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Notes and Comments on some particular Features of Wind-Tunnel Design following Measurements of Flow Distribution, Wall Pressures etc. in the N.P.L. 7 ft (Low Turbulence) Wind Tunnel

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Summary.

Various measurements are recorded and some of the features (good and otherwise) of the design are discussed. The conclusions have relevance both to the modification of existing wind tunnels and to the design of new ones.

1. *Introduction.*

Accessible information about the performance of existing wind tunnels is far from being adequate. Once a tunnel is constructed the subject too often becomes a matter of low priority or else such information as is obtained is not usefully analysed and recorded. In the present instance the acquisition of the data was in the main intended to assist an appraisal of the consequences of some imminent modifications. It showed promise, however, of being useful in relation to modifications in mind for other tunnels. On further examination it also appeared to provide a suitable framework for discussing various aspects in a rather more general sense. This record of information and comment is by no means comprehensive but is set out in a form intended to be suitable for possible amplification later.

2. *The Original Wind Tunnel.*

The 7 ft low-turbulence wind tunnel was built (1940 to 1943) with the primary object of providing a stream with a very low level of turbulence. Since then it has also usefully served to illustrate the reliability or otherwise of the design data available at that time. The main features were (Fig. 1a):

(a) A long settling length (with honeycomb straightener).

(b) An $8 \cdot 15$:1 contraction ratio.

(c) A very long working section (regular 16 sided with opposite sides 7 ft apart—area 39 sq. ft). The breather slot was close to No. 1 corner.

(d) A return circuit main diffuser angle of 7°.

(e) A windmill in the main diffuser.

* Replaces N.P.L. Aero. Note No. 1023—A.R.C. 25 256. Published with the permission of the Director, National Physical Laboratory.

Except for the outer shell of the fan unit the cross-section was regular 16 sided throughout. The fan ($8\frac{1}{2}$ ft diameter with a 3 ft diameter hub fairing) was placed in the short leg between the first and second corners.

Immediately downstream of the first corner the cross-sectional area (7 ft polygon) was (and still is) 39 sq. ft; at the second corner ($8\frac{1}{2}$ ft polygon) $57\frac{1}{2}$ sq. ft; that of the fan annulus 50 sq. ft. The equivalent total cone angles of the two portions of the short leg are about 5° upstream of the fan and $3\frac{1}{2}$° downstream of it.

The cone angle of 7° for the main diffuser has been found to be too large. (The windmill may also be much too close to No. 3 corner.) The 'aerofoil' type vanes, as originally fitted into the corners, have not been as satisfactory as previous tests on much smaller vanes (and Reynolds number scale) had indicated. Partly because of the latter circumstance the 5° cone angle of approach to the fan has also been excessive.

The serious consequence of all this was found to be the presence of some long-period unsteadiness of the flow in the working section in the form of a tendency for the speed to switch spasmodically between two slightly different values.

3. *Early Modifications.*

The unsteadiness of the airflow mentioned in the previous section was more or less rectified by temporary devices which are also illustrated in Fig. 1a:

(a) A circular guide ring in the long diffuser (1944).

(b) Two screens in the settling length (1945).

The latter are woven from 0·0092 in. diameter wire spaced 30 to the inch giving a calculated open area 52·4%. They are situated respectively at about 9 in. and 5 ft upstream of the large end of the contraction; this is unusually close to the contraction especially in view of the originally available 28 ft of settling length.

The guide ring, being temporary, is liable to be structurally troublesome being subjected to fluctuating forces—a situation probably aggravated by aerodynamic inadequacies of the corner vanes. Despite these shortcomings however it has greatly improved the quality of the flow in the long return-duct.

4. *Later Modifications* (1961).

In later modifications the working section was restricted in length to 24 ft but otherwise enlarged to a corner-filleted square section with tapered fillets (for the reduction of static-pressure gradient—*see* Section 17). It is now therefore 8 sided (but not a regular octagon). It ends at the breather slot (Fig. 1a) and the balance and turntable are situated at its mid position. Downstream of the breather slot the section area *decreases* gradually to the unaltered 16-sided section of the first corner.

The contraction has been appropriately rebuilt to fit the new working section. It is still (regular) 16 sided at its inlet end but now changes to 8 sided in the first 3 ft or so. As in the original its area variation with axial length is still derived from Collar's suggested formula $dU/dt = Kx^3(L-x)^3$ (*see* Section 21). The geometrical contraction ratio is reduced to 7·15.

5. *Recent Modifications* (1963).

More recently a further major alteration has been made, in this case to the vane arrangement in the first corner. It is illustrated in Fig. 1b and is based on some experimental results recorded in

Ref. 3. The inner thick vane has been removed and replaced by 4 thin vanes ($\frac{1}{4}$ in. thick). Intermediate thin vanes have also been set up in 3 out of 5 of the other passages with the intention of fitting one more if it should be required.

Because of sundry inaccuracies in respect of manufacture and erection both of the old (thick) vanes and of the additional (thin) ones the overall geometry does not conform very closely to the design. Pending further experience, however, it meets what are considered to be the important requirements regarding such a modification as this. The leading-edge portions of the thin vanes are at about 5° (say $\pm 1°$) to the axis (positive incidence), the trailing-edge portions are at about 0° and the leading-edge profiles are approximately semi-elliptical in form (in this case a $3\frac{1}{2}$ to 1 axis ratio).

In the course of erection it was seen to be desirable to offset two of the new vanes and they were re-sited in such a way that the convergences and divergences tended to maintain a high wind speed at the inner wall of the tunnel. It is *not* important that the leading edges (or trailing edges) should be carefully located in one plane.

6. *Scope of Present Notes.*

The above brief record of the tunnel is not intended to be comprehensive but it provides the minimum information needed for what follows here and for any future work and comments of a similar nature.

From its beginning a considerable amount of investigation has been carried out into the details of the performance of the tunnel as equipment for producing a wind stream of the desired quality (L. F. G. Simmons, R. W. F. Gould, C. F. Cowdrey, W. G. Raymer). Reference will be made to this where appropriate. Most of it has not yet been published but in view of current interest is being recorded separately.

The present concern is to record and comment upon certain specific features which have been the subjects of recent investigation (*see* Section 1). They relate to those parts of the tunnel extending from the settling length to the fan.

7. *Apparatus of Measurement, etc.*

This included pitot- and static-pressure tubes, a surface creeper tube, a Betz manometer and a vane anemometer.

The (2 hole) creeper tube is sketched in Fig. 2. It was used for measuring 'surface' pressures in the contraction and in the first 9 ft or so of the working section. The creeper-tube method of measuring 'surface' pressures has been successfully employed elsewhere and found to be very satisfactory. It may not be suitable for very detailed exploration but it avoids many of the uncertainties which are often associated with 'holes in the side' and some form of it might at times be preferable as a pressure-tapping device for control of tunnel air speed.

Total and static pressures throughout were measured against external atmospheric pressure (which is denoted by B). All measurements are presented as being not so much specially precise as accurate enough for any conclusions here associated with them. Unless otherwise stated the observations relate to a dynamic pressure $\rho U_0^2/2$ in the working section (mean over the central region) of 20·9 mm head of water. The corresponding wind speed was about 60 ft/sec and the pressure difference between the actual control tappings (*see* below) was 18·6 mm.

The upstream set of tappings comprised 4 'holes in the side' (coupled together) on roof, floor and vertical sides $7\frac{1}{2}$ in. inside the large end of the contraction (X in Fig. 9). The low pressure tapping was a single hole situated in one of the lower fillets and $6\frac{1}{2}$ ft from and upstream of the small end (Y in Fig. 9).

