



MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL  
REPORTS AND MEMORANDA

# The Effect of Inlet Circumferential Maldistribution on an Axial Compressor Stage

*By*

R. C. TURNER, J. RITCHIE and C. E. MOSS

*Crown Copyright Reserved*

LONDON: HER MAJESTY'S STATIONERY OFFICE

1958

SIX SHILLINGS NET

# The Effect of Inlet Circumferential Maldistribution on an Axial Compressor Stage

By

R. C. TURNER, J. RITCHIE and C. E. MOSS

COMMUNICATED BY THE DIRECTOR-GENERAL OF SCIENTIFIC RESEARCH (AIR),  
MINISTRY OF SUPPLY

---

*Reports and Memoranda No. 3066\**

*February, 1957*

---

*Summary.*—This report describes tests on a single compressor stage with circumferentially non-uniform inlet conditions. The stage was a model of the first stage of a typical modern aircraft-engine compressor, and the tests were planned as part of an investigation into the surge behaviour of compressors with inlet flow maldistribution.

It was found that with a roughly rectangular inlet velocity distribution of amplitude  $\pm 25$  per cent of the mean value, the surge flow instead of showing an expected increase was almost unchanged, being in fact slightly reduced. The efficiency fell greatly, with an accompanying small drop in temperature-rise coefficient. The velocity profile was distorted and its amplitude greatly decreased at the outlet of the stage.

These results are important in that they suggest that the surge of the first stage is not the primary factor in determining the surge of a multi-stage compressor. It would appear that the primary effect of maldistribution is to decrease the efficiency of the first stage or stages, and thus alter the stage matching at the surge flow, which is, however, mainly determined by the later stages. The maldistribution will probably have disappeared at these later stages, which will thus exhibit their normal characteristics. These conclusions are supported by analysis of multi-stage compressor performance and by theoretical considerations.

---

1. *Introduction.*—It is common knowledge that the performance of a multi-stage axial-flow compressor may be seriously affected by the imposition of non-uniform inlet-flow conditions. In particular, the position and shape of the surge line is often changed adversely. There has, however, been little systematic investigation of the subject, although the use of inlet volutes in industrial compressors and high-velocity intakes sensitive to incidence in aircraft compressors, is making an understanding of the problem imperative.

The present tests were designed as part of an investigation into the effects of circumferential inlet-flow maldistribution on compressor surge, the method being to examine the performance of the first stage of a typical modern aircraft-type compressor under two conditions of maldistribution.

2. *Description of Apparatus.*—2.1. *The Test Rig.*—The stage was tested in the National Gas Turbine Establishment 114 Variable-Density-Return-Circuit Tunnel, described in Ref. 1. The main air circuit consists of the stage under test, a load throttle, a circuit-loss make-up fan, a cooler, and a venturimeter.

The stage annulus dimensions, including those of the inlet, are shown in Fig. 1. It will be seen that there is a rapid reduction of area before the inlet guide blades. In order to obtain two distinct non-uniform stage inlet conditions, baffle plates were inserted in the positions shown in

---

\* N.G.T.E. Report R.203, received 12th February, 1957.

Figs. 1 and 2. Fifty and seventy-five per cent of the inlet ducting area were blocked off in the two groups of tests, which were referred to as the '50 per cent blockage' tests and the '75 per cent blockage' tests respectively.

*Inlet Pressures.*—Eight static tappings were placed in the mid-plane of the struts in the approach ducting, as shown in Figs. 1 and 2. Eight circumferentially equi-spaced static tappings were placed immediately before the inlet guide blades. Each static tapping was connected to a separate manometer.

*Outlet Pressures.*—Eight circumferentially equi-spaced static tappings and 34 pitot-tubes were placed in a plane after the stator blades, each pressure line being connected to a separate manometer. The pitot-tubes were set at the mean diameter and were yawed to the theoretical air angle after the stator blades.

*Other Measurements.*—Input torque was given by an auto-setting weighbeam measuring the reaction on the casing of the driving turbine. Speed was measured by an electrical impulse method depending on the rotation of a magnet attached to the turbine rotor. Mass flow was estimated from the venturimeter, and inlet temperature was given by a nickel resistance thermometer in the approach ducting to the stage.

2.2. *The Stage.*—The stage consisted of inlet guide blades, rotor blades and stator blades and was a scaled-down model of the first stage of the N.G.T.E. 109 Compressor. This compressor is reasonably representative of modern aircraft practice; it has a constant outside diameter of 24.34 in. and a mean stage temperature rise at design point of 30 deg C. It is fully described in Ref. 2. The model stage had an outside diameter of 10 in.; the blades were relatively larger than in the 109 Compressor, in order to lessen the bending stresses.

Leading design details of the stage are:

Aerodynamic type	.. .. .	'Constant $\alpha_3$ '
Mean-diameter rotor-air-outlet angle	..	25.6 deg
Mass flow	.. .. .	12.5 lb/sec
Speed	.. .. .	23,100 rev/min
Rotor mean-diameter Mach number	..	0.70
Temperature rise	.. .. .	28 deg C
Mean blade speed	.. .. .	812 ft/sec
Diameter ratio at rotor inlet	.. .. .	0.60
Blade profile	.. .. .	C4
Blade camber-line	.. .. .	Parabolic (P40)

Further details of the blading are given in Appendix I.

3. *Test Technique.*—In all the present tests the stage was run at 7500 r.p.m. and with approximately atmospheric inlet pressure. The Reynolds number based on the mean-diameter blade speed is then  $1.4 \times 10^5$ . Full performance measurements were taken with uniform inlet conditions and with 50 per cent and 75 per cent inlet blockage. Care was taken to reduce the flow to values well below the surge point. Finally, all the blades were removed and the outlet pitot and static pressures were measured for the two blockage conditions, the airflow being provided by the circuit-loss make-up fan; these tests were referred to as 'bladeless runs'.

It was not found possible to identify the surge of the stage by sound or by discontinuities in the pressure or flow measurements. Accordingly, for these tests, surge is taken to occur at the peak of the pressure-rise characteristic. That this is reasonable has been confirmed by flow-fluctuation investigations, using capacity-type pressure pick-ups, on somewhat similar blading.

4. *Test Results and Calculations.*—4.1. *Overall Characteristics.*—The overall characteristics of the stage with the three inlet conditions (uniform, 50 per cent blockage and 75 per cent blockage) are presented in Figs. 3 to 7, where they are plotted as adiabatic efficiency, temperature-rise coefficient and pressure-rise coefficient against flow coefficient. Fig. 8 gives a further comparison. The method of calculation of these parameters is given in Appendix II.

Some difficulty was experienced in the calculation of the mean-stage pressure rise, because of the large circumferential variations of inlet pressure with the two blockage conditions. The inlet pressure was finally taken as the mean total pressure at the mid-plane of the approach ducting struts (plane AA of Fig. 1). It was calculated by assuming all the flow to be concentrated in the strut sectors opposite the 'unblocked' region, and adding the appropriate mean static pressure to the mean velocity head. The outlet pressure was taken as the mean of the 34 outlet pitot-tube readings. The stage pressure rise thus includes the losses between the blockage plane and the stage inlet. These losses will probably be the greater with the 75 per cent blockage condition, but even here the area contraction ratio is approximately 2. It is thought that the consequent discrepancies will not be sufficient to detract from the significance of the characteristics.

