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THE RESISTANCE TO AIR FLOW OF POROUS MATERIALS SUITABLE  
FOR BOUNDARY-LAYER-CONTROL APPLICATIONS USING  
AREA SUCTION

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SUMMARY

Measurements were made of the resistance to air flow of commercially available porous materials. Three general types of porous media were tested - granular (sintered metals), fibrous (felt cloths and filter papers), and perforated.

The flow-resistance characteristics of the porous materials tested are presented in a form intended to assist in the selection of materials for applications to boundary-layer control using area suction.

INTRODUCTION

Numerous investigations (e.g., refs. 1 to 6) have shown that large improvements in the aerodynamic characteristics of airplanes are possible by use of area suction for control of the boundary layer. Suction applied to a porous area covering the entire surface of an airfoil was effective in maintaining laminar flow for drag reduction, while suction over a small extent of porous area near the leading edge of moderately thick airfoils prevented leading-edge flow separation. Area suction is also effective for control of the turbulent boundary layer and has been applied experimentally to the ramps of scoop inlets, in the elbows of ducts, on trailing-edge flaps, and on the walls of wind tunnels. Each application involves the selection of a porous material with suitable permeability, strength, and serviceability.

Analysis of the power required for suction for a particular installation using area suction involves a knowledge of the resistance to air flow of the porous material. An example is given in reference 5 which presents an analysis of the power required for area suction on the leading edge of a moderately thick airfoil. In the course of the investigation reported in references 5 and 6, limited measurements were made of the resistance to air flow of a variety of commercially available permeable materials. In the present report, the flow-resistance characteristics of these materials are reported over a wide range of differential



pressures across the material. The flow resistance of one of the materials was determined for various values of air pressure at the upstream face of the material, and the characteristics of a second material were established with the free-stream air flow inclined and with the flow parallel to the surface. The flow resistances of the materials presented in this report are intended primarily for use in applications involving area suction. The flow resistances of wire cloths or screens such as are sometimes used in engine air intakes or for control of stream turbulence in wind tunnels are reported in references 7 and 8.

#### NOTATION

A	frontal area of porous sample, sq ft
g	acceleration due to gravity, ft/sec <sup>2</sup>
H	total pressure, lb/sq ft
$\Delta h$	pressure difference across porous material, inches of water
p	static pressure, lb/sq ft
t	temperature, °F
v	suction air velocity, normal to the upstream surface of the porous material, $\frac{w}{\rho g A}$ , fps
w	weight rate of air flow, lb/sec
$\tau$	index of resistivity, defined as the pressure difference in inches of water required to induce a suction air velocity normal to the surface of 1 foot per second through a porous material of a given thickness
$\phi$	value of the exponent used in the equation $\Delta h = \tau v^\phi$
$\rho$	mass density of air just upstream of porous sample, slugs/cu ft

#### Subscripts

1	station upstream of porous material (fig. 1(b))
2	station downstream of porous material (fig. 1(b))

## APPARATUS

The resistances of the porous materials to air flow normal to the surface were measured in the apparatus shown in figure 1. The apparatus consisted of a pipe in which the material to be tested was clamped between flanges. The upstream face of the material was normally open to the atmosphere. For these tests, flow was induced through the porous material by suction with a vacuum pump. The air flow was controlled by a gate valve downstream of the orifice meter. The flow resistance of one of the materials also was measured for various pressures at the upstream face of the material. Pressures less than atmospheric were obtained by inserting a second porous material in the duct at station 0 (fig. 1(b)). Pressures greater than atmospheric were obtained by blowing air through the porous material with the upstream flange of the apparatus connected by ducting to the outlet of an aircraft-type supercharger.

For most of the experiments, the air flow was normal to the surface of the porous material and passed through a 5-inch-diameter area of the material. The rate of air flow was measured with a standard A.S.M.E. orifice meter (ref. 9). The orifice size was varied for the different flow rates so as to keep the ratio of the pressure drop across the orifice to the upstream pressure less than 0.2 as recommended in reference 9. The pressure loss across the material was measured through static pressure orifices located as shown in figure 1. Thermocouples were installed in the duct to measure the air temperature near the porous material and near the orifice meter. The apparatus was checked at the start and completion of the test run for each of the porous materials to make certain there were no leaks in the duct.

As some of the materials tested were not strong enough to support themselves, it was necessary to back these materials with a 16-mesh (0.023 diam. wire) wire cloth. The pressure loss across the wire cloth was negligible throughout the range of air velocities tested.

In addition to the measurements with the air flow normal to the surface, a few measurements were made with the flow inclined and with the flow parallel to the surface. For the inclined flow, the porous material formed part of the upper surface near the leading edge of a two-dimensional airfoil mounted in the Ames 7- by 10-foot wind tunnel. For parallel flow, the porous sample was mounted flush with the wall of a small wind channel. In both cases the suction velocity was ascertained by means of an orifice meter in the ducting leading to the suction pump.

## MATERIALS

The porous materials investigated can be grouped into three general types: granular, fibrous, and perforated. For each of these types of



porous materials, several samples, each having a different permeability, were tested. All the materials are commercially available and are listed in table I. Detailed descriptions of the materials are given in the references noted in the table. Photographs are shown in figure 2.

The granular materials tested consisted of sintered metals - bronze and stainless steel. This type of porous material is generally considered to be the most feasible for applying boundary-layer control to aircraft. Wind-tunnel tests of models incorporating sintered bronze and stainless steel surfaces for area suction are reported in references 4 and 6, respectively. Sample 7, a sintered bronze, was originally impregnated with oil for use in bearings, but the oil was removed for these tests.

The fibrous materials - filter paper and felt cloth - were tested with backing screens. Filter paper (ref. 5) and felt cloth are useful in experimental applications of area suction because of simplicity of installation.

The perforated materials consisted of multihole plates and a woven wire filter cloth. Materials of this type may be used in conjunction with felt cloth to form a porous compact. The perforated plate forms the rigid outer surface, which, when backed by the felt cloth, gives the required permeability. Advantages of the combination for applications of area suction on an airfoil are that the thickness of the felt cloth can be tapered to provide a chordwise variation of permeability that will produce the desired flow distribution with suction. By combination with other materials, a rigid outer surface can be provided which can be formed to the airfoil contour (see ref. 6).

## RESULTS AND DISCUSSION

### Normal Flow

During the testing of the different porous materials, a problem arose in the selection of a useful form in which to present the results. In the literature on porous media (e.g., refs. 10 and 11) the results are frequently presented in terms of a permeability coefficient which satisfies Darcy's law for flow through granular media. Darcy's law, however, is valid only for laminar flow and, hence, is not applicable to the entire range of suction velocities and materials of the present tests. The results presented herein are, therefore, given in the form of the pressure loss across the porous material (in inches of water) as a function of the velocity of the suction air at the upstream face of the porous material (in fps).

