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On the Sub-Critical Stability of Variable Ramp Intakes at Mach Numbers Around 2

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Summary

The need to minimise the pre-entry drag of supersonic intakes demands an understanding of the link between the shock pattern in the region of the cowl lip, and aerodynamic instability consequent on shear planes or zones generated in the supersonic compression field entering the subsonic diffuser. The present Report aims to illuminate this link. It describes flow instabilities observed in tests with a range of model variable ramp intakes, and by invoking observations made during earlier experiments develops a consistent picture of instability in variable ramp intakes at Mach numbers of about 2.

In general two forms of instability were observed in the tests described. These, of similar frequency but appreciably different amplitude, are termed 'big' and 'little' buzz. Experimental observations suggest that the latter involves a flow separation from the internal surface of the cowl, whilst 'big' buzz is thought to be associated with separation of the ramp boundary layer. Flow instability in the Concorde intake is discussed in the light of these results. Although, because of the complexity of the phenomena investigated much work remains to be done, a design technique is suggested which offers the prospect of achieving minimum pre-entry drag with freedom from instabilities induced by shear planes or zones.

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* Replaces N.G.T.E. Report R311—A.R.C. 32 910.

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1. Introduction

The degree of sub-critical stability of an external compression supersonic air intake represents an important aspect of its performance, yet there remains an incomplete understanding of intake instability, commonly known as 'buzz'. This uncertainty surrounds all aspects of the phenomenon, from the mechanisms which can trigger instability, to the validity of wind tunnel model test results in relation to full scale flight conditions. The purpose of this investigation is to attempt some clarification of the triggering mechanisms with particular reference to the widely known Ferri criterion[1] for instability. This states that an intake may become unstable when the shear plane emanating from a shock intersection falls just inside the lip of the intake cowl. Whilst there is much evidence to support this hypothesis, it is also well known that the entrance of a shear plane does not necessarily affect stability. A need to clarify this situation is created by the developing emphasis on achieving low drag in intake designs, for the factors governing the occurrence of a shear plane in the region of the cowl lip also affect directly the pre-entry drag of the intake when it is operating in the critical or super-critical mode.

2. A Background Summary

A review[2] of the available literature on supersonic intake instability shows that much work has been carried out on various aspects of the problem, particularly in America. In most cases, for example, in Refs. 3 to 6, instability is ascribed either to the entering shear plane, after Ferri (Fig. 1(a)) or to shock wave-boundary layer interaction leading to flow separation on the supersonic compression surface (Fig. 1(b)). In the case of a rectangular intake, the significance of the sidewall boundary layers has also been demonstrated.[7]

Many other variables are thought to affect instability phenomena significantly—not necessarily in every case—but certainly in some. One such is the initial rate of subsonic diffusion,[1] while some doubt exists as to the effect of free stream turbulence, which varies from one test facility to another.[8] In one series of tests the position of the lip forming the down-stream edge of the ramp boundary-layer bleed-slot was shown to be important.[9] Opinions vary on the exact mechanisms which lead from triggering events to a cyclic oscillation, but there appears to be no reason why one theory should displace the rest. The mechanism in each case might depend on the detailed geometry.

The variable ramp intake proposed for Concorde and sketched in Fig. 1(c) exhibits in a uniform free stream two phases of instability (*see* Ref. 10 for example). After a small reduction in mass flow a low amplitude oscillation, the so-called 'little' buzz, suddenly appears, while further throttling initiates 'big' buzz. The latter is of much larger amplitude than little buzz although the frequency is similar. Big buzz is unaffected by changes in ramp angle and is almost certainly initiated according to the Ferri criterion, by the shear plane emanating from the intersection of the normal shock with the initial oblique shock wave generated by the fixed wedge upstream of the ramp hinge. The effect of ramp angle on little buzz[11] suggests that it is similarly triggered. In this case however the mechanism is thought to be the shear plane from the intersection of the normal shock with the ramp hinge shock and isentropic fan, whose positions depend on the ramp angle.

The observed difference between 'little' buzz and 'big' buzz inspired the thought that perhaps the amplitude of the oscillations encountered in a Ferri type instability might be dependent upon the total pressure gradient, or the total pressure change, across the shear plane. Thus, with an assumed shear plane of zero thickness there exists downstream of the intersection of the normal shock a step change in total pressure across the shear plane and, correspondingly, an infinite total pressure gradient. When the normal shock encounters the ramp hinge shock and isentropic fan however, the infinite total pressure gradient of the previous case is replaced by a more graduated one. In other words, the shear plane becomes a shear zone of finite width. Might a still more graduated total pressure gradient enter the intake without triggering any instability? Could such a low gradient system stem from a ramp compression field of acceptably low pre-entry drag—and preferably of lower pre-entry drag than sustained in current intakes of topical interest? What, if anything, would be the cost in pressure recovery and where, for efficient supersonic cruise operation would the best overall compromise lie? Such questions flow from the thought of designing the compression system to achieve some specified level of sub-critical stability whilst retaining minimum external drag. Ambitious though such an aim might be, it was thought some effort ought to be made to supersede the hit and miss design methods of the present. As Fig. 2 shows, the importance of doing so stems from the fact that, so far as Ferri type instability is concerned, a large stable sub-critical margin tends to imply a high pre-entry drag.

The present Report does not attempt to answer all the questions posed above. Moreover it is inevitably concerned with a restricted range of intake geometries. However, the geometries considered are not of purely academic interest, nor, it will be argued, are the results necessarily too restricted in application. The test geometries described below feature a subsonic diffuser closely resembling that proposed for Concorde, and a bleed of about 6 per cent of the capture flow evacuated through a ramp slot exactly as intended in that aircraft. The Rolls-Royce (BED) tests[12] to which extended reference is made also featured realistic models that could easily form the basis of practical powerplant designs. Such designs are not necessarily tied to supersonic transport aircraft. Many types of aircraft have a capability of around Mach 2, that is the level of Mach number considered in this Report, and the type of intake considered is, in principle, capable of application to them all.

3. Test Geometries

The basic approach in framing the experimental programme was to devise a number of test geometries featuring a wide range of pre-entry spill flows, and hence pre-entry drags. This was to be achieved by varying the relative positions of the cowl lip and ramp compression field while simultaneously keeping constant all other factors likely to influence the stability. Figure 3 shows the basic supersonic compression field. The ramp profile takes the form of a continuous curve from zero initial inclination to a final inclination of 15·75 degrees to the free stream flow direction. With an upstream Mach number of 1·90 the resulting isentropic fan is focussed at a single point, and the terminal supersonic Mach number is 1·36. It should of course be appreciated that such a profile is unlikely to find practical application. Its length is excessive for the supersonic turning it provides, although a factor in its favour is that on tilting it provides the maximum range of supersonic forespill.[13] In addition the terminal supersonic Mach number is too high for a pressure recovery approaching that given by the theoretical supersonic flow pattern. However, the latter consideration was regarded as unimportant in the present context since the achievement of high recoveries was not the object of the exercise. The supersonic compression field shown in Fig. 3 was in fact chosen because, by varying the position of the field relative to the cowl lip, it is possible to achieve a wide range of total pressure gradients in the region of the lip. The selected arrangement therefore offered the possibility of highlighting the effect of the graduation of the compression field on stability. The ramp profile was designed for inviscid flow, the assumption being that the displacement of the compression field by the ramp boundary layer could be offset during the experiments by reducing the ramp inclination.

In achieving a range of pre-entry spill flows with this compression field, the simple expedient of moving the cowl lip while leaving the ramp fixed could not be used, since it would have varied both the shape of the diffuser and the capture mass flow, two factors likely to affect subcritical stability. Instead the lip was fixed and the position and scale of the compression fan were varied, using different ramps placed in different positions, in such a way that the critical capture mass flow was left virtually unaltered. Thus it was possible to use the same subsonic diffuser throughout. Three ramps were manufactured, designated A, B and C in ascending order of size. All featured exactly the same continuously curved profile shown in Fig. 3, scaled to different sizes, and thus at the test Mach number generating the same wave pattern at three different scales. The scales were such that, in the Nomenclature of Figs. 3 and 4, the areas projected upstream by the three compression fans $A_{\mathrm{FAN\,A}}:A_{\mathrm{FAN\,B}}:A_{\mathrm{FAN\,C}}$ were in the ratio 0·8:0·9:1·0 respectively. Four different pairs of sideplates designated 1 to 4 inclusive were manufactured. These were such that in each build the sideplate leading edges intersected the tips of both the cowl and the profiled ramp. Together they permitted the three ramps (and thus their compression fields) to be mounted relative to the cowl lip in a range of different positions. Thus, as Fig. 4 shows, Sideplate 1 aligned the leading edge of the compression fan with the cowl lip. Sideplate 4 aligned the cowl lip with the downstream limit of the compression fan generated by Ramp C, whilst Sideplates 2 and 3 placed the cowl lip at two intermediate positions within the fan generated by this ramp. In addition Sideplate 3 aligned the downstream limit of the compression fan generated by Ramp B with the cowl lip, whilst with this ramp one intermediate position of the lip relative to the fan was provided by Sideplate 2. All the possible arrangements were such that, using the conventional nomenclature defined in Fig. 4, whilst $(A_\infty/A_{\mathrm{ENTRY}})$ the supercritical capture mass flow ratio varied according to the position of the cowl lip in the compression fan, A_{ENTRY} also varied so that in absolute terms A_∞, the intake capture flow, remained effectively constant. Hence, in moving the cowl lip 'backwards' in transferring from Build C1 through C2 and C3 to C4, and again from B1 through B2 to B3, the lip moved downstream along a common stagnation streamline. Thus with a fixed bleed flow the subsonic diffuser flow was virtually constant for all builds.

The size of the models, expressed in terms of the 'vertical' height of the cowl lip above the ramp tip, varied between 2·69 in. (6·84 cm) with Sideplate 1, and 2·79 in. (7·10 cm) with Sideplate 4.

4. Apparatus

4.1. Intake Model Geometry

Each ramp was supported at a hinge positioned at its upstream tip, and its downstream end was connected to a control linkage which allowed the ramp inclination to be varied.

So that the ramp compression surface could have a sharp leading edge, each build was equipped with a small 'platform' projecting upstream of the profiled ramp, with its upper surface parallel to the free stream flow direction. This is illustrated both in the photograph on Fig. 5, which shows a complete intake assembly, and also in the sectioned diagram at the bottom of the same figure. The circular glass windows which allowed observation of the flow in the intake throat are also shown. Each ramp was manufactured so that the upstream limit of the throat bleed slot could readily be formed from any one of a range of ramp trailing edges of various lengths and shapes.

The components described above were assembled on a chassis which simulated the internal geometry of the proposed Concorde intake downstream of the cowl lip and boundary layer bleed gap. A photograph and sectioned sketch of the complete model are shown in Fig. 6. There was a second variable ramp downstream of the bleed gap, which contributed to the transition from a rectangular cross-section at the throat to a circular section at the exit of the subsonic diffuser. The internal surface of the cowl lip was inclined at 12·5 degrees to the free stream flow direction.

4.2. Controls and Instrumentation

The model incorporated translating plug throttles for metering both 'engine' and bleed mass flows. The main throttle, like the variable ramps, was operated by an electronically controlled hydraulic actuator, whilst the setting of the bleed throttle was adjusted manually from outside the wind tunnel. The positions of the variable components were indicated on a digital voltmeter by potentiometers built into the actuators.

There was a 12-point rotating pitot rake mounted on a hemispherical bullet in the exit of the subsonic diffuser, the pitots being distributed on an equal area basis. The rake was positioned by an electric motor mounted outside the wind tunnel, and its position was shown by a 'Desynn' indicator. Other instrumentation included static pressure tappings on the subsonic diffuser walls, on the surface of the rotating bullet, and within the bleed void.

The model was equipped with four pressure transducers as shown in Fig. 6. These were numbered 1 to 4 and distributed as follows:

No. 1 measured the static pressure on the outer wall of the diffuser exit annulus;

No. 2 was mounted on the cowl side of the subsonic diffuser approximately opposite the tip of the second ramp. It measured either the wall static pressure or, with a pitot tube, the total pressure adjacent to the wall;

No. 3 was mounted in the bottom wall of the bleed void, and measured either the static pressure in the void or the total pressure in the main duct flow just downstream of the supersonic ramp. The pitot and flexible tube used for the latter purpose appear in the photograph of Fig. 7(a), which was taken through one of the sidewall windows;

No. 4 was mounted on the sidewall just upstream of the hinge of the second ramp, and was connected to a pitot tube measuring total pressure adjacent to the sidewall.

Figure 7(b) shows a view looking downstream into the subsonic diffuser of the model, revealing the pitot tubes connected to Transducers 2, 3 and 4. The equipment recording the output of Transducers 1 and 2 was designed to record oscillations of frequencies up to 1000 c/s, while that of Transducers 3 and 4 was limited to frequencies below 250 c/s. All outputs were connected to an ultra-violet recorder.

4.3. Test Facility

The tests were carried out in the 12 in. (30·5 cm) intake test rig at NGTE. They were performed at zero incidence using a free stream Mach number of 1·915. The tunnel stagnation pressure was 4·5 atmospheres, which gave a model Reynolds number based on the free stream conditions and capture height of approximately 4×10^6.

5. Test Procedure

The ramp inclinations were first adjusted so that the design flow patterns were achieved. In fact the small difference between the ramp design Mach number of 1·90 and the test Mach number of 1·915 offset to some extent the effect of boundary layer growth on the ramp surface in deflecting the compression system upstream of the design configuration. Thus to establish the design patterns it was only necessary to reduce the final ramp inclination from the figure of 15·75 degrees, used in the calculation assuming inviscid flow, to 15·5 degrees.

Some time was devoted to 'tuning' each configuration, with regard to the shape of the ramp trailing edge and its position relative to the cowl shock: the aim in each case was to position the foot of this shock at the upstream edge of the bleed gap. Although this had very little effect on the sub-critical stability characteristics, provided that a 'start–unstart' behaviour was not induced, it was thought desirable to preserve continuity, for example in bleed pressure recovery, from one configuration to the next. At the same time it is perhaps worth re-stating that the achievement of high recoveries was not an aim in these experiments; both the terminal supersonic Mach number and the boundary layer developed on the ramp surface were excessive from this point of view.

The exit area of the bleed throttle, and the configuration of the bleed gap, i.e. the position of the downstream ramp relative to the upstream one, were kept constant, except for limited investigations of their effects as variables which will be described later. The throttle was adjusted so that the bleed flow at critical was approximately 6 per cent of the total capture flow, and the second ramp was positioned so that the line passing through its tip and the shoulder of the supersonic ramp was parallel to the free stream flow direction.

