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TEST REPORT

MET - 369

GROUND EFFECT EXPERIMENTS
ON A FAN-IN-WING CONFIGURATION AT
ZERO FORWARD SPEED

BY

W. GRABE

DIVISION OF MECHANICAL ENGINEERING

OTTAWA

SEPTEMBER 1962

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TEST REPORT

Division of Mechanical Engineering

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CONFIGURATION AT ZERO FORWARD SPEED

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SUMMARY

In order to investigate ground effect on a fan-in-wing configuration, a test rig was built. A 1-ft. diameter fan was buried in a 3-ft. by 5-ft. wing section. A movable ground board permitted operation at ground to fan-exit distances between 6 and 1/2 fan diameters. For one series, a symmetry wall was attached to one end of the aerofoil. Tip speeds ranged from 425 to 625 f.p.s.

At 1 fan diameter above the ground, the loss in net thrust was 18 percent. This net thrust consisted of the computed momentum thrust which was modified by the forces acting on the underside of the wing, the fan base, and the fan annulus. Because of reduced mass flow, the momentum thrust at 1 diameter height was found to be 78 percent of that in "free air".

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LIST OF SYMBOLS

A	Area of fan annulus	ft. ²
D	Outside diameter of fan	ft.
d _s	Elemental chordwise length on wing surface	
d _x	Projection of "d _s "	
Δp	Pressure deviation from atmospheric	
f	Elemental force on wing surface	
f _v	Vertical component of "f"	
F _A	Force on fan annulus	lb. _f
F _B	Force on fan base	lb. _f
F _L	Force on under surface of wing	lb. _f
F _U	Force on upper surface of wing	lb. _f
g _o	Constant of proportionality	32.2 $\frac{\text{lb.}_m \text{ ft.}}{\text{lb.}_f \text{ sec.}^2}$
h	Height of fan exit above ground board	ft.
p _a	Ambient pressure	
p _o	Local static pressure	
p _{te}	Local total pressure across annulus at fan exit	lb./ft. ²
R _F	Radius of fan	ft.
R _B	Radius of base	ft.
ρ	Mass density (0.0765 at 15°C and 407 inch w.g.)	lb. _m /ft. ³
T _m	Momentum thrust of fan	lb. _f

LIST OF SYMBOLS (Cont'd)

$T_{m_{\infty}}$	Momentum thrust of fan in free air	lb. _f
T_N	Net thrust	lb. _f
$T_{N_{\infty}}$	Net thrust in free air	lb. _f
V_A	Velocity of air	
\bar{V}	Average axial velocity through fan	ft./sec.
W_C	Corrected mass flow through fan	lb. _m /sec.
$W_{C_{\infty}}$	Corrected mass flow through fan in free air	lb. _m /sec.
x_F	Radial station on fan	ft.
x_B	Radial station on base	ft.

GROUND EFFECT EXPERIMENTS ON A FAN-IN-WING CONFIGURATION
AT ZERO FORWARD SPEED

1.0 INTRODUCTION

One of the many problems which are encountered upon exploring the field of vertical take-off and landing (VTOL) is that which arises when an aircraft hovers near ground. Then various forces act on the craft which are absent in free air. Already existing forces, such as momentum thrust, are modified because of changing conditions. The interplay of these new or changed forces is generally summarized under the title "ground effect".

Of major importance for the behaviour of a VTOL craft in ground proximity are:

- (1) the general configuration of the aeroplane,
- (2) the aspect ratio of the wings,
- (3) the kind of lifting devices employed, and
- (4) the number and placement of these lifting devices.

Since the Engine Laboratory is at present concentrating its efforts on the fan-in-wing concept, the study of ground effect has been limited to this configuration. With the fan-in-wing, a relatively large mass of air is drawn into the bellmouth-shaped intake, and is accelerated through the fan downwards. In ground proximity, the downwash impinges upon the ground and is deflected horizontally (see Fig. 1). By means of turbulent mixing, the downwash entrains some ambient air. If a single fan is employed, this air is drawn in about equally from all sides along the underside of the wing which creates low pressure areas. The static or surface pressures become more negative as the gap between ground and aeroplane narrows, and the velocity of the air flow is increased. The differences between the local static pressures on the lower surface of the wing and ambient pressure results in a force opposing the thrust. By employing two or more fans, near ground positive pressure areas can be created between adjacent fans, in which case the force resulting from these positive pressures has the same direction as the momentum thrust. This description rather simplifies ground effect on an airframe; for further study

more detailed literature is available (Ref. 1, 2, 3, 4). If one considers a control volume as the one shown two-dimensionally in Figure 2, surface pressures on the fan base and fan annulus must also be investigated in lieu of direct force measurements on the complete configuration.

The performance of the fan turbine assembly which was employed for the tests had been investigated by H.S. Fowler. A paper dealing with this investigation is in preparation (Ref. 8).

No attempt was made to compute and evaluate possible pitching moments due to pressure distributions on the configuration. It must be borne in mind that the chordwise placement of the fan, which was at about 35 percent of the chord, was quite arbitrary. It was also felt that pitching moments will constitute much more of a problem during the transition period, so that those encountered at zero forward speed should be of secondary order (Ref. 5, 6, 7).

2.0 TEST APPARATUS AND INSTRUMENTATION

2.1 Test Apparatus

2.1.1 Test Stand

An all-welded test stand was built from 2-inch standard weight pipe (see Fig. 3). The choice of design and building elements was governed by the objective of providing a strong, vibrationless support for the fan turbine assembly and the wing section with the least amount of interference for the normal flow of air. The over-all dimensions of the structure were limited by the available space. It was felt, however, that the greatest possible distance between fan exit and ground board, which was 6 fan diameters, should provide "free air" conditions, and, also, that the wall effects should be negligible.

2.1.2 Turbine Fan Assembly

The turbine fan assembly represented a proven unit which had been tested previously. No trouble was anticipated and none was encountered. The pure impulse turbine was driven by compressed air which emerged from six nozzles, three on either side of the turbine. This arrangement eliminated axial thrust at the turbine drive. The power was transmitted by

shaft to the fan. The fan of 12-inch outside diameter and a hub/tip ratio of 0.5 consisted of 36 blades. These blades were of Sikorsky GSM 6 profile at the root which changed with a free vortex twist to a Clark Y profile at the tip (Ref. 8). The chord of the rotor blade was 1 inch, the thickness being 6 percent at the tip and 10 percent at the root. Downstream of the fan were eleven untwisted straightening vanes. In former tests, the stator inlet swirl had been found to be 35 degrees off the axis across the span, the outlet swirl having been between 10 and 15 degrees. The design speed of the turbine fan unit was 15,000 r.p.m.

2.1.3 Wing

Suspended separately was the 36-inch chord by 60-inch span wing of NACA 0018 profile. The fan was placed at 35-percent chord and mid-span. A gap of approximately 1/4-inch between the fan housing and the aerofoil permitted easy installation of the wing and allowed for small misalignment. Also, the wing could be exchanged without affecting the turbine fan assembly. Proper fairing provided for unobstructed smooth flow of air over the gap between bellmouth and wing. The fan/wing area ratio was 1/18 or 0.055.

2.1.4 Ground Board

The ground board consisted of a frame of 3-inch by 3-inch angle iron covered with 1/8-inch boiler plate. This relatively heavy construction was decided upon in order to have the ground board retain its flatness even when under heavy dynamic pressure, to keep it from vibrating, and, by its weight, to have it add to the rig's stability. As can be seen in Figure 3, four adjustable brackets with fine adjustment screws held the ground board in any desired position. The weight of the board was transmitted to the test rig. A changing of ground board level or attitude during a test run was not possible.

2.1.5 Symmetry Wall

For series No. 2, a symmetry wall was attached to one end of the wing (see Fig. 4). This symmetry wall was supposed to simulate a wing of twice the actual span with two fans placed one half span apart. The wall consisted of individual horizontal strips of plywood which were secured to a wooden structure. The arrangement allowed one to adjust the wall to the various positions of the ground board.

2.2 Instrumentation

2.2.1 Mass Flow Measurement

To find the mass flow through the fan, a cylindrical pitot arrangement of 14 tubes was installed in the inlet just between the bellmouth and fan. The 0.065-inch outside diameter tubes were positioned radially across the fan annulus, two adjacent tubes forming a pair. One tube of the pair had a 0.014-inch diameter hole facing the stream; the other tube had an equal hole at the same radial position but 180 degrees around the tube. Using the differences in pressure between these two orifices, and having calibrated this pitot arrangement in a calibrating tunnel, one could compute the dynamic pressures and, hence, the mass flow through the fan.

2.2.2 Fan Outlet Pressure Survey

A simple five-tube pitot rake was placed at the exit plane of the fan annulus. It was positioned midway between two straightening vanes. The readings one obtained merely gave a local total pressure, which could not be assumed uniform over the whole annulus because of the effects of the stator vanes. The objective was, by observing the exit total pressure profile at any point, to detect any sudden changes in profile which would be indicative of stalling of the fan blades.

2.2.3 Wing Surface Pressures

The surface pressures on the wing were picked up by means of pressure tapes (see Fig. 5). Twenty-hole tape was placed chordwise around the wing and fastened to it with friction tape. The ends of the tapes had been sealed and 1/32-inch diameter holes had been drilled at five chordwise positions on both sides of the wing to facilitate the pick-up of local pressures. The pressures were then transmitted through larger tubing to two 30-tube, self-illuminated manometer banks. A permanently installed camera recorded the manometer readings which were subsequently evaluated.

For series No. 1, spanwise symmetry of pressure distribution on the wing was assumed. The pressure tapes were staggered spanwise in such a fashion that each actual pressure reading could also be plotted at a corresponding location on the opposite semi-span of the wing. Thus 52 pick-ups rendered 98 readings over the whole aerofoil. With the installation of the symmetry wall, this assumption became

invalid. Each test run in series No. 2 had to be repeated with the pressure tapes being shifted to a second position.

The manometers were graduated in tenths of an inch. Readings in between graduations were rounded off to the nearest graduation. When interpreting the wing pressure charts, allowance should be made for this relative crudeness of instrumentation, especially where small pressure deviations from atmospheric were measured. Other manometer tubes indicated the pressures which were picked up by the inlet and exit pitot tubes.

