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The Use of Woollen Felt Screens as Air Cleaners for Supersonic Wind Tunnels

by

J. F. W. Crane

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THE USE OF WOOLLEN FELT SCREENS AS AIR CLEANERS FOR SUPERSONIC WIND TUNNELS

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SUMMARY

To combat dust erosion of models in two supersonic wind tunnels, pressed woollen felt screens were fitted in the settling chambers and were found to be very effective dust filters. Each screen was composed of a layer of felt mounted on a wire gauze screen.

Selection of the pressed woollen felt (to Specification D.T.D.590) followed comparative trials, in a test rig, of six possible materials. In addition, the felt has a relatively low pressure drop coefficient: approximately 2 per cent of that of an aircraft linen and 16 per cent of that of a parachute nylon.

Measured values of the pressure drop coefficient are given over a range of values of Reynolds number that should be sufficient for most applications.

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1 INTRODUCTION

Some years ago (1954 - 1956), during research work on laminar boundary layers on steel models in two supersonic wind tunnels, considerable trouble was experienced with erosion of surfaces by high speed dust particles. The erosion was sufficient to render impotent the sublimating solid technique of boundary layer transition indication and, in the worst cases, turbulent boundary layers were promoted. Microscopic examination of the damaged surfaces revealed craters, the majority of which were less than 5 microns in width.

The existing filters in the tunnel circuits were situated at distances remote from the working sections and, as a result, were unable to cope with any particles of drying agent and pipescale etc. introduced downstream of them. Therefore, a filter was required immediately upstream of each nozzle. Both tunnels were fitted with wire gauze screens in the settling chambers and it appeared simple to modify these by adding a layer of high solidity fabric to act as a dust filter.

Accordingly, tests were made in a rig, Fig.1a, to determine the most suitable material for this job, and from these tests a good quality pressed felt[1] was selected.

Filters consisting of one sheet of felt supported by wire gauze were installed in the settling chambers of both tunnels and considerable cleansing of the airstreams was immediately achieved.

Details of the pressure drop coefficient ($\Delta p/q$) of these filters are given and a comparison with other screens is drawn. The results are correlated against Reynolds number per foot (U/ν) and a sufficient range is covered for most design applications.

The filters were used at temperatures up to 50°C without detriment to their performance.

A further advantage of high drag screens is in the reduction of turbulence and flow instability[2].

2 COMPARISON OF VARIOUS SCREEN MATERIALS

2.1 Test rig

A test rig, Fig.1a, was made to the standard set by Ref.3, and was used to measure air mass flows and pressure drops across the various screen materials.

A sharp edged orifice plate of solidity s = 0.58, with corner tappings, was used for the measurement of mass flow, and calibration by pitot/static tube of the discharge coefficient of the orifice plate agreed very well with the standard value[3] of 0.605. The latter figure was then used in the reduction of the test results.

The pressure drop across the screen, ΔP, was measured at points one pipe diameter upstream and downstream of the screen.

The pressures were measured with manometers: oil manometers were used for small pressure differences such as the drop across the orifice plate, and mercury manometers were used for larger pressure differences such as the drop across the screen. Accuracy of scale reading was better than 0.02 inches in both cases.

2.2 Screen materials tested

The following materials were tested in the rig to ascertain their usefulness as dust filters and to measure their pressure drop.

(1) Common felt, $\frac{1}{8}$ inch thick (coarse grade, very uneven thickness).

(2) Aircraft linen (fibre diameter $\simeq$ 0.01 inch).

(3) Parachute nylon (fibre diameter $\simeq$ 0.0004 inch).

(4) Swansdown cloth.

(5) Surgical lint.

(6) R.S.7 pressed woollen felt to Specification D.T.D.590 (colour, off-white; nominal thickness 1/16 inch ± 0.02 inch; nominal weight 10 oz/sq yd ± 15%; fibre diameter $\simeq$ 0.001 inch).

(7) Round wire gauze (30 meshes/inch; wire diameter = 0.01 inch; S = 0.513). This screen was used as a support for the above materials in the tests.

(8) Round wire gauze ($\simeq$ 150 meshes/inch; wire diameter = 0.0023 inch).

2.3 Test rig results

2.3.1 Comparative filtration efficiency

By visual examination of the screens after testing in the rig it became apparent that the R.S.7 woollen felt material was the best dust collector.

Three materials spanning the range of fabrics namely (a) aircraft linen, (b) parachute nylon (D.T.D.556), both of which are screens of single fibre thickness and high solidity but with widely different fibre diameters, and (c) R.S.7 woollen felt were then tested to compare their filtration efficiencies.

In these tests, each screen was backed by a nylon screen (D.T.D.793) at a distance of $\frac{1}{4}$ inch and atmospheric air was drawn through at an entry velocity of approximately 20 ft/sec for 6 hours. Fig.7 gives the results showing both the dust collected by each material under test and also that passed through and collected by the backing screen. To some extent this technique offsets variations between the individual tests in the amount of dust present in the atmosphere. The superiority of R.S.7 woollen felt is confirmed.

Fig.8, which is a photomicrograph (20x magnification) of each screen, shows the variation between the meshes of the materials and the diameters of the fibres. The linen is a material of high solidity and large fibre diameter, and the parachute nylon is a material of high solidity and small fibre diameter. On the other hand the woollen felt is a material of low solidity and small fibre diameter ($\simeq$ 0.001 inch) but the depth of the material allows it to be likened to a large number of low solidity screens in series.

These results are in general agreement with the conclusions reached by Johnstone and Roberts[4] in their consideration of the removal of particles from moving gas streams, where, for particles larger than 1 micron in diameter the principal mechanism of removal is that of impaction. With screens, this is achieved best by those of high solidity but composed of fibres of small diameter. Thus the nylon (Fig.8b) might be expected to be a better dust collector than the linen (Fig.8a) as is indeed the case.

The felt has small diameter fibres and apparently low solidity (Fig.8c) but the depth of the material and random distribution of the fibres appear to give a very complete coverage of the airstream, resulting in its being superior to either the linen or the nylon (Fig.7). A big advantage of this material is its low pressure drop coefficient and this is discussed in the next section.

