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FURTHER MEASUREMENTS OF TRANSIENT PRESSURES ON A NARROW-DELTA WING DUE TO A VERTICAL GUST

by

D. R. Roberts
G. K. Hunt

SUMMARY

Transient pressures have been measured on the upper surface of a narrow-delta wing when it passed through nearly sharp-edged upward and downward gusts.

Some characteristics of the transient behaviour of the vortex flow on the wing have been identified and discussed.

It is shown that a gust-induced loss of lift on this kind of wing develops more rapidly than a gust-induced gain of lift, and thus produces the greater change of loading.

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* Replaces R.A.E. Technical Report 66124 - A.R.C. 28190

CONTENTS

1 INTRODUCTION

About five years ago a research facility was developed at R.A.E. Farnborough to investigate the transient effects induced on lifting surfaces by a discrete gust. A model wing is carried along a straight railway track on a rocket-propelled sledge, through the efflux from an open-jet wind tunnel blowing across the track. This facility is fully described in Ref.1, where the first measurements of gust-induced transient pressures are presented; these show the effect of an upward gust approached at zero incidence.

Since then several detailed improvements have been made to the facility. The number of data-transmission channels has been doubled, enabling pressures to be measured at four points instead of two; the model can be propelled along the track at a finite angle of incidence; and measurements can be obtained during departure from the tunnel jet as well as during entry into it. In addition a new miniature pressure transducer has been developed, expressly for use with this facility, and a new model has been built which retains the narrow delta planform of the original model but has rhombic cross-sections. This report describes these developments and presents the first results obtained by using all the capabilities of the facility in its improved form.

If a gust is defined as a single change in the velocity of the ambient air, measured normal to the flight path, then the two sides of the tunnel jet are effectively separate gusts. The width of the tunnel is twelve times the mean chord of the model, and this is sufficient to obviate interference between the effects of the two gusts. When the plane of the wing is normal to the tunnel axis, as in all the experiments completed so far, the gusts are effectively upward and downward relative to the wing and thus induce a gain and a loss of lift.

The experimental results show that the transient behaviour of the vortex flow over the wing is different in the two cases. The development of a gust-induced gain of lift is gradual and substantially independent of the initial angle of incidence. A gust-induced loss of lift occurs relatively abruptly if it reduces the lift to zero, and thus imposes the more severe loading on the wing; what happens when the lift is reduced to a finite value remains to be investigated.

2 EXPERIMENTAL TECHNIQUE

The experimental technique is basically similar to that described in Ref.1, but some detailed changes have been made. Experimental measurements are confined to pressures, and are obtained by means of transducers set in the surface of the wing. Recording equipment cannot be carried on the sledge, and is installed on the ground beside the track. Since continuous records of the transducer outputs are required in order to define the transient variation of pressure induced by the gusts, a separate transmission channel is provided between each transducer and the recorder. At present the number of pressure measurements that can be made simultaneously is limited by the small number of data channels that are available.

2.1 Data transmission and recording system

A diagram of the system is set out in Fig.1. Each pressure transducer is connected to a separate oscillator, whose output is frequency-modulated by variations in the capacitance of the transducer. The oscillators are built into the model as close as possible to the transducers in order to keep the connecting cables short and thus to minimise the effects of cable capacitance. All necessary power supplies are carried on the sledge, and connections between the sledge and the model are made through a flexible cable. The oscillators are all tuned to slightly different frequencies, and this allows their signals to be mixed and fed to one of two knives attached to an outrigger at the side of the sledge; the second knife provides an earth connection. The signals are conveyed by the knives to two strips of copper gauze secured in clamps beside the track, and from there by a screened cable to the common input connection to a group of amplifiers. The mixed signals are separated by the amplifiers, which are tuned to the same frequencies as the oscillators and are sufficiently selective to ensure that each amplifies only the signal from one oscillator. In this way, "cross-talk" between one channel and another is effectively eliminated. The output of each amplifier is fed to a discriminator, which gives a D.C. voltage output approximately proportional to the signal frequency and thus to the pressure applied at the transducer. This voltage is applied to one of the tubes of a multitube oscilloscope, and the resultant trace is recorded on a continuous photographic paper strip.

The discriminators are standard proprietary items, and were chosen because they were readily available, thus avoiding the delay involved in developing and manufacturing special units. The limited bandwidth of the discriminators restricts the number of data channels to four. The installation of longer copper gauze strips now allows recording of pressure measurements during the passage of the model right through the tunnel efflux.

Two tubes of the recorder are used to record the velocity of the sledge and the position of the model. A permanent magnet fixed to the underside of the sledge passes across a series of coils fixed to the railway track at known positions; the resultant e.m.f. induced in each coil in turn is recorded, and in conjunction with the timing marks on the record, provides data from which the velocity of the sledge is calculated. There is a special group of six closely-spaced coils near the tunnel. Since the speed of the sledge remains virtually constant during the short time that it takes to pass through the tunnel jet, the pulses from this group of coils form a convenient linear scale on the record. A beam of light crossing the railway track in line with the edge of the tunnel efflux impinges on a photo-electric cell, the output of which is connected to the remaining recorder tube. When the model interrupts the beam the cell output level is lowered, showing on the record the time when the model passes the cell. Since the speed of the model is known its position relative to the gust tunnel at any time can be calculated.

2.2 Pressure transducers

The pressure transducers used on the early experimental runs of the gust facility were of a type developed by Owen[2]. Although these instruments were adequately sensitive to the pressure changes being measured, and had a fast response-time, their physical dimensions prohibited the measurement of pressure-changes at points in close proximity to each other, or to the leading-edge of the model. In addition, they were found to be very sensitive to the vibration experienced on the sledge-borne model, and to the ingress of dust particles during the experimental runs, necessitating frequent repair and recalibration.

In an attempt to overcome these disadvantages, some smaller transducers of a similar type were developed; one of these instruments is shown in Fig.2. The pressure is measured at an orifice, which is connected to a small chamber, one wall of which consists of a diaphragm of "Melinex"* coated on one side with aluminium. The aluminium coating acts as the moving plate of a variable capacitor, the fixed plate being an insulated disc in the transducer body. Thus, a change in the pressure applied at the orifice causes a change in capacity between the two plates; the change of capacity produces a change in the frequency of the oscillator associated with the pressure-transducer.

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*"Melinex" is the I.C.I. registered trade name for polyester film made from polyethylene terephthalate.

Since each transducer measures the pressure differential across the diaphragm, a reference pressure is provided by connecting the cavity on the side of the diaphragm remote from the sensing orifice to a reference-pressure chamber. This chamber is sealed at atmospheric pressure prior to each experimental run.

A full static pressure calibration was performed on each pressure transducer under laboratory conditions. As a check before each experimental run, two known pressures were applied in turn to the reference pressure chamber, and hence to the reference connections of all the pressure transducers, while a short recording was made through the data transmission system.

Since the purpose of the experiments was to investigate transient phenomena a dynamic calibration of the complete pressure-measuring system was carried out by subjecting the transducer to a step change of pressure in a shock tube[3]. The resulting record is reproduced in Fig.3 and shows that, although the transducer is somewhat overdamped, the complete system has a rise-time of about one milli-second and that there are no acoustic or electronic transients.

2.3 The model

The model used to obtain the data has the same planform as the model described in Ref.1, and is shown in Figs.4, 5 and 6. The model is a narrow delta wing, of length 30 inches and span 18 inches. The section in any plane perpendicular to the longitudinal axis is rhombic; the rear half of the model has a constant centre-line thickness of 3 inches, and the centre-line profile over the front half is bi-convex. The leading-edges are sharp, and the trailing-edge is perpendicular to the model longitudinal axis.

An aluminium-alloy centre-plate forms the load-bearing spine of the model, and the required wing thickness distribution is obtained by adding laminations of teak. The wood is fixed permanently to one side of the centre-plate, and the pressure transducers are recessed into it so that their faces are flush with the wing surface. Part of the teak on the other side of the centre-plate is detachable, providing access to the backs of the transducers, to the oscillators and reference pressure chamber, and to all the connections between them. The reference pressure chamber is provided with a pipe leading to the exterior of the model at the trailing edge; this end of the pipe can be closed with a sealing screw.

2.4 The model suspension

The model is mounted on the front of an aerodynamically stable dart, which is suspended from the frame of the sledge by a helical coil spring and a gymbal. This device effectively isolates the transducers from the vibrations induced in the sledge by the rocket-motor combustion and track irregularities.

The model was propelled along the track with the plane of the wing vertical. Since the tunnel efflux was blowing horizontally across the track, this arrangement simulated the passage of a wing in level flight through two gusts, one upward and one downward. In these experiments the upper surface of the model was defined as the surface remote from the gust tunnel, and the efflux was regarded as having an upward velocity relative to the wing.

The attachment of the model to the dart includes a knuckle joint, which allows the model to be set at any angle of incidence up to 15 degrees, relative to the dart axis.

The stabilising tail-fins of the dart have been enlarged since the experiments described in Ref.1, to minimise the effect of a change in model incidence on the trim of the dart.

3 EXPERIMENTAL RESULTS

3.1 Records

Measurements have been made of the air pressure at certain points on the model upper surface, by means of the transducers A, B, C and D, see Fig.4. Provision was made for mounting transducers at various positions, but in these experiments they were sited at stations 30%, 40%, 50% and 60%, of the model length aft of the wing apex, and lay on the ray from the apex at 25% of the local semi-span inboard from the leading edge.

Data were recorded from the position-coils and from the photo-electric cell during the whole journey of the sledge along the track; data from the pressure transducers were recorded only when the knives on the sledge were cutting the copper gauze strips.

A typical photographic data record obtained during one traverse of the tunnel efflux, is shown in Fig.7. The velocity of the sledge was 180 ft per second, the tunnel efflux velocity was 47 ft per second, and the model was at zero angle of incidence relative to the dart. The peaks in the position-coil output trace show the times when the sledge traverses each coil. The trace from the photo-electric cell output indicates a number of occasions when the light-beam has been interrupted. These "dips" in the level of the trace represent the passage through the light-beam of the model, followed by various parts of the sledge structure.

During the passage of the model through the upward gust, the traces from the four pressure transducer outputs follow the same general pattern as the traces shown in Ref.1. The gust-induced pressure change registered by each transducer does not begin until the transducer encounters the leading edge of the gust; subsequently the form of pressure change registered by all four transducers is the same. There is an approximately exponential approach to the pressure associated with the new angle of incidence induced by the gust. On many of the records the first part of the exponential curve is masked by a more rapid pressure change which sometimes leads to a distinct suction peak (Fig.8).

All the pressure records indicate considerable turbulence in the tunnel jet. This is shown clearly in Fig.7 by the change in the character of the trace from each transducer as it passes through the upward gust.

During the passage of the model through the downward gust, each transducer responds only when it reaches the leading edge of the gust, and then the pressure reverts very rapidly to the level associated with conditions beyond the gust.

In addition to the photographic records referred to above, the angle of incidence of the model relative to the dart and the tunnel efflux velocity have been recorded for each experimental run. The runs performed are summarised in the table below:-

Run No.	Model incidence on dart (degrees)	Data obtained	
		Upward gust	Downward gust
63	0	Yes	No
69	0	Yes	No
72	0	Yes	Yes
73	0	Yes	Yes
74	0	Yes	Yes
75	0	Yes	No
79	0	Yes	No
80	5	Yes	No
82	5	Yes	No
85	10	Yes	No

3.2 Analysis and presentation of results

The data obtained were analysed in the way described in Ref.1. The mean initial and final levels were obtained, and an exponential curve was fitted to the traces with the final level as its asymptote; for this purpose the trace for the first few milliseconds was ignored. The co-ordinates of this smoothed curve were then read directly in terms of p/p_0, the fraction of total pressure change, and x_n/b_n, the distance penetrated into the gust expressed as a multiple of the local span at the section containing the transducer. (See Fig.8.) The smoothed curves so obtained are presented in Figs.9 to 14.