8. *First Corner. Upstream Side.*

At the side walls approaching the first corner the boundary layers are about 6 to 7 in. thick. Previous measurements with the working section in its original form (area 39 sq. ft—Section 2) indicated just about the same thickness on the floor both at 40 and at 100 ft/sec. The present *decrease* of cross-sectional area from $45\frac{1}{2}$ sq. ft at the breather to 39 sq. ft approaching the first corner has not therefore made much difference in this respect.

There is consequently still a considerable relative deficiency of momentum in the air entering the already somewhat restricted inner (short vane) passage of the corner vane unit (Fig. 1b). (The cross-section just upstream of the corner is 16 sided, i.e. nearly circular.)

9. *First Corner. Original Vanes. Downstream Side.*

The weakness of the flow at the upstream inner wall (C in Fig. 1b and Section 8) combined with some lack of turning effectiveness of the corner vanes resulted in a flow separation from that wall on the downstream side (D in Fig. 1b). This was observed by means of streamers. Although not very extensive it was nevertheless undoubtedly detrimental in its consequences. The defect was partly due to the restriction of the *number* of vanes in the No. 1 corner to 8. No. 4 corner with 20 vanes has been found to be fairly satisfactory (cf. Ref. 3); it is also interesting to note that many more vanes per unit were proposed by Prof. Taylor in Ref. 1.

The total-pressure (T) curve of Fig. 4—full line— shows the associated severe thickening of the boundary layer in a horizontal traverse about 6 ft upstream of the centre of the fan, i.e. roughly half-way between the corner vanes and the fan. (B refers to atmospheric pressure and U_0 to the air speed in the working section—Section 7.)

The static-pressure (S) curve shows, on and near the axis, the back-pressure effect of the fan hub fairing.

10. *Approach Flow to Fan. Original Vanes.*

The faulty distribution of total pressure mentioned in Section 9 naturally leads to an expectation of some unsteadiness of flow in the tunnel circuit but more immediately severe may have been its effect on the distribution alongside the hub fairing upstream of the fan blades (Fig. 1a). This is illustrated by the full lines in Fig. 5 from which the velocity traverse can be deduced if required. Near the surface of the fairing the velocity was particularly high (and the static pressure relatively low)—a normal consequence of the associated curvature of the flow.

Comparing Figs. 4 and 5 (full lines) it may be noted that the vane shadows remained very pronounced alongside the hub fairing; also that (at least for this horizontal traverse) there was an aggravation of the total-pressure losses in the tunnel-wall boundary layer between the two stations. Some aggravation was to be expected in any case because of the large increase in area between the corner vanes and the fan (Section 2). At the inner wall, however, it was specially severe and the thickness of the layer at the second station (original corner vanes) was at least 15 in.

The dissymmetry of the full-line curves of Fig. 5 means that, near the inner wall, the outer halves of the fan blades have to pass through a region of relatively much lower velocity and total pressure so giving rise to undesirable pulsations in the airstream and, of course, subjecting the blades to pulsating stresses.

11. *First Corner. Modified Vanes. Downstream Side.*

The two sets of traverses in Fig. 4 (full and dashed lines respectively) are not fully comparable, because of some differences in the processes of measurement. Even so it is clear that the modified vane unit has resulted in a striking improvement of the flow near the inner wall on the downstream side of No. 1 corner.

For easier study of the traverses the vane positions (with appropriately scaled spacing) are marked on the base line in Fig. 4—*see* also Fig. 1b and Section 5—but more evidence is required before the vane shadows can be fully correlated.

Measurement of static pressure in these conditions would not be expected to be very accurate. Taking the traverses as found, however, the change of static-pressure dissymmetry indicates an improvement in turning effectiveness (Ref. 3). The residual weakness of flow close to the inner wall (dashed total-pressure curve) is therefore probably due to the (in these circumstances) relatively thick boundary layer on the upstream side of the corner (Section 8 and Fig. 1b). Streamer observations confirm the residual flow weakness (D in Fig. 1b) but also show that there is no longer any separation of the flow at this station (cf. Section 9).

12. *Approach Flow to Fan. Modified Vanes.*

It is evident from Fig. 5 that the corner vane modification has greatly improved the flow distribution alongside the fan hub fairing. If the new traverse is a reasonable indication of what can be expected for the whole annulus then, except for some residual deficiency close to the inner wall, the distribution can now be regarded as being very good.

13. *Adjustment of Modified Corner Vane Unit.*

The question whether the insertion of another thin vane (Section 5) or any other adjustment of the No. 1 corner vanes might be worth while has not yet been fully considered. In any case further measurements are required prior to a decision or to any re-examination of fan design, etc.

Two further possible modifications come to mind:

(a) A few vortex generators on the inner wall on the upstream side of the corner.

(b) A deflector plate near the inner wall about half way between the corner and the fan.

14. *R.P.M. etc. of Fan.*

It is always desirable to know whether major tunnel alterations have resulted in any significant change in fan speed and fan power. The specific effect of the recent alterations to the corner vanes (Section 5) is shown in Fig. 6. In this figure it is convenient (following a long-standing custom) to plot against 'nominal ft/sec' instead of dynamic pressure in the working section. It is calculated on the assumption that the air density there is 0·00238 slugs/cu. ft (corresponding to 760 mm mercury and 15°C).

The power factor of Fig. 6 is an arbitrarily approximate one and is calculated from the formula

$$\left(\text{volts} \times \text{amps} \times \frac{550}{746}\right) \Big/ (\tfrac{1}{2}\rho A U_0^3).$$

In this ρ slugs/cu. ft is the (actual) air density in the working section, $A = 45$ sq. ft is the cross-sectional area at the middle station of the working section, and for U_0 see Section 7. Volts and amps are as indicated by the control-panel meters and are recorded in the same figure. With this definition the power factor is about 0·7 in the higher range and installation of the extra vanes appears to have made no significant difference in this respect.

One always hopes, of course, that the extra resistance, if any, of an otherwise beneficial modification will at least be rendered unimportant by an improvement of efficiency elsewhere. The power factor check is, however, not inherently a very accurate one and the relation between U_0 and fan speed is more reliable. Fig. 6 indicates that for any given motor speed U_0 has become smaller by about $1\frac{1}{2}\%$. (In the Compressed Air Wind Tunnel the installation of turning vanes resulted in an increase in the ratio.) The change is very small but the tendency is towards the fan blades having to operate at a slightly higher angle of incidence to the relative wind.

15. *Static Pressure along Axis of Tunnel.*

The variation of static pressure more or less along the centre line of the modified tunnel is shown in Fig. 7. A sketch of the corresponding 'mean *r*' wall profile (Section 21) is added. The actual observations are recorded in Table 1 (*see* also Fig. 11).

The pressure (near the axis) is not atmospheric at the breather but at the beginning of the working section. Downstream of the breather there is, of course, following the modifications of Section 4, a considerable acceleration of the stream associated with the gradual reduction of cross-sectional area in this region.

Other features are discussed in more detail in later sections.

16. *Total Pressure along Axis of Tunnel.*

For the record (again for the modified tunnel—Section 4) some incidental observations of total pressure are included in Table 1 and Fig. 7. Being single position readings and not spatially mean values they are not particularly useful for analysis (cf. Section 25). The apparent slight gradient (Fig. 7) may be fortuitous; in view of the low level of turbulence it probably only indicates a lateral variation of total pressure; if so it would result from the difficulty of making all the measurements along the same streamline. It is perhaps worth recording here that prior to the insertion of the screens the variation of $\rho U_0^2/2$ at the centre of the working section over an area at least 5 ft in diameter was found to be only $\pm 0 \cdot 5\%$. Unfortunately one has to expect that most screens are likely to result in greater variations than this even when perfectly clean.

