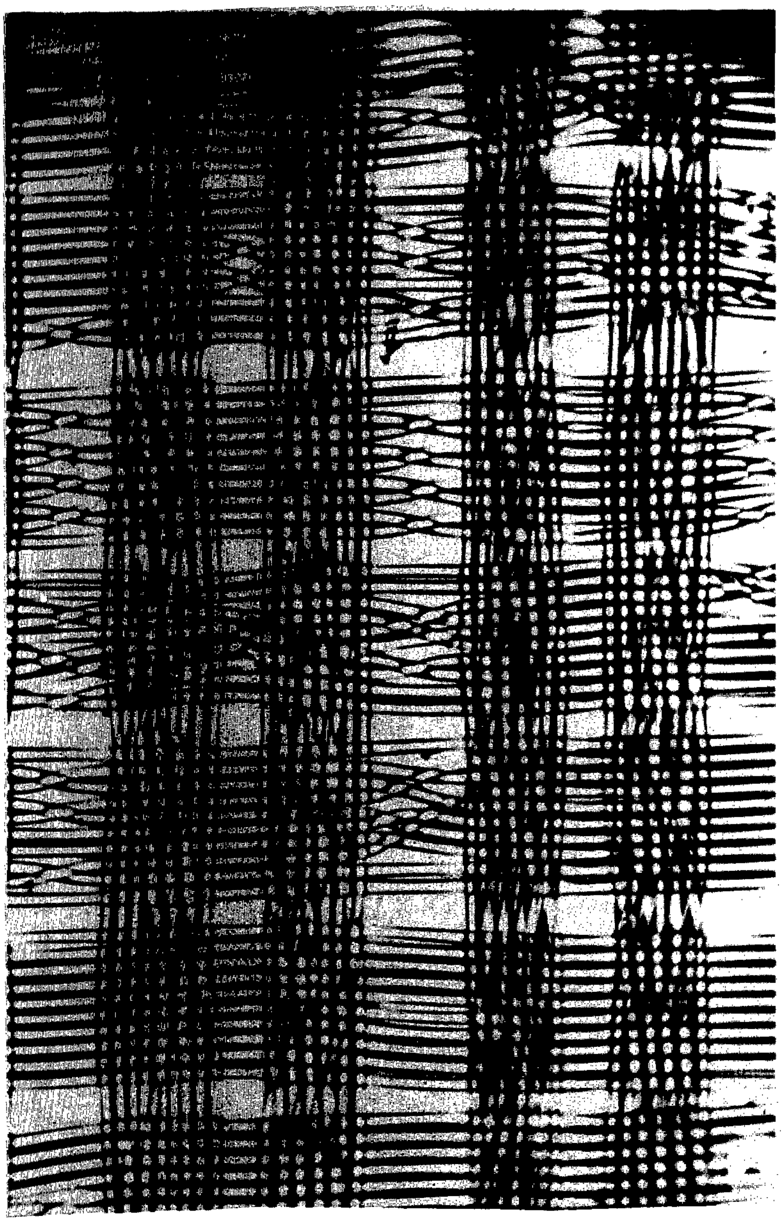


Figure 22. Photomicrograph of WADC Fabric No. 7 (Cheney Bros. White Rip Stop Finished).

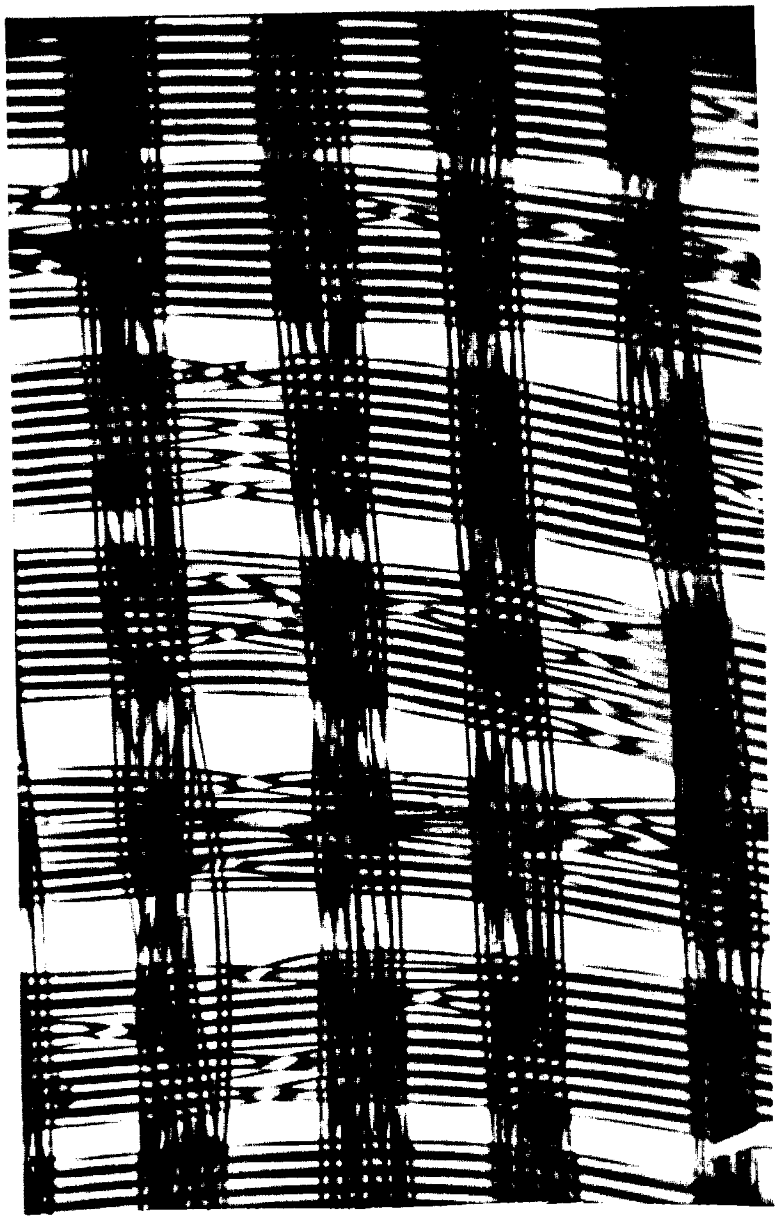


Figure 23. Photomicrograph of WADC Fabric No. 8 (Cheney Bros. White Rip Stop Greige).

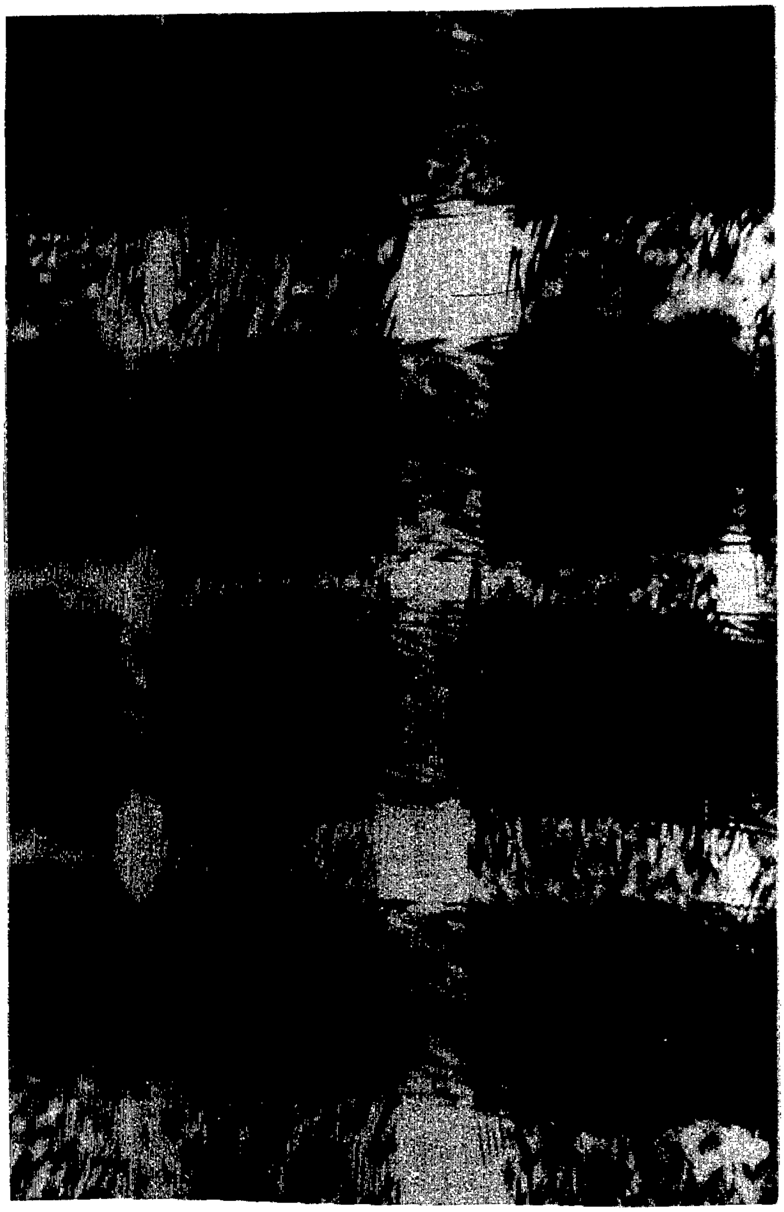


Figure 24. Photomicrograph of WADC Fabric No. 9 (Duplan Corp. White Dacron).

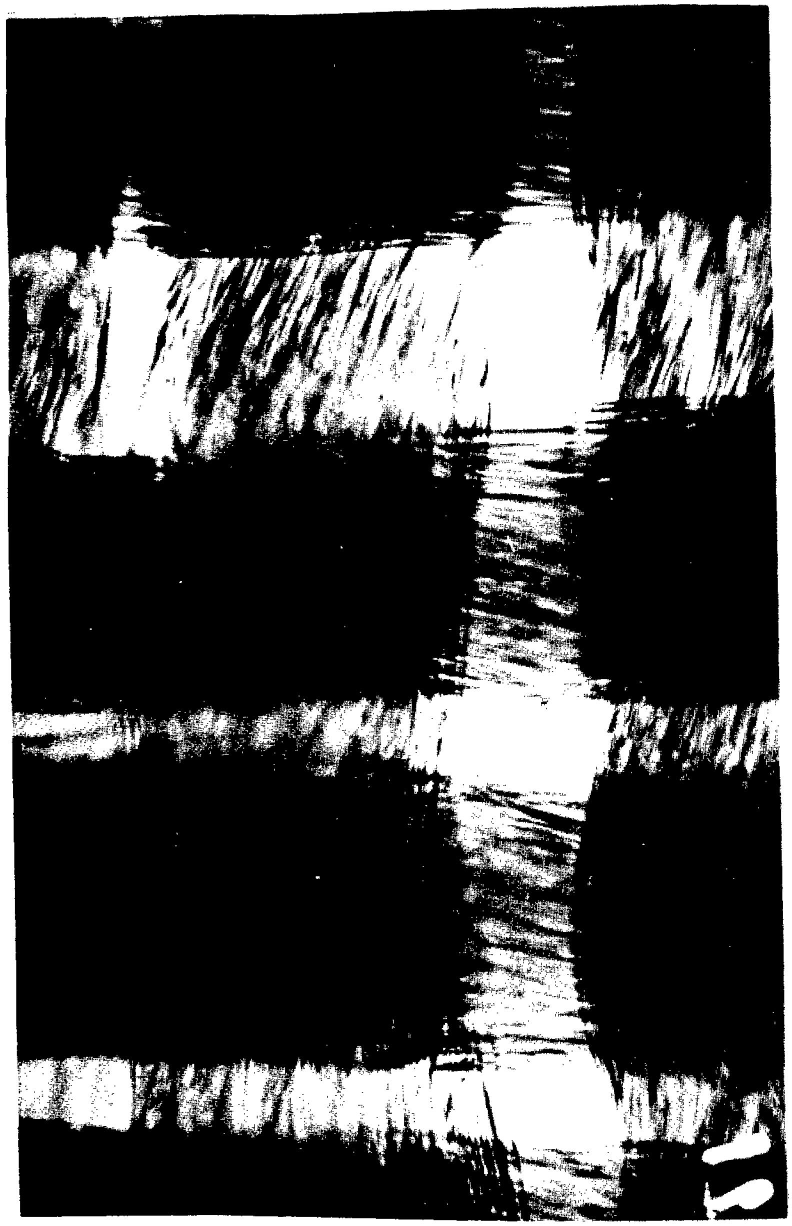


Figure 25. Photomicrograph of WADC Fabric No. 10 (Duplan Corp. White Orlon).

3. Dacron

The photomicrograph of the dacron fabric at 100 diameters showed the greater denier and higher twist of its warp and filling, which appeared to be the same size and contained more filament per thread than the nylon. A supplementary view at 50 diameters showed that the birds-eye weave caused the pore sizes to be irregular and some of the pore shapes to be trapezoidal.

4. Orlon

The orlon's appearance was similar to that of the dacron, i.e., higher twist, greater denier, more filaments per thread and irregular pore size and shape.

B. Effect of Finishing

Photomicrographs were taken of plain white cloth and of white rip-stop in both greige and finished states. The pore shapes in the greige were rectangular in general but much larger than in the finished cloth. The warp seemed to be much more closely packed (circular cross section), whereas in the finished cloth it had been flattened, and thus the spaces between were smaller. The filling had much the same appearance in both states.

C. Effect of Dirt in Air

In spite of the precautions taken (using an air-conditioned laboratory which was kept closed from the corridor and having its floor wet-mopped each morning), there was some air-borne dirt in the fan discharge. This was evident from the slight discoloration of that area of the sample exposed to flow of air. Photomicrographs of this dirty area, Figures 26 and 27, and of a clean piece of the same cloth, Figures 16 and 18, respectively, were made, and a comparison showed the dirt particles to be of the order of twice the diameter of one of the nylon filaments. It was found that the dirt did not tend to clog the cloth interstices but did cling to the outer surface of the threads. Thus, the interstices were left unobstructed.

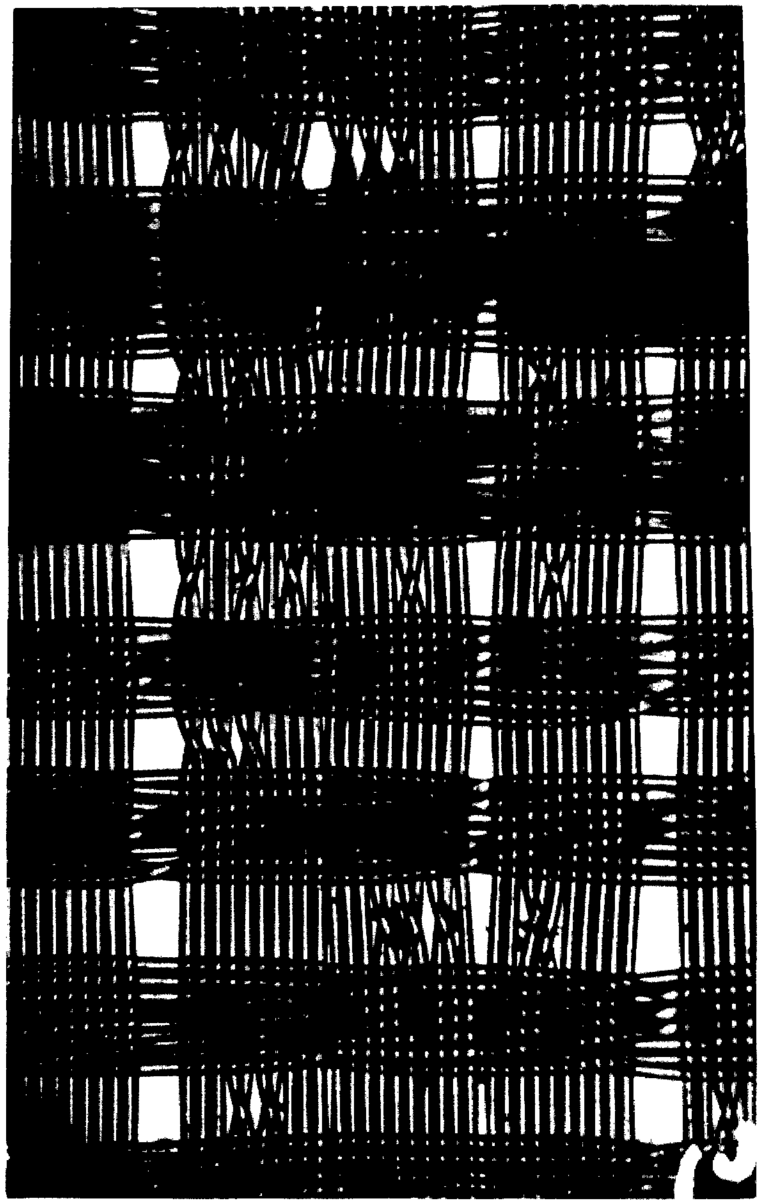


Figure 26. Photomicrograph of WADC Fabric No. 1 (USAF White Rip Stop) Showing Dirt Accumulation.

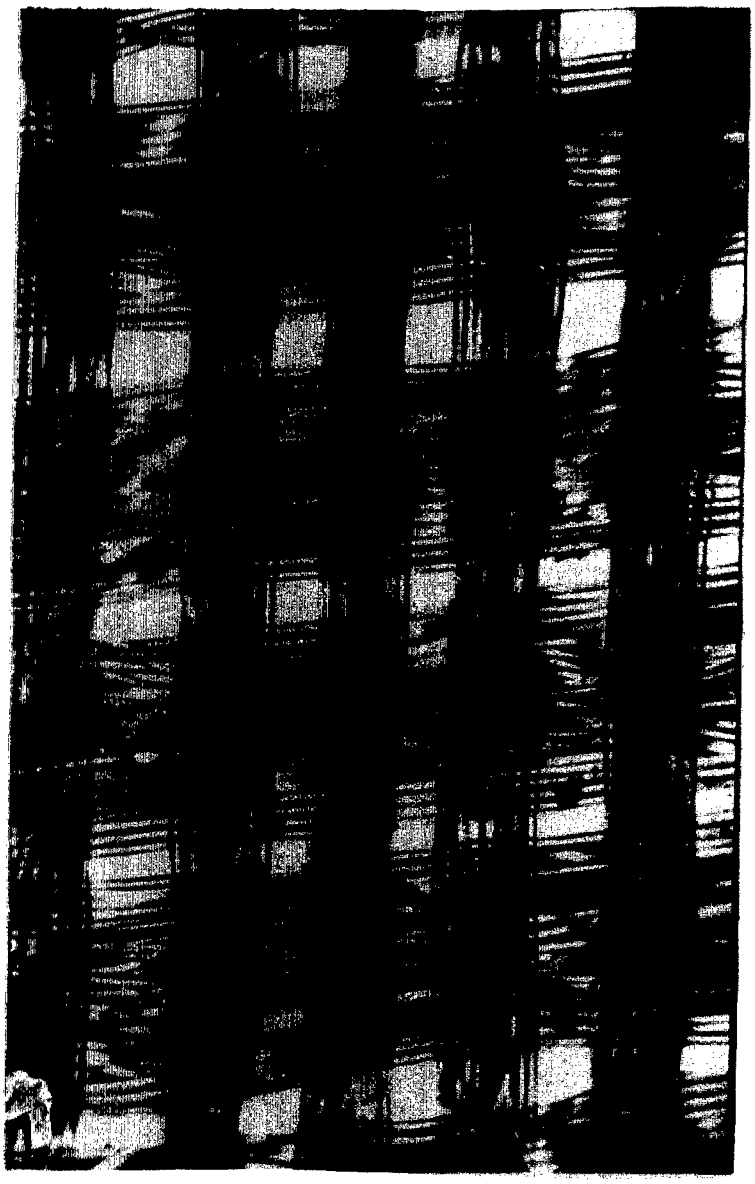


Figure 27. Photomicrograph of WADC Fabric No. 3 (USAF White Twill) Showing Dirt Accumulation.

VII. STATISTICAL ANALYSIS

A. Necessity for Statistical Analysis

Since a piece of fabric is the product of many varied and separate mechanical operations, its permeability (or any other property) is generally recognized to be widely variable from sample to sample within the same piece of cloth. The problem of determining the nature and extent of this variation yields most readily to a planned statistical analysis. The statistical analysis of data from this project was divided into three programs.

B. Program I

The first program consisted of a comparison of the readings of the flow orifice manometer for each of twelve samples from the same cloth. The variation could occur with the sample location in a direction along either the warp or the filling threads, or along both, and, in the case of permeability testing, some of the variation may be due to mounting technique. In order to produce suitable data for such an analysis, the samples were taken four in a row across the cloth width, in three rows spaced five yards apart along the length of the cloth. Data were taken on each sample at a static pressure of 35 inches of water and then the cloth was allowed to "relax" for exactly 24 hours after which each determination was repeated.

The original data shown in Table V were analyzed for the significance of the main effects and for all possible interactions of these main effects. The analysis showed that variation due to mounting, the procedure for which is described in Section V, B, was not significant (0. per cent). While the variation along the filling (across the cloth width) was considerable (13 per cent), it was much less than that along the warp (66 per cent). The analysis of variance showed the interaction of main effects

TABLE V

STATISTICAL DATA--PROGRAM I*

Values of Flow**		Orifice W1***	Manometer Reading (Inches of Water) W2***	W3***
F1	M1	3.99	2.63	2.46
	M2	3.93	2.73	2.42
F2	M1	4.37	3.23	2.63
	M2	4.31	3.26	2.63
F3	M1	4.30	3.34	2.61
	M2	4.14	3.33	2.71
F4	M1	3.74	3.06	2.65
	M2	3.73	3.03	2.71

*Static pressure constant at 35 inches of water.

**F is position across the cloth (filling variation). M is replication (= 2) of data (due to remounting).

***W is position down the cloth (warp variation).

W1 = 0 yards, W2 = 5 yards and W3 = 10 yards.

(warp and filling variation) yielded a 17 per cent contribution; an additional 4 per cent residual effect was calculated. The average of the values for samples taken in a row across the cloth was found to correspond to the value for any sample located at a point 1/4 of the cloth's width in from either selvage. This is in agreement with the findings at the British Ministry of Supply (16).