The outstanding features of the characteristics are:

- (a) The surge flow is changed only slightly by the presence of the blockage; the change is in the direction of reduced flow.
- (b) The 75 per cent blockage causes a large drop in efficiency and pressure-rise coefficient, with a small drop in temperature-rise coefficient. The 50 per cent blockage has a much smaller effect on the first two parameters and practically none on the third.

4.2. *Circumferential Velocity Distributions.*—Velocity distributions at mean diameter in the plane after the stator blades were calculated from the 34 pitot pressures, using static pressures interpolated from the eight static-tapping pressures. They are plotted as the local axial velocity divided by the mean axial velocity. Fig. 9 shows the distributions for the bladeless runs for the two blockage conditions, and Figs. 10 and 11 those for the stage performance tests at five flow coefficients, in the 50 per cent and 75 per cent blockage conditions respectively. Also repeated on Figs. 10 and 11 are the distributions for the corresponding bladeless runs. These latter distributions had been found to be substantially unchanged by changes in mean velocity. The circumferential positions of the blockage are indicated in the figures. The scatter of the points in Figs. 10 and 11 is probably due to the effect of the stator-blade wakes; each point corresponds to one of the 34 pitot-tubes. Smooth curves have been drawn through them.

It is considered that the bladeless-run distributions, although measured in the outlet plane, give a fair representation of the inlet conditions to the stage when it was operating with the corresponding blockages. They are seen to be roughly rectangular in form, with amplitudes of about 8 per cent and 25 per cent of the mean values for the 50 per cent and 75 per cent blockages respectively.

The following are the chief points of interest in the velocity distributions. They are most clearly seen in the 75 per cent blockage tests, but are generally supported by the 50 per cent tests:

- (a) The stage effects a considerable reduction in the amplitude of the velocity distribution.
- (b) The maximum amplitude of the outlet distribution remains almost unchanged over the whole flow-coefficient range.

- (c) Distortion of the distribution occurs as the flow coefficient moves into surge, with a tendency for the distribution as a whole to shift in the direction of rotation.

4.3. *Circumferential Incidence Distributions.*—Air incidence angles on the rotor blades at mean diameter are shown in Figs. 12 and 13 at flow coefficients of 0.55 and 0.65, for the two non-uniform conditions. It was assumed that the bladeless-run velocity distributions applied at the rotor inlet. Also shown is the estimated blade stalling incidence.

It is seen that there is a considerable variation of incidence with the 75 per cent blockage inlet condition, and at the 0.55 flow coefficient, which is approximately the surge point, the mean incidence is well above the estimated stalling value. This effect, however, has already been noted in the first stage of the N.G.T.E. 109 Compressor under uniform inlet conditions.

There would of course be less incidence variation on the stator blades, as the axial-velocity distribution there would correspond more closely to that at outlet.

4.4. *Prediction of Overall Characteristics with Non-uniform Inlet Conditions.*—An attempt was made to predict on a simple basis the overall characteristics of the stage in the 50 per cent and 75 per cent blockage conditions. Using the appropriate bladeless-run velocity distribution, the flow-coefficient distribution round the annulus was found for a given mean flow coefficient. The distribution of the pressure and temperature rise coefficients was then determined from the overall characteristics with uniform inlet conditions. The mean values of these parameters could then be found, being defined as

$$\int_0^{2\pi} \frac{Va}{\bar{Va}} \frac{\Delta P}{\frac{1}{2}\rho U^2} d\theta \quad \text{and} \quad \int_0^{2\pi} \frac{Va}{\bar{Va}} \frac{\Delta T}{\frac{1}{2}U^2} d\theta \quad \text{respectively.}$$

The predicted characteristics thus calculated are shown in Figs. 14 and 15. The agreement with the test results is seen to be poor for the pressure-rise coefficients and efficiencies, both as regards general magnitude of the parameters and the shapes of the curves. Some discrepancy in magnitude may be due to the pressure loss between the blockage and the stage inlet as noted in section 4.1. This, however, would not drastically alter the general shape of the characteristic.

It thus appears that a simple prediction of performance based on the inlet velocity distribution and the characteristics with uniform inlet conditions is not practicable. The prediction method of course assumes that the compressor can be divided into segments, each of which acts independently. That this is not so is shown by examination of the outlet velocity distributions; it had been hoped, however, that the predicted results would have approximated to the test values.

5. *Discussion.*—It has been observed that in some multi-stage compressors, the surge line moves in the direction of lower pressure ratio when the inlet conditions are made non-uniform. Since the present tests show a tendency for the stage to surge at lower flows when subjected to inlet maldistribution, it appears likely that the surge of a compressor is not primarily dependent on the surge of the first stage.

Analysis at N.G.T.E. of the performance of multi-stage compressors and a theoretical examination of stage stability has suggested that the cause of compressor surge lies in the last stage of a compressor rather than the first stage. The present tests lend support to this result.

Since at all flows, the present tests also show that the amplitude of the maldistribution is greatly reduced from the stage inlet to the outlet, it can also be deduced that inlet maldistribution is rapidly damped out through the initial stages of a multi-stage compressor. The performance of the later stages is thus unlikely to be much affected, and on the theory of the last paragraph, compressor surge will always occur when the last stage is subjected to the appropriate flow condition, the surge criterion being unaffected by the compressor inlet conditions.

Summarising the above, the change of position of a compressor surge line with inlet maldistribution is then due to the different matching conditions (consequent upon the change of performance of the first stages), when the surge criterion of the last stage is reached, this criterion being largely unaffected by the maldistribution.

It follows that in any attempt to predict the effect on the surge line of inlet maldistribution, it would be essential to estimate the change of performance of the first stages. The simple theoretical method of section 4.4 was not satisfactory; and a more empirical approach, based on the test results of stages under representative inlet conditions would probably be necessary.

6. *Conclusions.*—A compressor stage, typical of the first stage of a modern aircraft compressor, has been tested with circumferential maldistribution of the inlet flow. In the worst condition, the inlet velocity distribution was roughly rectangular in shape, with an amplitude of  $\pm 25$  per cent of the mean value.

Although it had been expected that the surge flow would be greatly increased, it was in fact slightly reduced, while the efficiency fell sharply, with a smaller drop in temperature-rise coefficient.

The circumferential velocity distribution at the stage outlet was considerably reduced in amplitude (as compared with the inlet distribution) at all flow coefficients, with a degree of distortion which increased as the flow moved into surge.

These results suggest that the primary effect of inlet flow maldistribution on a multi-stage compressor is to alter the matching conditions at any given mass flow; this change also accounting for any shift in the surge line. This suggestion is given support by analysis of multi-stage compressor performance and theoretical analysis of stage stability at N.G.T.E., which show that the surge of a compressor is probably determined by the flow conditions of the last stage rather than the first.

