R. & M. No. 3212

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MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1961
NINE SHILLINGS NET

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*Reports and Memoranda No. 3212**
October, 1958

Summary. The object of this investigation was the design of a supersonic wind tunnel for use in determining the internal flow in engine intakes between Mach 1·5 and Mach 3 and in ranges of pitch (± 15 deg) and engine mass flow experienced in flight. It was shown that from a theoretical standpoint an open jet tunnel was the most effective for this particular purpose provided that its aerodynamic efficiency was comparable with that of any alternative type. Little data on this last point was available so that experimental work was required to confirm the above choice. As preliminary tests showed that an efficient open jet tunnel was indeed possible, the experimental work was continued and an effective tunnel arrangement consisting of a simple variable Mach number effuser and variable geometry diffuser was developed.

This development work originally concerned the design of a practicable high-speed cell for an Engine Test Facility[1] and only later, using data accumulated in this investigation, a 6 in. × 6 in. tunnel capable of testing a 4 in. diameter inlet was constructed. A brief description of this tunnel is given.

1.0. *Introduction.* At the present time, the usual method of estimating the performance of an engine in combination with a supersonic intake is by calculation from the known engine performance and the performance of the intake as measured in tests on a scale model. In time, techniques and facilities may become available for the testing of the whole installation, in much the same manner as ramjets are tested at the moment, but even so test work on model intakes will still provide a majority of the data in the design and development stages. Thus there is a continuing demand for tunnels in which this type of work can be performed.

Tests on intakes are generally performed in tunnels designed for general aerodynamic work which in most cases means that the size of model which can be tested in a given size of tunnel is limited because of wall interference or choking. This limitation is less stringent for the tunnel described in this Report: for example, an intake of area one-third of that of the tunnel nozzle or effuser can be tested under any flow conditions likely to be met in flight.

Full utilization of the tunnel working-section area was an important factor in this design because the maximum working-section size, as determined by the dry air and suction capacity available, was 6 in. × 6 in. and it is probable that future models incorporating variable intake geometry and blow-off flaps would have to be at least 4 in. diameter.

*Previously issued as N.G.T.E. Report 229—A.R.C. 20,758.

A summary of the investigation which was necessary before the design work could proceed and a description of the final tunnel are given in this Report. The former was part of a design study for an Engine Test Facility high-speed cell.

2.0. *Some General Observations on Tunnel Design.* 2.1. *The Basic Tunnel.* The choice of tunnel design is mainly between a closed and a free jet one. Others such as those using perforated or slotted walls have no special advantage, as is shown later. Published data[2] indicates that the closed jet tunnel is generally appreciably more efficient than is an open jet one, from which fact it follows that a larger closed jet tunnel can be run from a given suction supply than an open jet one. However, the data of Reference 2 is for tunnels in which the model drag is insignificant, whereas for the type of tunnel now under consideration this is definitely not so. It is an obvious practical requirement that the tunnel should be able to test intakes inclined to the airstream at up to, say, 15 deg in either direction. In the case of a closed jet tunnel, this means that provision must be made for the pitching of the intake and nacelle with respect to the tunnel proper, which provision necessitates the mounting of the nacelle within a conical airshield with the intake projecting at the apex. The blockage caused by this shield would be expected to cause large losses in the airstream passing around the intake. On the other hand, with an open jet tunnel, the inlet and nacelle can be fixed with respect to the diffusing system and only the effuser need be pitched. This means that the flow path around the model can be made much cleaner than for the closed jet tunnel, and therefore high efficiencies can be more readily achieved, especially at low pitch angles. Therefore, the data in Reference 2 will not apply to the type of tunnel under consideration and it is quite possible that a free jet tunnel may be the most efficient.

However, the above arrangement makes the provision of a good aerodynamic entry to the effuser difficult, so that the airstream turbulence will tend to be higher than in an equivalent closed jet tunnel. Generally this is of no importance, but if large regions of laminar flow exist under full-scale conditions then a high airstream turbulence level may cause the results to be misleading.

It is well known that as the pressure ratio across a correctly proportioned supersonic wind tunnel is increased, a shock will move downstream from the effuser throat, past the model, and into the diffuser. On the other hand, if the total flow area in the region of the model is too small, the shock will be stabilized before the model, so giving effectively subsonic flow. Clearly then, it is important that the blockage caused by the model should be small enough to allow the supersonic flow to be established at the lowest test Mach number. Using the well-known method of calculating the maximum allowable contraction in a tunnel[2], the curve of Fig. 1 was determined. The particular example considered is one in which a conical centre-body intake of inlet area one-third that of the effuser is mounted in a closed jet tunnel wherein the cross-sectional area was constant up to the plane of the intake lip, and the figures as given neglect any viscous effects. It can be seen from Fig. 1 that it will not be possible to establish the flow at Mach numbers lower than $1 \cdot 9$, and as viscous effects invariably make things worse, starting at low Mach numbers will always be problematical. Of course, if the intake is mounted in a free jet tunnel rather than a closed jet one, the supersonic flow must always be established because of the absence of any flow area restriction around the intake.

For the results from model tests in a tunnel to be applicable to an intake in free flight, it is obvious that the airflow patterns in the two cases must be similar. This means, in general, that reflections from the walls and jet boundary of disturbances from the centre-body, etc. should not affect the flow entering the intake. Because there are marked differences between the shock reflection characteristics of a free and a closed jet tunnel, it might be expected that one should be superior to the other on this score, and this, in fact, was found to be so.

In a free jet tunnel, a shock reaching the boundary will be reflected as an expansion wave (Fig. 2a), for clearly a pressure rise cannot exist along the jet edge. On the other hand, in a closed jet tunnel arranged as in Fig. 2b, a shock will be reflected as a shock, and for the shocks met in intake testing, the pressure rise at the wall will generally cause a considerable boundary-layer disturbance (Fig. 2c), and in many cases too it will be found that a Mach shock will occur at the reflection (Fig. 2d). As the inclination of a shock is less than the forward edge of an expansion wave, *i.e.*, $\sin^{-1}$ (1/Mach number), interference with the intake flow by a reflected disturbance is much more probable in a closed jet tunnel than in an open one. The other effects mentioned, boundary-layer disturbance and the presence of a Mach shock, both tend to make this difference greater.

An open jet tunnel has the added advantage, discussed earlier, that the intake can be inclined with respect to the air stream by pitching the effuser so that the model can remain fixed during tests, thereby simplifying the instrumentation problem. Additionally, provision for the observation of the flow into the intake is facilitated because there is no necessity to fit the windows flush with the inner surface of the tunnel.

As mentioned earlier, it is not advantageous to use slotted or perforated walls in this type of tunnel even though they are widely used in transonic tunnels to reduce wall interference effects. The reason is that these walls only partially cancel impinging shocks, so that although the returning shock is weaker than that from a corresponding solid wall, the inclination of the shock is still less than in the case of an open jet, and therefore interference with the intake flow is more likely.

A semi-open jet tunnel, having two enclosing walls, has the advantage that the establishment of the supersonic flow is always assured, but interference by shock reflections from the solid walls is as in a closed jet tunnel. Therefore, it appears that the open jet tunnel is the most suitable type for intake testing purposes.

2.2. *Model Size.* Thus, and because early work on a variable Mach number effuser showed considerable promise (Section 4.0), all further analysis was based on the assumption that the intake would be mounted within a square section supersonic jet.