C. Program II

The variation along the warp was shown to be the most important, but the analysis had been based on only three sampling positions. In order to determine more accurately the pattern and the extent of this variation, data were obtained from 22 samples of plain-weave cloth, taken nine inches apart along the length of the cloth, the center of each sample being nine inches from the selvage edge of the 36-inch width. The 22 samples were divided into three groups by location, each succeeding group being separated from the last by three yards. All data were taken at static pressure of 35 inches of water.

The values of the flow orifice pressure differential for Group 1, consisting of ten samples, were in the ranges 3.25 and 3.80 with an average value of 3.5. Assuming that their values are "normally" distributed, 95 per cent of repeated measurements should be between 3.0 and 4.0 ($\bar{x} \pm 2\sigma_x$ or 3.5 ± 0.5). In Group 2 (six samples) the average value was 3.41 and the standard deviation was 0.48. This change in characteristics was attributed to the noticeable and abrupt change in the appearance of the fabric occurring in that portion of the cloth from which these six samples were taken. For the six samples of Group 3 the standard deviation was again 0.25, the same as for Group 1. The value of the mean, somewhat lower than either other group, was 3.16. Table VI is a summary of the above results.

The data for each of the three groups were subjected to an "analysis of variance." The variance between groups was shown to be not significant; therefore, an over-all average and standard deviation is proper. These values proved to be 3.39 and 0.35, respectively. The following 95 per cent confidence intervals were computed.

Number of Random Samples	Per Cent Deviation
1	20.4
4	10.4
9	7.0
16	5.2
25	4.2
36	3.5

Practical economics suggested a program of nine random samples, which should assure that, at worst, their mean value will be within ± 7 per cent of the true average value for 95 per cent of the determinations.

It is recognized that more than three groups for the analysis of variation might have revealed a small but finite variation. For this reason it was recommended that the nine samples be taken from as widely separated positions as possible, including the entire piece available for testing.

D. Program III

In an attempt to indicate the order of magnitude of the variation due to the type of weave, a third program of statistical work was performed in which nine random samples from ten different cloths of four different weaves were considered. The average flow orifice manometer reading (in inches of water), taken at static pressure of 40 inches of water for each cloth, and the standard deviation of each are presented in Table VII. The average and standard deviations show lack of control, and there is significant variation in both average level and variability from cloth to cloth.

TABLE VI

STATISTICAL RESULTS--PROGRAM II

Group	Number of Samples	Average Orifice Pressure, $\bar{x}$ (Inches of Water)	Standard Deviation,
1	10	3.50	0.25
2	6	3.41	0.48
3	6	3.16	0.25

TABLE VII

STATISTICAL RESULTS--PROGRAM III

Group	Number of Samples	Average Orifice Pressure, $\bar{x}$ (Inches of Water)	Standard Deviation,
1	10	4.091	0.302
2	9	3.677	0.287
3	9	3.468	0.244
4	9	2.066	0.191
5	9	2.802	0.1225
6	9	9.100	0.579
7	9	3.600	0.388
8	9	13.194	0.996
9	9	2.459	0.113
10	9	3.907	0.244

E. Limitations in the Analysis of Samples

It should be emphasized that in this project the representation of any one weave is by fabric from one loom in one mill. This fact limits the generalizations, based on results obtained, to comparison of these individual pieces of cloth, or to other pieces from the same loom if that loom were to be again operated under the same statistical quality control.

In view of these facts, conclusions are limited to the sample cloths supplied and application to each general type of cloth is not justifiable because of the very real possibility of significant variation in the permeability of the products of different looms, different mills, etc., manufacturing the cloth of the same weave, denier, twist, threads per inch, etc.

The program of investigation of various weaves produced on the same loom under the standarized conditions in the weave room here at Georgia Tech permits broader generalization, and the results of this study will be presented in a subsequent technical report.

VIII. LOW-PRESSURE TUNNEL AIR PERMEABILITY RESULTS

A. WADC Cloths

1. Description of Samples

Table VIII serves to provide identification for this set of ten fabrics, using the designations Fabric No. 1 through 10; the physical and textile properties for the cloths are recorded in Table IX, using the indicated designation.

2. Summary Data and Results

Figure 28 represents the graphical summary of the porosity-permeability characteristics for the 10 WADC cloths. Appendix III, Section 1 is the tabular summary of data from which Figure 28 was prepared.

TABLE VIII

IDENTIFICATION OF WADC CLOTHS*

Fabric Number	Source of Supply	Color and Type	Style
1	USAF	White Rip Stop	200-300, 118187A
2	USAF	Orange Rip Stop	200-300, 135744A
3	USAF	White Twill	000-100, 131461A
4	USAF	Camouflage Twill	081-110, 2695-05B
5	Cheney Bros.	White Finished	179362
6	Cheney Bros.	White Greige	179362A
7	Cheney Bros.	White Rip Stop Finished	176498
8	Cheney Bros.	White Rip Stop Greige	176498A
9	Duplan Corp.	White Dacron	S 111
10	Duplan Corp.	White Orlon	S 193

* Fabrics numbered 1 through 8 are nylon cloths.

TABLE IX

PHYSICAL AND TEXTILE PROPERTIES OF WADC CLOTHS

Fabric Number	1	2	3	4	5	6	7	8	9	10
Actual Width (Inches)	37-1/8	36-3/4	36-1/4	36-7/16	36-5/8	39-1/4	37	39-7/8	34-1/8	36-5/8
Construction	120x117	126x117	127x76	126x77	125x74	118x72	122x119	116x117	68x68	51x50
Warp Yarns:										
Denier	30	30	40	40	40	40	30	30	150	200
Filaments	10	10	13	13	13	13	10	10	60	80
Diameter*	0.00505	0.00483	0.00533	0.00531	0.0052	0.00547	0.00557	0.00442	0.0112	0.0131
Filling Yarns:										
Denier	30	30	70	70	70	70	30	30	150	200
Filaments	10	10	34	34	34	34	10	10	60	80
Diameter*	0.00788	0.00836	0.0118	0.0121	0.0110	0.0107	0.00812	0.00743	0.0125	0.0170
Weight										
(Oz./Yd.^{2})	1.03	1.05	1.45	1.53	1.49	1.50	1.04	0.98	2.88	2.63
(Oz./Yd.)	1.06	1.07	1.46	1.55	--	--	--	--	--	--
Grab Break: (Pounds)										
Filling	54.5	48.9	86.8	79.3	95.6	64.6	58.8	41.6	146.	109.
Warp	56.1	53.7	74.6	72.4	96.6	73.3	52.	37.5	153.	109.

TABLE IX (Continued)

PHYSICAL AND TEXTILE PROPERTIES

Fabric Number	1	2	3	4	5	6	7	8	9	10
Elongation: (Per Cent)										
Filling	38.2	38.2	44.9	32.6	43.3	27.5	36.5	18.8	26.	20.
Warp	29.9	25.9	35.3	33.2	45.7	31.0	22.2	13.8	30.5	17.5
Twist:										
Filling	1.5	1.5	1.2	1.1	1.0	0.9	0.8	0.7	8.	5.5
Warp	9.0	9.0	8.0	8.5	8.0	8.5	7.0	8.4	8.	6.0
Thickness** (Inch) Liggin	0.00245	0.00246	0.00337	0.00362	0.0034	0.00398	0.00225	0.00279	0.00526	0.00663
Densometer*** (Gurley)	7.53	7.30	5.17	5.46	5.95	3.17	7.84	3.08	6.94	5.34

*Diameter obtained from photomicrographs.

**Liggin obtained these from thickness gage readings.

***Time seconds for the passage of 350 cc of air under static pressure of 1.22 inches of water, gage.

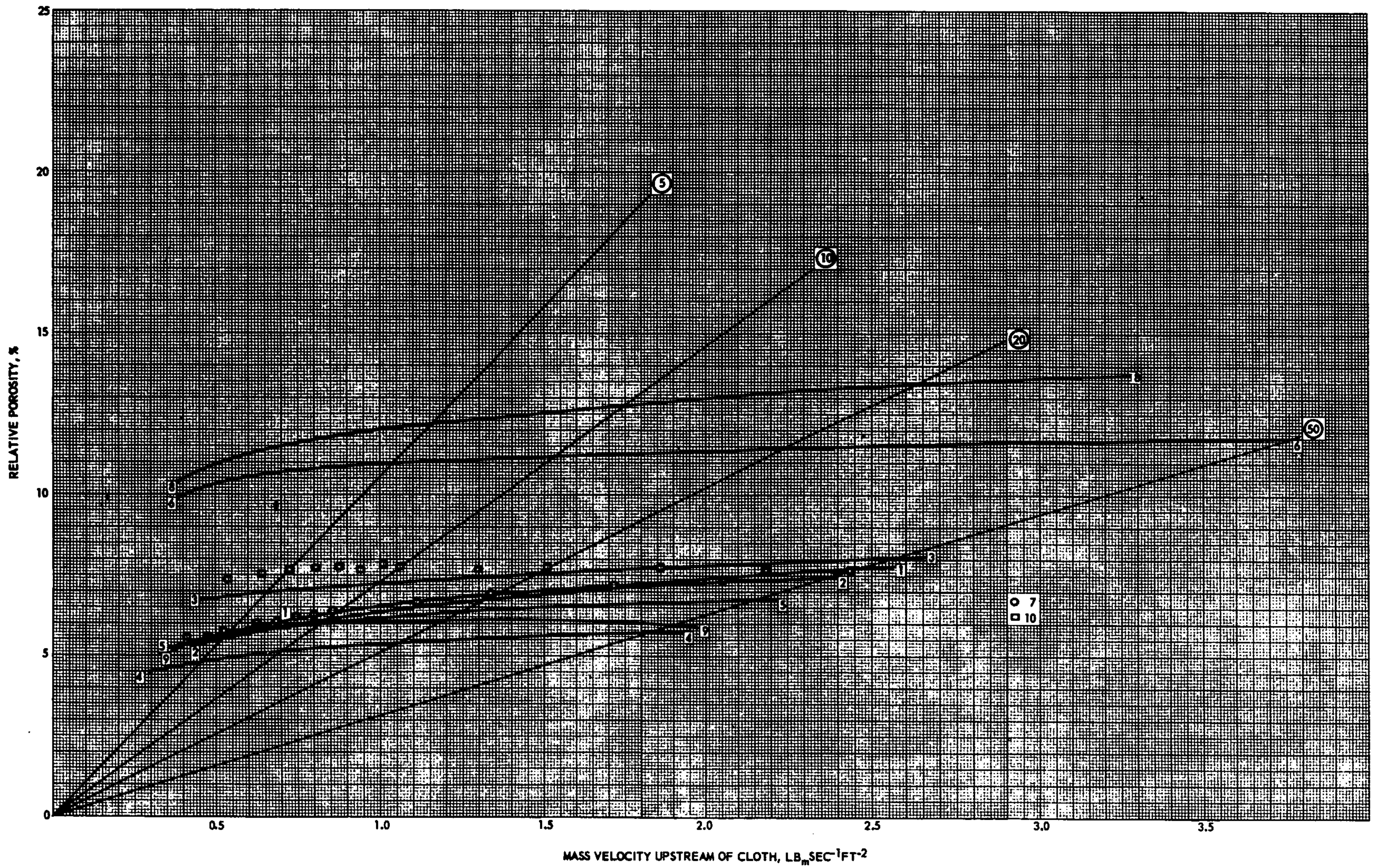


Figure 28. Porosity-Permeability Characteristics of the Ten WADC Cloths.

In view of the nature of the definition of relative porosity and its relation to mass velocity upstream of the cloth, the loci of points corresponding to a constant static pressure drop across the cloth are straight lines through the origin of coordinates. The loci for constant static pressure drops of 50, 20, 10 and 5 inches of water column are indicated. Evident from the presence of these loci on the porosity-permeability plot is the indication that an increase of pressure differential across a fabric causes a reorientation in the order of increasingly porous (and therefore permeable) fabrics. For example, at five inches of water static pressure drop in the order of increasing porosity one finds the sequence 4, 2, 5, 9, 1, 7, 3, 10, 6, 8, whereas at a 50-inch drop the ordering becomes 4, 9, 5, 2, 7, 10, 1, 3, 6, 8.

B. Bally Ribbon Cloths

1. Description of Samples

The Wright Air Development Center furnished this project with 59 nylon ribbon cloths; these had been manufactured by the Bally Ribbon Mills and were prepared incorporating different weaves, threads and picks per inch, different deniers of warp and filling threads and combinations of these. Each bolt of cloth was nine inches wide with selvage at each edge; the lot ranged from quite dense fabrics to rather open weaves of fine thread. All samples had been subjected to identical mill finishing processes; accordingly, no contribution to permeability variations was expected from this source. A summary of the specifications of the cloth as furnished by the Wright Air Development Center is given in Table X.

2. Statistical Considerations

The same statistical considerations apply to the ribbon material as were proposed for the fabrics 36 inches wide. The test equipment required a sample at least nine inches in diameter with an area of 0.2

TABLE X

IDENTIFICATION OF BALLY RIBBON CLOTHS

		Manufacturers Data					Wright Field Data		
		Thread Count Per Inch		Yarn Denier			Thread Count Per Inch		
Item Number	Mill Style	Warp	Filling	Warp	Filling	Weave	Warp	Filling	Weight (oz/yd^2)
1	7171	138	110	30/10	30/10	Plain	135	113	1.05
2	7172	"	120	"	"	"	133	122	1.08
3	7173	"	110	"	"	2/1 Twill	132	113	1.03
4	7174	"	120	"	"	"	133	125	1.09
5	7175	"	95	"	40/13	Plain	134	99	1.12
6	7176	"	105	"	"	"	137	110	1.20
7	7177	"	95	"	"	2/1 Twill	136	94	1.08
8	7178	"	105	"	"	"	135	103	1.15
9	7180	120	95	40/13	40/34	Plain	119	85	1.192
10	7181	"	105	"	"	"	118	83	1.175
11	7182	"	95	"	40/13	"	122	95	1.21
12	7183	"	105	"	"	"	123	105	1.24
13	7184	"	75	"	60/20	"	"	75	1.30
14	7185	"	85	"	"	"	125	87	1.40
15	7186	"	75	"	"	2/1 Twill	124	75	1.28
16	7187	"	85	"	"	"	125	86	1.38
17	7188	100	75	60/20	60/20	Plain	100	75	1.48
18	7189	"	85	"	"	"	102	84	1.55
19	7190	"	75	"	"	2/1 Twill	101	75	1.49
20	7191	"	85	"	"	"	"	85	1.51
21	7192	90	68	70/34	70/34	"	88	66	1.50
22	7193	"	78	"	"	"	"	78	1.60
23	7194	"	68	"	"	2/2 Twill	89	69	1.55
24	7195	"	78	"	"	"	91	71	1.68
29	7209	"	68	"	"	5 H. Satin	93	70	1.58
30	7210	"	78	"	"	"	92	80	1.67
31	7211	"	68	"	100/34	2/1 Twill	91	69	1.80
32	7212	"	78	"	"	"	91	78	1.95
33	7213	"	68	"	"	2/2 Twill	92	68	1.80
34	7214	"	78	"	"	"	90	77	1.97
35	7215	"	68	"	"	5 H. Satin	92	73	1.78
36	7216	"	78	"	"	"	94	80	1.94
37	7217	76	57	100/34	100/34	2/1 Twill	79	57	1.82
38	7218	"	67	"	"	"	79	66	2.00
39	7219	"	57	"	"	2/2 Twill	81	57	1.83
40	7220	"	67	"	"	"	79	69	2.02
45	7225	"	57	"	"	5 H. Satin	82	57	1.87

TABLE X (Continued)

IDENTIFICATION OF BALLY RIBBON CLOTHS

		Manufacturers Data					Wright Field Data		
		Thread Count Per Inch		Yarn Denier			Thread Count Per Inch		
Item Number	Mill Style	Warp	Filling	Warp	Filling	Weave	Warp	Filling	Weight (oz/yd²)
46	7226	76	67	100/34	100/34	5 H. Satin	81	67	2.00
49	7229	180	80	150/68	150/68	4x4 Basket	188	80	5.81
50	7230	"	90	"	"	"	"	92	6.11
51	7231	"	80	"	"	5 H. Satin	183	77	5.58
52	7232	"	90	"	"	"	181	76	5.52
53	7233	"	80	"	210/34	"	186	"	6.34
54	7234	"	90	"	"	"	185	78	"
55	7235	"	80	"	260/17	"	181	79	7.00
56	7236	"	90	"	"	"	185	"	7.05
57	7237	120	80	210/34	210/34	2x2 Basket	120	76	5.75
58	7238	"	90	"	"	"	"	78	5.76
59	1239	"	80	"	"	5 H. Satin	122	68	5.60
60	7240	"	90	"	"	"	120	70	5.64
61	7241	"	70	"	260/17	2x2 Basket	"	"	6.15
62	7242	"	80	"	"	"	"	80	6.64
63	7243	"	70	"	"	5 H. Satin	123	69	6.01
64	7244	"	80	"	"	"	122	72	6.11
65	7245	97	60	260/17	"	2x2 Basket	100	60	5.78
66	7246	"	70	"	"	"	102	70	6.07
67	7247	"	60	"	"	4x4 Basket	100	60	5.61
68	7248	"	70	"	"	"	99	71	6.03
69	7249	"	60	"	"	5 H. Satin	103	60	5.88
70	7250	"	70	"	"	"	"	65	6.13

Notes: Items 1/48 Inclusive: The yarns shall have approximately 1.0 turns per inch twist.

Items 49/ Inclusive: The yarns shall be twisted to produce yarns suitable for clothing fabrics.

(1) Calculated breaking strength based on 100% yarn efficiency.

square foot of cloth exposed to air flow; accordingly, there was no possibility of effecting a study of permeability variation in the filling direction. Each cloth sample, therefore, was assumed to represent the average permeability as concerns variation in filling direction. To introduce the effect of variations in warp direction, again as with the standard cloths, nine samples were taken at intervals of five yards. Finally, the handling of the data obtained was identical with the manner employed for all data derived from the low-pressure tunnel; it should be remembered that the Bally Ribbon cloths were not subjected to study in the high-pressure tunnel.

3. Data and Results

The relative porosity-permeability results for the 59 Bally Ribbon samples are presented graphically in Figures 29 to 35 and in Tables XI through XVI in Appendix III. The samples numbered BR-49 through BR-70 are not parachute weaves; accordingly, only the graphical summaries of the results for these 22 samples are presented (Figures 34 and 35), and for the purpose of this report these results are not pursued any further.

In order to facilitate the making of comparisons among the remaining 37 cloths, the relative porosity-permeability curve for each of the samples was prepared. Furthermore, the relative porosity at a pressure differential of 20 inches of water was abstracted from the individual curves, and this value was used to indicate a measure of comparison among the various weaves.

Table XI shows the effect of thread count variation on relative porosity; clearly, in each of the successive pairs of samples the two cloths differ only in the measure of thread count in the filling. In general, one observes that, upon increasing the filling thread count, the relative porosity is decreased regardless of weave, denier and warp thread count.

Table XII serves to illustrate the effect of filling thread denier variation on the relative porosity. Here increasing the filling yarn denier generally lowers the relative porosity. One can also observe the relative effects of weave; some indication of this effect can be observed among the plain 5 harness satin, 2/1 twill and 2/2 twill weaves. The effect of weave is best observed by examining Tables XIII, XIV, XV and XVI wherein comparison is made in pairs between plain and 2/1 twill, 2/1 and 2/2 twill, 2/1 twill and 5 harness satin, and 2/2 twill and 5 harness satin. Figures 29-33 are graphical summaries among the various cloths in one-to-one correspondence as concerns variables with Tables XII-XVI inclusive.

IX. HIGH-PRESSURE TUNNEL CHARACTERISTIC LENGTH STUDY

A. Theory

The complexity of the geometry of a parachute cloth precludes the prediction *a priori* of its permeability from analytical considerations of fluid mechanics. Such geometric difficulties are found to be similar to those arising in the fields of chemical engineering and mechanical engineering, wherein such problems as the flow of fluids through packed beds of particles, sweat cooling and boundary layer control are considered. In the case of parachute cloths, attempts (22) have been made to consider the cloth as a series of orifices, and a correlation based on orifice discharge coefficients has been suggested. Others (4) have attempted to consider the geometry of the cloth utilizing fabric-like structure and observing flow photographically; these conclude that a similarity can only be postulated if an applicable linear dimension is determined. Hoerner (1) argued that, if a Reynolds number could be prescribed for a flow through a cloth, then at low values of the Reynolds number viscous forces predominate, and at high Reynolds numbers dynamic forces control. Lacking in each of these presentations is any suggestion as to the appropriate length parameter that might be employed to characterize the geometry of the cloth. Green and Duwez (2), in considering the flow of fluids through porous media, obtained a measure of success in characterizing porous media through the assumption that the pressure gradient at an interior point of the flow is due to the presence of inertia and viscous contributions combined linearly. In particular they argue that the gradient takes the form $-\frac{dp}{dx} = \alpha\mu v + \beta\rho v^2$ (1) where $-\frac{dp}{dx}$, a positive quantity, is the space rate of pressure decrease in the direction of flow; here a viscous coefficient, α, has dimension negative two in length (L^{-2}), and β, the inertia coefficient, has dimension negative one in length (L^{-1}). α and β might conceivably represent, respectively, wall effect and successive channel expansions and contractions per unit length of passage. If this same assumption be employed in the consideration of air flow through parachute cloth and, furthermore, if changes in cloth geometry brought about by air loading are considered negligible, then the momentum equation written to include momentum effects on a macroscopic scale becomes

$$dp + \alpha\mu v \, dx + \beta\rho v^2 \, dx + \rho v \, dv = 0 \qquad (2)$$

Now multiplying through by ρ and by defining the mass velocity, G, as equal to the product ρv, equation (2) becomes

$$\rho \, dp + \alpha\mu G \, dx + \beta G^2 \, dx + G\rho d(\frac{G}{e}) \qquad (3)$$

Furthermore, the assumption is made that G is independent of x and that the gas has the equation of state* $\rho = P/RT$; equation (3) becomes

$$\frac{P}{RT} \, dp + \alpha\mu G \, dx + \beta G^2 \, dx - G^2 \frac{dp}{P} = 0 \qquad (4)$$

- - - - -

*Green and Duwez erroneously state that this condition implies "isothermal flow of a perfect gas."