17. *New Working Section: Effectiveness of the Tapered Fillets.*

In the new working section the fillets taper continuously from $18\sqrt{2}$ in. wide at the upstream end to $16\sqrt{2}$ at the breather. The resulting slight diffuser effect is, of course, intended to lead to constancy of static pressure along the axis in this region.

The total increase in area is 136 sq. in. which is about what would be deduced from a calculation of the growth of the boundary layer assuming it to have zero thickness somewhere in the small end of the contraction—say $l = 10$ in Fig. 7. On such a basis the dashed line in Fig. 7 represents (for 60 ft/sec) the estimated axial gradient with non-tapered fillets. The actual gradient may be expected to improve very slightly at higher wind speeds but even so it would appear that downstream of $l = -4$ the taper could with advantage have been nearly doubled. It may be that compensation would have been more effective if the calculated taper had been distributed over all the wall surfaces.

18. *New Working Section*: *Thickness of Boundary Layer.*

The thickness of the boundary layer on the floor near the middle of the section is about $2\frac{1}{2}$ in. (40 to 100 ft/sec). This again agrees well with calculation and confirms that the contraction profile is probably one that leads to a thin boundary layer in its small end.

19. *Effective Length of the New Working Section.*

It appears from Fig. 7 that notwithstanding the immediate tapering of the fillets the acceleration effect of the contraction is continued for a foot or so into the (so-called) working section. This feature is not uncommon and in this case the distance is small because of the gradual trailing off of the contraction profile. Any attempt to rectify it by running the working section taper up into the small end of the contraction would probably have a detrimental effect on the wall pressures (Fig. 11 and Section 31—*see* also end of Section 33).

Fig. 7 also shows that the fillets become ineffective at a station upstream of the breather.

It may be said therefore that the 'effective' working section extends approximately from $l = -1$ to $l = -23$. Various important details of design, both in respect of contraction and working section, have led to this being an unusually large proportion of the intended length (24 ft); few wind tunnels are so fortunate.

On the other hand for some investigations (bearing in mind the wall pressure curves of Fig. 11) it could be said to extend from, say, $l = +5$ to $l = -30$. We are thinking here of cases where stream distortion or disturbance (due to a model) extends axially a considerable distance (either way or both ways) but where greater tolerance may be accepted in the quality of the undisturbed stream at distances corresponding to the end regions of the disturbed field.

In other sections of these notes, however, reference to the working section will usually imply the formal geometrical working section.

20. *Contractions. Preliminary Remarks.*

Contractions are such important features of wind tunnels that much attention has been given to their design. Unfortunately however little is known about the detailed performance of completed units in actual working conditions. In this instance the information already obtained has been both interesting and illuminating but at the same time it has indicated a need for even more investigations with a prospect of leading to some very useful conclusions. Consequently it is proposed to record in these notes (for later application) more data and comment (geometrical and otherwise) than is immediately required.

For the objects in mind we may first note that in addition to certain other specifications it is usual to require

(a) that the boundary layers in the working section shall be as thin as is reasonably practicable;

(b) that, in connection with (a), there shall be no pressure recovery in the surface pressure characteristic in the small end (nor, of course, in the working section);

(c) that it shall be possible to find suitable pressure points for speed control.

In respect of (c) the downstream pressure point needs to be

(i) near enough to the working section to provide a sufficiently large pressure difference for accurately controlling the air speed;

(ii) far enough from any 'model' placed in the working section to ensure freedom from 'back pressure' due to the presence of the model;

(iii) so placed that the pressure in the take-off tube is also adequately steady and consistent.

21. *Geometry of the New Contraction.*

It has already been stated in Section 4 that the contraction is now regular 16 sided at the upstream end and a filleted square where it joins the working section. It is in fact filleted square for most of its length.

The cross-sectional area is derived from Collar's suggested relation for the acceleration

$$dU/dt = Kx^3(L-x)^3$$

where (as calculated) x is the distance from the *large* end and L is the (arbitrary) total axial length. The side faces at the large end are 20 ft apart; the basic square at the small end is 7×7 ft with the fillets $18\sqrt{2}$ in. wide at this station. The area distribution is given by A in the equation

$$\frac{1}{A^2} = 0{\cdot}09874 + 4{\cdot}9511(35-84\alpha+70\alpha^2-20\alpha^3)$$

where α is x/L.

The total length L was fixed at 20 ft and Table 2 records A and $1/A$ together with the radius r that the contraction would have if it were circular in section throughout.

In the same table are recorded the design profiles y_1 for the centre lines of the floor, roof and vertical sides, y_2 for the centre lines of the fillets and y_3 for the corner joints between adjacent faces. These design profiles, superimposed on the r profile, are plotted in Fig. 8. This is done because it may have to be considered in due course whether such profiles are (aerodynamically) significantly different from one another in circumstances of a similar nature to the present ones (cf. Section 31).

In this connection the 'scaled' curves of Fig. 8 are relevant. These were obtained by multiplying both abscissae and ordinates of each y curve by the ratio r_0/y_0 where suffix $_0$ denotes the exit ordinate in each case so that the scaled curves all have the same ordinate at outlet as the axi-symmetric r curve. They can now be compared directly as regards both curvature and degrees of acceleration represented by each one separately.

The $1/A$ curve is plotted in Fig. 9.

In the tables and figures we have used l, the axial distance from the *small* end, as being (with occasional exceptions) generally more useful than x the distance from the large end. The non-dimensional co-ordinates and area ratios having been carefully calculated they are also recorded (Table 3).

As mentioned in Section 3 the second screen is only 9 in. upstream of the contraction and, in the wind, bulges a foot or so in its centre parts. It is found to introduce an aerodynamic interference (Sections 27, 28, 29) so that its presence must be regarded as an intrinsic feature of the present contraction unit.

22. *New Contraction. Streamer Exploration.*

As a further background to the following sections the general flow picture will be relevant.

In the course of a brief exploration with a streamer probe it was found that there was nothing seriously wrong with the flow in the contraction. There was no sign of separation or reverse flow but the speed appeared to be relatively low in the outer annulus (about 2 ft radially) of the large end.

The stream is very turbulent in the corners between adjacent panels but only for an inch or two from the corner. Otherwise the air flows very smoothly over the convex surfaces.

23. *New Contraction. Boundary-Layer Thickness.*

So far only one measurement of boundary-layer thickness has been made and that at (or near) one of the main stations of interest. On the floor at $l = 13$ ft (*see* Fig. 9) a total pressure traverse showed that the thickness is here less than a tenth of an inch (60 ft/sec in the working section). This is very small, as one would wish.

24. *New Contraction. Pressures along Axis.*

In amplification of Section 15 we turn now to the static pressure along the axis of the contraction (right-hand portion of Fig. 7). On the face of it the general shape of the curve is quite reasonable but some specific deductions can be made.

The first point of interest to consider might be the correlation between the velocity (near the axis) and the $1/A$ curve. This is illustrated in Fig. 9. In view of the assumptions in the calculation of the $1/A$ distribution (Section 21) we should not expect exact correlation in any case. Besides this the calculation of dynamic pressures from the measurements already quoted is not very accurate. Nevertheless if we do the best we can, estimate dynamic pressures in terms of mm of water and plot $\sqrt{\text{mm}}$ on such a scale that the curves coincide at $l = 0$ we obtain a comparison adequate for present purposes.

Comparing the two curves of Fig. 9 the cross-over at $l = 15$ would appear to lead to the significant conclusion that the effective contraction ratio is not as high as the geometrical one. This is discussed further in Section 25.

The residual gradient of static pressure at the small end of the contraction unit has already been examined in conjunction with the working-section gradients in Section 19.