The flow-resistance characteristics with the air flow normal to the surface are shown in figures 3, 4, 5, and 6 for sintered, fibrous, and perforated types of porous materials, respectively. In addition, the



pressure ratios across the porous material are given in the figures for a total pressure of 2116 pounds per square foot. Examination of the figures indicates that for small pressure differences across the porous materials, the pressure difference increased as a constant power of the velocity. With larger pressure differences, the pressure difference increased with velocity at a more rapid rate. Within the linear range of the logarithmic plots the flow resistance of the material can be expressed in an exponential form relating the suction velocity  $v$  to the pressure difference  $\Delta h$  as

$$\Delta h = \tau v^\phi$$

where the index of resistivity  $\tau$  is defined as the pressure difference in inches of water required to induce a suction air velocity normal to the surface of 1 foot per second through a porous material of a given thickness. The values of  $\tau$  and  $\phi$  are tabulated in table I for the materials tested. The value of the velocity above which the value of  $\phi$  increases is also given in the table.

The flow resistance  $\tau$ , for practical purposes, was found to be the same throughout a given sheet of sintered metal, roll of filter paper, or roll of felt cloth. However, a swatch taken from a second sheet or roll with the same manufacturer's designation differed by as much as 20 per cent in the value of  $\tau$ , although the value of  $\phi$  was found to remain constant. The flow-resistance characteristics presented in figures 3 to 6 are useful for design purposes in that a single figure summarizes the data for each type of porous media and will permit interpolation for materials with values of  $\tau$  other than those investigated.

The flow through a porous material will be discussed by first considering the characteristics of the perforated plates. As the perforated plates (fig. 5) were thin relative to the size of the perforation, the perforations can be considered to act as individual orifices. For the perforated materials, the pressure drop across the material  $\Delta h$  was proportional to approximately  $v^2$ . As the ratios of static pressure at the downstream face to that at the upstream face approached the critical ratio, 0.528 (sonic flow), the total-pressure loss increased very rapidly, indicating the attainment of a local Mach number of approximately unity in the perforations. As the pressure ratio was decreased below 0.528, choking of the flow would be expected to occur. With the total pressure ahead of the porous material held constant, no further increase in the weight rate of flow was possible. Further decrease in the downstream pressure only increased the losses through the plates.

Consider next the case of flow through a sintered or fibrous compact. The air passages are generally not straight through the material. The passageways change direction and cross-sectional area from point to point in the compact and appear to be much smaller in diameter than those in the perforated plates. It is believed that these changes in air-passage



size and direction result in the slightly different flow-resistance characteristics shown in figures 3 and 4. For example, consider, first, material 1 of figure 3. If material 1 is held against a lighted background, numerous pinholes of light are visible, indicating that many of the passageways are relatively straight through. The flow characteristics are similar to those of the perforated plates ( $\phi = 1.92$ ).

Materials 2 and 3 of figure 3 showed only about one-quarter the number of pinholes of light as material 1. The values of  $\phi$  for materials 2 and 3 were of the order of 1.7 (table I). The data indicate that with the smaller and more tortuous passages, the pressure necessary for overcoming internal friction was increased.

Materials 4 through 16 were considered to be dense compacts in that no light was visible through the materials if held against a lighted background. The smallness of the pores resulted in the flow through these materials approaching a capillary type as evidenced by the fact that for low velocities  $\phi$  was of the order of 1.2. The suction velocity through these samples continued to increase with increased pressure drop across the sample (but at a lower rate), up to the limit of the suction system. It is believed that the labyrinths of the passageways resulted in large increases in the pressure necessary for overcoming internal friction in the individual passages.

The preceding discussion is concerned with the test results for air at atmospheric pressure and density at the upstream face of the porous materials. The flow resistance characteristics of material 4 were also obtained for pressures at the upstream face from 830 to 3170 pounds per square foot. The results are presented in figure 7. From this figure it can be seen that the suction air velocity, for a given pressure loss, was independent of the air pressure at the upstream face of the material within the range of these tests.

#### Inclined and Parallel Flow

One of the sintered steel materials (material 2 of table I) was also calibrated for inclined and for parallel flow. The results are presented in figure 8. The inclined-flow calibration was obtained during tests of a two-dimensional wing (54-inch chord) with area suction from 0.3- to 3-percent chord on the upper surface. The permeable surface was made from the same sheet of sintered steel from which sample 2 was obtained. The data presented in figure 8 for the inclined flow are for a free-stream velocity of 162 feet per second and with the model at an angle of attack of  $12^\circ$ . The local Mach number outside the boundary layer varied from 0.70 at the leading edge to 0.40 (approximately) at the trailing edge of the suction area.

The parallel flow calibration was obtained with a sample of material 2 mounted flush with the inner surface of the side wall of a small wind



tunnel. The sample piece (4 inches square) was cut from the original piece used in the normal-flow calibrations. Suction was applied to the back side of the sample. The tunnel airspeed was held constant at 163 feet per second. The thickness of the natural boundary layer on the tunnel wall was approximately 0.1 inch at the upstream edge of the sample.

Inspection of the calibrations for normal, inclined, and parallel flows indicates that the flow-resistance characteristics of the sintered steel were independent of the free-stream flow direction for the conditions investigated.

#### CONCLUDING REMARKS

A survey has been made of the resistance to air flow of a variety of commercially available porous materials. Three general types of porous media were tested - granular (sintered bronze and steel), fibrous (felt cloth and filter paper), and perforated.

For small pressure differences across the porous material, the pressure difference increased as a constant power of the suction air velocity. With larger pressure differences, the pressure difference increased with velocity at a more rapid rate. The flow resistance of a sample of sintered bronze was independent of the air pressure at the upstream side of the material for values of absolute pressure from 830 to 3170 pounds per square foot.

The flow resistance of a sample of sintered steel was independent of the direction of the flow approaching the material.