Integration of equation (4) now under isothermal conditions over the flow length, L, taken here at the cloth thickness, gives

$$\frac{P_1^2 - P_2^2}{L} = \alpha(2\mu RT)G + (\beta + \frac{1}{L}\ln\frac{P_1}{P_2})2RTG^2 \tag{5}$$

Examination of data in the light of equation (5) appears to indicate that $\beta \gg \frac{1}{L}\ln\frac{P_1}{P_2}$; accordingly, equation (5), for the purpose of this study, takes the form

$$\frac{P_1^2 - P_2^2}{L} = \alpha 2\mu RTG + \beta 2RTG^2 \tag{6}$$

Neglecting the contribution of the term of measure $_n(\frac{1}{L}\ln\frac{P_1}{P_2}2RTG^2)$ is tantamount to saying that the momentum effects on a macroscopic scale are negligible, and, accordingly, integration of equation (1) under the restrictions G constant, $\rho = P/RT$ and isothermal flow would have given equation (6), directly.

Now the Reynolds number for the flow through the cloth can be inferred from its definition as the ratio of inertia to viscous forces at a point in the flow and from the significance of the terms in equation (1); viz.,

$$N_{Re} = \frac{\text{Inertia Force}}{\text{Viscous Force}} = \frac{\beta\rho v}{\alpha\mu} = \frac{\frac{\beta}{\alpha}G}{\mu} \tag{7}$$

where β/α, whose measure is length, is now understood to characterize the geometry of the flow through the interstices of the cloth. Furthermore, from equations (1) and (6) one can infer the existence of a dimensionless coefficient of flow-through resistance as the ratio of the sum of inertia and viscous contributions to the inertia term; viz.,

$$C_f = \frac{-\frac{dp}{dx}}{\frac{\beta\rho V^2}{2}} = \frac{\frac{\nabla P^2}{L}}{\beta RTG^2} = \frac{\frac{1}{\beta}\frac{\nabla P^2}{L}}{RTG^2} \tag{8}$$

Should the flow be confined to the viscous regime entirely, then equation (8) reduces to

$$C_f = \frac{2}{N_{Re}}. \tag{9}$$

Similarly, if inertia effects predominate, then equation (8) becomes

$$C_f = 2. \tag{10}$$

Accordingly, for the range of flows considered, equation (8) may now be written as

$$C_f = \frac{2}{N_{Re}} + 2. \tag{11}$$

This equation, then, describes completely the hydrodynamic behavior for the air flow through the parachute fabric hypothesized to have negligible deformation over the range of flows considered.

B. Experimental Results

A series of ten parachute cloths was examined in the light of the indications of equation (6), employing the test procedure and computational devices indicated earlier in this report. The ten families of results and the recommended fits are shown in Figures 36 through 45 (Appendix IV). Table IV (Appendix IV) records the values for α and β and the ratio β/α for the ten fabrics. Figure 46 serves to show the existence of a trend in a relation between α and β and the relative porosity at 20 inches of static pressure. Figure 47 is the universal plot for all the fabrics and represents the flow-through-resistance coefficient, C_f, vs. the Reynolds number based on the characteristic length β/α.

C. Discussion and Recommendation

Given a parachute fabric whose textile description is known completely, what is its behavior when subject to air flow through its interstices? If an answer to this question were available a priori, then the parachute designer could specify with certainty the performance of the parachute when its behavior was dependent upon permeability characteristics alone. The objective of this study, apart from obtaining quantitatively a measure of the permeability of various cloths in the range of pressure differentials up to 55 inches of water, was to examine the possibility of the existence of a characteristic length prescribed from hydrodynamic considerations alone. A partial answer to the question above is given in that the measure of the ratio β/α does give such a characterization. There remains as yet the problem of establishing a correlation, if one exists, between the ratio β/α and those necessary and sufficient physical designations which establish the cloth from a textile point of view. Stated differently, the flow of air through a parachute fabric presents the problem of interrelating the effects of mechanical deformation of the cloth upon the permeability and its characterization, as herein attempted. That is, as the flow of air is increased through the interstices of the cloth, the cloth will deform; thus, the geometry of the passages traversed by the air will change, and the characteristic length β/α will change.

The recommendation is made, therefore, that a study be undertaken to examine the extent of the significance and the importance of variation of geometry, due to deformation of cloth, upon its hydrodynamic characterization as herein defined.

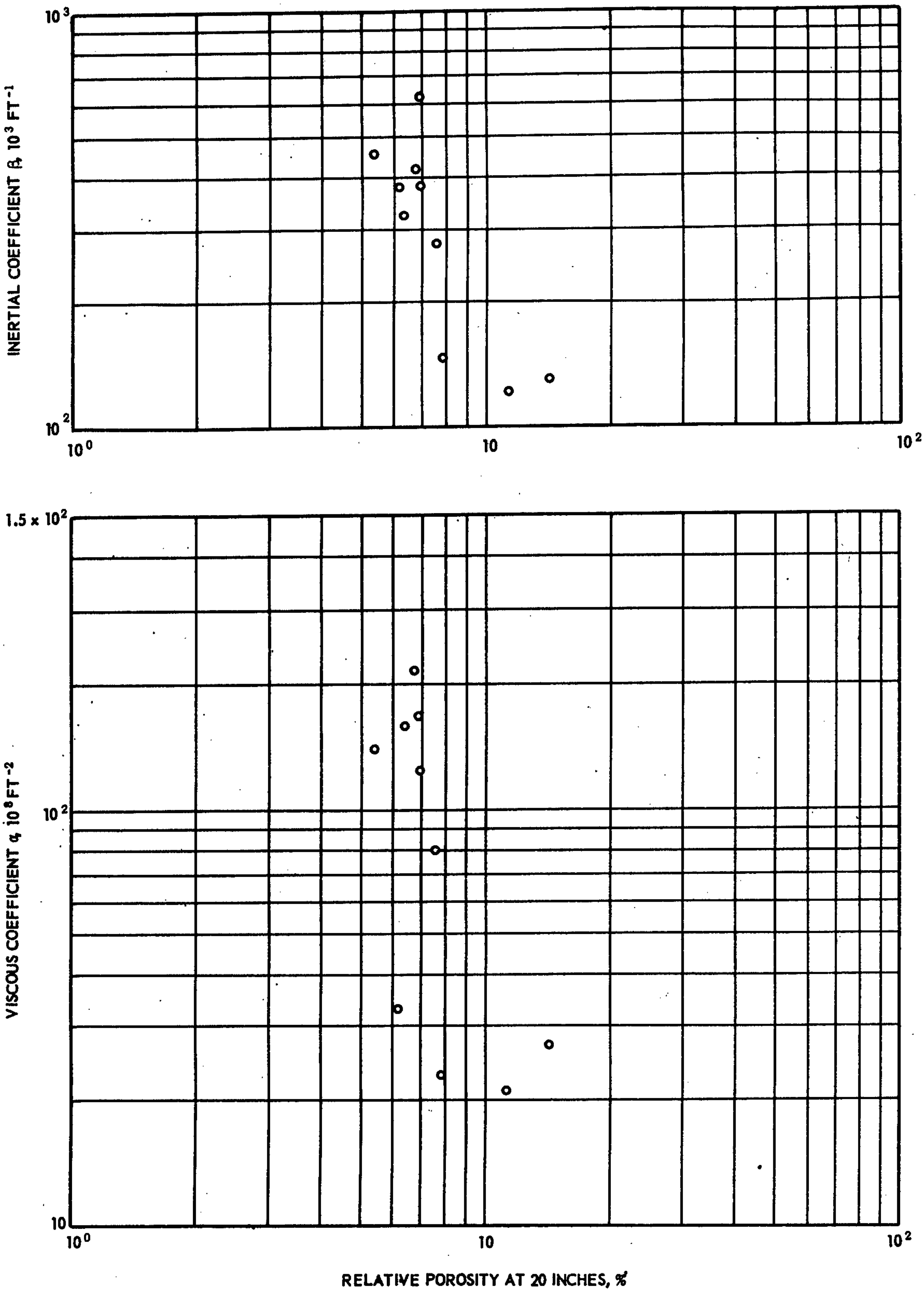


Figure 46. α and β versus Relative Porosity.

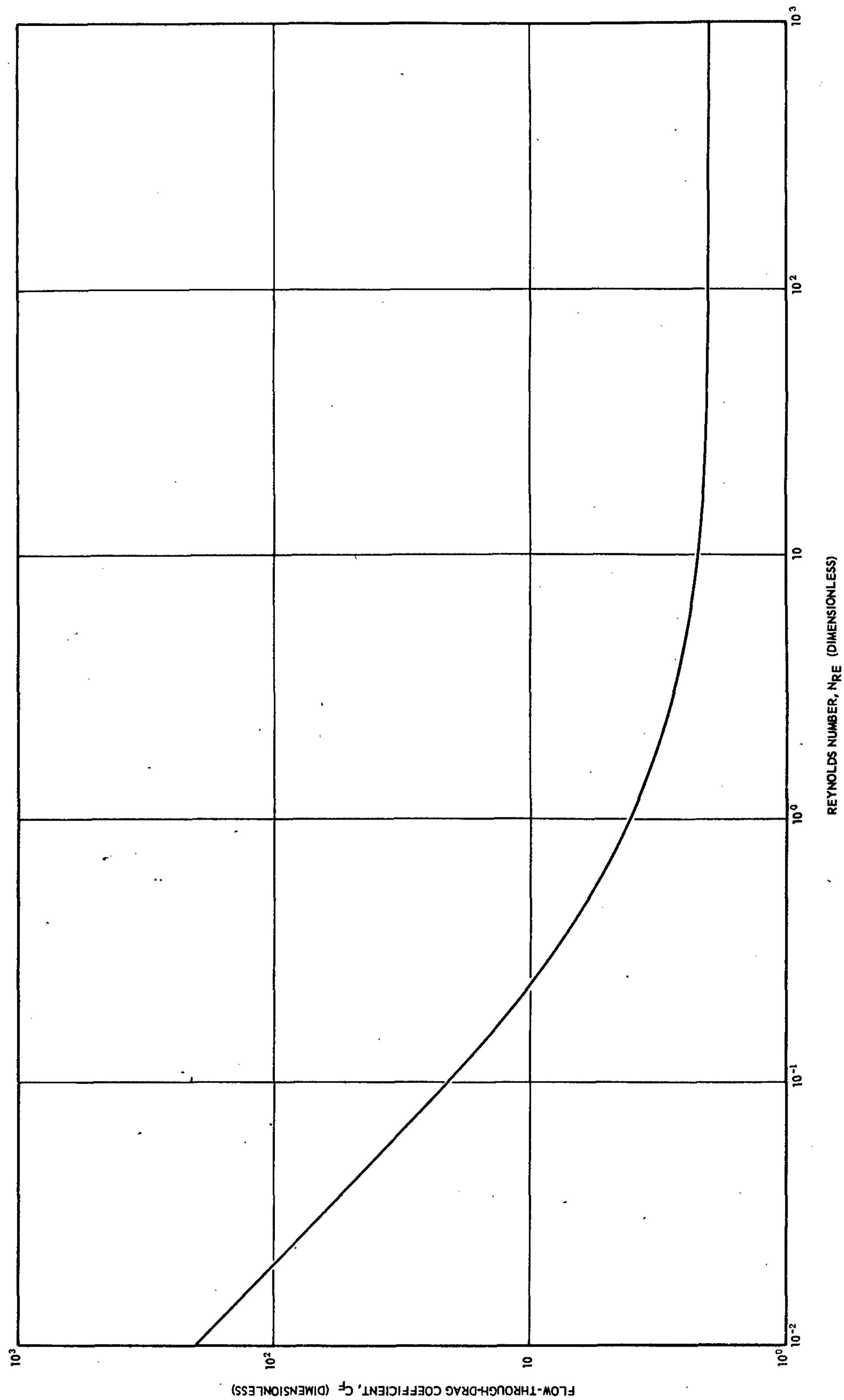


Figure 47. Relation of Flow-Through-Drag Coefficient to Reynolds Number

Appendix I

BIBLIOGRAPHY AND ABSTRACTS

I. PERMEABILITY

A. Theory

1. Hoerner, S. F., Aerodynamic Properties of Screens and Fabrics. Wright Air Dev. Center, Aerodynamics Branch, Aircraft Laboratory, Dayton, Ohio.

   Using the Reynolds number, the ratio of dynamic forces to viscous forces on a mass of flowing fluid, to characterize flow, Hoerner is able to show viscous forces to predominate at low values of N_{Re}, while at high values the dynamic forces are the controlling factor.

2. Green, Leon and Duwez, Pol, "Fluid Flow Through Porous Media." J. of App. Mech. 18, No. 1, 39-45 (March 1951).

   Paper is primarily concerned with flow through porous metals but theories are applicable to any media.

   (a) Viscous flow pressure drop can be expressed as
   $$-\frac{dp}{dx} = (\text{Constant})\left(\frac{\mu v}{\delta^2}\right)$$
   where μ = viscosity,
   v = superficial bulk velocity and
   δ = a length characterizing pore opening.

   (b) Turbulent flow pressure drop can be expressed as
   $$-\frac{dp}{dx} = (\text{Constant})\left(\frac{\rho v^2}{\delta}\right)$$
   where ρ = density.

   (c) To describe the entire range of flow (viscous, transition, turbulent) the pressure drop may be expressed as a sum:
   $$-\frac{dp}{dx} = \alpha\mu v + \beta\rho v^2$$
   where α and β contain the length term .

   (d) Granting compressibility of the fluid (ρv is constant, G), the momentum balance is $dp + \alpha v dx + \beta\rho v^2 dx + \rho v dv = 0$.

   (e) Granting perfect gas and isothermal flow, $\frac{P}{RT}\,dp + \alpha\mu G dx + \beta\frac{G^2}{g}\,dx + \frac{G^2}{g}\frac{P}{RT}\,d\left(\frac{bT}{P}\right) = 0$.

   (f) Integration over a path length L yields:
   $$\frac{\Delta(P^2)}{L} = \alpha(2RT\mu)\,G + \left[\beta + \frac{1}{L}\ln\left(\frac{P_1}{P_2}\right)\right]\left(\frac{2RT}{g}\right)G^2.$$

   (g) In the case of flow through metals, experiment showed that the momentum change term $\frac{1}{L}\ln\frac{P_1}{P_2}$ was negligible.

3. Longnecker, Kenneth W., Development of a Theoretical Formula for Calculating Air Flow Through Woven Materials Under Certain Restricted Conditions. M.S. Thesis, Lowell Text. Inst., June 1950.

Description is given of apparatus which was used to determine permeability of both screens of various mesh sizes and fabrics of different weaves. Resulting data is presented. h = 1/2 inch of water is mistakenly used in place of $h = \Delta P/W$ for air which makes his calculations questionable. For example, his reported velocities are only 1/50 of what would be expected.

4. Penner, Stuart E., A Study of Flow Through Fabric-Like Structures. M. S. Thesis, Inst. of Text. Tech., Charlottesville, Va., June 1950.

The theories of models and of similarity are utilized in designing an apparatus for observing, photographically, the mechanics of flow through orifices similar to fabric pores. The photographs so obtained were analyzed and the conclusion reached that fabric pores can be considered as orifices only if the applicable orifice dimension is determined.

5. Taylor, G. I. and Davies, R. M., Aerodynamics of Porous Sheets. Publication Board No. 92975 (Brit. Info. L, 30 Roch Place, New York 20). [Biblio. of Sci. & Ind. Reps. 10, No. 5, (Nov. 1948).]

Description of measurements of air resistance of perforated sheets, gauze and some fabrics and of the drag coefficients of flat circular sheets dropped as parachutes in air and in water. Correlation by a proposed theory is shown.

B. Apparatus

6. Draper, S., Investigation of a New Method of Determining Porosity of Fabrics, Thesis, Mass. Inst. Tech. [Text. Res. J. 18, 650-8 (1948), from Bacher's Thesis, M.I.T.]

The conclusion is drawn that, qualitatively, air permeability is directly proportional to the yarn twist and looseness of weave and inversely related to the texture, the amount of carding, the yarn diameters and the extent of fabric felting (in woolens).

7. Landsberg, M. I. and Winston, Gerald, Relationship Between Measurements of Air Permeability by Two Machines. Pub. Board 97014 (Q.M.C. TSR 35).

Deviation of the empirical relationship between the readings of the Frazier and the Gurley instruments, both commonly used for determining the air permeability of fabrics, etc. The limitations of each machine are discussed, and the number of specimens required for testing. The correlation is applied to data from both machines operating at 0.5 and 1.26 inches of water.

8. Shinkle, John H., and Morean, Arthur J., "The Apermeter, A New Air Permeability Determination Apparatus." Am. Dyestuff Reptr. 36, 245-7 (5 May 1947). [Text. Tech. Digest 4 No. 11, 459 (Nov. 1947).]

Design of the aperameter, developed at Lowell Textile Institute, is described, and the correlation of its data with results of tests with a Frazier tester is shown.

9. Teres, J., and Sharnoff, P., "Calibration of Silk Porosity Meters." Rayon Textile Monthly 20, No. 10, 589-90 (Oct. 1939). [Engineering Index (1939).]

Description by schematic diagram of the porosity meter developed by the National Bureau of Standards and adapted at Wright Field for the purpose of insuring accuracy in measuring porosity of parachute fabrics.

10. Anonymous, "Fabric-Porosity Testing Apparatus." Engineering (London) 148, No. 3856, 634 (8 Dec. 1939). (W.P.A. Bibliography on Aeronautics, Supp. 5.)

Description of a practical apparatus for rapid permeability determination. Sample is held over the end of a tube of definite cross section by rubber bands. Air is drawn through the sample by a suction pump. Reading is the pressure drop required to give 1 cubic foot per minute flow.

C. Data, For Fabrics

11. Anonymous, "Gas Permeability." Tech. News Bulletin, No. 328 51-8 (1944). [Text. Tech. Digest 1, No. 4, 3 (Sept. 1944).]

Discussion of balloon fabrics and of test methods in use at the National Bureau of Standards. Neoprene has low gas permeability.

12. Brown, W. D., Air Flow Through Materials Liable to be Used for Man-Carrying Parachutes with Special Reference to Celanese. E(RAE)TN Aero 1041 Reel 3757 Frame 905, Reel 3780 Frame 603. (Air Documents Index)

Weight, strength and porosity of substitute materials for silk in man-carrying parachutes are considered. Cotton proved superior to, nylon similar to, and Celanese inferior to silk.

13. Brown, W. D., The Effect of Tension on the Porosity of A Parachute Fabric. A.R.C., R & M 2325 (7543), Brit. Min. of Supply, T.N., Jan. 1944.

The technique of prestressing fabric samples of a cruciform shape is described, and data for pressure drop of 5 and 10 inches of water through a number of different weaves of fabrics are given.

The conclusion is reached that tensions and air pressures corresponding to flight conditions must be established in experimental testing procedures if satisfactory prediction of parachute performance is expected.

14. Clayton, F. B., "Measurement of Air Permeability of Fabrics." J. Text. Inst. 26, T171-86 (1935). [Text. Res. J. 18, 650-8 (1948), from Bacher's Thesis, M.I.T.]

Air Permeability varies linearly with twist. Increase in picks per inch from 35 to 65 resulted in a linear decrease in permeability of a plain weave fabric; above 65 the curve flattens out, indicating approach to complete closure. Air permeability was found to vary linearly also with filling count as the filling yarns were increased in size in a plain weave.

Clayton, in lieu of total air permeability, considers what he calls "sectional" air permeability which is the product of total permeability and the cloth thickness.

15. Doetsch, H., A Comparison of the Air Permeability of the Material to the Resistance of the Parachute. Z.W.B. /FBI/ 230 Reel 2717 Frame 724 (Jan. 1935). [Air Documents Index]

Tests conducted with various types of material used in the manufacture of parachutes to determine the degree of resistance offered by the different types of cloth.

16. Glaskin, A., A Statistical Note on the Variation of Porosity of Nylon Fabric to Specification D.T.D. 556A. A.R.C., R & M 2313, Brit. Min. of Supply, A.R.C., T.N. (June 1945).

A large number of porosity (permeability) measurements, at pressure drop of 9.15 inches of water, on twill and plain weave fabrics show that porosity varies across the width but not along the length of a piece of fabric. The minimum porosity occurs at the selvage and the maximum at the center of the width. In general, the average value occurs at a distance of 9 inches from the selvage. (The standard width for this specification is 36 inches.)

By a consideration of probability, it is shown that little is gained by using the average of more than 10 random measurements to establish the mean.

17. Glaskin, A., A Note on the Variation of Porosity of Cotton Fabrics to Specification D.T.D. 562 and D.T.D. 624. E/R.A.E./T.N. Aero 1664 Reel 3760 Frame 1451. [Air Documents Index]

An investigation of variation of porosity of two types of cotton fabrics used in manufacture of supply-dropping parachutes was made. Results are shown in graphs and tables.

18. Johns, T. F. and Anterson, E. I., The Porosity of Nylon Fabrics for Man-Carrying Parachutes. E/R.A.E./T.N. Aero. 1176 Reel 3564 Frame 608 (April 1943).

Recommendations for porosity for various denier yarn of parachute fabrics made of American nylon yarns are presented.

19. Marsh, M. C., "Some Notes on the Permeability of Fabrics to Air." J. Text. Inst. 22, T56-63 (1931). [Chem. Abs. 25, 5035 (1931).]

Description of an apparatus similar to that of Sale and Hedrick is given and results of its use to determine permeability of many fabrics. When a fabric is milled, its air permeability decreases markedly.

20. Rainard, L. W., "Air Permeability of Fabrics I." Text. Res. J. 16, 473-80 (1946). [Test. Res. J. 18 640-8 (1948), from Bacher's Thesis, M.I.T.]

The following relationship is established:

$$F_1 (\overline{AP}) + F_2 = Pa/\overline{AP}$$

where $\overline{AP}$ is air permeability,
Pa is pressure differential,
F_1 (slope of curve) is dependent on pore radius and number of pores per square inch, and is independent of fabric thickness, and
F_2 (intercept) is dependent on pore radius, number of interstices per inch and fabric thickness.