The captured mass flow at a given point on a characteristic was determined by summing the flows passing through the main throttle and bleed throttle, assuming that each was choked. Both throttles had previously been calibrated, so that a knowledge of plug settings, along with the respective reference pressures—the area mean total pressure at the diffuser exit in the case of the main throttle, and the mean of two static pressures measured immediately upstream of the bleed throttle—led to the total mass flow. To measure the total pressure at the diffuser exit the rotating pitot rake was stepped through 60 degree intervals to yield 36 separate pressures, which were averaged to give an area mean.

The stability characteristic for a given geometry and bleed setting was obtained by setting the ultra-violet recorder in motion and then closing the main throttle over the full range of interest in one continuous movement. A trace indicating throttle position was included on the recording, so that the transducer outputs could subsequently be related to the captured mass flow. No recordings were made while the throttle was being opened.

6. Description of Stability Characteristics

Figure 8 shows the stability characteristics of all configurations tested, arranged to correspond with the layout of Fig. 4. The peak-to-peak amplitudes of the oscillations measured at the compressor face (Transducer No. 1), non-dimensionalised with respect to the free stream total pressure, are plotted against the ratio of the capture mass flow to the mass flow captured at critical. The intakes generally exhibited two phases of instability. The first, referred to as 'little' buzz, usually occurred immediately upon detachment of the cowl shock, while the second, 'big' buzz, appeared with a much higher amplitude after an intermediate relatively stable range of mass flow. These oscillations occurred at definite frequencies, while random noise occurred elsewhere on the characteristic.

For each configuration several recordings were made of the transducer outputs, and the shaded regions of Fig. 8 indicate the ranges of mass flow within which the onset or cessation of instability was observed; in other words these are margins of uncertainty. Strictly, these steps should not necessarily be vertical because of the effect of instability on the mean pressure recovery which controlled the mass flow passing through the throttles: mass flow measurement was not generally attempted during buzz because of the uncertain effect of the pressure oscillations on manometer readings. A step signifying the onset of buzz appears at the mass flow which existed immediately before the event, while that signifying the cessation of buzz appears at the mass flow which existed immediately after. In other words, in drawing the characteristics it was assumed that the mass flow varied continuously with throttle position despite the onset of instability. Such was unlikely to have been the case, and over the unstable flow ranges the characteristics might best be regarded as plots of amplitude against throttle opening rather than against mass flow.

The frequencies of the pressure pulsations are noted in Fig. 8. Where little buzz occurred over an appreciable range of mass flow, an increasing frequency was observed as the throttle was closed, and the extremes of the ranges were noted. No such variations of frequency were noticed during the big buzz but only limited closure of the throttle was attempted after this high amplitude oscillation had commenced.

The Configurations C1 and C4 exhibited departures from the usual behaviour. The former was stable until the onset of big buzz, with no little buzz, while the latter featured a wide range of little buzz which merged with big buzz. There was also a small stable range before little buzz occurred in the case of C4, although this was preceded by a narrow range of very mild oscillation as the cowl shock detached. Configuration C4 was also peculiar in that there were intermittent high amplitude pulsations, sometimes only a single cycle, before the regular oscillations of big buzz appeared.

As noted in Fig. 8 the effect of changing the bleed throttle setting was investigated with Configurations B3, C1 and C2. In the case of C1 the bleed flow was varied over a wide range with no discernible effect on the total mass flow reduction before the onset of big buzz, while more limited variations with the other two builds affected neither big buzz nor little buzz. The bleed flow immediately before big buzz was normally 8 per cent of the maximum capture flow (compared with approximately 6 per cent at critical): the notes in Fig. 8 indicate the experimental range of bleed variations just prior to buzz.

The sensitivity of the stability characteristic to the relative positions of the tip of the second ramp and the shoulder of the first ramp was investigated with Configuration C4. The second ramp tip was moved both up and down from its datum relative to the first ramp by a distance equal to 1·5 per cent of the intake throat height, without altering the characteristic shown in Fig. 8. This behaviour is in apparent contrast with that reported in Ref. 9, in which the position of the second ramp was found to significantly influence sub-critical stability. This could be a result of the substantially shorter axial gap across the bleed slot of the intake described in Ref. 9. On the other hand it may merely be a further reflection of the complexity of the phenomenon being discussed, and its undoubted dependence upon parameters other than those systematically varied in the present investigation. Moreover the possibility of a different mechanism leading to instability in the present investigation from that in the tests of Ref. 9 cannot be overlooked.

7. Little Buzz

7.1. Establishment of a Criterion

7.1.1. *Evidence of Ferri instability*

The insensitivity of the stability characteristics to bleed flow, in the cases where this was varied, and to bleed slot geometry in the case of Build C4, necessitates looking elsewhere for explanations of the widely varying behaviour depicted in Fig. 8. The obvious area to examine is the compression field in the region of the cowl lip, and, as might be expected, Fig. 8 suggests that this indeed critically influences the sub-critical characteristics. It is seen, for example, that as the configuration changed from that of C1, progressively through C2 and C3 to C4, the incidence of little buzz increased from zero to sizeable in terms of both amplitude and mass flow range. A similar trend was displayed as the configuration changed from C1 to A1, through B1, and from B1 to B3. Two possible explanations for these trends are considered here; first there are the changes over the range of test builds in the pressure gradients to which the sidewall boundary layers are subject in the region of the cowl lip, second there are the changes in the flow downstream of the intersection of the detached cowl shock with the ramp compression fan.

The sidewall pressure gradients are steepest in the region of the cowl lip, because of the focussing of the ramp compression waves. Thus the possibility was mooted that the pattern of sidewall pressure gradients reproduced in the range of test builds produced a corresponding pattern of separation and hence a matching pattern of instability. Possible evidence for an instability theory founded on sidewall separation comes from some experiments by Dawson,[7] who was able to suppress an instability in a Concorde type intake through the use of sidewall bleed. That sidewall separation is therefore the trigger initiating instability does not however seem altogether clear. For example, in earlier experiments at N.G.T.E. with variable ramp intakes [14] the sidewall boundary layer flow patterns, and therefore one might surmise their separation characteristics, were profoundly influenced by the amount of bleed removed from the surface of the ramp, whereas in the present tests variations of ramp bleed produced no effect on stability. Further doubt that sidewall separation initiated instability in the present tests arises if, for example, the stability characteristics of Builds C1 and C4 are compared. From Fig. 4 it may be deduced that adjacent to the cowl lip the sidewall pressure rise across the detached cowl shock is greatest on C1. (This follows because in the region of the sidewall nearest to the cowl lip the detached cowl shock occurs at a higher Mach number with C1 than with C4, for with the latter build much of the supersonic compression occurs ahead of the sidewall leading edge.) It might therefore be supposed that the propensity for separation is greatest on C1, whereas Fig. 8 shows that instability arises first with C.4. Moreover, whilst the authors would not assert that in this respect their findings are conclusive, neither with C1, nor with any of the other test builds did the limited model instrumentation reveal any evidence of sidewall boundary layer separation. On the other hand, as will be described, the evidence for separation on the cowl side of the subsonic diffuser was substantial. Attention was therefore transferred to the consequences, over the range of test builds, of the changes in the flow downstream of the intersection of the cowl shock with the ramp compression fan, following the criterion put forward by Ferri and Nucci.[1] In making this step, however, it should be borne in mind that with other intakes—particularly those featuring extended sidewalls, and thus considerable boundary layer growth ahead of the ramp shock system—other mechanisms of instability may well be operative.

Reverting to the present tests, further evidence consistent with a relationship between the flow downstream of the shock intersection and the onset of little buzz was given by additional tests in which the inclination of the supersonic ramp was increased from the normal datum value. The results for Build B2 are typical and are shown in Fig. 9. The progressive movement of the fan upstream from the cowl lip that occurred with increasing ramp turning was accompanied by a gradually increasing range of stable flow prior to the onset of little buzz. This behaviour is typical of Ferri-type instability, since forward movement of the ramp-compression field necessitates increased forward movement of the normal shock before the shear layer from the intersection strikes the cowl lip. This can be seen from Fig. 2. Finally, Fig. 9 shows that the progressive retardation of the onset of little buzz ultimately causes the two regions of instability to merge.

7.1.2. *Formation of the shear zone*

The diagram at the top right of Fig. 10 illustrates the development of a shear zone. The cowl shock is shown an infinitesimal distance upstream of its critical position (at which it is attached to the cowl lip), so that in the diagram the cowl lip lies just downstream of the intersection and thus in the ensuing shear zone. The theoretical total pressure variation across the zone immediately downstream of the intersection is shown in the diagram. A maximum total pressure recovery of 0·967 is achieved at the innermost extremity of the zone as a result of the free stream flow being turned isentropically through the full ramp turning of 15·75 degrees before being decelerated through a normal shock to a subsonic Mach number. At the opposite extremity the total pressure recovery only reaches 0·767, this corresponding with the loss through a normal shock at the free stream Mach number. The change in total pressure across the shear zone is thus 20 per cent of the free stream total head.

The remaining diagrams on Fig. 10 show for each of the test builds the total pressure distribution calculated according to the method just described, and arranged to correspond with the layout of Figs. 4 and 8. In addition the diagrams show the total pressure gradient (dP/dy) across the zone, where y is the distance measured across the zone from a zero at the cowl lip. Distances are shown as positive when measured across the capture flow, and negative measured into the spill, and for every build y equals 0 at the cowl lip and 1 at the ramp surface. Total pressure, P, is nondimensionalised with respect to the free stream total pressure. It should be emphasised that these plots are intended primarily to give a qualitative comparison of the relative extents and strengths of the different shear zones. In fact for example, Schlieren observation confirmed that the cowl shock was not completely normal, particularly on the external side of the lip, as the calculations assume. Subject to this proviso however, it will be observed that the mean values of the total pressure gradients plotted fall very broadly into three categories, the 'low' for the 'C' builds, the 'medium' for the 'B' builds and the 'high' (in fact infinite) for the 'A' builds.

For each configuration the portion of the shear zone passing on the external side of the cowl at the critical condition is indicated by cross hatching on the graph of (dP/dy). The graphs also show, for the same condition, the total pressure differentials in the zone passing both internally and externally to the cowl lip. By referring to the inset diagram in Fig. 10 it can be seen that as the normal shock moves upstream from its critical position due to throttle closure the whole of the shear zone moves towards the ramp surface and increases in breadth, so that the total pressure gradient in the zone decreases. During this process the portions of the zones represented by the cross hatching move across the lip so that, excluding Builds A1, B1, and C1, the total pressure difference across the entrant portion of the zone simultaneously increases. The breadth of each hatched portion gives a measure of the extent of the sub-critical mass flow range during which the shear zone remains in contact with the lip.

7.1.3. *The gradient across the zone and its proximity to the lip*

A study of Fig. 10 in conjunction with Fig. 8 indicates a connection between the occurrence of little buzz and both the severity of the shear zone, in terms of total pressure gradient, and the breadth of the portion of the shear zone passing on the external side of the cowl at critical. This is shown in Fig. 11. There it will be seen that the experimental points can be very broadly classified according to the 'low', 'medium', and 'high' categories of total pressure gradients that were noted earlier. At a given level on the vertical scale the unstable flow range decreases with decreasing gradient in the shear zone. Thus for example at zero in the vertical scale, the stability improves in passing from Build A1 to C1 through B1. In making this passage though, the theoretical pressure recovery at the critical condition progressively decreases, as will be deduced from Fig. 4, and it occasioned no surprise that in fact the tests demonstrated an exactly similar reduction in measured pressure recovery. In effect therefore the three builds just mentioned demonstrate the exchange between pressure recovery and stability. (This exchange is analogous to the familiar expedient of operating super-critically to defer the onset of unstable conditions.) The same exchange is illustrated by moving along one of the lines of approximately constant shear-zone total-pressure gradient. For example the improvement in stability achieved by moving from C4 to C3 and C2 to C1 entails in fact the deterioration of pressure recovery that would be inferred from a comparison of the flow patterns in Fig. 4. In this case however the simultaneous reduction in pre-entry drag would enter an overall intake optimisation.

Further study of the stability characteristics throughout the range of geometries investigated suggests the following hypothesis for little buzz: while there is a shear zone of sufficiently steep gradient in contact with, or close to, the internal surface of the cowl lip under sub-critical conditions, the intake is unstable. A weak gradient can be in contact with the lip without causing buzz, while a strong gradient could trigger oscillations when it is some distance from the lip. For supporting argument consider the changes in flow pattern entailed in moving from Build A1, through B1 to C1, and the corresponding changes in stability. With Build A1 there is a step change in total pressure, i.e. an infinite gradient, a simple shear plane in fact, impinging on the cowl lip at the critical condition. This takes the form of a narrow shear zone moving away from the internal surface of the cowl as the cowl shock detaches. Because of the initially small width of this zone its total pressure gradient is very high and it will be observed that instability exists over an appreciable range of mass flow. The same reasoning applies to a lesser extent to B1. In the case of C1, from which little buzz is absent, the total pressure gradient is much less, and even smaller when it moves out of contact with the cowl surface as it does immediately upon detachment of the cowl shock. With Configurations B2, C2 and C3 the shear zone maintains contact with the lip over a small subcritical range of mass flow, and Fig. 8 shows the ranges of mass flow over which oscillations occurred. For these three configurations the mass flow range exhibiting the oscillation was widest in the case of B2 which, as Fig. 10 shows, features the highest pressure gradient.

7.1.4. *The total pressure difference across the zone*

In terms of the preceding argument, the small stable sub-critical margins noted with Builds B3 and C4 prior to the onset of little buzz might reflect a total pressure gradient too weak to promote instability, until the entrant shear zone had moved some distance towards the ramp—a very small distance in the case of B3. However, it is thought more likely that the total pressure difference across the entrant portion of the shear zone has to reach a certain level for the onset of instability. This level is reached when the normal shock has moved sufficiently far upstream from its critical position, and thereafter the shear zone is of sufficient strength, in terms of both difference and gradient, and remains sufficiently close to the cowl to maintain instability over an appreciable range of shock movement. According to this argument the stable sub-critical margin with Build B3 was much less because of the higher total pressure gradient in the shear zone. This would have had the combined effect of reducing the necessary total pressure difference to be introduced to the entrant flow before instability occurred, and of reducing the range of shock movement required to introduce a given difference. Thus it is suggested that three factors are operative in determining whether an entrant shear zone will trigger instability:

(a) the change in total pressure across the shear zone;
(b) the breadth of the shear zone in relation to the total pressure change; i.e., the total pressure gradient across the zone; and
(c) the distance between the shear zone and the cowl lip.

With regard to (a) one quantitative result can be extracted from Fig. 10: as far as is possible to tell from the results, the lowest total pressure differential across an entrant shear zone sufficing to cause instability is approximately 7 per cent of the free stream total pressure. Figure 10 indicates that such a difference exists across that part of the shear zone passing inside of the cowl of Build B2 at the critical condition, and with this build there is no stable sub-critical margin. The entrant total pressure difference in this case is about one third of that across the whole shear zone. With a lower gradient a much higher difference causes no instability (for example Build C1, where the full 20 per cent difference entered adjacent to the cowl), while for higher gradients the limit may be lower than 7 per cent; instability might commence with a lower difference in the case of B3 for example.