Prediction of the effect of inlet maldistribution on a compressor up to the surge point would thus appear to depend on a prediction of the performance of the first one or two stages, since the amplitude of the maldistribution is probably negligible in later stages. A simple prediction method has proved inadequate, and use will probably have to be made of the test characteristics of stages with representative inlet conditions.

## NOTATION

$U$	Blade speed at mean diameter
$Va$	Axial velocity (assumed constant radially)
$\bar{V}a$	Mean axial velocity in annulus
$\Delta T$	Stage temperature rise
$\Delta P$	Stage total-pressure rise
$\rho$	Air density
$\eta$	Adiabatic efficiency
$c$	Blade chord
$s$	Blade pitch
$t$	Blade maximum thickness
$\alpha_3$	Air angle measured from the axial direction before stator-blade row

---

## REFERENCES

- | <i>No.</i> | <i>Author</i>   | <i>Title, etc.</i>   |
|------------|---|--|
| 1          | A. G. Smith, C. E. Moss, R. D. Pearson and G. R. Green .. | Measurements of the static-pressure rise in a single-stage fan at low Mach numbers over a wide range of Reynolds number. A.R.C. 15738. November, 1952. |
| 2          | A. D. S. Carter, S. J. Andrews and E. A. Fielder .. .. .  | The design and testing of an axial compressor having a mean stage temperature rise of 30 deg C. R. & M. 2985. November, 1953.                          |
-

APPENDIX I  
*Blading Details*

	I.G.		Rotor		Stator	
	In	Out	In	Out	In	Out
Inner diameter of annulus (in.) .. ..	5.67	5.93	6.01	6.30	6.42	6.72
Mean diameter of annulus (in.) .. ..	7.83	7.96	8.00	8.15	8.21	8.36
Outer diameter of annulus (in.) .. ..	10.00	10.00	10.00	10.00	10.00	10.00
Inner blade gauge diameter (in.) .. ..	6.302		6.492		6.878	
Mean blade gauge diameter (in.) .. ..	7.946		8.054		8.316	
Outer blade gauge diameter (in.) .. ..	9.588		9.616		9.754	
Inner blade angles (deg) .. .. .	0.00	— 15.68	45.2	6.00	48.39	13.59
Mean blade angles (deg) .. .. .	0.33	— 25.67	49.2	20.51	48.71	20.86
Outer blade angles (deg) .. .. .	0.00	— 36.33	53.04	34.84	48.94	28.04
Inner camber angles (deg) .. .. .	15.68		39.20		34.80	
Mean camber angles (deg) .. .. .	26.00		28.70		27.85	
Outer camber angles (deg) .. .. .	36.33		18.20		20.90	
Inner stagger angle (deg) .. .. .	10.50		— 18.30		— 24.40	
Mean stagger angle (deg) .. .. .	17.75		— 29.30		— 29.38	
Outer stagger angle (deg) .. .. .	25.00		— 40.30		— 34.36	
<i>s/c</i> inner .. .. .	0.94		0.66		0.65	
<i>s/c</i> mean .. .. .	1.19		0.82		0.78	
<i>s/c</i> outer .. .. .	1.44		0.97		0.92	
Chord, everywhere (in.) .. .. .	1.00		1.00		1.00	
Number of blades .. .. .	21		31		34	
<i>t/c</i> inner per cent .. .. .	9.00		11.0		8.0	
<i>t/c</i> mean per cent .. .. .	9.00		9.0		9.0	
<i>t/c</i> outer per cent .. .. .	9.00		7.0		10.0	
Air outlet angle (mean deg) .. ..	— 22.83		+ 25.57		+ 25.69	



## APPENDIX II

### *Note on Calculation of Overall Performance Parameters*

*Pressure-Rise Coefficient* ( $\Delta P / \frac{1}{2} \rho U^2$ ).—The inlet pressure was taken as the mean total pressure in plane AA (Fig. 1). This was calculated from the mean of the static tapings in the strut segments opposite the unblocked area of the blockage plane and the appropriate mean velocity head. The outlet pressure was taken as the arithmetic mean of the 34 outlet pitot-tube readings. The density was based on the mean value of the static tapings before the inlet guides, and the velocity was that of the rotor blade mid-plane mean diameter.

*Temperature-Rise Coefficient* ( $\Delta T / \frac{1}{2} U^2$ ).—The total temperature rise was calculated from the input torque and mass flow, and is expressed in mechanical units.

*Adiabatic Efficiency* ( $\eta$ ).—The adiabatic efficiency was based on the pressure rise calculated as above, and the total temperature rise.

*Flow Coefficient* ( $\bar{V}a/U$ ).—The axial velocity was calculated from the mass flow, the air density before the inlet guide blades and the annulus area at the rotor-blade mid-plane. The peripheral velocity was taken at the rotor mid-plane mean diameter.

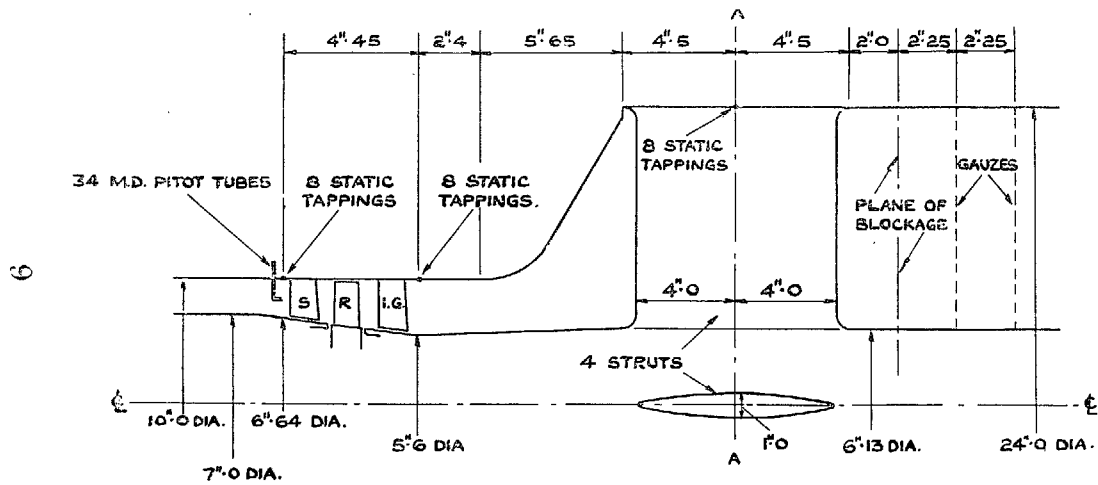
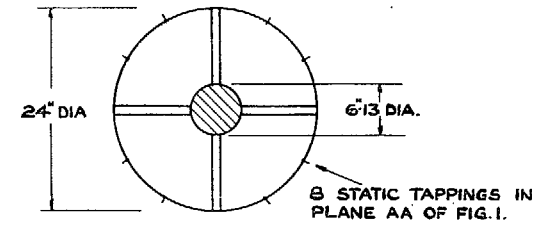
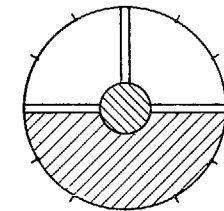


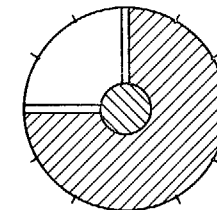
FIG. 1. Leading annulus dimensions.