2.3.2 Comparison of pressure drop measurements of various screens

The measurement of pressure drop through screens has attracted a large number of workers. The picture that emerges from their work is that for low Reynolds number flow the pressure drop coefficient, $\lambda = \Delta P/q$, decreases with increase in Reynolds number in a manner similar to that of the drag coefficient for low Reynolds number flow normal to a cylinder. At higher Reynolds number, λ remains sensibly constant at its lowest value (however, with screens of very high solidity this condition may not be reached, because of compressibility effects, e.g. linen and nylon, Fig.2).

At high velocity, compressibility has the effect of increasing λ, e.g. linen and nylon, Fig.2, and the flow may be considered to be through a nozzle or sharp-edged orifice according to whether the leading edges of the screen elements are rounded or sharp. Hence the screen solidity (which defines the contraction ratio imposed on the stream-tubes of the airflow), the inlet Mach number and the Reynolds number are important parameters.

Fig.2 shows the variation of λ with velocity for some of the screens tested and shows that the R.S.7 woollen felt has a much lower pressure drop than either the aircraft linen or parachute nylon materials despite its greater thickness and seemingly higher solidity. Approximately, the minimum value of the pressure drop coefficient of linen is 50 times, and that of nylon 6 times, that of felt, and the reason for this can be seen from Fig.8 which shows the relatively wide mesh, and hence low solidity of felt compared with the linen and nylon materials (note comments in section 2.3.1).

The effect of compressibility appears only in the cases of linen and nylon, Fig.2, and the limit for completely subsonic flow

$$P_2/P_o = (2/\gamma+1)^{\gamma/\gamma-1}$$

$$= 0.528 \quad \text{for} \quad \gamma = 1.4$$

is reached for both. In the case of linen, full sonic choking at the interstices has occurred at an inlet Mach number of 0.0164.

Fig.3 shows the variation of maximum inlet Mach number with solidity, calculated for the flow model shown. In this case, solidity

$$s = 1 - \frac{A_x}{A_1}$$

and Mach number and area ratio values were taken from isentropic flow tables. The maximum inlet Mach number of 0.0164 obtained for linen would correspond to a solidity of 0.97 and it is suggested that where the metrological measurement of solidity is impracticable, this aerodynamic method may be used.

3 EXPERIENCE OF THE USE OF R.S.7 WOOLLEN FELT SCREENS AS AIR CLEANERS IN SUPERSONIC WIND TUNNELS

3.1 Description of tunnel filter installations

3.1.1 No.1 Tunnel, R.A.E./Bedford

Fig.1(c) shows the size and position of the felt screen placed normal to the flow in the settling chamber of the above tunnel. It consisted of a single sheet of felt supported by a wire gauze (30 mesh, d = 0.01 inch) mounted on a square wooden frame which was easily removed for inspection and cleaning. A sag of 4 inches at the centre of the screen was allowed to reduce the stress on the wire support under air load.

The tunnel had a fixed wooden nozzle for a Mach number of two and hence the velocity in the settling chamber was constant at 17 ft/sec with slight variation according to the air temperature. The maximum temperature attained was $40^{\circ}C$.

The range of pressure covered was from 1 to 3 atmos.

3.1.2 No.5 Supersonic Tunnel, R.A.E./Farnborough

Fig.1(b) gives details of the screen installation in this tunnel. The settling chamber was of circular cross-section and could be fitted with up to 4 screens in series. The felts were mounted on wire gauzes (30 mesh, d = 0.01 inch).

The tunnel had a range of wooden nozzles which gave fixed Mach numbers of 3, 4 and 4.5 and corresponding air velocities in the settling chamber were around 12.5, 6.5 and 3.3 ft/sec. In general, the air temperature was about $40^{\circ}C$ but occasionally $50^{\circ}C$ was reached.

The range of pressure covered was from 1 to 6 atmos.

3.2 Results of tunnel tests

3.2.1 Filtration efficiency of felt screens in tunnels

In both tunnels the woollen felt screens eliminated model erosion by dust particles and enabled the use of chemical indicators when studying boundary layer transition.

In the No.1 tunnel, the filter was extremely effective in clearing up dust from the activated alumina drying agent, which had leaked into the tunnel circuit. After a few runs the filter was vacuum cleaned to remove the heavy deposit but thereafter very little vacuum cleaning was required. No measurable increase of pressure drop due to dust pollution of the felt was obtained, for example, an air mass flow of 4 lb/sec ft^2 was passed for 25 hours without measurable increase in the screen pressure drop.

Previously a filter consisting of about 6 layers of butter muslin[5] coated with a light oil had been used, with only limited success, as a dust filter.

In the No.5 tunnel felt screens were used for a much longer period, 1954 to 1958, and it was found that with two or more screens in series a longer time may elapse between inspections. At each inspection, the upstream felt was discarded and a clean felt positioned at the downstream end of the filter section. A further advantage of a series of screens is the extra cleansing which takes place.

3.2.2 Measurements of pressure drop of felt screens in tunnels

Over the years when they were in use, measurements of the pressure drop across the felt screens were made, covering a range of operating conditions, and results are given in Table 1.

Fig.4 shows the variation of pressure drop with pressure (downstream of screen) for four different flow velocities. The velocities in the settling chambers were computed from working section Mach number and throat to settling chamber cross-sectional area ratios. The pressure drop is seen to vary linearly with pressure over the range of conditions covered.

The results given in Table 1 are plotted in the form λ versus Reynolds number per foot in Figs.5 and 6. Fig.5 refers to the results for single screens and Fig.6 to results for series screens. In both cases λ is the pressure drop coefficient for a single screen. The Reynolds number was not made dimensionless for reason of simplicity, since no correlation with other porous screens is intended.

The correlation against Reynolds number is very good and covers wide ranges of pressure and velocity and a large number of screen samples.

Scatter can arise from variations in screen material (note, from section 3.2.1, that one felt was replaced at each inspection). The tolerance on weight per square yard of material was ±15 per cent and an arbitrary tolerance band of ±15 per cent on pressure drop coefficient has been added to Figs.5 and 6. All the results lie within this band including the curve representing the test rig results of Fig.2.