2.2.4 Fan Base Pressures

For series No. 2, a row of surface pressure taps was installed on the base of the fan. A pressure tape of the kind employed on the wing was used. Eight holes over the radius of the base permitted a fairly close check on the surface pressures. The elemental forces which were derived from these pressures were integrated over the area of the base to give a total force.

3.0 TEST PROCEDURE

Ground effect tests were conducted at corrected fan speeds of 8,100, 10,250, and 11,900 r.p.m. With a design speed of 15,000 r.p.m., these velocities were considered to be within mechanically safe limits. The ground board was adjusted before the test to the desired height. The heights at which testing was carried out were in 1-foot increments (= 1 fan diameter) with the exception of the last board position which was one-half fan diameter from the fan exit. In all tests, the attitude of the board was kept horizontal. After steady conditions had been established for a certain fan speed, three photographic shots were taken of the pressure readings on the wing. Later on, an arithmetic average of the three readings, which seldom varied by more than 0.1 inch, was taken. Between exposures, the other manometers were read directly. This procedure was repeated for each fan speed. During series No. 1, a simple tuft study was undertaken to determine whether any wall effects were present. In series No. 2, some effort was made to establish by tufts the flow of the re-circulated downwash underneath the wing.

4.0 RESULTS AND DISCUSSION

It must be emphasized at this point that neither the turbine nor the fan nor the fan-in-wing configuration was under test as such. The turbine fan unit was merely employed to produce a downwash of reasonable size and velocity and of a characteristic similar to that of a future full-size lifting fan. Whenever feasible, the technique used was that of expressing all data relative to "free air" conditions, i.e. relative to comparable data at 6 diameters. Thus the investigation was strictly limited to the effect of ground proximity on the fan-in-wing configuration. Where, for various reasons, this technique could not be applied the test results should nevertheless be seen in this light. While 6 fan diameters height was thought of as "free air", 1 diameter was assumed to be the lowest height which any VTOL craft could reasonably attain. The following discussion of test results has therefore been limited to this range of heights.

In many cases, the test results from all three fan speeds were collapsed to a single curve by non-dimensionalizing them by the appropriate momentum thrust. Thus one representative best curve could be drawn. The fact that the results could successfully be collapsed might be taken as an indication that the velocities were high enough to avoid adverse Reynolds number effects, and low enough to avoid serious Mach number effects.

4.1 Mass Flow Through Fan

The relative mass flow was plotted against height in Figure 6. The results of both series are shown together, in order to emphasize the fact that the changing of the test conditions through installation of the symmetry wall did not affect the mass flow. Test fluctuations which were within 3 percent excepted, no change in mass flow occurred between 6 and 3 diameters height. Below 3 diameters, the mass flow was reduced appreciably. This reduction reached a value of between 10 percent and 12 percent at 1 diameter height. Back pressure on the fan was held responsible for this drop in mass flow. It will be seen later (Section 4.6) that the reduction in mass flow in the form of reduction in momentum thrust was primarily responsible for the adverse ground effect on the fan-in-wing configuration.

4.2 Check on Fan Blade Stalling

As a check on possible stalling of the fan blades, an exit total head rake was installed midway between two straightening vanes. A plot of local total pressures against radial position is shown in Figure 7. The absolute value of the measured total head is of no particular significance. Examining the efflux characteristics, one can detect a slight reduction in total pressure between 60 percent and 85 percent of the fan radius at 1 diameter and, somewhat more, at 1/2 diameter. This was found to be the case for all three fan speeds in both series. Considering the extremely low height of 1/2 fan diameter, the reduction in total pressure at the exit appears to be insignificant. The absence of any sudden pronounced deterioration in the outlet total pressure profiles as the ground was approached indicated freedom from serious stalling effects.

4.3 Forces on the Wing

As mentioned earlier in the report, both upper and lower surfaces of the wing were provided with pressure taps. The taps were spaced in such a fashion that each represented the mean for a projected area of about equal size. A brief explanation as to the computation of the forces on the wing will be found in Appendix A.

4.3.1 Forces on Upper Surface of Wing

The value of the pressure measurements on the upper surface of the wing appears to be doubtful from the ground effect point of view. If a control volume as indicated in Figure 2 is selected, then the upper surface must be considered as an extension of the bellmouth. The forces which act on this surface are accounted for by the momentum thrust and cannot be used again for modifying this thrust

As a separate study, however, a brief discussion of the pressures on the upper surface might be permitted. The two upper curves in Figure 8 show that the integrated forces over the upper surface of the wing remain fairly constant over the whole range of heights. In both series, the suction forces increased slightly until they reached a maximum at 2 and 3 diameters respectively. The forces then decreased without, however, reaching a value much below the initial one at 6 diameters. This fact is surprising when one considers that at 1/2 diameter the mass flow had been reduced by about

18 percent. Another interesting observation was that the forces on the upper surface were between 44 percent and 92 percent higher in series No. 2 than in series No. 1. The pressure profiles on the wing surface for 6 and 1 diameters are shown in Figures 9, 10, 11 and 12. The corresponding measured values can be seen in Figures 9(a), 10(a), 11(a) and 12(a).

No logical reason has been found for the slight increase in negative surface pressure at 2 or 3 diameters or for the generally higher negative pressures in series No. 2. Two phenomena might be given consideration. Because of reduced mass flow in ground proximity, the negative pressures on the upper surface must decrease. On the other hand, possible re-circulation, which may be at a maximum at a certain height, might increase the negative pressure.

4.3.2 Forces on Under Surface of Wing

Unlike the forces on the upper surface, those on the underside of the wing have to be counted as contributors to ground effect. In Figure 8, the mean value of the integrated forces, non-dimensionalized, have been plotted against height. As the ground was approached and the escape cross-section between ground and wing was decreased, the velocity along the wing increased, leading to a decrease in static pressures. This decrease became more rapid as the ground was approached. Considering, again, 6 diameters as "free air", then at 1 diameter mean suction forces of 7 percent (series No. 1) and 10 percent (series No. 2) of momentum thrust in free air were acting on the under surfaces. Since no complete flow studies were undertaken, the mechanics of the air flow under the wing are not fully understood. It is believed that the downwash, through turbulent momentum transfer around the periphery of the jet, entrains ambient air which has to be supplied by the surrounding area. The downwash upon impinging on the ground deflects radially outward and flows along the ground in a rather thin sheet. Two flows, one outward and one inward, must exist. Upon nearing the ground, a point might be reached where the outflowing downwash occupies the whole space between ground and wing. Then the negative pressures on the underside of the wing would be the result rather of the deflected downwash than of the inflowing ambient air. Spreemann and Sherman have done some work towards exploring the flow in this area (Ref. 1). It is felt, however, that a closer examination of the flow field between ground and wing would be useful.

In series No. 1, at 6 diameters the under surface was subjected to an irregular pattern of very low negative pressures. About two-thirds of the wing surface showed negative pressure deviations of 0.1 inch w.g.. With reduction of height, these negative pressure areas expanded and increased until at 1 diameter the whole underside experienced negative pressures ranging from 0.1 to 0.4 inch w.g., (see Fig. 13, 13(a)).

With the installation of the symmetry wall, the pattern became extremely irregular. At 6 diameters, about three-quarters of the wing surface indicated low negative pressures between 0.1 and 0.3 inch w.g. (see Fig. 14, 14(a)). Ambient pressure prevailed on a strip along the symmetry wall. Down one foot, at 5 diameters, this strip showed first traces of positive pressures. The downwash which was deflected towards the symmetry wall, followed the wall upwards, and was deflected once more to flow underneath the wing in the direction of the fan exit where it was entrained. The lower sketch in Figure 1 illustrates this assumed flow. The above description holds true only for the flow normal to and in the direction of the symmetry wall. Flow at any other angle to the wall has an "outward" bias, and will flow along the described path but will possess an outward component away from the spanwise plane through the centre of the fan. Each deflection resulted in a region of positive pressures which effected the bending of the stream tubes. Upon reducing the fan exit height below 5 diameters, the area between fan and line of atmospheric pressure was subjected to higher negative pressures; the positive pressures along the symmetry wall increased by a small amount. The outer semi-span experienced very little change. The pattern which the high negative pressures displayed at 1 diameter indicated strong turbulence underneath the inner semi-span of the wing (see Fig. 15, 15(a)). These high negative pressures accounted for 85 percent of the total force acting on the underside of the wing at this height. The same pressures were also responsible for the generally greater suction forces in series No. 2 than in series No. 1. The pressure deviations on the outer semi-span, on the other hand, did not differ significantly between the two series.

In series No. 1, the suction forces on the underside of the aerofoil reached a value of 8 percent of the momentum thrust in free air, whereas in series No. 2 this force came to about 14 percent. These forces constituted the second important contribution to ground effect, the first one being reduction in mass flow. In Figure 16, the non-dimensionalized forces of series No. 2 are plotted against height.

4.4 Forces on the Fan Base

During the course of series No. 1, a quick check revealed that substantial pressure deviations from ambient existed on the face of the fan base. For series No. 2, pressure taps were installed, and readings were taken for all heights between 6 and 1/2 fan diameters. The pressure distribution across the radius of the base can be seen in Figure 17. Only a small pressure gradient existed near the edge of the base. Otherwise the pressures were quite constant. The manometer columns were extremely steady which indicated very little, if any, flow over the base.

The elemental forces were computed and integrated over the base. The mean, non-dimensionalized forces were plotted against height in Figure 16. Although the base had an area of only 0.2 square foot, in free air the total force on it matched that acting on the underside of the wing. This fact may emphasize the importance of the role which the fan base plays in ground effect studies and in fan efficiency. Below 3 diameters, the negative pressures decreased and somewhere between 1 and 2 diameters turned positive. The absolute force on the base increased between 6 and 1 diameters by 9.5 percent of the momentum thrust in free air. Von Glahn and other investigators have studied the annular jet and the lifting fan and have found a similar behaviour of pressures on the base plate (Ref. 9). In these cases, a sudden change from negative to positive pressures on the base led to a discontinuity in the force curves. The results of series No. 2 permitted one to draw a smooth curve through the test points, although a closer study might reveal an unstable region at this critical height.