21. Rainard, L. W., "Air Permeability of Fabrics II." Textile Res. J. 17, 167-70 (1947). [Chem. Abs. 41, 3630h (1947).]

Discussion of the application of the Haggenbach equation to flow through fabrics. This equation applies to streamline flow through tubes with a correction for kinetic effects.

22. Robertson, A. F., Air Porosity of Open Weave Fabrics. I. Metallic Meshes. Tech. Rep. No. 1, Proj. 5007, Inst. of Text. Tech., Charlottesville, W. Va.

(a) History of Project is given.

(b) Methods of other investigators are reviewed.

(c) Open area defined as $(1 - td)^2$

where t is wires (or threads) per inch and
d is wire (or thread) diameter.

(d) It is suggested that porosity be correlated by two dimensionless groups of variables, Reynolds number, Re, and discharge coefficient, C.

$$Re = \frac{DV\rho}{\mu}$$

where D is diameter of circular orifice or width of square orifice,
V is velocity,
ρ is density and
μ is viscosity.

$$C = \frac{Q}{A_2 \left[2gh/(1-A_\circ^2)\right]^{.5}}$$

where h is pressure head of flowing fluid,
g is acceleration of gravity,
A_2 is nozzle projected open area,
A_1 is upstream flowchannel area,
$A_\circ$ is A /A and
Q is volumetric flow rate per pore.

(e) Data for screens for Re values from 4 to 1000 are presented as plots of Re vs. C, and good correlation is shown.

(f) Comparison with other data for fabrics of a plain weave shows that the correlation should apply equally well to textile fabrics.

(g) Concern is expressed over obtaining discharge coefficients greater than unity.

23. Robertson, A. F., Air Porosity of Open Weave Fabrics. II. Textile Fabrics. Tech. Rep. No. 2, Proj. 5007, Inst. of Text. Tech., Charlottesville, W. Va.

(a) Good correlation is shown for each weave except twill by plotting Re vs C (as described in previous report) for 45 different open weave fabrics over a wide range of fabric weights and porosities in the following four weave patterns: (1) plain, (2) basket, (3) moch-leno, (4) twill.

(b) Lack of correlation of the data for twill weave is attributed to much smaller open space obtained in this weave and the greater opportunity for movement of the yarns.

(c) Abnormally high discharge coefficients (mentioned in previous report) are explained by faulty technique in measurement of pressure drop across the fabric, accurate measurement of which gave reasonable values for the discharge coefficient.

(d) Accurate prediction of open area is made possible by the relation of "effective" diameter, ϕ of yarn and denier.

$$\phi = \frac{d}{(\alpha)^{1/2}}$$

where d is actual yarn diameter,
α is denier of yarn and
ϕ is a constant for a particular fabric construction.

(e) Although the twist was shown to have small effect on porosity, a standardization called the twist multiplier (TM) was defined as

$$TM = \frac{T.P.I. (\alpha)^{1/2}}{K}$$

where T.P.I. is twist in turns per inch,
α is yarn denier and
K is a dimensionless constant (which for viscose rayon is 72.8).

(f) Porosity (as used in these reports) is defined as a measure of the ability of a fabric to allow passage of fluid (A3/min A2).

24. Robertson, A. F., "Air Porosity of Open Weave Fabrics." Text. Res. J. 20, No. 12, 838-57 (Dec. 1950). [Engineering Index 51, 1622 (1951).]

Analysis of flow through metallic meshes is correlated on basis of two dimensionless ratios: Reynolds number and discharge coefficient. 45 different weaves were studied and data presented.

25. Schiefer, H. E., Cleveland, R. S., Porter, J. E., and Miller, J., "Effect of Weave on Properties of Cloth." Nat. Bur. of Stds. J. Res. 11, 441-51 (1932). [Text. Res. J. 18, 650-8 (1948), from Bacher's Thesis, M.I.T.]

Air permeability is lower in firm, closely woven cloth having a large number of thread interlacings per unit area and short floats than in cloths of the same weight which are loosely woven, sleazy, with a small number of threads interlacings per unit area and long floats. For a given texture, sateens possess the highest permeability followed in order by herring bone twill, herring bone twill--modified, oxford and plain weave.

26. Siemenske, M. A. and Hotte, G. H., "The Permeability of Fabrics I." Rayon Text. Monthly, 68-70 (Jan 1945). [Tech. Data Digest (AAF), 33 (Mar. 1945).]

Detailed bibliography and discussion of development of permeability test methods and apparatus. General methods: (1) volume of air passing through unit area in unit time, (2) back pressure at a given rate of air passage, and (3) rate of flow under a given pressure drop through fabric.

27. Siemenske, M. A. and Hotte, G. H., "The Permeability of Fabrics II." Rayon Text. Monthly, 61-2 (March 1945). [Tech. Data Digest (AAF), 36 (June, July 1945).]

(a) Permeability increases with tension in fabric.

(b) Permeability decreases with time of flow (due to dirt clogging pores, matting of fibers, etc.).

(c) Increase in temperature should result in increased permeability.

(d) No data are shown for effect of absolute pressure.

(e) Permeability at 3 per cent relative humidity was six times that at 97 per cent, with straight line relationship between.

(f) Fabric structure, in order of permeability: (1) plain weave, (2) twill, (3) satin. Foil with small orifices was 15 per cent more permeable than single orifice of area equal to sum of small orifice areas.

28. Westbrook, F. A., "Permeability of Fabrics to Air and Water Vapor." Text. Manufacturer 73, 451-3 (Oct. 1947). [Text. Tech. Digest 5 (1948).]

Test methods and results of starches on fabric permeability to air and water vapor at low velocities (fraction of an inch differential pressure).

29. Williams, K. A., Jr., The Air Permeability of Woven Fabrics. M.S. Thesis in M.E., Rensselaer Polytech. Inst., 1949.

Alteration of a commercial apparatus to measure the weight rate of flow of air through woven materials is described. Data taken with this instrument over a range of pressure drops and atmospheric conditions (temperature and humidity) for different types of weaves are presented. The flow is characterized as occurring in a fashion analogous to flow in parallel through a multiplicity of orifices. Results indicate that permeability is maximized by using a square weave with the lowest possible denier yarn, and would be minimized by use of the greatest possible denier yarn woven by a system which contained many more threads in the warp than in the weft (or vice versa).

II. PARACHUTES

A. General

30. Alkan, R., "Contributions a l'etude a lessai des Parachutes." Aeronautique 16, No. 179, 37-43 (Apr. 1934). [Engineering Index (1934).]

A study of the performance of modern parachutes, pointing out the importance of porosity and resilience of parachute tissues, tests of chronophotographic control of parachutes.

31. Anonymous, Report of Research and Experiments on the High-Speed Parachute. Tech. Intelligence, Air Mat. Com. Translation No. F-TS-430-RE, 18 July 1946.

(a) Utilization of an auxilliary parachute as an "air-brake" was investigated and abandoned due to danger of fouling main chute shroud lines.

(b) Use of loose knit fabric in area around vent at crown of chute resulted in nearly eliminating shock on opening.

(c) Improved method of folding chute into its container so as to facilitate its opening in order from skirt resulted in a reduction of 2/3g in comparison with ordinary chute.

Techniques (b) and (c) are recommended to be used simultaneously.

32. Brown, W. D. and Harrison, K., Design of Parachutes for Large Bombs. Aero. Res-Council, R & M No. 2324 (5899), A.R.C. Tech. Report.

Defining porosity as the reciprocal of air permeability (which is the pressure in pounds per square foot required to cause a flow of 14.4 cubic feet of air per minute through one square foot of material) the drag of the parachute was found to vary directly with the porosity of its material. Drag = $C_D A \frac{\rho v^2}{2}$

C_D is a function of porosity. Squidding develops at V_c which is increased in value by reducing porosity.

33. Jarnagin, L. B., Phase of Parachute Problem. U.S.A.F., Air Tech. Intell.; Tech. Data Digest 13, No. 2, 7-12 (1948). [Eng. Index (1948).]

Discussion of research and development of parachutes of high- and low-porosity fabric.

34. Johns, T. F. and Picken, J., Cotton Supplies-Dropping Parachutes: Tests with Containers Loaded to 500 Pounds. E/Royal Air Estab./ T.N. Aero 1554 Reel 3423 Frame 857 (Nov. 1944). [Air Documents Index.]

Discussion of tests on the use of a strong panel at the vent and of more porous material for the strong panel.

35. Johns, T. F., Parachute Design. Royal Aircraft Estab., Farmborough, Tech. Note No. Arm. 365, Dec. 1946.

This report is a résumé of work done on parachutes in general at the Royal Air Establishment, Farmborough, and contains the suggestion that permeability (called porosity in the report) be correlated by plotting $\frac{v}{V}$ against C_D/C_{D_o}.

where v is velocity of flow through the cloth ($v = 1/2 \rho V^2$),

V is parachute velocity,

C_{D_o} is a constant for a given type of parachute and

C_D is the drag coefficient

$$(C_D = \frac{Drag}{(1/2\rho V^2)(\frac{D^2}{4})}).$$

It is suggested that $C_D = C_{D_0}(1-2.5\frac{v}{V})$.

36. Madelung, George, Report on the Works of the Parachute Department (Forschungsanstalt Gref. Zopplin). Air Mat. Com., Tech. Intell. Summary Rept. No. F-SU-1107-ND, 20 May 1946.

The work done on parachutes in general at the institute of Flying Techniques (Germany), as well as other research on the subject of parachutes by other activities, is reviewed. Description of an innovation--the ribbon parachute--and its applications to many different uses are given. Textiles, paper and artificial materials are also discussed. Photographs of retractible and reefable parachutes in use on aircraft are included.

37. Stevens, G. W. H., Experimental Work on Parachutes Used in Air Defense Apparatus. E/Roy. Air. Estab., Rept. No. Exc. 114 Reel 3432 Frame 633 (Jan. 1942). [Air Documents Index]

Porous cloths have low drag values, but, since they are lighter, the drag-weight ratios are not appreciable different.

38. U. S. Army Air Forces (T-2 Translation), Report of Research and Experiments on the High-Speed Parachute. T-2 Translation 430, July 1946.

A special weave which reduces opening shock and methods of testing are given.

39. Weinig, F. S., The Theory of the Parachute. J.D.L. I, 620-21 (1940). [P.B. 24231]

The theory of the previous fabric parachute is given.

40. Weinig, F. S., Parachutes with Canopies Composed of Self-Supporting Ribbons. Tech. Intell., Air Mat. Com., Tech. Rept. No. F-TR-2148-ND, Oct. 1947. [G.S. - A.A.F. - Wright Field No. 22.]

Behavior during uniform descent of parachutes in general and fabric requirements are discussed. Stresses during uniform descent are relatively easily calculated, but those occurring during the opening process are difficult and are comptued from drop tests. Requirements for dynamic similarity in models are discussed. Calculations and an illustrated example for the design of a self-supporting ribbon parachute are given.

B. Theory

41. Duncan, W. J., The Cause of the Spontaneous Opening and Closing of Parachutes (The Phenomena of Squidding). Aero. Res. Council

Tech. Rept., R & M No. 2119 (7293), Dec. 1943. [Brit. Min. of Supply]

An open parachute with a porous canopy will collapse to a "squid" shape at a critical value of the relative air speed. Upon further reduction of the relative air speed the collapsed canopy will reopen at a second (lower) critical speed.

The phenomena is explained on the basis of increased porosity with increased pressure drop through the canopy. The critical speed is higher for longer shroud lines, greater porosity (or venting).

If the force of the flow of air (radically) out of the canopy, across its lip, is not greater than the inward radical component of the tension in the shroud lines, the canopy will "squid". The maximum diameter in this condition has been found to be approximately one-third of the maximum diameter (normal, full extended).

42. Duncan, W. J., Stevens, G. W. H. and Richards, G. J., Theory of the Flat Elastic Parachute. Aero. Res. Council Tech. Rept., R & M No. 2118 (5893), Mar. 1942. [Brit. Min. of Supply]

The behavior of flat parachutes under load depends largely on the elasticity of the fabric. Their form and the stresses in them are expressed mathematically by relations derived in this report. The assumption that the canopy (at least near the crown) is a surface of revolution is made. In practice, canopies usually fail at places of stress concentration, such as rigging line attachments, etc. However the tensile stress at the crown determines an upper limit of load-carrying capacity. When the greatest permissable stretch is very small, the permissible load is proportional to the fourth root of this stretch.

43. Johns, T. F. and Anterson, E. I., The Effects of Various Factors on Parachute Characteristics. Aero. Res. Council, R & M 2335, 1950. [Aero. Eng. Review 9, 65 (Oct. 1950).]

Three important factors are drag, critical opening speed and stability. Porosity causes a decrease in drag. This change is about 40 per cent over the normal range of porosities encountered in parachute textiles. Other factors have only small effect on drag coefficients.

Critical opening speed is mainly dependent on porosity, is higher when less porous fabric is used and is affected by shape of parachute. Porosity is the main factor controlling the stability of the parachute, which is improved by increased porosity and is affected by parachute shape.

44. Jones, R. A., On the Aerodynamic Characteristics of Parachutes - A Complete Account of Researches Incorporated in Various Papers

Submitted to the Advisory Committee for Aeronautics, Aero. Res. Council, A.C.R., R & M 862.

Discussion of weight analysis and shape of parachutes and stress analysis methods. Wind tunnel data on models of different shapes are given including pressure distribution and drag coefficients. Tests showed porosity had no effect on the drag coefficients.

45. O'Hara, F., "Notes on the Opening Behavior and the Opening Forces of Parachutes." Roy. Aero. Soc. J. 53, No. 467, 1053-62 (Nov. 1949). [Aero. Eng. Index]

The rate of canopy development is computed from the excess of the mean velocity of the outflow through the end and the porosity of the fabric, and the formula is used for an analysis of parachute opening forces. The critical opening speed above which the chute will "squid" depends on porosity of fabric and on the number and length of the rigging lines.

46. Scher, S. H. and Gale, L. J., Wind Tunnel Investigations of the Opening Characteristics, Drag and Stability of Several Hemispherical Parachutes (NACA). NACA Tech. Note No. 1869, April 1949.

Drag coefficients were measured and motion picture studies were made of seven different designs of parachutes (hemispherical) at air speeds up to 200 m.p.h. Drag coefficient is defined as the force of drag divided by the product of the dynamic pressure and the projected area. For a given parachute, increased air speeds generally impaired opening characteristics, lowered drag coefficients, and improved stability.

Beneficial effects on the opening characteristics were obtained with longer shroud lines relative to parachute diameter, with a strip of low porosity fabric around the canopy just above the hem line and with floating hem lines tacked to prevent the hem line loops pulling out under load.

47. Simmons, L. F. G., Gould, R. W. F. and Cowdrey, C. F., Wind Tunnel Experiments on the Squidding of Parachutes. [Aero. Res. Council R & M No. 2523 (7062), 8 Nov. 1943.]

The underlying causes of collapse of a parachute (squidding) are investigated. Pressure measurements along the surfaces of models representing squidded and fully extended parachutes were made in a wind tunnel. Both fabric and rigid sheet metal (perforated to simulate the same porosity) models were used. Squidding occurs at the air speed at which the net pressure on the lip of the chute is inward, and the chute resumes a fully extended shape only when the air speed is reduced (to a speed much lower than the critical, squidding speed) until the sum of flow pressures, tension of rigging, and hem lines, etc. is outward.

C. Textiles for Parachutes

48. Anonymous, Rot Proof Parachute Canopy Fabrics. Roy. Aircraft Estab., Farmborough, Rept. CN No. 742. [Tech. Data Digest (AAF) (Aug. 1945).]

Tests of porosity of treated fabrics by (1) Cambridge low pressure instruments and (2) Met/Ch instrument for measuring air flow at high wind speed equivalent are discussed.

49. Anonymous, "Parachutes and the New Fabrics They Require." Textile World 93, No. 10, 65-8 (Oct. 1943). [Engineering Index (1943).]

Data on rayon and nylon constructions for special textiles now being procured; physical properties of parachute fabrics are discussed.

50. Appel, W. D. and Warner, R. K., Investigation of Cotton for Parachute Cloth. NACA Tech. Note No. 393, Sept. 1931. [Engineering Index (1931).]

Development of light-weight cotton fabric of suitable air permeability for parachute manufacture is presented.

51. Bacher, Stanley, The Relationship Between the Structural Geometry of Textile Fabrics and Their Physical Properties. P.B. 95956 (Q.M.C. T.S.R. No. 52) Aug. 1948. [Biblio. of Sci. and Ind. Reptr. 11, No. 3, 249 (Mar. 1949).]

This report is a literature review with tables of data and 36 references. The relationship between structural characteristics and gas permeability is shown. [See also: Textile Res. J. 18 650-8 (1948) and Chem. Abs. 43 1193 (1949).]

52. Bartell, F. E., Purcell, W. R. and Dodd, C. G., "Measurement of the Effective Pore Size and of the Water Repellancy of Tightly Woven Textiles." Discussions of the Faraday Society 3, 257-64 (1948). [Text. Tech. Digest]

A method for the quantitative determination of effective pore size in fabrics is described and equations are given. The procedure is to apply a variable pressure differential across a fabric sample which has been wet with a liquid and so mounted that a thin layer of the liquid lies upon it. The appearance of the first bubble indicates the pressure value to be used in the given equation.

53. Brown, W. D., A Note on the Development of Artificial Silk for Parachutes with Special Reference to Their Use on U. S. Army Stores. E/Roy. Air. Estab./T.N. Aero. 1457 (June 1944) Reel 3785 Frame 997.

The development of a parachute for USA mines and fragmentation bombs is discussed, as is the recommendation of a measuring instrument developed at Farmborough for porosity determination.

54. Cleary, C. J., "Textile Materials Used in Aircraft." Silk Journal & Rayon World 17, No. 198, 21-3 (Nov. 1940). [Engineering Index (1940).]

Major technical advances and applications of textiles made during the first World War. Performance and properties of parachute fabrics.

55. Cleary, C. J., "Parachute Fabrics." Airway Age 10, No. 11, 1766-8 (Nov. 1929). [Engineering Index (1929).]

Rate at which air flows through the main sail of a parachute has a definite relation to its performance with reference to its rate of descent and its ability to withstand shock load of opening. Probable limit of permeability discussed on basis of a series of tests made. Specifications of future fabrics are discussed.

56. Hamburger, W. J., "Effect of Yarn Elongations on Parachute Fabric Strength." Rayon Textile Monthly 23 No. 3, 151-3, No. 5, 291-2, No. 6, 332-4 (1942). Also Silk J. & Rayon World 19, No. 222, 27-9 (1942). [Engineering Index (1942).]

Resistance to impact in canopy fabrics is discussed, and a brief review of various types of textile fabrics is given.

57. Heinrich, Helmut, Tests on Stability of Parachutes and Development of Parachutes of Standard Permeable Fabrics. P. B. 37256 (1943).

Development of a new ribbon-like structure for parachutes is described.

58. Johns, T. F. and Hallum, M. E., Note on the Useful Life of Silk Parachutes Used by Paratroops. E/Roy Aircraft Estab./T.N. Aero 1405 Reel 3653 Frame 658 (1944). [Air Documents Index]

After 25 descents parachutes showed sufficient increase in porosity to necessitate discarding.

59. McNicholas, H. J. and Hedrick, A. F., The Structure and Properties of Parachute Cloths. N.A.C.A. T.N. No. 335 March 1930. [Engineering Index (1930.]

Requisite properties of parachute fabrics and methods for measuring them are discussed. Comparison of domestic and imported fabrics showed the superiority in some respects of domestic materials. Specifications for manufacture are given.

60. Pierce, F. T., "Geometrical Principles Applicable to the Design of Functional Fabrics." Textile Research Journal 17, 123-47 (1947). [Text. Res. J. Abs. 18, 650-8 (1948), from Bacher's Thesis, M.I.T.]

Flow resistance is primarily a function of warp cover factor, provided the weave is firm enough to hold the close warp yarns firmly in place. Flow is proportioned to the pressure drop per unit thickness for any shape cross section.

D. Further References

61. Anonymous, "Navy Testing American Silk Cloth for Parachutes." U.S. Air Services 12, No. 5, 27 (May 1927). [W.P.A. Bibliography on Aeronautics, p. 24.]

62. Anonymous, Physical Characteristics of Parachute Cloth Under Varying Atmospheric Conditions. U. S. Gov't. Printing Office, Air Corps Info. Circular No. 651, 1930. [W.P.A. Bibliography on Aeronautics, p. 24.]

63. Battles, H. G., Neoprene Coated Nylon Rip-Stop Parachute Fabric. P.B. 95555 (Sept. 1948). [Biblio. of Sci. & Ind. Reptr. 11, No. 1 (Jan. 1949).]

64. Black, J., "Trustworthiness in Fabrics Vital in Parachute Use." Textile World 78, No. 4, 28-30 (26 July 1930). [Engineering Index (1930).]

65. Holgate, B. A., Parachutes and Parachute Materials Used in Germany. F.I.A.T. 465 (P.B. 3882) 1945. [F.I.A.T. Reptr. Office of Tech. Serv., Dept. of Comm., Jan. 1948.]

66. Johns, T. F., Parachutes with an Axial Cord as Well as Cords Over the Canopy. A.R.C. R & M 2336, 1944.

67. Laroso, P. and Burton, A. C., Parachutes. B.I.O.S. Evaluation Rept. 477 Mar. 1946. [Bibliography of Sci. & Ind. Reptr.]

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Appendix II

COMPARISON OF GEORGIA TECH AND WADC HANDLING OF DATA

COMPARISON OF GEORGIA TECH AND WADC HANDLING OF DATA

The following remarks are submitted to facilitate the reduction of GIT data to the manner employed by WADC or vice versa.

1. WADC Technique

The permeability data made available by experiments at WADC is currently summarized graphically by plotting the quantity $\sqrt{\frac{q}{\nabla p}}$ versus ∇p for each parachute fabric. The definition of each of these quantities is given in terms of the observed pressure drop imposed across the cloth to produce a time rate of flow of air--the permeability, $\mathcal{P}$,--measured in cubic feet (at a standard temperature, pressure and relative humidity) per unit area of cloth exposed to the air flow.