ZERO BLOCKAGE [UNIFORM INLET]



50% BLOCKAGE



75% BLOCKAGE

VIEWS ARE TAKEN LOOKING DOWNSTREAM.  
FOR AXIAL POSITIONS OF BLOCKAGE AND  
OF STATIC TAPPINGS, SEE FIG. 1.

FIG. 2. Blockage details.

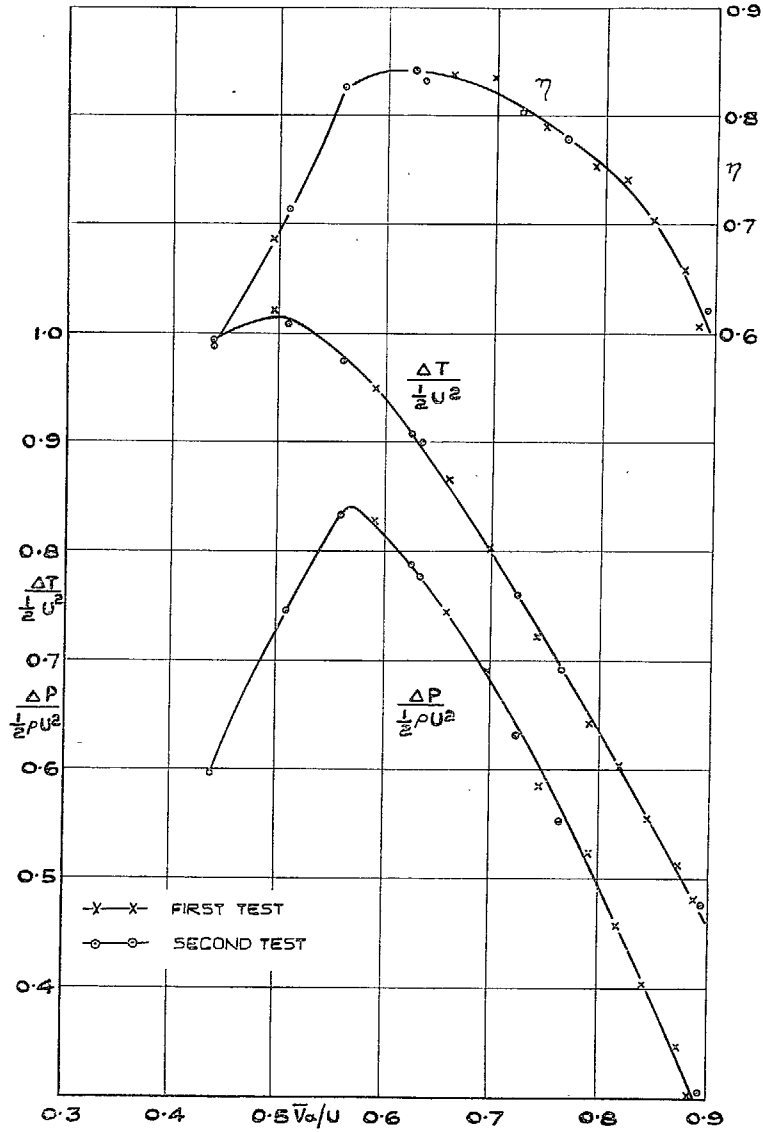


FIG. 3. Characteristics—uniform inlet.

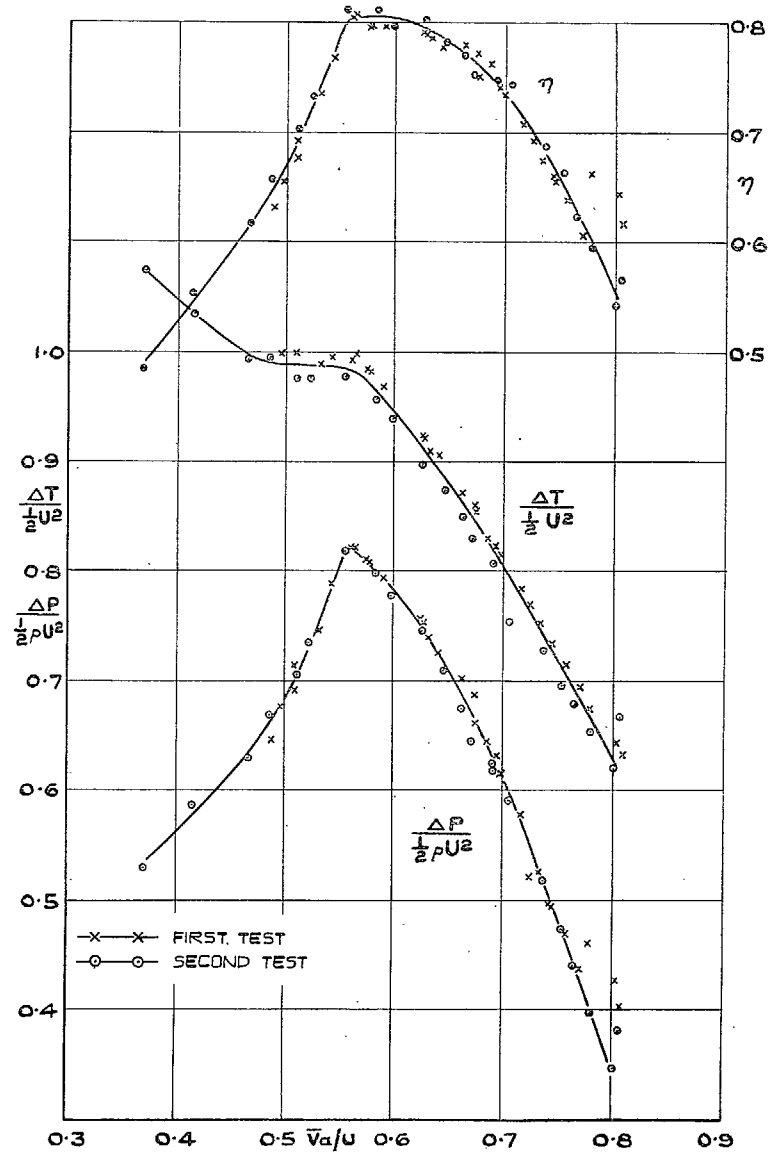


FIG. 4. Characteristics—50 per cent blockage.