In practice, it is quite probable that the maximum size of model which can be tested in a tunnel will be limited by the available driving pressure ratio, but in the design stage it is more important to know the order of the ratio of jet size to model size necessary to avoid interference caused by shock reflections. There are three major variables which affect this ratio: the flow Mach number, the pitch or yaw, and the quantity of air passing through the intake. It is difficult to calculate the effect of all these variables in combination, so the effects of Mach number with pitch or yaw and Mach number with airflow will be considered independently.

Obviously it would be neither practical nor necessary at this stage to calculate the required ratio of jet size to model size for every conceivable intake design. Rather, all that is required are figures for a typical example. To study the effect of Mach number and pitch or yaw in combination, a conical centre-body intake designed for $M = 2 \cdot 5$ was considered (Fig. 3). The angles of the shocks from the centre-body were determined using Reference 3, and then the jet boundary was so proportioned that the leading edge of the expansion wave just intersected the intake lip. This calculation was repeated at yaw angles of 0 deg, 5 deg, 10 deg and 15 deg and several free-stream Mach numbers. From the resulting figures, it was found that the point about which the nozzle should be pitched so as to give the minimum ratio of jet size to model size is a little upstream of the plane of the intake lip (Fig. 3). In practice, however, it is probable that the effuser will be positioned by a linkage system, *e.g.*, *see* Fig. 16, with which arrangement the point of intersection of the tunnel and the effuser centre-lines will vary with pitch angle. Thus a knowledge of the precise position of the optimum pivot line is of little practical value.

Also calculated was the ratio of the maximum intake diameter to the jet width, and this data is given in Fig. 3 as a function of both pitch and Mach number. It will be seen that the angle of pitch has less effect on the ratio of the maximum intake size to jet diameter than has Mach number. Also noted on this figure is the value of intake area/jet area which was later chosen as a suitable compromise between intake size and the need for good flow simulation. It can be seen that with this proposed 'standard' intake size, flight simulation is achieved at all Mach numbers and angles of pitch.

Before considering the effect of the intake flow on the required ratio of the intake to jet area, it is obviously desirable to make an estimate of the flow changes expected in practice. Whilst a propulsive unit—ramjet or a turbojet—is operating normally, the quantity of air spilled round the lip of its intake would, by design, be small so that only malfunctioning could cause any appreciable spilling of the flow. With a ramjet, a small amount of intake spill can result if the rate of burning of fuel is excessive, but if the combustion is extinguished, the intake will operate supercritically with no spill. With a turbojet however, if combustion is extinguished, the engine will windmill and pass only about 60 per cent of its full flow. Thus, it might be argued that tests may have to be made with as little as 60 per cent of the design flow. However, aircraft will no doubt be provided with blow-off flaps so that in such an event the surplus air can be by-passed to avoid intake flow instability. Thus it is reasonable to assume that a test with the intake passing as little as 60 per cent of the normal flow will be an exception, and that a more usual figure will be 80 to 90 per cent.

The determination of the shock configuration before a centre-body intake when not accepting its normal flow is difficult, but for a pitot intake it is quite straightforward. However, since the pitot intake results usually underestimate the centre-body intake size that can be tested in a given tunnel, it is an adequately safe criterion.

The shape of the shock before a pitot intake was determined by the method of Reference 4, and the minimum size of jet which could just enclose the transonic part of the bow shock was calculated, the results being given in Fig. 4. It will be seen that intake flow is much more important than pitch, and at low Mach numbers with 60 per cent of the design flow, the model simulation will be imperfect with the proposed intake size. On the other hand, if the relative mass flow is 90 per cent, aerodynamic simulation is correct down to $1 \cdot 4$ Mach number.

It can be concluded, therefore, that for most practical test conditions flow simulation into the intake will be satisfactory with the intake diameter proposed for the final tunnel, namely $0 \cdot 67$ times the width of the effuser, but if tests are contemplated at low flows at low Mach numbers, it will be necessary to use a smaller intake.

Of course, this conclusion applies strictly to axially symmetric intakes only, and some slight modification may be necessary when applying the data to, say, two-dimensional intakes.

2.3. *Working-Section Design.* At about the time experimental work on this tunnel was started, it was learnt that a simple design of variable Mach number effuser had been developed in the U.S.A.[5]. Since such an effuser was potentially more useful than the alternative, a series of fixed effusers, as well as probably being cheaper, work was initiated on a similar device for this tunnel. That the jet of air in which the model was to be placed would have to be square was not considered a disadvantage, because the tunnel diffuser would, in any case, have two-dimensionally variable geometry to accommodate any changes in airflow by-passing the intake. Of course, when testing an axially symmetric intake in a square jet tunnel the jet corners are wasted, but this may not be so for intakes of the letterbox variety.

Early diffuser tests showed that the most effective arrangement was one in which, to obtain the required pitch angle, the effuser only was tilted, which lay-out enables changes in yaw to be made easily whilst the tunnel is operating and also simplifies the instrumentation problem.

3.0. *Effuser*. 3.1. *Design and Performance.* Some time after this variable effuser had been started at the National Gas Turbine Establishment, details were published[6] of the design and performance of an almost identical effuser which had been developed in Sweden. The general form of this type of effuser is shown in Fig. 5 and it consists of a pair of pivoted rigid sections attached to a pair of flexible walls, the other ends of which are constrained in an axial direction at the effuser exit. The Mach number is thus changed by jacking the rigid sections in and out in the manner indicated.

The design and development of this effuser is discussed in detail in Reference 7. The most successful development, that of Fig. 5, gave the Mach number distribution of Fig. 7. It can be seen that the flow uniformity in the region where an intake would be mounted was good, even though there was some asymmetry of the flow due to unavoidable inaccuracies in the manufacture and assembly.

3.2. *Mechanical Design.* The only parts requiring special care in the mechanical design of the effuser are the flexible plates. These are stressed by two loads, that which elastically deflects the wall to its required shape, and the differential air pressure. The stress due to bending the plates can readily be calculated by well-known methods and, as an example of the stresses involved, Fig. 8 gives the results for the effuser of the final 6 in. tunnel whose dimensions were scaled from Fig. 5 (except for the wall thickness which was made $0 \cdot 15$ in.).

Although the air loading across the plates and the consequent stress can be calculated fairly easily when the jet issuing from the effuser is parallel, the data is of little practical value because this load is negligible compared with that which occurs during the starting or stopping of the tunnel. These intermittent loads could not be determined theoretically, so the necessary tests were made on a suitably instrumented wooden replica of the effuser. From the airloads thus determined, the stresses were calculated. These tests were all made at about the upper limit of the Mach range where the total stress, bending plus air load, was a maximum. Fig. 9 illustrates the values calculated for the 6 in. square nozzle at Mach $2 \cdot 8$.

Because both the bending stress and air-load stress are functions of the plate thickness, the former being proportional to the thickness and the latter to its inverse squared, there must be an optimum thickness with the least total stress. This can easily be shown to be that thickness at which the bending stress is twice the air-load stress, but this is rather an oversimplification of the problem, as fatigue and impulse loading factors should also be considered.

3.3. *Manufacturing Tolerances.* To keep the effect on the airflow of manufacturing tolerances well within the $\pm$ 1 per cent Mach number limit and yet minimize costs, some theoretical study was obviously desirable. Most of the flow deviations due to manufacturing inaccuracy are caused directly by waviness in the side walls and flexible plates and, fortunately, most of these effects are readily calculable.

Taking a simplified case in which the waviness is in the direction of flow, and is sinusoidal, the variation in surface angle can be readily shown to be $\pm 180a/\lambda$, where a is the peak to trough amplitude and λ is the wavelength.