25. *Effective Contraction Ratio by Pressure Measurements.*

For estimating the efficiency of a contraction (for example in reducing turbulence in the neighbourhood of the axis) it is helpful to consider an 'effective' contraction ratio defined as the ratio of the air velocity near the axis a short way inside the working section to that at the large end of the contraction.*

Using Fig. 7 and Table 1 in order to estimate its value for the new contraction we obtain an answer (depending on details in our assumptions) lying somewhere between 5 and 6, i.e. considerably less than the anticipated 7·15.

This evidence, however, even in conjunction with the streamer explorations of Section 22 and the provisional deduction from the $1/A$ comparison (Section 24 and Fig. 9), is still not conclusive. Confirmation (or otherwise) has therefore been sought by other methods.

26. *Effective Contraction Ratio by Vane Anemometer.*

A vane anemometer was set up near the axis in the large end of the contraction. As the screen bulged under the wind loading to the extent of a foot or so the instrument was necessarily about one foot inside the large end where under running conditions it was, in general, about 9 in. from the screen.

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* It is not known whether this practical approach has previously been seriously considered, other than by the authors, or whether similar situations have been experimentally investigated.

In this test (25 to 100 ft/sec in the working section) the ratio of air speeds was found to be 5·0. There is unlikely to have been any important error in the readings; swirl in the airstream, if any, must have been very slight; furthermore the screens had been recently cleaned (although perhaps not with complete thoroughness). We can, however, make use of the pressure curve of Fig. 7 to agree that the value should possibly be increased by 10%, i.e. to 5·5 to allow for the anemometer being *inside* the large end. This agrees well enough with the value found in Section 25. A further check is referred to in Section 28.

27. *Tests for Importance of Screen Location.*

The apparent loss of contraction ratio raised the thought that the screens might be too close to the contraction and some model tests were therefore carried out with the object of investigating the point.

A small wind tunnel (6·8 in. diameter) being conveniently available, a wooden contraction was made to be a sliding fit in it. The general set-up is illustrated in Fig. 3. The block reproduced the contraction shape of the 7 ft tunnel except in being slightly truncated at the upstream end; the line of maximum slope was continued straight to the wall instead of being turned over to be co-linear with it. It included 2·7 in. of parallel extension of the small end corresponding to about 8 ft of full-scale working section. The geometrical contraction ratio was 7·4.

The rearward pointing static-pressure tube passed through and just fitted a carefully cut hole in the screen. It was supported outside the tunnel on a cruciform of thin metal strips one inch wide set up in two diametral planes.

The wire gauze screen was one of 34 S.W.G. (0·0092 in. diameter) wires spaced 30 to the inch—open area ratio 52·4% as in the full-scale tunnel. The Reynolds numbers of the tests were relatively very low but the wind speed through the screen (10 to 20 ft/sec)was much as in full scale and therefore about right in relation to the screen resistance coefficient.

28. *Results of Tests for Importance of Screen Location.*

The results are plotted in Fig. 10. In this figure as in what follows here the sliding contraction unit is imagined to be complete and *not* truncated as described in Section 27 (*see* also Fig. 3). Consequently z is the distance of the non-truncated contraction from the screen and the ordinates are explained by reference to Fig. 3. For the purposes of the deductions it has not been necessary to apply any corrections.

The results indicate that the contraction block begins to affect the values of the measured pressures S_1 on the axis and S_2 at the wall, i.e. to affect the flow through the screen, when z decreases to about $3\frac{1}{2}$ in. or roughly half of the upstream diameter. Full-scale dimensions being approximately $35z$ this corresponds to about 10 ft. On the face of it therefore we have to deduce that in the 7×7 ft wind tunnel the screens ought not to be located within 10 ft of the contraction.

In an attempt to measure the effective contraction ratios of the 6·8 in. tunnel directly from dynamic pressure ratios it was found that it would be impossible to obtain reliable observations without a considerable elaboration of the test rig. It is possible, however, from the change in the value of S_1 (Fig. 10) to make a rough deduction of what the effective contraction ratio becomes when the spacing z (Fig. 3) between the contraction block and the screen changes from $3\frac{1}{2}$ in. (10 ft full scale) to $\frac{1}{4}$ in. (9 in. full scale). The full value of 7·4 (Section 27) is assumed for large spacings and it was established that $B - H = 1{\cdot}42\rho V_0^2/2$ (Fig. 3).

On this basis the deduced ratio is $7 \cdot 4/\sqrt{(1+0 \cdot 8 \times 1 \cdot 42)} = 5 \cdot 1$, i.e. about the same as that measured in the 7 ft wind tunnel (Sections 25 and 26).

29. *True Axial Length of the New Contraction.*

It has always been a surprising feature of the contraction (old or new) of the 7 ft wind tunnel that in a general sense it appeared to be so effective although (for its contraction ratio) axially quite short. There appears, however, to be enough evidence in previous sections to provide at least part of the explanation and it is reasonable to deduce that 10 ft or so of the settling length should have been regarded as being part of the new contraction unit (and probably an even greater portion as part of the old one).

It may be, on the other hand, that in its present position the screen, at the cost of a large reduction in the effective contraction ratio, prevents any obvious flow separation from the walls in the large end of the contraction. There is a strong case for further investigation, perhaps the more conveniently on a model unit of reasonably large dimensions.

If the screens were removed the actual contraction length in the sense of being the acceleration distance would of course, because of the boundary-layer development, include the whole of the settling length.

30. *Smoothing Screens. Resistance Coefficients, etc.*

Theoretical considerations (Ref. 4) indicate that complete smoothing of moderate spatial non-uniformity of velocity should be achieved by the use of a screen with a resistance coefficient of about $2\frac{3}{4}$. Experience has shown that, for the range of wind speeds over which the coefficient does not vary much, such a screen (or a closely spaced set of the same total coefficient) is in fact extremely effective even for a quite large amount of non-uniformity. It has long been in question, however, whether this is true at low speeds where the coefficient of any given screen becomes much greater.

The question is relevant to this tunnel. Each screen (Section 3) has a coefficient of roughly $1\frac{3}{4}$ measured at an approach speed of about 50 ft/sec. The *maximum* speed in the settling length is, however, only 20 to 25 ft/sec at which speed the coefficient (again for each screen) is about 2. At 5 ft/sec it is at least 3 and at still lower speeds it rises very steeply.

In order to examine the smoothing efficacy of single woven wire screens at low wind speeds an investigation was carried out in the 18 in. wind tunnel at 2 and 5 ft/sec. This showed that $2\frac{3}{4}$ (the value mentioned above) is far from being the optimum coefficient in this very low range. The actual coefficients were quite large (up to 30 or so) but the values are not important. What matters are the main findings which are as follows:

(a) At these low wind speeds one can still achieve good, although incomplete, smoothing of severe non-uniformity (say, 2 to 1 velocity ratio) with the same screen that one would use at 50 ft/sec.

(b) Optimum smoothing is effected with a screen having a coefficient, measured at 50 ft/sec, of about 5 or 6. (Where such a large coefficient is required an equivalent multiple-screen unit is of course preferable.)

The circumstances of the investigation were not strictly comparable to the present application; nevertheless it may be tentatively deduced that in the 7 ft tunnel, whereas 3 screens would probably be better, the present combination of 2 is (except as regards location—Section 28) as suitable as it need be for the present purposes.

It is desirable however to supplement this conclusion by mention of some other considerations that must not be forgotten. (We are still concerned here only with the establishment of a uniform distribution of mean local velocity and not with the reduction of turbulence.)

(i) Uniformity of mesh (not easily obtainable) is obviously important.

