N.A.E.

R. & M. No. 2915
(15,733)
(A.R.C. Technical Report)

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

The Determination of the Pressure Distribution over an Aerofoil Surface by means of an Electrical Potential Analyser

By

Professor S. C. REDSHAW, D.Sc., Ph.D., M.I.C.E., F.R.Ae.S.

LONDON: HER MAJESTY'S STATIONERY OFFICE
1954
ELEVEN SHILLINGS NET

The Determination of the Pressure Distribution over an Aerofoil Surface by means of an Electrical Potential Analyser

By

Professor S. C. REDSHAW, D.Sc., Ph.D., M.I.C.E., F.R.Ae.S.

Reports and Memoranda No. 2915*

December, 1952

Summary.—The potential flow, both with and without circulation, around several thin aeroplane wings has been studied by means of a three-dimensional potential analyser. It is shown that, by using the normal assumptions made in the exercise of the linear perturbation theory, it is possible to obtain the pressure distribution for small angles of incidence, as well as the slope of the lift-incidence curve, easily and rapidly.

Experiments are also described in which it was attempted to remove the effect of boundary restraint in a manner analogous to that used in a flexible-walled wind tunnel.

Suggestions are made for producing a potential analyser of increased scope together with the possibility of extending the work to curved and twisted thin wings.

---

1. *Introduction.*—An approximation to the pressure distribution over an aerofoil surface of high aspect ratio, moving at a low subsonic uniform velocity, has been satisfactorily computed by the use of lifting-line theory. After the pressure distribution has been determined the lift, pitching moment and other aerodynamic properties may be easily calculated.

The problem of the determination of the pressure distribution over low aspect ratio swept and unswept plan forms, presents considerable difficulty when using analytical methods based on lifting-surface theory ; this report describes the use of a three-dimensional electrical potential analyser for the solution of problems of this nature.

The method consists, basically, of using an electrical analogy whereby the electrical potential, in an appropriately set up pure resistance network, represents the velocity potential of the disturbed flow in the vicinity of the aerofoil surface. Pressure can be calculated from the velocity potentials ; the calculation of other aerodynamic properties follows in the normal manner. It must be emphasised that this method only provides a potential flow solution, although with circulation, for thin plates at small angles of attack.

Two electrical analogies for the pressure distribution on a lifting surface have been discussed by Campbell[1] ; the first analogy he mentions is that used in this report, in his proposed second analogy electrical potentials represent the acceleration potentials of the fluid flow. Campbell's proposal is to apply the analogy using a deep electrolytic tank. The acceleration potential analogy is useful for cases in which it is desired to calculate quantities such as control hinge moments.

Malavard and Duquenne[2], using the velocity potential analogy, have recently studied lifting surfaces by means of an electrolytic tank. They considered that the velocity potential analogy is preferable to the acceleration potential analogy, advocated by Campbell, except for very special cases.

---

*Boulton Paul Aircraft Ltd.Tech. Report No. 101, received 17th March, 1953.

The electrolytic tank possesses an advantage over an electrical network because it provides a direct analogy to a continuous solution, whereas a network will only provide an analogy to the finite difference form of the appropriate differential equation, it only being possible to take readings at the discrete points provided by the nodal points of the net. Nevertheless, the electrolytic tank presents considerable experimental difficulty; for that reason an electrical network in the form of a three-dimensional potential analyser, which is extremely simple to operate, was chosen for the present investigation.

This report incorporates the work of two previous unpublished reports on the same subject[3,4].

2. *List of Symbols.*

x, y, z	Cartesian co-ordinates referred to right-hand orthogonal axes. The origin O is taken at the centre of the bottom edge Ox of the master tier of the analyser; the faces $y = 0$ and $z = 0$ are used as reflecting surfaces, while $y = \hat{y}$ and $x = \pm \hat{x}$ are referred to as walls and $z = \hat{z}$ as the end of the analyser; $z = 0$ is referred to as the master tier
X, Y, Z	Cartesian co-ordinates obtained by an affine transformation from co-ordinates x, y, z
x, ω	Two orthogonal co-ordinates such that x represents the distance of a point from the plane of a disc and ω the radial distance of that point from the axis of the disc.
r, θ	Polar co-ordinates
c	Radius
U, V, W	Velocities along the x, y and z-axes respectively
u, v, w	Perturbation velocities along the x, y and z-axes respectively
Φ	Velocity potential
ϕ	Perturbation potential, also electrical potential
ψ	Stream function
M	Mach number
p	Fluid pressure
p_0	Fluid pressure in undisturbed stream
Δp	Excess pressure defined by $\Delta p = p - p_0$
ρ	Fluid density, also specific resistivity
q	Dynamic pressure
C_L	Lift coefficient
α	Angle of incidence
A	Wing area
I	Total current from source
i	Current density
L	Distance between equal source and sink
D	Strength of doublet, *i.e.*, limit of IL as $I \to \infty$ and $L \to 0$ in such a manner that their product remains finite
n	Unit normal vector
ds	Element of area
R	Electrical resistance
Q	A non-dimensional quantity defined in the text.

3. *Aerodynamic Theory*.—3.1. *Two-dimensional Fields of Flow*.—The assumptions made with regard to the two-dimensional potential flow of an incompressible fluid are that it possesses no vorticity and no viscosity. As a consequence of the absence of vorticity, the flow may be described by means of a velocity potential function ϕ such that the velocity is equal to the gradient of ϕ. Due to the condition of continuity there also exists a stream function ψ whose gradient gives the mass flow per unit length at right-angles to the flow. Provided the motion is irrotational, a velocity potential exists whether the fluid is compressible or incompressible. The stream function exists only when compressibility is negligible, irrespective of whether the motion is rotational or irrotational.

Two electrical analogies, devised by Taylor and Sharman[5], exist for the solution of problems concerning two-dimensional fields of flow.

3.2. *Three-dimensional Fields of Flow*.—For three-dimensional fields of flow the velocity potential ϕ still satisfies Laplace's equation and is analogous to the electrical potential for the steady flow of electricity through a block of conducting material. The stream function ψ at a given point is no longer defined except in the special case of axisymmetrical flow. The reason for this being that a point specifies a certain streamline ; in the two-dimensional case this line is sufficient to divide the flow into regions, whereas in the three-dimensional case a surface is required. For axially symmetrical flow the surface formed by the revolution of the streamline about the axis of symmetry can be used ; as might be expected, even here ψ is no longer a solution of Laplace's equation and although streamlines are still normal to equipotential surfaces there is no form of analogy corresponding to the second analogy of Taylor and Sharman.

3.3. *Linear Perturbation Theory*.—With certain limitations the linear perturbation theory considerably simplifies the analysis of certain cases of potential flow.

If we place an aerofoil in a uniform stream moving with a velocity U parallel to the x-axis, say, the motion will be perturbed and the velocity potential will become

$$\Phi = Ux + \phi(x, y, z) \qquad \text{(1)}$$

so that ϕ is the perturbation potential.

The velocity at any point which was formerly $(-U, 0, 0)$, now becomes $(-U+u, v, w)$. The perturbation is said to be linear if u/U, v/U and w/U are small quantities of the first order whose squares and products are negligible. No limitation is imposed on U which may be either large or small. The approximation fails near a stagnation point where $-U+u=0$ so that $u/U=1$.

Therefore the assumptions made in the exercise of the linearised theory are :—

(*a*) The aerofoil is represented by an infinitely thin plate

(*b*) The camber of the aerofoil must be small

(*c*) Only small angles of incidence may be considered

(*d*) The vortex lines at the rear of the aerofoil surface remain in the same plane as the aerofoil surface and run immediately aft.

An aerofoil defined by these limiting assumptions is suitable for high speeds and therefore in this case the linear theory will give satisfactory results.

The Prandtl-Glauert equation, satisfied by the perturbation potential is

$$(1-M^2)\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}=0 \qquad (2)$$

where M is the Mach number of the undisturbed flow.

Glauert[6] and Prandtl[7] have shown that, at subsonic speeds, a distribution of potential satisfying Laplace's equation will also satisfy the linearised compressible-flow equation (equation (2)) if the distribution $\phi(x, y, z)$ is foreshortened along the direction of motion by the affine transformation

$$X=\frac{x}{\sqrt{(1-M^2)}},\ Y=y,\ Z=z. \qquad (3)$$

Using (3) equation (2) transforms to

$$\frac{\partial^2\phi}{\partial X^2}+\frac{\partial^2\phi}{\partial Y^2}+\frac{\partial^2\phi}{\partial Z^2}=0 \qquad (4)$$

which is Laplace's equation.

Thus, if we start with a fictitious aerofoil longer in the x-direction than the true one and calculate the potential distribution for this aerofoil by methods applicable to incompressible flow, the correct dimensions and correct distribution of ϕ are obtained when the affine transformation is applied; the transformation is not conformal. As will be seen later, the Prandtl-Glauert method can be applied directly with great advantage to the experimental results obtained from the potential analyser.

As the linearised theory only permits small angles of incidence to be considered and, for small angles of yaw, we may ignore the free-stream component velocities V and W in the y and z-axes respectively in comparison with the velocity U along the x-axis. Then if p is the pressure at any point and p_0 is the pressure in the unperturbed stream we have, from Bernoulli's theorem

$$p+\tfrac{1}{2}\rho[(-U+u)^2+v^2+w^2]=p_0+\tfrac{1}{2}\rho U^2 \qquad (5)$$

and on the assumption that u, v and w are so small that their squares and products may be neglected, and defining the excess pressure as

$$\Delta p=p-p_0$$

and

$$q=\tfrac{1}{2}\rho U^2 \qquad (6)$$

we have from (5)

$$\Delta p=\frac{2u}{U}q. \qquad (7)$$

The assumption that as the perturbation velocities and the angle of incidence are small, so that their squares and products may be neglected, fails at a stagnation point, for there $u=U$. This entails infinite pressure at the leading edge except for the ideal angle of attack[8]. Campbell points out that there is no trouble in the absence of discontinuity in the streamline direction at the leading edge, for in this case $u=0$. Rounding the leading edge removes the infinite velocity except, of course, at the stagnation point. At a finite lift the stagnation point moves to the lower surface but if the thickness, curvature and angle of incidence are diminished, the domain in which the error is considerable shortens to the immediate neighbourhood of the leading edge[9].

The Joukowski condition that the air speed at the trailing edge must be finite, has to be satisfied in order that the flow of an ideal fluid may approximate to that of a real fluid. This postulates that the streamlines at the trailing edge of a thin aerofoil must be continuous in direction with no infinite velocities.

The incidence of the aerofoil is given by the ratio of the vertical velocity, in a region not affected by the wing, and the horizontal velocity thus

$$\alpha = \frac{W}{U} \qquad (8)$$

The pressure increment per radian of incidence is, from equations (7) and (8)

$$\frac{\Delta p}{\alpha} = \frac{2u}{W} q \qquad (9)$$

Hence

$$\frac{\Delta p}{q\alpha} = \frac{2u}{W} \qquad (10)$$

Noting that the pressure on the lower surface of the wing is equal and opposite to the pressure on the corresponding point of the upper surface, we have for the lift coefficient

$$C_L = \frac{1}{A} \int_{-s}^{s} dy \int_{0}^{c} \frac{2\Delta p}{q}\, dx \qquad (11)$$

from which

$$\frac{\partial C_L}{\partial \alpha} = \frac{\partial}{\partial \alpha} \frac{1}{A} \int_{-s}^{s} dy \int_{0}^{c} \frac{2\Delta p}{q}\, dx . \qquad (12)$$

4. *The Electrical Analogy*.—If we identify fluid flow with electrical flow we have a direct analogy in which the velocity potential is represented by an electrical potential.

Now as
$$u = -\frac{\partial \phi}{\partial x} \qquad (13)$$

and, at a point remote from the aerofoil

$$W = -\frac{\partial \phi}{\partial z}, \qquad (14)$$

we may rewrite equation (10) as

$$\frac{\Delta p}{q\alpha} = 2 \frac{\partial \phi / \partial x}{\partial \phi / \partial z} \qquad (15)$$

where ϕ denotes either velocity or electrical potential. From equation (12), by the use of equations (13), (14) and (15) we have

$$\frac{\partial C_L}{\partial \alpha} = \frac{4}{A\, \partial \phi / \partial z} \int_{-s}^{s} dy \int_{0}^{c} \frac{\partial \phi}{\partial x}\, dx$$

$$\frac{\partial C_L}{\partial \alpha} = \frac{4}{A\, \partial \phi / \partial z} \int_{-s}^{s} (\phi)_{x=c}\, dy \qquad (16)$$

since ϕ is zero at the leading edge.