Ames Aeronautical Laboratory  
National Advisory Committee for Aeronautics  
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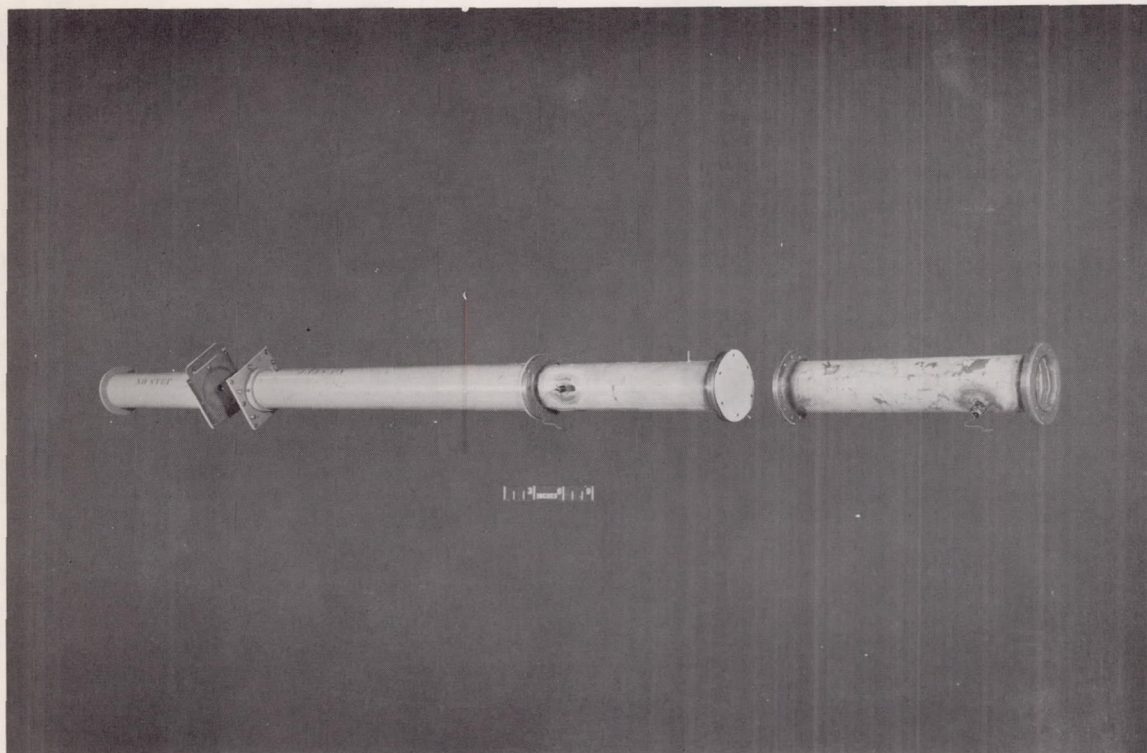
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21. Anon.: Industrial Screens, Colorado Fuel and Iron Corp. (Denver), 1949.



TABLE I.- CHARACTERISTICS OF POROUS MATERIALS TESTED

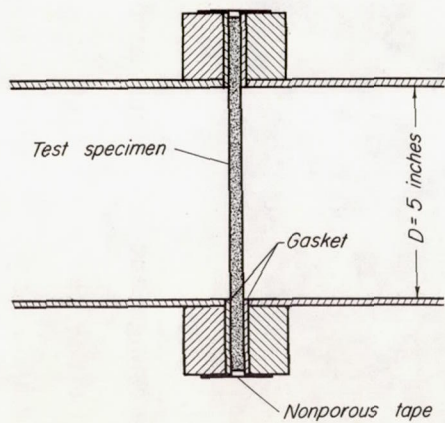
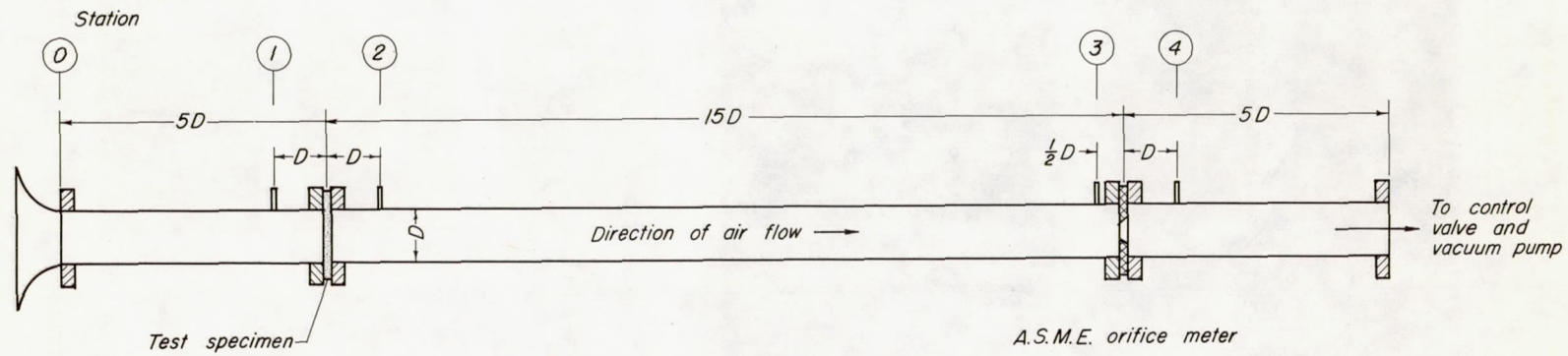
Material		Refer- ence	Backed with screen	Nomi- nal thick- ness, in.	$\Delta h = \tau v \phi$					
No.	Description				$\tau$	$\phi$	Limit v, fps			
Granular - sintered metal										
1	Oilite filter, MH-34	12	No	0.125	0.063	1.92	37			
2	APM, grade E	13	-do.-	.031	.33	1.66	19			
3	Oilite filter, MH-46	12	-do.-	.125	.54	1.73	11			
4	Wel-Met, MS-804	14	-do.-	.062	3.6	1.17	7			
5	APM, grade D	13	-do.-	.062	4.5	1.20	6			
6	Porex, grade 4	15	-do.-	.129	9.9	1.26	7			
7	Oilite strip, R-8001	12	-do.-	.031	48.0	1.15	2			
Fibrous - felt cloth										
	Color	Lb per yd	Percentage							
			Wool	Cotton						
8	White	1.0	35	65	16	Yes	0.125	0.41	1.22	15
9	Black	4.2	60	40	16	-do.-	.525	1.40	1.21	10
10	White	2.1	100	0	16	-do.-	.125	3.6	1.06	7
11	-do.-	8.4	100	0	16	-do.-	.508	7.7	1.06	5
12	-do.-	15.1	100	0	16	-do.-	.521	73.0	1.03	1.5
Fibrous - filter paper										
13	S & S 410, single sheet				17	Yes	0.0085	2.60	1.23	7
14	E-D 954, -do.-				18	-do.-	.0065	6.4	1.17	4
15	E-D 952, -do.-				18	-do.-	.007	23.9	1.14	3
16	E-D 950, -do.-				18	-do.-	.007	109.0	1.18	2
Perforated plates										
	Round hole	Hole diam., in.	Holes per sq in.	Per- cent open						
17	No. 00 staggered	0.020	714	23.0	19	No	0.021	0.009	1.98	65
18	No. 1/20 staggered	.050	57	11.2	19	No	.031	.016	1.98	40
	Square hole									
19	65-count, 0.005- in. hole size		4225	10.5	20	No	.006	.018	1.95	50
Woven wire cloth, filter grade										
20	20x200, double weave				21	No		0.075	1.81	30
Drilled metal plate (0.028 diam. hole)										
21	Hole spacing, 0.125x0.10 in. staggered				- - -	No	0.125	0.20	1.94	14



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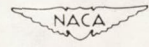
(a) General arrangement of porous material sample and A.S.M.E. orifice.  
Figure 1.— Duct for calibration of porous material with normal air flow.