Previous tests[10] on the air intake proposed for the Concorde provided information which supplements the results of the present investigation, since the tests were performed at the same upstream Mach number, using an identical subsonic diffuser passing a very similar capture mass flow. As stated earlier, almost certainly one and probably both phases of instability exhibited by this intake were promoted by the entry of shear planes or zones; the first from the intersection of the normal shock with the hinge shock and isentropic fan—this being a complex shear zone rather than a pure shear plane—and the second from the intersection of the normal shock with the initial wedge shock. Now the changes of total pressure across both discontinuities can be shown to equal about 10 per cent of the free stream total pressure. A lower total pressure difference across a shear plane (as opposed to a zone) was provided by modifying one of the isentropic ramps of the present tests to generate three discrete shocks of appropriate strength, as shown in Fig. 12. As a result of the modification the maximum intake capture flow was reduced—by some 6·5 per cent—so that perhaps some qualification of the results is required. Nevertheless the shear plane originating at the third oblique shock, which involved a step change in total pressure of approximately 6 per cent of the free stream value, was able to enter at the cowl lip without causing instability. This further emphasises the importance of the magnitude of the total pressure discontinuity.

The hypothesis for little buzz advanced earlier might now be elaborated so: a shear zone having a given total pressure difference across its width initiates instabilities which vary in extent according to the total pressure gradient across the zone. A sufficiently steep gradient can cause instability when it is in contact with, or close to the cowl lip. On the other hand a weaker gradient can be in contact with the lip without causing instability. If the total pressure difference across the shear zone is sufficiently reduced, then even an infinite gradient, i.e. a pure shear plane, can make contact with the cowl lip without causing instability. Within the limits of the variables covered in the present tests, it would seem that to avoid instability the difference with infinite gradient must be reduced to between 6 and 7 per cent of the free stream total pressure.

7.1.5. *Supplementary evidence*

Experimental results fitting into the above framework come from Rolls-Royce (BED)[12] who have tested variable ramp intakes featuring the compression systems shown in Fig. 13. Both gave very wide stable sub-critical margins, there being no instability at all until one analogous to big buzz was initiated after the mass flow had been reduced from the critical value by about 16 per cent. In achieving this reduction the shear plane emanating from the intersection of the terminal normal shock and the most downstream of the three ramp shocks would certainly have entered the intake. Perhaps too a further plane originating at the central ramp shock would also have entered. The maximum total pressure difference across the shear planes was approximately 7 per cent for the test at $M = 2{\cdot}1$ and 6 per cent at $M = 1{\cdot}8$. Although the subsonic diffuser used in the Rolls-Royce tests was longer than that of the Concorde intake and the intakes of the present tests, these figures compare sensibly with those quoted earlier: differences in the present tests of 6 per cent which allowed stable flow and 7 per cent which triggered instability, and of about 10 per cent in a model Concorde intake at the onset of both little buzz and big buzz.

In the present context it is noteworthy that in the presence of the wing flow field, it has been stated that the Concorde intake little buzz is apparently eliminated. This may well result from the Mach number gradients under the wing so spreading the shear zone (suggested as being associated with little buzz) that the total pressure gradients are reduced to an extent sufficient to eliminate instability.[15] It may on the other hand merely emphasise the difficulties which are encountered when studying the instability phenomenon. The tests without the wing flow field were not conducted in the same facility as those which included it, and variation between results yielded by different facilities, even with identical Reynolds numbers, has been demonstrated.[8] The discrepancies have been attributed to different turbulence levels in the free stream.

7.2. The Triggering Mechanism

Simple one-dimensional theory predicts that a total pressure discontinuity entering a diffuser in close proximity to one wall can produce conditions likely to lead to flow separation on that wall, and this has been advanced[1] as an origin of Ferri instability. Replacing the discontinuity by a total pressure gradient or shear zone need not alter this state of affairs, and experimental evidence from the present tests strongly suggests that the mechanism of little buzz does indeed involve separation on the cowl side of the subsonic diffuser.

Figure 14 was traced from a portion of a typical ultra-violet recording, and shows the behaviour of the four pressure transducer outputs as throttle closure caused the intake, in this case Configuration B3, to pass through little buzz. Transducers 2, 3 and 4 were connected to their respective pitot tubes, while No. 1 was measuring static pressure at the diffuser exit. The onset and cessation of the pressure oscillations are clearly indicated by the output of Transducer No. 1. Transducer No. 2 (on the cowl side of the subsonic diffuser approximately opposite the tip of the second ramp) registered a marked decrease in mean total pressure level during little buzz which was substantially recovered when the oscillations ceased. It is recognised that this change in mean level must be regarded with a certain amount of caution in view of the length of tubing required between the pitot mouth and the transducer. However, the gradual fall in pressure at the onset of buzz and the subsequent gradual recovery at its termination was closely reproduced when the transducer was connected directly to a static hole at the same point. Moreover the arrangement was then identical to that used throughout with the Transducer No. 1 (diffuser exit static pressure) which during the instability never registered such a change in mean pressure.

At the bottom of Fig. 15 the stability characteristic of Configuration B3 is shown, reproduced from Fig. 8 but here plotted on an abscissa of throttle opening rather than mass flow to remove the doubt concerning mass flow measurement during instability. Directly above this the pressures measured at Transducer No. 2 are plotted on the same abscissa. The results came from two tests; one in which the transducer was measuring static pressure and another illustrated in Fig. 14, where it was measuring the total pressure adjacent to the wall. During little buzz these pressures are shown plotted in bands, whose vertical heights reflect the respective oscillation amplitudes. The total and static oscillations were in phase. The mean levels of both pressures, as measured by the transducer, were markedly reduced during little buzz—that of the total pressure more so than the static. This behaviour is consistent with a flow separation downstream of the intake cowl.

Further evidence of such a separation came from the pitot rake at the diffuser exit, where the manometers registered a decrease in pressure on the cowl side during little buzz which was not reflected in the overall pressure recovery. Again it is recognised that manometer readings taken in unstable conditions are to be treated with caution, so that little notice should be taken of the quantitative measurements, but it is nevertheless considered significant that a decreased total pressure was measured on the cowl side only. At the top of Fig. 15 the mean pressure measured by the four outer pitots on the cowl side, with the rake positioned perpendicular to the cowl, is plotted against mass flow ratio. That portion of the curve covering the range of little buzz is drawn through a single experimental point obtained during little buzz, parallel to the curve which would apparently have existed had the intake remained stable. The overall mean pressure recovery, obtained from the 36 individual readings, is included for comparison.

The apparent involvement in the instability process of a separation on the internal surface of the cowl, coupled with the significance argued for both the total pressure difference and its gradient across an entrant shear zone, prompts some discussion of the properties of the zone thought likely to be relevant. A simple shear plane entering the intake closely adjacent to the cowl surface can be regarded as dividing the diffuser flow into two streams. The one remote from the cowl surface, and forming the major part of the capture flow, will virtually dictate the diffuser pressure rise, and this will be imposed on the other entrant stream. This is the basis of the argument of Ferri and Nucci.[1] Thus the flow adjacent to the cowl surface, suffering at the outset from a deficit of total pressure, is confronted with the pressure rise dictated by the higher energy flow. In the limit the shear plane could so enter the intake that only the cowl boundary layer would develop from the lower energy capture stream, whilst the higher energy stream would comprise the main diffuser flow and prescribe the diffuser pressure rise. Evidently the tendency for separation, and thus for instability, will increase as the total pressure difference across the plane increases, exactly as the experiments indicate. The argument can readily be extended to cover the apparent effects of a total pressure gradient across a shear zone, for such a zone can be regarded as being formed from a series of shear planes of a number and spacing sufficient to equal the overall gradient of the zone and its total pressure difference.

The instability cycle described by Ferri and Nucci involved choking within the intake as a result of a flow separation downstream of the cowl lip. As Ref. 1 observes, the choking can occur at a station in the subsonic diffuser where the average Mach number is high (i.e. well upstream in the subsonic diffuser), because even without any separation the area at such a station is close to the critical value corresponding with sonic conditions. On the other hand the choking plane could remain at the throttle. In either case the forward expulsion of the cowl shock following the separation decreases the entering volume flow. The consequent reduction in back pressure leads to the return downstream of the shock and thus to a repetition of the cycle. From the simple one-dimensional treatment of Ferri and Nucci it can be concluded that, with a given velocity discontinuity across the vortex sheet, separation is most likely when the vortex sheet passes internally, closely adjacent to the cowl lip. Thus, with progressive throttling the vortex sheet is gradually driven further and further from the cowl lip until, on the one-dimensional argument, the cowl separation is suppressed and stable sub-critical operation ensues, and to this extent the argument is supported by the experimental results.

Aside from the main line of the discussion it may be of interest to consider briefly one minor point: if in fact the flow does choke during unstable operation at some station in the subsonic diffuser upstream of the throttle, it might be thought that with two chokes in series, opening the downstream throttle would not in itself suffice to restore a stable condition. However, this is not so. The upstream, or aerodynamic choke, is an intermittent phenomenon which is effective with the cowl shock at the down-stream limit of its oscillation. Sufficiently opening the throttle so reduces the diffuser pressure gradient imposed on the capture flow as the pulsating cowl shock moves downstream towards the lip, that the tendency to separate is suppressed. Thus the aerodynamic choke is eliminated.

8. Big Buzz

Figure 8 shows that the mass flow reduction before the onset of big buzz was scarcely affected by changing the position of the compression fan relative to the cowl lip. The only recognisable trend was one of changing amplitude of big buzz from one configuration to the next.

The buzz margin was also insensitive to bleed mass flow. This tends to rule out the possibility of big buzz in the intakes of Fig. 4 being initiated by a separated ramp boundary layer escaping past the bleed gap into the subsonic diffuser, thereby causing a sudden drop in pressure recovery, and a consequent reduction in mass flow through the throttle. Increasing the bleed flow would surely have delayed the onset of buzz if this were the case. Nor is it thought that the instability could be ascribed to another phenomenon described by Ferri and Nucci,[1] where oscillation was apparently initiated by the reaction of the cowl boundary layer to the shear plane from the intersection of the lambda foot of the normal shock. In tests where the shock was visible through extra windows in the sideplates, the lambda foot was seen to be of quite minor proportions.

It is thought that the most likely mechanism of big buzz was that proposed by Dailey,[4] involving a separation of the ramp boundary layer in the face of the pressure rise associated with the expelled terminal shock, and—as Dailey puts it—an effective 'blocking' of the inlet. Figure 16 contains a Schlieren photograph of the flow in the throat, taken immediately prior to the onset of big buzz. The significant reduction in flow area caused by the separated ramp boundary layer can clearly be seen. Separated flow can also be seen leaving the top edge of the sidewall upstream of the cowl lip, supplying evidence for sidewall boundary layer separation that, it will be recalled, was lacking during little buzz. Such separation would have still further reduced the throat area, whilst an indication of the locally sonic conditions is given by the inclination of the train of weak shock waves spanning part of the throat flow. There was no obvious change to the shape of the flow boundary over the bleed gap when the bleed mass flow was varied, presumably because the maximum rate of turn of the flow at this boundary was limited by the pressure difference across it. Most of the bleed flow entered the slot at its extreme downstream edge.[16]

Figure 17 shows the behaviour of the four transducer outputs as the intake passed through the transition from stable operation to big buzz. All were connected to pitot tubes except No. 1, which measured the static pressure on the outer wall of the diffuser exit annulus. In each case buzz began with a sudden drop in pressure, but this was preceded by a slight rise in mean level at Transducer No. 2, which was at the downstream end of the intake throat. It is thought likely that this pressure rise was caused by the compression wave which was originated by choking of the throat flow and propagated upstream to initiate the first forward movement of the normal shock. Once the shock began to move forward, its continued motion upstream would have been assured by further reduction of the flow area in the throat, and it may well have moved as far upstream as the ramp tip. This wide range of shock movement is thought to be the principal explanation for the occurrence of the large amplitude big, rather than little, buzz. The oscillations probably continued in a manner similar to that described by Dailey,[4] with shock expulsion, accompanied by exhausting through both upstream and down-stream ends of the intake, being followed by super-critical operation. It is also possible to visualise isolated cycles of oscillation, as were encountered with Configuration C4, occurring through this mechanism.

Referring back to Fig. 8, the increasing amplitude of big buzz as the intake configuration was changed from that of C1 to C4, and similarly from B1 to B3, is thought to have been caused by the increased length of ramp ahead of the cowl lip, and a consequently increased range of shock movement. The reason for the change in amplitude between A1 and C1 is not clear—the ramp lengths ahead of the lip were identical—although the lower basic pressure recovery of Configuration C1 may well have contributed.

As stated in Section 2, big buzz in the Concorde intake was apparently initiated by the entry of a shear plane. However, it is thought likely that the mechanism of the oscillation also involved choking at the intake throat, as described above. The widely differing amplitude from that of little buzz is otherwise difficult to explain. The shear plane entry probably triggered an oscillation which would have been of relatively low amplitude had the normal shock not travelled sufficiently far upstream during the first cycle to cause the throat flow to choke. The amplitude of big buzz in the Concorde intake was, at 25 to 30 per cent of the free stream total pressure, somewhat lower than the amplitudes measured in the present tests and, it may be noted, the intake features a correspondingly shorter ramp. Thus its lower big-buzz amplitude fits into the pattern of the present tests in which big-buzz amplitude tends to increase with ramp length. Although the authors have no record of the big-buzz amplitudes of the intakes tested by Rolls-Royce (BED) it seems probable that the instability itself was initiated in a manner similar to that suggested for big buzz in the Concorde intake: Ref. 12 ascribes the wide stable margin of the Rolls-Royce (BED) design to the shock de-focussing. The wide margin might allow the terminal shock to be expelled upstream by throttling sufficiently far to cause a shear plane from the intersection of the terminal shock with the leading ramp shock to enter the intake. The total pressure difference across the shear plane would then be between 10 and 12 per cent, and on the basis of the earlier discussion this would be expected to initiate instability. Big rather than little buzz might then ensue according to the throat choking argument.