The potential analyser will be fully described in the next section but, for the purpose of illustrating the analogy, it may be described here as consisting essentially of a cubical mesh of resistances so arranged that there are ten square tiers placed one above the other, each tier having a mesh separation of 1/24 the side length. The analogy, can then be realised by :—

(*a*) Slitting the bottom tier in its own plane over an area corresponding in shape to the aerofoil considered

(*b*) Short-circuiting the area surrounding the model and short-circuiting the whole of the top tier

(*c*) Applying a known electrical potential between the short-circuited top tier and the short-circuited margin of the bottom tier.

In practice the bottom tier is not actually slit because as the flow is applied normal to the model this tier may be considered as a plane of symmetry. It is, therefore, only necessary to double the value of the resistances over the area which represents the model. It will be observed that this analogy is a three-dimensional form of the direct analogy of Taylor and Sharman.

An alternative method of representing the velocity potential analogy when using an electrolytic tank has been proposed by Campbell, who arranged that constant currents should be fed into a number of electrodes representing the aerofoil surface, the short-circuited margin surrounding the aerofoil being set at zero potential. Thus a distribution of source-link doublets or dipoles is used to produce the perturbation velocity.

Apart from being an easier method to apply when an electrolytic tank is used, this method possesses the advantage that twisted and cambered wings may be represented and ' flexible walls ' also may be more easily represented at the boundaries of the instrument.

Although this alternative method was not used in this investigation, there is no inherent limitation in the design of the potential analyser which prevents this method being applied.

If experiments concerning potential flow without circulation are made, boundary conditions present no difficulty but special consideration must be given to practical cases which require flow with circulation. When flow with circulation is being investigated the Joukowski condition at the trailing edge has to be satisfied ; this may be realised by ensuring that points immediately behind the trailing edge shall be at the same potential as corresponding points along the trailing edge. On the potential analyser this is effected by short-circuiting lines along the x-axis, and raising the potential of each individual line so that its potential is the same as at the corresponding point on the trailing edge, one mesh separation away from it. We thus have in the wake, as ϕ is independent of x.

$$\phi_{\mathrm{W}} = \phi_{\mathrm{T.E.}}$$

$$\text{and} \qquad \left(\frac{\partial\phi}{\partial x}\right)_{\mathrm{W}} = 0 . \qquad \qquad (17)$$

The second of these conditions applying since the pressure, which is proportional to $\partial\phi/\partial x$, vanishes on either side of the wake and is, of course, zero at the trailing edge. ϕ must be continuous at the trailing edge as any discontinuity would cause an infinite velocity there.

5. *Description of Potential Analyser.*—The three-dimensional potential analyser, which was used for the experiments, has been previously fully described[10]. The instrument consists essentially of a cubical mesh of resistors arranged in nine main tiers with an auxiliary tier, each tier consisting of a square array of 25 × 25 points interconnected with resistors to form a square mesh. The nodal points on each tier were connected to the adjacent tiers through inter-tier resistors of the same value as the tier resistors. The individual mesh resistances were provided by special precision woven resistors having a tolerance of ± 1 per cent on a nominal resistance of 200 ohms.

Resistance elements were not assembled on the master tier but Post Office type terminals were used instead, these terminals being connected to the inter-tier resistors in the normal manner. Resistors, depending on the nature of the particular experiment in hand, were attached to the terminals of the master tier as required. The resistors on the right-hand side and bottom edges of each tier were doubled in value, while the inter-tier resistors connecting the bottom right-hand corners of the tiers were quadrupled in value, thus providing ' selvedges ' for problems involving a field of single or double symmetry. The reason for using the doubled resistors is that the net can be considered to be split at the plane of symmetry. When resistance elements are added to the master tier, which is a plane of symmetry, they are also doubled in value. Figs. 1 and 2 show front and rear views of the instrument. The analyser is capable of solving the three-dimensional finite difference form of Laplace's equation.

6. *Experimental Procedure.*—6.1. *Flow Normal to the Surface.*—It was decided that the first series of experiments should be concerned with the combined undisturbed and perturbed potential flows, without circulation, normal to the following four plan forms :—

(*a*) A circular lamina

(*b*) A rectangular wing, constant chord, aspect ratio 6

(*c*) A delta wing, 45-deg sweep, aspect ratio 4

(*d*) A swept-back wing, 45-deg sweep, constant chord, aspect ratio 3.

The setting-up procedure, alike for the four experiments, consisted of representing the plan-form of the model by a resistance mesh on the master tier, which normally had no tier resistors. As this tier coincides with a plane of symmetry, the resistors used were double the value of the standard mesh resistors. The remaining area of the tier was short-circuited with heavy copper wire.

As the circular lamina and the rectangular wing each possess two axes of symmetry in plan-form, it was possible to set these forms up on the master tier so that the axes of symmetry coincided with the mutually perpendicular selvedges of the tier.

With the other two forms only one axis of symmetry existed and therefore one selvedge only could be used. All the nodes on the auxiliary tier (tier 9), were short-circuited and a potential of one volt was maintained between this tier and the short-circuited portion of the master tier.

A certain amount of importance is attached to the model size, the optimum size is the one having the largest number of points available for measurement while remaining unaffected by channel restraint due to the proximity of the boundary. The actual model sizes which were used are shown in Fig. 3.

A potential of one volt was applied to the analyser and the tiers were scanned by plugging in a probe at each socket in turn, the potentials being measured by means of a Muirhead Type D.72A potentiometer. All readings were taken to the nearest millivolt, this being the limit of accuracy of the potentiometer. The electrical circuit which was used for the experiments is shown in Fig. 4.

In the case of the circular lamina the boundary of the model cut through the square mesh and therefore resistors having a resistance value proportional to the reduced mesh arm were mounted on the master tier at the boundary of the model. This method of using a reduced resistance is analogous to the use of an irregular star in the relaxation process[11].

A brief description of each experiment is given here in order to illustrate the technique employed.

6.1.1. *The Circular lamina.*—Two sizes of model were used having mesh separations of $\frac{1}{6}$th and $\frac{1}{12}$th of the diameter of the circle. This experiment provides the only possible example of axial symmetry and a theoretical solution to the problem exists.

Fig. 5 shows the results for the coarse and fine nets respectively, this figure represents the variation of velocity potential with radius for the master tier and tiers one and two.

The theoretical curves have been drawn by using the equation

$$\frac{\pi\phi}{2W} = Q + x \tan^{-1} \frac{x}{Q} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (18)$$

where

$$Q = \sqrt{\left\{ \frac{[(x^2 + \omega^2 - c^2)^2 + 4c^2x^2]^{1/2} - [x^2 + \omega^2 - c^2]}{2} \right\}} \qquad \ldots \quad \ldots \qquad (19)$$

x and ω being two orthogonal co-ordinates such that x represents the distance of a point from the plane of the disc and ω the radial distance of this point from the axis of the disc, ϕ is the potential at point (x, ω) for a flow velocity W normal to a disc of radius c.

This expression has been derived directly from Lamb's theoretical work[12].

It will be seen that a closer approximation to the theoretical value is obtained when a finer mesh is used. Additional curves illustrate the improvement to the results which can be obtained by using Richardson's correction, which gives results approximating to the use of a still finer mesh[13].

Using the relaxation technique the nodal residuals for the experiments were calculated ; the results show that the discrepancy between the experimental and theoretical curves cannot be attributed to experimental errors, as essentially the same result would have been obtained from a relaxation calculation. The differences can probably be attributed to mesh size, the boundary of the model not coinciding with the net nodes as assumed. A discussion on the effective model size will be given in a later section.

The times taken to set up the apparatus and perform the various experiments are given in Table 1. One semi-skilled person was employed throughout, with the assistance of an unskilled person during the reading and recording stage.

TABLE 1

Experiment	Setting-up time hours	Reading and recording	
		Semi-skilled hours	Unskilled hours
Circle (3 unit radius)	4	20	20
Circle (6 unit radius)	4	12	12
Rectangular wing ..	4	24	24
Delta wing	8	32	32
Swept-back wing ..	8	28	28

6.1.2. *Rectangular wing, constant chord, aspect ratio* 6.—Owing to its double axis of symmetry it was only necessary to set up a quarter of the rectangular wing, thus allowing a model of enhanced size to be used. The results call for no particular comment.

6.1.3. *Delta wing, 45-deg sweep, aspect ratio* 4.—In the case of the delta wing only one axis of symmetry exists and only one selvedge of the board could be used. The model which was used for this experiment was about the largest which could have been selected, as an examination of the results showed that there was a slight amount of channel restraint as evidenced by the readings in the region of the tier edges.

6.1.4. *Swept-back wing, 45-deg sweep, constant chord, aspect ratio* 3.—The swept-back wing and delta experiments were very similar; only one axis of symmetry could be used and the model size was approximately the same. The accuracy of the readings was comparable with those obtained from the other experiments.

6.2. *Flow Normal to the Surface using the Flexible-Wall Analogy.*—In the experiments described in the foregoing section, the model size for the analyser was influenced by two opposing considerations; the model had to be sufficiently large to enable a reasonably fine mesh to be used, and yet not so large as to give rise to undue channel interference.

The use of a graded net with a mesh which is fine near the model growing coarser further away, would be one method by which this problem could be attacked[14, 15].

An alternative method would be to start with a very small model, observe the boundary potentials and use these for a larger model. This method would not be very reliable as, with the coarse mesh necessitated by a small model, the model size becomes uncertain and the model boundary might not be correctly interpreted as ending at the net nodal points.

In the tests which are described in this report, and which have previously been reported by Bruce[4], a correction was introduced to offset the effect of what might be termed channel interference. This correction was not obtained by coarsening the mesh at a point remote from the model, but by calculating the boundary conditions for a finite net which give the same distribution of potential for a particular model, a doublet, as if it were immersed in an infinite net; the correction, which is reasonably independent of small changes in the model, was suggested by Mr. K. V. Diprose of the Royal Aircraft Establishment, and is analogous to the use of a slotted wind tunnel[16].

This section of the report is not concerned with circulation and therefore the analogy between the electrical and fluid flow problems is complete. It has been found convenient to treat the present problem in electrical terms.

6.2.1. *Theory of analogy to flexible-walled tunnel.*—The case of a doublet immersed in a uniform infinite conducting medium is considered; the current flow normal to, and the potential distribution over the walls of a cube containing the model being calculated. The conditions within the cube are unaltered if boundary resistors are used instead of the further medium, providing that these resistors give the right ratio of potential to normal current.

The potential distribution at a distance r from an isolated source is found as follows :—

$$\begin{aligned} \rho i &= -\operatorname{grad}\phi \\ \operatorname{div} i &= 0, \\ \int_s^i ds &= I, \end{aligned} \qquad (20)$$

hence

$$i = \frac{I}{4\pi r^2}$$

and

$$\phi = \frac{\rho I}{4\pi r} . \qquad (21)$$

The potential distribution due to a doublet strength D, see Fig. 6, is thus

$$\phi = \frac{\rho D \cos\theta}{4\pi r^2}\,. \tag{22}$$

The value of the wall correction boundary resistors may be found from the ratio of the potential to the normal potential gradient at the appropriate point, the potential gradient representing the density of the outward flowing current. Consider a rectangular wind tunnel with a flat plate normal to the current flow and take the origin O in the plate with right-hand orthogonal axes Ox, Oy, Oz, such that Oz is the axis of the doublet, that is to say Oz is normal to the plate. Let the radius vector from the origin O to some point on the tunnel wall be r and let the unit vector normal to the wall at this point be n, then the density of current flow normal to the wall is

$$\frac{n \operatorname{grad} \phi}{\rho} \tag{23}$$

where the components of grad ϕ are

$$\frac{\partial\phi}{\partial x} = \frac{\partial\phi}{\partial r}\cdot\frac{\partial r}{\partial x} + \frac{\partial\phi}{\partial\theta}\cdot\frac{\partial\theta}{\partial x}\,\text{etc.} \tag{24}$$

Now,

$$\phi = \frac{\rho D \cos\theta}{4\pi r^2}\,. \tag{25}$$

Therefore

$$\frac{\partial\phi}{\partial r} = -\frac{\rho D\cos\theta}{2\pi r^3} \tag{26}$$

and

$$\frac{\partial\phi}{\partial\theta} = -\frac{\rho D \sin\theta}{4\pi r^2}$$

while

$$r^2 = x^2 + y^2 + z^2 \tag{27}$$

and

$$\tan^2\theta = \frac{x^2+y^2}{z^2}\,.$$

Hence

$$\frac{\partial\phi}{\partial x} = \frac{-\rho D}{2\pi}\left[\frac{\cos\theta}{r^3}\cdot\frac{x}{r} + \frac{\sin\theta}{2r^2}\cdot\frac{x}{z^2\tan\theta\sec^2\theta}\right]$$

$$= \frac{-3\rho D x\cos\theta}{4\pi r^4}\,. \tag{28}$$

Similarly,

$$\frac{\partial\phi}{\partial y} = \frac{3\rho D y\cos\theta}{4\pi r^4}$$

and

$$\frac{\partial\phi}{\partial z} = -\frac{\rho D}{2\pi r^4}\left[z\cos\theta - \frac{(x^2+y^2)}{r}\right]$$

$$= -\frac{\rho D}{2\pi r^5}[z^2 - x^2 - y^2]. \tag{29}$$

For a tunnel wall parallel to Oyz the components of n are (1, 0, 0) hence

$$\rho i = \frac{3\rho D x \cos\theta}{4\pi r^4}$$

and

$$\frac{\phi}{i} = \rho\,\frac{r^2}{3x}\,. \tag{30}$$

For a resistance network this becomes :—

$$R_{\text{termination}} = R_{\text{net}} \left(\frac{x^2 + y^2 + z^2}{3x} \right) \quad \ldots \quad (31)$$

x, y and z now being measured in mesh units.