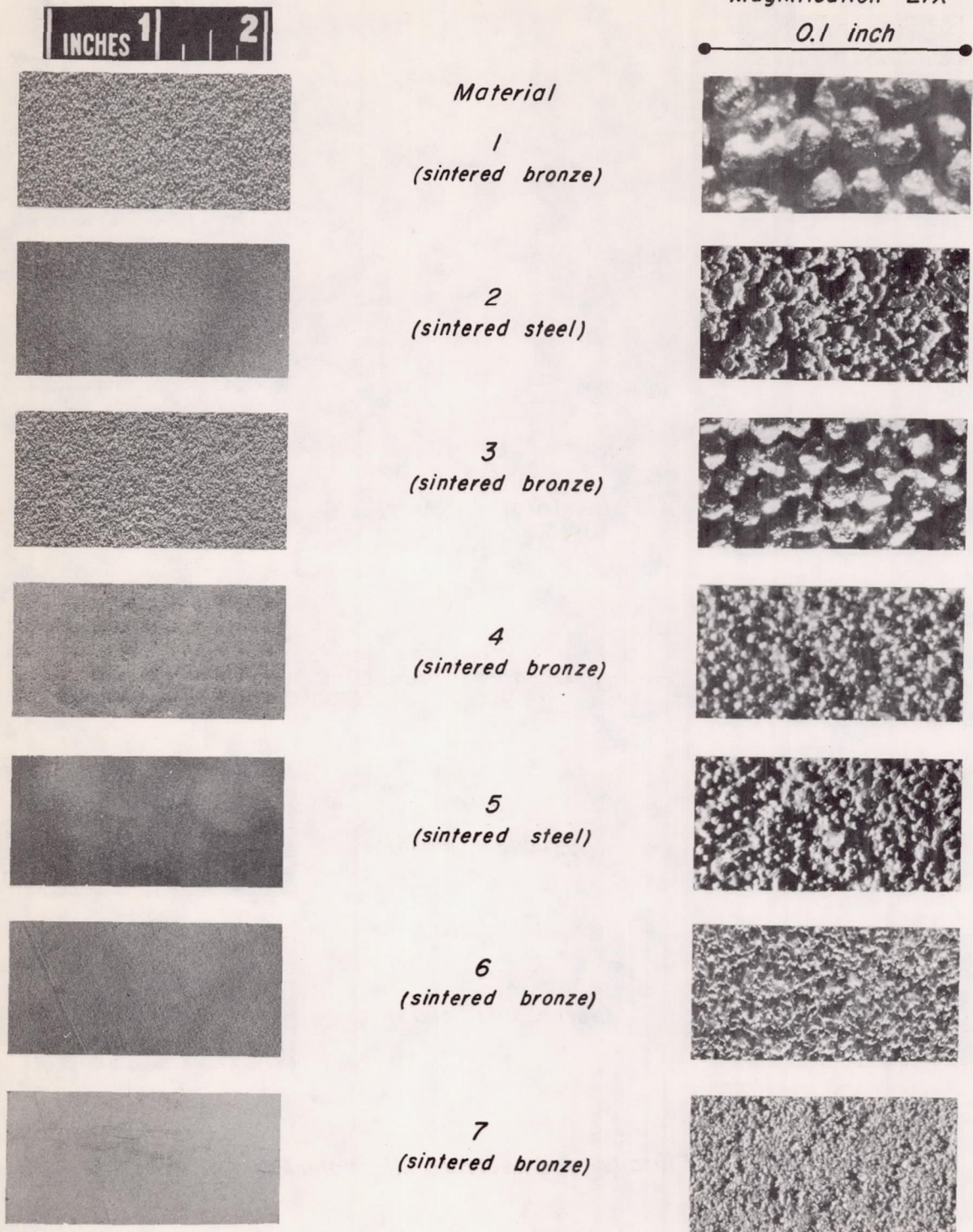




(b) Location of test specimen relative to ASME orifice.

Figure 1. - Concluded.





(a) Granular materials.

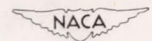


Figure 2.- Photographs of the samples of various porous materials.

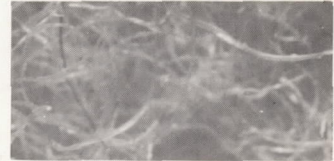




Magnification 21X  
0.1 inch



10  
(felt cloth)



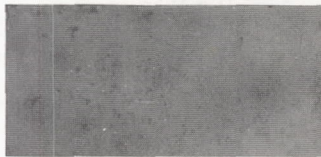
14  
(filter paper)



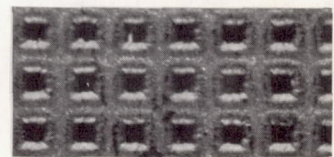
17  
(perforated plate)



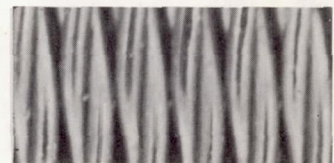
18  
(perforated plate)



19  
(65-count mesh)



20  
(woven wire cloth)



(b) Fibrous and perforated materials.

Figure 2.- Concluded.