The curves relating to passage through the upward gust are presented separately for each run in Fig.9. Fig.9a presents the results for which α, the angle of incidence of the model relative to the dart, is zero, and the curves from all four transducers are shown on each graph. Similarly, Fig.9b and Fig.9c present the results for which $\alpha = 5°$ and $\alpha = 10°$ respectively. On the single run depicted in Fig.9c, only the two transducers nearest the model apex furnished readable records. A summary of all the measurements made during runs through the upward gust is given in Fig.10, in the form of the envelopes containing the individual curves obtained at $\alpha = 0$, $\alpha = 5°$ and $\alpha = 10°$ respectively. Also shown in Fig.10a is the envelope containing the curves in Ref.1.

The curves relating to passage through the downward gust are presented separately for each run in Fig.11 and are summarised in Fig.12. The summarised results for the upward and downward gusts are compared in Fig.13.

The distribution of air speed across the tunnel jet, in the plane of the track centre line, is shown in Fig.15. The kinematics of entry into the tunnel jet and of departure from it are illustrated in Fig.16.

4 DISCUSSION OF RESULTS

The curves showing the transient variation of pressure induced by an upward gust on a narrow delta wing at zero incidence (Figs.9a and 10a) resemble those presented in Ref.1 and obviously confirm the early results. They also show that the difference between the cross-section shapes of the old and the new models is unimportant. Measurements have now been obtained which show the effect of an upward gust on a narrow delta wing when it is at an angle of incidence large enough to establish vortex flow before it meets the gust (Figs.9b and 9c). They show that the transient pressure variation is similar to that which occurs when the wing meets the gust at zero incidence. Thus the transient effect of an upward gust on a narrow delta wing is substantially independent of the initial angle of incidence. This implies that any lift on the wing when it meets an upward gust is sustained and the development of the incremental lift, associated with the change of angle of incidence induced by the gust, is independent of the initial angle of incidence.

The present results do nothing to solve the enigma of the initial suction peak that has often been recorded at the moment of meeting an upward gust. The shock-tube calibration of the pressure transducer and the recording system (Fig.3) shows that the initial peaks on the records are not caused by the transducer or its associated electronic equipment. It was suggested in Ref.1 that the peaks may be associated with the mixing zone at the edge of the gust, and that the variety of peak shapes may be due to variations in the instantaneous velocity profile across the mixing zone. The velocity fluctuations caused by turbulence in the mixing zone have not yet been measured, and the curves of air speed in Fig.15 show average values only.

Measurements of the transient pressures induced by a downward gust are confined to the particular case in which the gust reduces the lift on the wing to zero. They have been analysed in the same way as the results obtained from upward gusts, to allow the effects of the two kinds of gust to be compared. Comparison of all the data from upward and downward gusts (Fig.13) shows that the change of pressure induced by a downward gust, in this particular case at any rate, occurs much more rapidly than the change induced by an upward gust. This result is insufficient to allow completely general conclusions to be drawn about the effects of downward gusts on narrow-delta wings. Experimental evidence is needed to show what happens when the gust reduces the angle of incidence to a finite value that is large enough to sustain vortex flow. Nevertheless it is already clear that a gust-induced loss of lift can occur more abruptly than a gust-induced gain of lift. There will then be less alleviation, and therefore the change of loading imposed on the wing will be greater.

It must be pointed out that the method of plotting the variation of transient pressure against x_n/b_n produces an imperfect collapse of the results. The method was evolved during analysis of the measurements presented in Ref.1. Then the differences between the individual histories of transient pressure, obtained from the separate measurement points during a single run, were reduced by plotting in this way. The differences were in fact over-corrected, but the residual *differences were smaller and the choice of* b_n *as the reference length* appeared to be vindicated. When the new measurements were analysed for the present report the differences were over-corrected so much by plotting against x_n/b_n that the expected collapse of the data was not obtained. The extent of the over-correction is shown by Fig.14, in which the data from the four measurement points are plotted separately. Nevertheless, all the curves presented with this report are plotted against x_n/b_n so that they may be compared directly with those in Ref.1. For future work, other methods of analysis and presentation will be investigated.

Entry of the model into the tunnel jet correctly simulates an encounter, during flight through still air, with a gust that is perpendicular to the flight path. However, after the model has entered the jet it is constrained to continue along a path parallel to the track. Then, relative to the air in the jet, it has a component of velocity that is equal and opposite to the jet velocity and a resultant velocity that is inclined to the edge of the jet (Fig.16). Therefore departure of the model from the tunnel jet simulates an encounter, during flight through still air, with a gust that is not perpendicular to the flight path*. The tangent of the angle between the flight path and the gust front is the ratio between the speed of the model along the track and the speed of the tunnel efflux. In these experiments the angle was about 76 degrees, and it is likely that the broad conclusions drawn from the results remain valid when the angle is 90 degrees. However, the effects of a downward gust will be investigated in future experiments during entry into the tunnel jet, with the model inverted.

A further consequence of the constraint of the model is that it cannot respond to the gusts as it would in flight, and there is therefore less alleviation of the loading induced by the gusts.

5 CONCLUSIONS

The R.A.E. gust research facility has been used to obtain measurements of the transient pressures induced on the upper surface of a narrow delta wing when it meets discrete upward and downward gusts.

When a narrow delta wing meets either an upward or a downward gust, the loading on any spanwise section of the wing remains unaffected until that particular section reaches the edge of the gust. Then it begins immediately to change.

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* The attention of the authors was drawn to this point by Mr. N. C. Lambourne of the National Physical Laboratory.

When a narrow delta wing meets an upward gust, the lift already on the wing is sustained and the gust-induced gain of lift takes a finite time to develop. At any spanwise section of the wing this corresponds to the time taken by the wing to travel a distance equal to about five times the local span at that section.

Before general conclusions can be drawn about the effects of a downward gust, experimental evidence must be obtained to show what happens when the gust reduces the lift to a finite value. Nevertheless it is already clear that a gust-induced loss of lift on a narrow delta wing can occur much more quickly than a gust-induced gain of lift and will then impose the greater change of loading on the wing.

SYMBOLS

α	angle of model wing plane relative to axis of dart
b	gross span
b_n	local span at station n
c_o	centre-line chord = model total length
x_n	distance penetrated beyond gust leading edge by station n
p	difference between a pressure on the wing surface at any instant after encountering a gust and the pressure at the same point before encountering the gust
p_o	the maximum value of p

REFERENCES

No.	Author	Title, etc.
1	G. K. Hunt D. R. Roberts D. Walker	Measurements of transient pressures on a narrow-delta wing due to an upward gust. C.P. 624, 1961
2	T. B. Owen	Techniques of pressure-fluctuation measurements employed in the R.A.E. low-speed wind tunnels. AGARD Report 172, (A.R.C. 20780) (1958)
3	A. L. Knight Mrs. M. Chapman	A shock tube for the dynamic testing of pressure transducers. R.A.E. Technical Note IR.3, (A.R.C. 25351), 1962