Fig.6 collects the results for series screens and shows that the average pressure drop per screen is very similar to the values for single screens.

4 CONCLUSIONS

The use of good quality woollen felt with small fibre diameter such as the type R.S.7 in the Specification D.T.D.590 is recommended as a suitable dust filter for wind tunnels. Tests showed it to be superior to other materials as a dust collector and it has a relatively low pressure drop coefficient (Fig.2). The best place for mounting a filter is immediately upstream of the nozzle and it is suggested that the settling chamber offers the best site, by suitable adaptation of the customary wire gauze screens.

The woollen felt has been used at temperatures up to 50°C without detriment to its performance.

LIST OF SYMBOLS

A	Area of stream cross-section
d	diameter of wire or fibre
M	Mach number
P	pressure
ΔP	pressure drop across a single screen
q	dynamic pressure

LIST OF SYMBOLS (Contd.)

R Reynolds number per foot (U/ν)

s solidity ($1 - A_x/A_1$)

U average velocity of stream

γ ratio of specific heats of air

λ pressure drop coefficient ($\Delta P/q$)

ν kinematic viscosity of air

Suffixes

o reservoir condition

1 condition upstream of screen

2 condition downstream of screen

x condition at throat of screen

(MAX) maximum value

LIST OF REFERENCES

No.	Author	Title, etc.
1	-	D.T.D. 590 material Specification (Pressed Felt). Ministry of Aircraft Production, 1945.
2	Lukasiewicz, J.	Elimination of flow instability in two high speed wind tunnels by means of high drag screens. N.A.E. Canada Report LR-83, Nov. 1953.
3	-	British Standard Code B.S.1042:1943, Flow Measurement. British Standards Institution.
4	Johnstone, H.F. Roberts, M.H.	Deposition of aerosol particles from moving gas streams. Industrial and Engineering Chemistry, Vol.41, No.11, P.2417, 1949.
5	Taylor, G.I. Davies, R.M.	The aerodynamics of porous sheets. R & M 2237. April, 1954.

TABLE 1

Measured values of pressure drop and pressure drop coefficient for R.S.7 felt screens in wind tunnels

Screen arrangement	P_2 (lb/in^2)	U_2 (ft/sec)	ΔP (lb/ft^2)	λ (per screen)	$R \times 10^{-4}$	Mach number in tunnel working section
Single screen (1/16 inch felt supported by 30 mesh wire gauze)	14.3	6.52	11.3	250.6	3.49	4
	30.1	6.52	12.71	133.8	7.35	4
	44.5	6.44	14.8	105.4	11.27	4
	44.6	6.52	14.12	100.5	10.88	4
	59.7	6.52	16.25	86.3	14.58	4
	62.5	6.44	17.2	87.4	15.8	4
	63.3	6.52	16.25	81.4	15.46	4
	63.5	6.44	17.5	87.5	16.08	4
	30.62	12.46	33.4	92.5	14.81	3
	44.5	12.46	39.85	76	21.55	3
	61	12.46	47.3	65.9	29.5	3
	14.75	16.95	35.3	104.9	10.65	2
	20.05	16.81	40.9	89.4	14.71	2
	24.3	16.95	46.6	84.1	17.55	2
	29	16.85	50.9	76.9	20.4	2
	34.25	17.1	60	76.75	24.2	2
	39.2	17.1	65.65	73.4	27.7	2
	44.15	17.28	70.65	70.1	30.76	2
2 screens as above in series	75.9	3.27	7.76	12.9	9.3	4.5
	46.2	3.32	6.5	171.5	5.75	4.5
	14.25	6.5	10.35	253	3.49	4
	20.45	6.5	11.5	178.5	5.01	4
	35.1	6.5	14.05	127	8.6	4
	44.7	6.5	15.62	111	10.95	4
	14.7	12.7	26.53	150.6	7.04	3
	29.4	12.7	35	99.5	14.08	3
	44.1	12.7	42.4	83.6	21.12	3
	58.8	12.7	53.1	75.3	28.16	3
	73.5	12.7	56.6	64.3	35.2	3
	73.5	12.7	63.7	72.3	35.2	3
4 screens in series	13.48	11.95	21.6	138.75	7.3	3