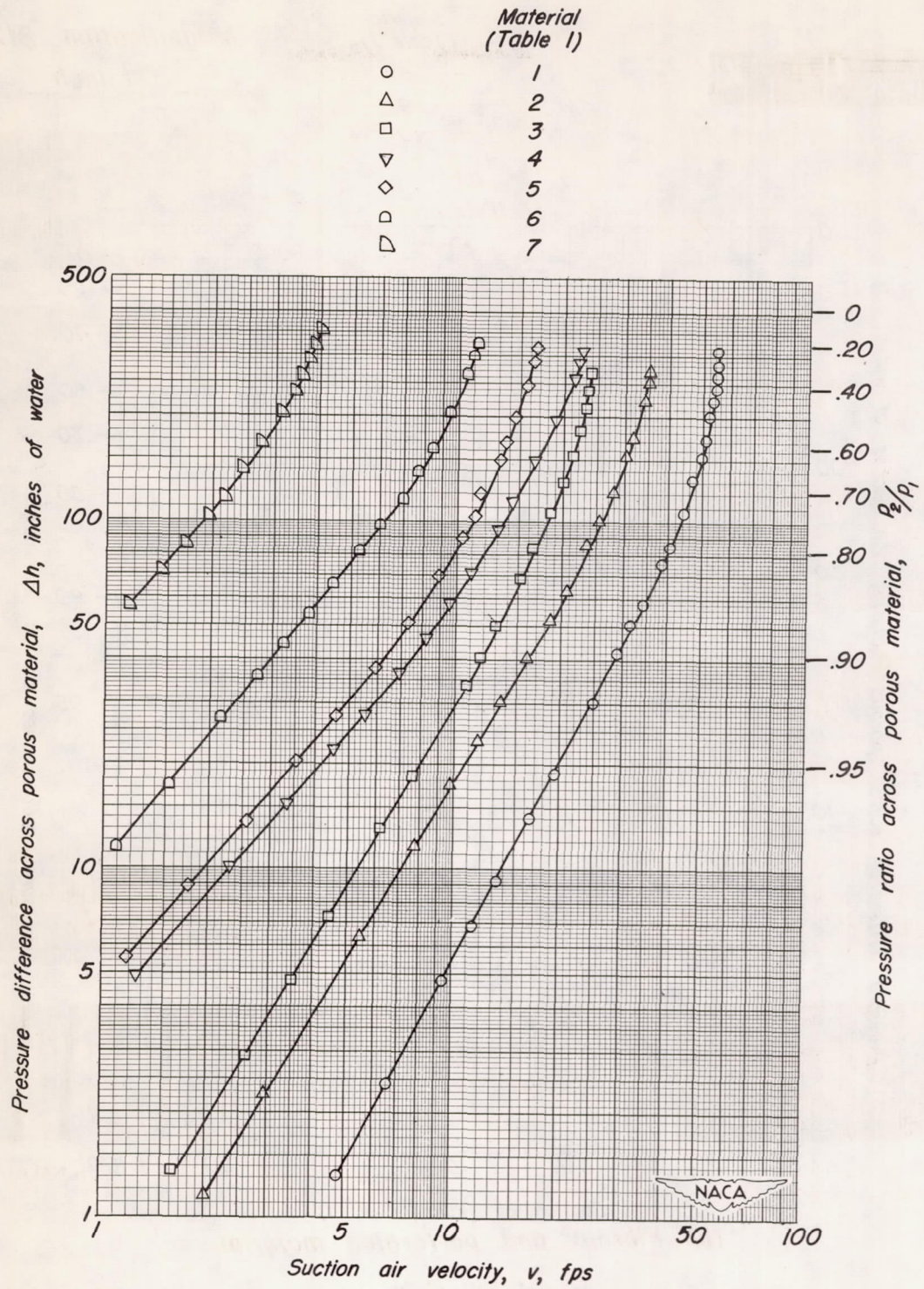
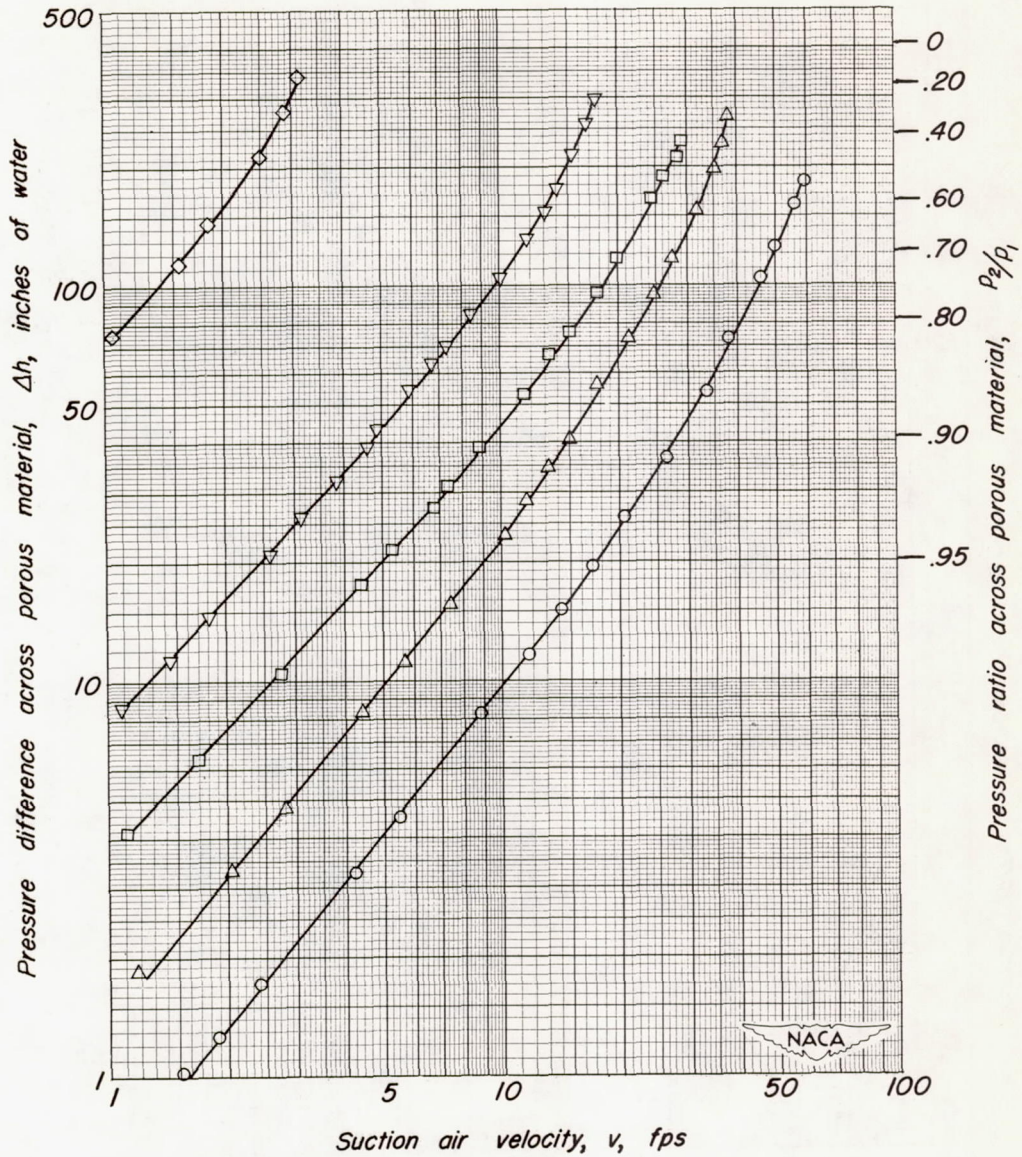


Figure 3.- Resistance to air flow of various sintered types of porous materials for normal flow,  $H_1 = 2116 \text{ lb/sq ft}$ ,  $t_1 = 67^\circ\text{F}$ .