Similarly for a wall parallel to Oxz :—

$$R_{\text{termination}} = R_{\text{net}} \left(\frac{x^2 + y^2 + z^2}{3y} \right) \quad \ldots \quad (32)$$

while for a tunnel end parallel to Oxy

$$\begin{aligned} \frac{\phi}{i} &= \frac{r^3 \cos \theta}{2(z^2 - x^2 - y^2)} \\ &= \frac{r^2 z}{2(z^2 - x^2 - y^2)} \quad \ldots \quad (33) \end{aligned}$$

or for the network

$$R_{\text{termination}} = R_{\text{net}} \frac{z}{2} \frac{(x^2 + y^2 + z^2)}{(z^2 - x^2 - y^2)} \quad \ldots \quad (34)$$

It will be observed that this result postulates negative values of R when the value of z, for the furthest tier, is less than the greatest radial distance of any point on the tiers from the Oz-axis.

$$\text{i.e., } z_{\max} < [\sqrt{(x^2 + y^2)}]_{\max} \quad \ldots \quad (35)$$

6.2.2. *Application of the theory*.—The investigation in the previous section considered termination resistances for a model which could be represented sufficiently accurately by a single doublet. In consequence, this case covered only perturbation velocity potentials for flow without circulation ; under these conditions, the model was represented by a set of current sources, the current at each point being proportional to the slope of the centre of the aerofoil at that point. Nodes outside, but in the plane of the model, were held at a uniform zero potential and the ends of all terminating resistances were also taken to zero potential.

In the actual experiments which were undertaken, the model was a flat plate and the velocity potentials which were observed were the total velocity potentials for flow normal to the plate ; that is to say, the sum of the perturbation velocity potentials and the undisturbed flow potentials. The alteration to the boundary conditions was such that no connection was made to the nodes on the model, while the nodes over the most remote tier were raised to a uniform potential ; under these conditions the channel and terminating resistors had to be omitted, while the wall resistors were not connected to zero potential but to the potential at infinity, appropriate to their own particular tiers. For the actual analyser which was used the end resistors could not, in any case, have been used, for many of them would have to be of negative value.

Where circulation was represented on the analyser, the appropriate terminating resistances could not be found for the surface through which the trailing-edge vortex sheet passed.

The models considered had an axis of symmetry and this axis was represented as the axis Ox and, therefore, the surface $y = 0$ was a reflecting surface and not a channel wall ; that is, it needed no terminating resistors.

Fig. 7 shows, diagrammatically, the electrical circuit used for the channel wall resistors. A view of the apparatus set up for an experiment is shown in Fig. 8.

The resistance values of the wall resistors are tabulated in Appendix I, to this report.

6.2.3. *Experiments using flexible-wall analogy.*—Experiments were carried out to determine the velocity potentials for flow normal to flat plates of the following wing shapes :—

(*a*) Rectangular

(*b*) Delta

(*c*) Swept-back.

These were represented on the master tier, as before, by leaving the corresponding mesh nodes disconnected while shorting the remaining points on the master tier to zero potential. In case (*a*), the rectangular plate had to be moved to the centre of the master tier as the terminating resistors had been calculated on the assumption of a doublet at this point.

The flow normal to the plates was again represented by raising the auxiliary tier, $z = 9$, to a potential of 1,000 units, approximately 1 volt, and the experiments then consisted of measuring the potentials at other nodes. Terminating resistors on tier 1 had a potential of 111 ± 5 units at their far end and 222 ± 5 units on tier 2, etc., these potentials being derived from a 5-ohm potential divider with 100 tapping points.

6.2.4. *Results and comments.*—The experiment which was made to the delta model was the only one which showed any significant difference from the experiments which have been described in section 6.1. In the flexible-wall experiment the potentials over the centre of the model increased by about 2 units, approximately 1 per cent change. A visual inspection of the various model shapes and sizes, compared with the tier size, showed that the delta model would certainly be one which would be most affected by channel constraint.

It seems likely that the end effect will swamp the wall effect, for the analyser has only 9 tiers, on either side of the master tier, although it has an equivalent cross-section of 24 × 48 units. It is impossible, however, to add correcting resistors to the top tier ; this is due both to the method of application of the flow conditions and to the fact that even if this were rectified by representing perturbation flow only, as suggested in this report, then negative resistors would be required. The solution of this difficulty would appear to lie in the addition of a net of increasing coarseness.

6.3. *Flow Normal to the Surface with Circulation.*—It has already been pointed out that it would have been possible to have made tests to determine the perturbation flow without circulation, together with the circulation originating in a trailing vortex sheet, but without the undisturbed flow normal to the aerofoil surface. However, for the purpose of this investigation it was decided to combine the three flows ; therefore the results of this section, when combined with the desired amount of undisturbed flow along the aerofoil surface, give the complete solution to the problem under consideration without recourse to the results of the previous experiments.

In this series of experiments it was not possible to use the flexible-walled terminal analogy because the appropriate terminating resistances could not be found for the surface through which the trailing-edge vortex sheet passed.

With the exception of the circular lamina all the planforms previously investigated were re-investigated to determine the effect of circulation.

A diagrammatic arrangement of the set-up for the master tier is shown in Fig. 9. Reference to this illustration shows that the model was set out on the tier in the normal way and that the portion of the tier unoccupied either by the model, or the vortex sheet immediately behind it, was short-circuited and set at zero potential. Commencing with nodal points, such as A′, B′, C′, etc., which are one mesh unit to the rear of corresponding points A, B, C, etc., successive nodal points were shorted to the boundary of the tier. Thus the area from one unit behind the trailing edge to the boundary was shorted by bars running in one direction only. Each shorting bar was connected through a rheostat to a potential divider. The condition for circulation is that the potential at a point immediately behind the surface shall be at the same potential as the corresponding point on the surface trailing edge. The experimental procedure was to apply a uniform unit voltage at the auxiliary tier and then by means of the potential divider and rheostats, to adjust the potential on the shorting bars so that the potentials at A′, B′, C′, etc., coincided with the potentials at the corresponding points A, B, C, etc. It will be appreciated that adjustment to the potential on any bar upset the values of the potentials on neighbouring bars and the setting up developed into what might be termed an electrical iteration process. It was found, however, that with a little practice the setting up of a model was quite rapid. After the set up had been completed the method of scanning was identical to that carried out for the previous experiments.

The results of these experiments are given in Appendix II to this report.

6.3.1. *Results and comments.*—From the foregoing experiments the velocity potential ϕ was plotted for chordwise sections of the aerofoil, these curves being graphically differentiated to obtain values of $\partial\phi/\partial x$. Then, by the use of equation (15), values of $\Delta p/q\alpha$ were computed and are pictorially represented in Figs. 10, 11 and 12 for the three experiments. These figures call for no special comment although it will be observed that in each case the load distribution curves appear to be reasonable.

Values of $\partial C_L/\partial\alpha$ for each aerofoil were calculated from equation (16) and are compared with theoretical values, supplied by Mr. W. P. Jones of the National Physical Laboratory, in Table 2.

TABLE 2

Experiment	$\frac{\partial C_L}{\partial \alpha}$	
	Theoretical	Experimental
Rectangular wing Aspect ratio = 6	4·26	4·80
Delta wing Aspect ratio = 4	3·47	3·22
Swept-back wing Aspect ratio = 3	2·75	2·75

When making these calculations it was difficult to assess the true area of the aerofoil, a difficulty which has been previously mentioned in section 6.1.1. The difficulty arises because the net used was too coarse for the true boundary position to be precisely located. The actual locus of the boundary must lie between lines joining the nodal points on the assumed boundary, which was short-circuited on the model set up on the analyser, and lines joining the nodal points one mesh distance within the model from the short-circuited boundary. For the purpose of the present investigation the true boundary was assumed to lie along lines one half mesh distance inside the model, from the short-circuited boundary. This difficulty could have been obviated if the tier size had been larger, this would have allowed a larger model to be used with, of course, a finer mesh separation.

7. *Conclusions.*—The potential analyser proved to be easy and quick to operate, even by unskilled personnel. The apparatus was designed for the general solution of the three-dimensional form of Laplace's equation and this, to a certain extent, proved to be a handicap when it was used for the particular flow problems described in this report.

For problems concerning potential flow around thin plates, under conditions in which the linear-perturbation theory applies, it is only necessary to measure the electrical potentials over the master tier. It would thus be possible to have a very large master tier, thus permitting a small mesh separation, so avoiding the difficulty regarding the indeterminancy of the model boundary. The effect of additional tiers would have to be produced but, as the tiers would not need to be accessible, a considerable simplification in the construction would be possible. Furthermore, a graded resistance net could be used, thus increasing the effective size of the network.

In addition to the study of problems of the type described in this report, curved and twisted aerofoils could also be studied and in this connection there are many practical advantages to be gained in using an electrical network as opposed to an electrolytic tank.