9. Further Work, and Application of the Results

The results demonstrate the avoidance of the instability referred to as little buzz through spreading the compression waves across a plane perpendicular to the ramp surface and passing through the cowl lip. The waves can be arranged so that they all pass between the cowl lip and the ramp surface, and thus into the intake, at a spacing providing a weak total pressure gradient across the compression fan. As has been observed, when taken by itself this merely implies a trade-off between pressure recovery and stability equivalent to that exploited in the familiar expedient of matching the intake, such that it normally operates in a super-critical mode. However, it has also been shown that a shear plane involving a total pressure discontinuity of about 6 per cent of the free stream total pressure can cross the cowl lip without promoting instability. A satisfactory design might therefore be based on a series of oblique shock waves so positioned that in critical operation they pass externally to the lip, and of strengths corresponding to the creation of 6 per cent total pressure discontinuities—or less—with the cowl shock expelled. The outstanding question concerns the minimum spacing which could be used between the shocks without exceeding the effective total pressure gradient discussed earlier. For example, in the limit the ramp shocks would focus adjacent to the cowl lip so that a consequent shear zone would feature a step change much greater than 6 per cent of the free stream total pressure. At the other extreme the shock waves can be envisaged as so far apart that they are substantially independent of each other.

It is therefore suggested that to produce a design eliminating little buzz and featuring minimum external drag, the ramp shocks should be so deployed that as the terminal shock advances upstream during an excursion into sub-critical conditions, the successive shear planes (of strength such that in their own right they do not generate instability) cross the cowl lip at the minimum spacing that will ensure their independence of each other. The type of design that emerges is illustrated in Fig. 18. The most down-stream of the ramp shocks lies against the cowl lip at the design point, thereby avoiding it giving rise to penalties on either pre-entry drag or theoretical shock recovery. Moving upstream the next ramp shock is so positioned that during sub-critical operation, as shown in Fig. 18(b), the two shear planes are sufficiently remote from each other for them to be effectively independent. An optimum positioning occurs when moving the shocks closer introduces instability and moving them further apart, instability having already been eliminated, merely increases pre-entry drag. It is interesting that the arrangement suggested in

Fig. 18 so nearly conforms with the intakes tested by Rolls-Royce (BED). The major outstanding query on the latter concerns the extent to which the ramp shocks might have been brought closer together, thus economising on pre-entry drag, without adversely affecting stability. A smaller point is that in view of the favourable effect on diffuser outlet flow distortions of isentropic compression[14] (by virtue, it is believed, of giving the sidewall boundary layers a smoother pressure rise) it might be beneficial to substitute an isentropic curve for the central ramp shock. This could be arranged without affecting the basic stability argument. However, it is thought likely that the favourable effect of this substitution would not be apparent, other than in a high performance intake already featuring a low 'extra to shock' loss.

The possible influence of subsonic diffuser length was mentioned earlier. There is clearly scope for further work here, as well as in determining the most favourable ramp shock disposition. A suitably designed diffuser may, by easing the static pressure gradient, render possible somewhat stronger ramp shocks at a closer spacing than is supposed above. On the other hand it could be that the critical pressure rise is that occurring in the throat of the subsonic diffuser. This may be primarily a function of the terminal shock pattern and less dependent on the diffuser shape.

Summing up, many questions evidently remain to be answered. However, the deductions that have been made from the experimental results reviewed seem to offer serious hope for the beginnings of a rational method of design taking due account of little buzz. There remains of course the question of tackling big buzz. If the diagnosis of throat choking in the present tests is correct then an obvious first step is to provide ramp bleed upstream of the existing slot, to reduce the separation occurring during sub-critical operation. This measure was adopted with good effect in the experiments reported in Ref. 17. It seems feasible that a configuration of slots or performations could be aerodynamically pressure balanced so that no flow passed under normal conditions.

10. Conclusions

The mass flow margin against instability in variable ramp intakes consequent on the entry of shear planes or zones to the subsonic diffuser is a function of the pre-entry drag at the critical condition. To secure a required stability margin with minimum external drag it is therefore important to understand properly methods of controlling the processes initiating instability. These were investigated experimentally with a range of model variable-ramp intakes which, whilst inevitably restricted, incorporated features typical of current intake technology such that the results are thought not unduly restricted in practical application. The tests were made at a Mach number of 1·9, and combine with tests made at similar Mach numbers at Rolls-Royce (BED) and earlier tests at N.G.T.E. to provide a consistent picture of intake instability at this level of flight speed.

On the evidence of the tests a hypothesis was advanced: a shear zone having a given total pressure difference across its width initiates instabilities which vary in extent according to the total pressure gradient across the zone. A sufficiently steep gradient can cause instability when it is in contact with, or close to, the cowl lip. On the other hand a weaker gradient can be in contact with the lip without causing instability. If the total pressure difference across the shear zone is sufficiently reduced, then even an infinite gradient, i.e. a pure shear plane, can make contact with the cowl lip without causing instability. The mechanism of the instability apparently involved flow separation from the internal surface of the cowl.

A second phase of instability analogous to big buzz in the Concorde intake, and involving oscillations of a higher amplitude, is thought to be associated with separation of the ramp boundary layer. A discussion of the smaller oscillation, or little buzz, has led to proposals for a rational design method apparently offering the minimum pre-entry drag consistent with freedom from the instability.

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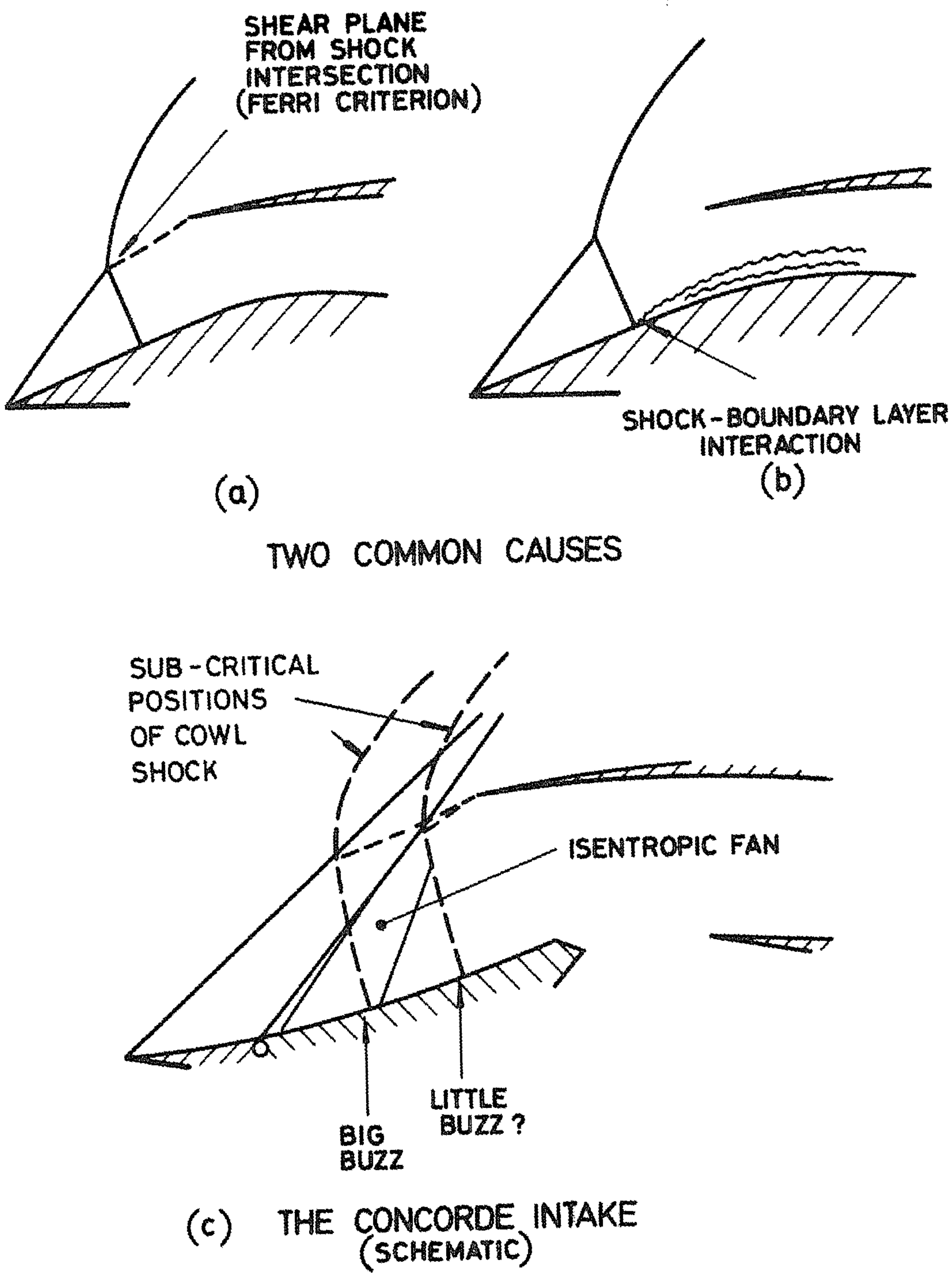


FIG. 1. Origins of intake instability.

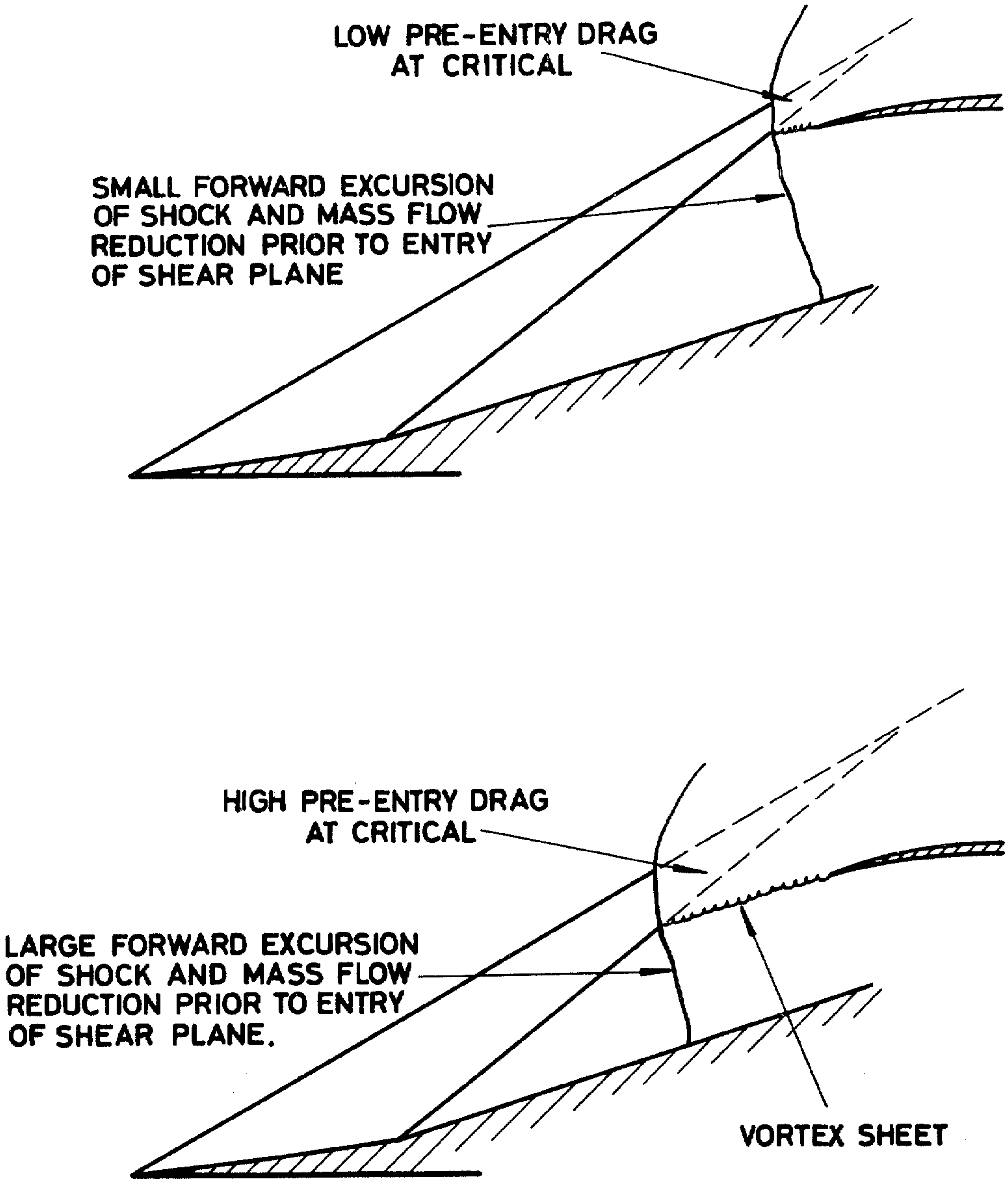


FIG. 2. Relationship between Ferri type instability and pre-entry drag.

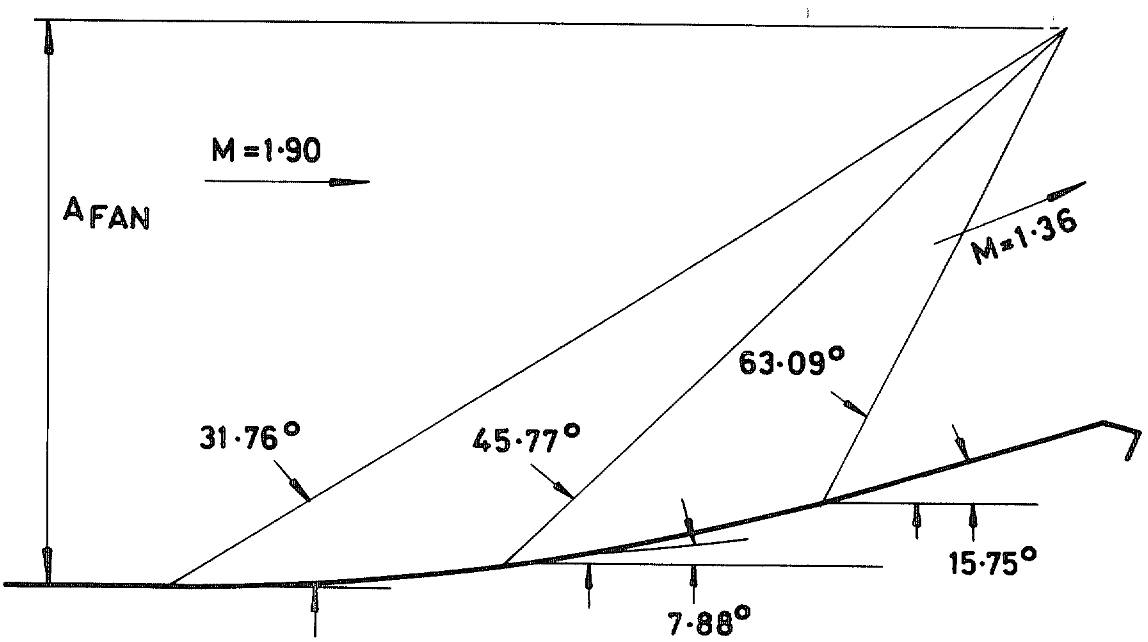


FIG. 3. Supersonic compression field.