(ii) Maintenance of screen cleanliness is equally so and much more attention is found to be required than is generally anticipated. The greatest accummulation of dirt is on the lower part of the screen and its effect on the velocity distribution in the working section can be severe even when, on visual examination, one might confidently feel that the pollution is negligible.

(iii) It has long been known that a cascade of screens each of (relatively) low resistance is preferable to a fewer number of high resistance screens. It has now been shown (Refs. 5 and 6) that a 'microjet coalescence' instability is usually present when the open area of a screen is less than (probably) 57%. (This may incidentally be expected to affect screen spacing requirements.)

There are many other factors of course but these are the ones with particular relevance to the scope of this paper. What has to be pointed out is that any re-appraisal of the arrangement of the screens should have these points in mind in conjunction with the velocity distribution in the working section in the absence of the screens (Section 16) and in addition to the considerations of effective contraction ratio (Sections 25 to 28) and requisite contraction length (Section 29).

31. *New Contraction. Surface Pressures.*

In Fig. 11 are reproduced the surface pressure characteristics for:

(a) the centre line of the floor of the contraction;

(*b*) the centre line of a lower fillet (long diffuser side);

(c) the corner joint between the two.

The actual values are recorded in Table 1.

The measurements extended into the working section, the surface pressures of which are appropriately considered here in conjunction with those of the contraction unit. Superimposed in the same figure is the static pressure characteristic for the axis upstream of $l = 0$.

For the first 5 ft (axial) from the large end the surface pressure is greater than on the axis; this is, of course, normal as is also the reverse effect further downstream. There is a linear decrease from $l =$ about 13 to $l = 5$ (Z in Fig. 11) where the pressure is atmospheric. It is negative downstream of Z and into the working section but in this region the characteristic is not such a smooth curve.

There is little difference between the three surface pressure curves in Fig. 11 and the question that arises is whether a difference might be expected. At first glance the actual profile curves of Fig. 8 do not appear to be much unlike one another but the 'scaled' curved (Section 21 and Fig. 8) certainly are. We may deduce, therefore, that this much change of the cross-sectional shape can be tolerated while still leaving the surface pressure characteristics mainly determined by the area variation in the direction of the axis. This is relevant if one wishes to assess the reliability of the arbitrary selection of the axial length of the contraction (Section 21).

The rather sharp change of slope at Z in Fig. 11 is to be noted. This is due to a contraction shape which (at least at this Reynolds number) does not quite result in a suction peak with a significant pressure recovery.

32. *New Contraction. Speed-Control Tappings.*

The location of the upstream pressure tapping for speed control of a wind tunnel usually presents no difficulty; that of the other, however, has to be chosen with some care (Sections 7 and 20).

In this tunnel a hole in the floor of the working section about 6 in. from the contraction is definitely unsatisfactory. Fig. 11 indicates that this is not surprising and it may be assumed to apply to any position downstream of station Z. On the other hand, it has been found that holes in a fillet at $l = 6\frac{1}{2}$, $8\frac{1}{2}$ and $10\frac{1}{2}$ ft, i.e. in the region of steep surface pressure gradient, are completely reliable.

It has been noticed elsewhere that the steep part of such a surface pressure characteristic is usually quite stable; where unsteadiness is encountered it is more likely to be due to causes which are not inherent in the contraction, e.g. bad approach flow conditions.

33. *New Contraction. Suitability of Design.*

From the point of view of its effect on the boundary layer in the working section a surface pressure characteristic in which there is a significant pressure recovery is, of course, highly undesirable. In some cases the change of slope at Z in Fig. 11 would be too pronounced.

It may be, however, that because of unavoidable restriction of axial length, difficulties of manufacture, requirements of the pressure tappings, and so on, it will often be considered in practice that a characteristic which is just free from a pressure recovery (which, if there were one, would be a little downstream of Z in Fig. 11) is a good criterion for such a wind tunnel as this. In these circumstances it would also appear, from what has already been said in previous sections, that there is some prospect of being able to take as being basic, say, the downstream two-thirds of this contraction (axi-symmetric or not quite so) and add to it various upstream portions to suit different contraction ratios. (For a different size of working section the non-dimensional co-ordinates and area ratios recorded in Table 3 may be more conveniently used.) For the moment this is a tentative proposal and needs further consideration but it may be mentioned in passing that there is already other evidence to support it.

The practical difficulty of constructing the portion from $l = 0$ to say $l = 2$ (Table 2) has not been overlooked. This portion is very nearly parallel sided. Bearing in mind, however, the static pressure characteristic for the tunnel axis (Fig. 7 and Section 15) and the wall pressure curves of Fig. 11 this part of the profile must nevertheless be manufactured with reasonable care and (basically) still be regarded as part of the contraction rather than of the working section. In fact, the contraction unit might well include an extra foot (parallel sided) at the small end (cf. Section 19).

34. *Main Conclusions and Final Comments.*

Following past experience (including that recorded here) in the examination and use of this wind tunnel in its various forms it can be fairly said that, in spite of some faulty features of design, its working-section characteristics in its present form are for most purposes very satisfactory and include a reasonably low level of turbulence. The flow in the working section is good both as regards uniformity and pressure gradient. Even so further alterations to, and modifications of, those parts of the circuit not recently examined are probably desirable. The objects would be to improve the quality of the flow generally throughout the circuit and at the same time rectify structural weaknesses such as that of the guide ring (Section 3).

The contraction shape is in the main satisfactory but the smoothing screens are too close to it and the effective contraction ratio is consequently only about $5\frac{1}{2}$ instead of 7. If, however, the screens were moved to a more rational position it might be that the upstream third of the contraction would need to be 'stretched' axially in order to ensure freedom from flow separation at the walls in this region.

The process of fitting thin vanes between the original thick ones of the first corner has been successful and the way is now clear to reconsider the fan design now that its approach flow is more satisfactorily symmetrical and easily determined.

The data around which the report is written has provided an opportunity of discussing various features of wind tunnels in a more general manner. It is hoped that the content will be useful in respect of other wind tunnels both actual and proposed and that it will provide a suitable framework for the addition and discussion of other features. It is also hoped that due emphasis has been placed on the importance of regarding each part of the circuit as an item of aerodynamic equipment rather than as a geometrical design.

Special acknowledgement is due to Mr. R. W. F. Gould and Mr. C. F. Cowdrey in respect of extensive investigations carried out over a period of many years; to the work of the late Mr. L. F. G. Simmons; to Miss D. G. Goodman for the experimental investigation of smoothing screens; to Mr. P. Lawrence for the examination of screen location effects; finally to Dr. R. C. Pankhurst and Mr. C. Scruton for their most useful critical perusal of the draft report.