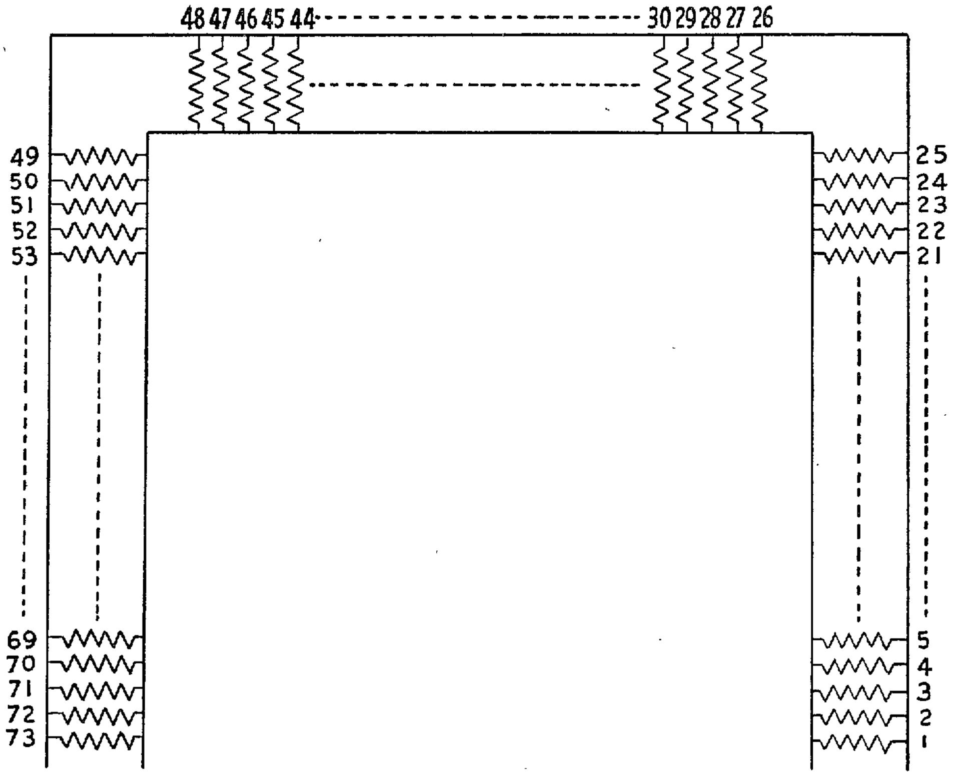
REFERENCES

No.	*Author*	*Title, etc.*
1	W. F. Campbell	Two electrical analogies for the pressure distribution on a lifting surface. National Research Council of Canada Report No. MA.219. 1949.
2	L. Malavard and R. Duquenne	Étude des surfaces portantes par analogies rhéoeléctriques. *La Recherche Aeronautique*, No. 23. 1951.
3	S. C. Redshaw	A three-dimensional electrical potential analyser. Boulton Paul Aircraft Limited, Technical Report No. 79. 1950. (Unpublished.)
4	D. M. Bruce	The representation of a flexible-walled wind tunnel by an electrical potential analyser. Boulton Paul Aircraft Limited, Technical Report No. 87. 1951. (Unpublished.)
5	G. I. Taylor and C. F. Sharman	A mechanical method for solving problems of flow in compressible fluids. R. & M. 1195. 1928.
6	H. Glauert	The effect of compressibility on the lift of an aerofoil. R. & M. 1135. 1927.
7	L. Prandtl	General considerations on the flow of compressible fluids. N.A.C.A. Tech. Memo. 805. 1936.
8	L. M. Milne-Thomson	*Theoretical aerodynamics*, p. 147. Macmillan and Co. 1948.
9	T. von Kármán and J. M. Burgers	*Aerodynamic theory*, Vol. 2. W. F. Durand (editor). Julius Springer. 1934.
10	S. C. Redshaw	A three-dimensional electrical potential analyser. *British Journal of Applied Physics*, Vol. 2, pp. 291–295. 1951.
11	S. C. Redshaw	*Institution of Mechanical Engineers Proceedings*. Vol. 159 (War emergency No. 38), pp. 55–62. 1948.
12	H. Lamb	*Hydrodynamics*. 4th edition. Chapter V. Cambridge University Press. 1916.
13	L. F. Richardson	*Phil. Trans. Roy. Soc.*, A., 210, pp. 307–357. 1910.
14	G. Liebmann	Solution of partial differential equations with a resistance network analogue. *British Journal of Applied Physics*, Vol. 1, No. 4. 1950.
15	L. Tasny Tschiassny	The triangulation of a two-dimensional continuum for the purpose of the approximate solution of second-order partial differential equations. *Journal of Applied Physics*, Vol. 20, No. 5. 1949.
16	C. N. H. Lock and J. A. Beavan	Tunnel interference at compressibility speeds using the flexible walls of the Rectangular High Speed Tunnel. R. & M. 2005. 1944.

APPENDIX I

Correction Resistors

The arrangement of the wall correction resistors for the tiers 1 to 8 inclusive is shown diagrammatically below.



The following table gives the values of each resistor for each tier.

	BOUNDARY POINT RESISTOR (Ohms)							
TIER POINT	1	2	3	4	5	6	7	8
1	1800	1800	1800	1800	1800	2200	2200	2200
2	820	820	820	820	1000	1000	1000	1200
3	820	820	820	1000	1000	1000	1000	1200
4	820	820	820	1000	1000	1000	1200	1200
5	820	1000	1000	1000	1000	1000	1200	1200
6	1000	1000	1000	1000	1000	1200	1200	1200
7	1000	1000	1000	1000	1200	1200	1200	1500
8	1000	1000	1200	1200	1200	1200	1500	1500
9	1200	1200	1200	1200	1200	1500	1500	1500
10	1200	1200	1500	1500	1500	1500	1500	1800
11	1500	1500	1500	1500	1500	1500	1800	1800
12	1500	1500	1500	1500	1500	1800	1800	1800
13	1800	1800	1800	1800	1800	1800	1800	1800
14	1800	1800	1800	1800	1800	1800	2200	2200
15	1800	1800	1800	1800	2200	2200	2200	2200
16	2200	2200	2200	2200	2200	2200	2200	2700
17	2200	2200	2200	2200	2200	2700	2700	2700
18	2700	2700	2700	2700	2700	2700	2700	2700
19	2700	2700	2700	2700	2700	2700	2700	2700
20	2700	2700	2700	2700	2700	3300	3300	3300
21	3300	3300	3300	3300	3300	3300	3300	3300
22	3300	3300	3300	3300	3300	3300	3300	3900
23	3300	3300	3300	3300	3900	3900	3900	3900
24	3900	3900	3900	3900	3900	3900	3900	3900
25	2200	2200	2200	2200	2200	2200	2200	2200
26	2200	2200	2200	2200	2200	2200	2200	2200
27	2200	2200	2200	2200	2200	2200	2200	2200
28	1800	1800	1800	2200	2200	2200	2200	2200
29	1800	1800	1800	1800	1800	2200	2200	2200
30	1800	1800	1800	1800	1800	1800	2200	2200
31	1800	1800	1800	1800	1800	1800	1800	2200
32-42	1800	1800	1800	1800	1800	1800	1800	1800
43	1800	1800	1800	1800	1800	1800	1800	2200
44	1800	1800	1800	1800	1800	1800	2200	2200
45	1800	1800	1800	1800	1800	2200	2200	2200
46	1800	1800	1800	2200	2200	2200	2200	2200
47	2200	2200	2200	2200	2200	2200	2200	2200
48	2200	2200	2200	2200	2200	2200	2200	2200
49	1500	1500	1500	1500	1500	1500	1500	1500
50	3900	3900	3900	3900	3900	3900	3900	3900
51	3300	3300	3300	3900	3900	3900	3900	3900
52	3300	3300	3300	3300	3300	3300	3300	3900
53	3300	3300	3300	3300	3300	3300	3300	3300
54	2700	2700	2700	2700	2700	3300	3300	3300
55	2700	2700	2700	2700	2700	2700	2700	3300
56	2700	2700	2700	2700	2700	2700	2700	2700
57	2200	2200	2200	2200	2700	2700	2700	2700
58	2200	2200	2200	2200	2200	2200	2700	2700
59	1800	2200	2200	2200	2200	2200	2200	2200
60	1800	1800	1800	1800	2200	2200	2200	2200
61	1800	1800	1800	1800	1800	1800	1800	2200
62	1500	1800	1800	1800	1800	1800	1800	1800
63	1500	1500	1500	1500	1500	1800	1800	1800
64	1500	1500	1500	1500	1500	1500	1800	1800
65	1200	1200	1500	1500	1500	1500	1500	1800
66	1200	1200	1200	1200	1500	1500	1500	1500
67	1200	1200	1200	1200	1200	1500	1500	1500
68	1000	1000	1200	1200	1200	1200	1500	1500
69	1000	1000	1000	1200	1200	1200	1200	1500
70	1000	1000	1000	1000	1200	1200	1200	1500
71	1000	1000	1000	1000	1000	1200	1200	1200
72	1000	1000	1000	1000	1000	1200	1200	1200
73	1800	1800	1800	2200	2200	2200	2200	2700

APPENDIX II

Tabulated Results of Experiments ;
Flow with Circulation

THREE DIMENSIONAL POTENTIAL ANALYSER

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A																									
B																									
C																									
D																									
E																									
F																									
G																									
H																									
J																									
K																									
L																									
M																									
N											0	0	0	0	0	0									
O											0	120	168	191	204	204									
P											0	168	243	281	299	299									
Q											0	194	281	331	356	356									
R											0	208	308	363	389	389									
S											0	219	326	384	413	413									
T											0	226	338	399	430	430									
U											0	232	345	410	442	442									
V											0	236	351	417	450	450									
W											0	238	355	422	456	456									
X											0	240	358	426	460	460									
Y											0	241	360	428	462	462									
Z											0	241	361	428	463	463									

PROBLEM. NORMAL FLOW WITH CIRCULATION

MODEL SIZE. RECTANGULAR. 12 MESH UNITS SEMI-SPAN. 4 MESH UNITS CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9.

TIER Nº 0

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
A		112		111		111		111		111		111		110		111		112		111		111		112		A
B																										B
C		112		111		111		111		111		111		111		111		111		111		112		111		C
D																										D
E		111		111		111		111		111		111		111		112		112		112		113		113		E
F																										F
G		111		111		111		112		112		112		113		113		114		114		115		115		G
H																										H
J		111		111		112		113		113		115		116		118		117		119		120		119		J
K																	122	119	122							K
L		111		111		112		114		116		121		126		129	126	103	131	132		132		132		L
M										119	123	129	135	139	142	144	145	143	147	148	148	148	148			M
N		111		112		113		116		123	131	146	159	168	174	178	179	180	182	183	183	183	183	184		N
O										129	146	192	226	247	260	267	270	272	273	274	274	274	275			O
P		112		113		114		117		134	159	227	277	309	328	337	341	344	345	346	346	346	346	346		P
Q										140	169	250	312	352	376	388	392	395	397	398	398	398	399			Q
R		112		113		115		122		143	176	266	335	381	408	420	426	429	431	432	433	433	433	433		R
S										146	182	277	352	402	431	445	451	454	457	458	458	459	459			S
T		112		114		116		124		149	186	285	364	417	448	462	469	472	475	476	477	478	478	478		T
U										151	189	291	373	427	459	474	481	485	488	489	490	491	491			U
V		112		113		116		129		152	191	925	378	434	468	483	490	495	497	498	500	500	500	500		V
W										152	193	298	382	440	474	489	497	501	504	505	506	507	507	507	508	W
X		112		114		116		125		153	194	300	385	443	478	493	501	506	508	510	511	511	512	512	512	X
Y										153	194	301	387	445	480	496	503	508	511	512	513	514	514	614	515	Y
Z		112		112		117		126		153	194	302	388	446	481	497	504	509	511	513	514	515	515	515	516	Z
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	

PROBLEM. NORMAL FLOW WITH CIRCULATION

MODEL SIZE. RECTANGULAR. 12 MESH UNITS SEMI-SPAN. 4 MESH UNITS CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9

TIER Nº 1

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A		222		222		222		223		222		222		223		222		222		223		223		223	
B																									
C		222		222		222		222		222		222		223		223		223		224		224		224	
D																									
E		222		222		222		223		223		223		224		224		225		225		225		226	
F																									
G		222		222		222		223		224		225		226		227		228		229		229		229	
H																									
J		222		222		223		224		227		229		232		235		238		237		237		238	
K																		250	247						
L		222		222		224		227		232		239		247		254	260	287	262	258		257		257	
M										236	242	249	254	262	267	272	276	282							
N		222		223		225		230		242	252	265	278	288	297	302	307	309		311		311		311	
O										249	265	290	313	331	344	352	357	360							
P		222		224		227		235		256	278	314	347	371	388	399	405	409		413		414		413	
Q										263	290	333	373	404	425	438	446	449							
R		223		225		229		240		269	300	348	393	428	452	467	475	480		485		487		487	
S										274	307	359	408	447	473	489	498	504							
T		224		226		231		243		277	312	367	419	460	488	505	515	521		527		530		530	
U										279	316	373	427	470	499	516	527	534							
V		224		226		232		245		281	319	377	433	477	507	525	536	543		550		553		554	
W										283	321	380	438	482	512	531	543	550							
X		224		227		232		247		283	322	383	441	485	516	536	547	554		561		564		565	
Y									261	284	323	384	442	487	518	538	550	557							
Z		224		229		233		247		285	323	385	443	488	519	539	551	557		565		568		569	

PROBLEM. NORMAL FLOW WITH CIRCULATION

MODEL SIZE. RECTANGULAR, 12 MESH UNITS SEMI-SPAN. 4 MESH UNITS CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9.

TIER Nº 2

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	2	4	6	8	10	12	14	16	18	20	22	24
A	333	333	333	333	333	333	333	334	333	334	335	335
C	333	333	333	333	333	334	334	334	334	335	335	336
E	332	333	333	334	334	335	336	336	336	337	338	338
G	332	332	333	334	335	337	339	340	341	341	342	342
J	332	333	334	336	338	342	346	349	352	352	352	352
L	333	333	335	339	345	353	361	369	379	375	374	374
N	333	335	337	343	355	375	396	410	418	420	421	421
P	334	336	340	349	369	409	450	474	485	490	492	491
R	335	337	342	355	382	436	493	526	541	547	550	550
T	335	338	344	358	391	454	519	558	578	584	588	589
V	336	339	346	361	396	465	535	578	597	606	610	611
X	336	340	347	363	399	470	543	587	608	617	621	623
Z	337	340	347	363	400	471	546	590	611	621	624	626

PROBLEM. NORMAL FLOW WITH CIRCULATION.

MODEL SIZE. RECTANGULAR. 12 MESH UNITS SEMI-SPAN. 4 MESH UNITS CHORD. UNIFORM VOLTAGE 1·000 AT TIER 9.