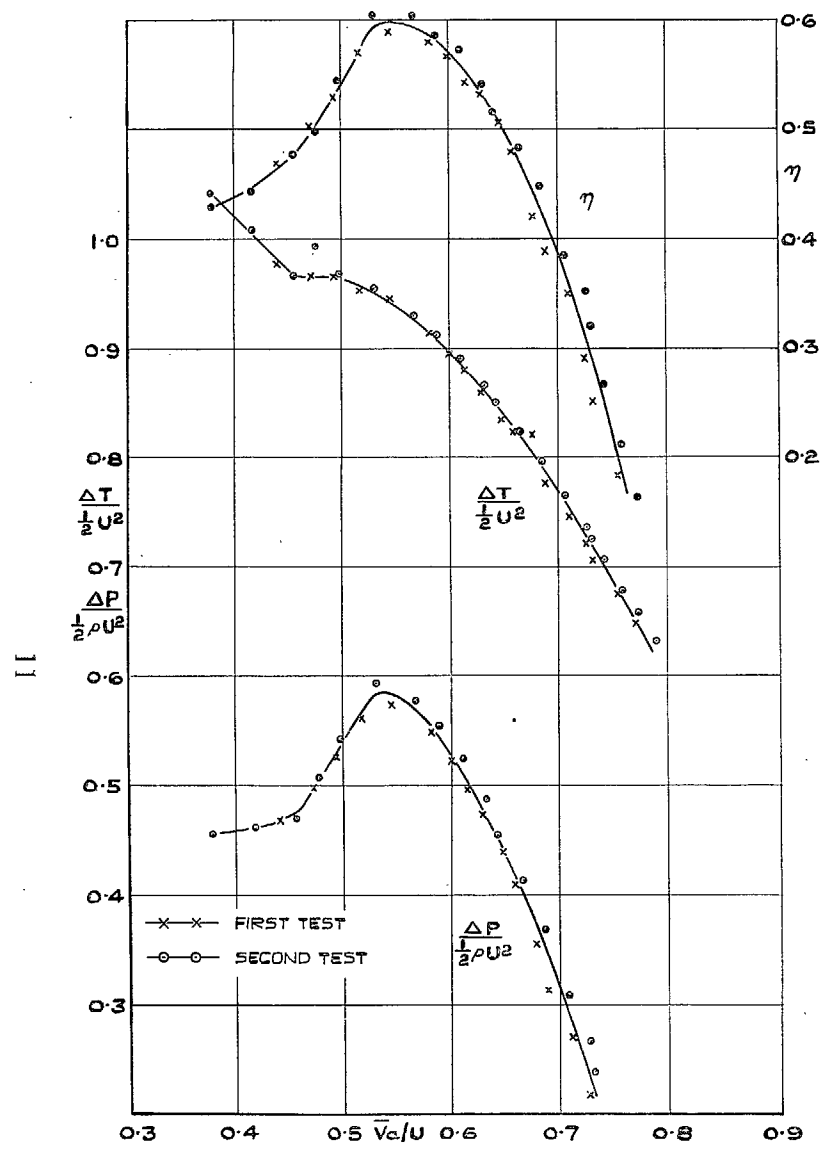


FIG. 5. Characteristics—75 per cent blockage.

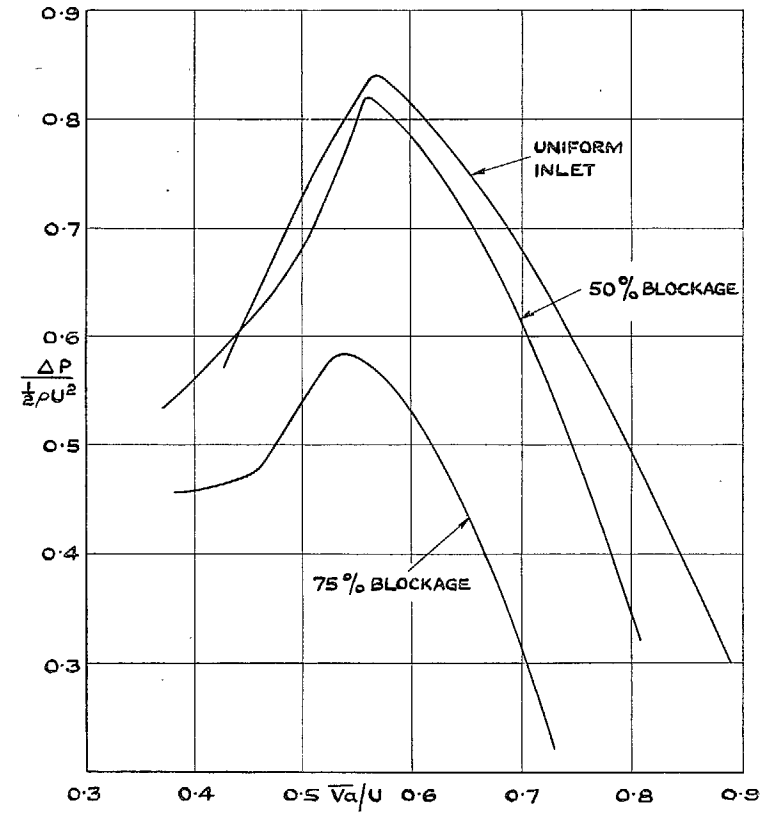
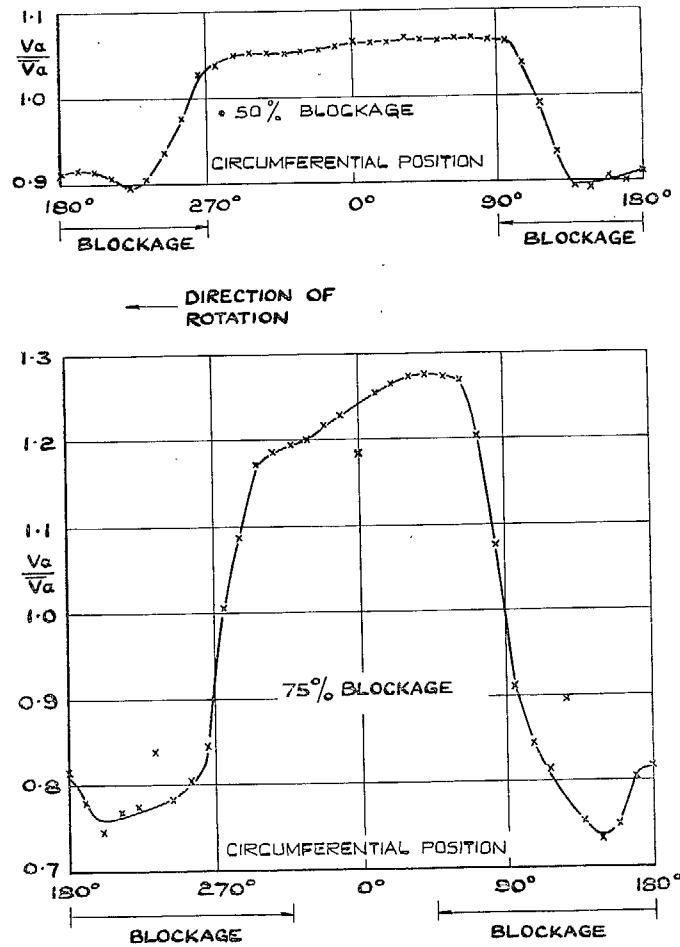


FIG. 6. Pressure-rise characteristics (All inlet conditions).





DISTRIBUTIONS MEASURED IN SAME PLANE AS IN BLADED RUNS i.e. AFTER STATOR BLADES.