It is interesting to note that the pressures on the base started to become more positive at a point where the negative ground effects on the fan and wing began. Together with the forces on the fan annulus, which will be discussed next, those on the base partially offset the negative ground effects. This positive trend is illustrated in the "pulling up" of the net thrust curve between 3 and 1 diameters. If it were not for this retarding action, the slope of the net thrust curve would have been the algebraic sum of that of the momentum thrust curve and the "force on underside of wing" curve.

From the point of view of stability, it may be useful to investigate further the critical height, i.e. the neighbourhood of 1.5 diameters. Sudden reversals between negative and positive pressures on fan base and annulus may well affect the manoeuvrability of the craft.

4.5 Forces on Fan Annulus

Whereas all forces discussed up to now were based on actual measurements those on the fan annulus were estimated. It was reasoned that if a substantial pressure difference existed at the edge of the base and some pressure near atmospheric prevailed on the edge of the wing forming the outer boundary of the annulus, then a pressure gradient must exist between these two lines. As is common practice, this gradient was assumed to be linear. Unfortunately, no direct static taps in the annulus walls were available. Thus the static pressures measured on the base approximately 1/16 inch away from the edge and an average value computed from the points on the wing nearest to the fan exit were employed for computing the forces on the annulus. These forces were plotted against height in Figure 16. The inherent inaccuracy of this procedure is realized. It was felt, however, that by including these computed approximate forces in the total ground effect picture, the net thrust would be brought closer to reality.

The force acting on the fan annulus must be a function of that acting on the base, because pressures on the outer edge of the annulus were nearly atmospheric in most instances. Above the critical height, the forces on the annulus were found to be, on the average, 1.48 times those on the base; below this height they were 1.15 times the forces on the base. This difference can be explained by the fact that no matter how small were the pressures on the outer edge of the annulus, they were always negative, whereas the sign of the pressures on the base changed at the critical height.

In the meantime, four static taps have been installed both on the inner and outer walls of the annulus. The average readings of these taps will provide, in future tests, better information as to the static pressures at the fan exit.

4.6 Momentum Thrust

The momentum thrust was computed from the mass flow which, as mentioned in section 4.1, was obtained by cylindrical dynamic tubes at the inlet. With the corrected mass flow being

$$W_c = \rho A \bar{V}$$

the mean velocity was computed. The momentum thrust, T_m , then followed from

$$T_m = \frac{W}{g_o} \bar{V} = \frac{\rho A \bar{V}^2}{g_o}$$

The mass flows and thrusts obtained by this means compared favourably to integrated values and were felt to be of adequate accuracy for the purpose of this investigation.

The computed momentum thrusts after having been modified by the forces on base and annulus were found to be about 20 percent higher than the measurements previously obtained from a balance with only a 16-inch diameter bellmouth and no wing. A large part, if not all, of this 20 percent of thrust difference can be ascribed to the improved inlet conditions. The relative momentum thrust, non-dimensionalized by that at 6 diameters, was plotted against height in Figure 16. If the momentum thrust at 6 diameters was called unity, at 1 diameter only 78 percent of it was available. The reason for this severe reduction in thrust is that the fan velocity appears to the second power in the expression for the momentum thrust. As can readily be seen from Figure 16, the steepness of the momentum thrust curve below 3 diameters indicates that the decay of this thrust was primarily responsible for the adverse ground effect.

4.7 Net Thrust

Finally, a net thrust was obtained by modifying the momentum thrust by the forces acting on the underside of the wing, the base, and the annulus. This net thrust, non-dimensionalized, was plotted against height in Figure 16. It will be noticed that in free air the net thrust amounted to about 83 percent of the pure momentum thrust. This fact will surely be of interest to the power plant and fan designer. From the ground effect point of view, however, the net thrust in free air was called unity. No changes occurred until about $3\frac{1}{2}$ diameters. At this point the net thrust decreased and at 1 diameter it had been reduced by about 14 percent of the momentum thrust. Below 1 diameter, the thrust curve fell off quite steeply which was primarily because of the high suction forces on the under surface of the wing. Another approach to the net thrust decay can be seen in Figure 18. Net thrusts

with respect to that in free air were plotted against height. In this case, only 82 percent of the net thrust in free air was available at 1 diameter.

5.0 CONCLUSIONS

One may briefly summarize the test observations as follows:

- (1) No evidence of serious stalling of the fan blades was found. This observation may apply only to the fan employed.
- (2) In free air, the suction forces on the under surface of the wing amounted to 1.5 percent (series No. 1) and 4.5 percent (series No. 2) of the momentum thrust. As the ground was approached, the negative pressures spread and increased in magnitude until at 1 diameter they constituted a suction force equivalent to 8 percent and 14 percent of momentum thrust in free air in series No. 1 and No. 2 respectively.
- (3) Although the fan base was of relatively small area, high negative pressures acting on it in free air resulted in a substantial suction force. This force was equivalent to 5 percent of momentum thrust in series No. 2. Fortunately, this suction force, having been constant from 6 to 3 diameters, decreased below 3 diameters and, between 1 and 2 diameters, turned positive. At 1 diameter, a thrust augmenting force equivalent to 2 percent of momentum thrust in free air acted on the base.
- (4) The mass flow at 1 diameter showed a reduction of 12 percent from that in free air.
- (5) The momentum thrust, which was derived from the mass flow measurements, had lost, at 1 diameter, 22 percent of its value in free air. This reduction in thrust was the primary contribution to negative ground effect on the configuration.
- (6) Finally, the net thrust which was obtained by modifying the momentum thrust, showed, at 1 diameter, a decrease of 18 percent from that in free air.

- (7) Whenever it seemed advantageous, the test data obtained at the three fan speeds were successfully collapsed by non-dimensionalizing them by the momentum thrust. In future tests, one fan speed, perhaps the highest of the three, should be sufficient to work at.

6.0 FUTURE WORK

Since VTOL aircraft of the passenger or cargo carrying type will probably employ a certain number of lifting fans in each wing, the spacing of these fans may be critical (Ref. 11). To investigate the effect of distance between adjacent fans on ground effect, a series of tests is suggested with the symmetry wall being moved closer to the fan. If the outer semi-span of the wing is left untouched, the present fan/wing ratio of 1/18 will be increased and will approach the recommended ratio of 1/10.

7.0 REFERENCES

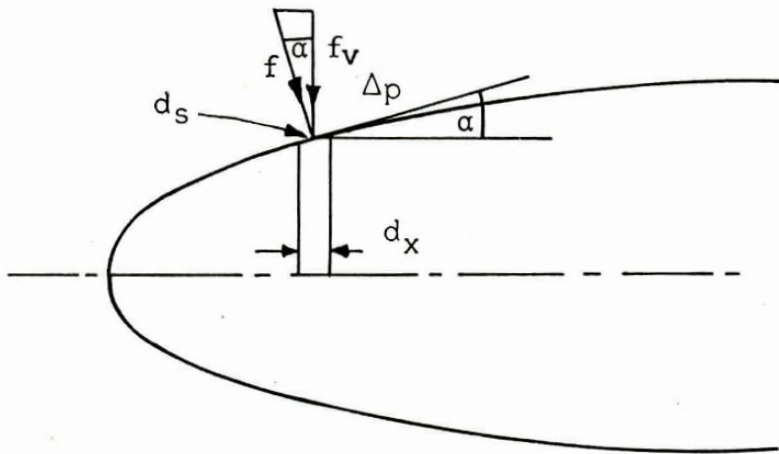
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/AM

APPENDIX A

FORCES ON THE WING



Let the local pressure deviation from atmospheric on the wing surface be represented by Δp , and let this pressure act on an area of length d_s and unity width (see Fig. A-1). Then the elemental force, f , is equal to

$$f = \Delta p d_s$$

Fig. A-1

The vertical component of f one may call f_v and

$$f_v = f \cos \alpha = \Delta p d_s \cos \alpha$$

but

$$d_s = \frac{d_x}{\cos \alpha}$$

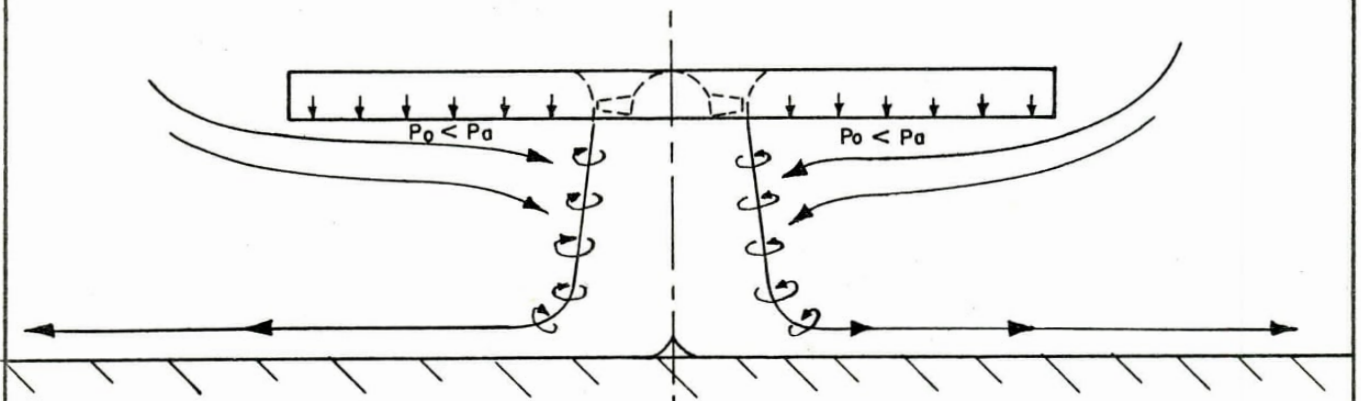
hence

$$f_v = \Delta p \frac{d_x}{\cos \alpha} \cos \alpha$$

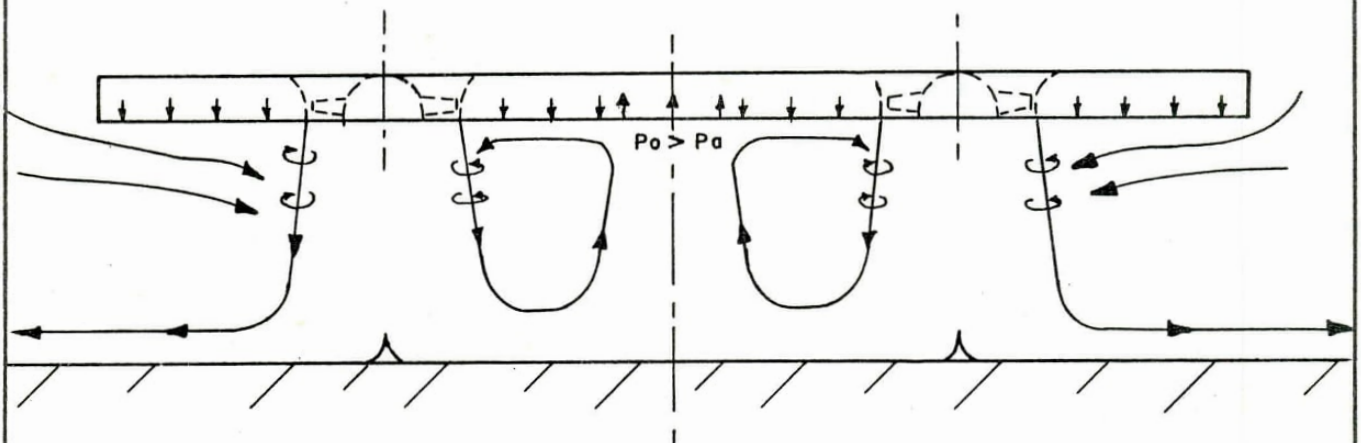
$$f_v = \Delta p d_x$$

Finally, the total force was found by numerically integrating the elemental forces over the wing.