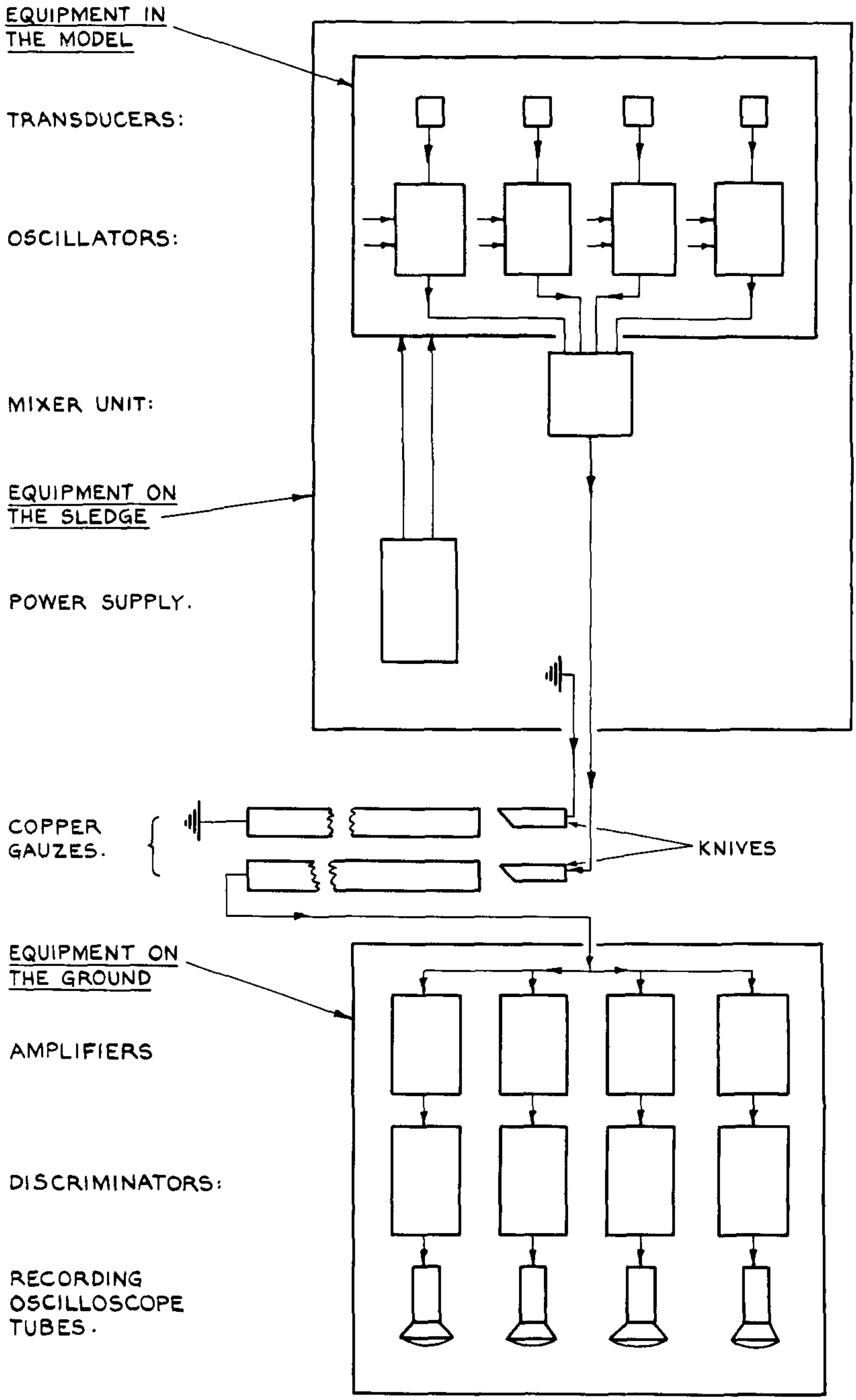


FIG.1 DIAGRAM OF INSTRUMENTATION SYSTEM

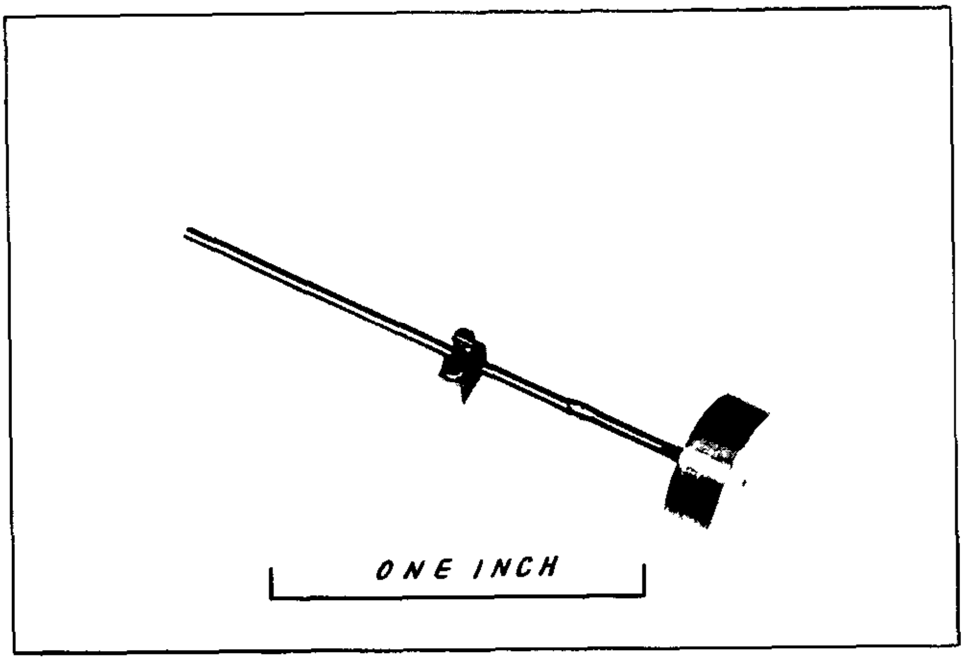


Fig.2 Pressure transducer

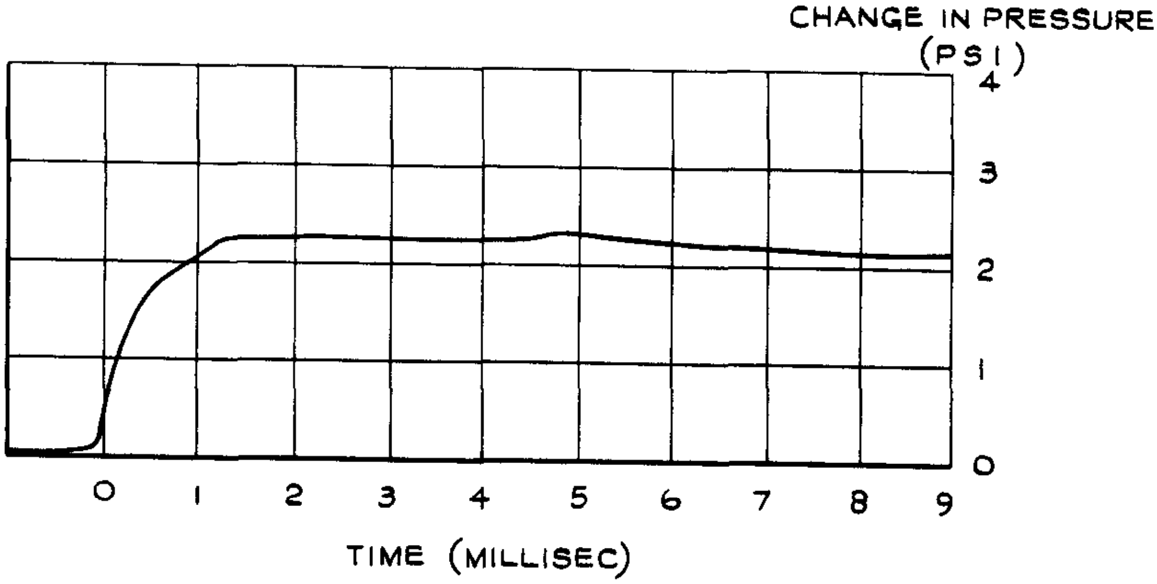


Fig. 3 Response of pressure - measuring system to step change of pressure

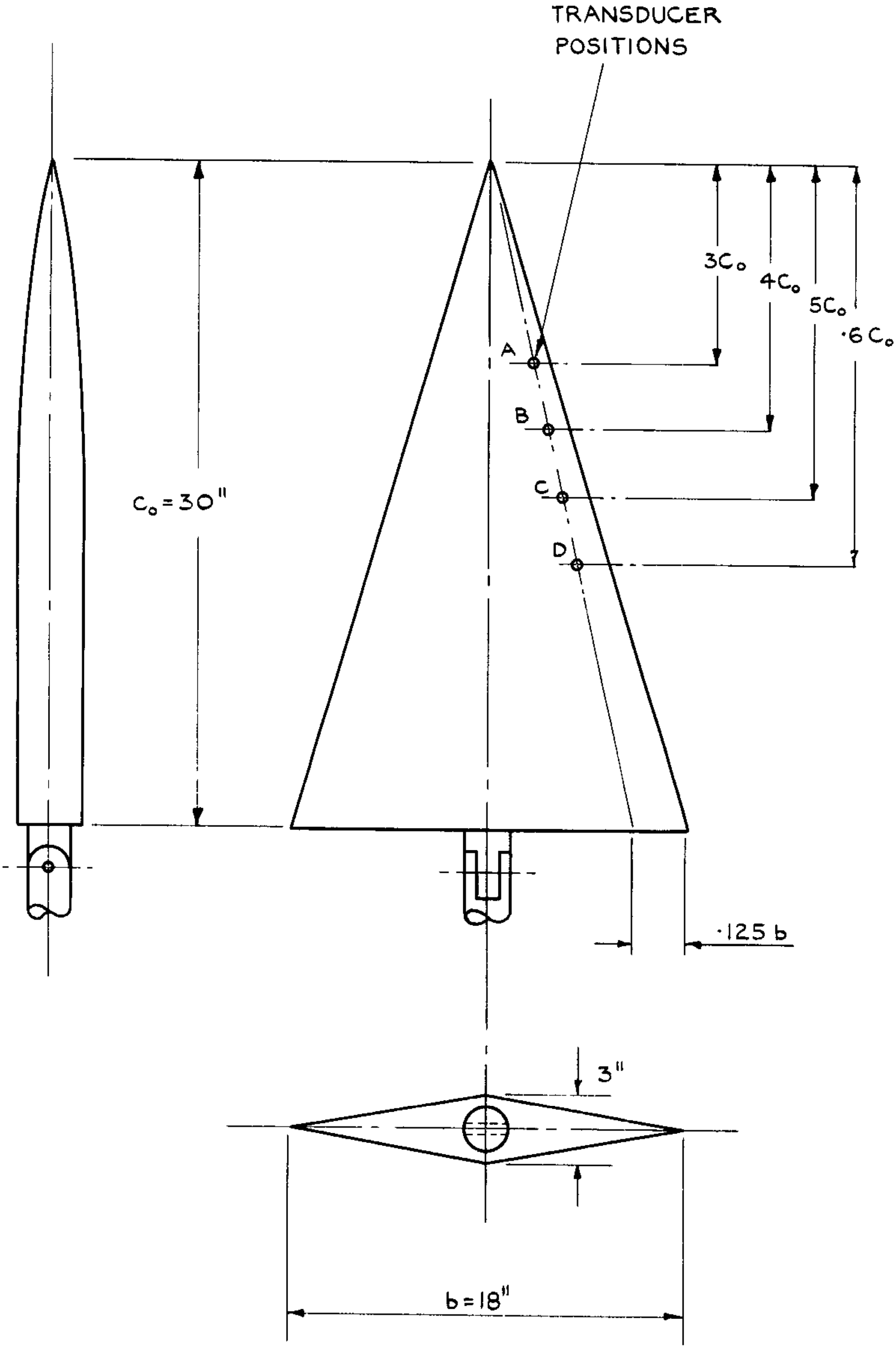
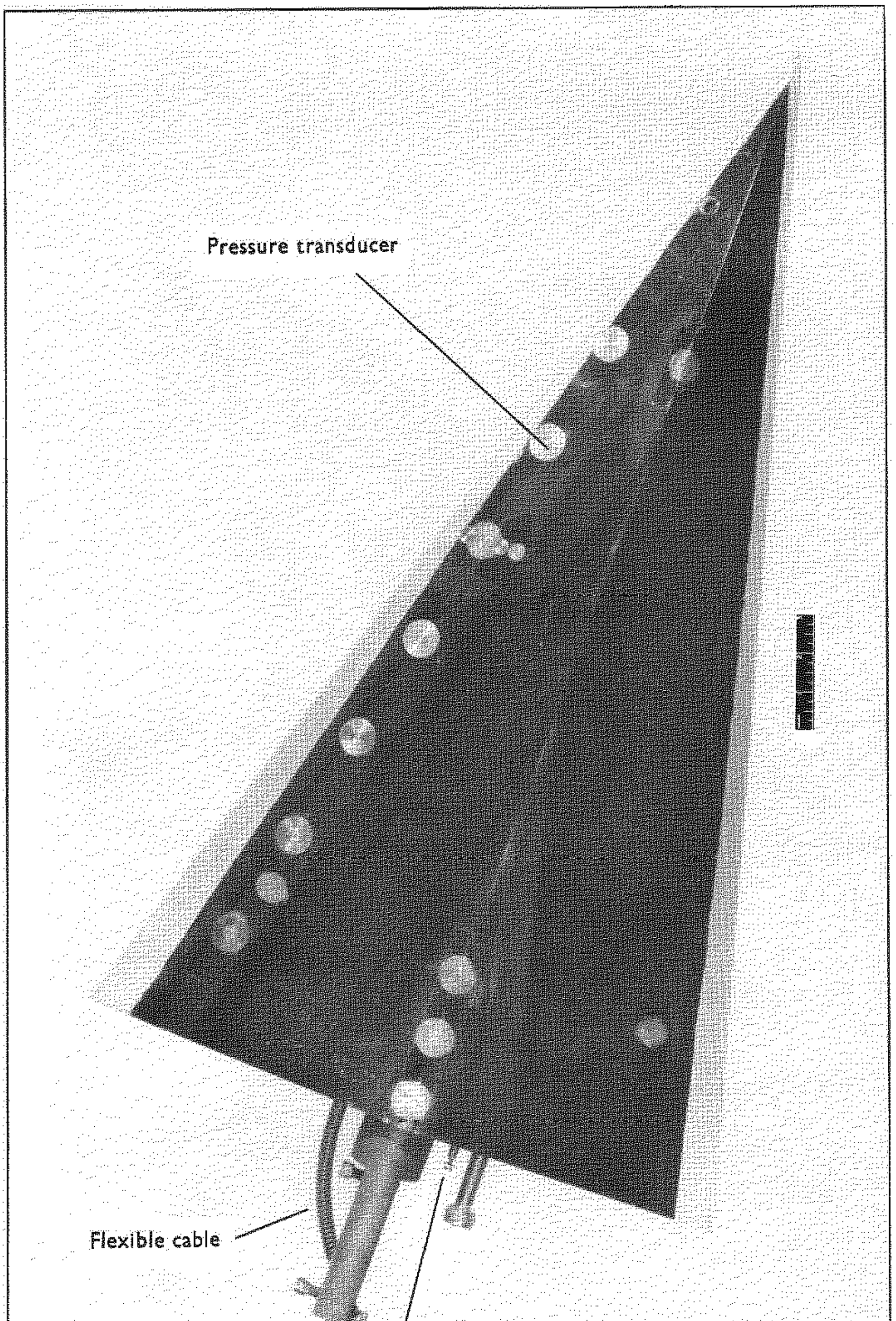