FIG. 9. Circumferential velocity distributions (Bladeless runs—50 per cent and 75 per cent blockages).

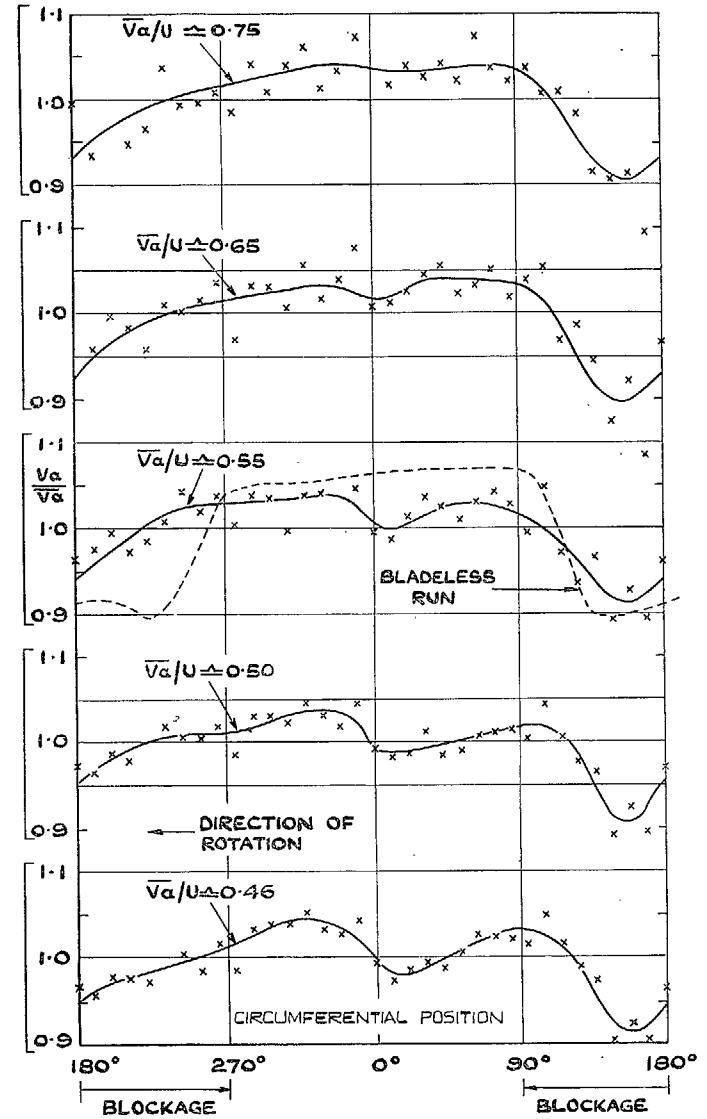


FIG. 10. Circumferential velocity distributions after stator blades—50 per cent blockage.

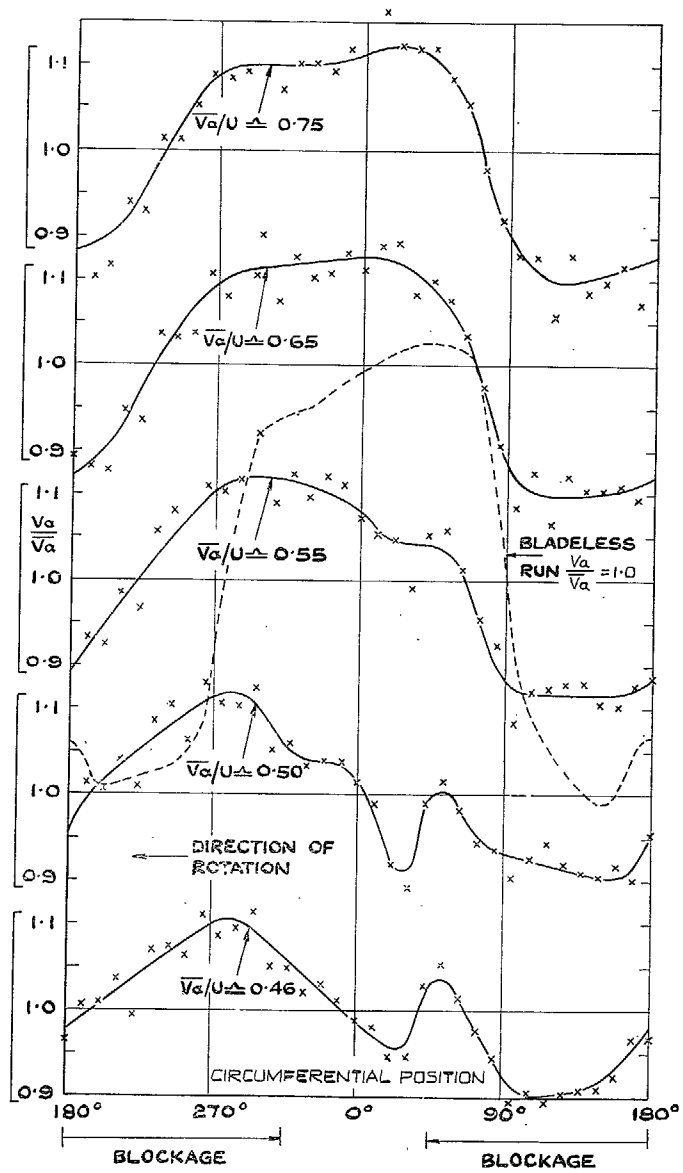


FIG. 11. Circumferential velocity distributions after stator blades—75 per cent blockage.

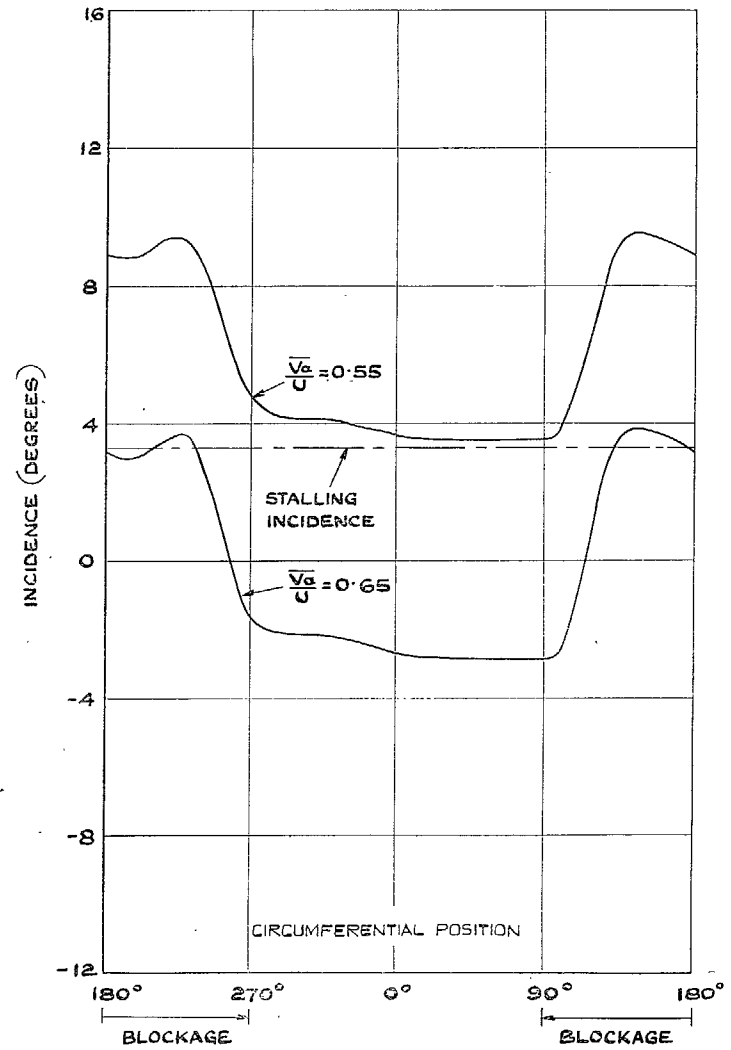


FIG. 12. Circumferential rotor incidence distributions at mean diameter—50 per cent blockage.