This slope variation along the wall will produce on the airstream an approximately sinusoidal Mach number variation in the direction of flow. At some point in the working section, it is not inconceivable that the flow variations caused by all four walls might be additive, so that the total variation is four times that of one wall alone, but this condition is so unlikely to be found in practice that is is neglected in the following example.

From tables of the properties of supersonic flow, it will be found that the largest percentage flow variation due to a given change in flow angle occurs at the lowest Mach number; in this case at Mach $1 \cdot 5$, where a $\pm$ 1 per cent change in Mach number is caused by a $\pm 0 \cdot 45$ deg change in angle. Combining this information with the previous formula, it is found that

$$a/\lambda < 0 \cdot 0025.$$

For the effect of wall waviness to be negligible compared with the approximate nature of the aerodynamic shape of the effuser, a suitable tolerance would be about one-tenth that given by the above equation.

As might have been anticipated, short wavelength waviness is the more important, but this fact involves no technical manufacturing difficulty because most machining operations are such as to make this type of inaccuracy unlikely.

In addition to the surface waviness of the side walls, a discrepancy in the effuser shape is possible if the flexible plate is non-uniform. Some indication of the order of this effect can be obtained by the consideration of two idealized cases: a linear taper, and a sinusoidal thickness variation. It can be shown that, to a first order, a linear taper in plate thickness does not introduce error, which fact emphasizes the similarity between this effuser and that of Reference 5.

However, if the beam thickness varies in a sinusoidal fashion, it is found that there is a difference between the ideal and the actual flexed shape of the beam. This difference gives rise to angular errors of

$$\pm 0 \cdot 24 \frac{\Delta T}{T} \frac{\lambda}{L} \theta \text{ provided } \lambda \leqslant L$$

where ΔT is the variation in beam thickness,

T the mean beam thickness,

λ the wavelength of the thickness variations,

L the length of the beam,

and θ is the angular deflection of the beam

(this formula being a first order approximation for a beam flexed by a bending moment only).

For example, the 6 in. effuser, which has a flexible plate $0 \cdot 15$ in. thick (T) and at a deflection of $9 \cdot 9$ deg (θ), gives a flow Mach number of $2 \cdot 8$. Assuming machining errors have a wavelength (λ) of half the length of the plate (L), the angular error $= \pm 7 \cdot 27 \Delta T$.

At $M = 2 \cdot 8$, the change in flow angle to cause a ± 1 per cent change in Mach number is $\pm 0 \cdot 57$ deg, so that $\Delta T < 0 \cdot 0783$ in.

Obviously it is very simple to machine the plate so that the thickness variations are less than one tenth this figure.

Another practical problem is what effect will wall scratches and steps etc. have on the flow from the effuser? Theoretical estimates can be made only if the step or scratch spans the whole side wall and is normal to the flow, but this is unlikely in practice and so the following estimates can be taken only as a rough guide. It has been shown[8] that the fractional static pressure increase in supersonic flow due to a step in the wall profile is $1 \cdot 81 \sqrt{(h/y)}$, where h is the height of the step and y is the normal distance from the wall to the point in the flow at the variation being measured.

As with surface waviness, the effects are greatest at the lowest Mach number, namely $1 \cdot 5$. Inserting the Mach number variation with pressure, it follows that

$$h/y = 5 \cdot 9 \times 10^{-6}$$

for a 2 per cent Mach number change (*i.e.*, + 1 per cent to − 1 per cent). 'y' will range from 0 to 6 in. (or larger for disturbances reflected by the walls) so that the permissible step height on the effuser working surfaces is extremely small. However, the three-dimensional effects mentioned earlier and the cushioning effect of the wall boundary layer will no doubt modify the above requirement considerably, but even so, it is clear that the working surfaces of the effuser should be polished and, as far as possible, free from scratches or steps.

Summarizing the above conclusions, it can be stated that it is most important to machine the working parts of the nozzle to give a flat smooth surface, and that variations in thickness of the flexible plate will have comparatively little effect on the aerodynamic performance.

4.0. *Development of the Tunnel Diffuser.* In all the model tunnels tested, dry air at atmospheric pressure was sucked through a fixed Mach number effuser to produce the supersonic jet in which an intake was mounted. Part of this air passes into the intake and is efficiently diffused, but the greater portion is by-passed and its energy is recovered in what is generally termed the 'spill diffuser'. As it was found during the course of experimentation that sucking a small fraction of the air (termed 'bleed air') from the plenum chamber around the jet improved the pressure recovery, the final arrangement had three air outlets—the bleed pipe, the intake outlet and the spill diffuser outlet. For practical reasons, the last two were arranged in these experiments to discharge ultimately into a common duct.

Two exhausting systems were available for operating the tunnels: ejectors driven by compressed air being the main one, and the other being a pair of mechanical exhausters for the bleed circuit. As the bleed air pressure was at that of the effuser exit, it was found necessary to fit (between the tunnel and the exhausters) an ejector driven by atmospheric air. However, even with this arrangement, it was difficult to create the necessary depression for sucking above Mach 3, so if the working range of the tunnel is extended, either an alternative source of power or the omission of the 'bleed' circuit may be necessary.

In an endeavour to develop the most efficient layout many tunnels were constructed and tested, but one proved far better than the rest, so it is with this type and its performance that the following Sections are concerned.

4.1. *Description of Tunnel Arrangement.* A sketch of the working parts of the tunnel in which the development tests were made, showing the arrangement of the diffusing passages and inlet, is given on Fig. 11. It will be seen that the test intake projects through a central wedge which splits the air spilling round the nacelle into two equal parts, and that the diffusing surfaces are the fixed top and bottom walls, the central wedge and two hinged movable walls. The diffuser thus consists of two identical passages each composed of a long contracting section, a constant area throat, and a diverging section which leads to a fixed geometry subsonic diffuser. Two pairs of jacks are fitted to the tunnel so that the throat and diffuser inlet areas can be adjusted whilst the tunnel is operating; the first set to give the optimum efficiency and the second set to ensure that the jet from the effuser is parallel.

The intake air passes through a pipe embedded in the central wedge to a measuring section and throttle before entering into the main suction ducting.

The effuser in these tests was 3 in. × 3 in. fixed Mach number type and was mounted on a quadrant so that it could be tilted about a centre located on the intake lip. In the experimental set-up, no seals were fitted at the effuser-bulkhead joint, and so each time an adjustment was made, this joint had to be resealed.

4.2. *Tunnel Performance.* Throughout the preliminary experimental work, the same supersonic intake model was installed, as using different designs or sizes could have given misleading comparisons. This model was a conical centre-body type designed for Mach 2·9 and it had an area of one-third that of the effuser exit, so corresponding to the 'value proposed' in Figs. 1, 3 and 4.

The performance of the tunnel, *i.e.*, the minimum pressure ratio at which the plenum chamber pressure and the static pressure at the effuser exit could be balanced, as measured at Mach 1·56, and 2·48 at different angles of pitch and different intake flows, is illustrated in Fig. 12.

From this diagram, it can be seen that decreasing the flow through the intake or increasing the pitch angle increases the pressure ratio required to operate the tunnel, and that these increases are relatively greater at $M = 2\cdot48$ than at $M = 1\cdot56$. The pressure ratio required to operate the tunnel in the absence of pitch and with the intake accepting the full flow is comparable with that of most other wind tunnels[2], so it is reasonable to conclude that this particular configuration is essentially an efficient one, and that only minor improvements are possible. One such improvement was made by extending the adjustable diffuser walls forward until their leading edges were level with the intake lip, for which reason small discrepancies exist between Fig. 12, and later Fig. 15.