TIER Nº 3

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
A		555		555		555		555		555		555		556		556		557		557		557		557		A
B																										B
C		555		555		555		555		555		555		556		556		556		557		558		558		C
D																										D
E		554		554		555		556		556		557		557		558		559		560		560		561		E
F																										F
G		554		552		555		556		558		560		561		562		564		565		565		565		G
H																										H
J		555		554		556		558		562		565		568		571		574		575		575		574		J
K																										K
L		555		556		557		561		566		573		580		586		590		591		592		592		L
M																										M
N		555		557		560		565		573		585		599		610		616		619		620		621		N
O																										O
P		556		558		562		570		583		603		625		641		650		655		657		659		P
Q																										Q
R		557		559		565		575		593		620		649		670		682		688		691		693		R
S																										S
T		558		560		566		578		600		633		666		691		705		712		715		717		T
U																										U
V		558		561		568		581		606		641		677		704		719		727		731		733		V
W																										W
X		559		561		568		583		608		644		683		711		727		736		740		741		X
Y																										Y
Z		559		562		569		583		608		646		684		713		729		738		742		744		Z
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	

PROBLEM. NORMAL FLOW WITH CIRCULATION

MODEL SIZE. RECTANGULAR. 12 MESH UNITS SEMI-SPAN. 4 MESH UNITS CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9.

TIER Nº 5

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A		778		778		777		776		775		776		777		777		778		778		779		779	
B										773						776									
C		777		777		777		775	774	769	773	776		776	776	774	777	778		779		779		779	
D										774						771									
E		777		776		777		777		776		778		778	777	776	778	780		780		780		780	
F				771												779									
G		775	771	749	772	776		778		779		780		781		781		783		784		783		783	
H				771																					
J		776		775		777		779		781		783		785		787		788		788		789		789	
K																									
L		775		775		775		779		784		788		792		794		796		797		798		798	
M	770	773																							
N	765	771	774	775		775		781		789		796		801		805		808		810		811		812	
O	770	773																							
P		774		777		780		786		794		803		811		818		823		826		827		828	
Q																									
R		775		779		782		788		797		809		821		831		837		841		843		843	
S																									
T		778		779		782		789		801		815		829		841		848		853		855		855	
U						783																			
V		779		779	782	777	787	790		803		819		835		847		856		861		863		863	
W						785																			
X		780		779		784		792		805		821		838		851		860		865		867		867	
Y																									
Z		780		781		784		792		806		822		839		852		861		865		868		869	

PROBLEM. NORMAL FLOW WITH CIRCULATION.

MODEL SIZE. RECTANGULAR. 12 MESH UNITS SEMI-SPAN. 4 MESH UNITS CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9

TIER Nº 7

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A																									
B																									
C																									
D																									
E																									
F																									
G																									
H																									
J																									
K																									
L																									
M																									
N																			0	0					
O																		0	138	138					
P																	0	174	248	248					
Q																0	190	268	334	334					
R															0	198	308	371	404	404					
S														0	202	303	391	437	461	461					
T													0	206	323	383	453	489	509	509					
U												0	200	317	400	442	502	531	547	547					
V											0	196	314	396	457	488	539	564	578	578					
W										0	178	306	385	448	485	537	568	589	601	601					
X									0	173	282	360	429	483	525	560	587	606	617	617					
Y								0	149	254	333	398	455	503	541	573	599	617	627	627					
Z							0	091	192	277	349	410	464	509	547	578	602	620	630	630					

PROBLEM. NORMAL FLOW WITH CIRCULATION.

MODEL SIZE. DELTA. 12 MESH UNITS SEMI-SPAN. 12 MESH UNITS ROOT CHORD. UNIFORM VOLTAGE OF 1·0000 AT TIER 9.

TIER Nº 0.

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A		112		111		111		111		111		111		110		111		112		111		111		112	
B																									
C		112		111		111		111		111		111		111		111		111		111		112		111	
D																									
E		112		111		111		111		111		111		111		112		111		112		112		112	
F																									
G		111		111		111		111		110	109	110		112		112		113		114		114		114	
H										109	105	109													
J		111		111		111		111		112	109	111	112	113		115		115		118		119		119	
K																									
L		111		111		112		112		112		114		116		119	118	098	132	129		129		130	
M																		128	137	140	142	142			
N		111		112		112		113		114		117		122		130		147	160	166	170	171		173	
O														126		142	157	180	223	236	241	243		245	
P		112		112		113		115		117		123		134		164	194	254	296	310	316	319		321	
Q		112		113		114		116		120		128		147	167	205	272	329	364	378	385	387		390	
R		112		113		114		117		122		135		169	206	281	348	396	426	438	444	446		449	
S		112		114		115		119		127		147	169	208	286	358	414	454	478	489	494	497		499	
T		112		114		116		121		134		167	207	287	362	423	469	502	522	532	537	539		541	
U		112		114		118		125		145	165	204	284	360	424	475	514	542	559	567	572	574		576	
V		113		114		118		129		161	199	278	354	419	473	516	549	573	588	596	600	602		604	
W		113		115		119		136	154	191	266	342	408	464	510	547	576	597	611	617	621	623		625	
X		113		115		121		146	179	250	323	388	446	495	535	569	595	614	626	632	636	638		640	
Y		113		115		123	134	160	224	293	358	417	468	513	550	581	606	624	636	642	645	647		648	
Z		113		114		125	139	180	243	308	370	426	476	519	555	586	609	627	639	645	648	650		651	

PROBLEM. NORMAL FLOW WITH CIRCULATION.

MODEL SIZE. DELTA. 12 MESH UNITS SEMI-SPAN. 12 MESH UNITS ROOT CHORD. UNIFORM VOLTAGE OF 1.000 AT TIER 9.

TIER Nº 1.

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A		222		222		222		222		222		222		223		222		222		223		222		223	
B																									
C		222		222		222		222		222		222		222		222		223		223		223		224	
D																									
E		222		222		222		222		222		222		223		223		224		224		225		225	
F										222		222													
G		222		222		222		223	222	221	218	222	224	224		225		227		227		228		228	
H										219	196	219													
J		222		222		222		223	223	223	220	223	226	227		229		234		234		235		236	
K										224	224							243							
L		222		222		223		224		226		228		232		239	257	276	255	252		253		253	
M																		262	265	267	269	270			
N		223		222		224		225		228		233		241		255		276	286	293	256	300		301	
O																271	287	306	325	337	343	347			
P		223		223		225		238		234		243		261		295	320	350	375	389	396	400		403	
Q														277	299	329	366	400	425	440	448	453			
R		223		225		227		233		243		263		301	334	376	417	450	474	488	496	500		503	
S												279	302	336	381	426	446	497	517	630	538	542			
T		224		226		231		240		260		301	335	381	429	473	509	537	556	568	574	579		582	
U										273	297	331	378	428	474	514	546	571	588	598	605	609			
V		225		228		235		252		291	325	372	422	470	512	548	577	598	614	623	629	633		637	
W								260	282	315	360	410	459	503	542	574	600	620	634	643	648	652			
X		226		230		240		270	300	343	393	442	487	526	563	593	617	635	648	657	662	665		668	
Y						243	257	281	319	366	414	461	504	543	576	604	627	645	657	665	670	673			
Z		226		232		244	259	287	327	374	421	468	510	548	580	608	631	648	650	668	673	676		678	

PROBLEM. MODEL FLOW WITH CIRCULATION

MODEL SIZE. DELTA. 12 MESH UNITS SEMI-SPAN, 12 MESH UNITS ROOT CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9

TIER Nº 2

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	2	4	6	8	10	12	14	16	18	20	22	24
A	333	333	333	333	333	333	333	333	333	334	334	335
B												
C	333	333	333	333	333	333	334	334	334	334	335	336
D												
E	332	333	333	333	333	334	335	335	335	336	337	337
F												
G	332	332	333	333	336	337	337	338	339	340	341	341
H												
J	332	332	333	334	337	339	340	343	347	348	350	350
K												
L	333	333	334	335	338	341	346	353	370	367	369	370
M												
N	332	334	335	337	341	347	357	372	390	405	411	414
O												
P	334	335	337	341	347	359	378	408	445	473	484	487
Q												
R	335	336	340	347	359	379	415	467	518	548	561	565
S												
T	336	338	343	355	376	413	422	536	595	613	625	630
U												
V	338	341	349	368	403	463	533	594	637	661	672	676
W												
X	339	343	355	383	437	508	576	630	668	689	699	703
Y												
Z	339	344	358	392	453	526	591	643	679	699	708	712

PROBLEM. NORMAL FLOW WITH CIRCULATION

MODEL SIZE. DELTA. 12 MESH UNITS SEMI-SPAN. 12 MESH UNITS ROOT CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9

TIER Nº 3

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	2	4	6	8	10	12	14	16	18	20	22	24
A	555	554	555	555	555	555	556	556	556	557	557	557
B												
C	554	555	555	555	555	554	556	555	556	557	558	558
D												
E	554	554	554	555	556	556	556	557	558	559	560	560
F												
G	553	552	554	556	558	559	559	560	562	563	564	564
H												
J	554	554	555	557	559	562	563	565	569	571	572	573
K												
L	555	555	556	558	560	564	568	574	580	585	588	589
M												
N	555	556	557	560	563	569	578	589	601	610	616	618
O												
P	556	557	560	563	569	579	595	613	632	647	655	660
Q												
R	557	559	563	569	579	596	619	646	671	689	699	704
S												
T	559	561	567	576	593	617	649	682	709	727	737	742
U												
V	560	564	571	585	609	642	679	714	740	757	767	771
W												
X	561	565	575	594	624	662	701	735	760	776	785	788
Y												
Z	562	566	578	598	630	670	709	742	767	782	791	794

PROBLEM. NORMAL FLOW WITH CIRCULATION

MODEL SIZE. DELTA. 12 MESH UNITS SEMI-SPAN. 12 MESH UNITS ROOT CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9

TIER Nº 5

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A		777		777		777		776		776		777		777		777		778		778		778		779	
B																									
C		777		777		776		775		769		776		776		774		778		779		779		779	
D																									
E		776		774		776		777		776		777		778		775		779		780		780		780	
F																									
G		775		747		775		777		778		779		779		780		782		783		782		783	
H																									
J		776		776		777		778		779		780		782		783		785		786		787		788	
K																									
L		777		777		778		779		781		783		786		788		792		795		796		797	
M																									
N		778		778		778		780		785		788		792		797		802		807		809		811	
O																									
P		777		778		780		783		788		794		800		808		817		823		827		829	
Q																									
R		777		779		781		786		791		800		811		823		834		842		847		849	
S																									
T		779		781		783		789		798		810		824		838		851		860		865		867	
U																									
V		780		782		786		794		805		820		836		852		865		874		879		880	
W																									
X		782		782		788		797		811		828		846		862		875		883		888		889	
Y																									
Z		781		783		788		799		814		831		850		865		877		886		890		892	

PROBLEM. NORMAL FLOW WITH CIRCUTION

MODEL SIZE. DELTA. 12 MESH UNITS SEMI-SPAN. 12 MESH UNITS ROOT CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9.

TIER Nº 7

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A																									
B																									
C																									
D																									
E																									
F																									
G																									
H																									
J																									
K																									
L																									
M																									
N																									
O																									
P																									
Q														0	0	0	0	0	0	0	0				
R													0	153	197	212	213	197	185	185					
S												0	174	262	302	318	319	304	304						
T											0	181	280	338	368	381	379	379							
U										0	183	286	350	389	411	418	418								
V									0	180	286	353	398	425	438	438									
W								0	175	279	349	396	426	444	444										
X							0	164	266	337	387	421	441	441											
Y						0	143	241	312	366	406	430	430												
Z					0	089	184	263	327	375	408	408													

PROBLEM. NORMAL FLOW WITH CIRCULATION.

MODEL SIZE SWEPT BACK. 9 MESH UNITS SEMI-SPAN. 6 MESH UNITS CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9.

TIER Nº 0.

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A		111		111		111		111		111		111		110		110		112		110		111		111	
B																									
C		112		111		111		110		110		111		110		111.		111		111.		111.		111.	
D																									
E		111.		111.		111		111.		110		111.		111.		111.		111.		111.		112		112	
F																									
G		111.		111		111		111		111		111.		111		112		112		112		113		112	
H																									
J		111		111.		111.		112		111		112		112.		113		113		114		114		113	
K																		114.	120	117.					
L		111.		111.		111.		112.		112.		113		115.		116	114	097	143	123	119	117		117.	
M																		118	125	122					
N		111.		112		112.		113		114		117.		120		122		124.		124		124.		124.	
O																									
P		112.		113.		113		116.		119.		126		137.	142	145	146	147	148	148.	147.	147.	148.	148.	
Q													147.	162	173	180	182	182	182	182	182	182.			
R		113.		114.		116.		121.		130		154	181.	231	258	271.	275	273	271.	271.	271.	270		270	
S											158.	189	252	302	332	347.	352	351.	351.	351.					
T		113.		115.		120.		131.		159.	193.	260	320	362	389	403	408	409	410	410		411.		411.	
U									157.	193.	262	325	375	409	430	441.	445	447.							
V		114		117.		127.		155	189	260	325	377.	416	442	457.	464.	468.	470.		472.		473		473.	
W							150	183	252	318	373	414	444	462	472	477.									
X		115.		121.		142.	173	239	305	361	405	437	459	471	478	482		486		488		488		489.	
Y					132	156	215	279	337	385	422	448	463	472.											
Z		115		122.	137.	175	233	294	348	393	426	447	459	467.		476.		479		481.		481.		482.	