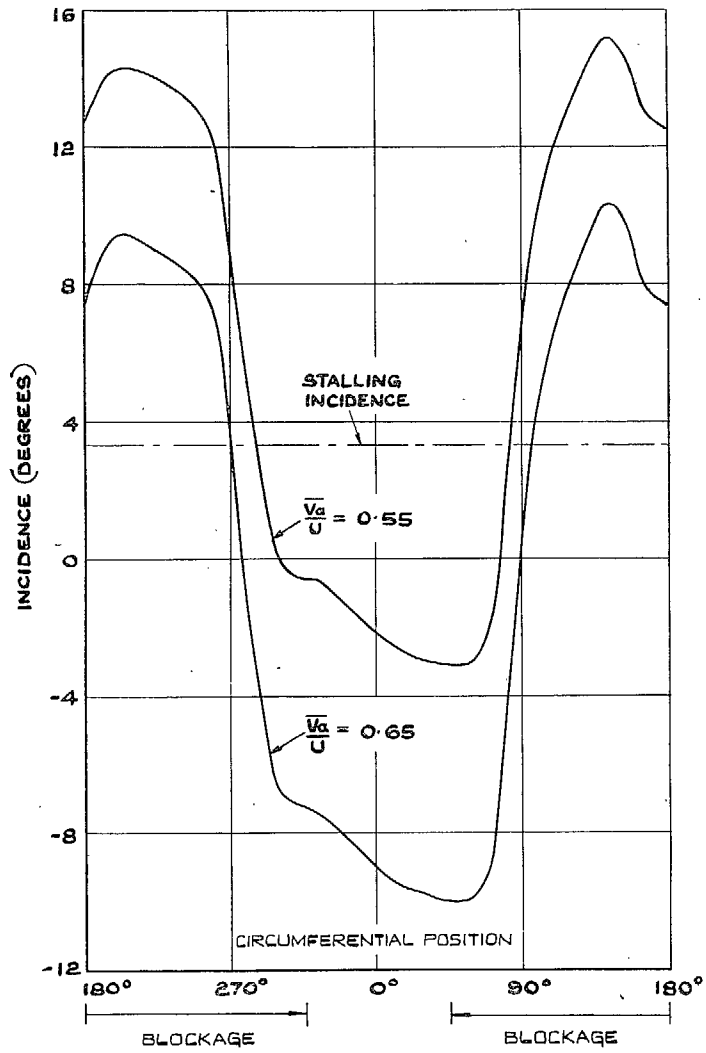


FIG. 13. Circumferential rotor incidence distributions at mean diameter—75 per cent blockage.

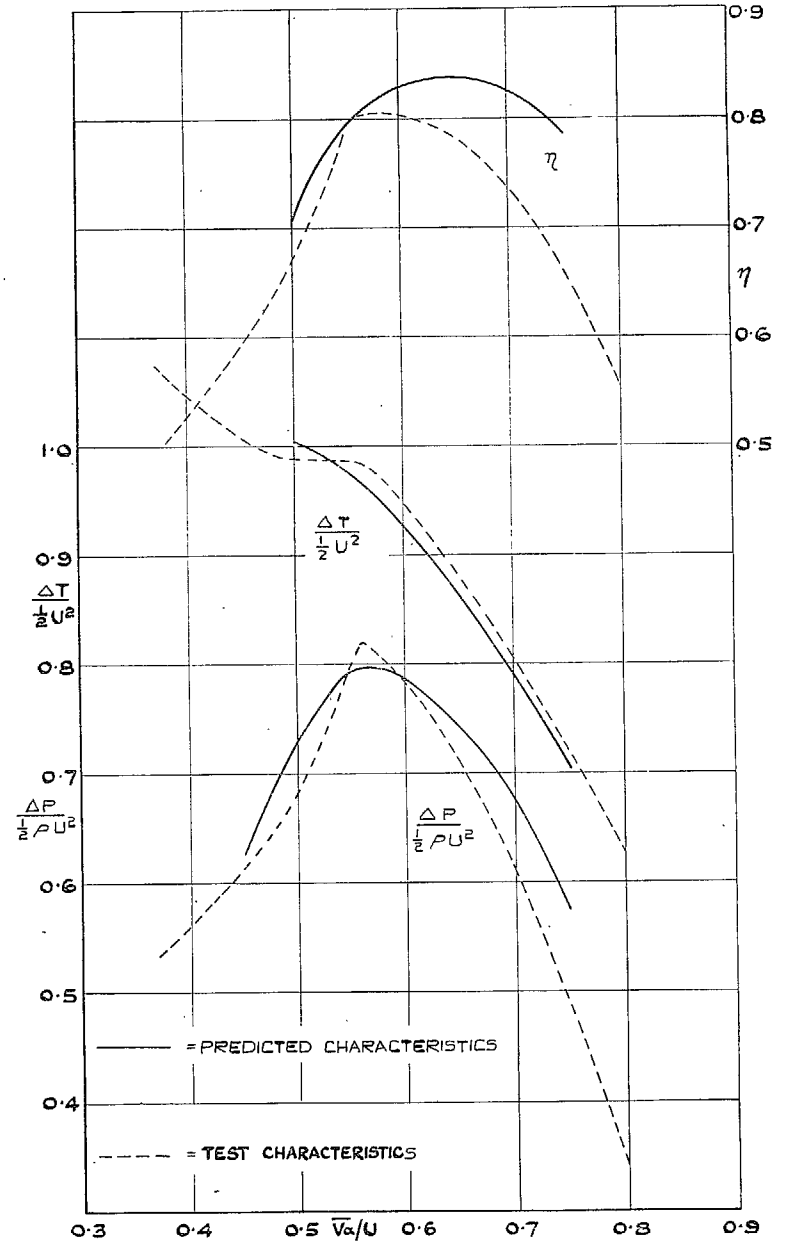


FIG. 14. Predicted characteristics—50 per cent blockage.