It is sometimes thought that the vertical component of the pressure rather than the pressure itself should be multiplied by the projected area. The above development shows that this is not true.

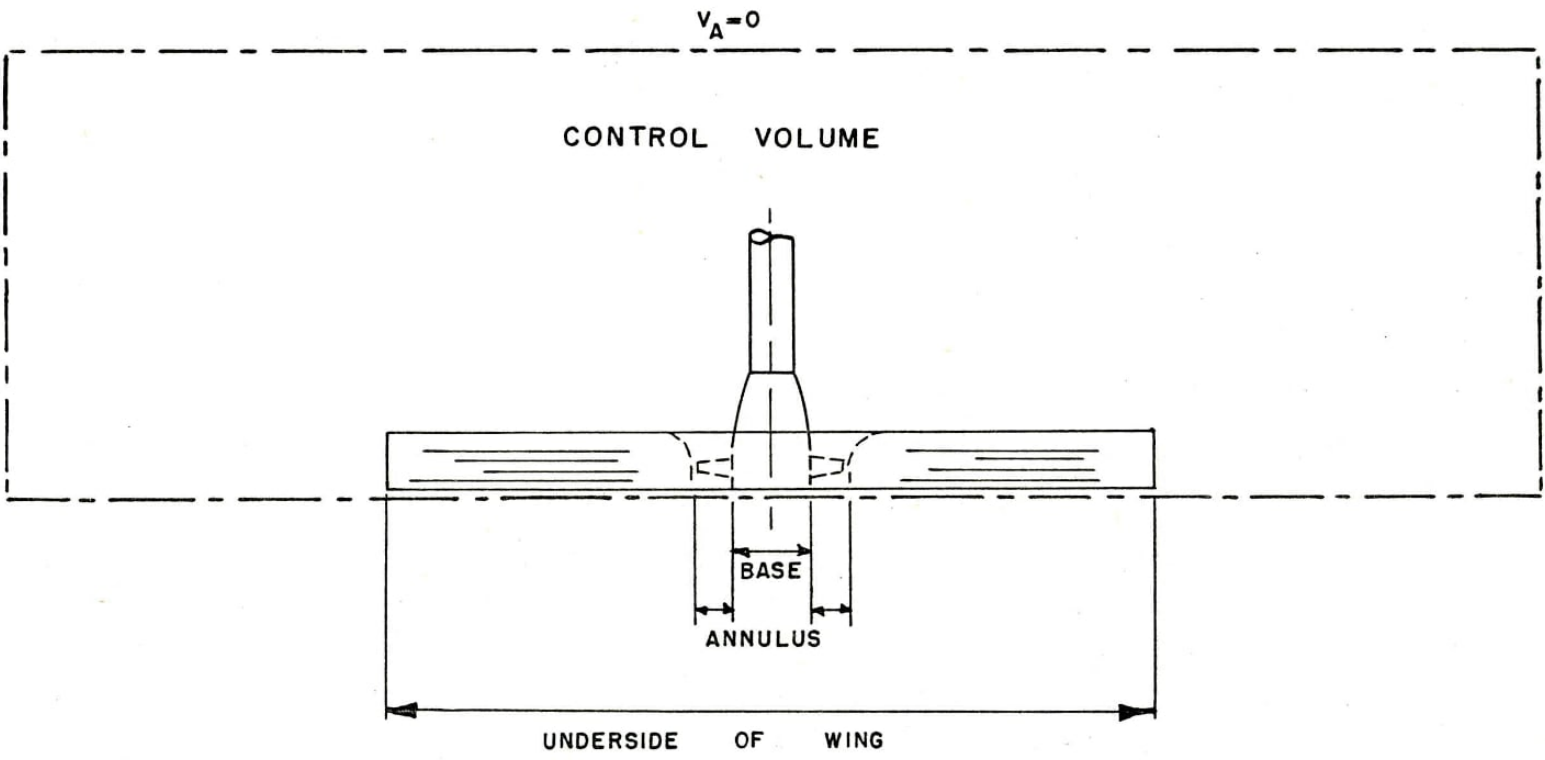


SINGLE FAN IN WING



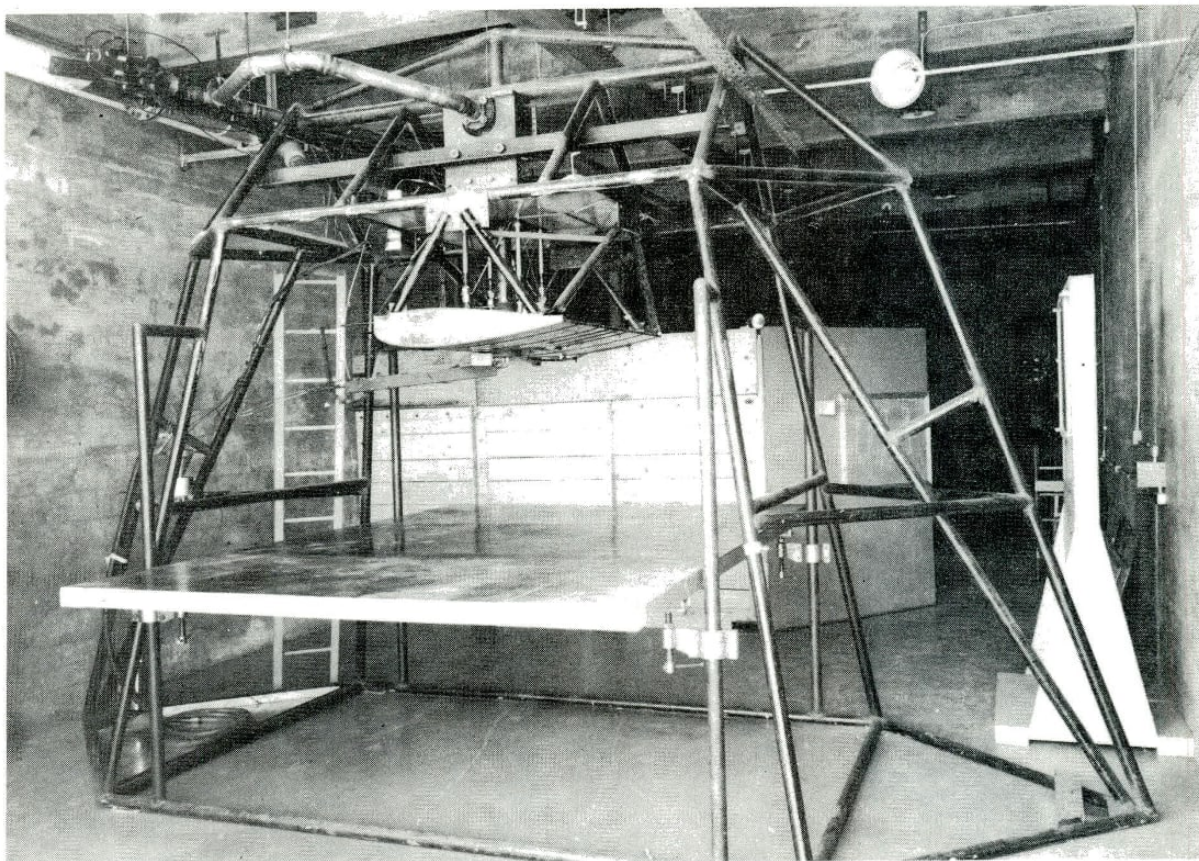
TWO FANS IN WING

GROUND EFFECT RESULTING FROM DOWNWASH
OF FAN-IN-WING CONFIGURATION