FIG.4 GENERAL ARRANGEMENT OF THE MODEL



Transducer calibration connection

Fig.5 Model exterior

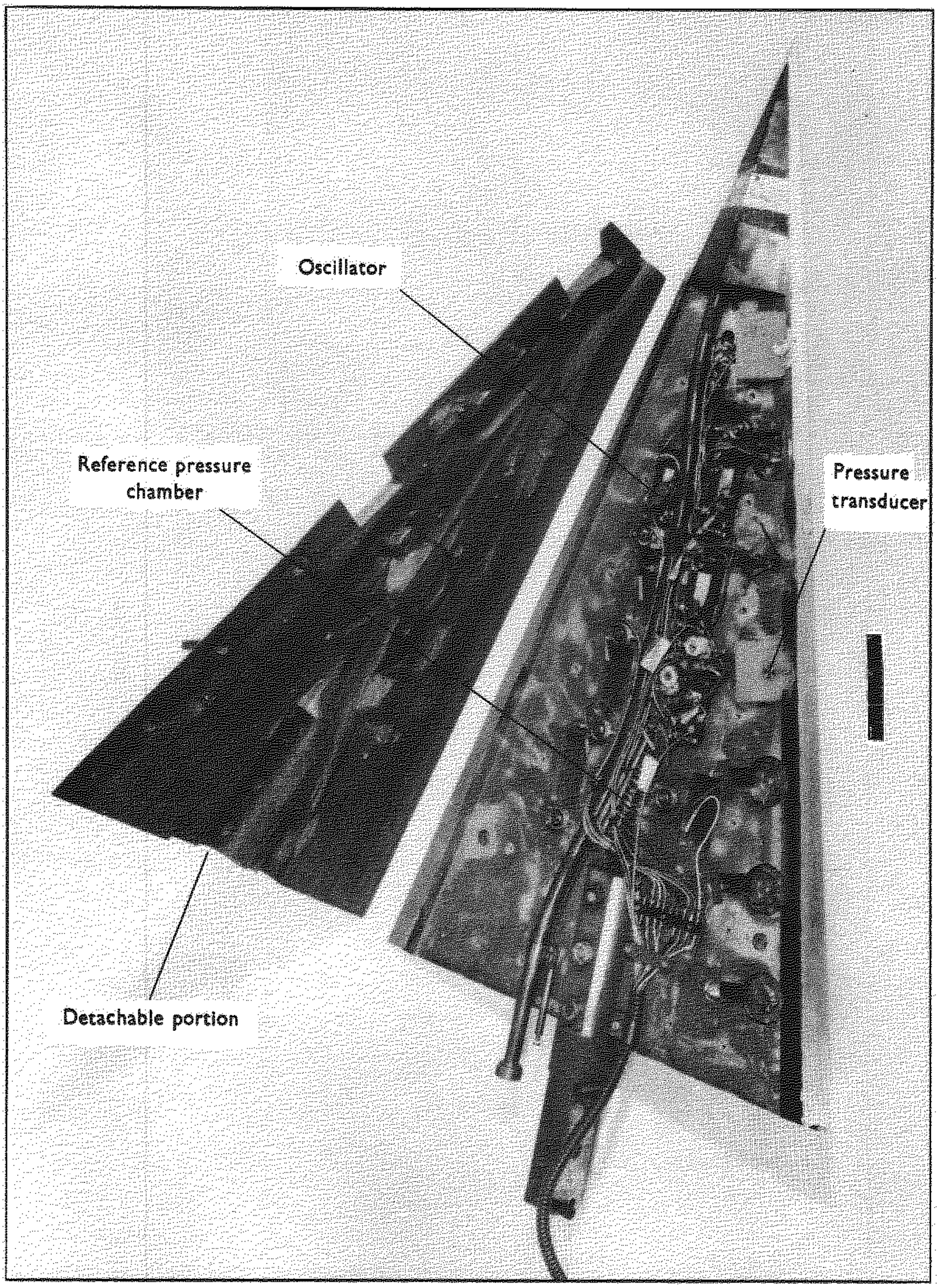


Fig.6 Model interior

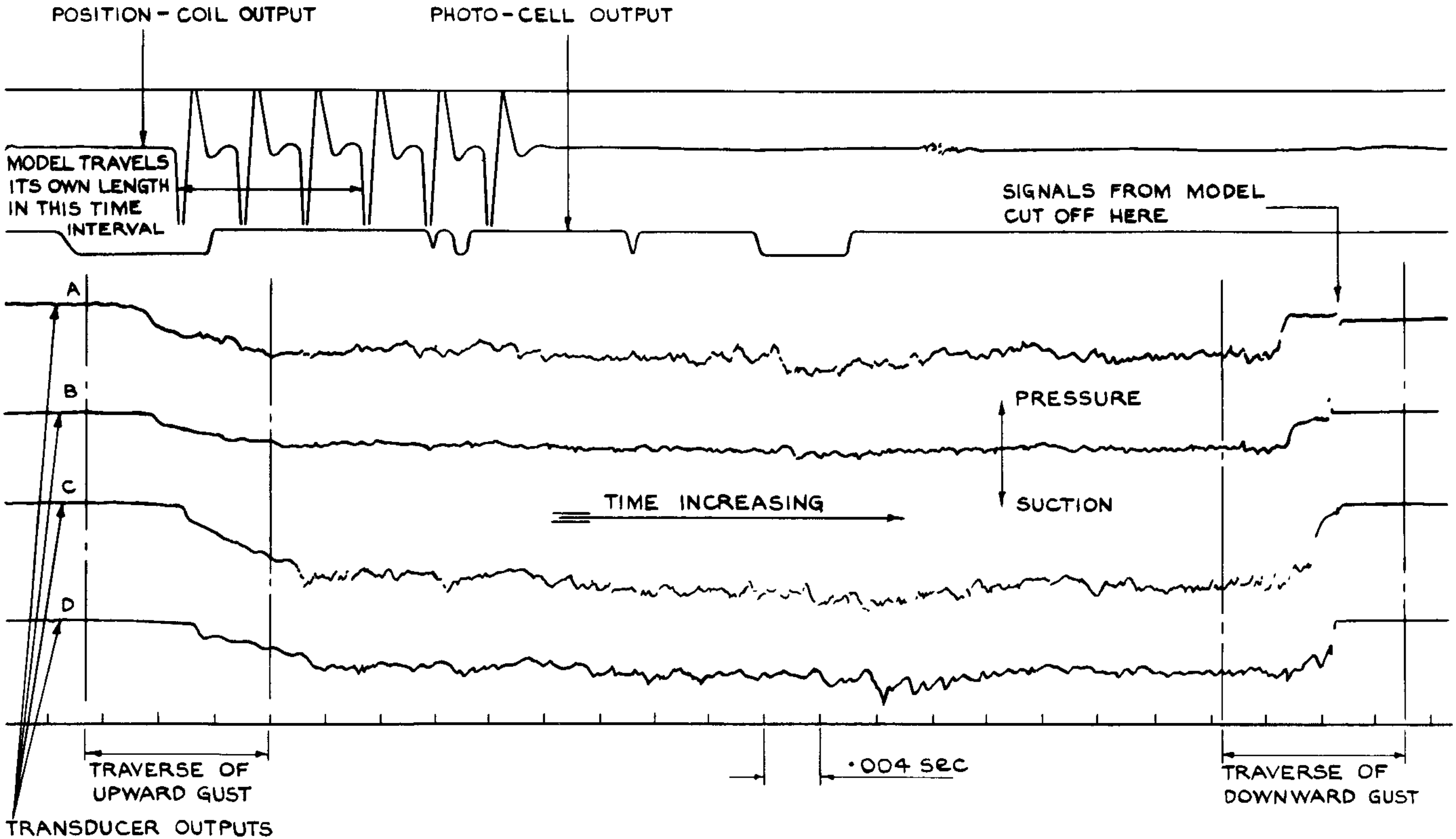


FIG.7 TYPICAL RECORD OBTAINED DURING ONE RUN THROUGH THE TUNNEL EFFLUX

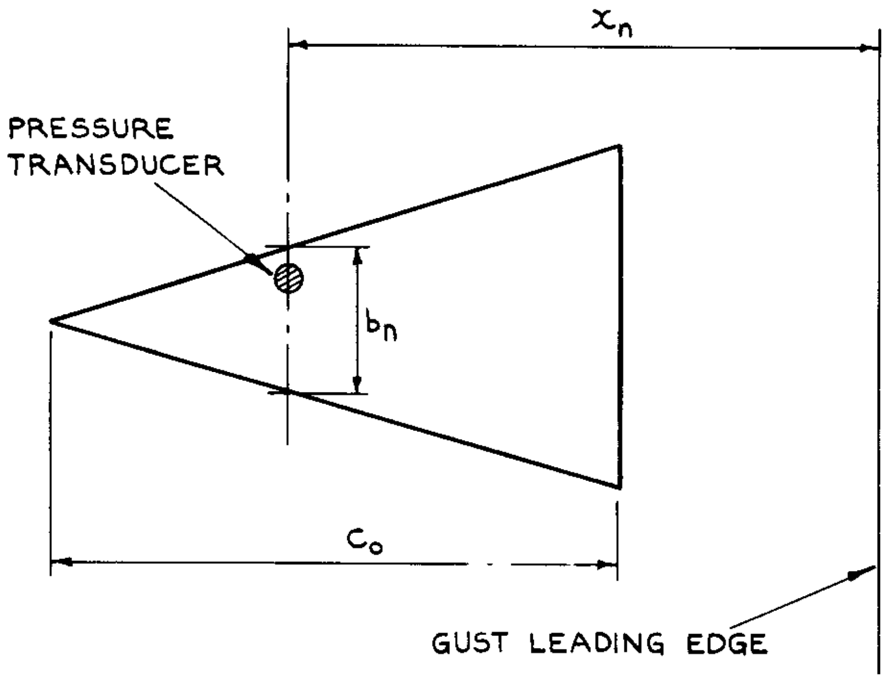


FIG 8 (a) MEASUREMENTS OF LENGTH

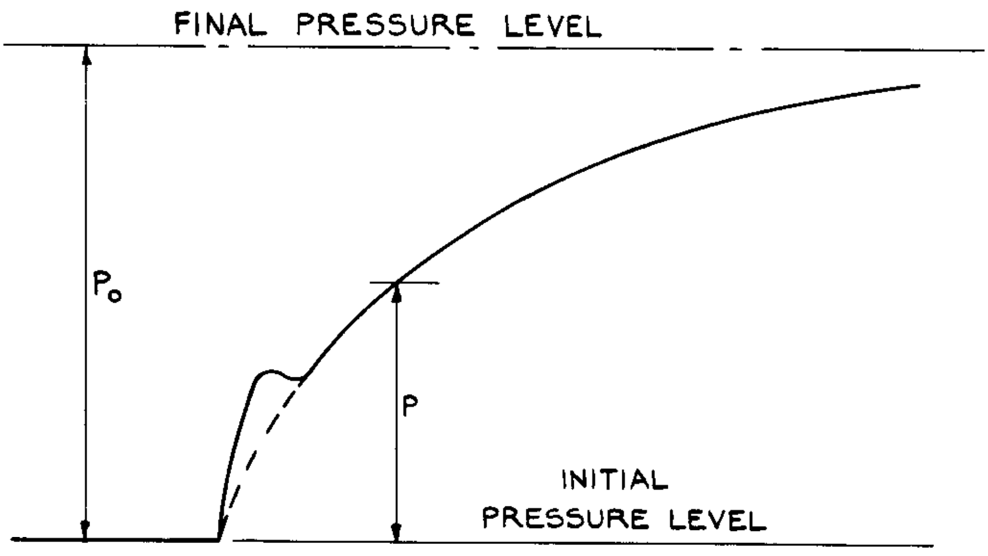