Another attempt was made to improve the tunnel performance by pitching the intake nacelle $7\frac{1}{2}$ deg to the tunnel axis, so that the overall pitch range of 0 to 15 deg could be obtained by swinging the effuser $\pm 7\frac{1}{2}$ deg. This scheme proved very satisfactory for axially symmetric intakes as the loss in performance at large pitch angles was substantially reduced. However, with rectangular intakes, it was much worse than the original system, and as it was desirable that only one internal wedge shape should be used in all tests, the scheme had to be abandoned.

The optimum jack positions for a particular set of test conditions were fairly critical so that any change in the model which affected the tunnel efficiency, *i.e.*, an increased pitch angle or reduced intake flow, necessitated the readjustment of both the lip and the throat of the diffuser. Thus the onset of intake instability ('buzz') which is invariably accompanied by a drop in tunnel efficiency, demands a considerable adjustment of the jack settings.

In some circumstances, *e.g.*, in a flight simulation tunnel for engine testing, it may be more practical to adjust the tunnel pressure ratio rather than the jacks to keep the jet from the effuser parallel. To do this, the jacks must be so positioned that the operating pressure ratio over the whole range is a minimum and so some reduction in performance is inevitable. Relevant tests have shown that most practical requirements can be met with an increase in pressure ratio (above the optimum) of about $0 \cdot 1$ at $M = 2 \cdot 48$.

Whilst the tunnel was operating at about zero pitch with the intake accepting its full flow, it was found possible to reduce the throat areas in the diffuser after the flow had been established and so gain a noticeable improvement in the pressure recovery. This property of a supersonic diffuser is of course well known and understood, but the fact that it was found in this diffuser shows that its flow must be fairly smooth despite the disturbance caused by the intake.

Earlier, in Section 2.2, it was shown that exact flow simulation over the whole Mach range $1 \cdot 5$ to 3 could not be achieved with the maximum size of intake accepting only $0 \cdot 6$ maximum flow, so that in certain circumstances smaller intake models will have to be used. Also, it is reasonable to expect that the tunnel will require a smaller driving pressure ratio with a smaller intake, so that either the maximum Mach number of the tunnel with a given driving pressure ratio could be raised, or the intakes tested at a larger pitch. It follows that the effect of intake size on the performance is of considerable practical interest, and a series of tests was therefore made in which the performance was measured with intakes of differing size but identical geometry. These tests showed (Fig. 13) as expected, that the pressure ratio required became smaller as the intake was reduced.

Since all these tests were made with a single design of intake, a conical centre-body type, further work was necessary to ensure that the tunnel performance could be maintained when testing other types of intake. The relevant tests were made with a series of intakes of area one quarter that of the effuser exit and of the following designs: a conical centre-body type designed at $M = 2 \cdot 9$ (as used in the main tests), a conical centre-body type designed at $M = 2 \cdot 34$, an isentropic centre-body type designed at $M = 2 \cdot 9$, and a two-dimensional type designed at $M = 2 \cdot 48$. The test results (Fig. 14) showed that the tunnel performances differed only slightly with the type of intake design, and that, as might have been expected, the variation was in the same sequence as the external drag of the different intakes.

Another subsidiary test series was made to determine how the tunnel performance was affected by changes in the geometry of the wedge which splits the flow round the intake nacelle. Three separate tests were made: one with the original layout, one with the wedge removed entirely and one with a thick blunt wedge. Rather unexpectedly, it was found that the performance of the tunnel without a wedge to split the flow was inferior to the standard design, so showing that the obstruction due to the wedge was more than compensated by the cleaner flow path which it produces. The thicker wedge caused the tunnel performance to fall compared with the standard, which result is quite understandable. The cross-over of the curves on Fig. 15 at large pitch angles is more probably due to the different maximum flow areas in the different builds rather than to aerodynamic changes. In the application of this diffuser design to the 6 in. $\times$ 6 in. tunnel described later, it was imperative that the overall efficiency be as high as possible irrespective of whether this made model instrumentation a little more difficult. Hence a slim wedge centre-body of 12 deg included angle was used, much the same as in the tests just described. If the tunnel were for the test of a full-scale intake engine combination, it would probably be preferable to use a somewhat blunter wedge, as in such an application it would be as well to provide ample room for installing the engine at the expense of tunnel performance.

Certain other minor tests were made, their general aim being to ascertain whether any detailed change in the diffuser would improve the overall performance. It is not proposed to describe these tests in detail as the general conclusion was that the tunnel dimensions as described were for all practical purposes an optimum.

Strictly, before the test figures quoted can be used in the design of a larger tunnel, adjustments must be made to allow for the effects of a change in Reynolds number, and for the effects of adopting a variable effuser rather than the fixed blocks which were used for the working section and diffuser development. From published data, it appears that the correction for the effect of Reynolds number on the performance of a normal supersonic diffuser is quite negligible, but, in the case of a free jet tunnel, allowance must be made for the fact that the boundary-layer flow from the effuser is effectively a negative bleed flow. It will be remembered that the effusers used for the above tests were for a fixed Mach number, and consequently were relatively quite a bit shorter than the variable one used in the 6 in. × 6 in. tunnel. Thus, on this score, the boundary-layer flow in the 6 in. × 6 in. tunnel will be relatively greater than that in the 3 in. × 3 in. tunnel, but this effect will be countered to a small extent by a small increase in Reynolds number. However, a test in which the length of the effuser was extended to simulate the above effect showed that the difference between the minimum operating pressure ratios of the two tunnels should be less than 0·05 at Mach 1·5, and negligible at Mach 2·48.

5.0. *Description of the* 6 *in.* × 6 *in. Tunnel.* This 6 in. × 6 in. tunnel is in the main just a scaled-up version of the 3 in. × 3 in. development version, and the methods of construction are quite conventional, so it is not proposed to describe the tunnel in great detail.

From the photographs Fig. 16 and 17, which were taken during the construction, it will be noted that the variable Mach number supersonic effuser is so supported by a linkage that it can turn about a centre located in the plane of the intake under test. The scantlings are designed so that the effuser can be tilted ± 15 deg to the tunnel axis by two pneumatic jacks. The positioning signal for these jacks is transmitted electrically[9] and a simple follow-up servo-mechanism adjusts the jack operating pressure until the correct angle is attained.

The whole effuser assembly is supported by the front bulkhead so that the front of the tunnel can be removed in one piece to allow free access to the model.

The effuser itself is constructed of two ground mild steel side walls, $\frac{5}{8}$ in. thick, between which are mounted the flexible plates and rigid throat sections as in Fig. 5. In this design, the rigid sections of the effuser are aluminium alloy castings and the flexible plates were machined in an armour-plate steel. The two walls of the effuser operate together by means of motor-operated screw jacks which can be controlled from the same panel as the pitch angle. Since the primary purpose of this 6 in. × 6 in. tunnel is of course the testing of supersonic intakes, high efficiency is required of the spill diffuser not to save power but only to ensure that the available pressure ratio is adequate to run the tunnel. Thus it is unnecessary to position the diffuser jacks for optimum diffuser recovery at every test condition and they will therefore need only an occasional adjustment. For this reason it was not considered necessary to motorize these jacks, which are therefore simply an improved version of the manual ones which were fitted to the 3 in. × 3 in. tunnels.