1. Assume that the permeability $\mathcal{P}$ is measured, for example, in ft^3 sec^{-1} ft^{-2}, and
2. That the corresponding pressure drop ∇p is given in lb_f ft^{-2}.
3. Now define the dynamic head as

$$q = \frac{\rho \mathcal{P}^2}{2}$$

4. Also define the pressure drop in terms of a velocity of descent, i.e., in terms of the relative velocity V between a falling parachute cloth and still air a great distance from the cloth; viz.,

$$\nabla p = \frac{\rho V^2}{2}$$

5. In both (3) and (4) ρ is the actual air density in the undisturbed air; ρ may be assumed constant throughout the field of flow. The quantity $\sqrt{\frac{q}{p}}$ then becomes equal to

$$\frac{\mathcal{P}}{\sqrt{\frac{2\nabla p}{\rho}}},$$

The plotting of $\frac{q}{p}$ versus the pressure drop ∇p results in a characteristic variation for a particular cloth.

2. Georgia Tech Technique

The data obtained in the low-pressure tunnel at the Georgia Institute of Technology are reduced to show the variation of what is termed the relative porosity with the mass velocity, G, of the air upstream of the cloth. The relative porosity is dimensionless, and G is measured in units of pounds mass per second per square foot of cloth.

Flow data obtained from the orifice permit the calculation of the mass rate of air flow, M, through the cloth. Given the effective projected area, A, of the cloth subjected to this air flow, the quantity G results as the ratio M/A.

Now M must equal the air flow through the cloth; this, in turn, might be expressed in terms of a product of an effective open area for the cloth, (a), a corresponding velocity, v, and an air density ρ, viz.,

$$M = \rho_2 a v_2.$$

Furthermore, M has a measure given by a corresponding product AV_1, where (a) is the effective projected area of the cloth sample and V_1 is the velocity of approach of the air. Thus, the continuity equation becomes

$$\rho_2 a v_2 = \rho_1 A V_1.$$

Under conditions of operation for the low-pressure tunnel ($p \leq 50$ inches of water), the density ρ may be taken as a constant; then continuity reduces to

$$\frac{V_1}{v_2} = \frac{a}{A}.$$

V_1/V_2 is termed the relative porosity in view of the significance of the ratio a/A. In order to evaluate the relative porosity, V_1 and v must be measured. V_1 is given by the equation $V_1 = \frac{M}{A\rho} = \frac{G}{\rho}$; and v is arbitrarily taken as $\sqrt{2\frac{\nabla p}{\rho}}$ where ∇p is the pressure drop across the cloth. Thus, there results the equality

$$\frac{a}{A} = \frac{V_1}{\sqrt{2\frac{\nabla p}{\rho}}}$$

A plot of relative porosity, $\frac{a}{A}$ vs. mass velocity upstream of the cloth results in a characteristic variation for each fabric.

3. Comparison

In the case of the independent variables, the WADC data are referenced to the pressure drop ∇p across the cloth, whereas the Georgia Tech data are examined as a function of the mass velocity G upstream of the cloth. The choice of G stems from the fact that upon establishing a characteristic length, L, to describe the geometry of the fabric an immediate conversion to a Reynolds number would be possible, viz.,

$$N_{Re} = \frac{GL}{\mu}.$$

Thus, plotting versus G is in effect plotting versus the Reynolds number, since μ is essentially constant for any one test procedure.

Now in the case of the dependent variables $\sqrt{\frac{q}{\nabla p}}$ and a/A, these are dimensionless and are related in the following manner as can easily be shown:

$$\sqrt{\frac{q}{\nabla p}} = \frac{a}{A} \cdot \frac{\rho_s}{\rho}$$

where ρ_s is the air density at standard conditions corresponding to WADC determination and ρ is that of Georgia Tech determinations. Since the Georgia Tech data reported includes the density variation, the interconversion of data is immediately possible.

Clearly, then, the two methods of handling the low-pressure data are simply related. The Georgia plot includes the pressure drop variation (see Low-Pressure Tunnel Air Permeability plot for 10 WADC cloths, Fig. 28) which appears as the independent variable for the WADC procedure. Furthermore, the Georgia Tech plot is essentially a nondimensional plot. Neither of these plots, however, is as general as the flow-through-drag coefficient vs. Reynolds number (C_f, N_{Re}) plot proposed in this report.

Appendix III

POROSITY-PERMEABILITY RESULTS FROM THE LOW-PRESSURE TUNNEL

Tabular Summary of Data for Figure 28

Static Pressure Upstream of Cloth (Inches Water)	Air Density Upstream of Cloth ($lbm\ ft.^{-3}$)	Mass Velocity of Air Upstream of Cloth ($lbm\ sec.^{-1} ft.^{-2}$)	Relative Porosity of Cloth (Per Cent)
Fabric Number 1			
50	.0753	2.44	7.7
40	.0737	2.1	7.5
30	.0721	1.74	7.2
20	.0702	1.34	6.86
15	.0694	1.11	6.64
10	.0686	.85	6.3
9	.0683	.8	6.23
8	.0683	.74	6.10
7	.0680	.68	6.04
6	.0680	.61	5.88
5	.0678	.54	5.68
4	.0675	.467	5.47
Fabric Number 2			
50	.0756	2.37	7.4
40	.0740	2.04	7.24
30	.0724	1.7	7.04
20	.0707	1.31	6.68
15	.0696	1.08	6.43
10	.0688	.84	6.15
9	.0688	.725	5.63
8	.0686	.72	5.93
7	.0683	.655	5.76
6	.0683	.60	5.72
5	.068	.535	5.51
4	.068	.458	5.36
Fabric Number 3			
50	.075	2.53	8.04
40	.0734	2.19	7.82
30	.0718	1.85	7.73
20	.0704	1.45	7.48
15	.0694	1.23	7.31
10	.0685	.975	7.19
9	.0685	.923	7.20
8	.0680	.858	7.11
7	.0680	.80	7.10
6	.0680	.735	7.02
5	.0675	.635	6.93
4	.0675	.590	6.93
3	.0671	.498	6.78

Tabular Summary of Data for Figure 28 (Continued)

Static Pressure Upstream of Cloth (Inches Water)	Air Density Upstream of Cloth (lbm ft.$^{-3}$)	Mass Velocity of Air Upstream of Cloth (lbm sec.$^{-1}$ft.$^{-2}$)	Relative Porosity of Cloth (Per Cent)
Fabric Number 4			
50	.0758	1.83	5.73
40	.0741	1.59	5.61
30	.0724	1.33	5.48
20	.0707	1.05	5.36
15	.0698	.880	5.27
10	.069	.685	5.04
9	.0688	.640	4.97
8	.0687	.600	4.95
7	.0685	.550	4.86
6	.0684	.500	4.76
5	.0681	.445	4.67
4	.068	.390	4.59
3	.0678	.337	4.56
Fabric Number 5			
50	.0755	2.11	6.67
40	.0738	1.83	6.52
30	.0721	1.53	6.38
20	.0704	1.21	6.28
15	.0695	1.02	6.14
10	.0687	.801	5.92
9	.0685	.755	5.85
8	.0684	.70	5.82
7	.0682	.645	5.72
6	.068	.585	5.58
5	.0678	.524	5.52
4	.0677	.465	5.45
3	.0675	.393	5.40
Fabric Number 6			
50	.0753	3.77	11.8
40	.0737	3.29	11.7
30	.0721	2.78	11.5
20	.0702	2.20	11.3
15	.0694	1.88	11.3
10	.0686	1.51	11.1
9	.0683	1.42	11.0
8	.0683	1.33	11.0
7	.068	1.24	11.0
6	.068	1.14	10.9
5	.0678	1.04	11.0

Tabular Summary of Data for Figure 28 (Continued)

Static Pressure Upstream of Cloth (Inches Water)	Air Density Upstream of Cloth ($lbm\ ft.^{-3}$)	Mass Velocity of Air Upstream of Cloth ($lbm\ sec.^{-1} ft.^{-2}$)	Relative Porosity of Cloth (Per Cent)
Fabric Number 6 (Continued)			
4	.0675	.920	10.9
3	.0675	.790	10.7
2	.0672	.630	10.5
1	.0669	.427	10.1
Fabric Number 7			
50	.075	2.40	7.58
40	.0734	2.05	7.29
30	.0718	1.72	7.16
20	.0704	1.34	6.88
15	.0694	1.11	6.62
10	.0685	.855	6.33
9	.0685	.800	6.26
8	.068	.745	6.15
7	.068	.685	6.03
6	.068	.625	6.00
5	.0625	.525	5.74
4	.0678	.473	5.57
3	.0671	.409	5.58
Fabric Number 8			
50	.0754	4.53	14.3
40	.0738	3.93	13.9
30	.0721	3.31	13.8
20	.0703	2.59	14.1
15	.0695	2.19	13.1
10	.0687	1.73	12.7
9	.0685	1.63	12.6
8	.0683	1.52	12.6
7	.0681	1.41	12.5
6	.068	1.29	12.3
5	.0678	1.17	12.2
4	.0677	1.02	11.9
3	.0675	.87	11.8
2	.0673	.685	11.4
1	.0672	.461	10.8
Fabric Number 9			
50	.0756	1.90	5.95
40	.0739	1.72	6.09

Tabular Summary of Data for Figure 28 (Concluded)

Static Pressure Upstream of Cloth (Inches Water)	Air Density Upstream of Cloth ($lbm\ ft.^{-3}$)	Mass Velocity of Air Upstream of Cloth ($lbm\ sec.^{-1} ft.^{-2}$)	Relative Porosity of Cloth (Per Cent)
Fabric Number 9 (Continued)			
30	.0723	1.48	6.11
20	.0705	1.18	6.10
15	.0697	1.02	6.11
10	.0688	.815	5.99
9	.0687	.765	5.96
8	.0685	.715	5.91
7	.0683	.660	5.84
6	.0682	.600	5.73
5	.068	.540	5.68
4	.0678	.468	5.51
3	.0676	.387	5.23
Fabric Number 10			
50	.0760	2.44	7.63
40	.0743	2.18	7.70
30	.0726	1.86	7.73
20	.0709	1.51	7.75
15	.0701	1.30	7.73
10	.0692	1.06	7.77
9	.0691	1.01	7.82
8	.0689	.935	7.66
7	.0687	.875	7.73
6	.0686	.810	7.70
5	.0684	.725	7.62
4	.0682	.640	7.48
3	.068	.540	7.33

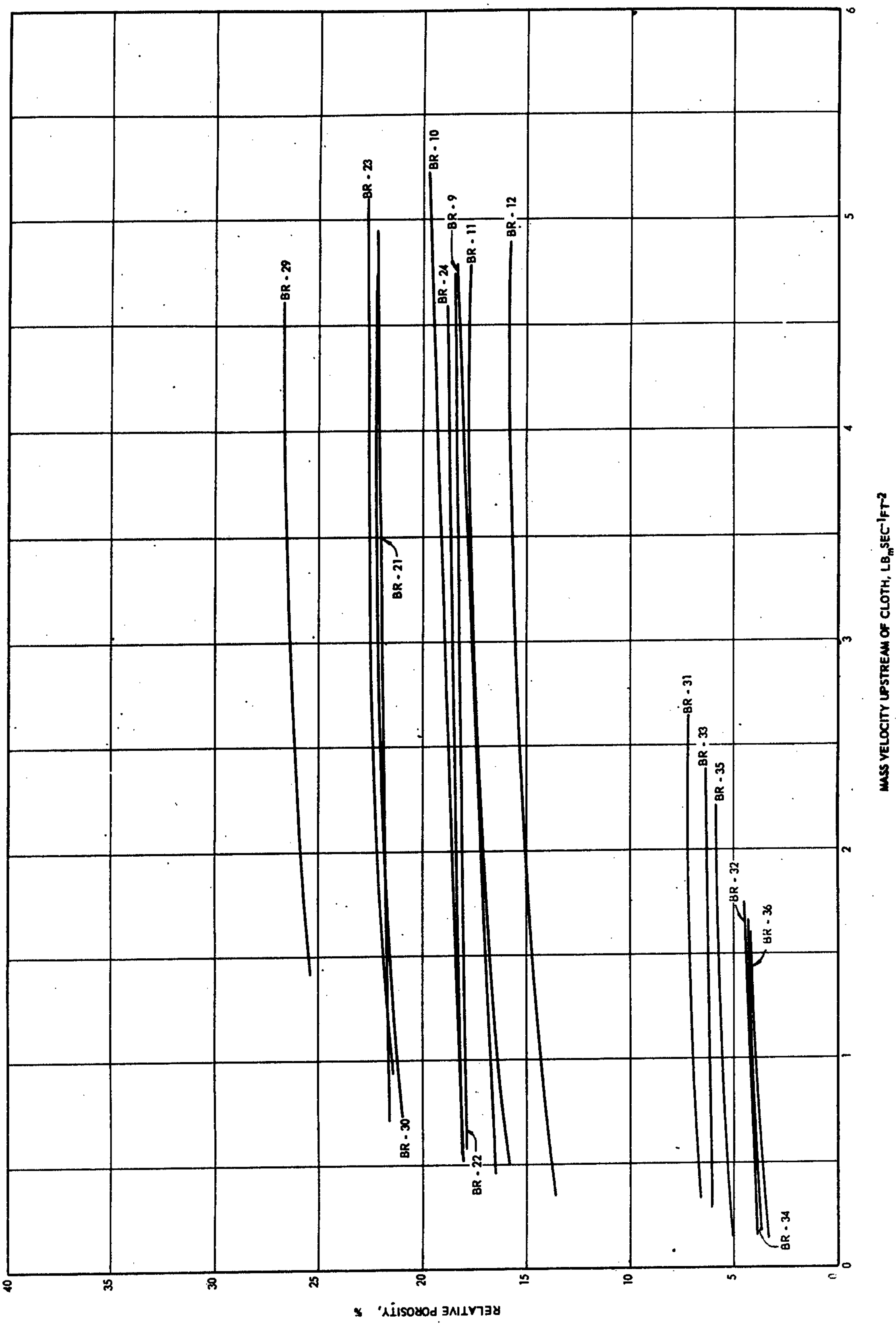


Figure 29. The Effect of Filling Thread Denier on Relative Porosity.

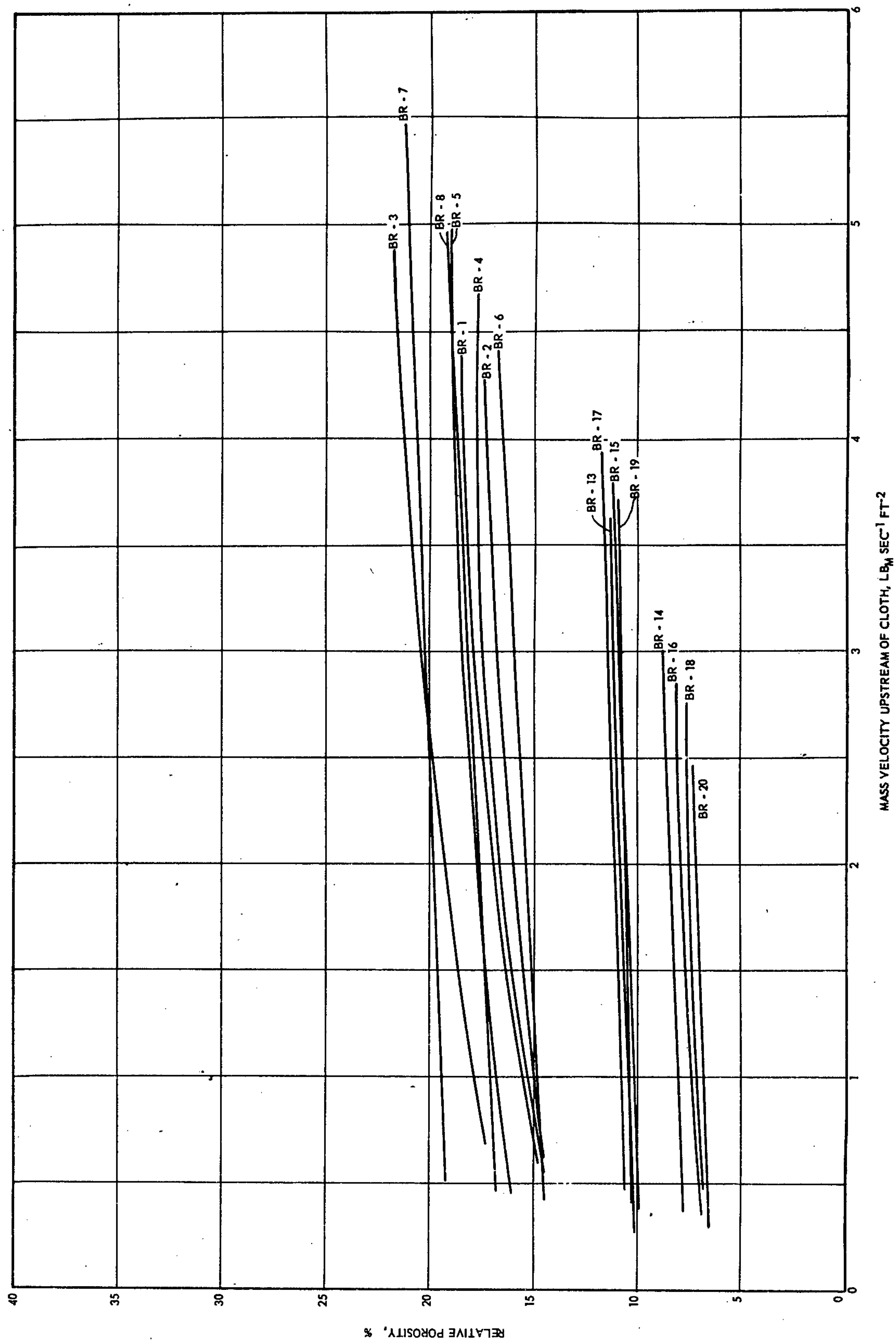


Figure 30. The Effect of Type of Weave (Plain and 2/1 Twill) on Relative Porosity.

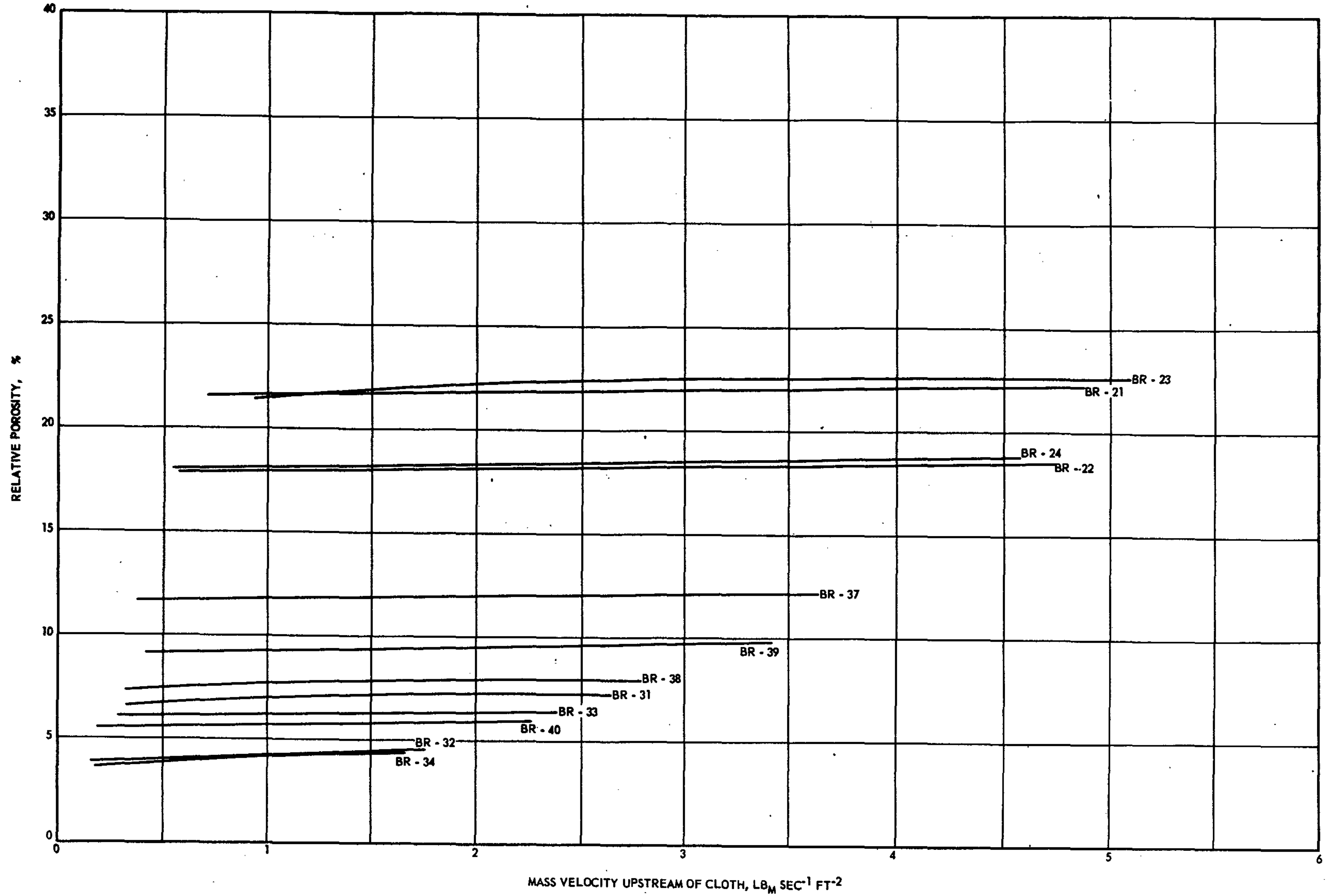


Figure 31. The Effect of Type of Weave (2/1 and 2/2 Twill) on Relative Porosity.