PROBLEM. NORMAL FLOW WITH CIRCULATION

MODEL SIZE. SWEPT BACK 9 MESH UNITS SEMI-SPAN 6 MESH UNITS CHORD UNIFORM VOLTAGE OF 1·000 AT TIER 9.

TIER Nº 1.

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
A		222		222		222		222		222		221		222		222		221		222		222		222		A
B																										B
C		222		222		221		222		221		221		222		222		222		222		222		222		C
D																										D
E		221		221		221		222		222		222		223		223		223		223		224		224		E
F										222	228	221														F
G		221		222		222		222	222	221	218	221	223	224		224		224		225		225		225		G
H									222	218	196	219	223					226								H
J		222		222		222		223	223	222	219	223	225	226		227	228	230	229	228		227		228		J
K										222	124	225	226					237	235	232						K
L		222		222		223		224		225		227		229		233	239	264	246	238	234	233		233		L
M																		245	243	241						M
N		222		223		224		226		229		233		238		243		247		247		245		245		N
O																										O
P		223		224		226		230		237		247		261	267	272	275	277	278	278	278	278	277	276		P
Q													272	286	297	304	308	310	311	311	311	312				Q
R		224		226		231		239		254		282	302	326	344	356	361	363	363	364	364	364		364		R
S											286	312	344	373	394	407	413	416	417	418						S
T		226		229		238		254		288	316	352	388	417	437	450	456	460	462	463		464		464		T
U									286	315	354	393	427	453	471	482	489	492								U
V		227		233		248		282	312	351	393	429	460	482	496	506	511	514		518		519		520		V
W							275	304	344	386	425	457	483	501	513	520										W
X		229		238		265	291	330	373	413	449	477	498	512	522	528		535		538		539		540		X
Y					253	274	309	351	393	431	462	487	505	517												Y
Z		230		244	256	280	317	359	400	436	466	489	506	517		531		537		540		541		541		Z
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	

PROBLEM. Normal Flow With Circulation.

MODEL SIZE. Swept Back 9 Mesh Units Semi-Span. 6 Mesh·Units Chord. Uniform Voltage Of 1·000 At Tier 9.

TIER Nº 2

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A		332		332		332		332		332		332		333		333		333		3		3		4	
B																									
C		332		332		332		332		332		333		333		333		333		333		334		334	
D																									
E		331		332		332		333		333		333		334		334		334		334		335		335	
F																									
G		332		332		332		333		335		336		335		336		336		336		337		337	
H																									
J		332		332		333		334		337		338		338		339		342		341		340		340	
K																		347	346	345					
L		333		333		334		335		338		340		342		346	349	355	362	350	348	347		347	
M																		356	356	355					
N		333		334		336		338		342		347		353		358		362		368		362		362	
O																									
P		335		336		339		344		351		362		375		386		391		394		394		393	
Q																									
R		336		338		344		353		369		393		424		445		454		456		457		456	
S																									
T		338		342		351		368		399		443		486		512		523		527		528		529	
U																									
V		341		347		362		393		442		497		537		559		569		573		575		576	
W																									
X		343		353		377		424		482		532		564		581		590		594		596		597	
Y																									
Z		346		366		385		439		498		543		572		587		594		599		600		601	

PROBLEM. Normal Flow With Circulation.

MODEL SIZE. Swept Back 9 Mesh Units Semi-Span. 6 Mesh Units Chord. Uniform Voltage of 1·000 At Tier 9.

TIER № 3

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A		554		554		553		553		554		555		555		555		556		556		556		556	
B																									
C		554		553		553		554		554		554		555		555		555		556		557		557	
D																									
E		553		552		553		554		555		555		555		556		556		557		558		558	
F																									
G		553		551		553		555		556		557		557		558		559		559		560		559	
H																									
J		554	553	553	554	554		556		559		560		560		562		563		563		563		563	
K																									
L		554		555		555		558		560		562		565		568		570		570		570		570	
M																									
N		555		556		558		560		563		568		573		578		581		582		583		583	
O																									
P		556		558		561		565		571		580		590		598		603		605		606		608	
Q																									
R		558		561		566		574		585		601		617		629		635		639		640		642	
S																									
T		560		564		572		585		604		627		648		663		671		675		678		678	
U																									
V		563		568		580		599		626		653		676		690		699		703		705		705	
W																									
X		565		572		587		613		643		671		693		707		714		718		720		721	
Y																									
Z		566		574		591		618		650		678		698		712		719		723		725		725	

PROBLEM. NORMAL FLOW WITH CIRCULATION

MODEL SIZE. SWEPT BACK. 9 MESH UNITS SEMI-SPAN. 6 MESH UNITS CHORD. UNIFORM VOLTAGE OF 1·000 AT TIER 9

TIER Nº 5

—THREE DIMENSIONAL POTENTIAL ANALYSER—

	2	4	6	8	10	12	14	16	18	20	22	24
A	777	776	774	774	775	776	776	776	777	778	778	778
C	776	774	768	773	768	775	776	774	777	778	778	778
E	775	771	773	775	775	776	777	774	778	779	778	779
G	773	745	774	776	777	778	778	779	780	780	780	780
J	776	775	776	777	778	779	780	781	782	782	782	782
L	777	776	776	778	780	782	784	785	786	787	786	787
N	777	777	777	780	785	787	789	791	792	793	794	794
P	776	778	780	784	789	794	797	801	803	806	805	806
R	776	779	783	788	794	802	809	814	818	819	820	821
T	780	782	784	793	803	813	822	829	833	836	836	836
V	782	783	783	798	811	823	834	841	846	848	849	849
X	784	785	792	804	818	832	842	849	854	856	857	857
Z	784	787	794	806	822	834	845	851	856	858	859	859

PROBLEM. NORMAL FLOW WITH CIRCULATION.

MODEL SIZE. SWEPT BACK 9 MESH UNITS SEMI-SPAN. 6 MESH UNITS CHORD, UNIFORM VOLTAGE OF 1·000 AT TIER 9.

TIER Nº 7

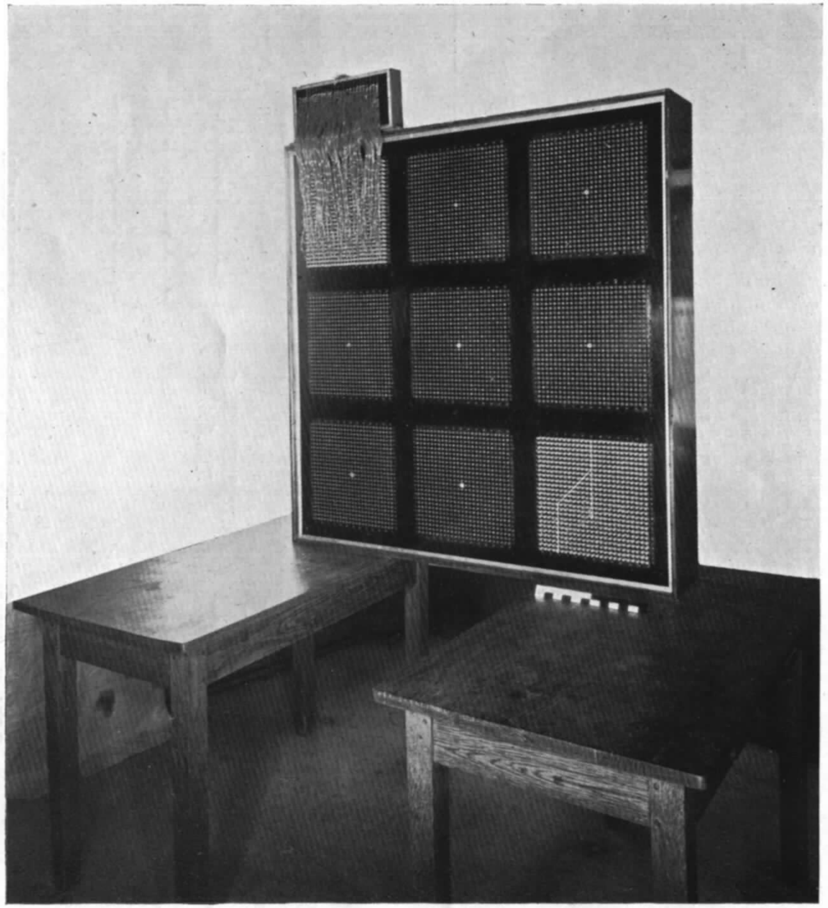


FIG. 1. General view of potential analyser.

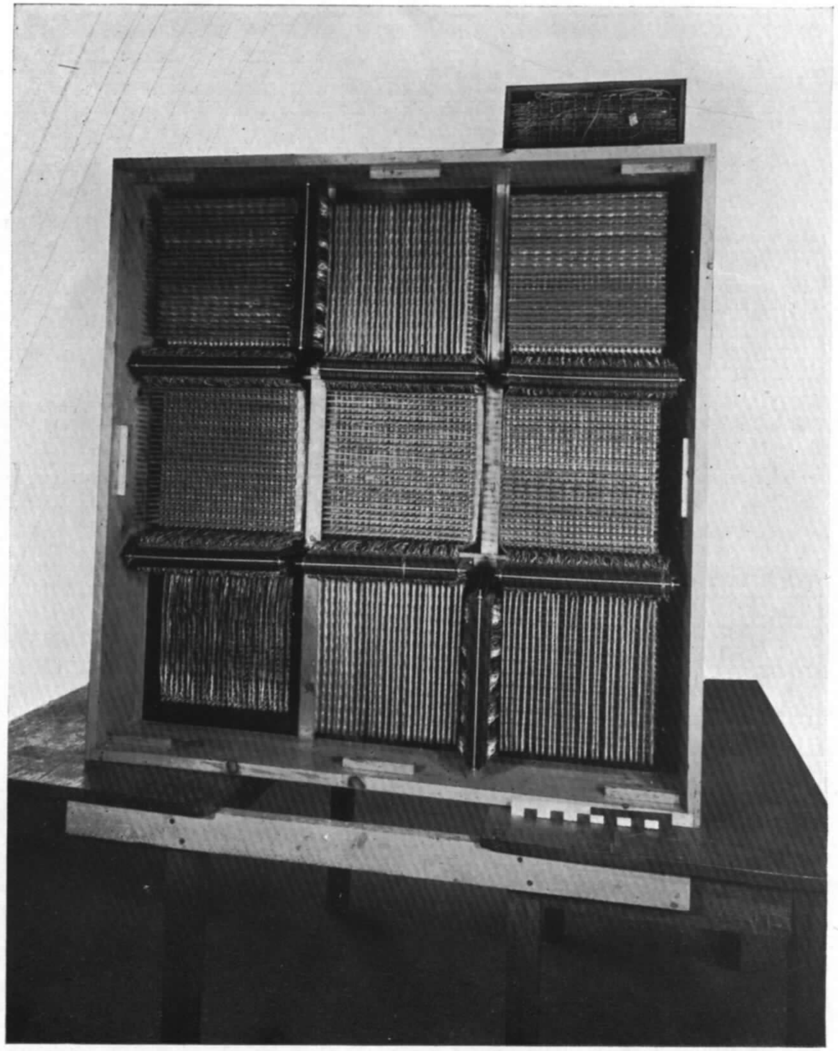
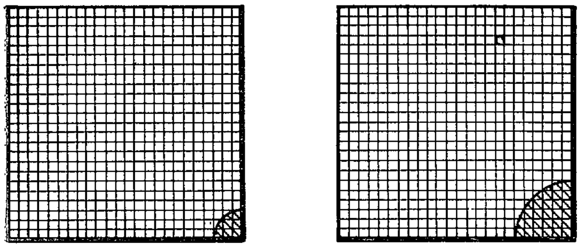
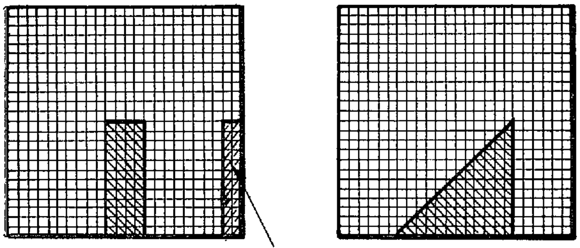


FIG. 2. Rear view of potential analyser.



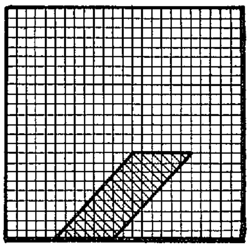
CIRCULAR LAMINA. CIRCULAR LAMINA.