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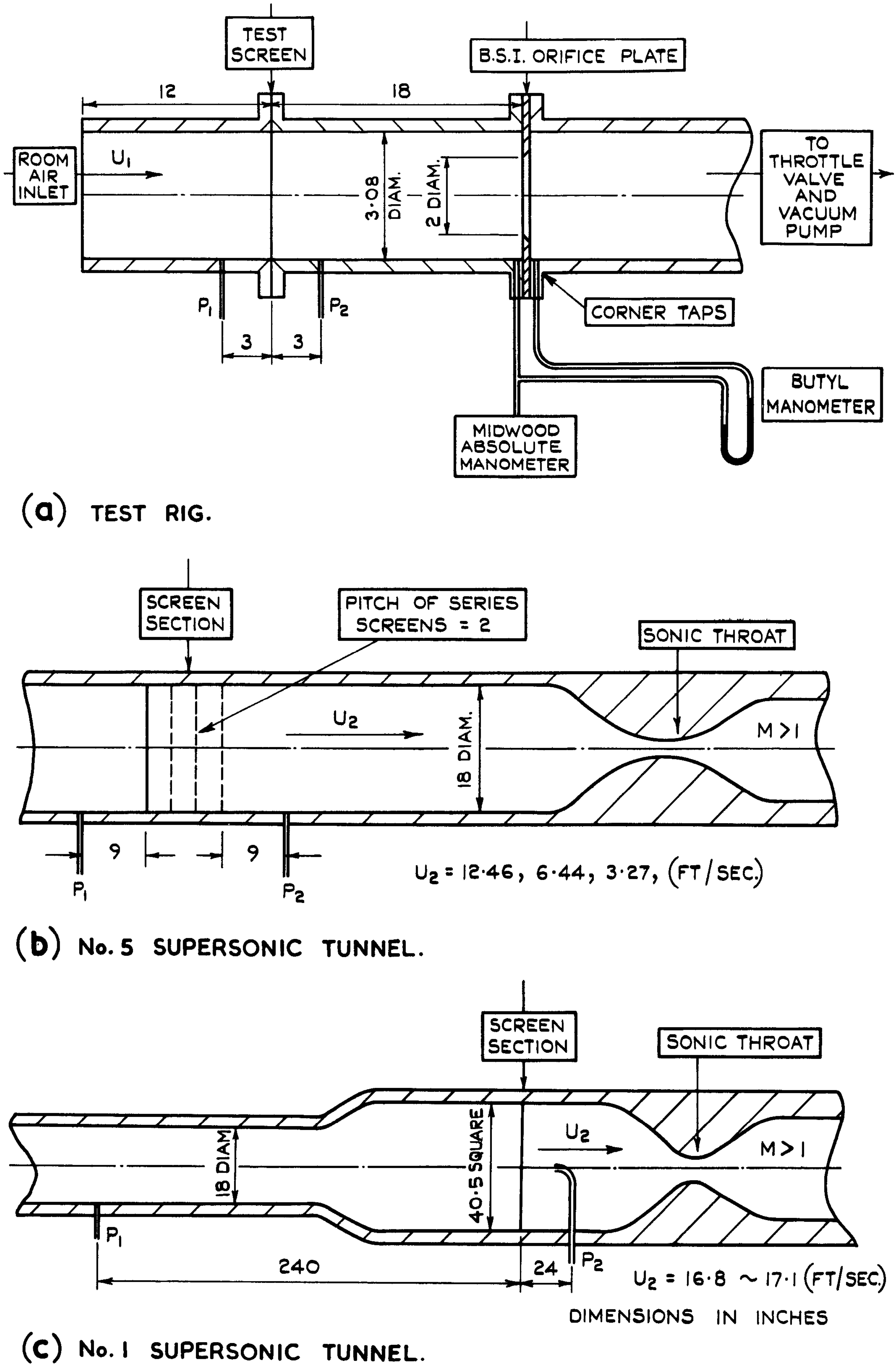


FIG. 1. DIAGRAMS OF TEST RIG AND TUNNEL FILTER INSTALLATIONS.

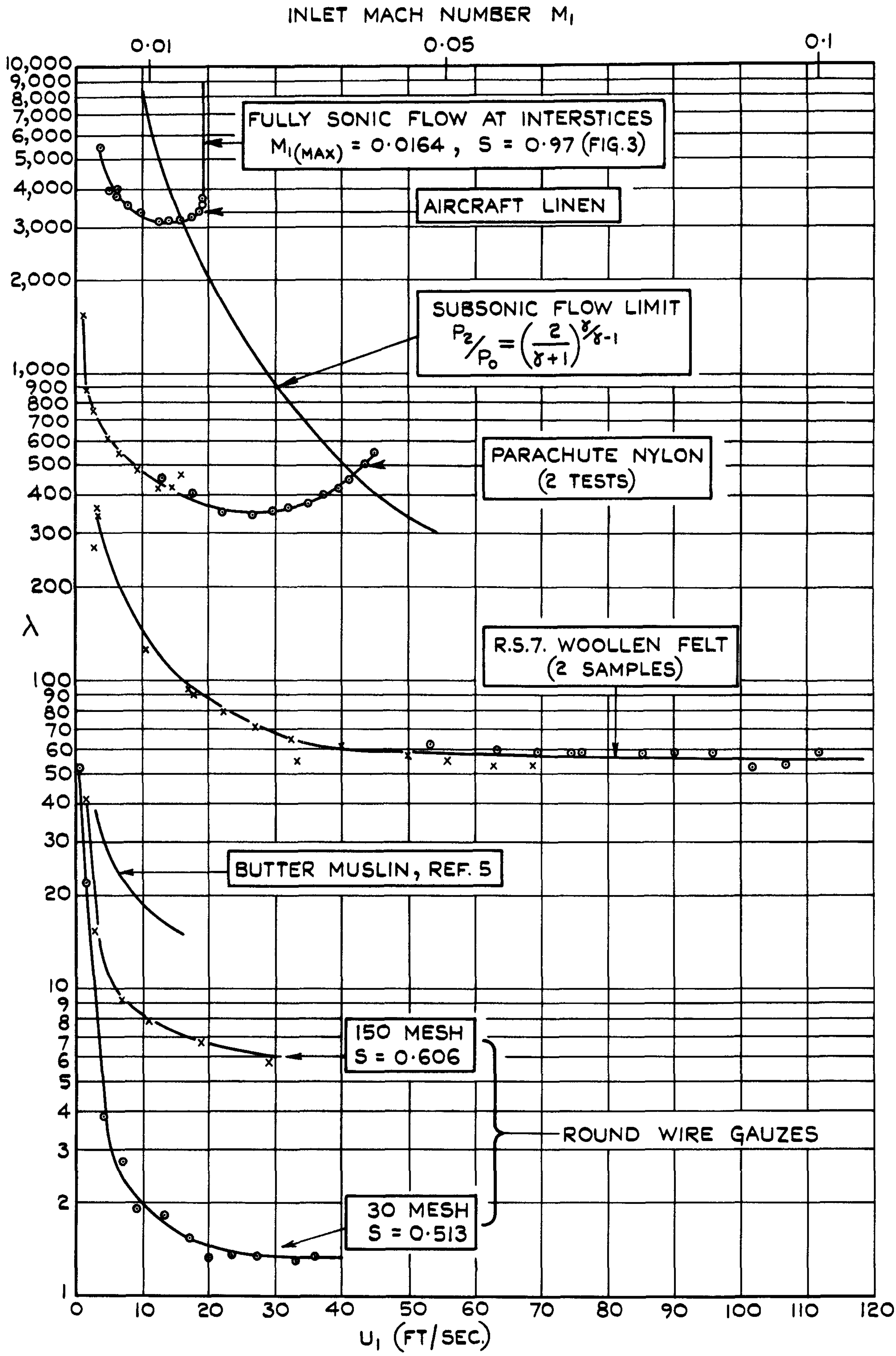


FIG. 2. COMPARISON OF PRESSURE DROP COEFFICIENT FOR VARIOUS SCREENS.