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TABLE 1

Pressure Measurements

l feet	On Axis $\frac{S-B}{\frac{1}{2}\rho U_0^2}$	On Axis $\frac{T-B}{\frac{1}{2}\rho U_0^2}$	l feet	Wall Pressures $\frac{S-B}{\frac{1}{2}\rho U_0^2}$ Floor	Fillet	Joint
−48	−0·40	0·966	− 9		−0·033	−0·029
−42	−0·344		− 8		−0·024	−0·029
−36	−0·193	0·971	− 7	−0·026	−0·019	−0·024
−33	−0·129		− 6	−0·022	−0·019	−0·024
−29	−0·081		− 5	−0·015	−0·014	−0·019
−27	−0·043	0·971	− 4	−0·017	−0·019	−0·019
−26	−0·031		− 3	−0·024	−0·017	−0·024
−24	−0·019		− 2	−0·017	−0·017	−0·019
−22	−0·010		− 1	−0·011	−0·019	−0·014
−20	−0·011	0·981	0	−0·030	−0·021	−0·019
−16	−0·014		+ 1	−0·017	−0·024	−0·033
−14	−0·014		+ 2	−0·026	−0·031	−0·033
−12	−0·014	0·986	+ 3	−0·013	−0·024	−0·033
−10	−0·012		+ 4	−0·006	−0·007	−0·014
− 8	−0·010		+ 5	0	−0·007	+0·010
− 6	−0·010		+ 5	+0·009		
− 4	−0·005		+ 6	+0·078	+0·067	+0·053
− 2	−0·005	0·986	+ 7	+0·156	+0·139	+0·127
− 1	−0·005		+ 8	+0·247	+0·225	
0			+ 9	+0·336	+0·303	+0·304
+ 1	+0·005	0·990	+10	+0·443	+0·419	
+ 2	+0·014		+10·9	+0·540	+0·522	+0·507
+ 3	+0·033		+11·8	+0·623	+0·610	
+ 4	+0·062		+12·8	+0·721	+0·718	+0·706
+ 5	+0·100	0·993	+13·6		+0·804	
+ 5	+0·105		+14·5	+0·866	+0·880	+0·885
+ 8	+0·354	0·981	+15·9	+0·951	+0·969	+0·969
+10·5	+0·584		+17·3	+0·990	+1·005	+1·010
+12·8	+0·803		+19·1	+0·999		
+17·3	+0·928					
+19·1	+0·945					

B = atmospheric pressure

TABLE 2

Contraction Geometry

(Section 21)

l (ft)	100/A	A (sq. ft)	Axisymmetric r (ft)	Design Profiles		
				Floor y_1 (in.)	Fillet y_2 (in.)	Joint y_3 (in.)
0	2·24718	44·500	3·7636	42·00	46·66	48·37
1	2·24697	44·504	3·7638	42·02	46·68	48·39
			3·7645			
2	2·44178	44·560	3·7661	42·05	46·71	48·42
			3·7694			
3	2·23381	44·767	3·7749	42·13	46·80	48·49
			3·7832			
4	2·21015	45·245	3·7950	42·35	47·04	48·80
			3·8110			
5	2·16807	46·124	3·8317	42·76	47·75	49·28
			3·8577			
6	2·10376	47·534	3·8898	43·41	48·22	50·10
			3·9285			
7	2·01504	49·627	3·9745	44·36	49·28	51·17
			4·0286			
8	1·90133	52·595	4·0916	45·65	50·72	52·54
			4·1646			
9	1·76364	56·701	4·2484	47·42	52·68	54·57
			4·3445			
10	1·60446	62·326	4·4541	49·71	55·22	57·30
			4·5792			
11	1·42764	70·046	4·7219	52·70	58·55	60·64
			4·8845			
12	1·23836	80·752	5·0699	56·58	62·86	65·00
			5·2817			
13	1·04317	95·862	5·5239	61·65	68·49	70·89
			5·8013			
14	0·85015	117·626	6·1190	68·30	75·88	78·65
			6·4824			
15	0·66938	149·391	6·8958	76·96	85·81	88·65
			7·3610			
16	0·51364	194·688	7·8722	87·88	97·61	100·11
			8·4100			
17	0·39833	251·040	8·9392	99·77	111·0	114·90
			9·4050	105·6	115·7	
18	0·33503	298·479	9·7472	111·0	118·1	
			9·9520	115·4	119·4	
19	0·31575	316·706	10·0405	118·1	119·9	
			10·0620	119·7	120·0	
20	0·31423	318·239	10·0647	120·0	120·0	
16·4			Inflexion			

TABLE 3

Contraction Geometry (Non-Dimensional)

(Section 21)

r_0	r/r_0	$(r/r_0)^2$	$(r_0/r)^2$
0·0	1·00000	1·00000	1·00000
0·133	—	—	—
0·266	1·00005	1·00010	0·99990
0·399	1·00023	1·00045	0·99955
0·532	1·00067	1·00134	0·99866
0·665	1·00154	1·00307	0·99693
0·798	1·00299	1·00599	0·99405
0·931	1·00520	1·01043	0·98968
1·064	1·00834	1·01676	0·98352
1·197	1·01258	1·02532	0·97530
1·33	1·01808	1·03649	0·96479
1·463	1·02501	1·05064	0·95180
1·596	1·03352	1·06817	0·93618
1·729	1·04381	1·08953	0·91783
1·862	1·05603	1·11521	0·89670
1·995	1·07040	1·14576	0·87278
2·128	1·08715	1·18190	0·84609
2·261	1·10654	1·22443	0·81671
2·394	1·12882	1·27423	0·784785
2·527	1·15433	1·33247	0·750485
2·66	1·18346	1·40059	0·713985
2·793	1·21671	1·48037	0·675505
2·926	1·25461	1·57406	0·635300
3·059	1·29782	1·68434	0·593705
3·192	1·34709	1·81465	0·551070
3·325	1·40336	1·96941	0·507767
3·458	1·46772	2·15420	0·464210
3·591	1·54142	2·37596	0·420883
3·724	1·62582	2·64328	0·378318
3·857	1·72238	2·96661	0·337072
3·99	1·83224	3·35710	0·297876
4·123	1·95583	3·82527	0·261420
4·256	2·09164	4·37499	0·228572
4·389	2·23455	4·99321	0·200272
4·522	2·37515	5·64133	0·177263
4·655	2·49892	6·24462	0·160138
4·788	2·58986	6·70736	0·149090
4·921	2·64426	6·99212	0·143018
5·054	2·66776	7·11697	0·140509
5·187	2·67349	7·14754	0·139908
5·32	2·67421	7·15141	0·139833
4·36 (approx.)	Inflexion		

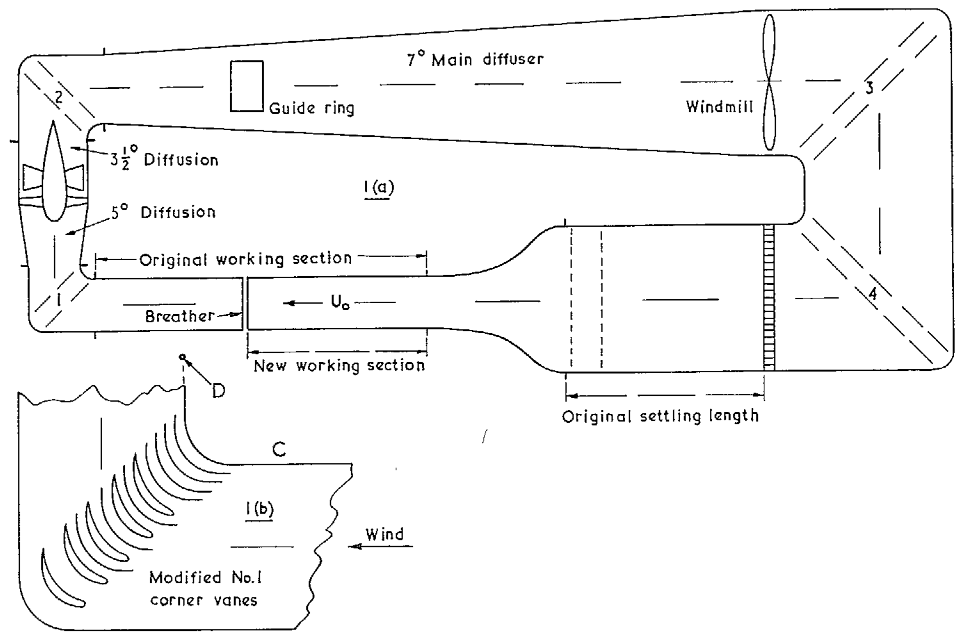

FIG. 1. N.P.L. 7 ft wind tunnel.