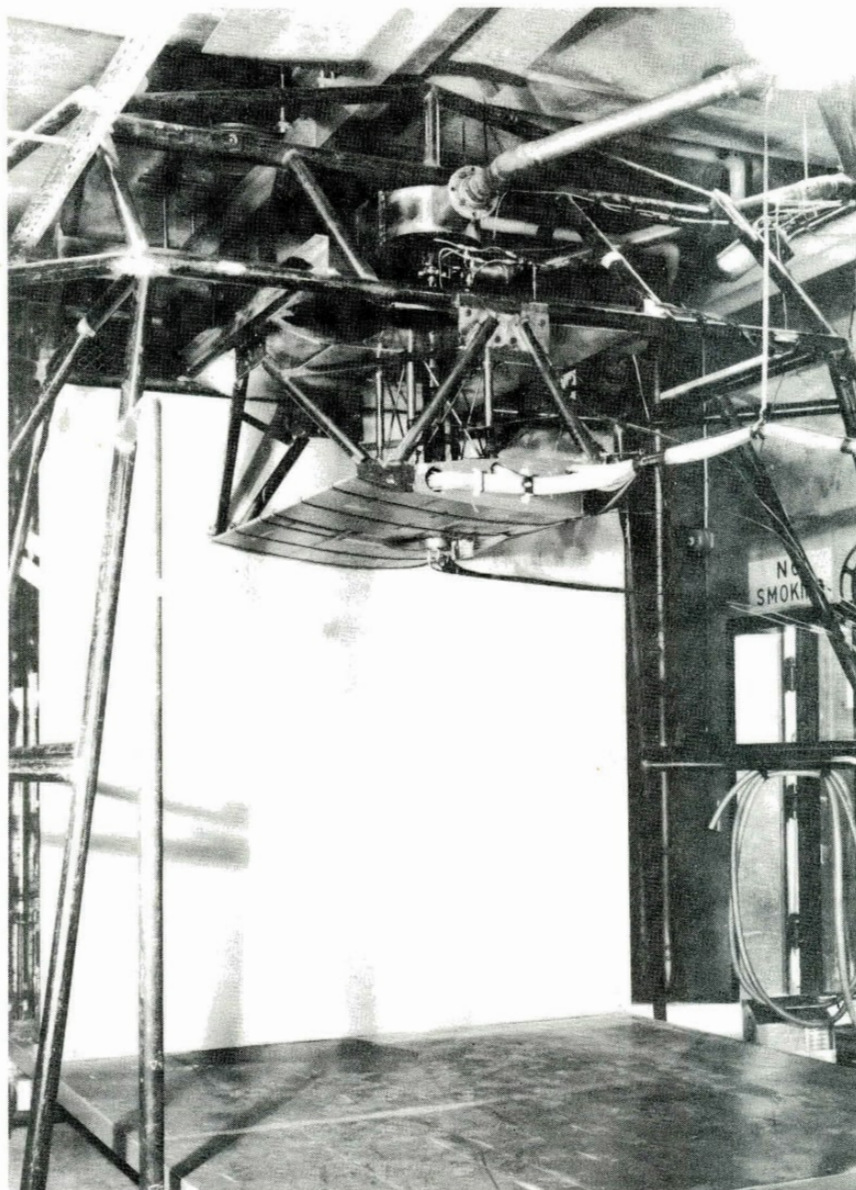


FAN - IN - WING AND CONTROL VOLUME

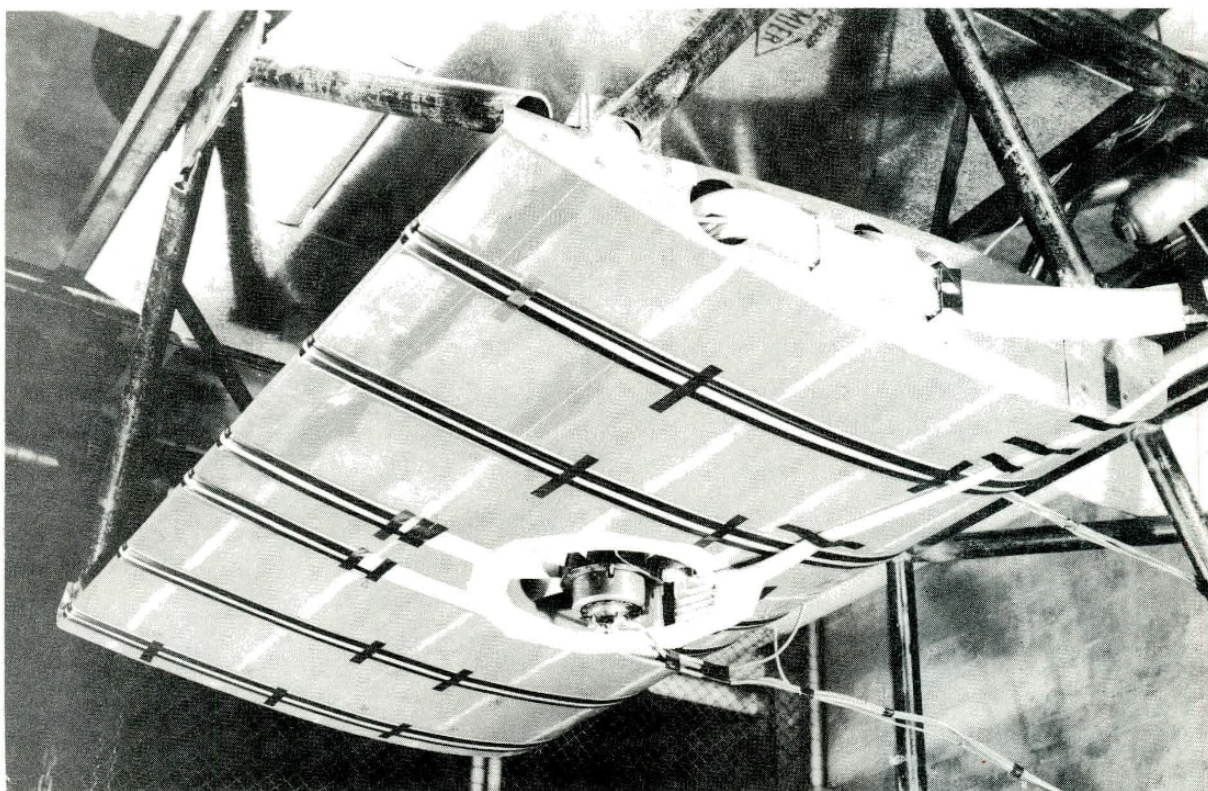
FIG. 3
MET-369



GROUND EFFECT TEST RIG FOR SERIES NO. 1

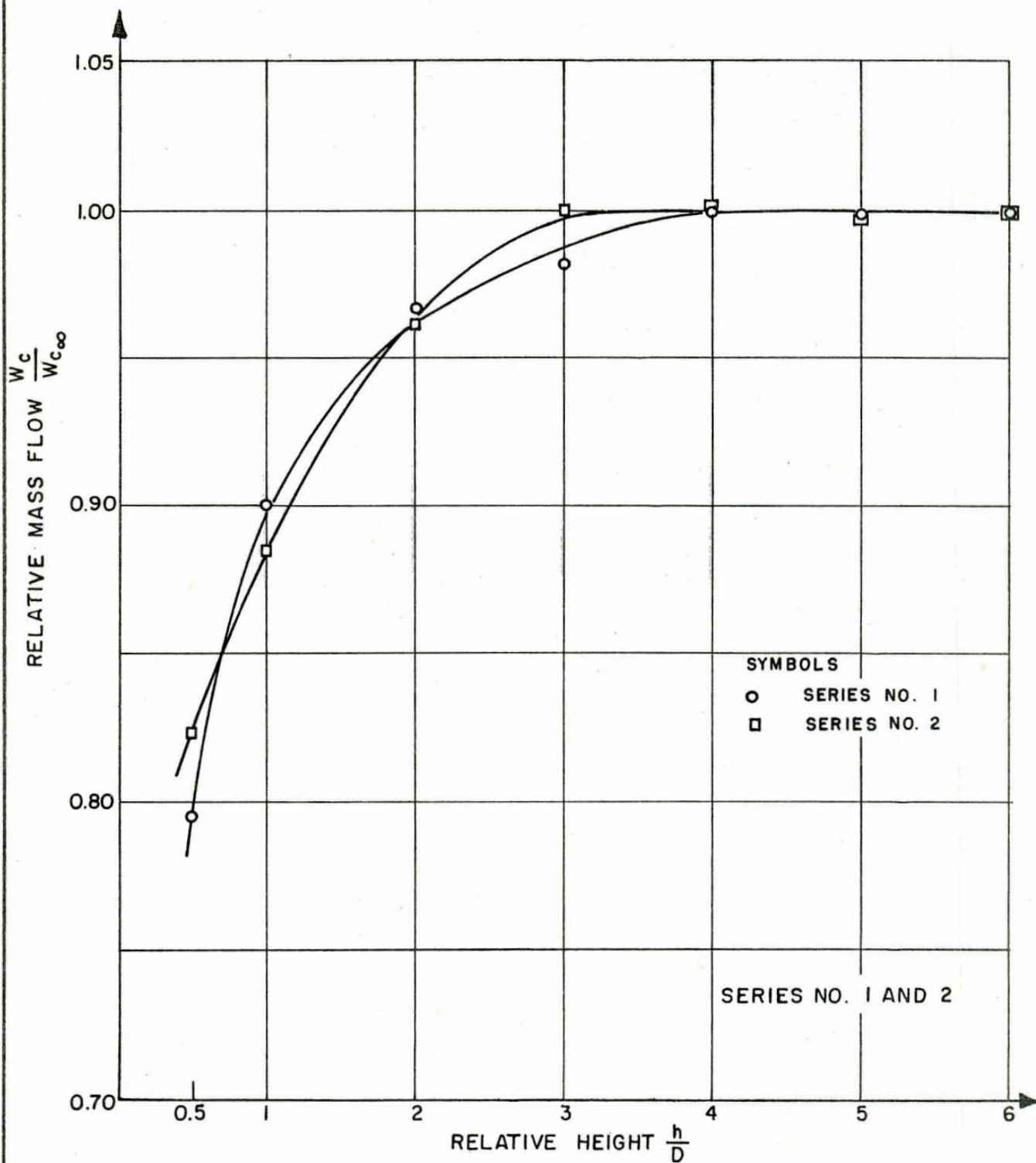


GROUND EFFECT TEST RIG WITH SYMMETRY
WALL FOR SERIES NO. 2



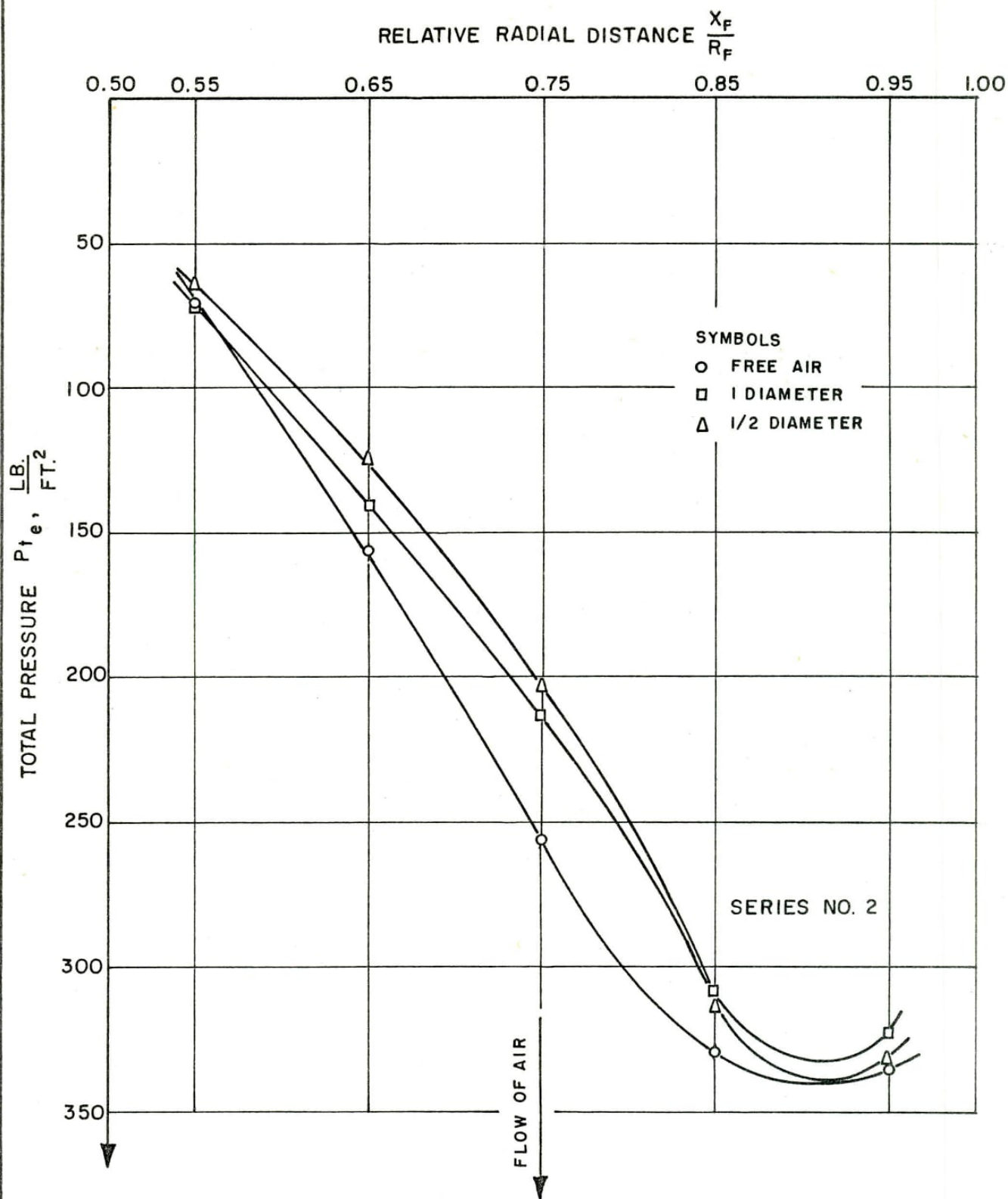
UNDERSIDE OF WING INSTALLATION

FIG. 6