(P_1 = 1 ATMOS.)

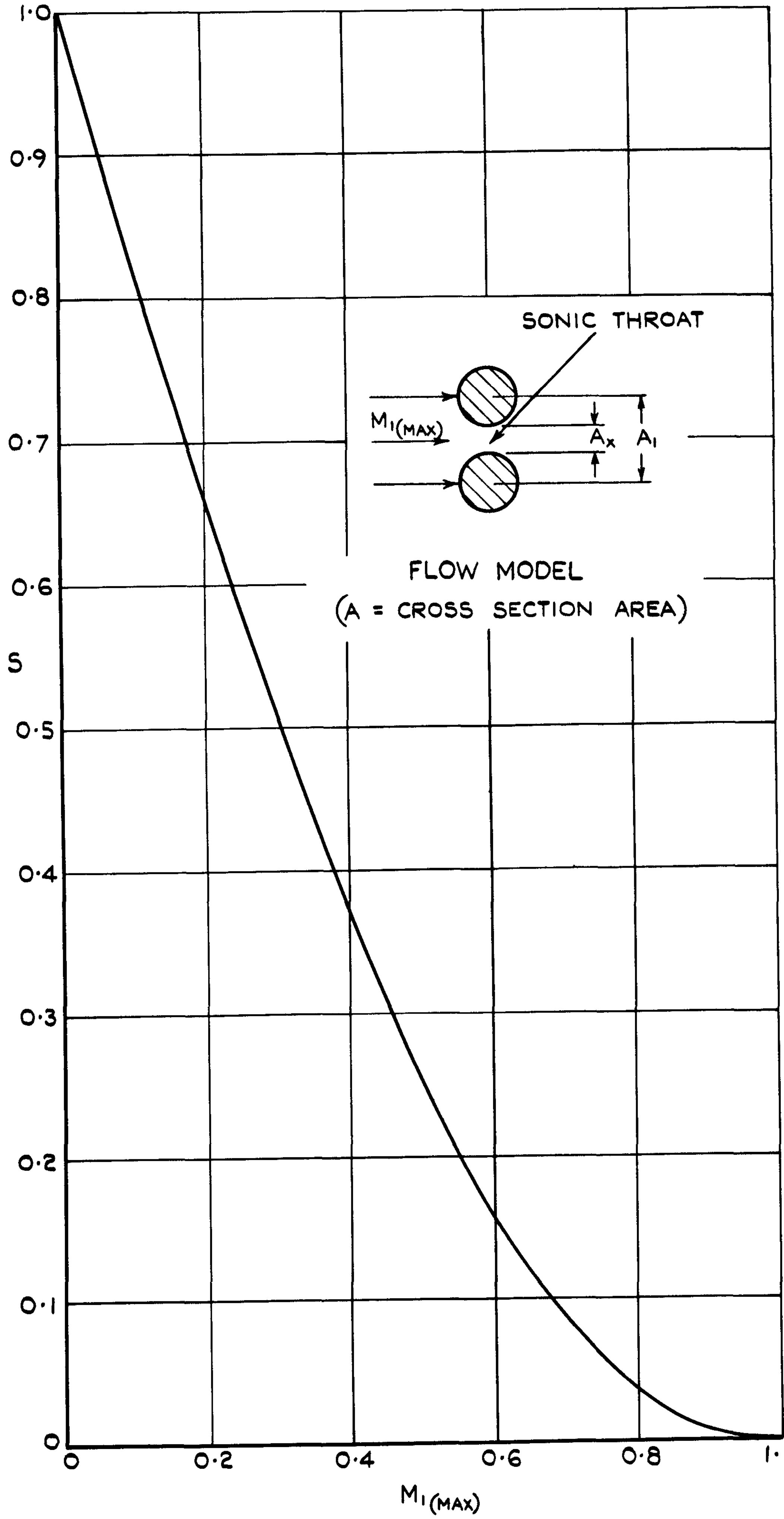


FIG. 3. MAXIMUM INLET MACH NUMBER VERSUS SOLIDITY.