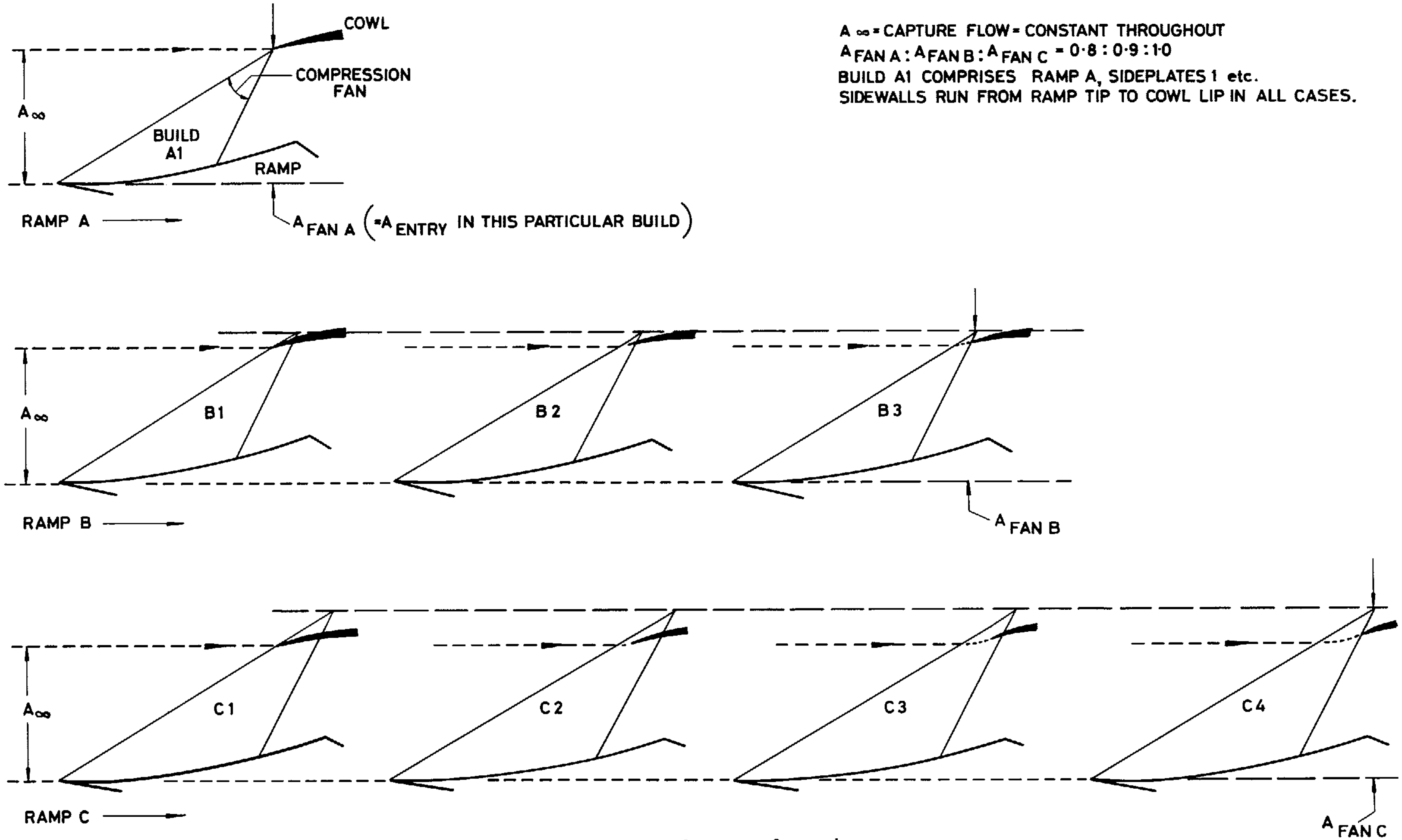
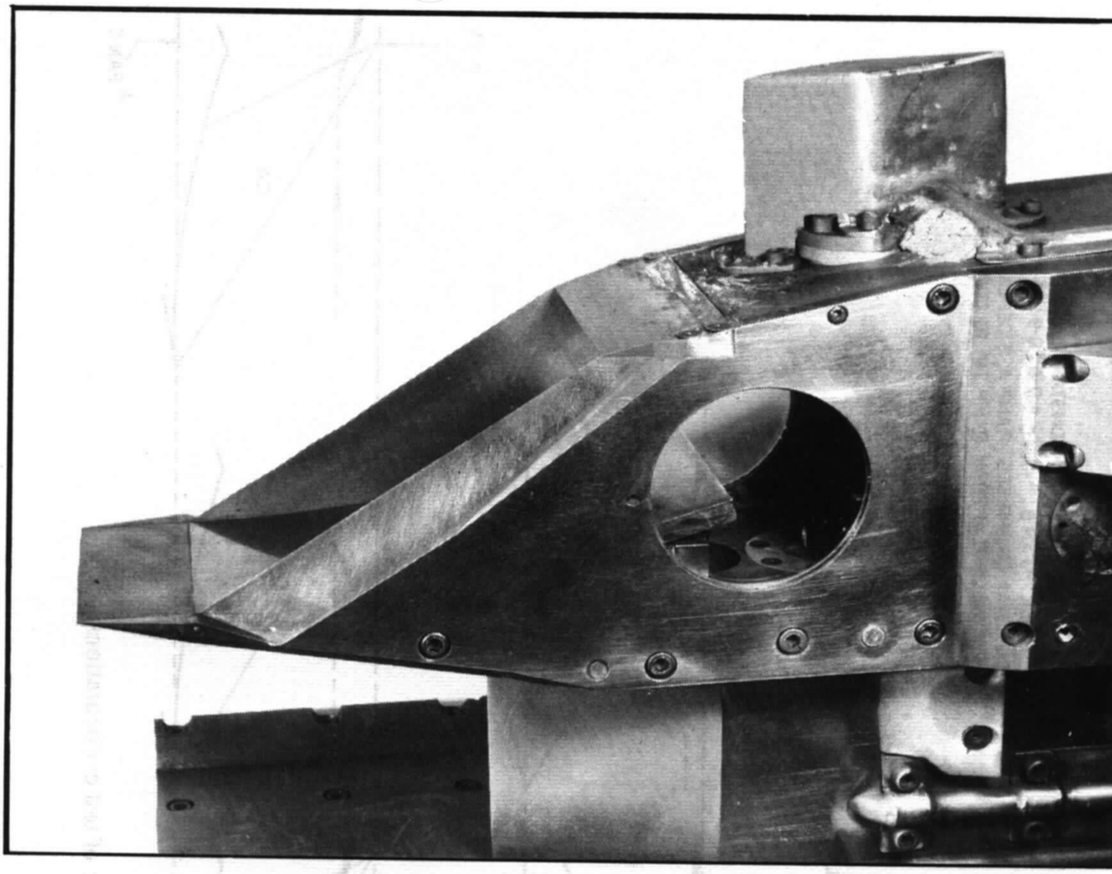


FIG. 4. Range of test configurations.



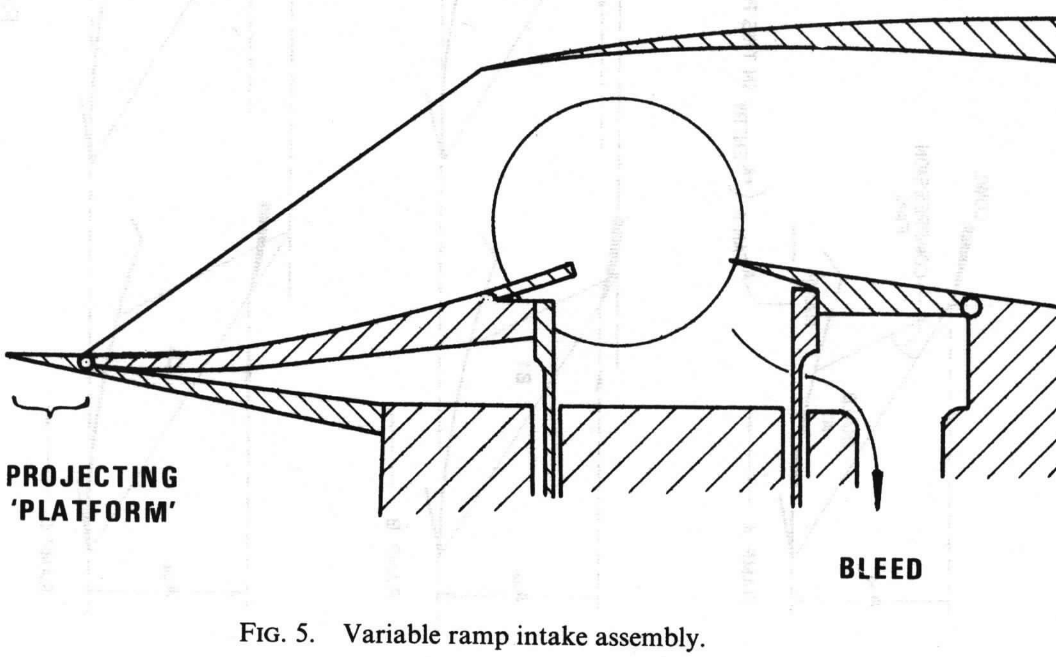
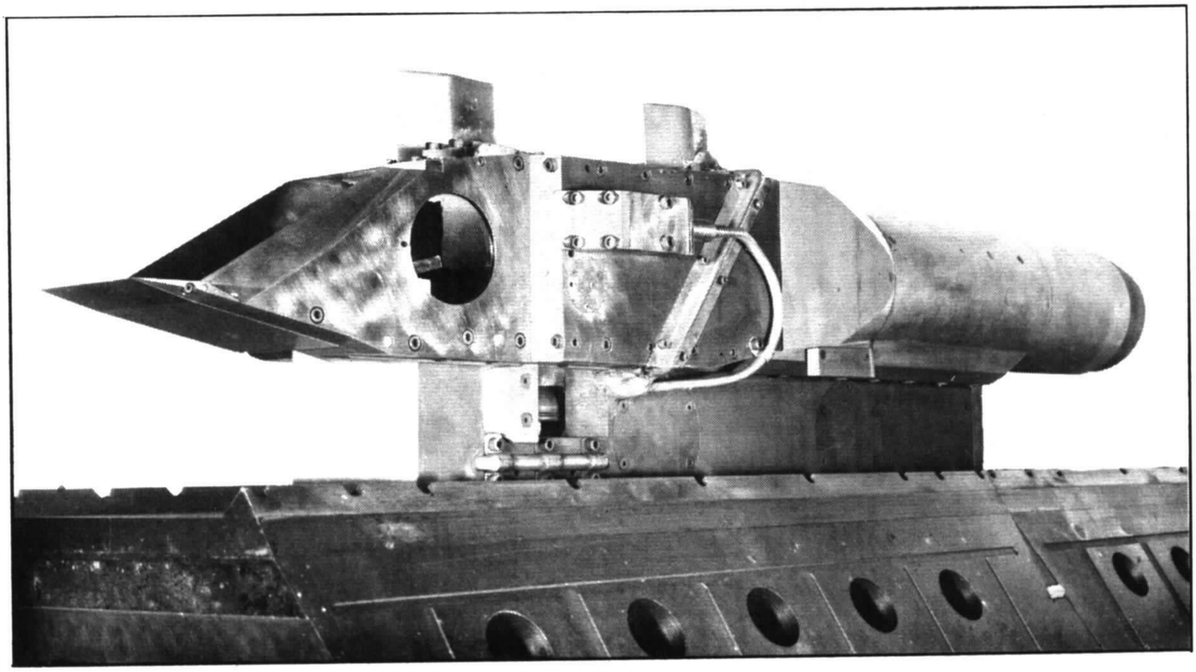


FIG. 5. Variable ramp intake assembly.