MET-369



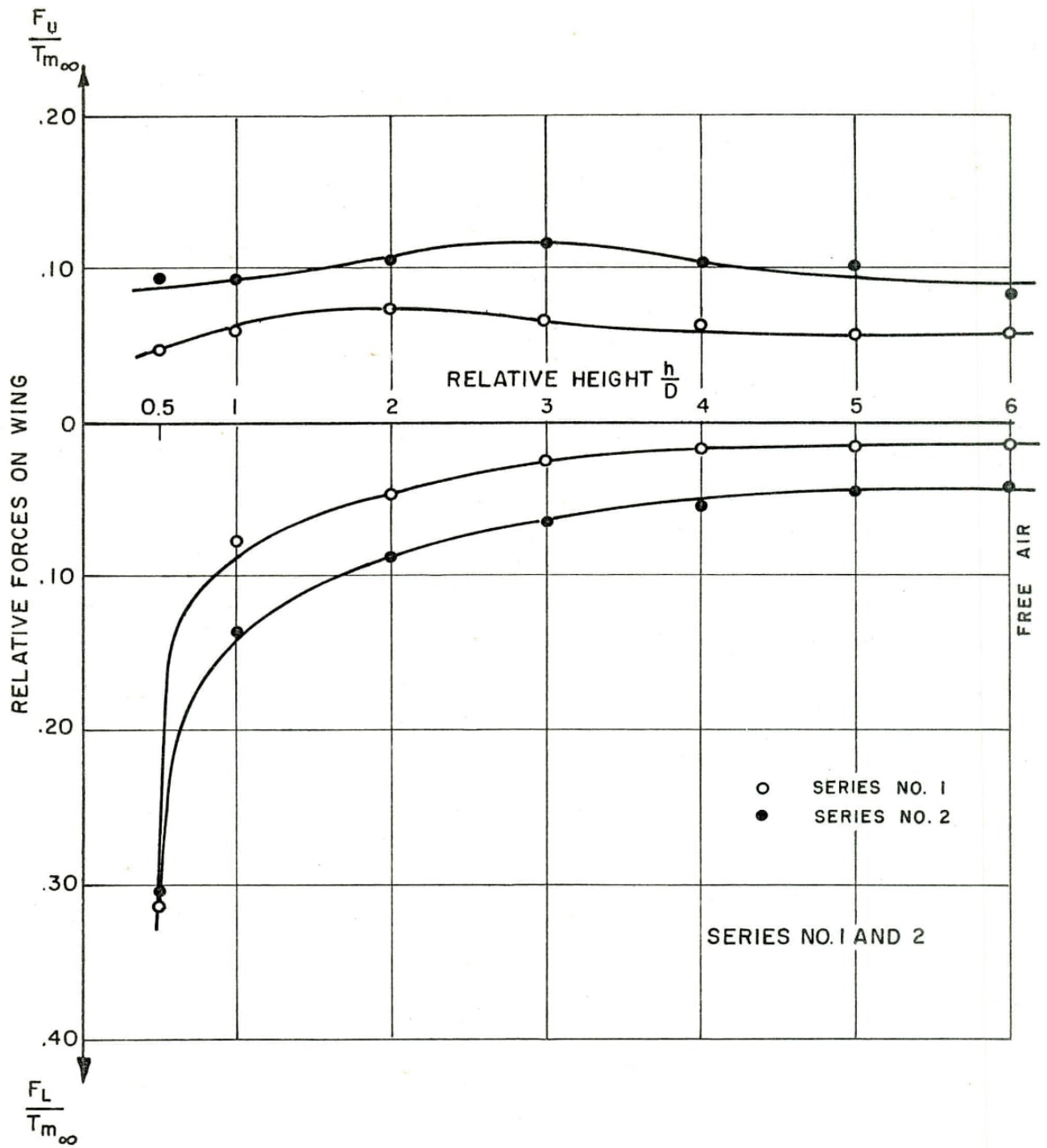
EFFECT OF HEIGHT ON FAN MASS FLOW

$$\frac{W_c}{W_{c\infty}} \text{ vs. } \frac{h}{D}$$



EFFLUX CHARACTERISTICS AT FAN EXIT

N_c 11900 R.P.M.



FORCES DUE TO PRESSURE DIFFERENCES ON UPPER AND LOWER SURFACES OF WING

$$\frac{F_u}{T_{m_\infty}}, \frac{F_L}{T_{m_\infty}} \text{ VS. } \frac{h}{D}$$

RUN NO. 3R
N_c: 11900 R.P.M.