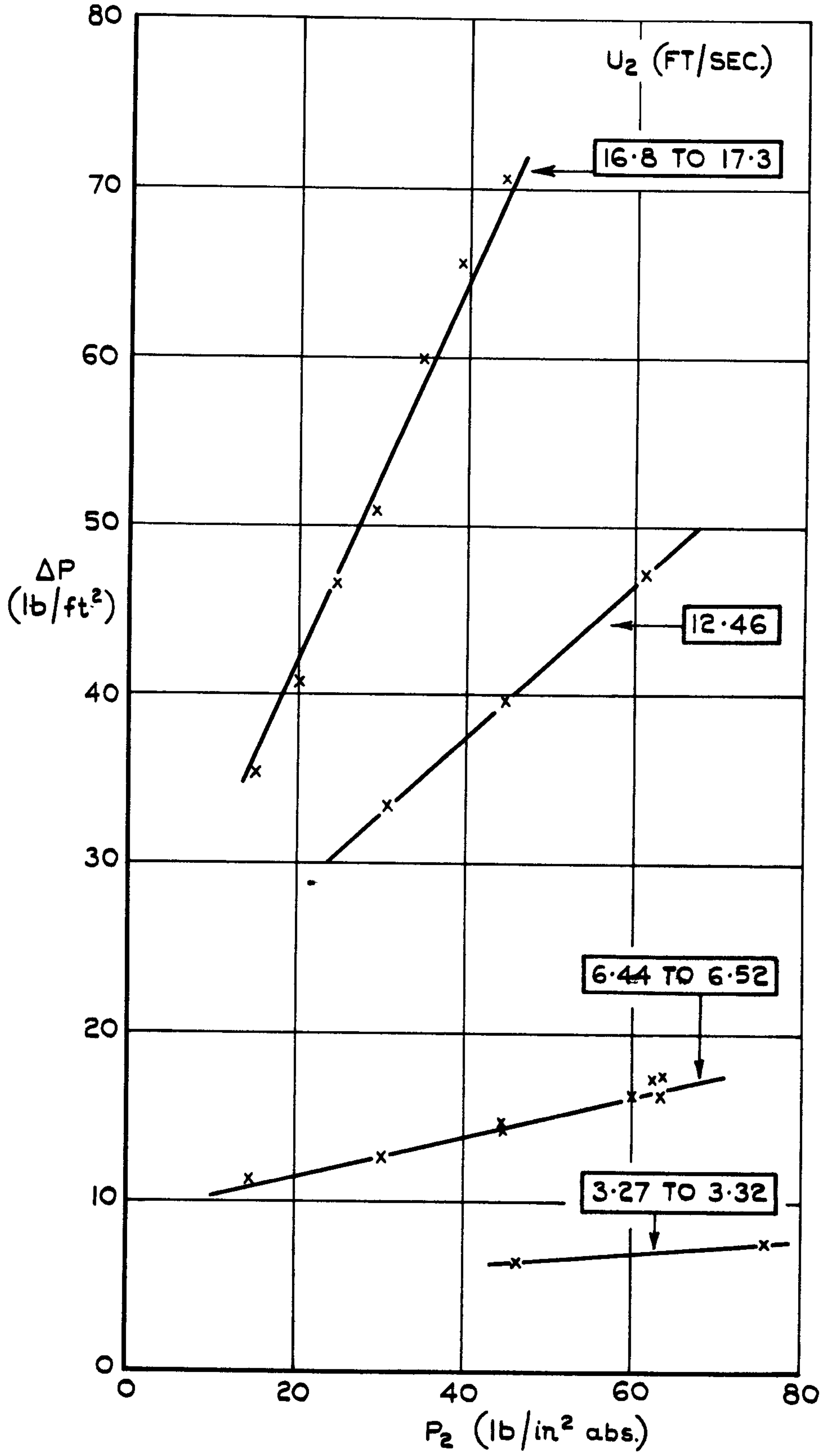


FIG. 4. THE EFFECT OF PRESSURE ON PRESSURE DROP ACROSS SINGLE FELT SCREENS IN TUNNELS.

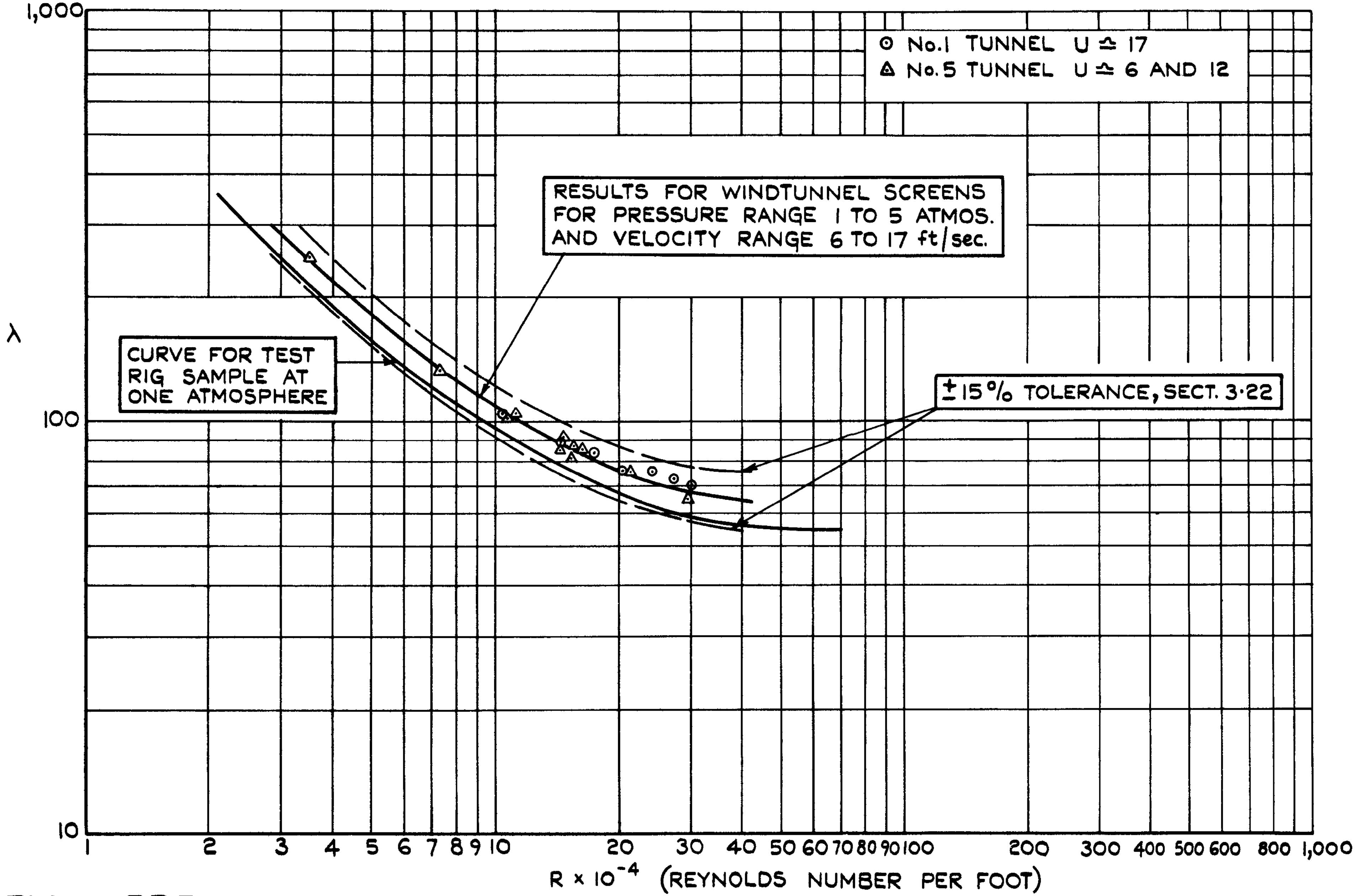


FIG. 5. PRESSURE DROP COEFFICIENT VERSUS REYNOLDS NUMBER PER FOOT FOR SINGLE FELT SCREENS IN WIND TUNNELS.