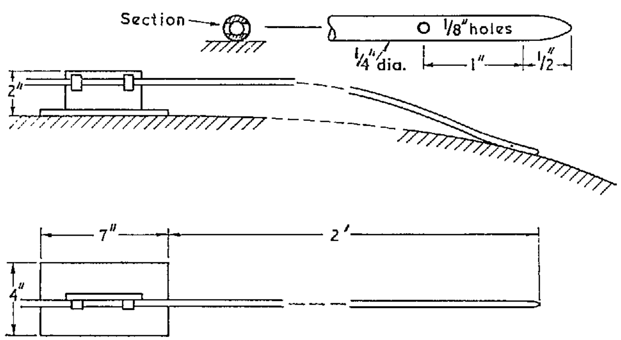

FIG. 2. Creeper tube for surface pressures.

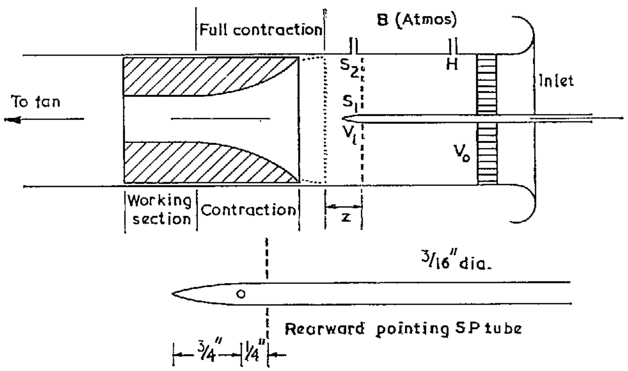

FIG. 3. 6·8 inches diameter test rig.

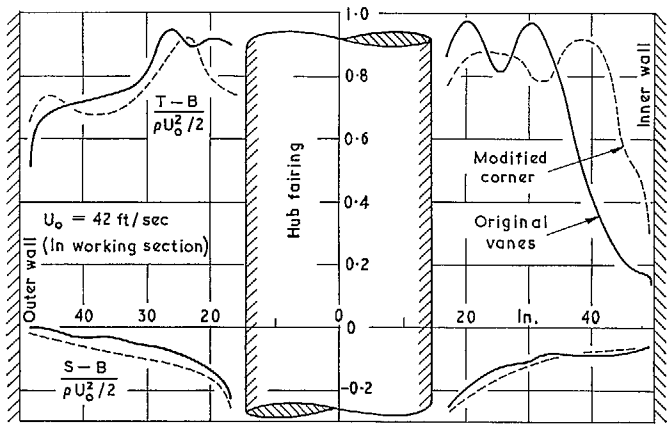

FIG. 5. Traverses 2 feet upstream of fan.

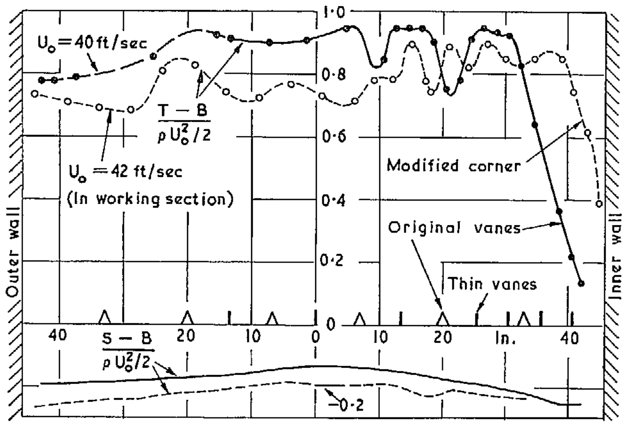

FIG. 4. Traverses 6 feet upstream of fan.

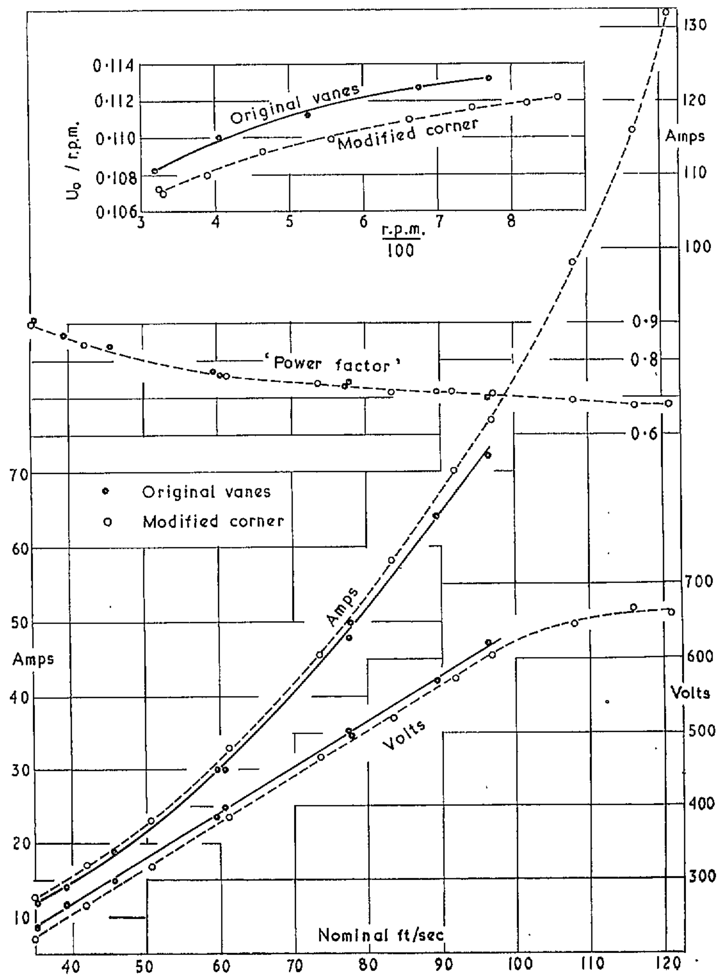

FIG. 6. Fan characteristics.

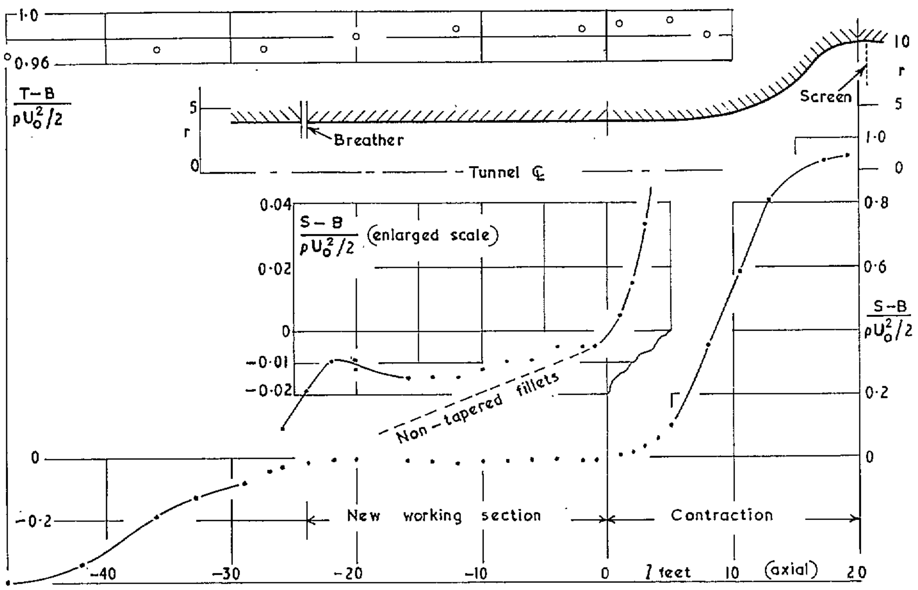

FIG. 7. Total and static pressures along axis.