DISC LOAD: 214 P.S.F.
H/D: 6

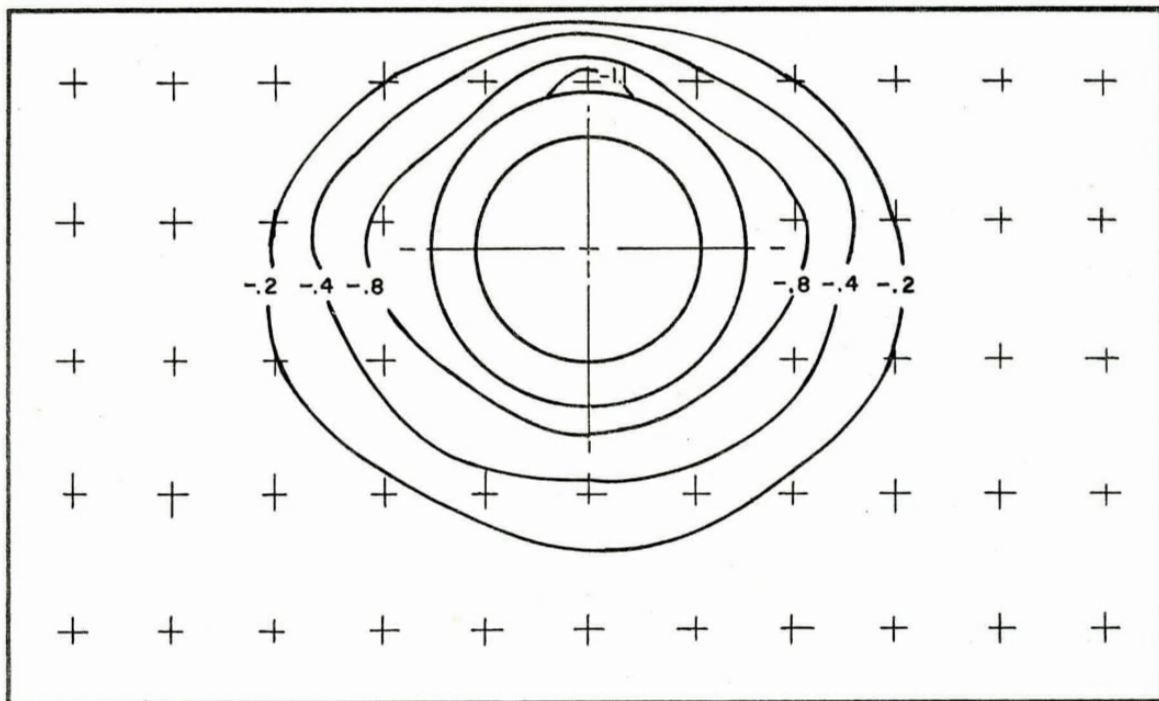


FIG. 9 WING PRESSURE PROFILE CHART - UPPER SURFACE - SERIES NO. 1

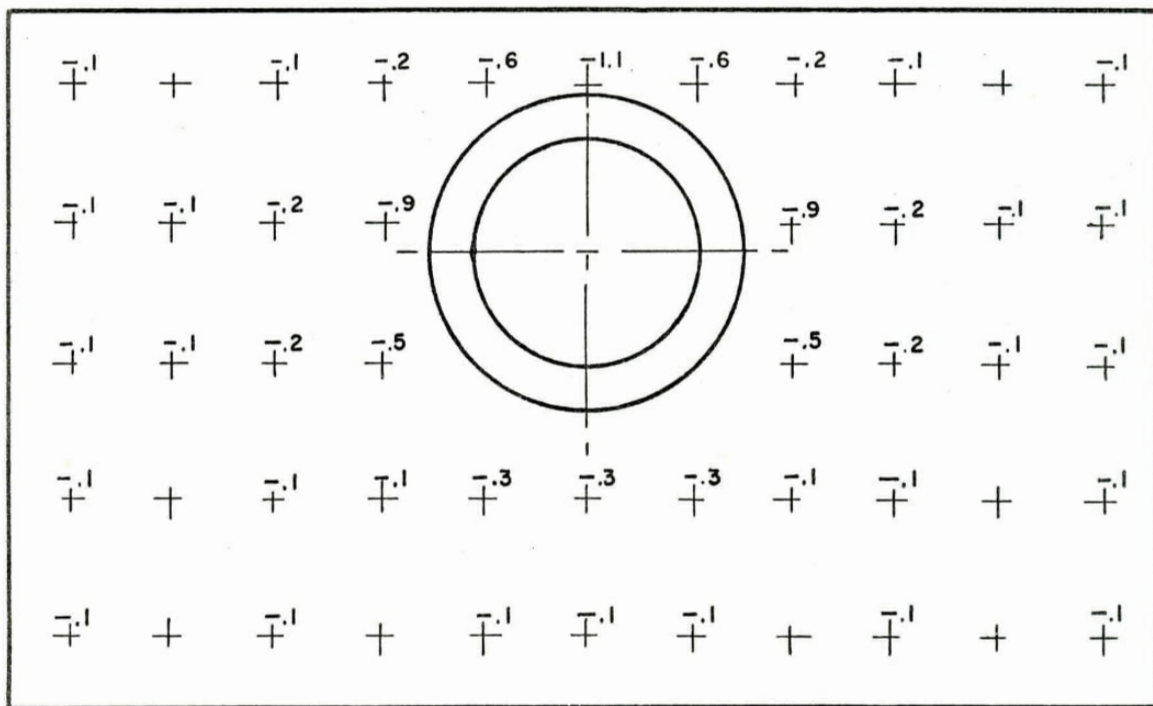


FIG. 9a WING PRESSURE CHART - UPPER SURFACE - SERIES NO. 1

NOTE: LOCAL STATIC PRESSURE DEVIATIONS FROM AMBIENT ARE GIVEN IN INCHES OF WATER

RUN NO. 24/45 R
N_c: 11900 R.P.M.

DISC. LOAD: 214 P.S.F.
H/D: 6

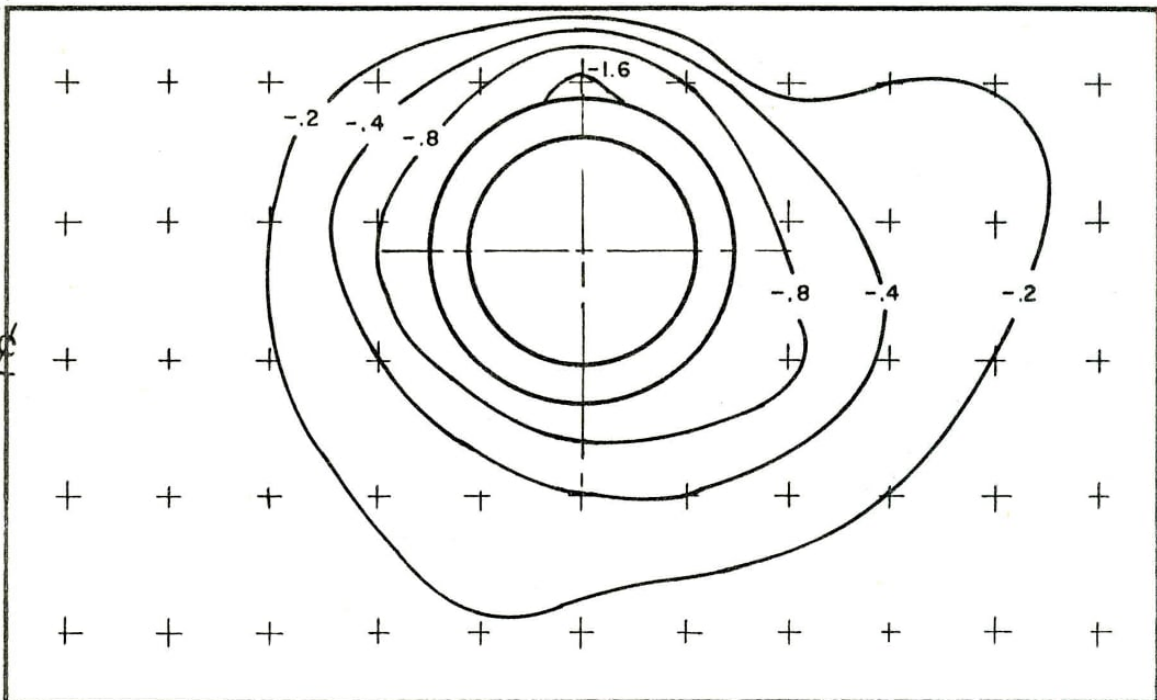


FIG. 10 WING PRESSURE PROFILE CHART - UPPER SURFACE - SERIES NO. 2

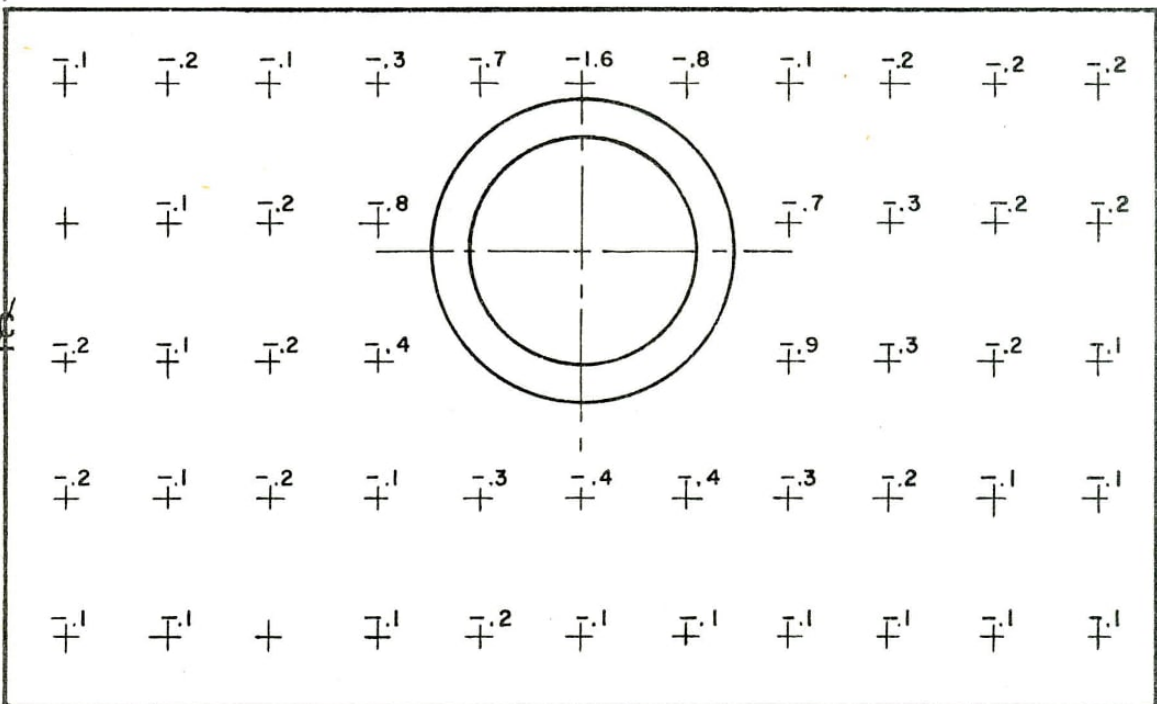


FIG. 10a WING PRESSURE CHART - UPPER SURFACE - SERIES NO. 2

NOTE: LOCAL STATIC PRESSURE DEVIATIONS FROM AMBIENT ARE GIVEN IN INCHES OF WATER

RUN NO. 18
N_c: 11900 R.P.M.