The wedge centre-body of the spill diffuser was made in two sections with the front part removable so as to facilitate model changes and adjustment. The intake air passes to a 6 in. diameter duct, a diffuser, and a flow-metering contraction before being discharged through an adjustable throttle into the main suction duct.

Throughout this tunnel, the airseals at the many sliding joints comprised $\frac{1}{8}$ in. diameter Neoprene cords recessed in one surface, pressing on the other with a nominal $0 \cdot 01$ in. nip.

The effuser takes dry air from a 3 ft diameter plenum chamber in which are fitted fairings to obviate serious flow separation at the effuser inlet at all pitch angles. At the other end of the tunnel, two ejectors extract the air from the spill diffusers and model and two exhausters supply the suction for the bleed air connection.

6.0. *Conclusion.* The development, design and construction of an advanced type of wind tunnel for the testing of supersonic intakes has been described. As well as the application to small wind tunnels, the data given should be relevant to the design of facilities for the testing of full-scale engines with their proper intakes under simulated flight conditions.

Although not mentioned earlier, it is obvious that the equipment described could also be used for various other types of tunnel work and that some of the data given, especially that on the diffuser and effuser design, may be helpful to the designer of more conventional aerodynamic test rigs.

Acknowledgements. The author wishes to acknowledge the invaluable assistance of Mr. K. E. Blake and Mr. F. W. Meade, both of the de Havilland Engine Co., Ltd., in the design, test and analysis of the spill effuser system; the work by Mr. A. D. Carmichael of the Bristol Engine Co., Ltd., and Dr. J. B. McGarry on the problems associated with the variable Mach number effuser.

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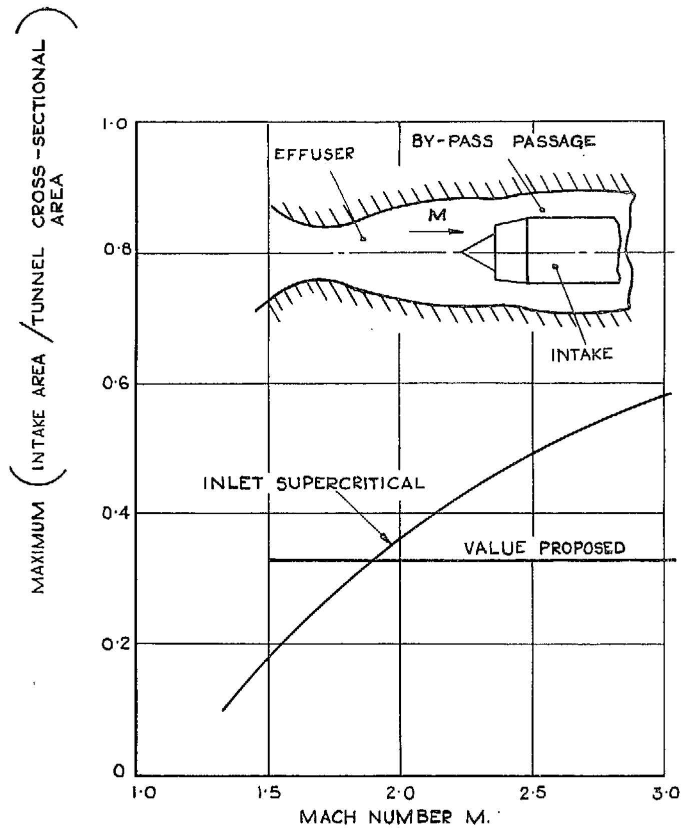

FIG. 1. Limitation of intake size in a closed tunnel.

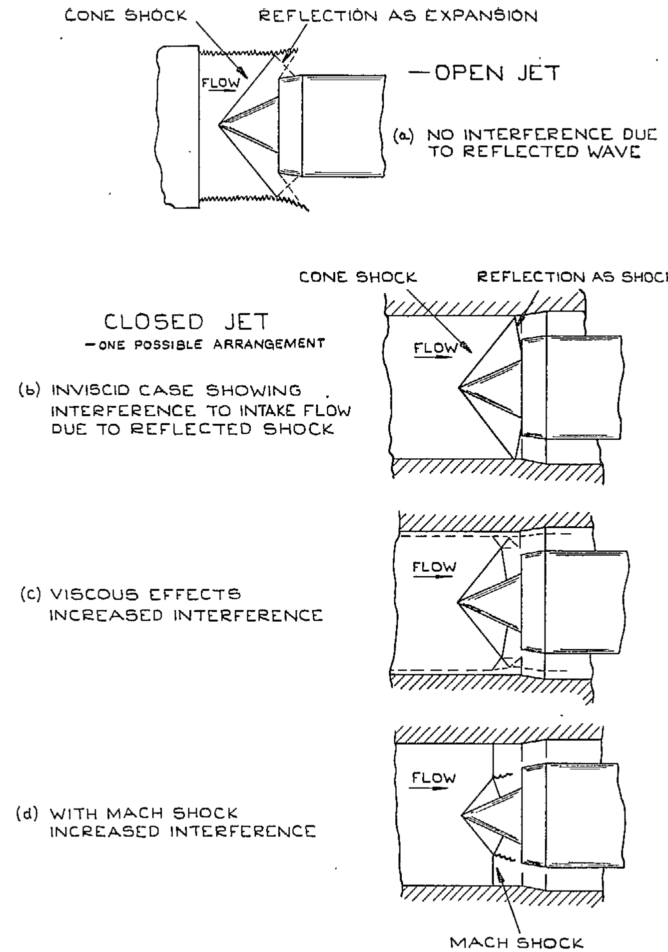

FIG. 2. Shock reflection characteristics of free and closed jet tunnels.

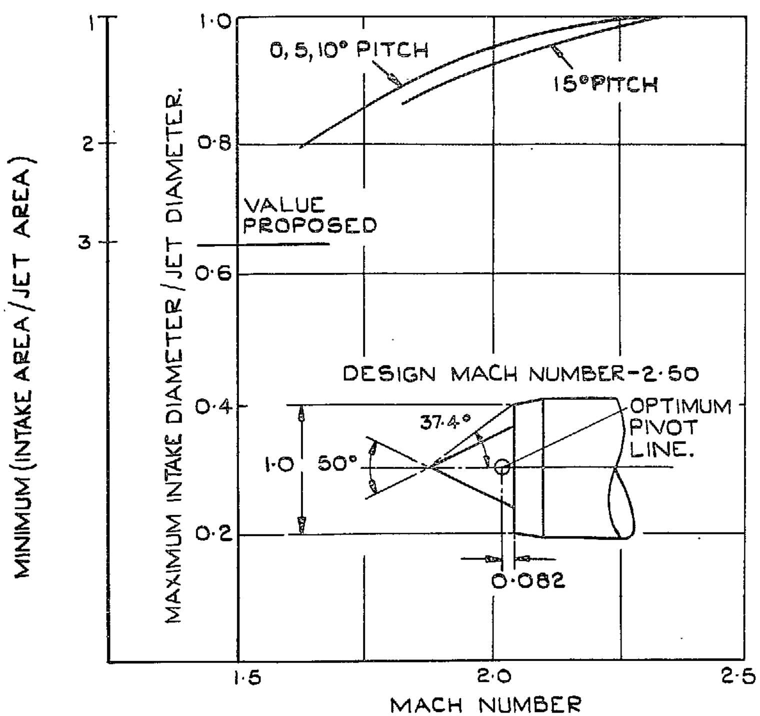

FIG. 3. Pitch and Mach number effects on the jet size required to test a conical centre-body intake.