RECTANGULAR WING ASPECT RATIO 6.

SET UP FOR FLOW WITHOUT CIRCULATION.

DELTA WING ASPECT RATIO 4.



SWEPT BACK WING. ASPECT RATIO 3.

FIG. 3. Model sizes.

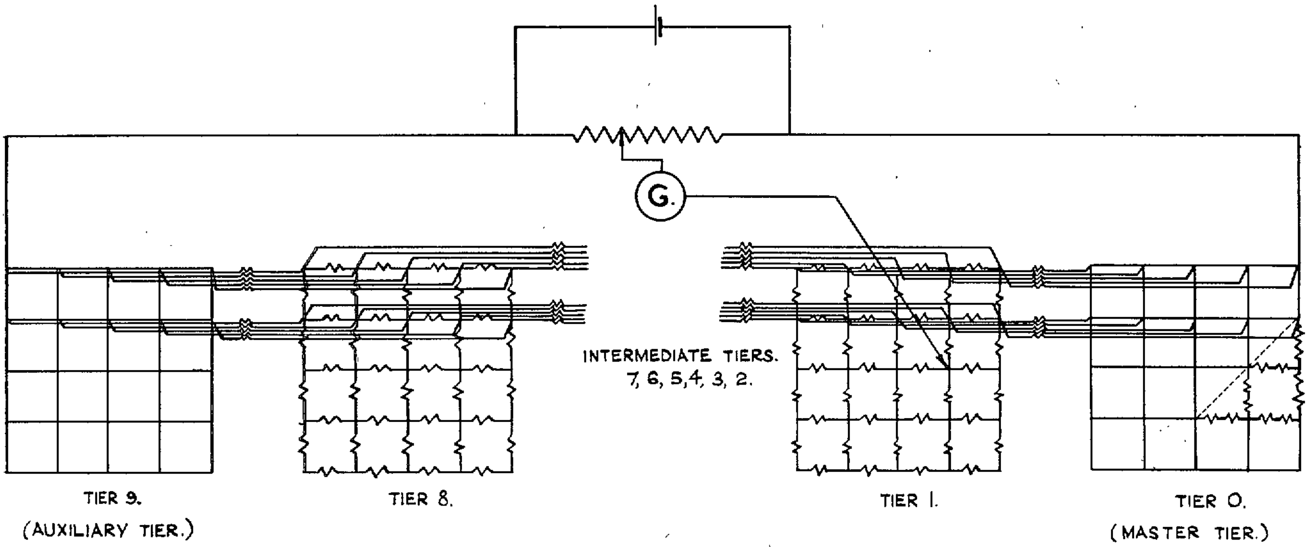


FIG. 4. Electrical circuit for analyser experiments.

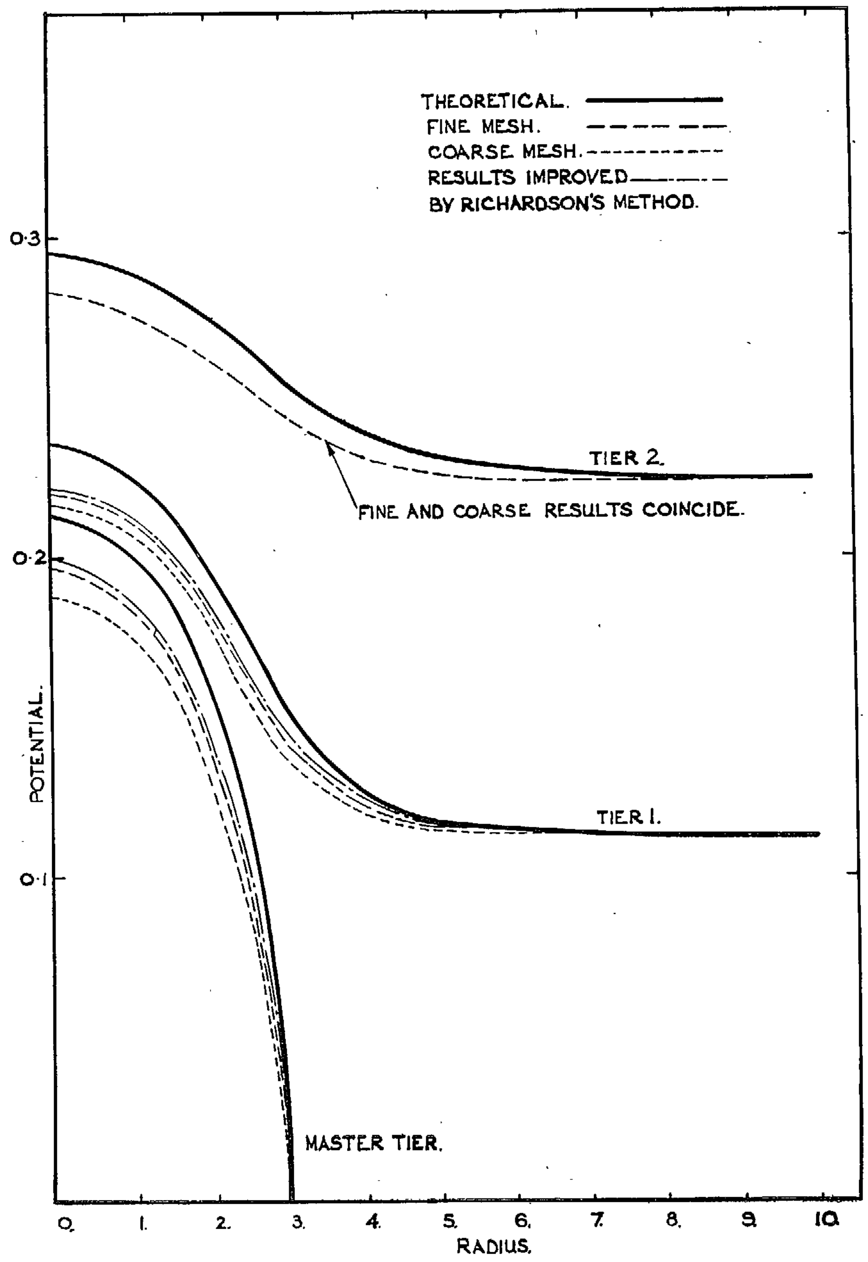


FIG. 5. Results of circular-disc experiments.

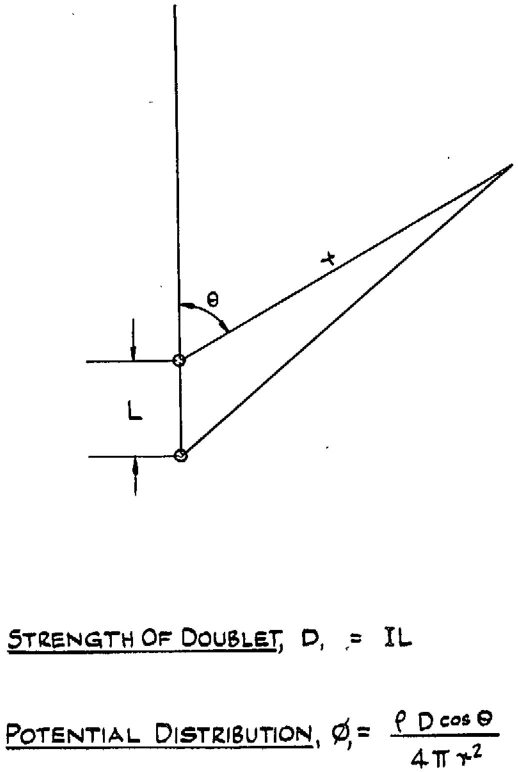


FIG. 6. Potential distribution due to doublet strength.

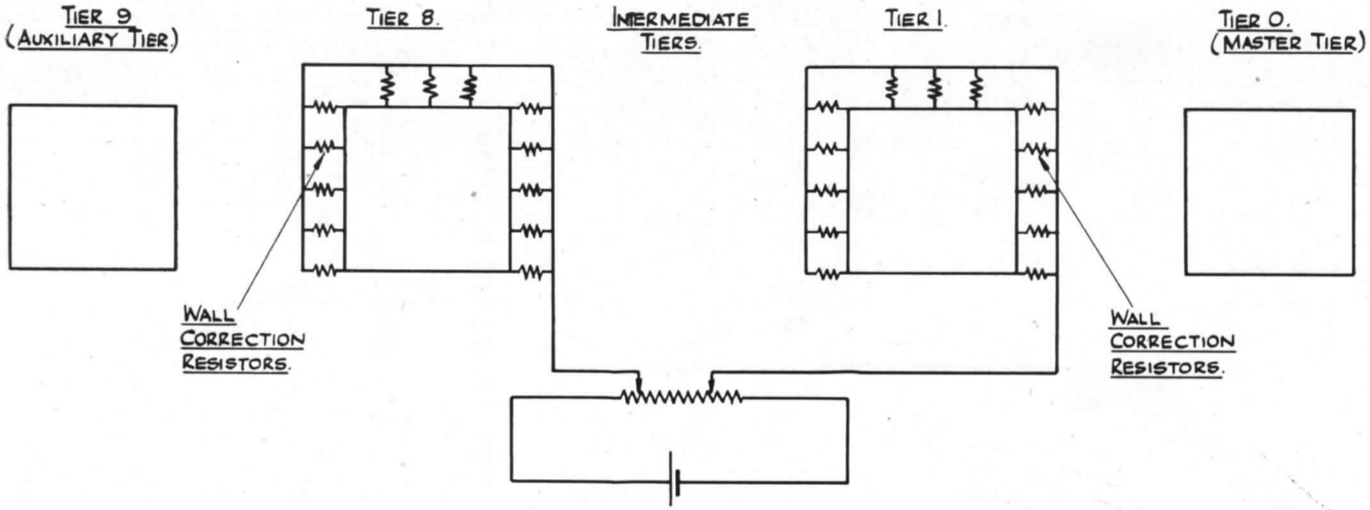


FIG. 7. Electrical circuit for channel wall resistors.

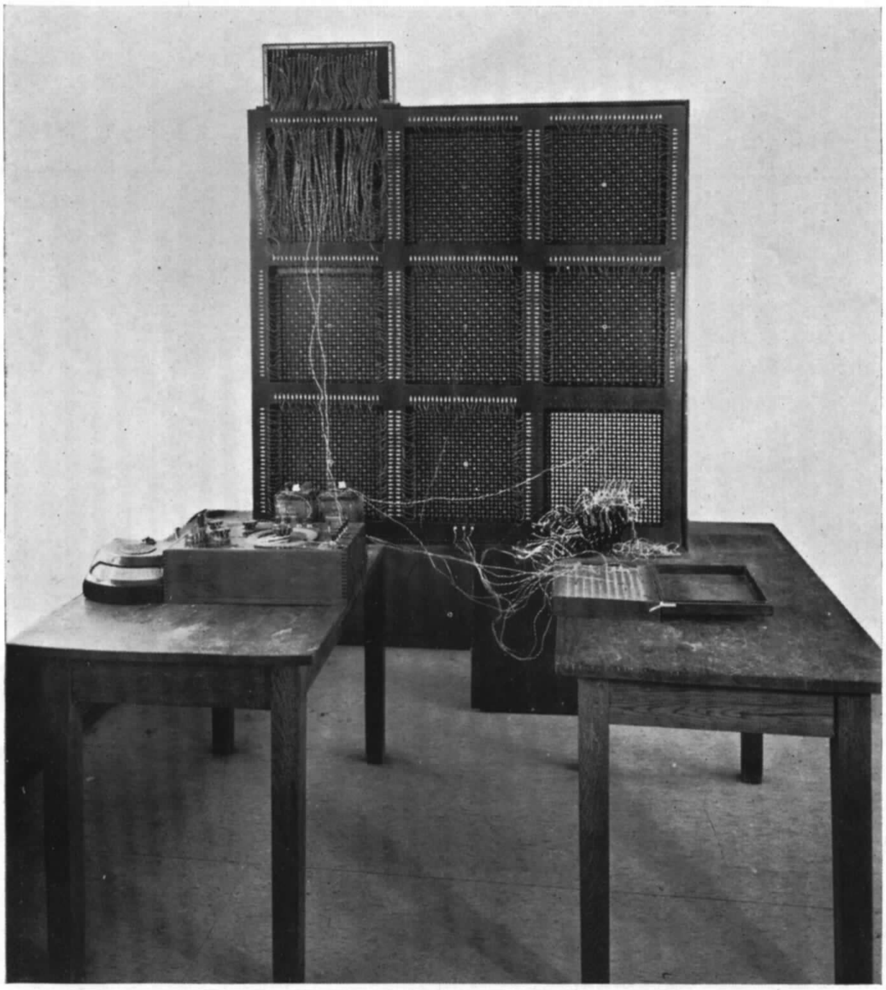


FIG. 8. Potential analyser set up for an experiment.