FIG. 8 (b) MEASUREMENTS OF PRESSURE

FIG 8 NOTATION USED IN PRESENTATION OF RESULTS

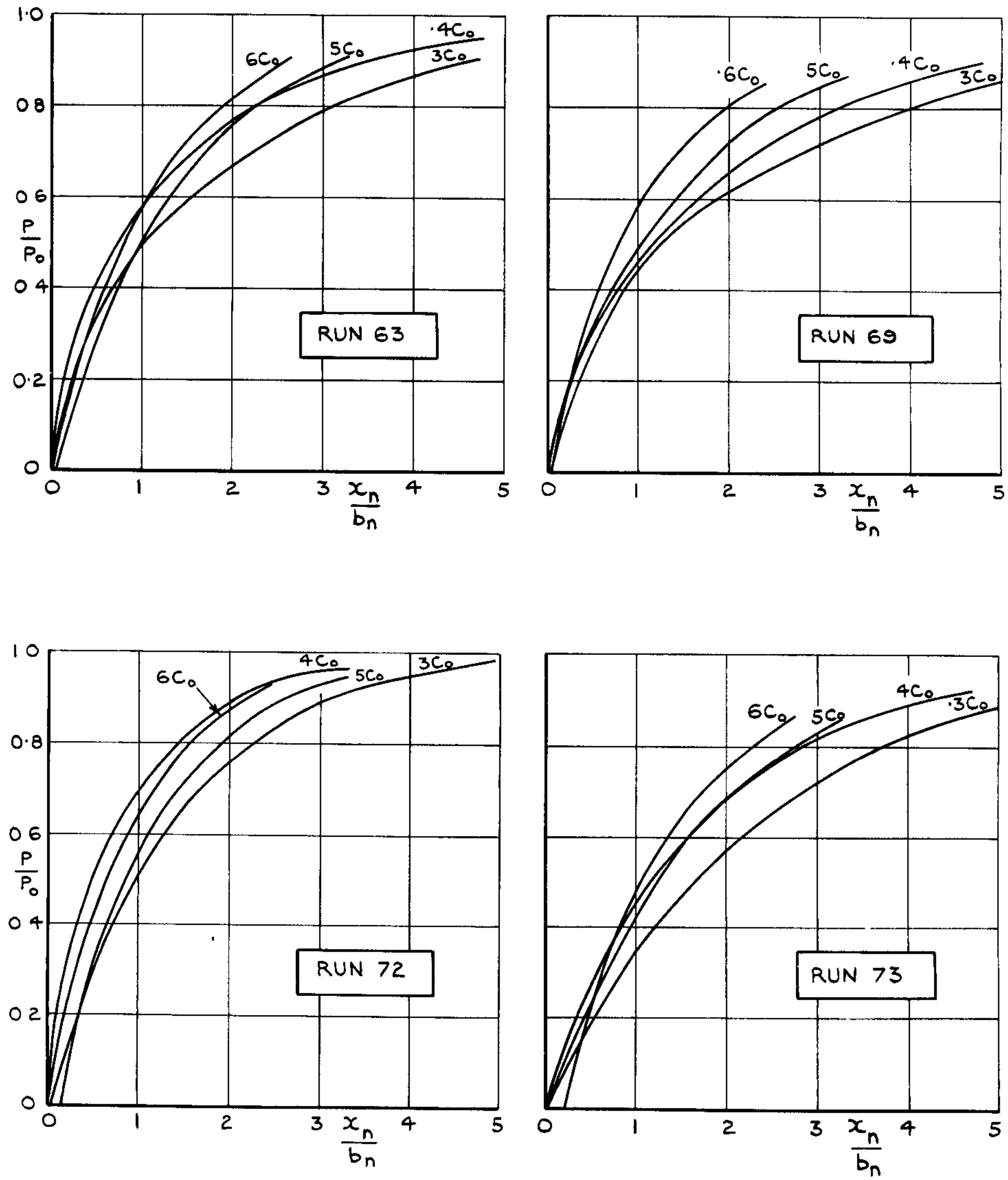
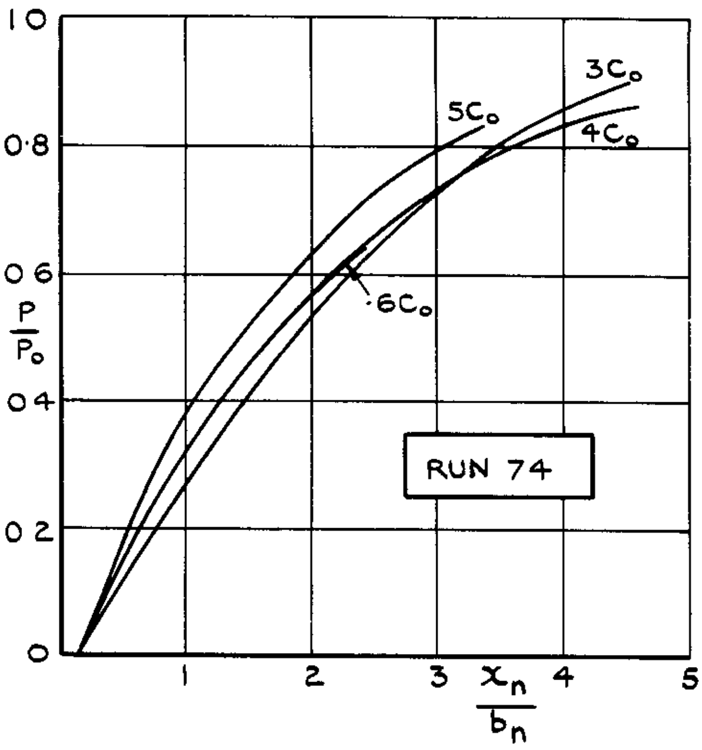
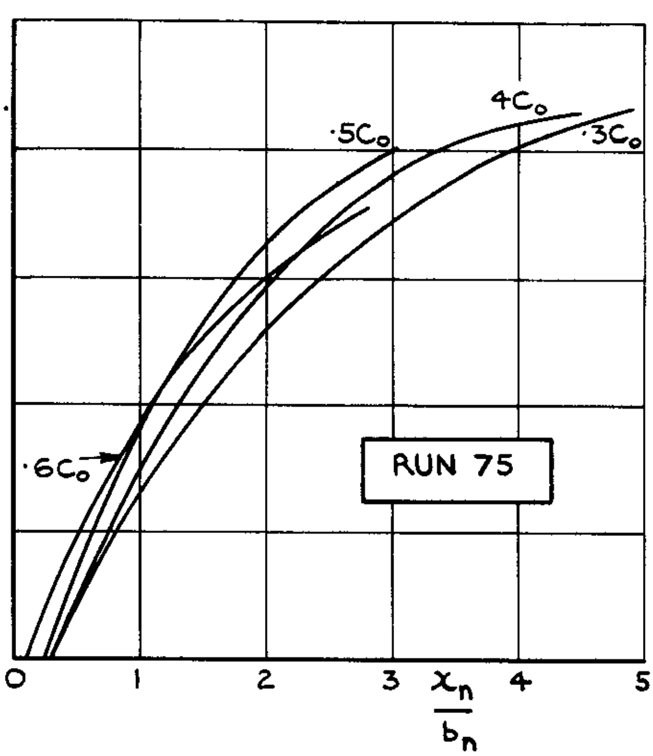


FIG. 9 (a) $\alpha = 0$

FIG. 9 UPWARD GUST PRESSURE MEASUREMENTS FOR EACH RUN





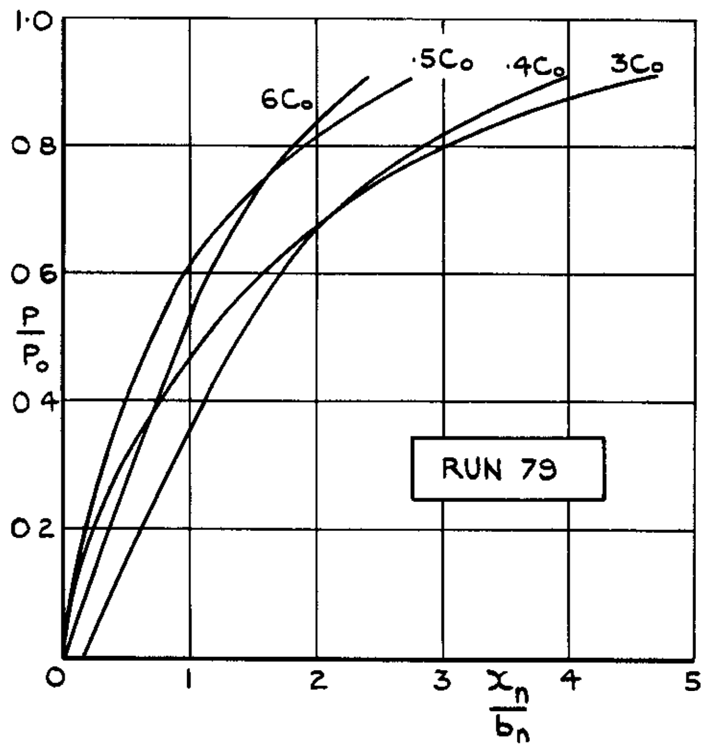
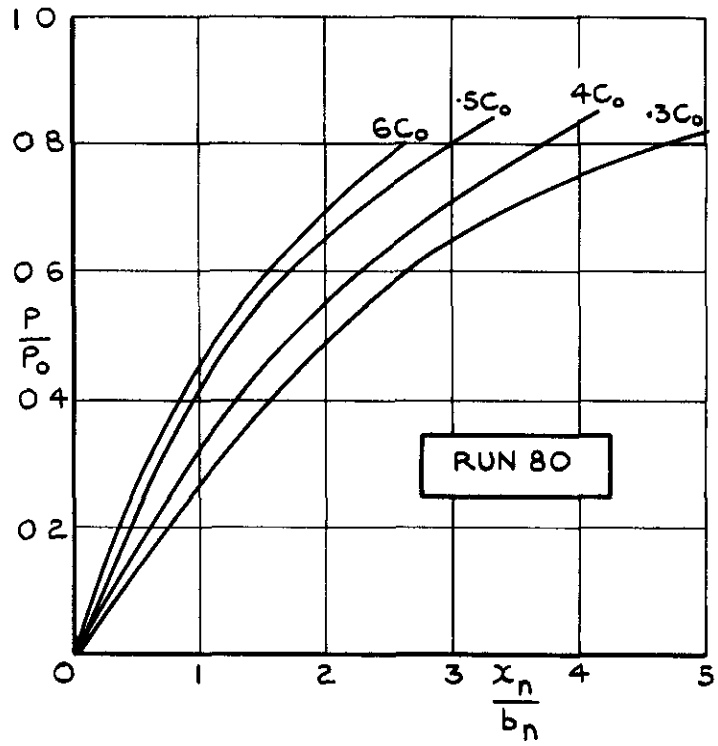


FIG. 9 (a) (CONT'D)