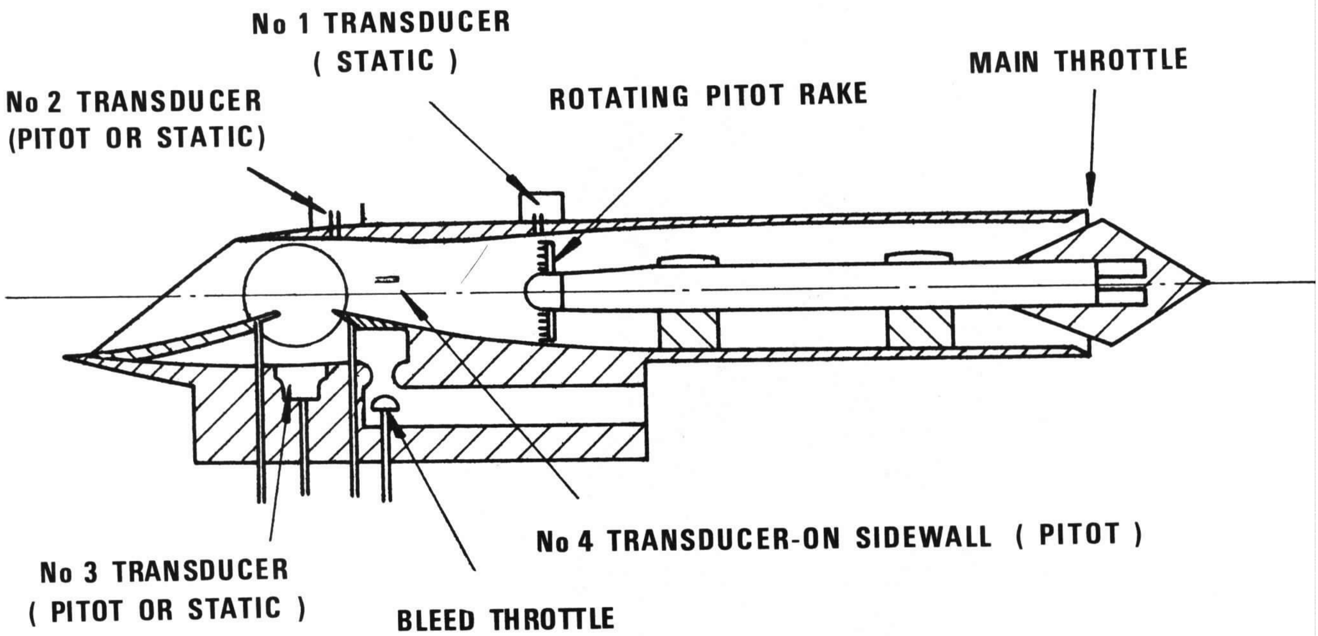
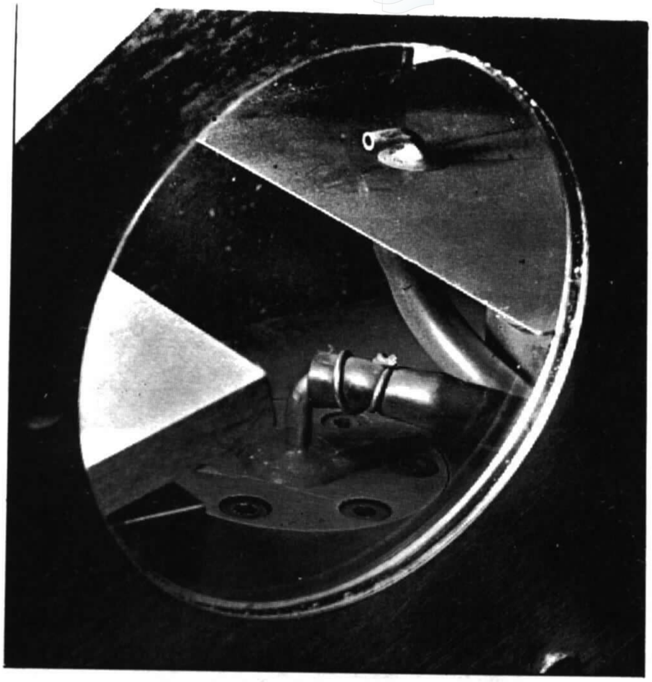
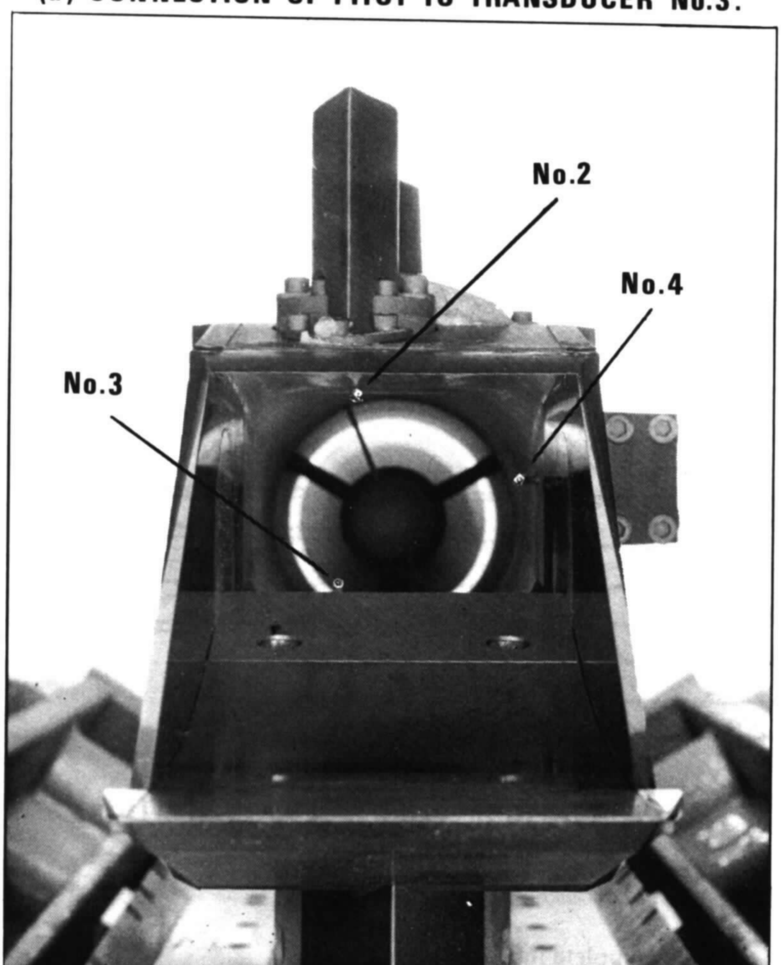


FIG. 6. The complete intake model.



(a) CONNECTION OF PITOT TO TRANSDUCER No.3.



(b) TRANSDUCER PITOTS MOUNTED IN SUBSONIC DIFFUSER

FIG. 7. Model instrumentation.

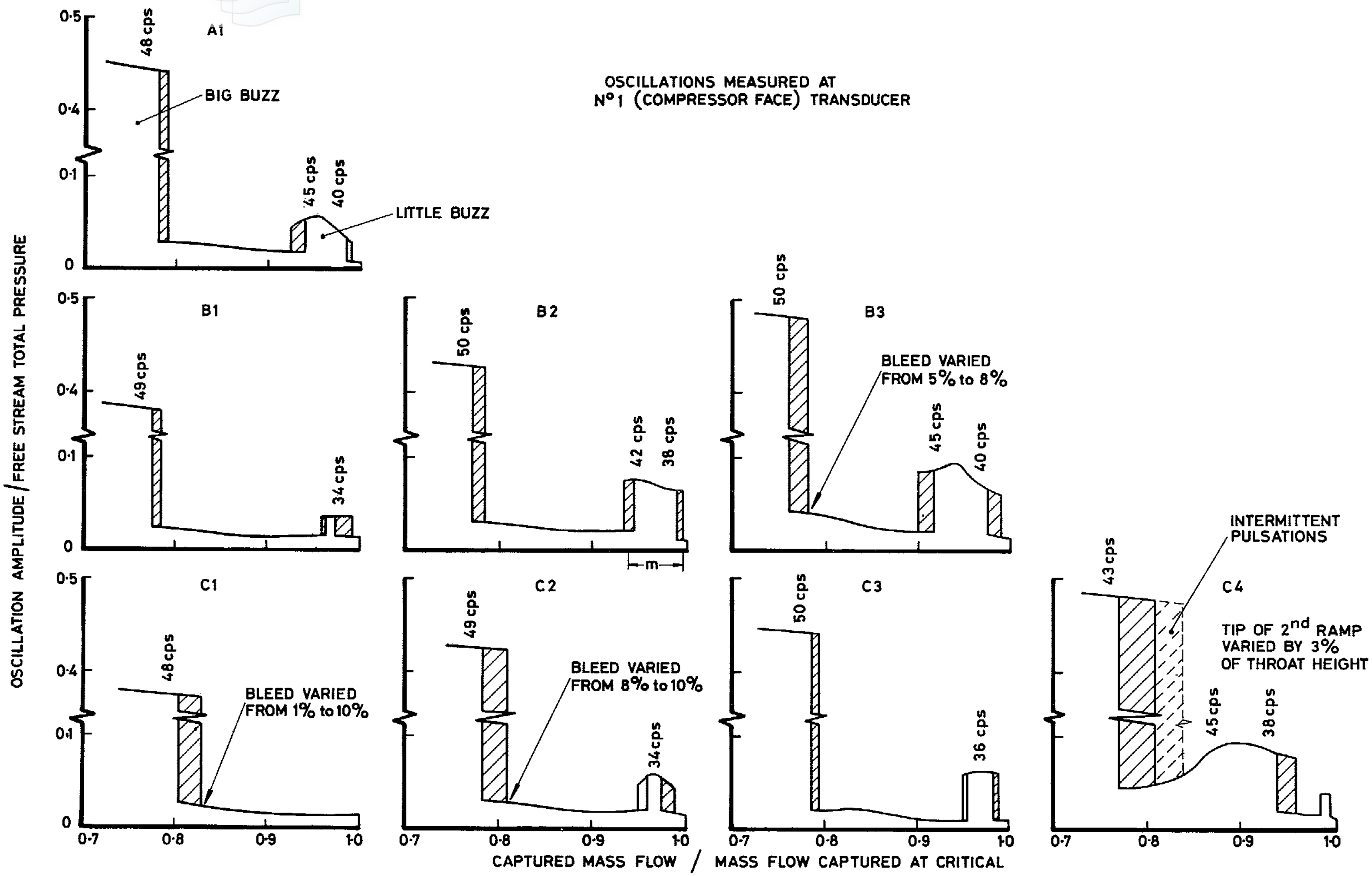


FIG. 8. Subcritical stability characteristics.

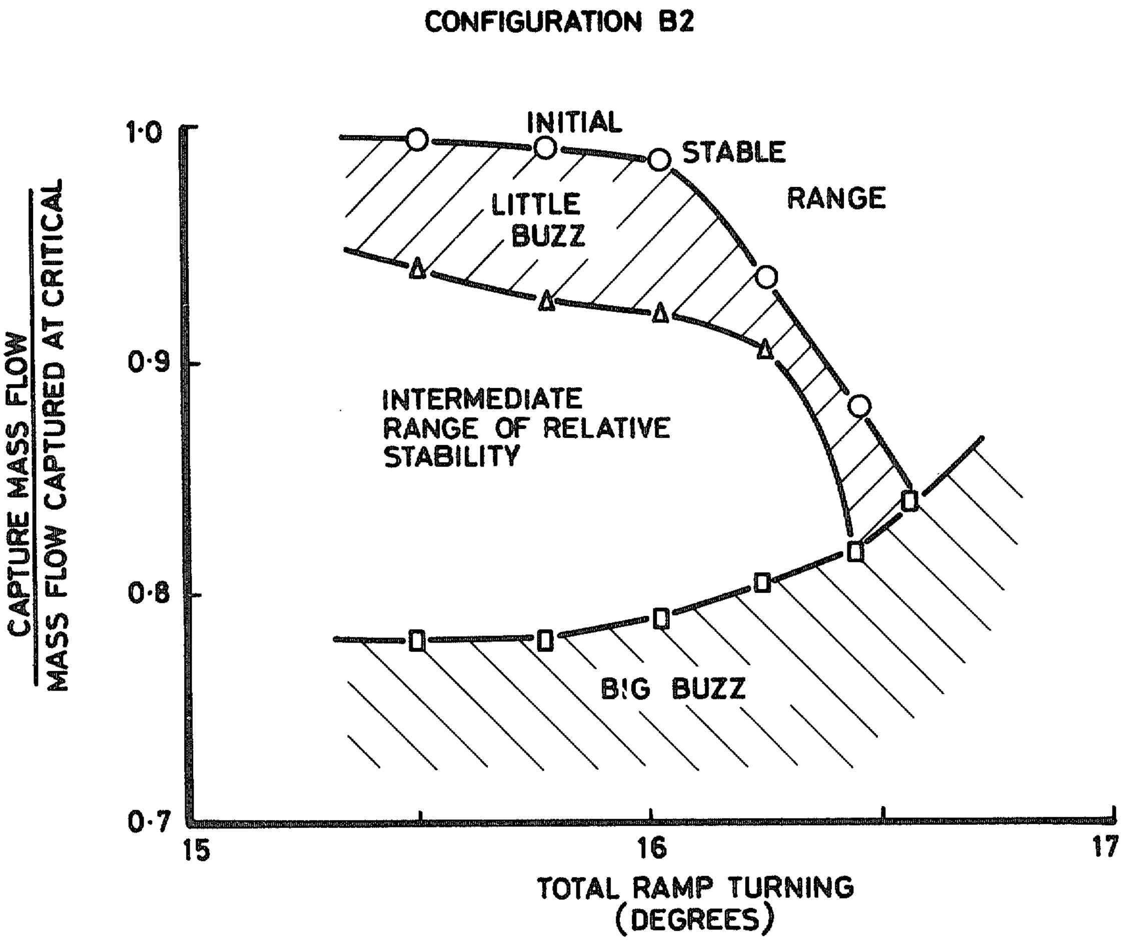


FIG. 9. Effect of ramp angle on stability.

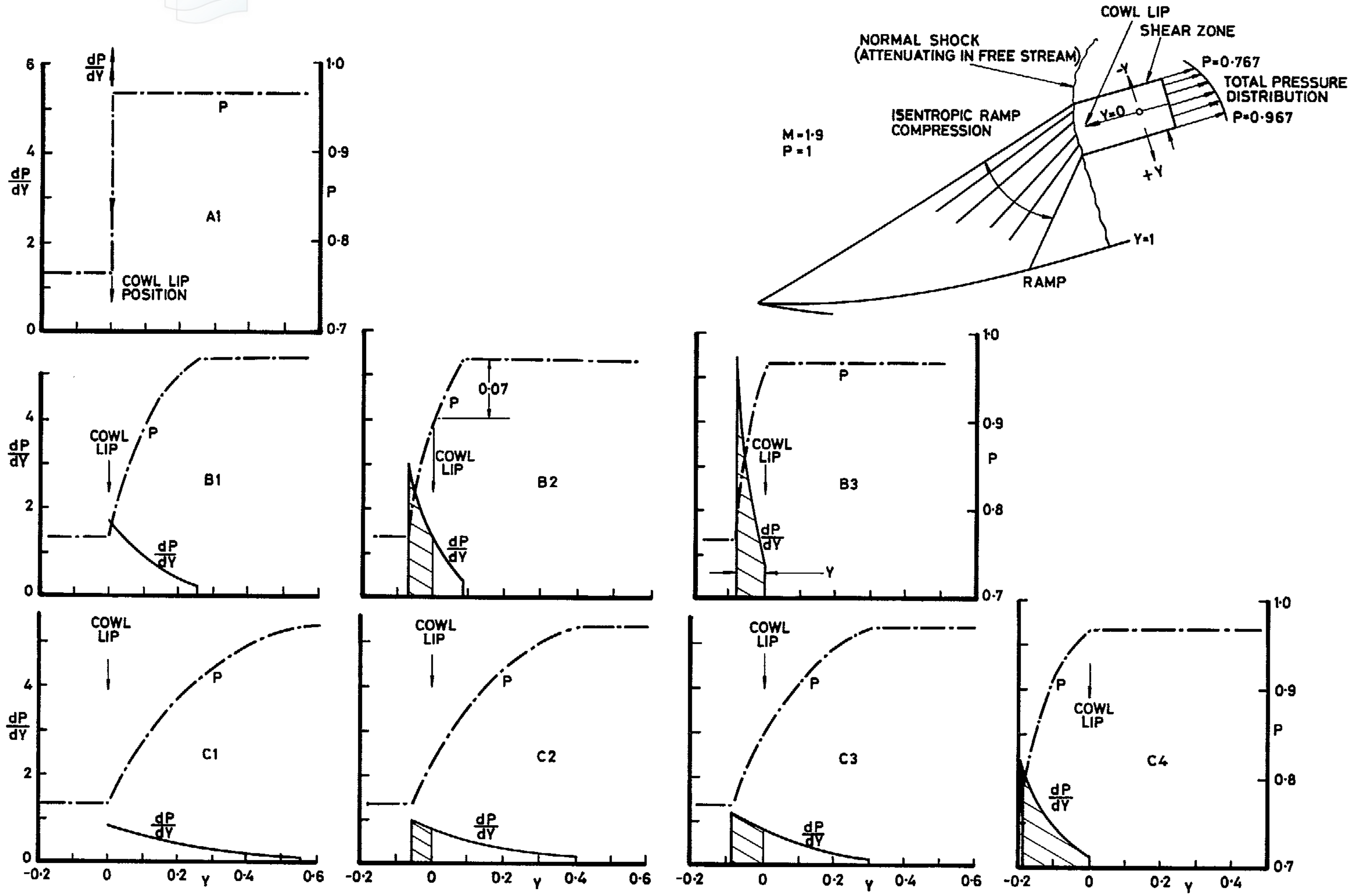


FIG. 10. Total pressure gradients at cowl lip.