Material  
(Table 1)

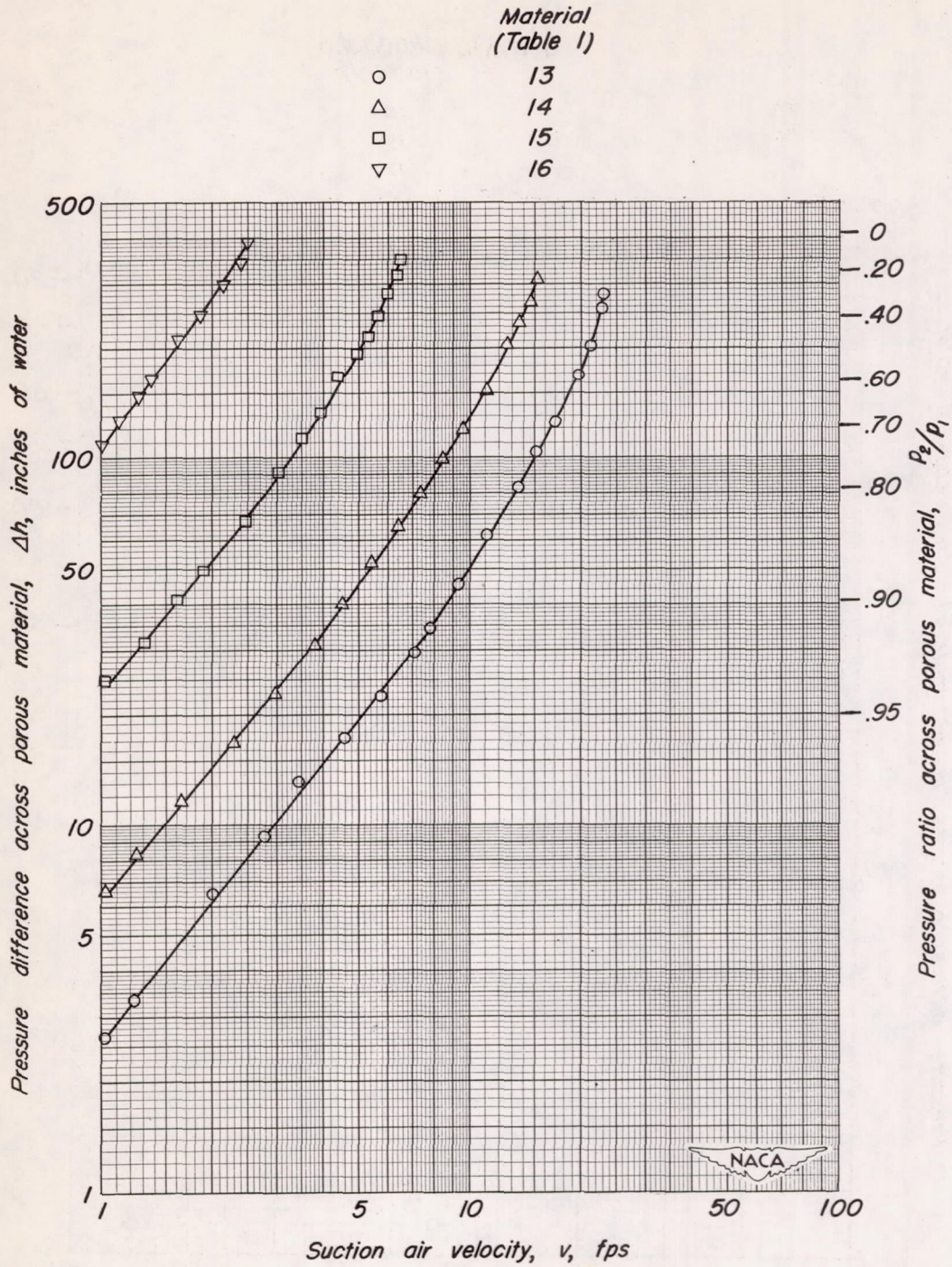
- 8
- △ 9
- 10
- ▽ 11
- ◇ 12



(a) Felt cloths.

Figure 4.-Resistance to air flow of various fibrous types of porous materials for normal flow,  $H_1 = 2116$  lb/sq ft,  $t_1 = 67^\circ\text{F}$ .





(b) Filter papers.

Figure 4.- Concluded.