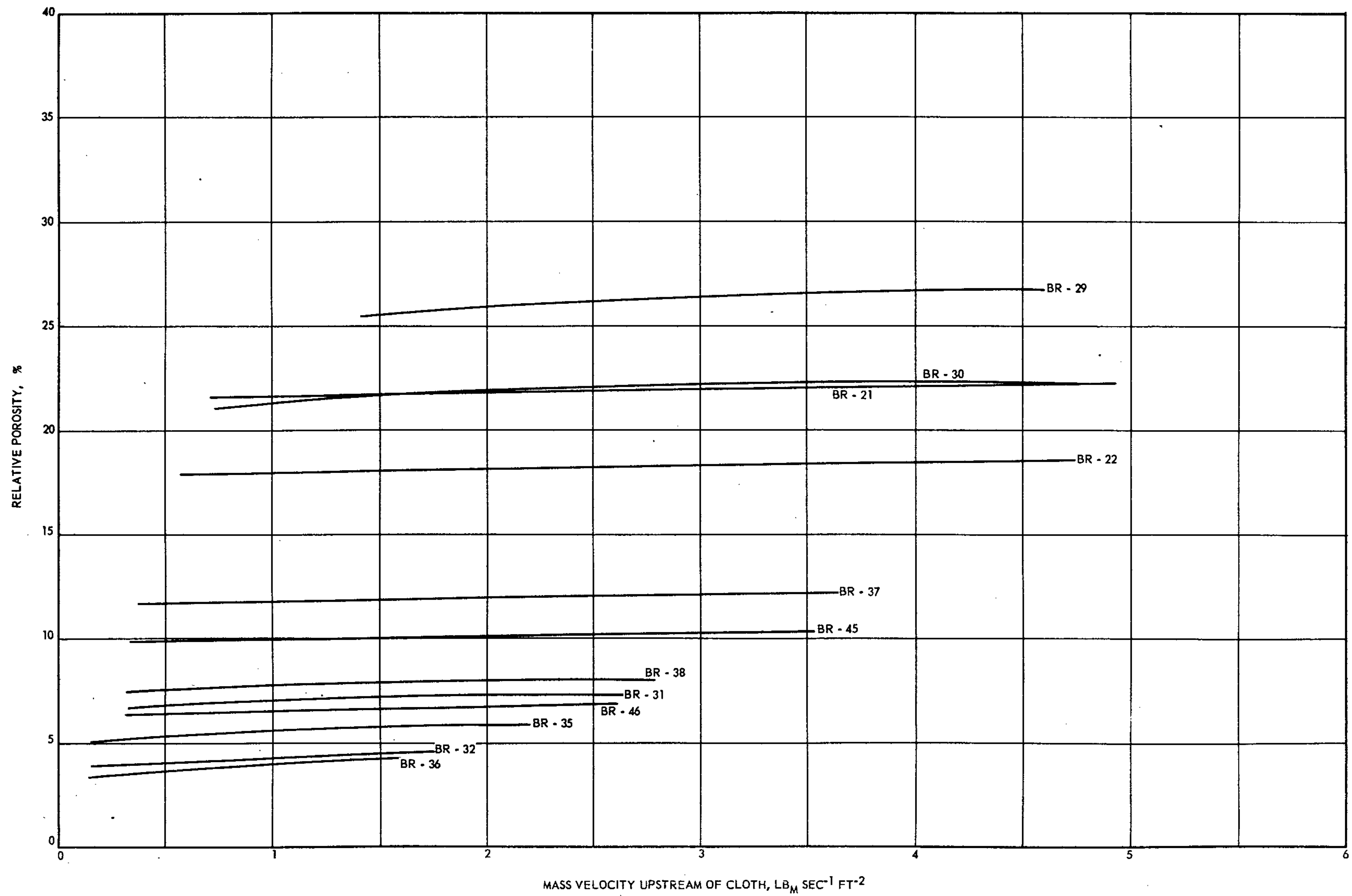


Figure 32. The Effect of Type of Weave (2/1 Twill and 5 Harness Satin) on Relative Porosity.

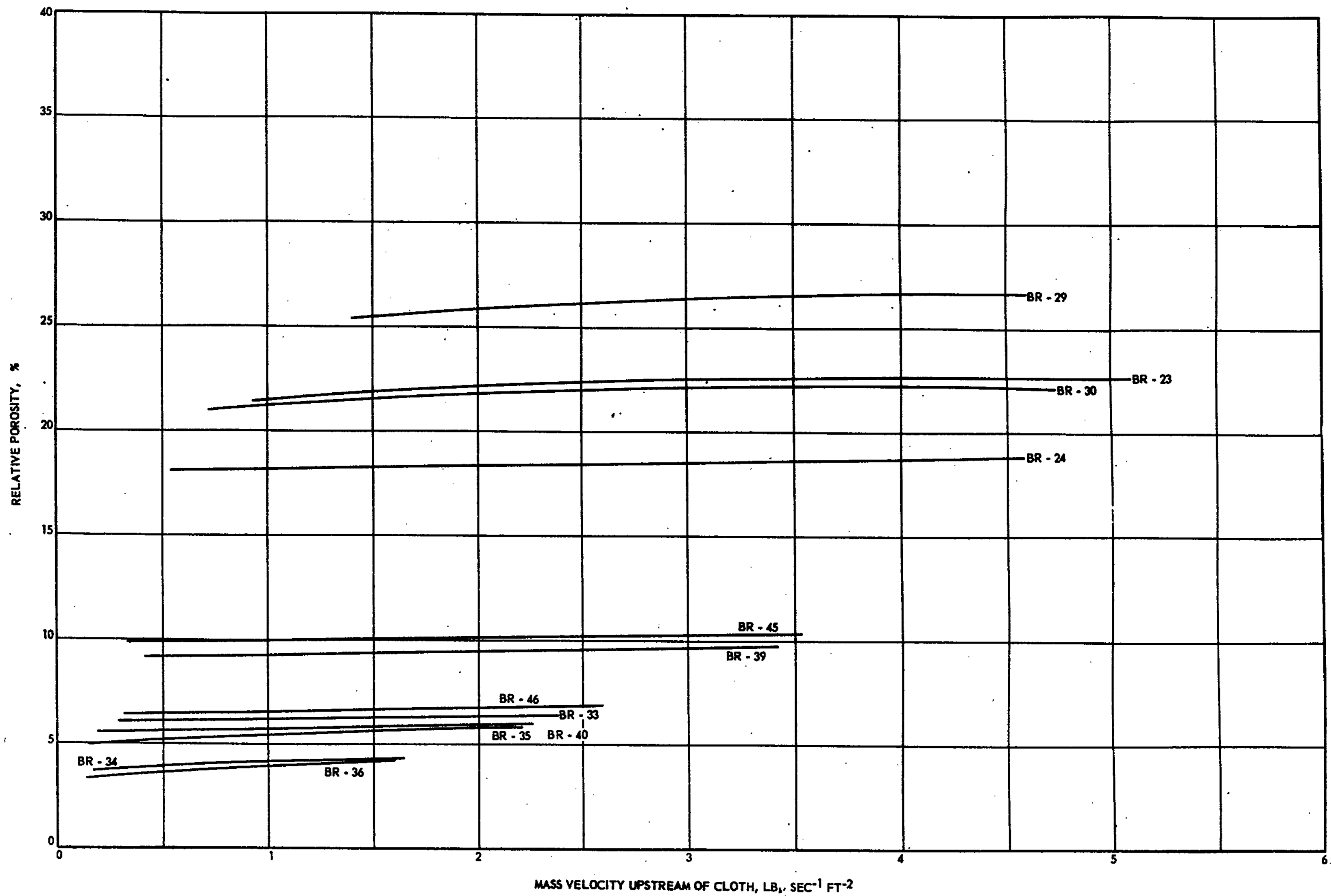
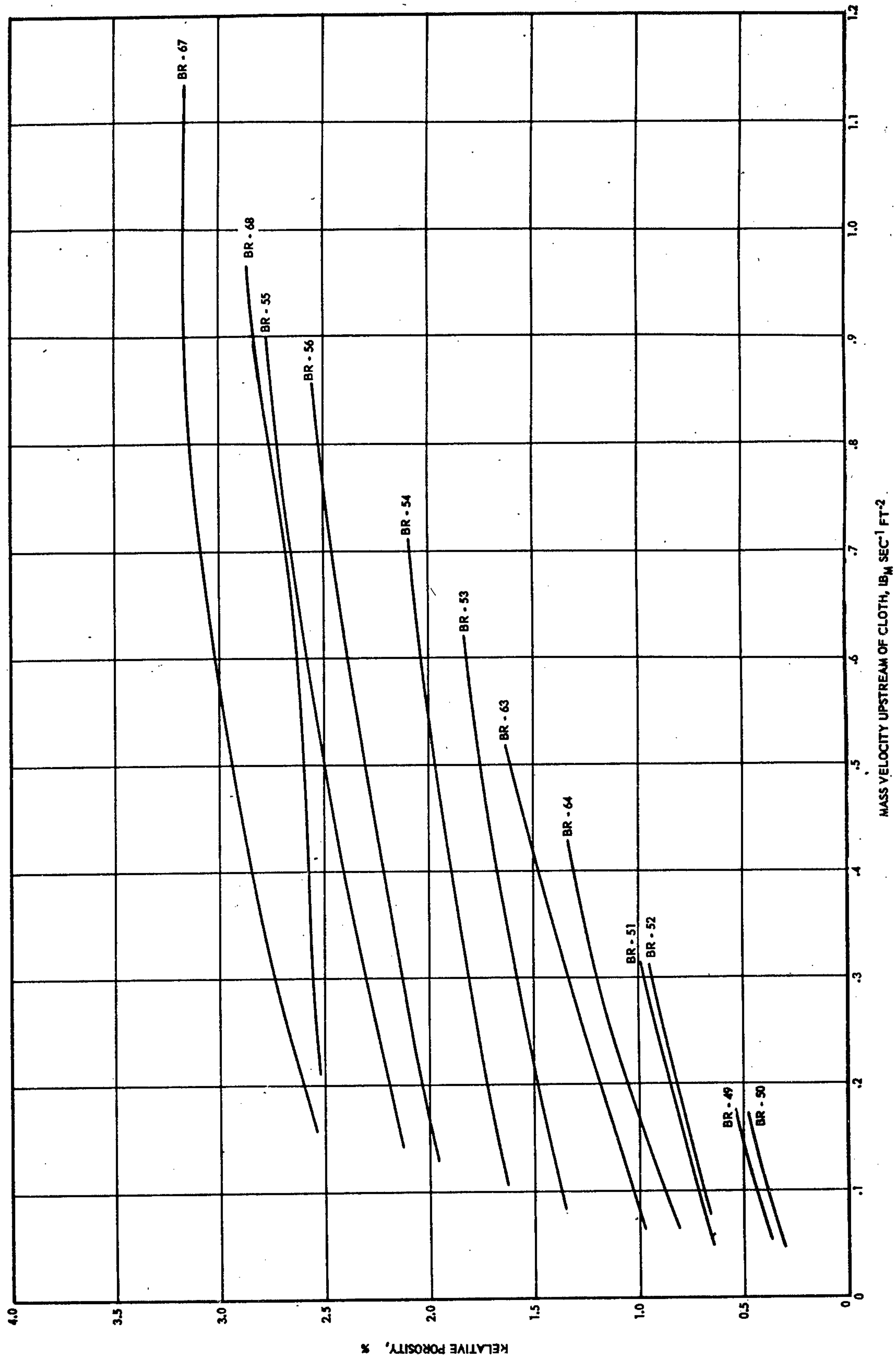


Figure 33. The Effect of Type of Weave (2/2 Twill and 5 Harness Satin) on Relative Porosity.


BR - 67
BR - 68
BR - 55
BR - 56
BR - 54
BR - 53
BR - 63
BR - 64
BR - 51
BR - 52
BR - 49
BR - 50
MASS VELOCITY UPSTREAM OF CLOTH, LB_M SEC^-1 FT^-2
RELATIVE POROSITY, %
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2

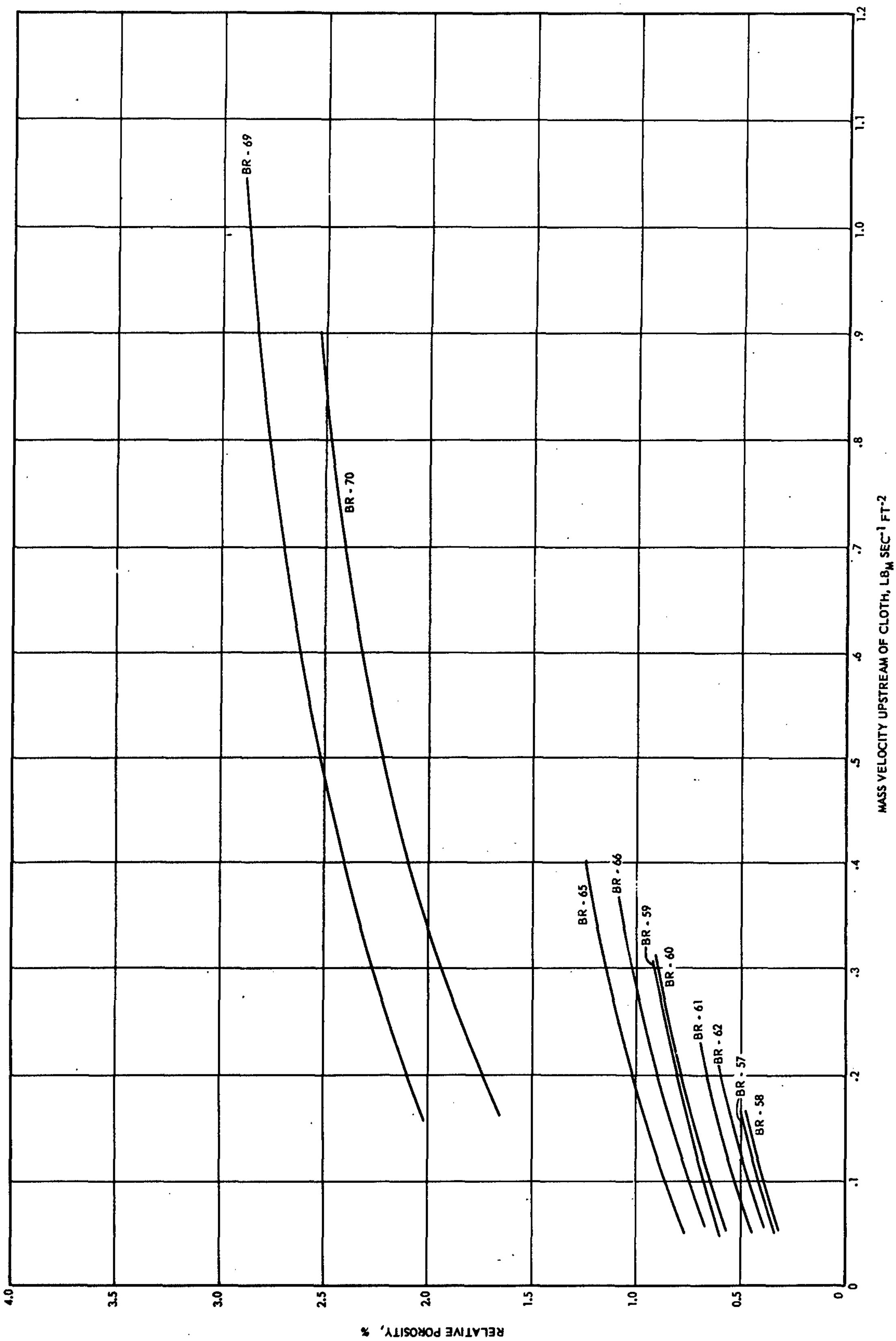


Figure 35. Porosity-Permeability Characteristics of 10 Bally Ribbon Mills Samples.

TABLE XI

THE EFFECT OF FILLING THREAD COUNT VARIATION ON RELATIVE POROSITY

Relative Porosity (20 Inches Water)	Item Number	Mill Style	Specification Thread Count Per Inch Warp	Filling	Yarn Denier Warp	Filling	Weave
17.9	BR-1	7171	138	110	30/10	30/10	Plain
16.8	BR-2	7172	"	120	"	"	"
21.5	BR-3	7173	138	110	30/10	30/10	2/1 Twill
17.4	BR-4	7174	"	120	"	"	"
18.7	BR-5	7175	138	95	30/10	40/13	Plain
15.8	BR-6	7176	"	105	"	"	"
20.8	BR-7	7177	138	95	30/10	40/13	2/1 Twill
18.5	BR-8	7178	"	105	"	"	"
17.7	BR-9	7180	120	95	40/13	40/34	Plain
19.2	BR-10	7181	"	105	"	"	"
17.7	BR-11	7182	120	95	40/13	40/13	Plain
15.4	BR-12	7183	"	105	"	"	"
10.8	BR-13	7184	120	75	40/13	60/20	Plain
8.25	BR-14	7185	"	85	"	"	"
10.6	BR-15	7186	120	75	40/13	60/20	2/1 Twill
7.72	BR-16	7187	"	85	"	"	"
11.2	BR-17	7188	100	75	60/20	60/20	Plain
7.38	BR-18	7189	"	85	"	"	"
10.6	BR-19	7190	100	75	60/20	60/20	2/1 Twill
7.03	BR-20	7191	"	85	"	"	"
22.1*	BR-21	7192	90	68	70/34	70/34	2/1 Twill
18.4*	BR-22	7193	"	78	"	"	"
22.6*	BR-23	7194	90	68	70/34	70/34	2/2 Twill
18.7	BR-24	7195	"	78	"	"	"

TABLE XI (Continued)

THE EFFECT OF FILLING THREAD COUNT
VARIATION ON RELATIVE POROSITY

Relative Porosity (20 Inches Water)	Item Number	Mill Style	Specification Thread Count Per Inch		Yarn Denier		Weave
			Warp	Filling	Warp	Filling	
26.7**	BR-29	7209	90	68	70/34	70/34	5 Har. Satin
22.3	BR-30	7210	"	78	"	"	"
7.14	BR-31	7211	90	68	70/34	100/34	2/1 Twill
4.28	BR-32	7212	"	78	"	"	"
6.25	BR-33	7213	90	68	70/34	100/34	2/2 Twill
4.71	BR-34	7214	"	78	"	"	"
5.48	BR-35	7215	90	68	70/34	100/34	5 Har. Satin
3.79	BR-36	7216	"	78	"	"	"
11.9	BR-37	7217	76	57	100/34	100/34	2/1 Twill
7.62	BR-38	7218	"	67	"	"	"
9.39	BR-39	7219	76	57	100/34	100/34	2/2 Twill
5.81	BR-40	7220	"	67	"	"	"
10.1	BR-45	7225	76	57	100/34	100/34	5 Har. Satin
6.56	BR-46	7226	"	67	"	"	"

*Interpolated value.

**Extrapolated value.

TABLE XII

THE EFFECT OF FILLING THREAD DENIER ON RELATIVE POROSITY

Relative Porosity (20 Inches Water)	Item Number	Mill Style	Specification Thread Count Per Inch Warp	Specification Thread Count Per Inch Filling	Yarn Denier Warp	Yarn Denier Filling	Weave
17.7	BR-9	7180	120	95	40/13	40/34	Plain
17.7	BR-11	7182	"	"	"	40/13	"
19.2	BR-10	7181	120	105	40/13	40/34	Plain
15.4	BR-12	7183	"	"	"	40/13	"
26.7**	BR-29	7209	90	68	70/34	70/34	5 Har. Satin
5.48	BR-35	7215	"	"	"	100/34	"
22.3	BR-30	7210	90	78	70/34	70/34	5 Har. Satin
3.79	BR-36	7216	"	"	"	100/34	"
22.1*	BR-21	7192	90	68	70/34	70/34	2/1 Twill
7.14	BR-31	7211	"	"	"	100/34	"
18.4*	BR-22	7193	90	78	70/34	70/34	2/1 Twill
4.28	BR-32	7212	"	"	"	100/34	"
22.6*	BR-23	7194	90	68	70/34	70/34	2/2 Twill
6.25	BR-33	7213	"	"	"	100/34	"
18.7	BR-24	7195	90	78	70/34	70/34	2/2 Twill
4.71	BR-34	7214	"	"	"	100/34	"

*Interpolated value.

**Extrapolated value.

TABLE XIII

THE EFFECT OF TYPE OF WEAVE
(PLAIN AND 2/1 TWILL) ON RELATIVE POROSITY

Relative Porosity (20 Inches Water)	Item Number	Mill Style	Specification Thread Count Per Inch Warp	Specification Thread Count Per Inch Filling	Yarn Denier Warp	Yarn Denier Filling	Weave
17.9	BR-1	7171	138	110	30/10	30/10	Plain
21.5	BR-3	7173	"	"	"	"	2/1 Twill
16.8	BR-2	7172	138	120	30/10	30/10	Plain
17.4	BR-4	7174	"	"	"	"	2/1 Twill
18.7	BR-5	7175	138	95	30/10	40/13	Plain
20.8	BR-7	7177	"	"	"	"	2/1 Twill
15.8	BR-6	7176	138	105	30/10	40/13	Plain
18.5	BR-8	7178	"	"	"	"	2/1 Twill
10.8	BR-13	7184	120	75	40/13	60/20	Plain
10.6	BR-15	7186	"	"	"	"	2/1 Twill
8.25	BR-14	7185	120	85	40/13	60/20	Plain
7.72	BR-16	7187	"	"	"	"	2/1 Twill
11.2	BR-17	7188	100	75	60/20	60/20	Plain
10.6	BR-19	7190	"	"	"	"	2/1 Twill
7.38	BR-18	7189	100	85	60/20	60/20	Plain
7.03	BR-20	7191	"	"	"	"	2/1 Twill

TABLE XIV

THE EFFECT OF TYPE OF WEAVE (2/1 AND 2/2 TWILL) ON RELATIVE POROSITY

Relative Porosity (20 Inches Water)	Item Number	Mill Style	Specification Thread Count Per Inch Warp	Specification Thread Count Per Inch Filling	Yarn Denier Warp	Yarn Denier Filling	Weave
22.1*	BR-21	7192	90	68	70/34	70/34	2/1 Twill
22.6*	BR-23	7194	"	"	"	"	2/2 Twill
18.4*	BR-22	7193	90	78	70/34	70/34	2/1 Twill
18.7	BR-24	7195	"	"	"	"	2/2 Twill
7.14	BR-31	7211	90	68	70/34	100/34	2/1 Twill
6.25	BR-33	7213	"	"	"	"	2/2 Twill
4.28	BR-32	7212	90	78	70/34	100/34	2/1 Twill
4.09	BR-34	7214	"	"	"	"	2/2 Twill
11.9	BR-37	7217	76	57	100/34	100/34	2/1 Twill
9.39	BR-39	7219	"	"	"	"	2/2 Twill
7.62	BR-38	7210	76	67	100/34	100/34	2/1 Twill
5.81	BR-40	7220	"	"	"	"	2/2 Twill

*Interpolated value.