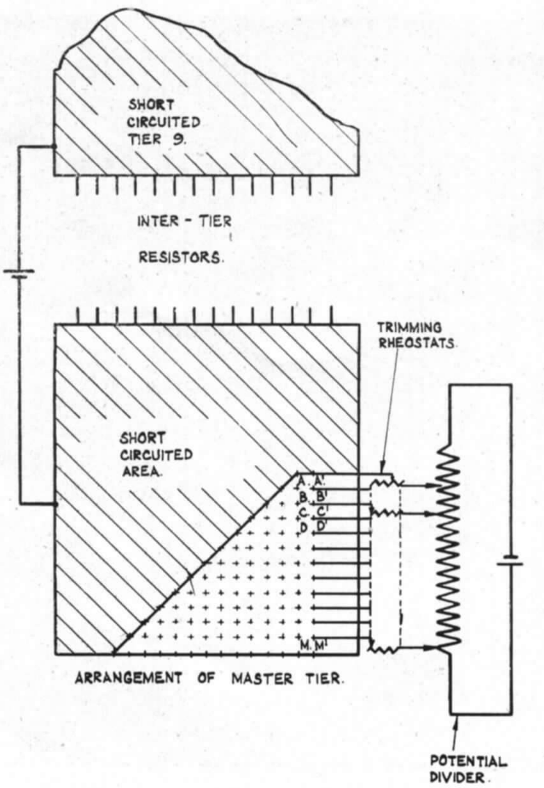


FIG. 9. Electrical circuit for flow with circulation.

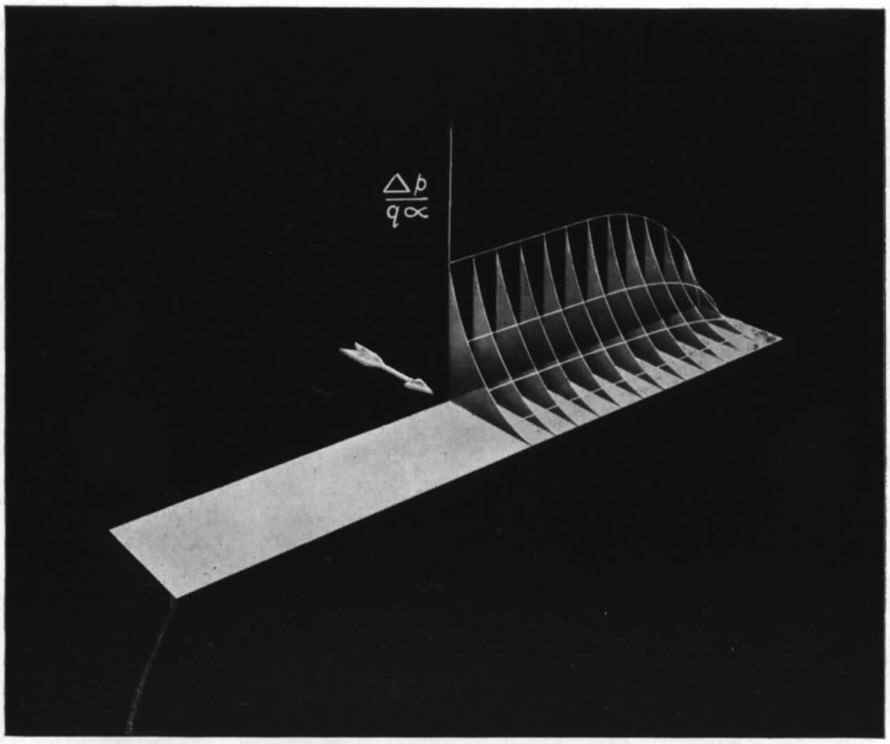


FIG. 10. Pressure distribution over rectangular wing.

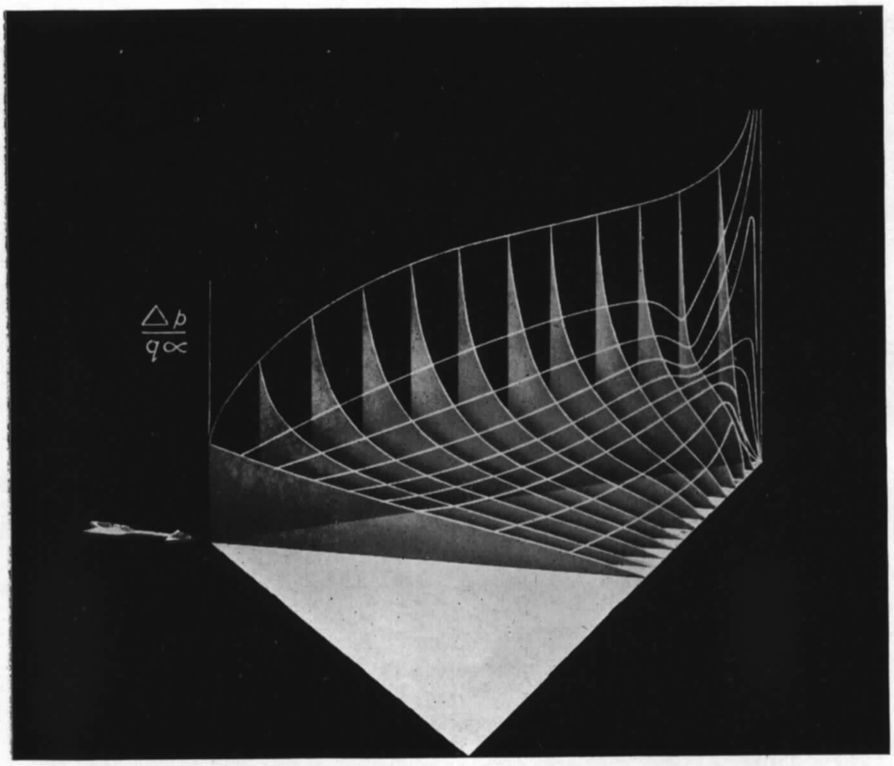


FIG. 11. Pressure distribution over delta wing.

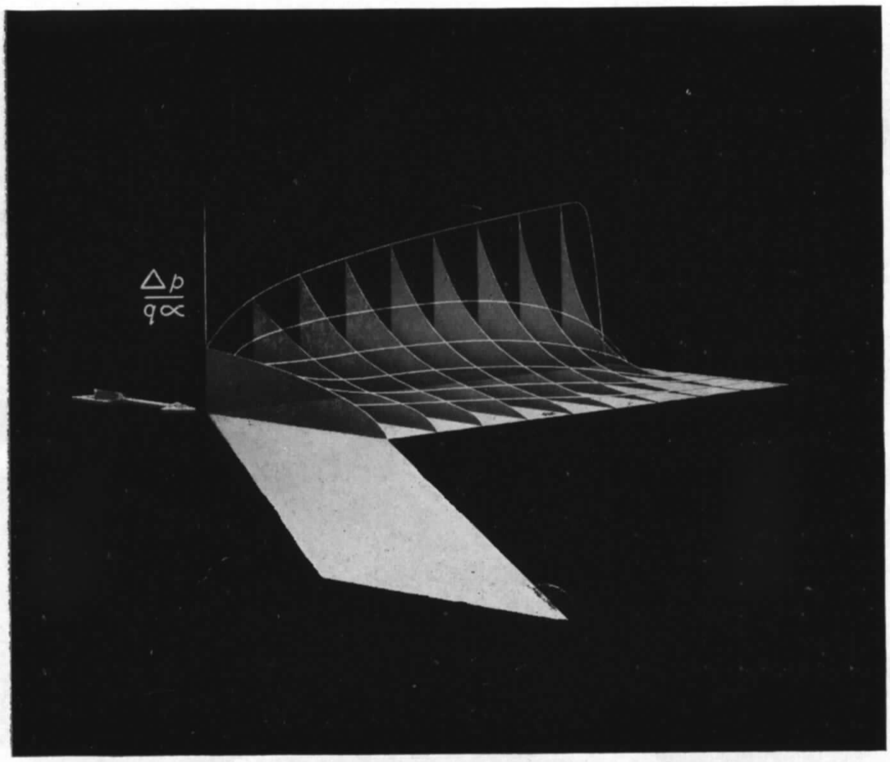


FIG. 12. Pressure distribution over swept-back wing.

J4305 17/680 K9 9/54 D&Co. 34/263

PRINTED IN GREAT BRITAIN

R. & M. No. 2915

Publications of the Aeronautical Research Council

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

1936 Vol. I. Aerodynamics General, Performance, Airscrews, Flutter and Spinning. 40s. (41s. 1d).
Vol. II. Stability and Control, Structures, Seaplanes, Engines, etc. 50s. (51s. 1d.)
1937 Vol. I. Aerodynamics General, Performance, Airscrews, Flutter and Spinning. 40s. (41s. 1d.)
Vol. II. Stability and Control, Structures, Seaplanes, Engines, etc. 60s. (61s. 1d.)
1938 Vol. I. Aerodynamics General, Performance, Airscrews. 50s. (51s. 1d.)
Vol. II. Stability and Control, Flutter, Structures, Seaplanes, Wind Tunnels, Materials. 30s. (31s. 1d.)
1939 Vol. I. Aerodynamics General, Performance, Airscrews, Engines. 50s. (51s. 1d.)
Vol. II. Stability and Control, Flutter and Vibration, Instruments, Structures, Seaplanes, etc. 63s. (64s. 2d.)
1940 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Icing, Stability and Control, Structures, and a miscellaneous section. 50s. (51s. 1d.)
1941 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Stability and Control, Structures. 63s. (64s. 2d.)
1942 Vol. I. Aero and Hydrodynamics, Aerofoils, Airscrews, Engines. 75s. (76s. 3d.)
Vol. II. Noise, Parachutes, Stability and Control, Structures, Vibration, Wind Tunnels. 47s. 6d. (48s. 7d.)
1943 Vol. I. Aerodynamics, Aerofoils, Airscrews, 80s. (81s. 4d.)
Vol. II. Engines, Flutter, Materials, Parachutes, Performance, Stability and Control, Structures. 90s. (91s. 6d.)
1944 Vol. I. Aero and Hydrodynamics, Aerofoils, Aircraft, Airscrews, Controls. 84s. (85s. 8d.)
Vol. II. Flutter and Vibration, Materials, Miscellaneous, Navigation, Parachutes, Performance, Plates, and Panels, Stability, Structures, Test Equipment, Wind Tunnels. 84s. (85s. 8d.)

ANNUAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL—

1933–34	1s. 6d. (1s. 8d.)	1937	2s. (2s. 2d.)
1934–35	1s. 6d. (1s. 8d.)	1938	1s. 6d. (1s. 8d.)
April 1, 1935 to Dec. 31, 1936.	4s. (4s. 4d.)	1939–48	3s. (3s. 2d.)

INDEX TO ALL REPORTS AND MEMORANDA PUBLISHED IN THE ANNUAL TECHNICAL REPORTS, AND SEPARATELY—

April, 1950 - - - -	R. & M. No. 2600.	2s. 6d. (2s. 7½d.)

AUTHOR INDEX TO ALL REPORTS AND MEMORANDA OF THE AERONAUTICAL RESEARCH COUNCIL—

1909–1949 - - - - -	R. & M. No. 2570.	15s. (15s. 3d.)

INDEXES TO THE TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL—

December 1, 1936 — June 30, 1939.	R. & M. No. 1850.	1s. 3d. (1s. 4½d.)
July 1, 1939 — June 30, 1945.	R. & M. No. 1950.	1s. (1s. 1½d.)
July 1, 1945 — June 30, 1946.	R. & M. No. 2050.	1s. (1s. 1½d.)
July 1, 1946 — December 31, 1946.	R. & M. No. 2150.	1s. 3d. (1s. 4½d.)
January 1, 1947 — June 30, 1947.	R. & M. No. 2250.	1s. 3d. (1s. 4½d.)
July, 1951 - - - -	R. & M. No. 2350.	1s. 9d. (1s. 10½d.)

Prices in brackets include postage.

Obtainable from

HER MAJESTY'S STATIONERY OFFICE

York House, Kingsway, London W.C.2 ; 423 Oxford Street, London W.1 (Post Orders : P.O. Box No. 569, London S.E.1) ; 13A Castle Street, Edinburgh 2 ; 39 King Street, Manchester 2 ; 2 Edmund Street, Birmingham 3 ; 1 St. Andrew's Crescent, Cardiff ; Tower Lane, Bristol 1 ; 80 Chichester Street, Belfast OR THROUGH ANY BOOKSELLER

S.O. Code No. 23-2915

R. & M. No. 2915