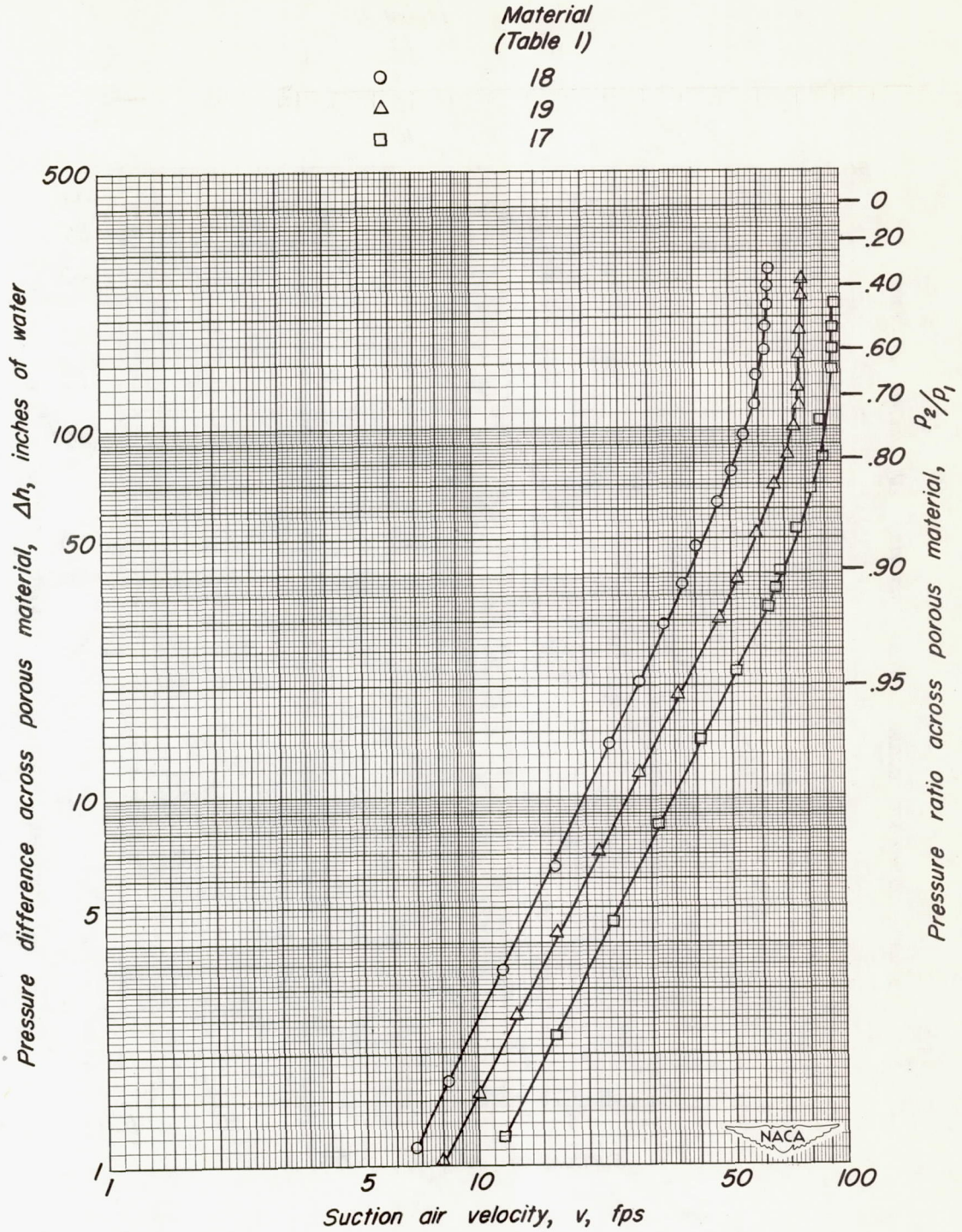


Figure 5.- Resistance to air flow of various perforated types of porous materials for normal flow,  $H_1 = 2116 \text{ lb/sq ft}$ ,  $t_1 = 67^\circ \text{F}$ .



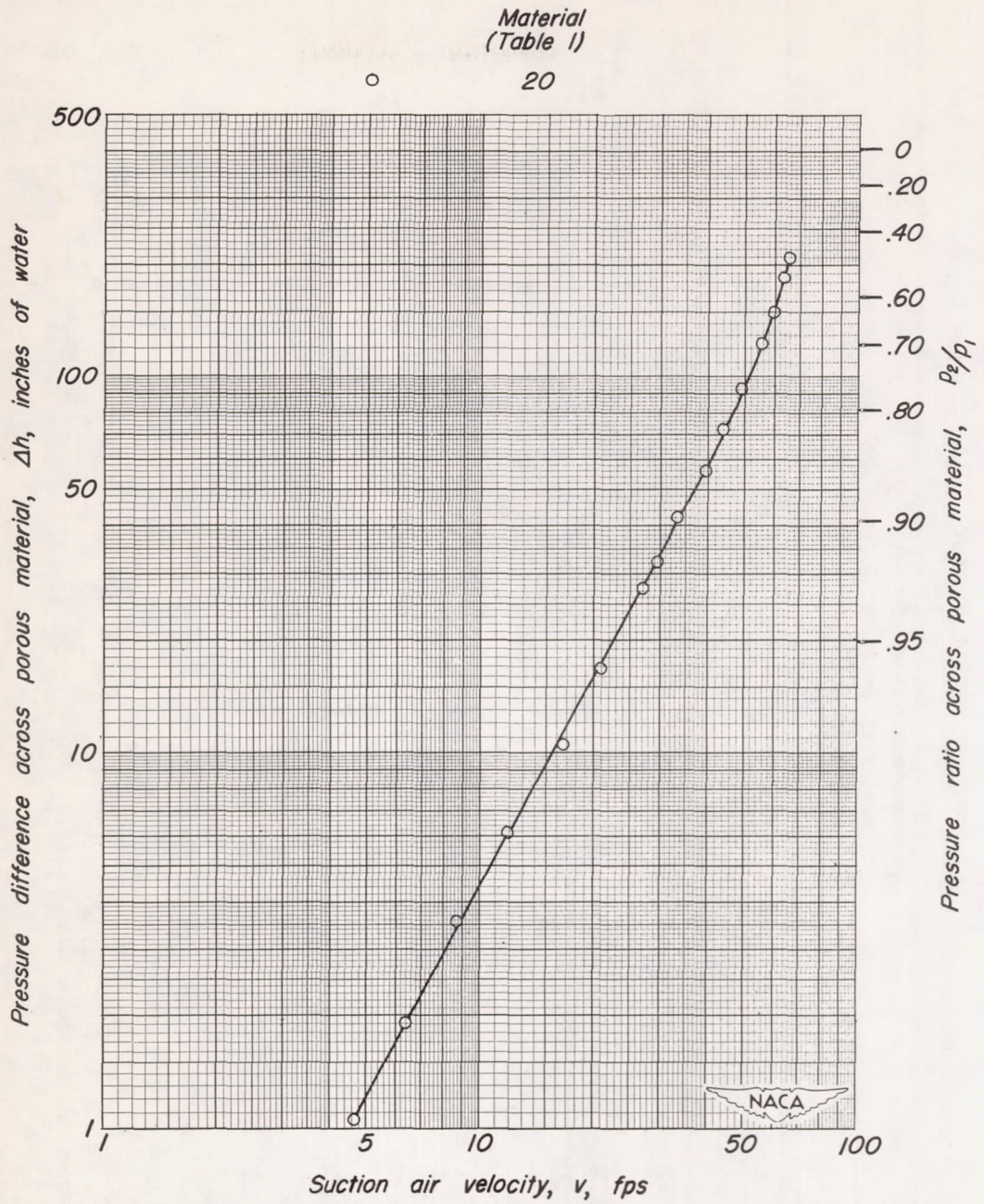


Figure 6.- Resistance to air flow of 20 x 200 double-weave filter wire cloth for normal flow,  $H_1 = 2116$  lb/sq ft,  $t_1 = 67^\circ\text{F}$ .