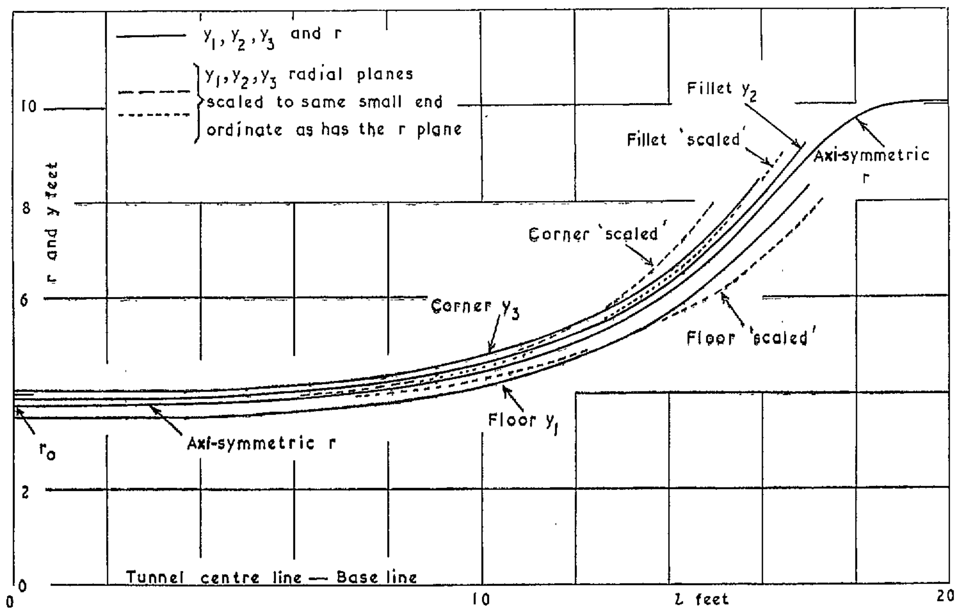

FIG. 8. Contraction profiles.

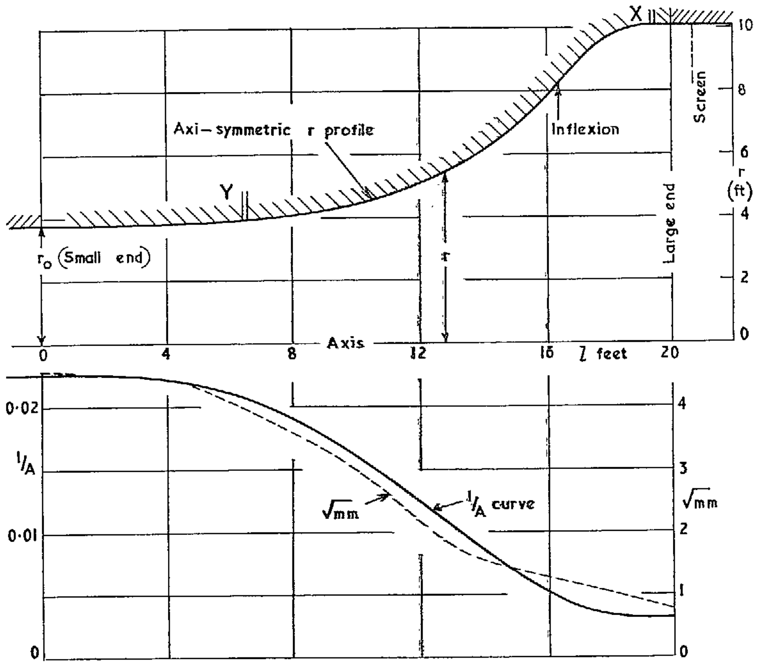

FIG. 9. $1/A$ and velocity comparison.

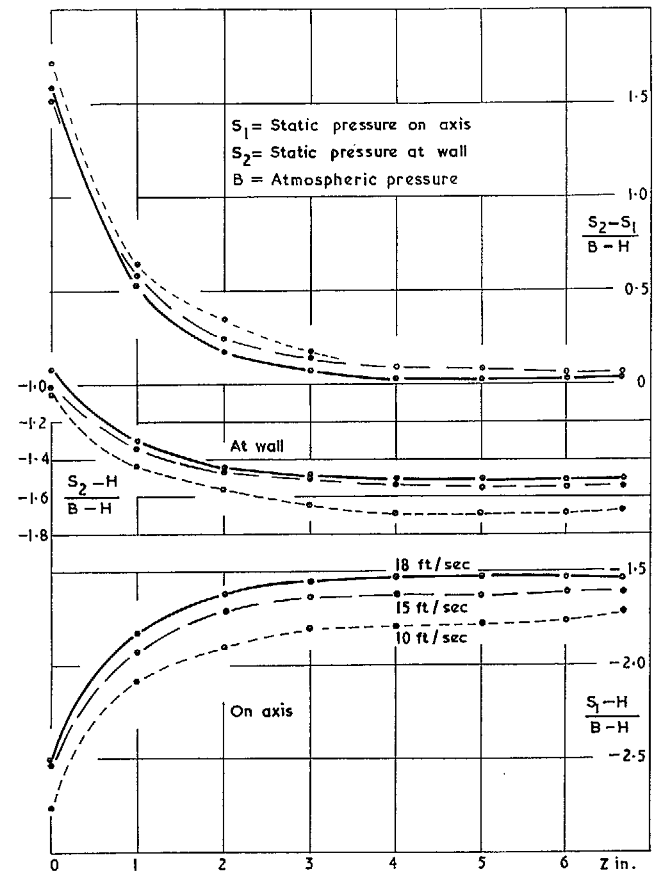

FIG. 10. Effect of varying screen location.

(90904) Wt. 66/2301 K.5 1/65 Hw.

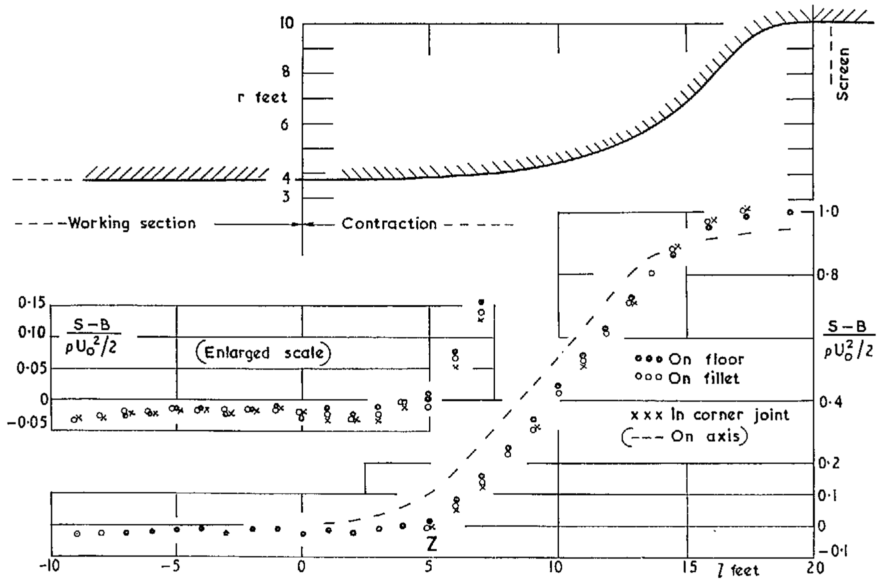

FIG. 11. Surface pressures in contraction.

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