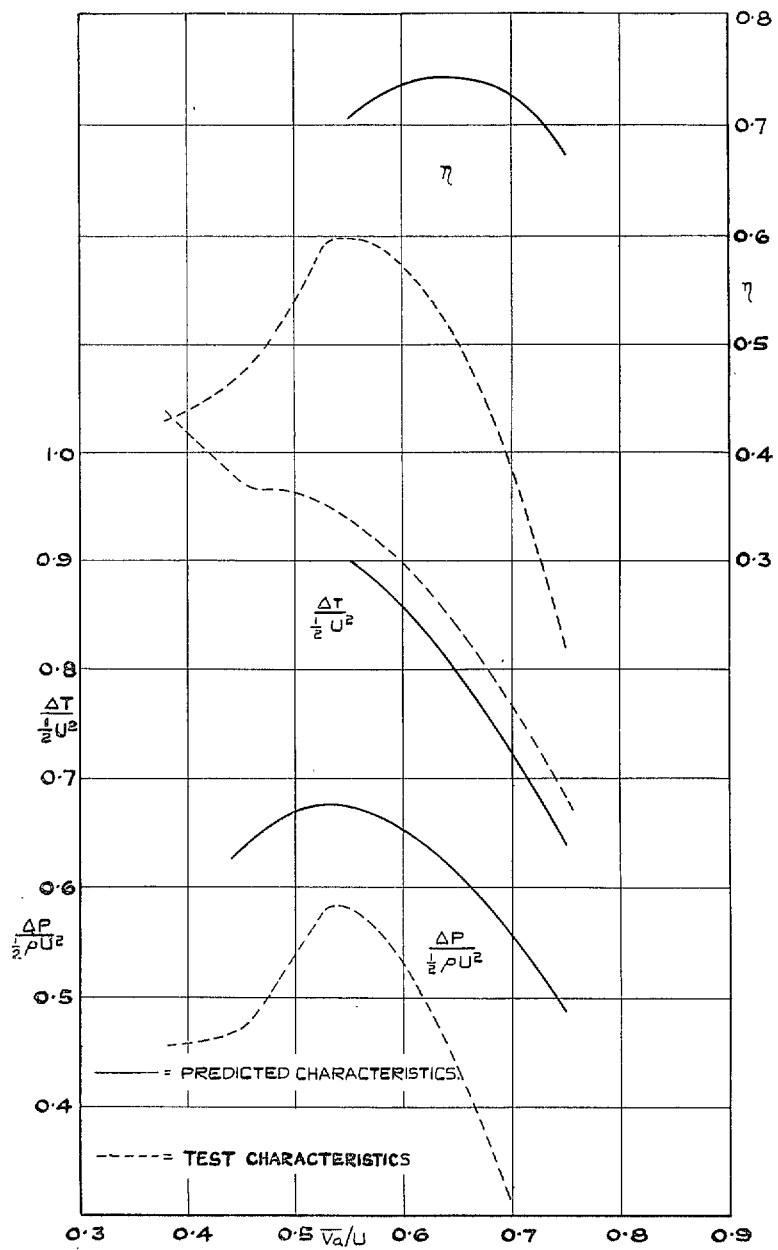


FIG. 15. Predicted characteristics—75 per cent blockage.

## Publication of the Aeronautical Research Council

### ANNUAL TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL (BOUND VOLUMES)

- 1939 Vol. I. Aerodynamics General, Performance, Airscrews, Engines. 50s. (51s. 9d.).  
Vol. II. Stability and Control, Flutter and Vibration, Instruments, Structures, Sea-planes, etc. 63s. (64s. 9d.)
- 1940 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Icing, Stability and Control Structures, and a miscellaneous section. 50s. (51s. 9d.)
- 1941 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Stability and Control Structures. 63s. (64s. 9d.)
- 1942 Vol. I. Aero and Hydrodynamics, Aerofoils, Airscrews, Engines. 75s. (76s. 9d.)  
Vol. II. Noise, Parachutes, Stability and Control, Structures, Vibration, Wind Tunnels. 47s. 6d. (49s. 3d.)
- 1943 Vol. I. Aerodynamics, Aerofoils, Airscrews. 80s. (81s. 9d.)  
Vol. II. Engines, Flutter, Materials, Parachutes, Performance, Stability and Control, Structures. 90s. (92s. 6d.)
- 1944 Vol. I. Aero and Hydrodynamics, Aerofoils, Aircraft, Airscrews, Controls. 84s. (86s. 3d.)  
Vol. II. Flutter and Vibration, Materials, Miscellaneous, Navigation, Parachutes, Performance, Plates and Panels, Stability, Structures, Test Equipment, Wind Tunnels. 84s. (86s. 3d.)
- 1945 Vol. I. Aero and Hydrodynamics, Aerofoils. 130s. (132s. 6d.)  
Vol. II. Aircraft, Airscrews, Controls. 130s. (132s. 6d.)  
Vol. III. Flutter and Vibration, Instruments, Miscellaneous, Parachutes, Plates and Panels, Propulsion. 130s. (132s. 3d.)  
Vol. IV. Stability, Structures, Wind Tunnels, Wind Tunnel Technique. 130s. (132s. 3d.)

### Annual Reports of the Aeronautical Research Council—

1937 2s. (2s. 2d.)      1938 1s. 6d. (1s. 8d.)      1939-48 3s. (3s. 3d.)

### Index to all Reports and Memoranda published in the Annual Technical Reports, and separately—

April, 1950 - - - - - R. & M. 2600 2s. 6d. (2s. 8d.)

### Author Index to all Reports and Memoranda of the Aeronautical Research Council—

1909—January, 1954      R. & M. No. 2570 15s. (15s. 6d.)

### Indexes to the Technical Reports of the Aeronautical Research Council—

December 1, 1936—June 30, 1939	R. & M. No. 1850 1s. 3d. (1s. 5d.)
July 1, 1939—June 30, 1945	R. & M. No. 1950 1s. (1s. 2d.)
July 1, 1945—June 30, 1946	R. & M. No. 2050 1s. (1s. 2d.)
July 1, 1946—December 31, 1946	R. & M. No. 2150 1s. 3d. (1s. 5d.)
January 1, 1947—June 30, 1947	R. & M. No. 2250 1s. 3d. (1s. 5d.)

### Published Reports and Memoranda of the Aeronautical Research Council—

Between Nos. 2251-2349	R. & M. No. 2350 1s. 9d. (1s. 11d.)
Between Nos. 2351-2449	R. & M. No. 2450 2s. (2s. 2d.)
Between Nos. 2451-2549	R. & M. No. 2550 2s. 6d. (2s. 8d.)
Between Nos. 2551-2649	R. & M. No. 2650 2s. 6d. (2s. 8d.)

*Prices in brackets include postage*

### HER MAJESTY'S STATIONERY OFFICE

York House, Kingsway, London W.C.2; 423 Oxford Street, London W.1 (Post Orders: P.O. Box 569, London S.E.1); 13a Castle Street, Edinburgh 2; 39 King Street, Manchester 2; 2 Edmund Street, Birmingham 3; 109 St. Mary Street, Cardiff; Tower Lane, Bristol, 1; 80 Chichester Street, Belfast,  
*or through any bookseller.*