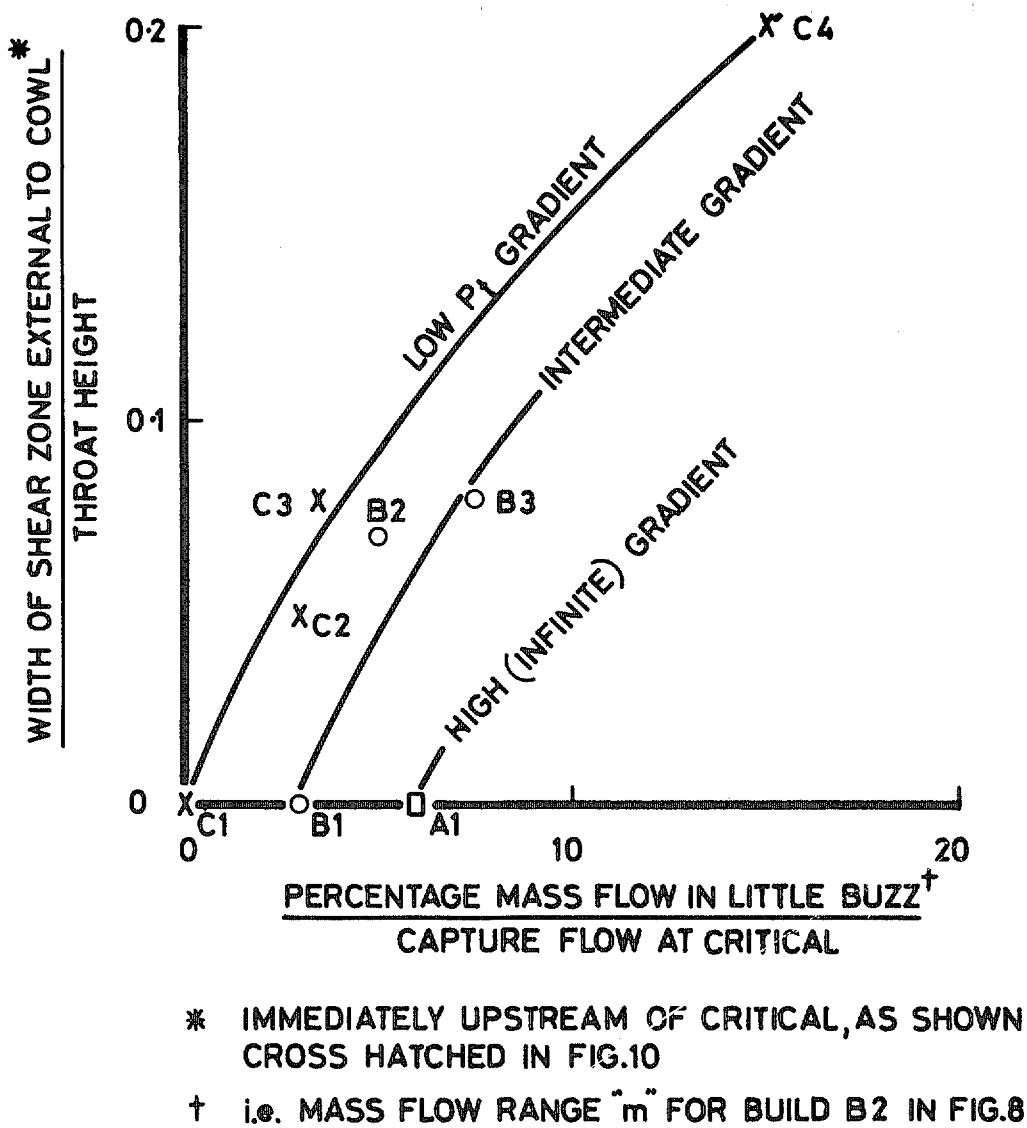


FIG. 11. Instability ranges to little buzz.

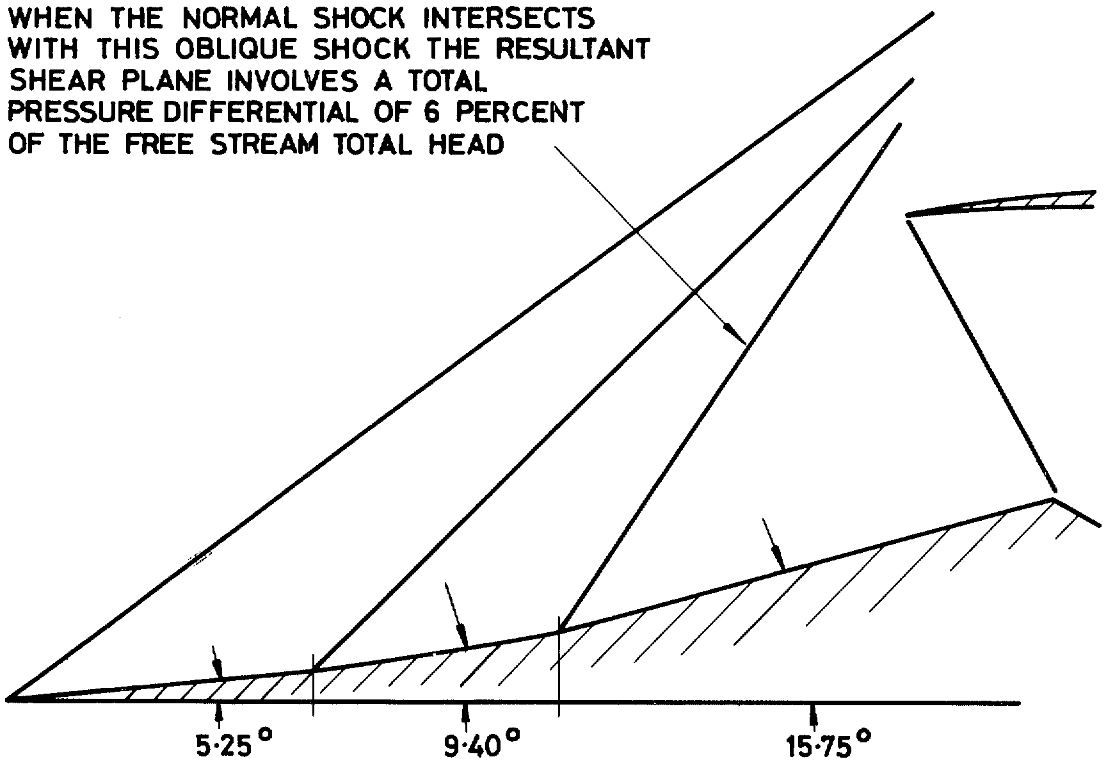


FIG. 12. Intake with 3-shock ramp.

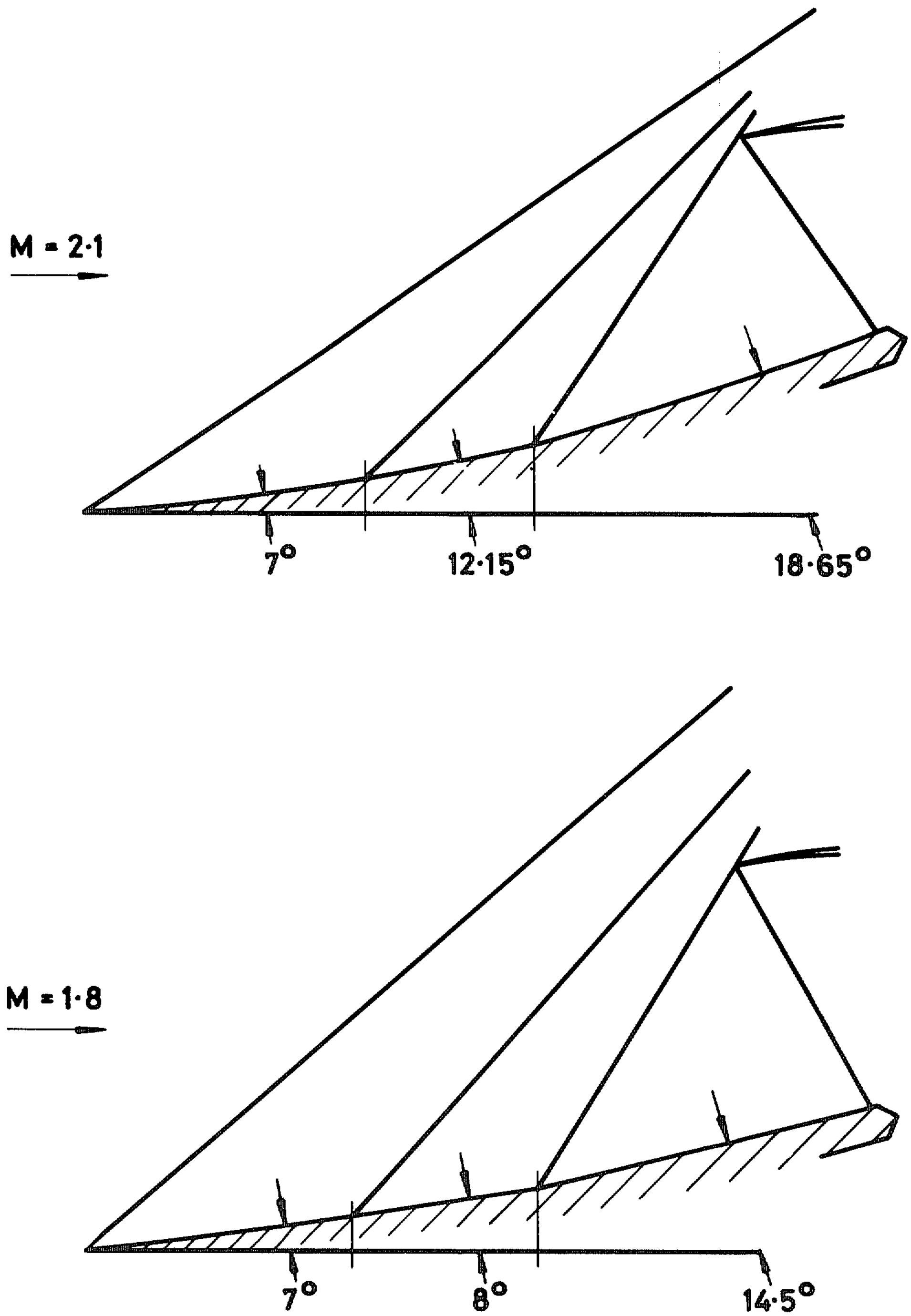


FIG. 13. The shock geometries of Ref. 12.

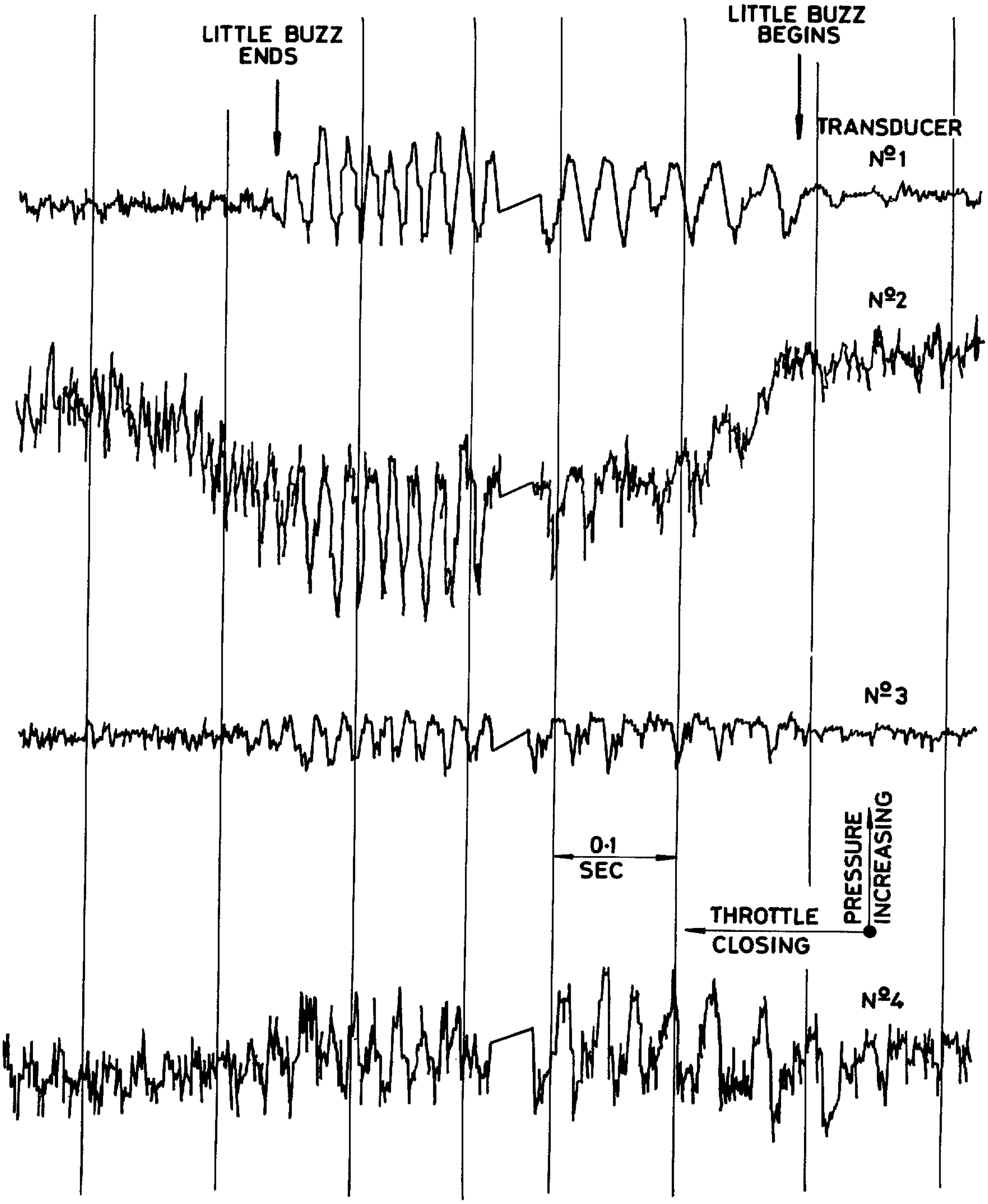


FIG. 14. Transducer recordings through little buzz—model configuration B3.