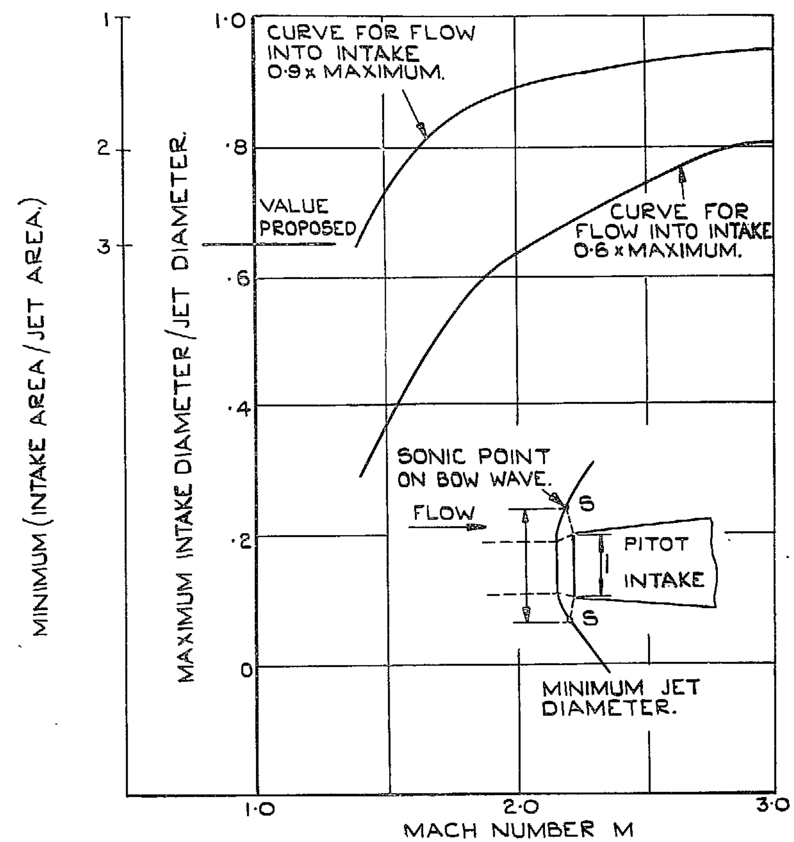

FIG. 4. Effect of intake spill on the jet size required to test a pitot intake.

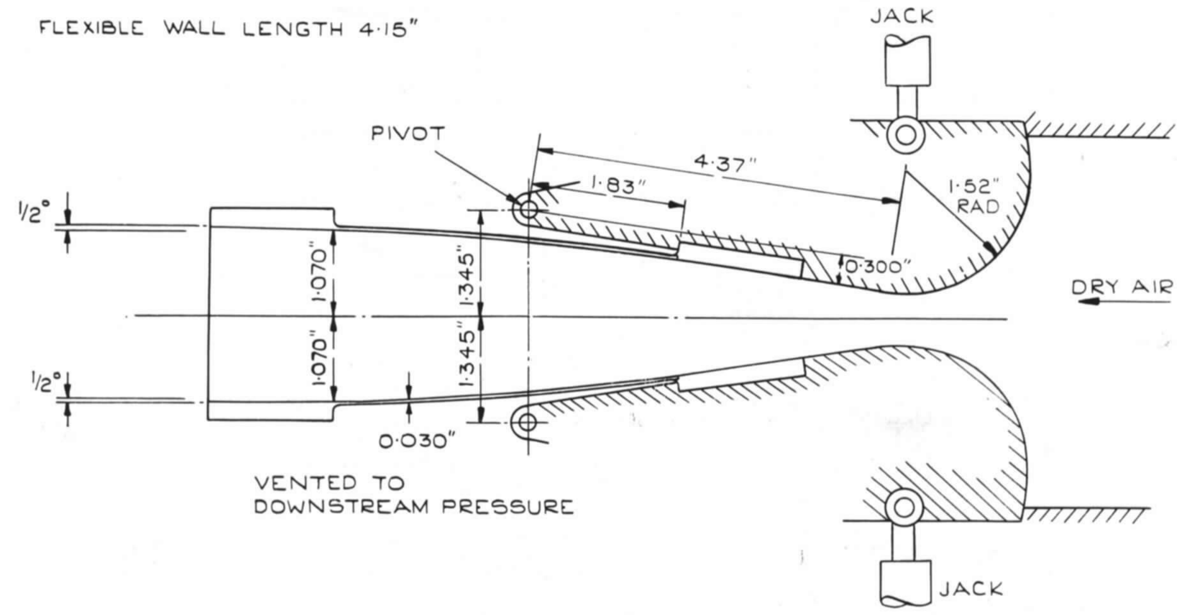

FIG. 5. Final variable Mach number effuser design.

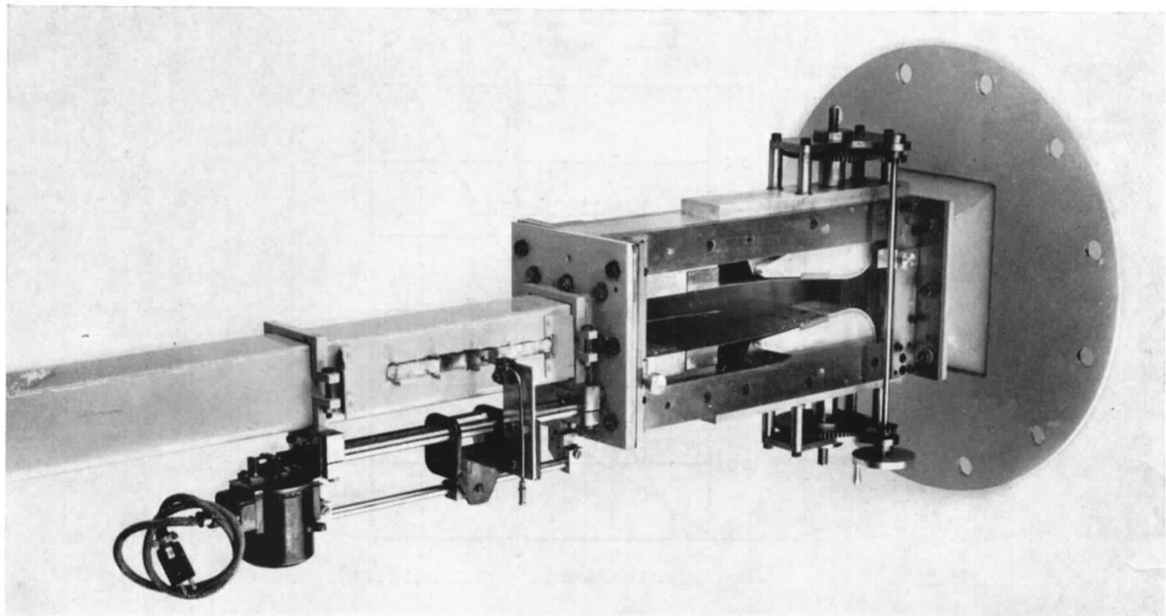

FIG. 6. Photograph of experimental effuser.