TABLE XV

THE EFFECT OF TYPE OF WEAVE
(2/1 TWILL AND 5 HARNESS SATIN) ON RELATIVE POROSITY

Relative Porosity (20 Inches Water)	Item Number	Mill Style	Specification Thread Count Per Inch		Yarn Denier		Weave
			Warp	Filling	Warp	Filling	
22.1*	BR-21	7192	90	68	70/34	70/34	2/1 Twill
26.7+	BR-29	7209	"	"	"	"	5 Har. Satin
18.4*	BR-22	7193	90	78	70/34	70/34	2/1 Twill
22.3	BR-30	7210	"	"	"	"	5 Har. Satin
7.14	BR-31	7211	90	68	70/34	100/34	2/1 Twill
5.36	BR-35	7215	"	"	"	"	5 Har. Satin
4.28	BR-32	7212	90	78	70/34	100/34	2/1 Twill
3.79	BR-36	7216	"	"	"	"	5 Har. Satin
11.9	BR-37	7217	76	57	100/34	100/34	2/1 Twill
10.1	BR-45	7225	"	"	"	"	5 Har. Satin
7.62	BR-38	7218	76	67	100/34	100/34	2/1 Twill
6.56	BR-46	7226	"	"	"	"	5 Har. Satin

*Interpolated value.

+Extrapolated value.

TABLE XVI

THE EFFECT OF TYPE OF WEAVE
(2/2 TWILL AND 5 HARNESS SATIN) ON RELATIVE POROSITY

Relative Porosity (20 Inches Water)	Item Number	Mill Style	Specification Thread Count Per Inch		Yarn Denier		Weave
			Warp	Filling	Warp	Filling	
22.6*	BR-23	7194	90	68	70/34	70/34	2/2 Twill
26.7+	BR-29	7209	"	"	"	"	5 Har. Satin
18.7	BR-24	7195	90	78	70/34	70/34	2/2 Twill
22.3	BR-30	7210	"	"	"	"	5 Har. Satin
6.25	BR-33	7213	90	68	70/34	100/34	2/2 Twill
5.36	BR-35	7215	"	"	"	"	5 Har. Satin
4.09	BR-34	7214	90	78	70/34	100/34	2/2 Twill
3.79	BR-36	7216	"	"	"	"	5 Har. Satin
9.39	BR-39	7219	76	57	100/34	100/34	2/2 Twill
10.1	BR-45	7225	"	"	"	"	5 Har. Satin
5.81	BR-40	7220	76	67	100/34	100/34	2/2 Twill
6.56	BR-46	7226	"	"	"	"	5 Har. Satin

*Interpolated value.

+Extrapolated value.

Appendix IV

PRESSURE SQUARE GRADIENT-MASS VELOCITY RESULTS FROM THE HIGH-PRESSURE TUNNEL

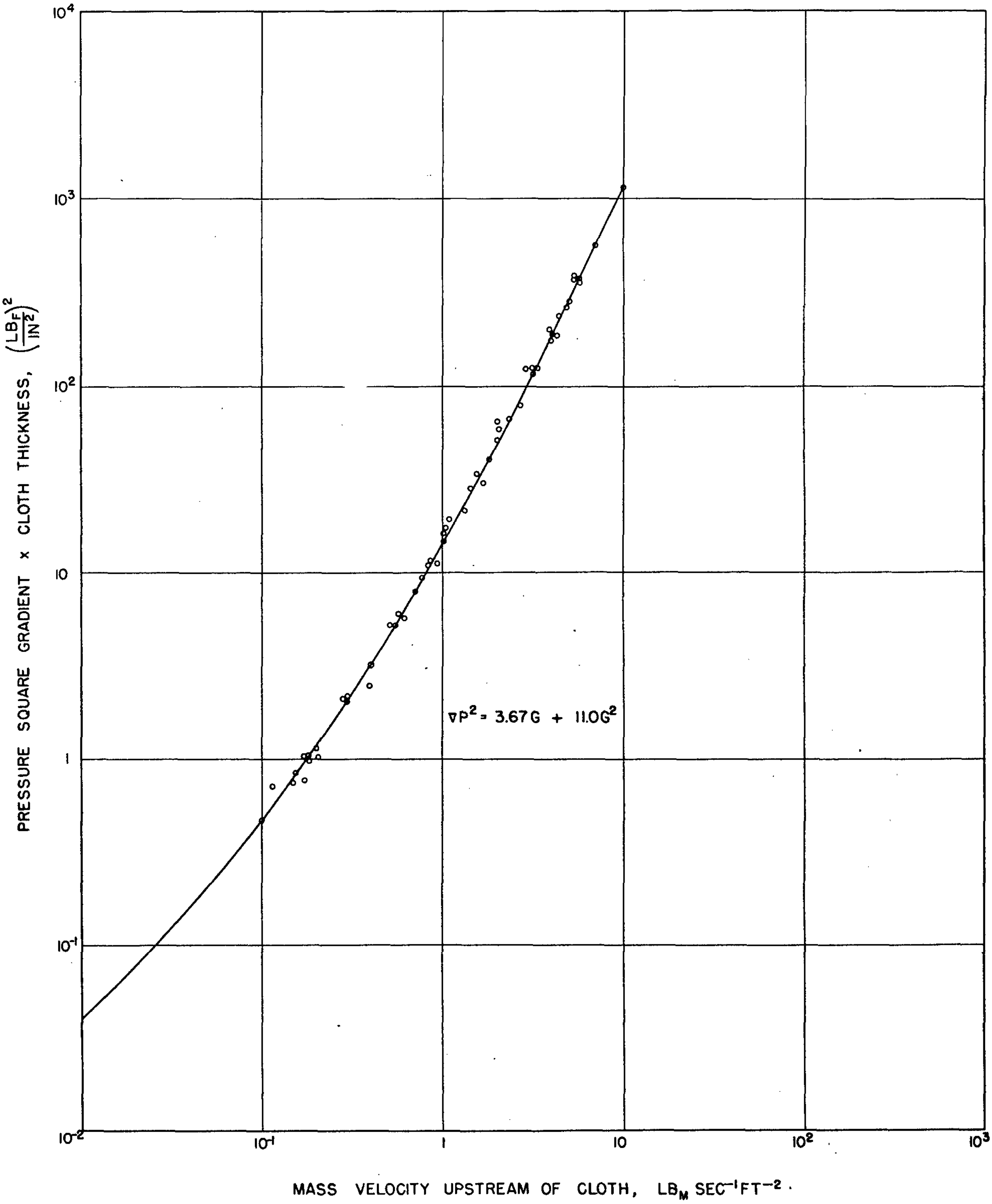


Figure 36. Relation of Pressure Square Gradient to Mass Velocity for WADC Fabric No. 1.

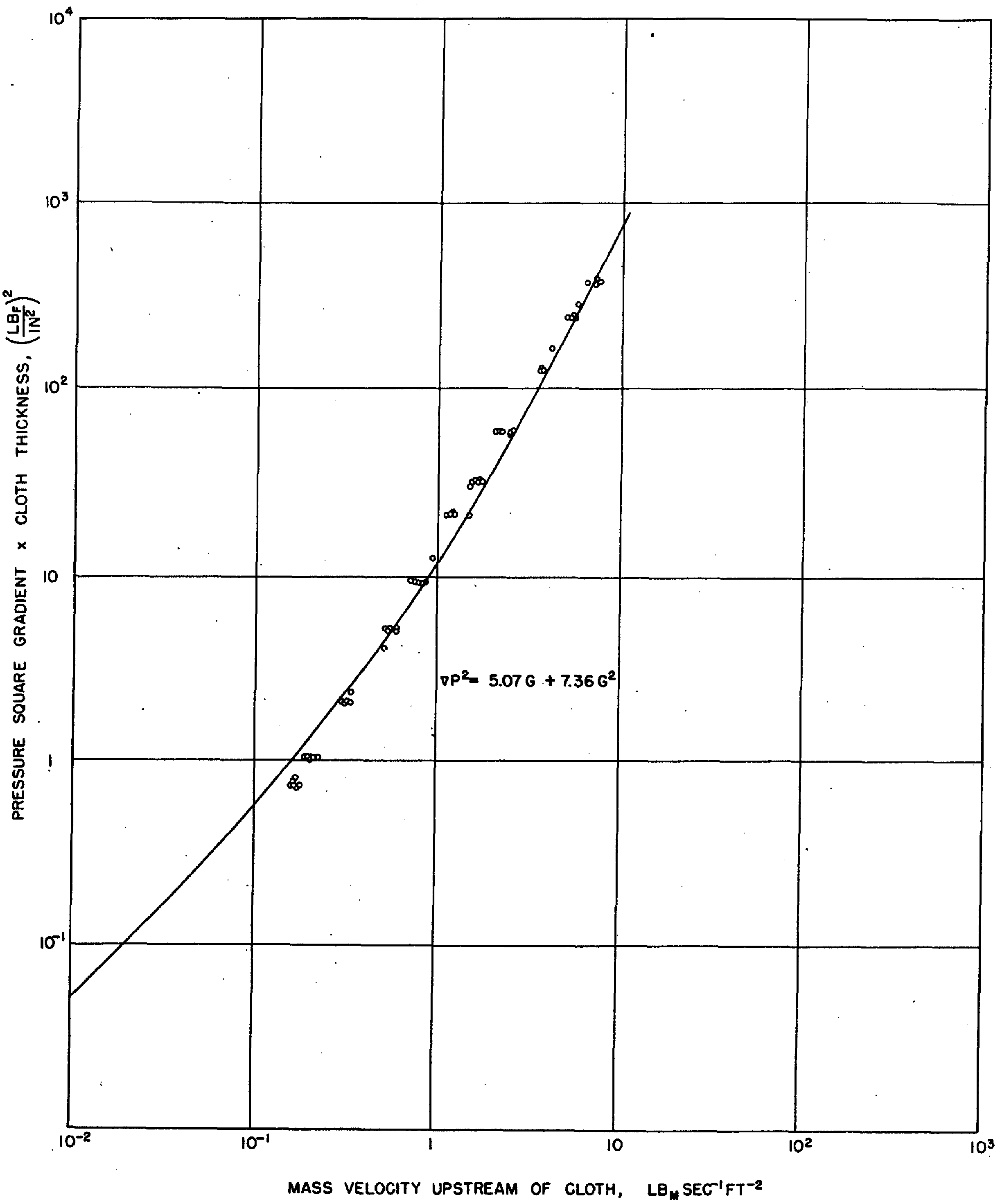


Figure 37. Relation of Pressure Square Gradient to Mass Velocity for WADC Fabric No. 2.

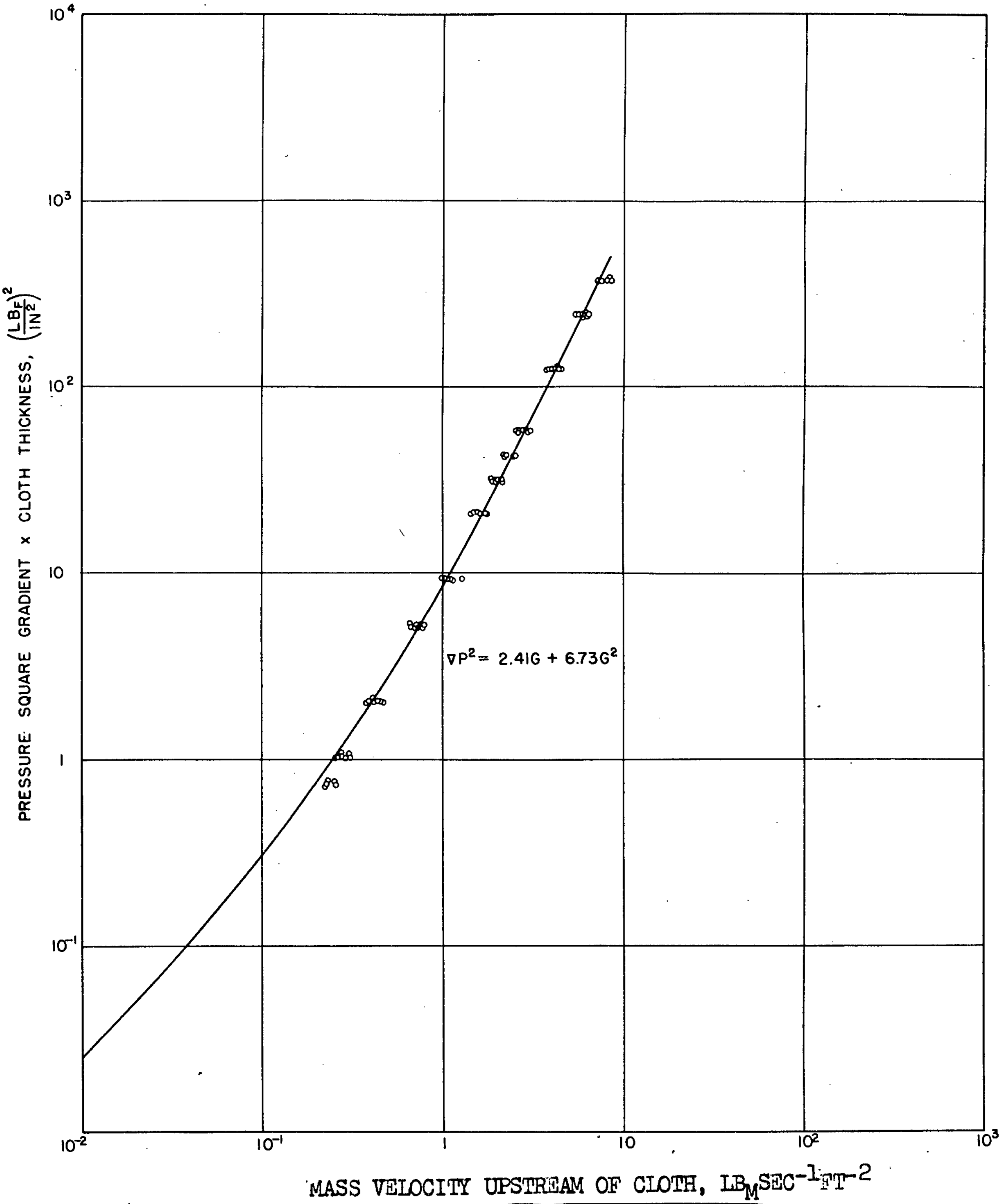


Figure 38. Relation of Pressure Square Gradient to Mass Velocity for WADC Fabric No. 3

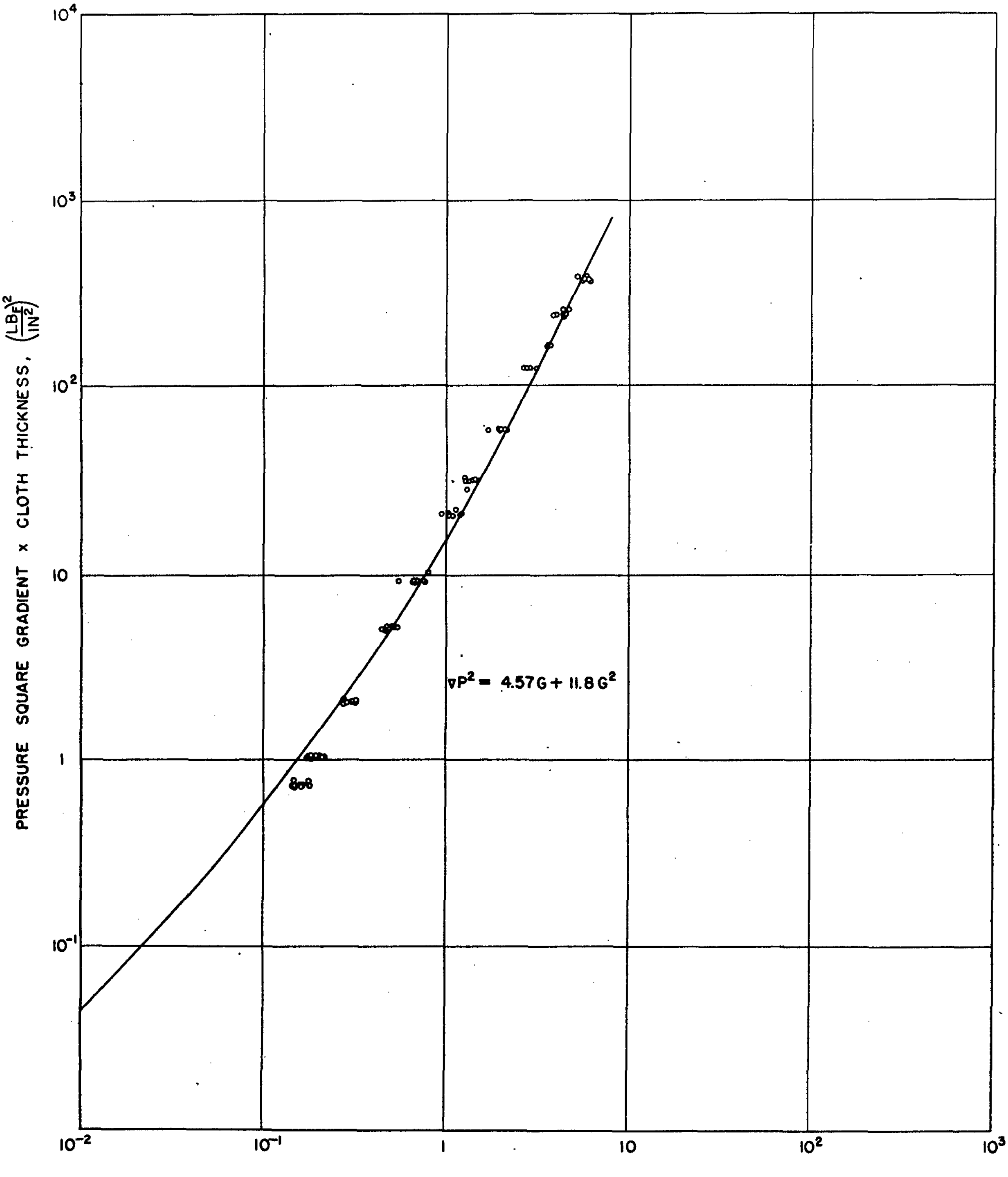


Figure 39. Relation of Pressure Square Gradient to Mass Velocity for WADC Fabric No. 4.

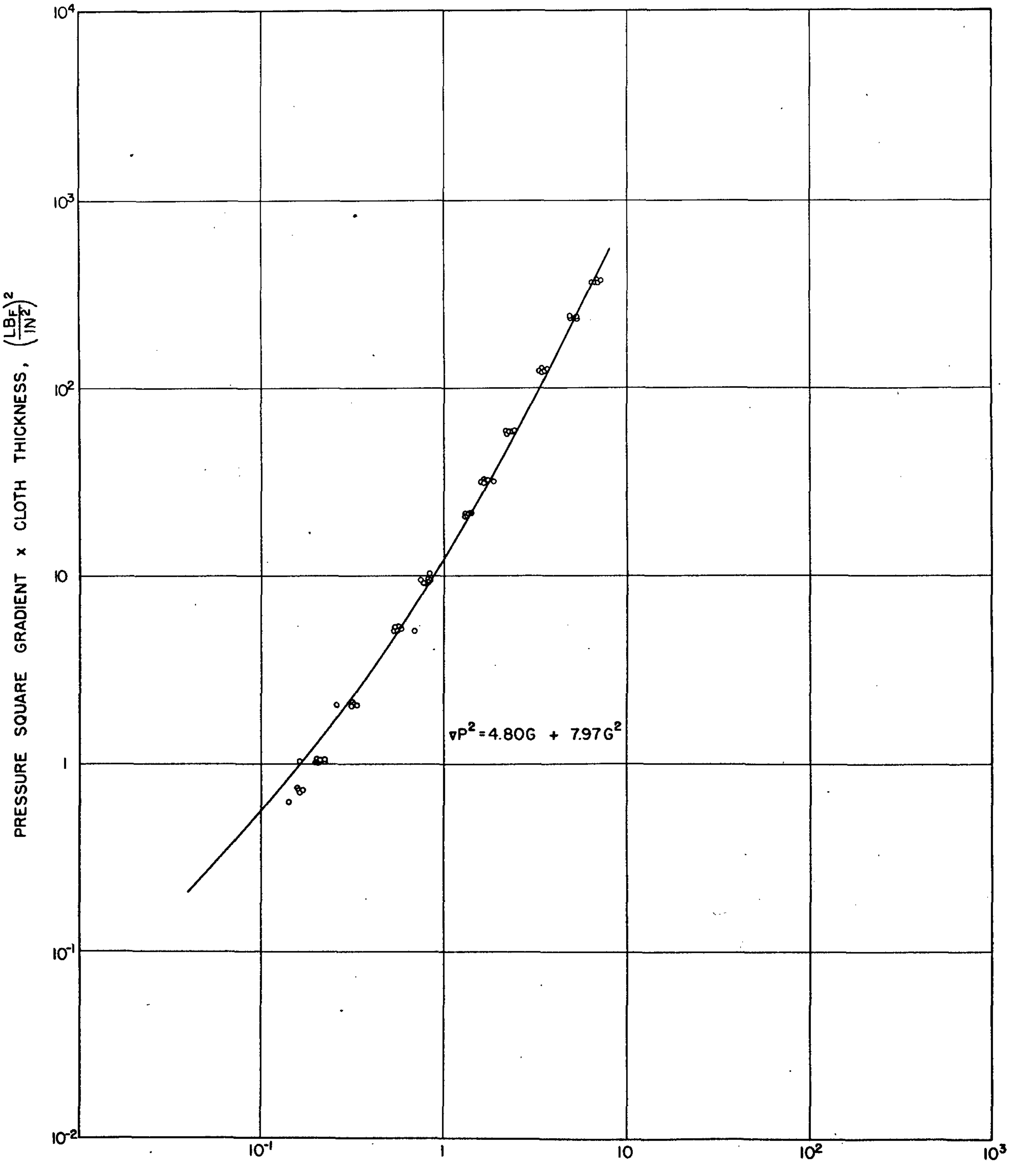


Figure 40. Relation of Pressure Square Gradient to Mass Velocity for WADC Fabric No. 5.