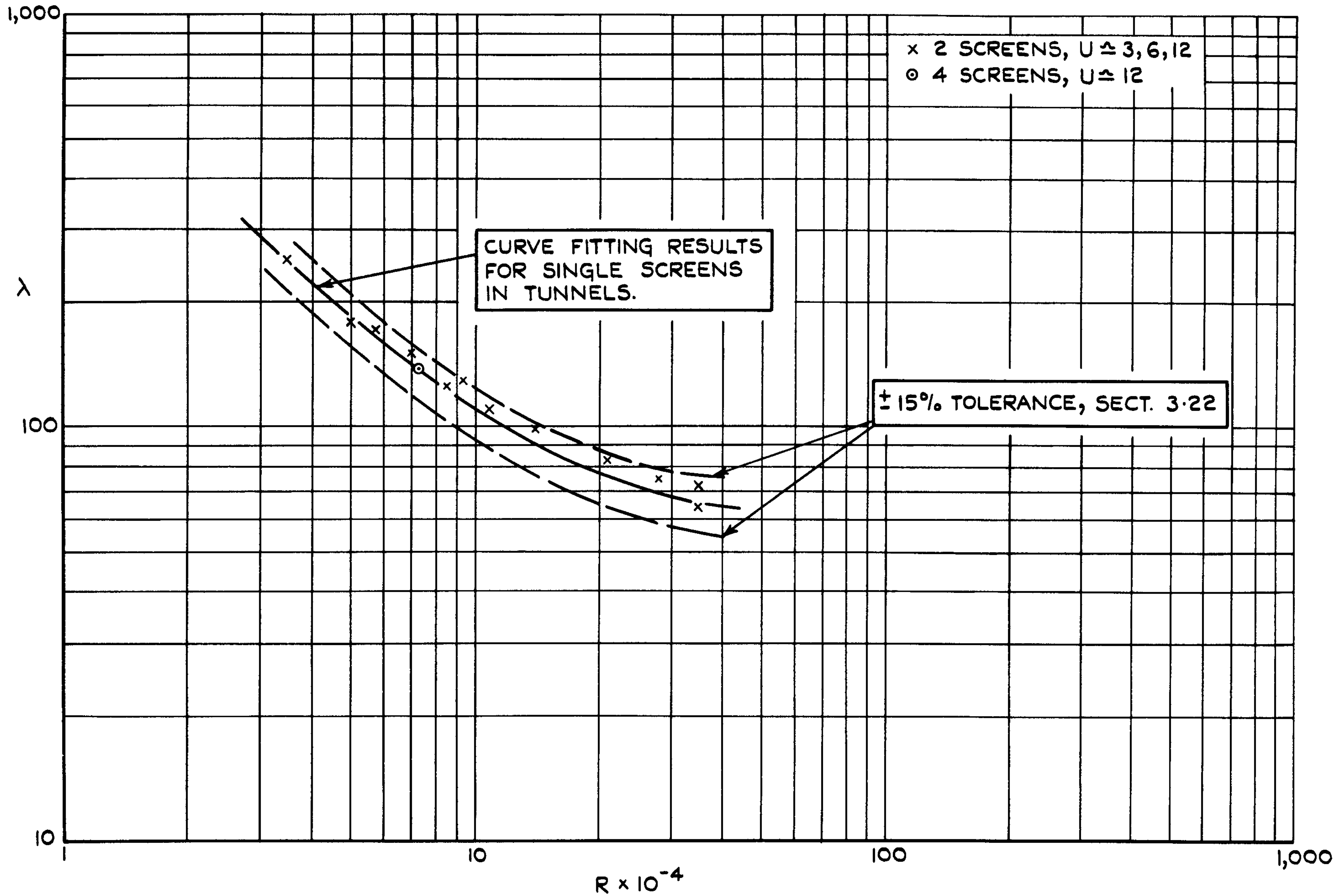


FIG. 6. PRESSURE DROP COEFFICIENT PER SCREEN VERSUS REYNOLDS NUMBER PER FOOT FOR SERIES SCREENS (No. 5 TUNNEL.)

AIRCRAFT
LINEN
($d \simeq 0{\cdot}010''$)