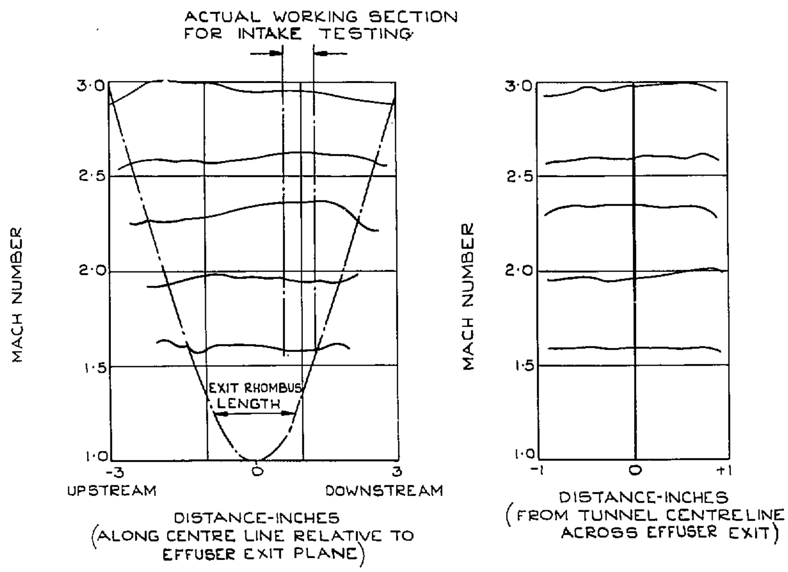

FIG. 7. Exit Mach number distribution from a simple variable Mach number effuser.

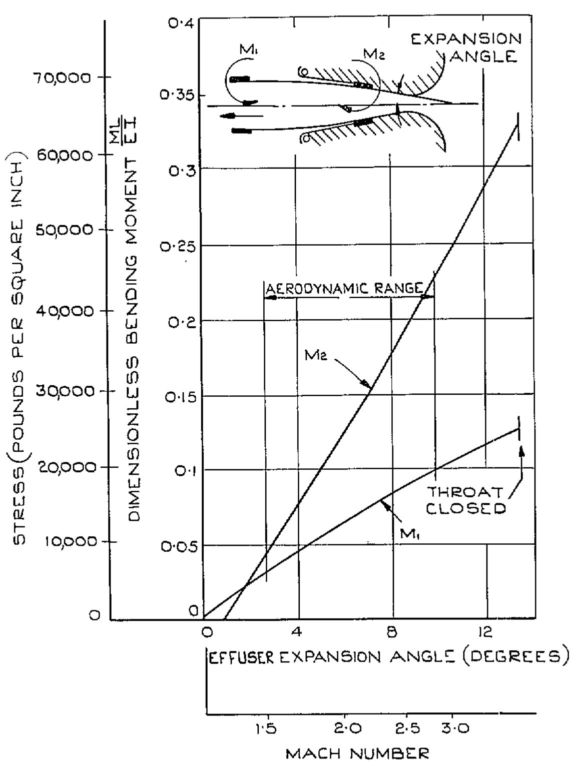

FIG. 8. Flexible wall bending stresses.

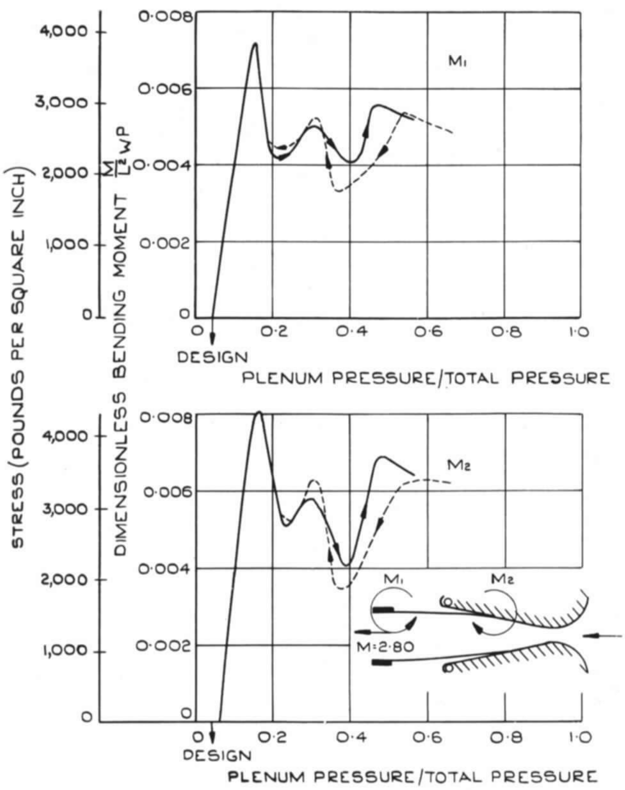

FIG. 9. Flexible wall stresses during starting up or closing down the air flow.

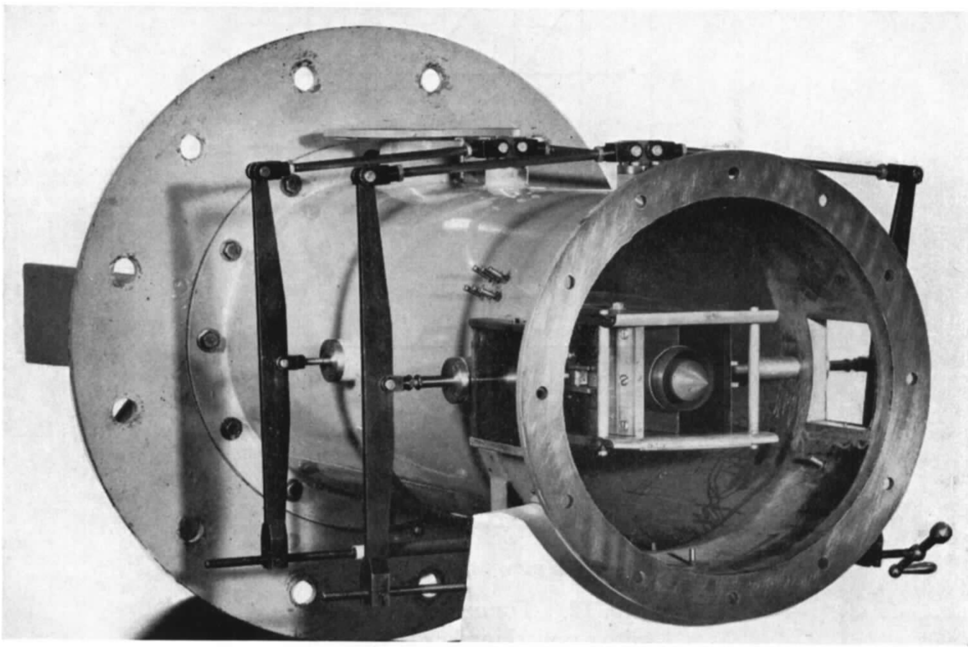

FIG. 10. Photograph of model tunnel.