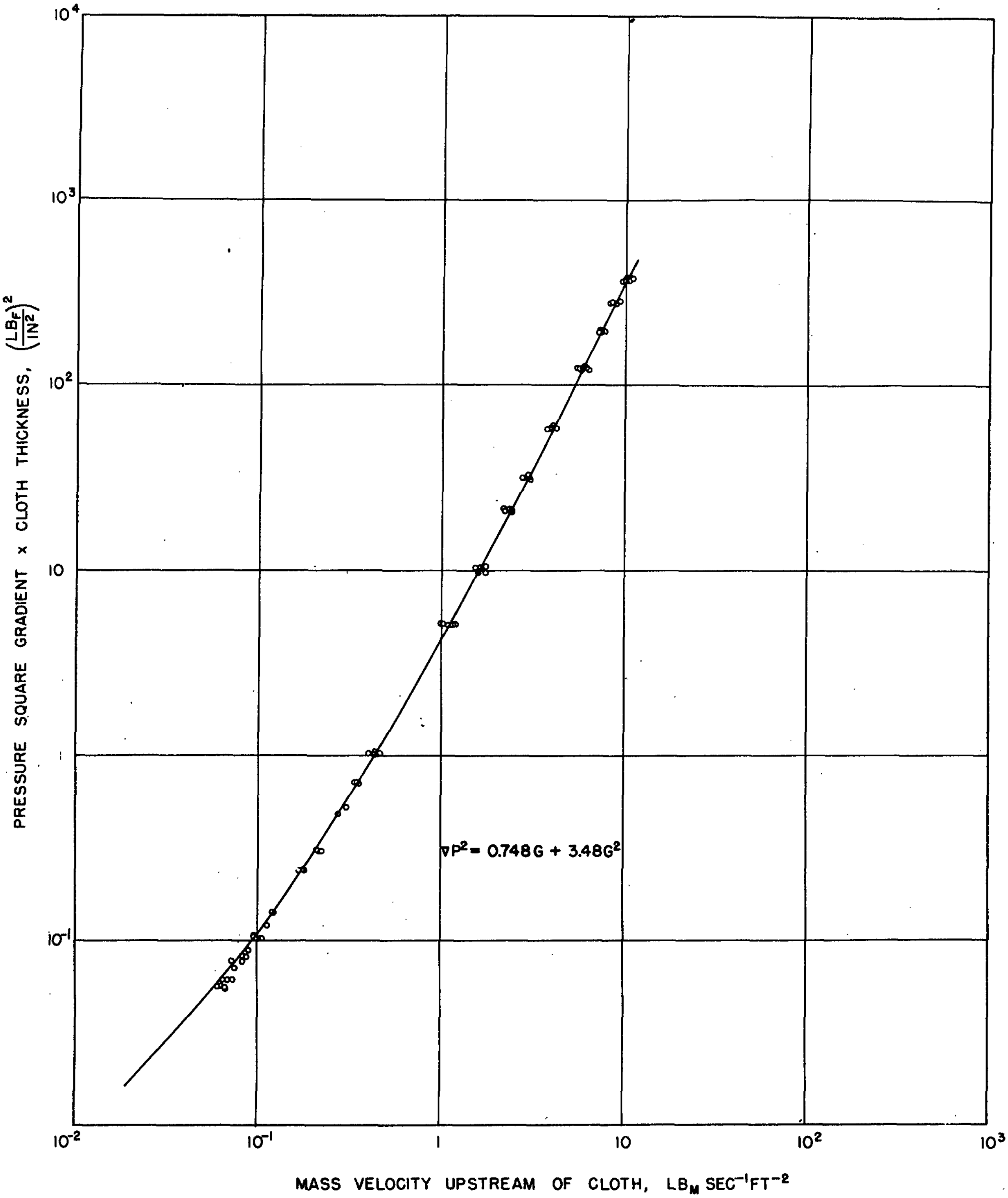


Figure 41. Relation of Pressure Square Gradient to Mass Velocity for WADC Fabric No. 6.

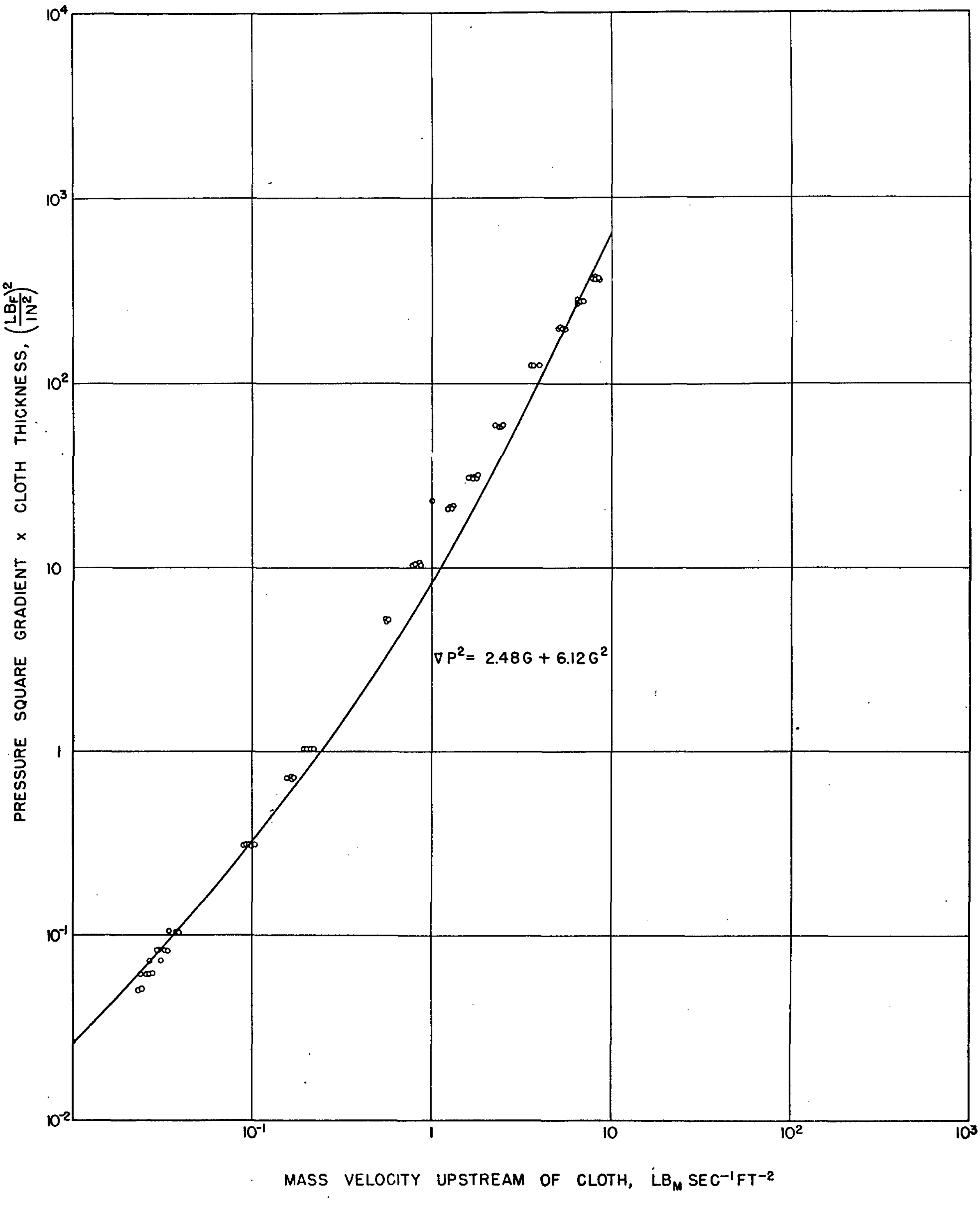


Figure 42. Relation of Pressure Square Gradient to Mass Velocity for WADC Fabric No. 7.

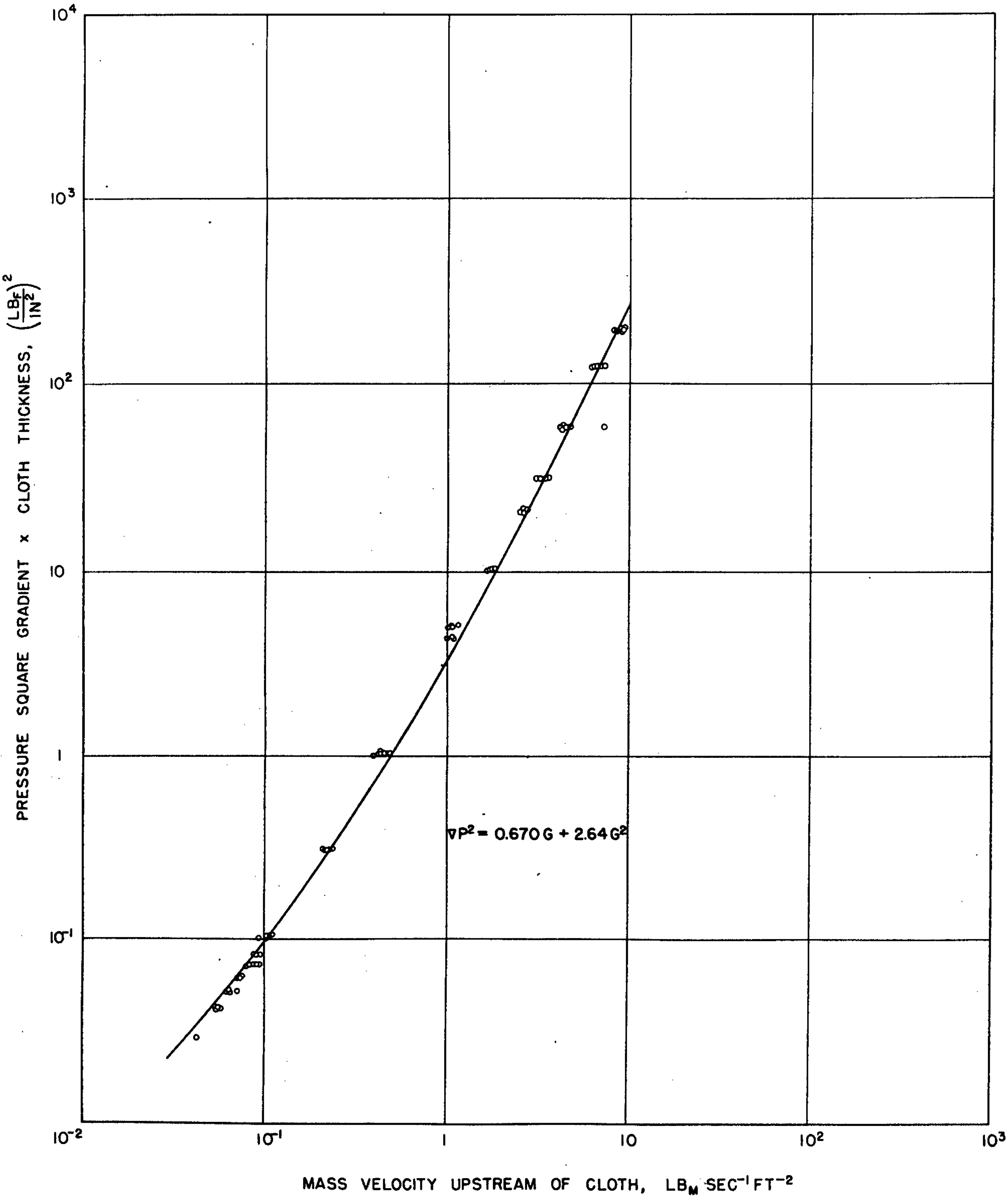


Figure 43. Relation of Pressure Square Gradient to Mass Velocity for WADC Fabric No. 8.

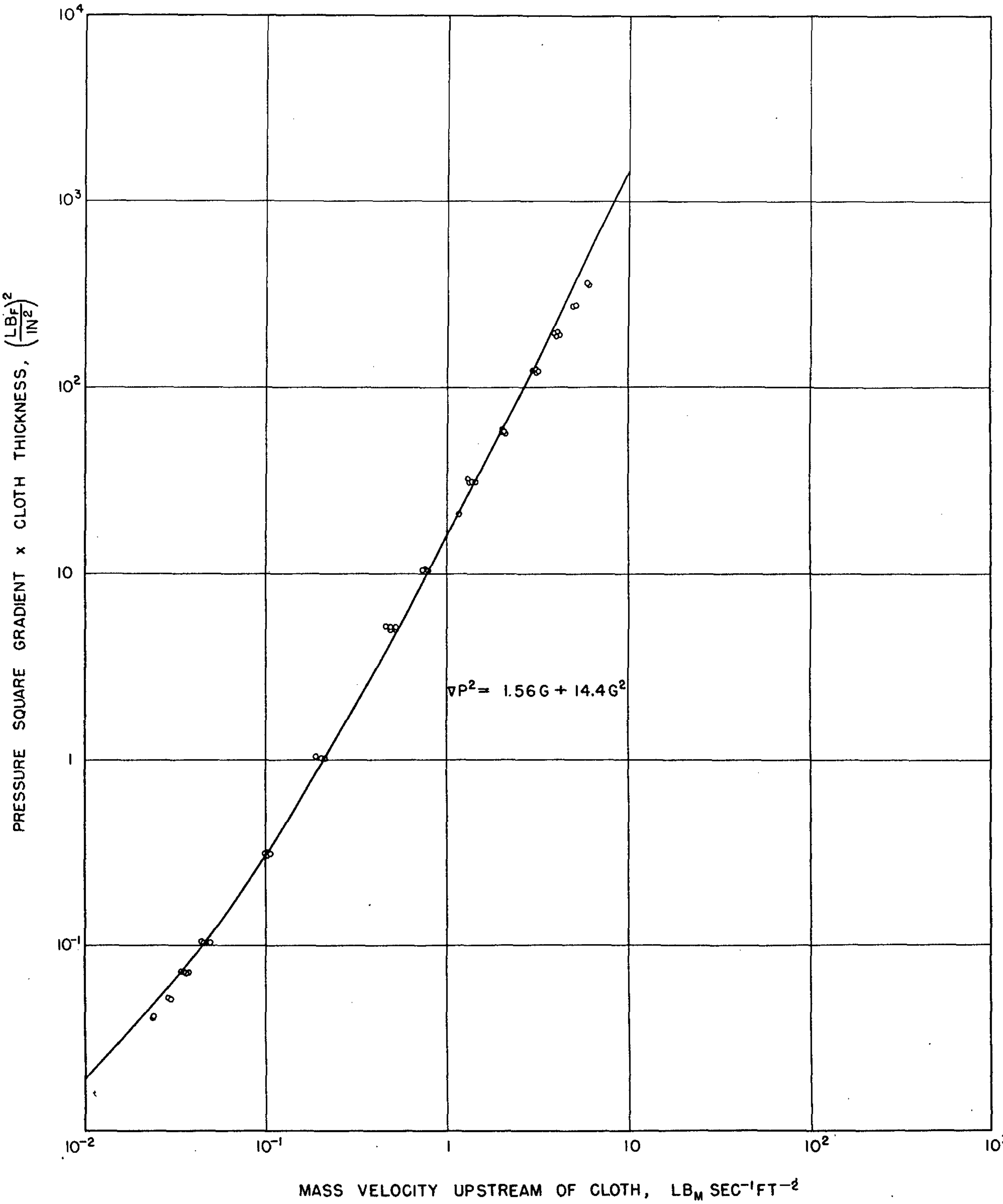


Figure 44. Relation of Pressure Square Gradient to Mass Velocity for WADC **Fabric No. 9.**

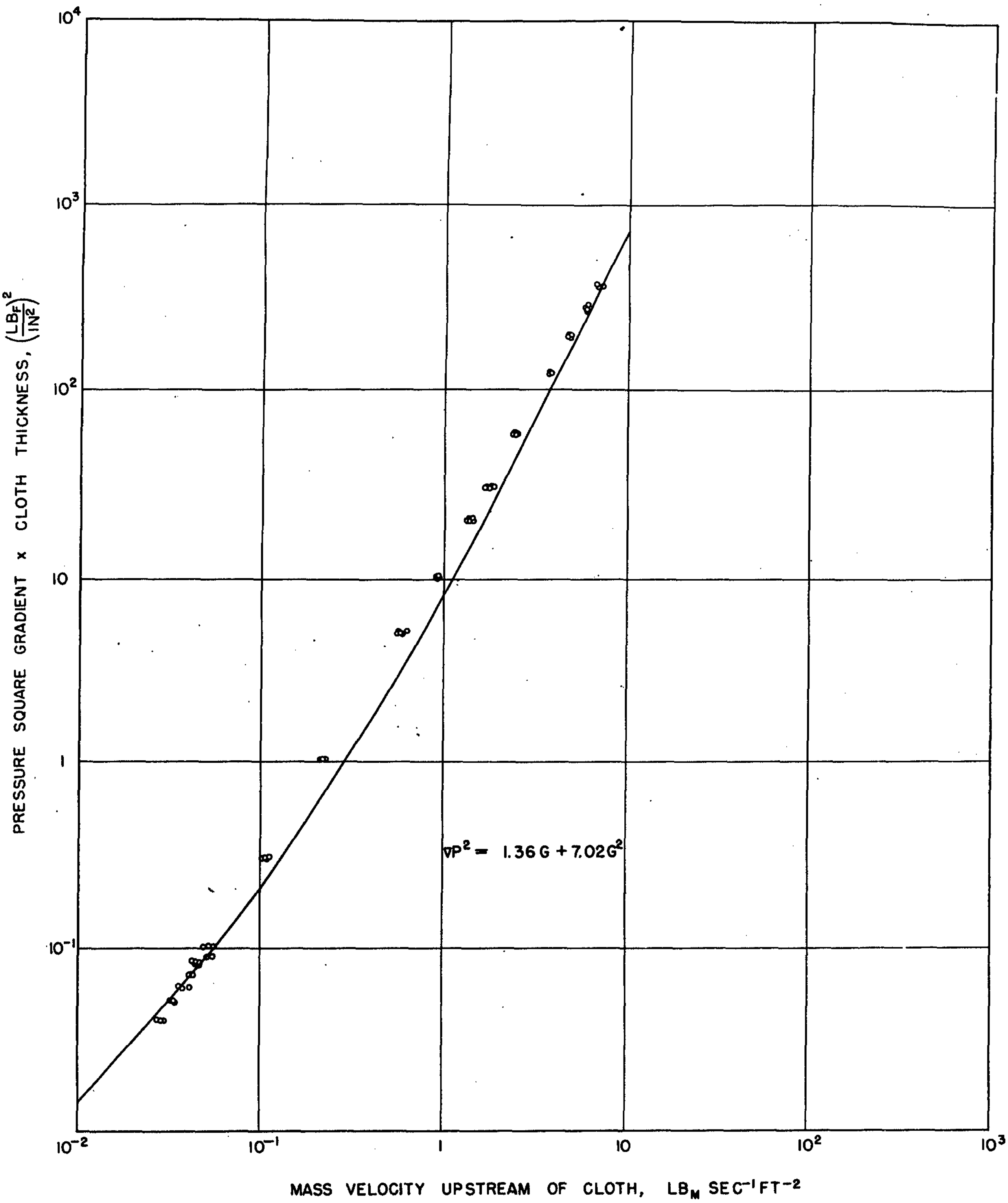


Figure 45. Relation of Pressure Square Gradient to Mass Velocity for WADC Fabric No. 10.

Explanatory Note for Table IV

The evaluation of α and β defined by the pressure square gradient equation

$$\frac{\nabla P^2}{L} = \alpha\left[\frac{2RT}{g_o d}\mu\right] G + \beta\left[\frac{2RT}{g_o d}\right] G^2 \qquad (12)$$

was effected in the following manner. (All symbols and units of measure are shown in Section I, Nomenclature.) The quantities α' and β' (enumerated in Table IV) were defined as

$$\alpha' = \left(\alpha\frac{2RT\mu}{g_o d} L\right) \qquad (13)$$

and

$$\beta' = \left(\beta\frac{2RT}{g_o d} L\right), \qquad (14)$$

reducing equation (12) to

$$\nabla P^2 = \alpha' G + \beta' G^2. \qquad (15)$$

α' and β' were determined from the data using the three methods for which the results are indicated in Table IV. Clearly, given α' and β', α and β are determined, and β/α $(= \mu\beta'/\alpha')$ as well. Here μ is taken as 1.24×10^{-5} $lb_m ft^{-1} sec^{-1}$ and T as 540° F abs.

TABLE IV

VISCOUS AND INERTIA COEFFICIENTS FOR TEN WADC FABRICS

WADC Fabric Number	Georgia Tech Relative Porosity at 20 Inches S.P.* (Per Cent)	Method of Least Squares		Graphical β Least Squares α		Method of Averages		Recommended (from Method of Averages)		
		α'	β'	α'	β'	α'	β'	α (10^8 ft^{-2})	β (10^3 ft^{-1})	β/α (10^{-5} ft)
1	6.86	1.96	11.6	3.50	11.6	3.67	11.0	168	626	3.62
2	6.68	14.6	5.32	5.15	8.38	5.07	7.36	[illegible]	417	1.80
3	7.48	9.21	4.91	2.00	6.64	2.41	6.73	80.1	278	3.46
4	5.36	29.8	5.35	4.51	12.3	4.57	11.8	141.	453	3.20
5	6.28	13.7	6.10	4.69	8.66	4.80	7.97	158.	326	2.06
6	11.3	6.52	2.75	0.834	3.56	0.748	3.48	21.1	122	5.77
7	6.88	19.9	3.22	2.53	6.42	2.48	6.12	124.	382	3.06
8	14.1	2.66	2.03	0.653	2.60	0.670	2.64	26.9	131	4.89
9	6.10	13.4	8.61	1.63	11.6	1.56	14.4	33.3	378	11.5
10	7.75	6.11	7.14	1.35	8.33	1.36	7.02	23.0	147	6.40

*These data [illegible] from the Low-pressure tunnel results.