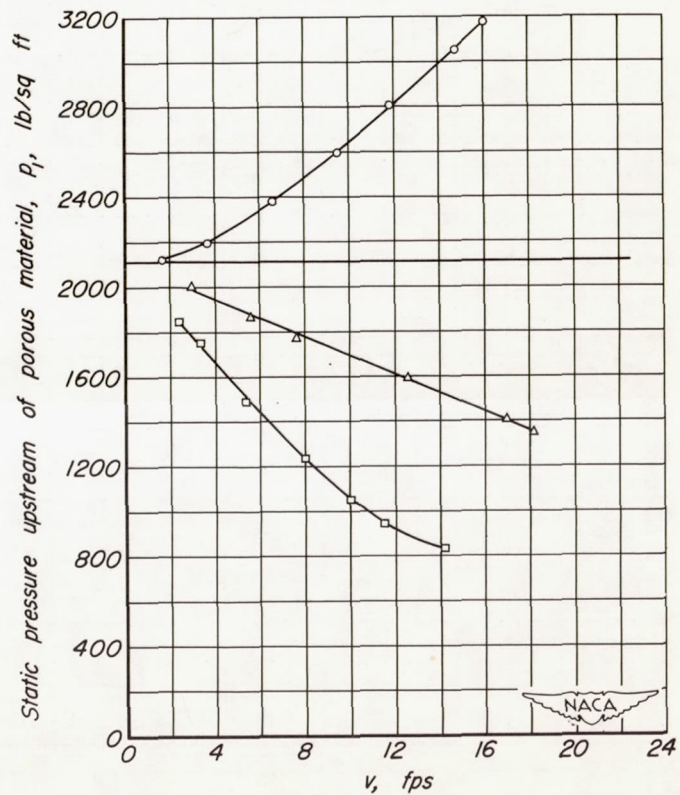
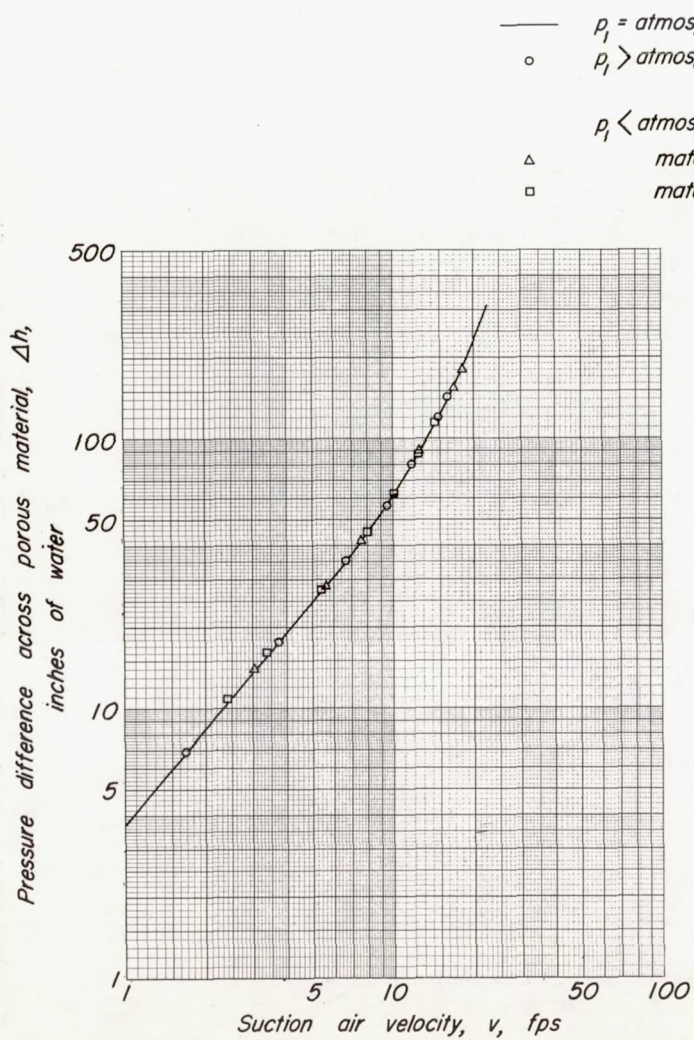


Figure 7.-Resistance to air flow of material 4 (sintered bronze) for various upstream pressures.



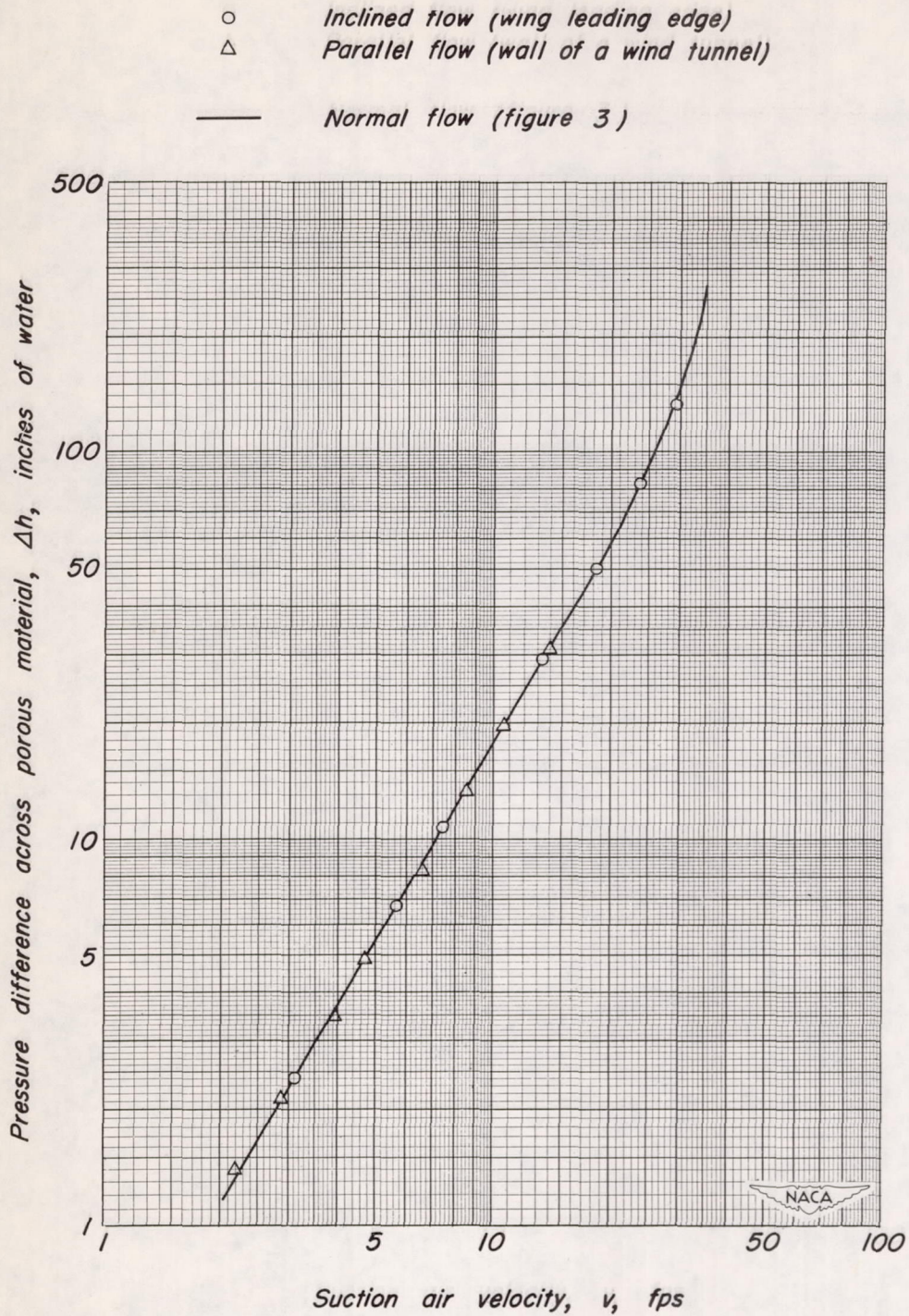


Figure 8.- Resistance to air flow of material 2 (sintered steel) for inclined and parallel flows. Free-stream velocity of 163 feet per second,  $H_1 = 2116$  lb/sq ft,  $t_1 = 67^\circ\text{F}$ .