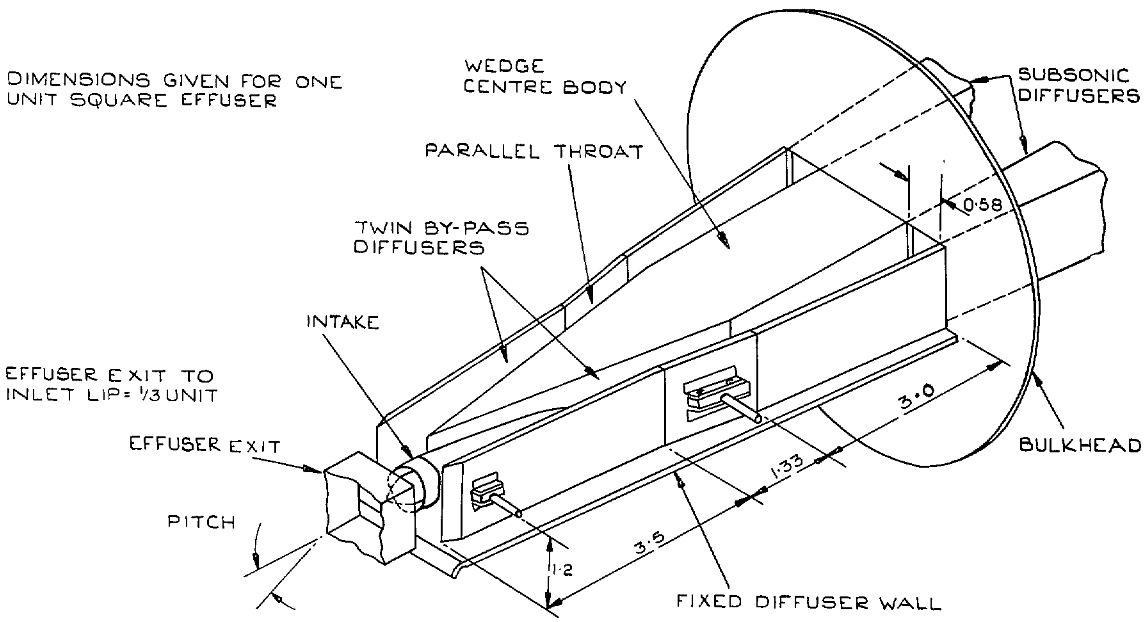

FIG. 11. A sketch of the by-pass diffuser system (with the outer casing and upper fixed wall removed).

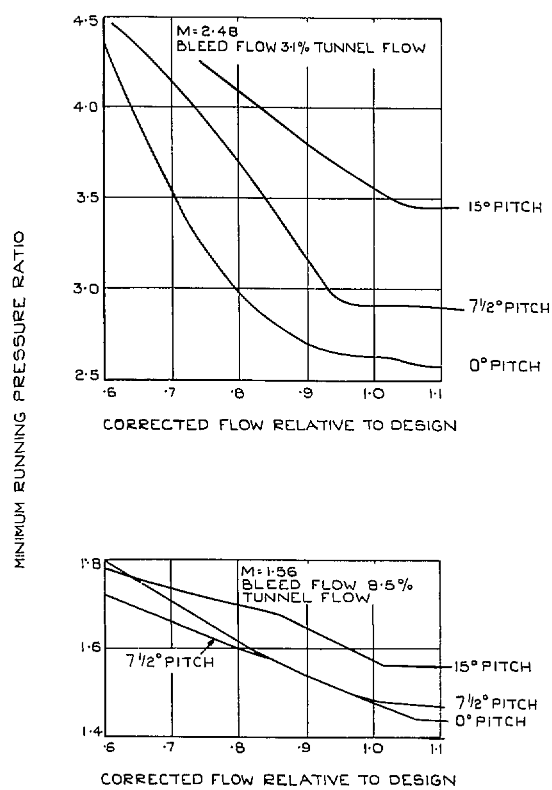

FIG. 12. Tunnel performance with a typical intake installation. (Intake area = one-third of effuser area.)

(S2494) Wt. 66/991 K.5 10/61 Hw.

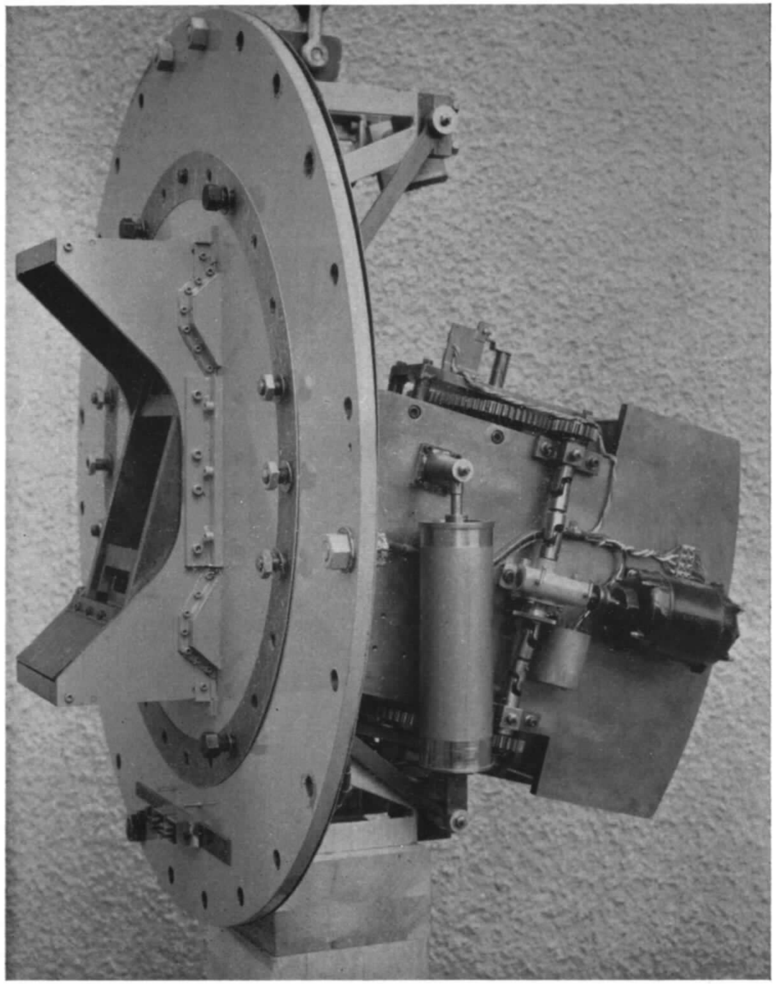

FIG. 16. The 6 in. × 6 in. effuser.

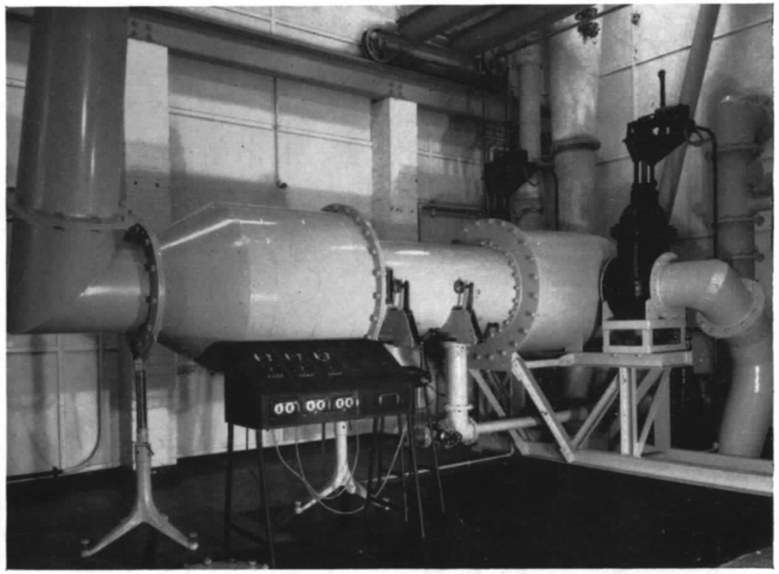

FIG. 17. The completed tunnel.

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This development work originally concerned the design of a practicable high-speed cell for an Engine Test Facility[1] and only later, using data accumulated in this investigation a 6 in. × 6 in. tunnel capable of testing a 4 in. diameter inlet was constructed. A brief description of this tunnel is given.

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