FIG. 9 (CONT'D) UPWARD GUST PRESSURE MEASUREMENTS FOR EACH RUN



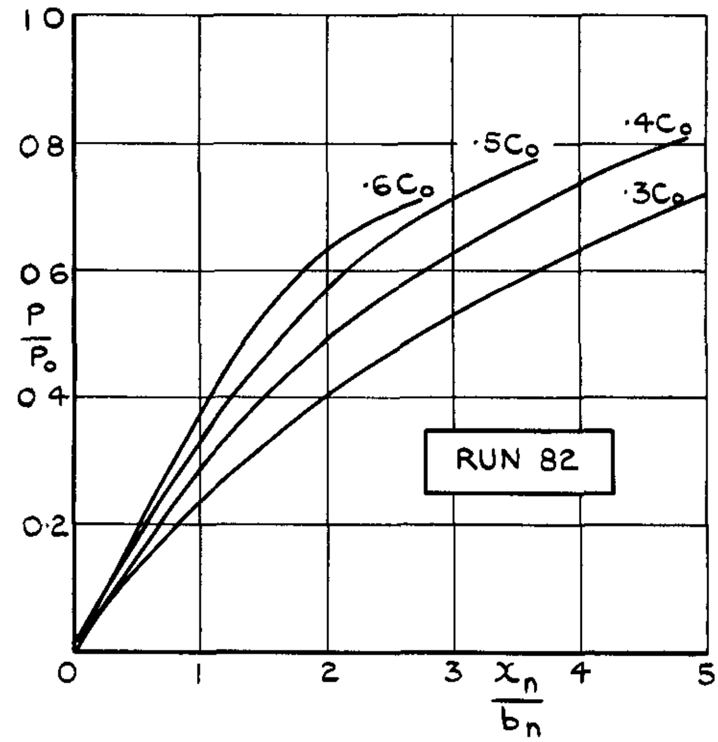


FIG. 9 (b) $\alpha = 5^\circ$

FIG 9 (CONT'D) UPWARD GUST PRESSURE MEASUREMENTS FOR EACH RUN

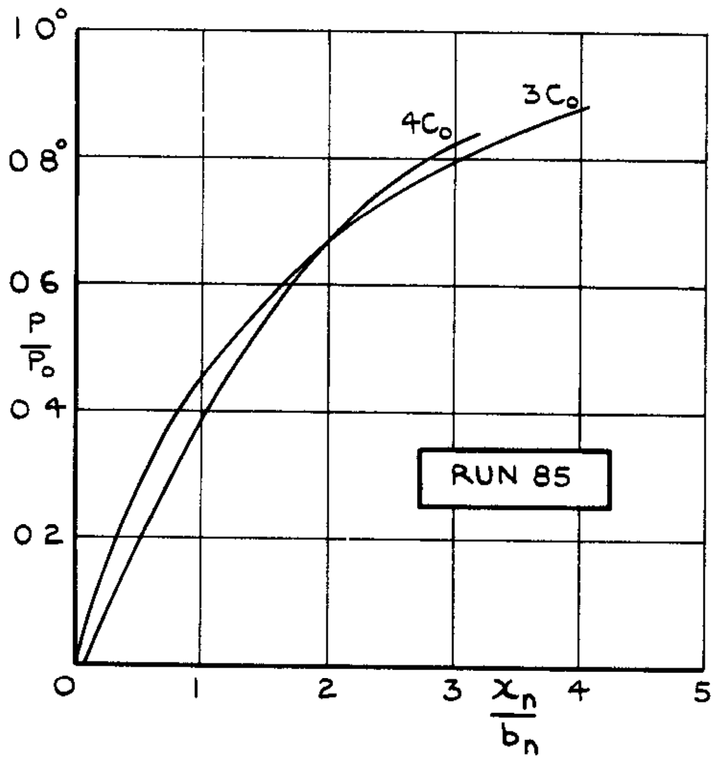


FIG. 9 (C) $\alpha = 10^\circ$

FIG. 9 (CONCL'D) UPWARD GUST PRESSURE MEASUREMENTS FOR EACH RUN

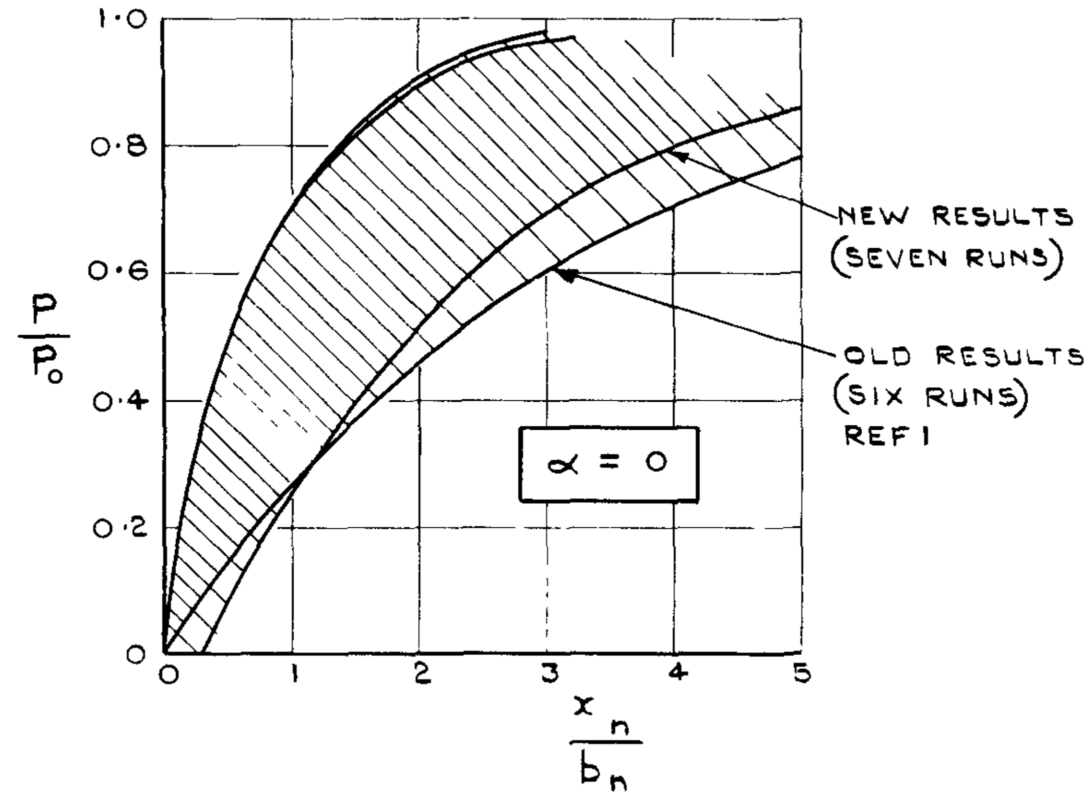


FIG 10(a)

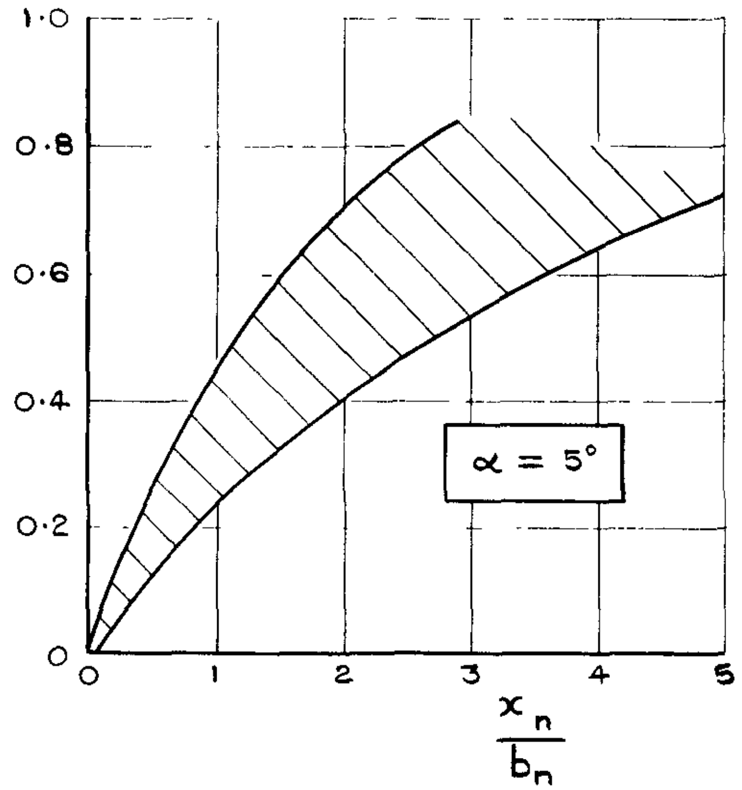
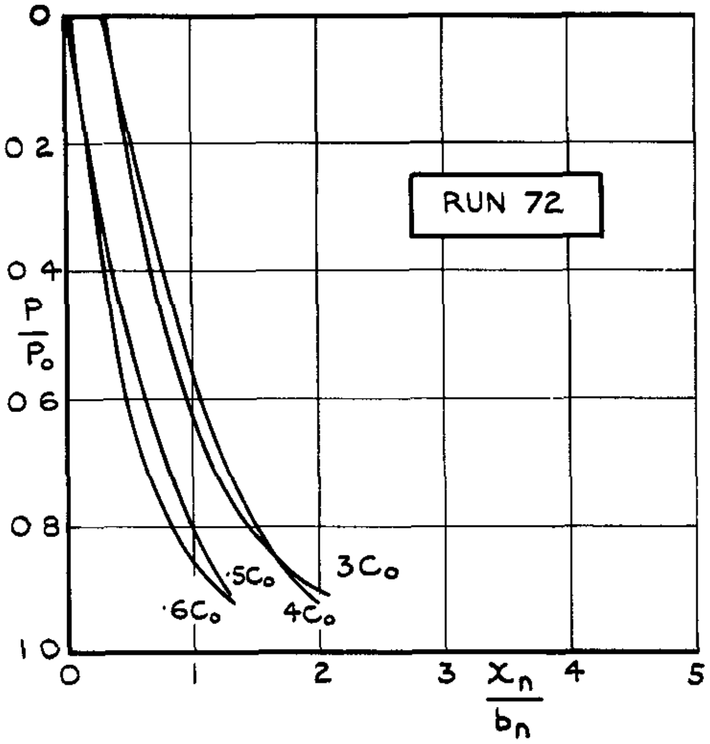
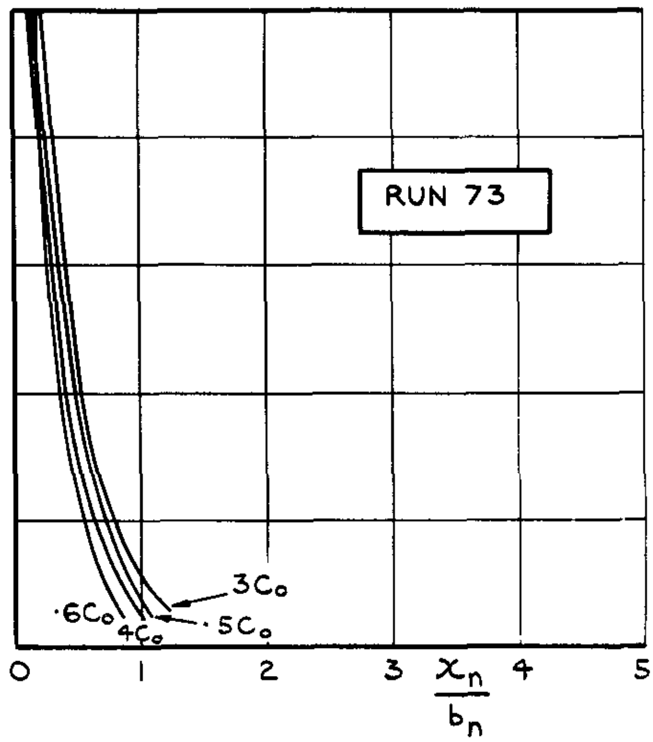


FIG 10(b)

FIG 10 SUMMARY OF UPWARD GUST PRESSURE MEASUREMENTS FROM ALL RUNS

(α = INCIDENCE OF MODEL RELATIVE TO DART AXIS)





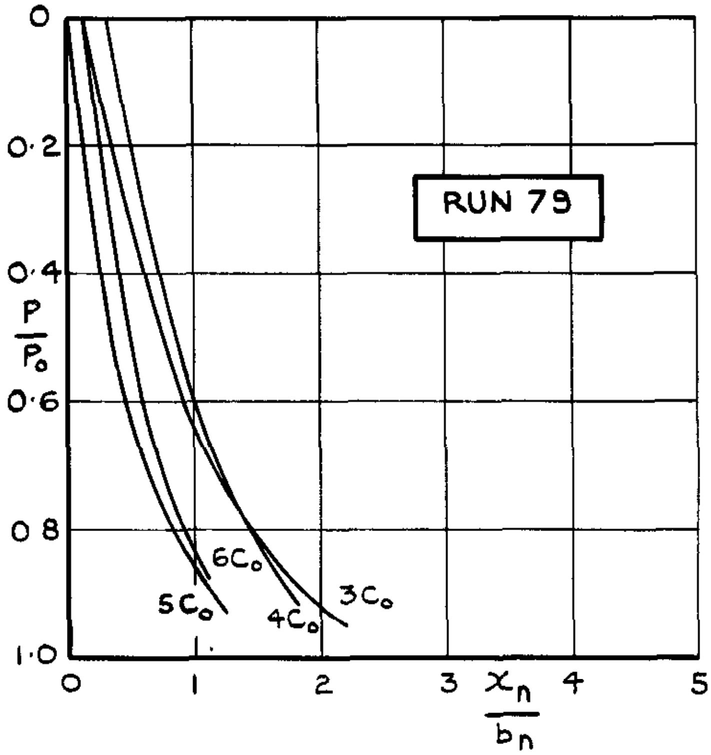


FIG. 11 DOWNWARD GUST PRESSURE MEASUREMENTS FOR EACH RUN ($\alpha = 0$)