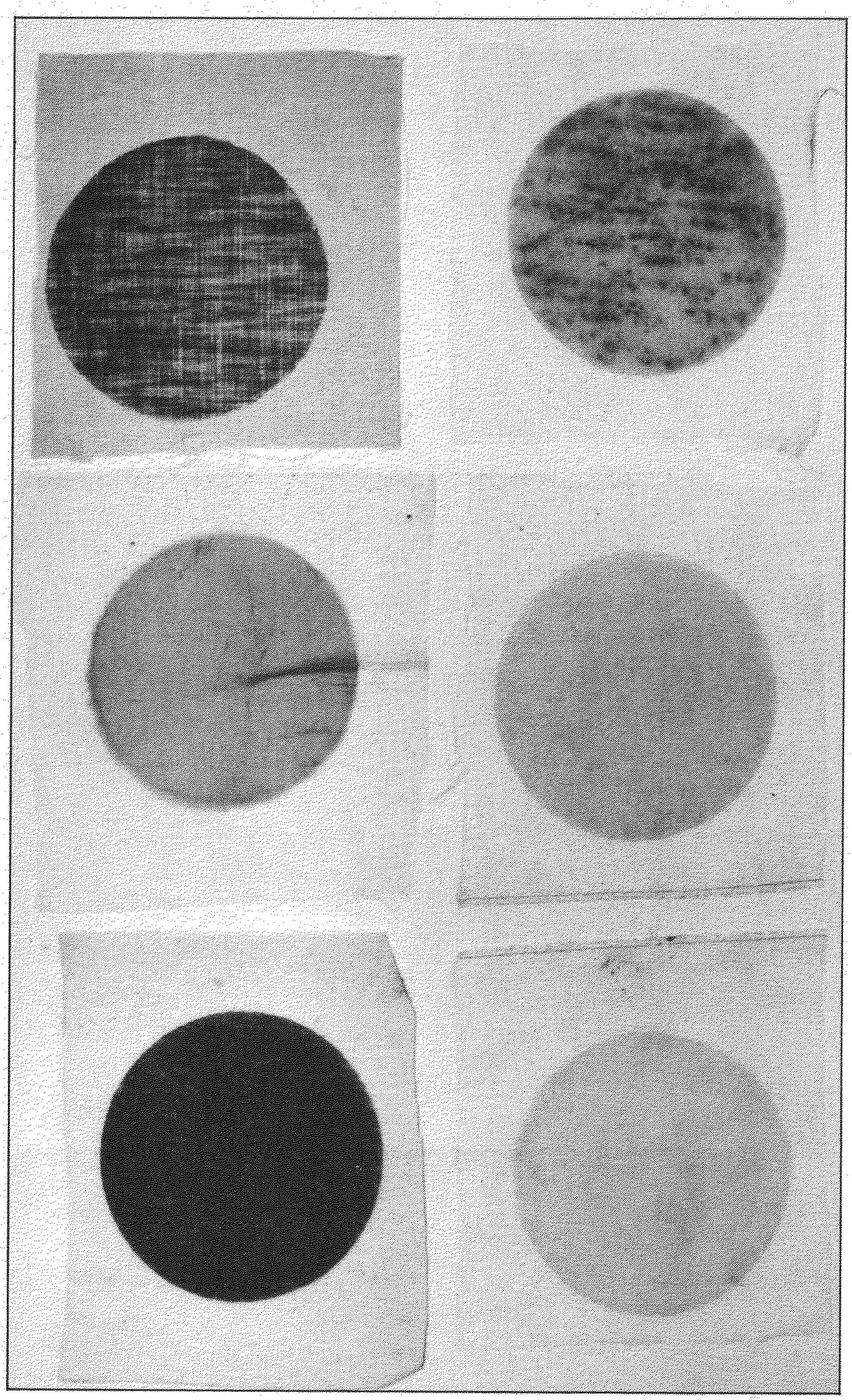
a

PARACHUTE
NYLON
D.T.D. 556
($d \simeq 0{\cdot}0004''$)

b

R.S. 7
WOOLLEN
FELT
($d \simeq 0{\cdot}001''$)

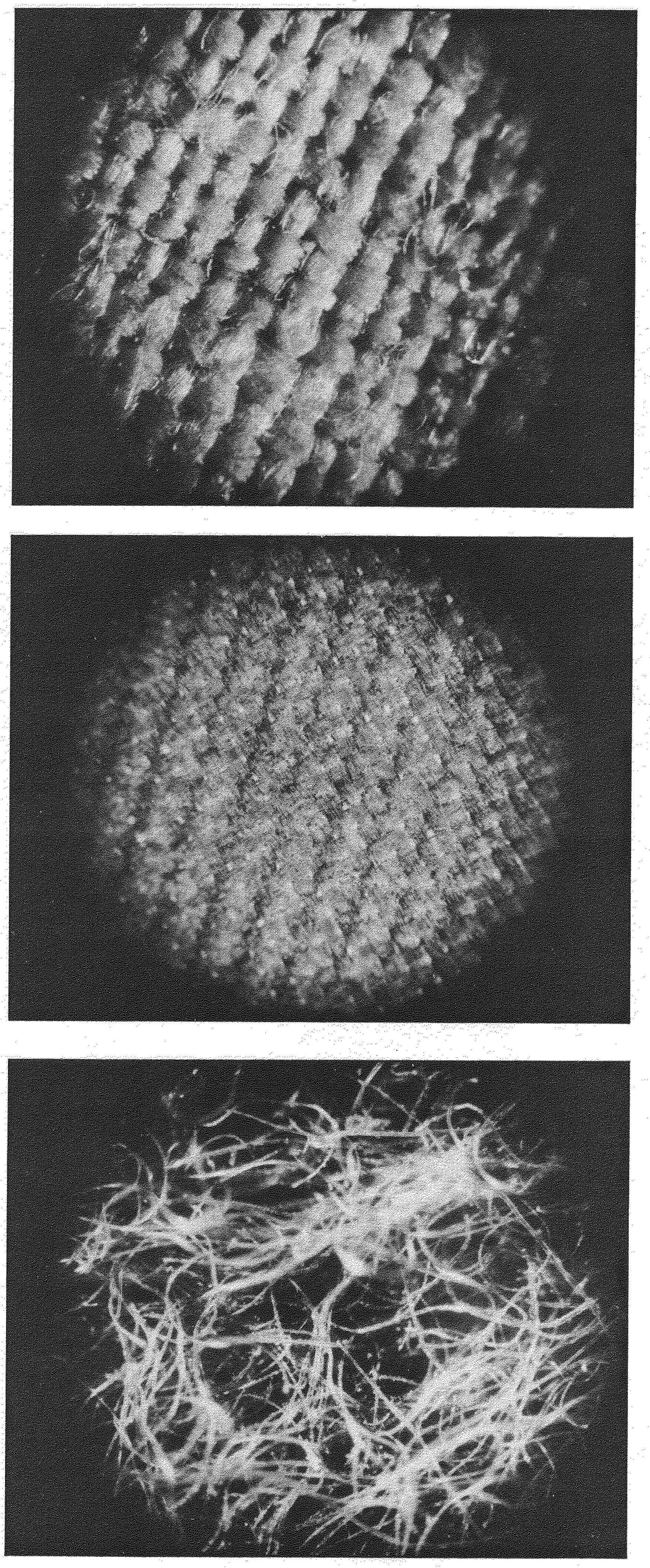
c



TEST
SCREENS

BACKING SCREENS
(PARACHUTE NYLON)
(D.T.D. 793)
$d \simeq 0{\cdot}0003''$

FIG. 7. COMPARATIVE FILTRATION EFFICIENCIES OF VARIOUS SCREENS SHOWING DUST THROUGHPUTS ONTO BACKING SCREENS ($\frac{1}{4}$ INCH SEPARATION) (6 HRS. $U_1 \simeq 20$ ft./sec., ATMOS. INLET). NOTE SUPERIORITY OF SCREENS WITH SMALL DIAM. FIBRES



a

b

c

FIG. 8. PHOTOMICROGRAPHS OF THE MESH ARRANGEMENTS OF (a) LINEN, (b) NYLON, AND (c) WOOLLEN FELT SCREENS

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