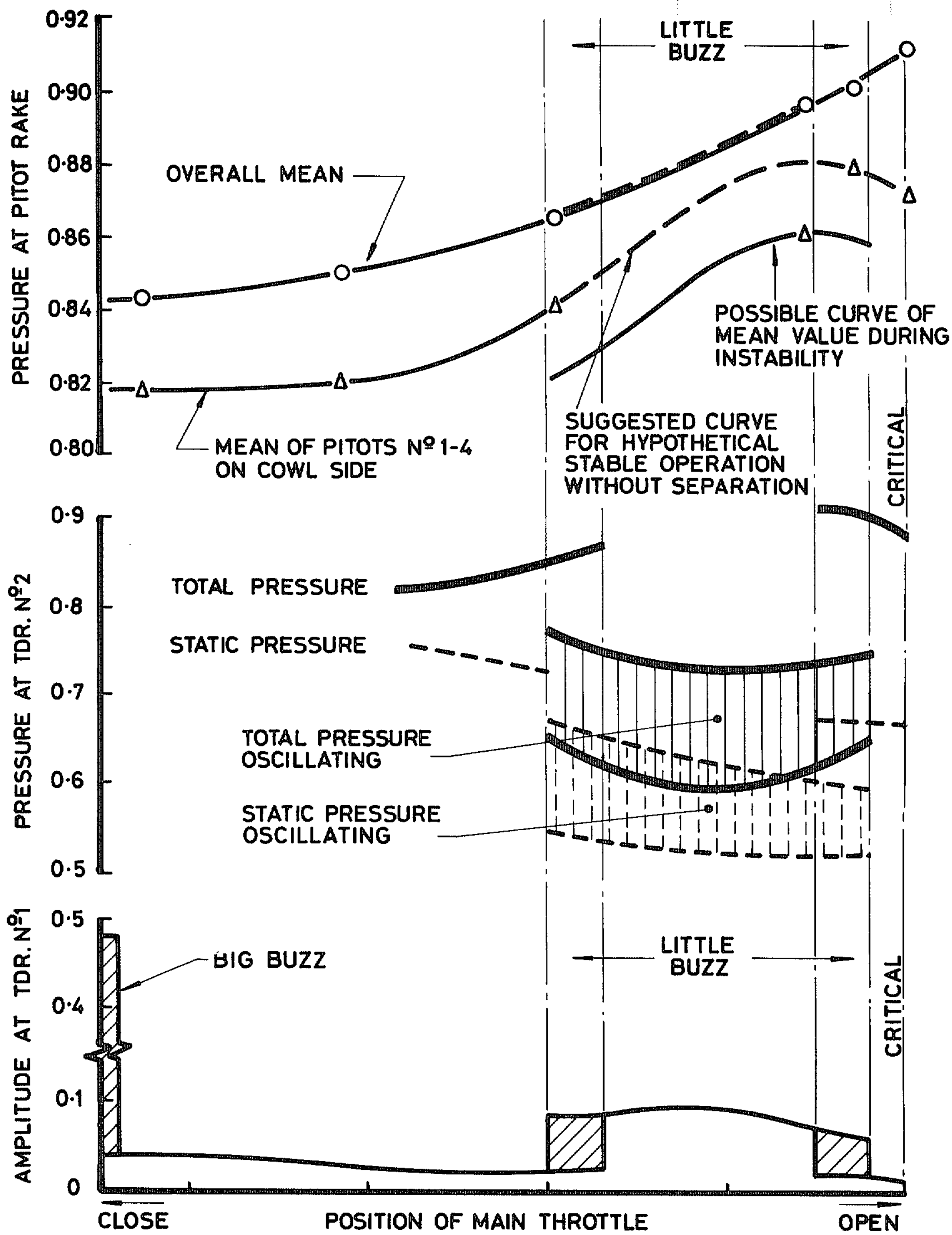
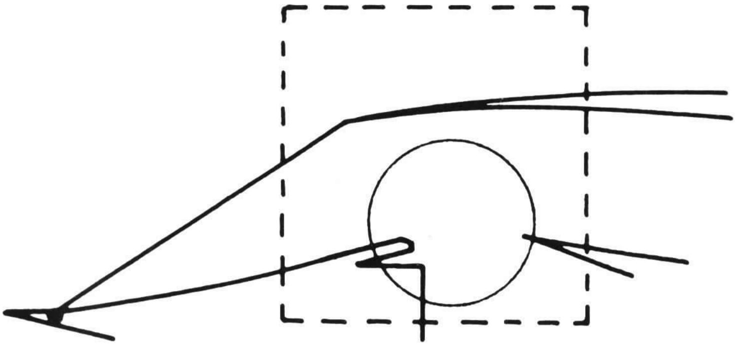


FIG. 15. Evidence of cowl side separation in little buzz—configuration B3.



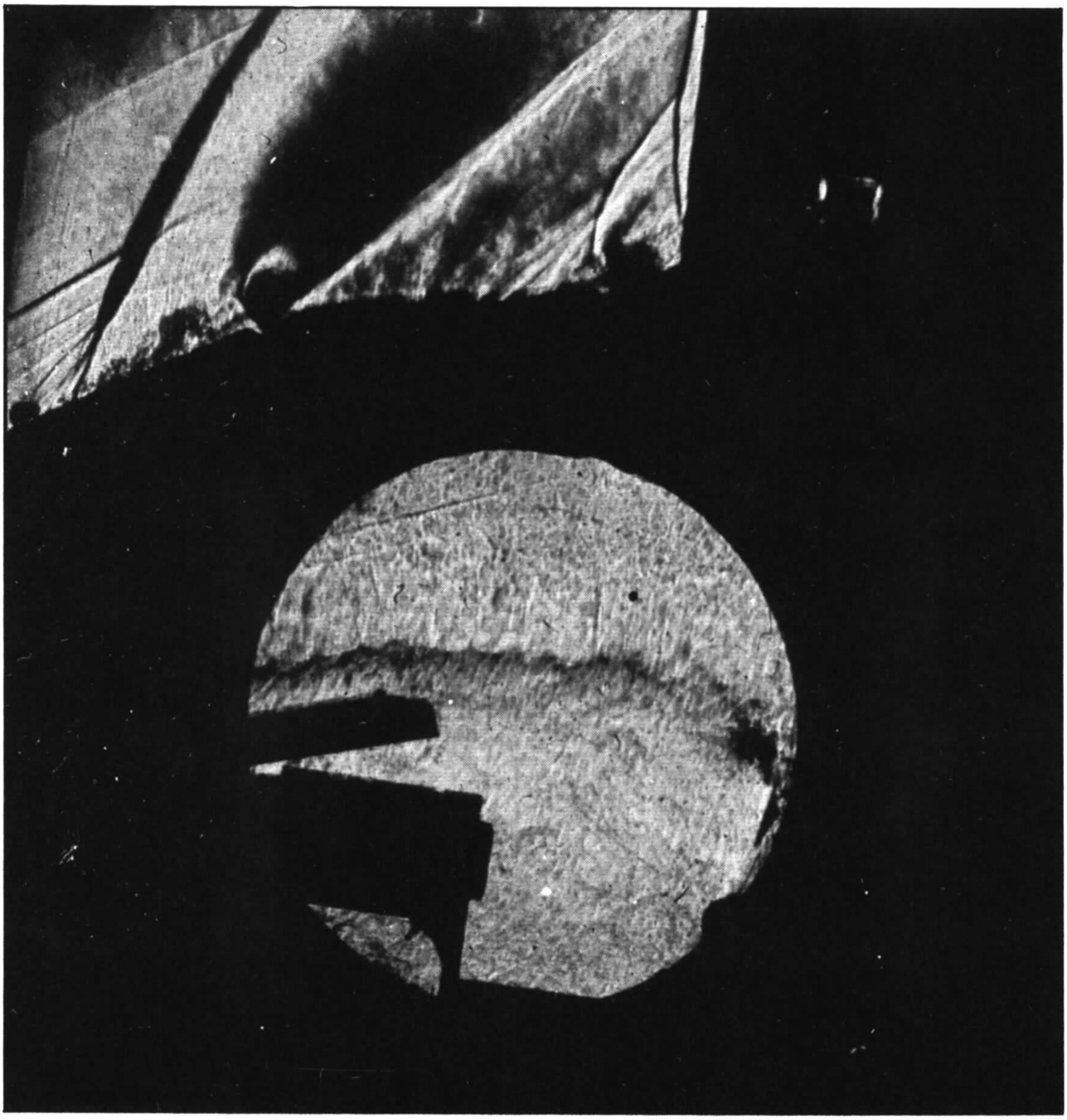


FIG. 16. Intake throat flow prior to onset of big buzz.

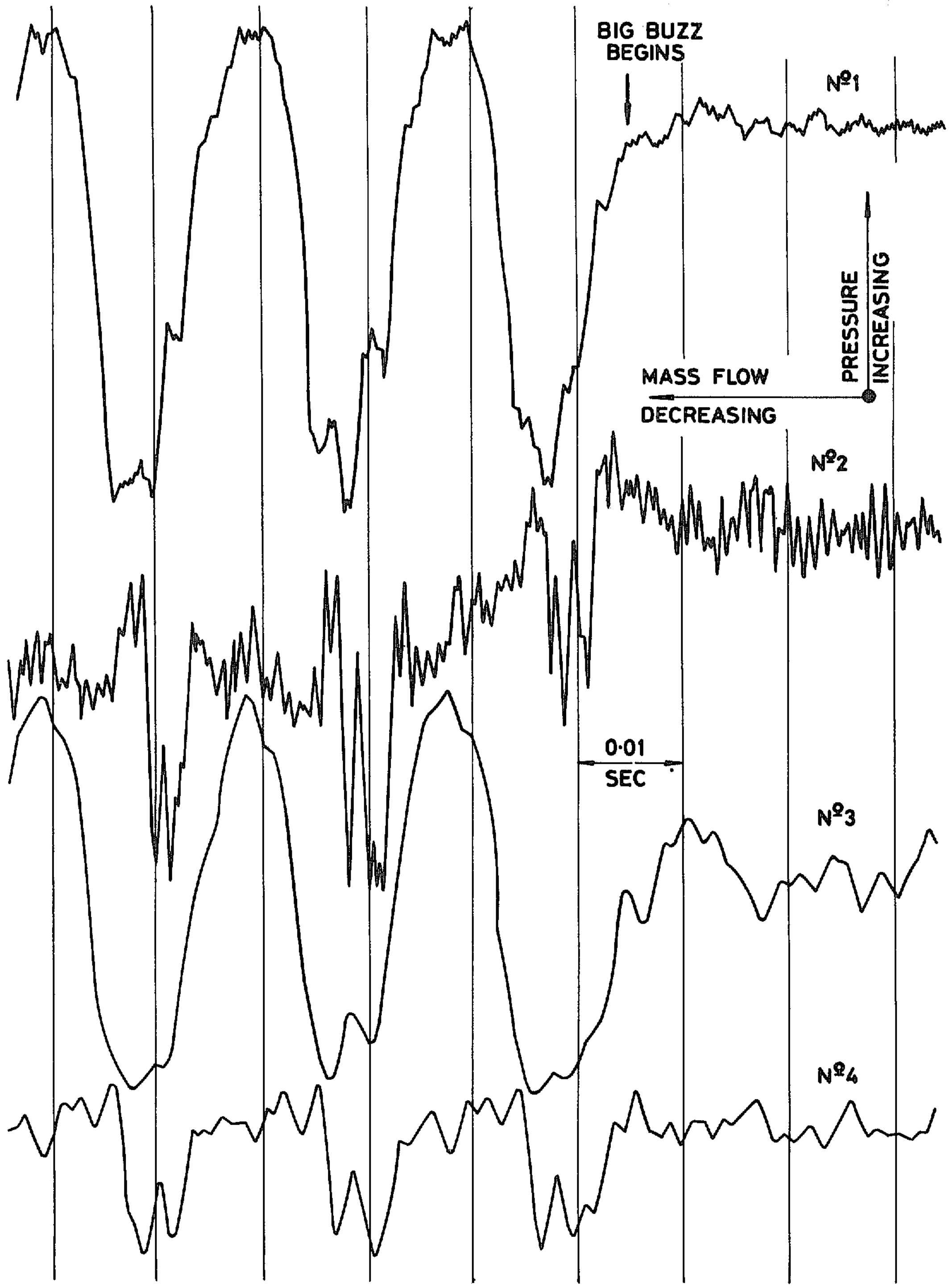
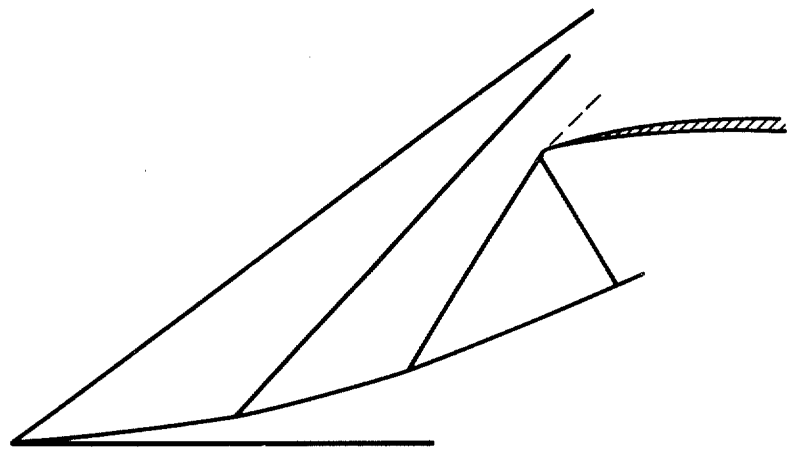


FIG. 17. Typical recording into big buzz.



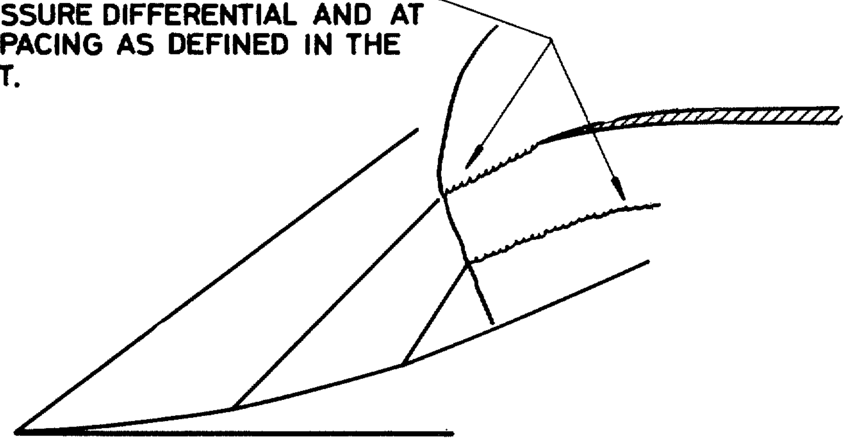


FIG. 18. Proposal for optimised intake design.

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