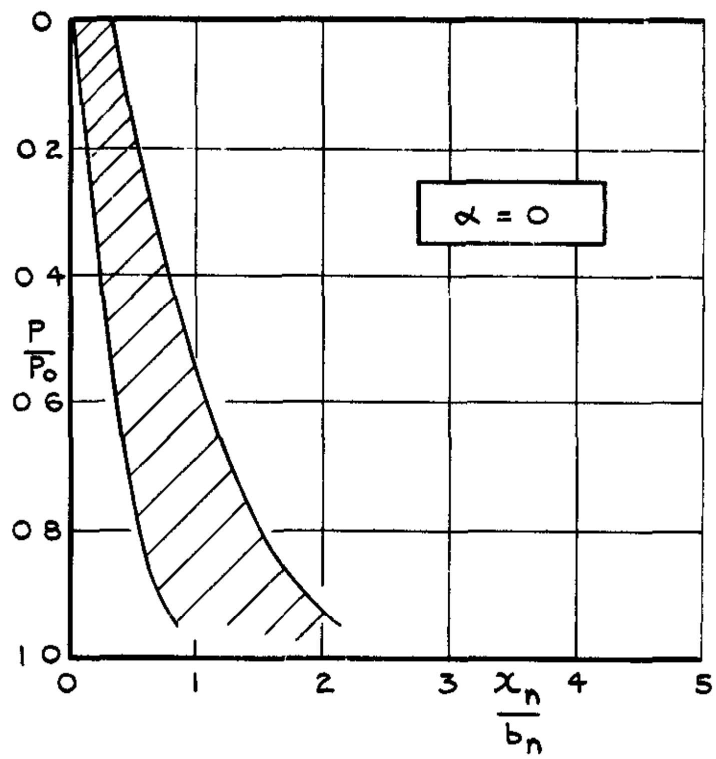


FIG. 12 SUMMARY OF DOWNWARD GUST PRESSURE MEASUREMENTS FROM ALL RUNS ($\alpha = 0$)

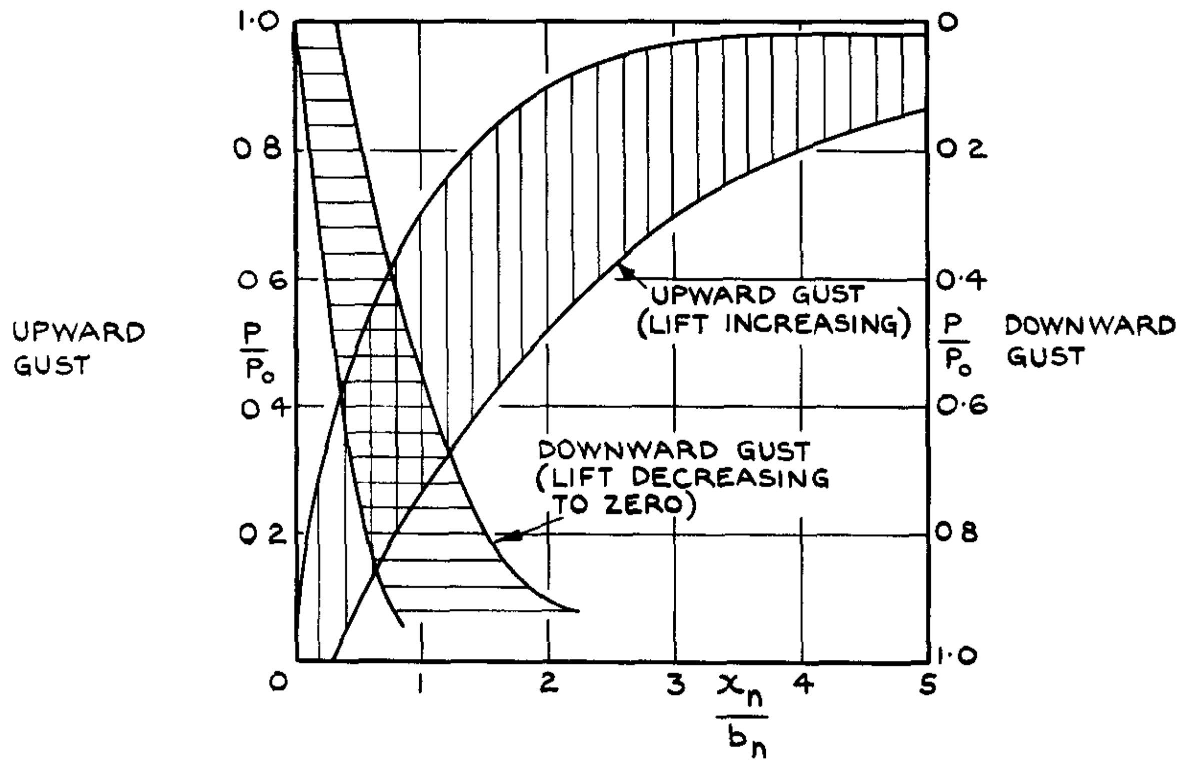


FIG.13 COMPARISON BETWEEN UPWARD GUST AND DOWNWARD GUST PRESSURE MEASUREMENTS

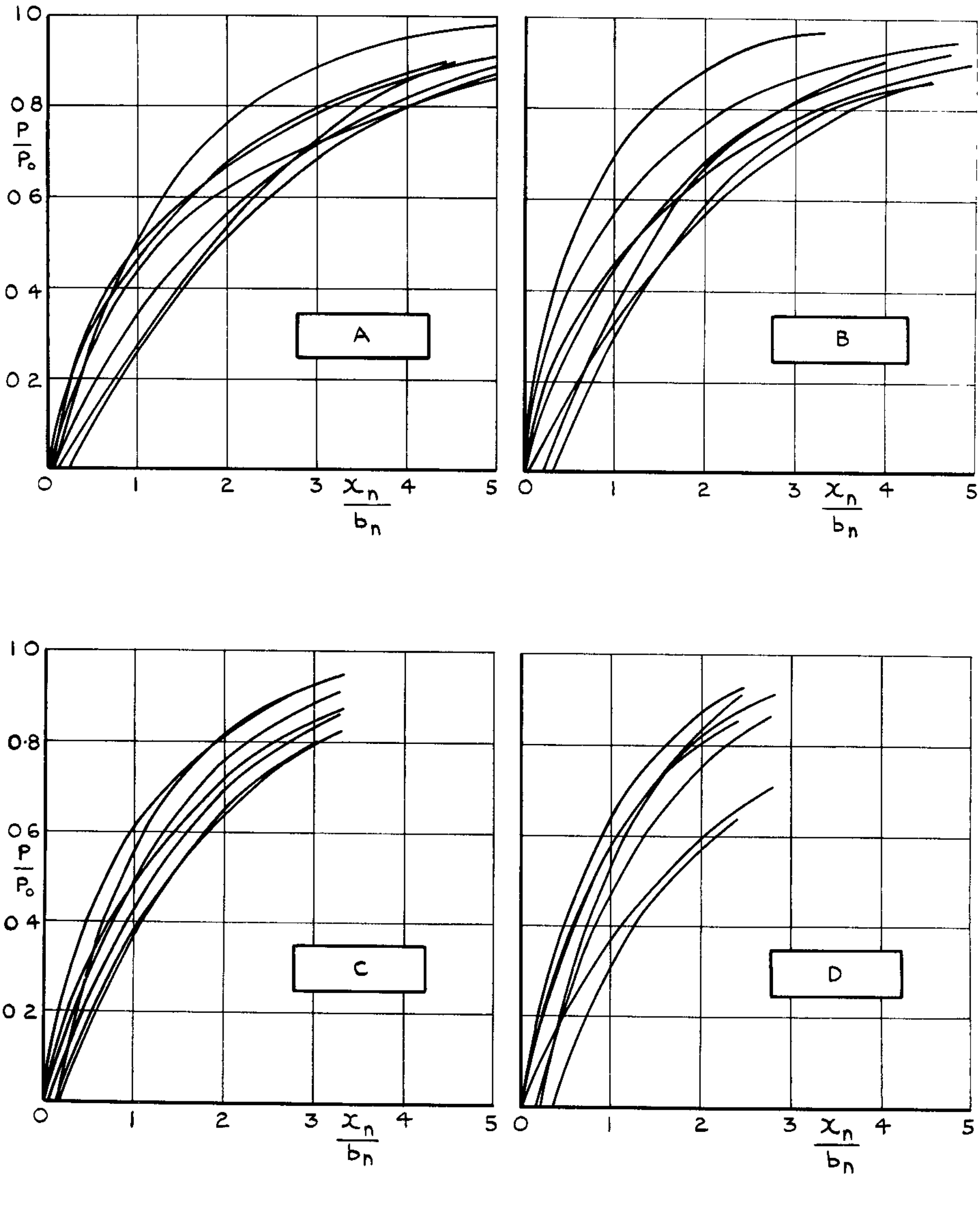


FIG. 14 (a)

FIG. 14 UPWARD GUST PRESSURE MEASUREMENTS FOR EACH TRANSDUCER $\alpha = 0$

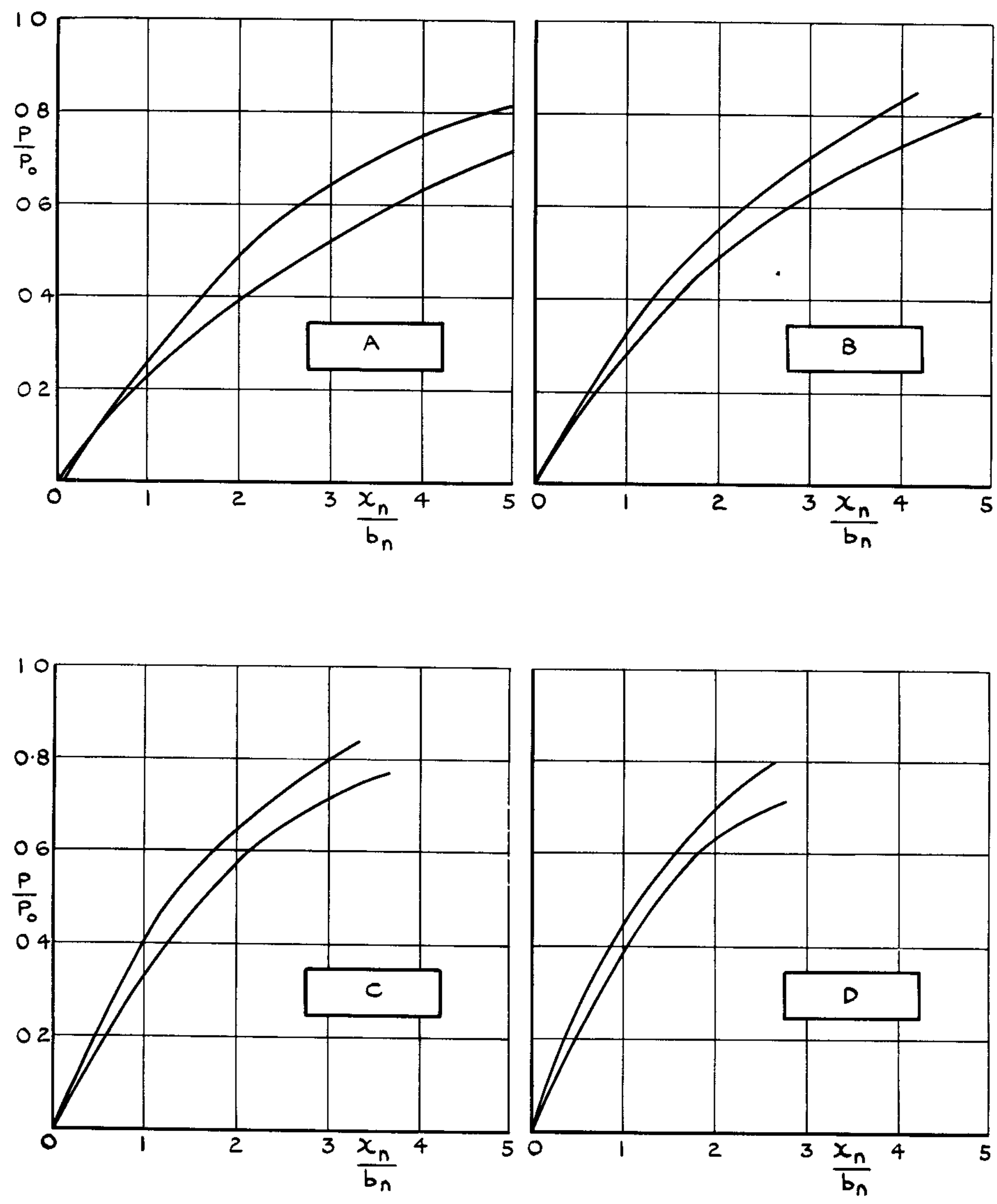


FIG. 14 (b)

FIG. 14 (CONT'D) UPWARD GUST PRESSURE MEASUREMENTS FOR EACH TRANSDUCER $\alpha = 5°$

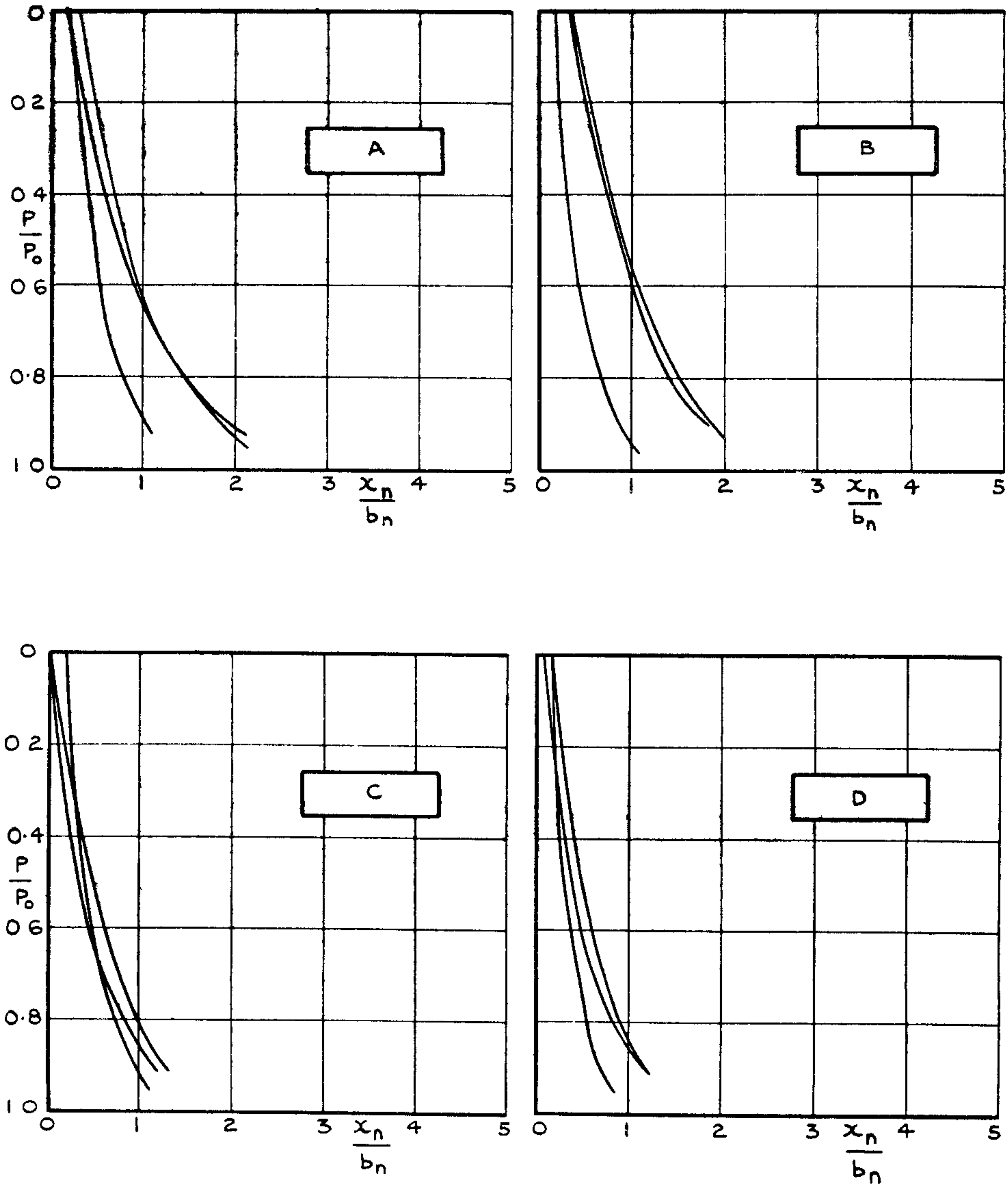


FIG 14 (c)

FIG. 14 (CONCL'D) DOWNWARD GUST PRESSURE MEASUREMENTS FOR EACH TRANSDUCER ($\alpha = 0$)

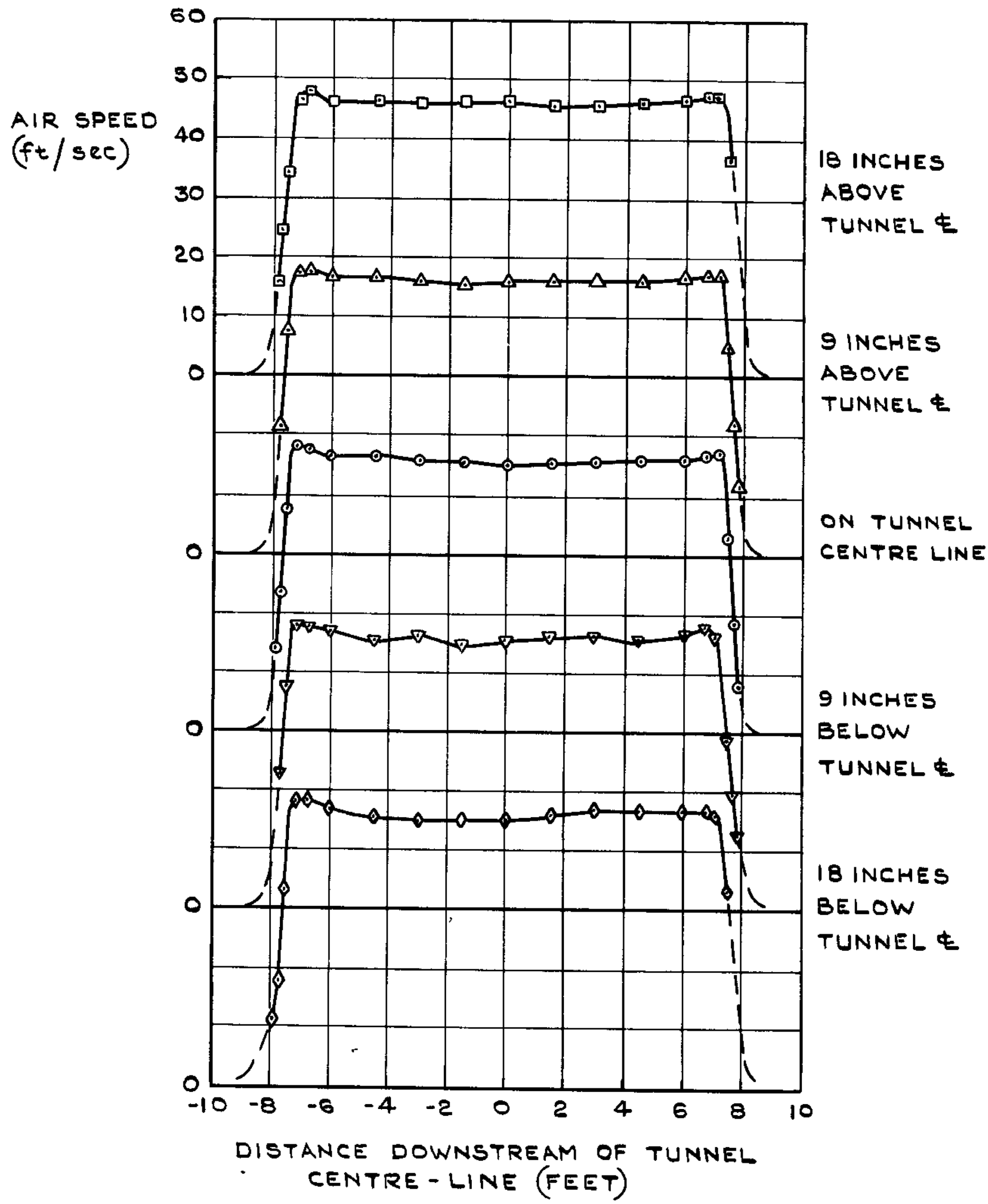


FIG.15 AIR SPEED DISTRIBUTION ACROSS THE TUNNEL JET, IN THE PLANE OF THE TRACK CENTRE LINE

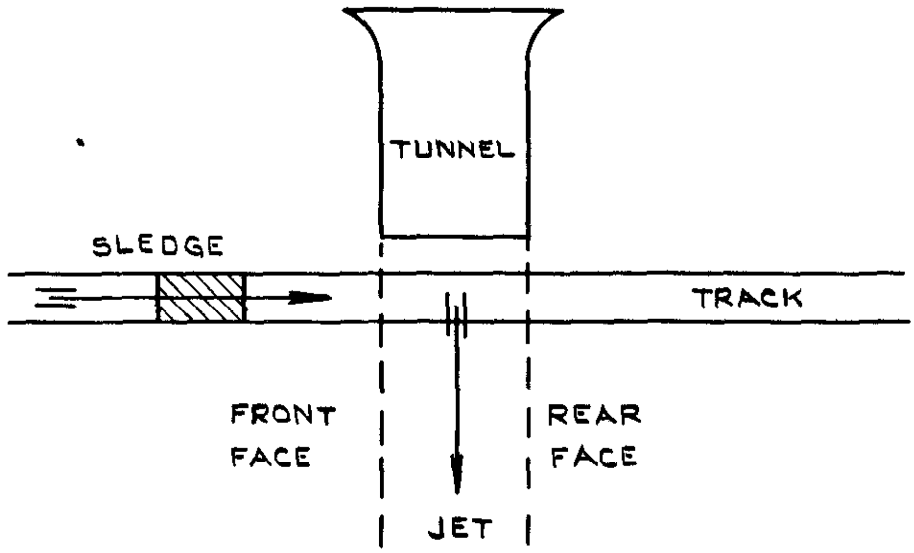


FIG.16 (a) SKETCH PLAN OF THE FACILITY

FIG.16 (b) MODEL APPROACHING THE JET

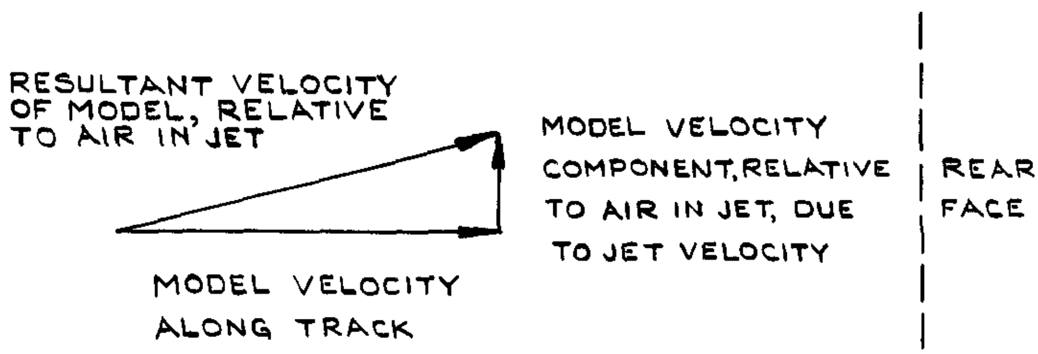


FIG.16 (c) MODEL IMMERSED IN THE JET

FIG.16 KINEMATICS OF ENTRY INTO THE TUNNEL JET AND EXIT FROM IT

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