DISC. LOAD: 214 P.S.F.
H/D: 1

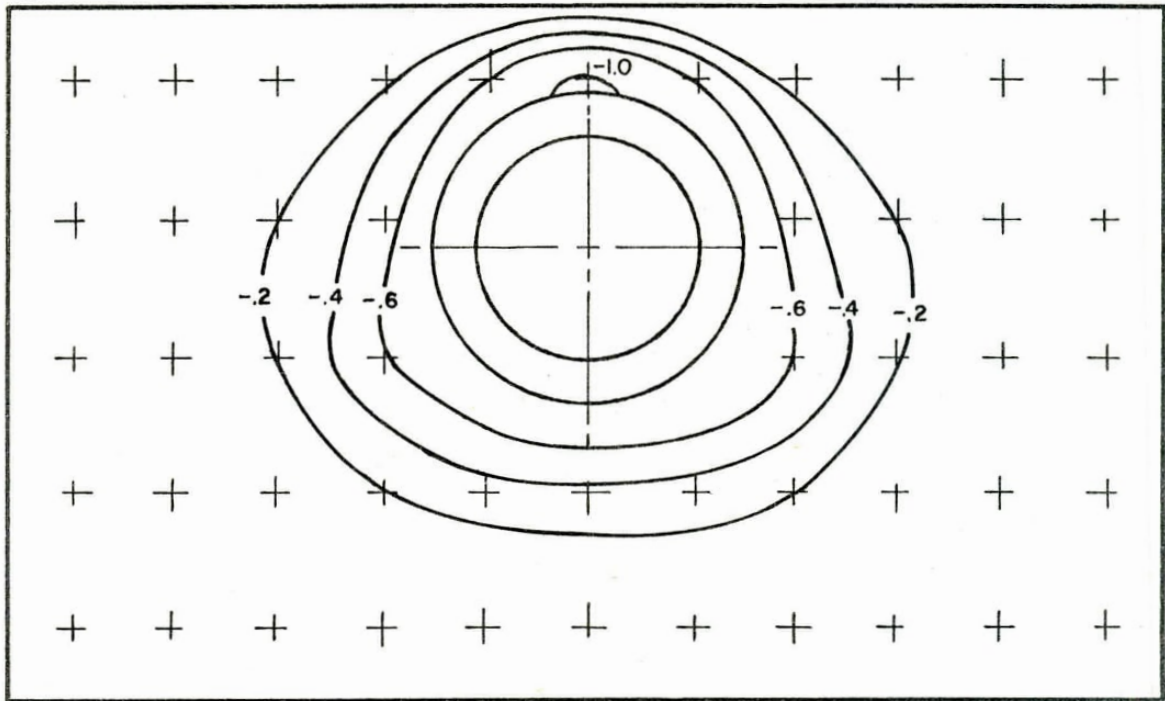


FIG. II WING PRESSURE PROFILE CHART-UPPER SURFACE-SERIES NO. 1

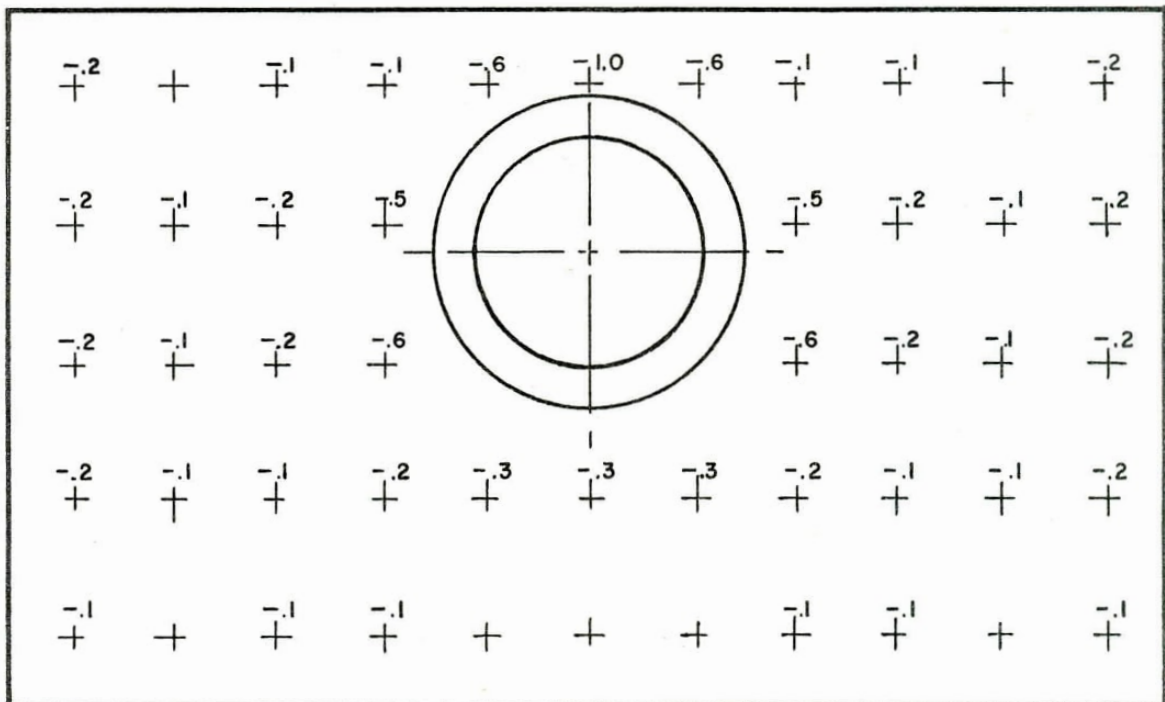


FIG. IIa WING PRESSURE CHART-UPPER SURFACE - SERIES NO. 1

NOTE: LOCAL STATIC PRESSURE DEVIATIONS FROM AMBIENT ARE GIVEN IN INCHES
OF WATER

RUN NO. 39/60
Nc: 11900 R.P.M.

DISC. LOAD: 214 P.S.F.
H/D: 1

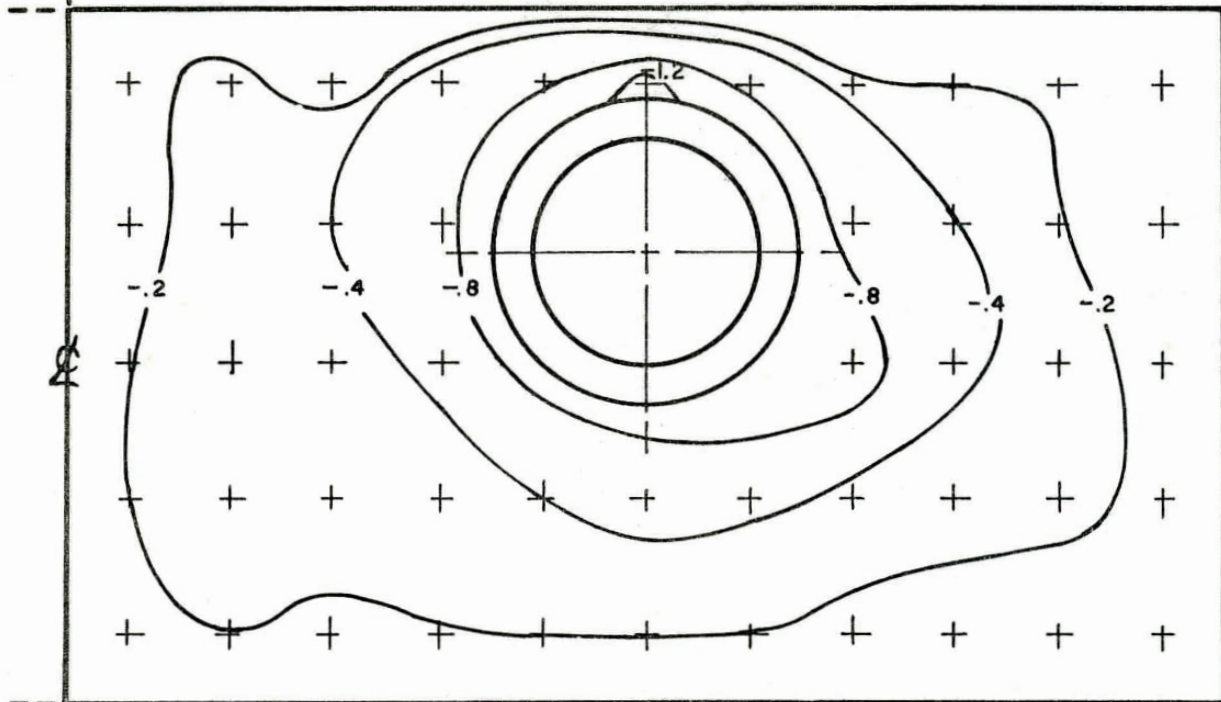


FIG. 12 WING PRESSURE PROFILE CHART-UPPER SURFACE-SERIES NO. 2

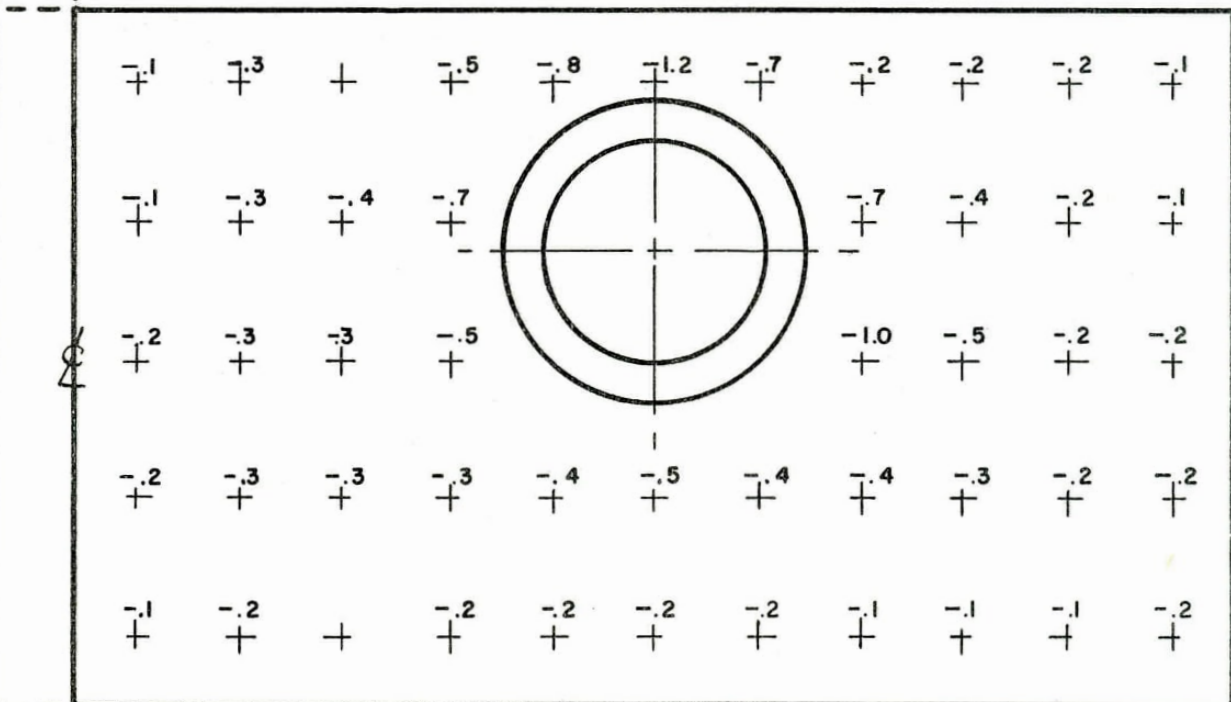


FIG. 12a WING PRESSURE CHART-UPPER SURFACE-SERIES NO. 2

NOTE: LOCAL STATIC PRESSURE DEVIATIONS FROM AMBIENT ARE GIVEN IN INCHES OF WATER

RUN NO. 18
N_c: 11900 R.P.M.

DISC. LOAD: 214 P.S.F.
H/D: 1

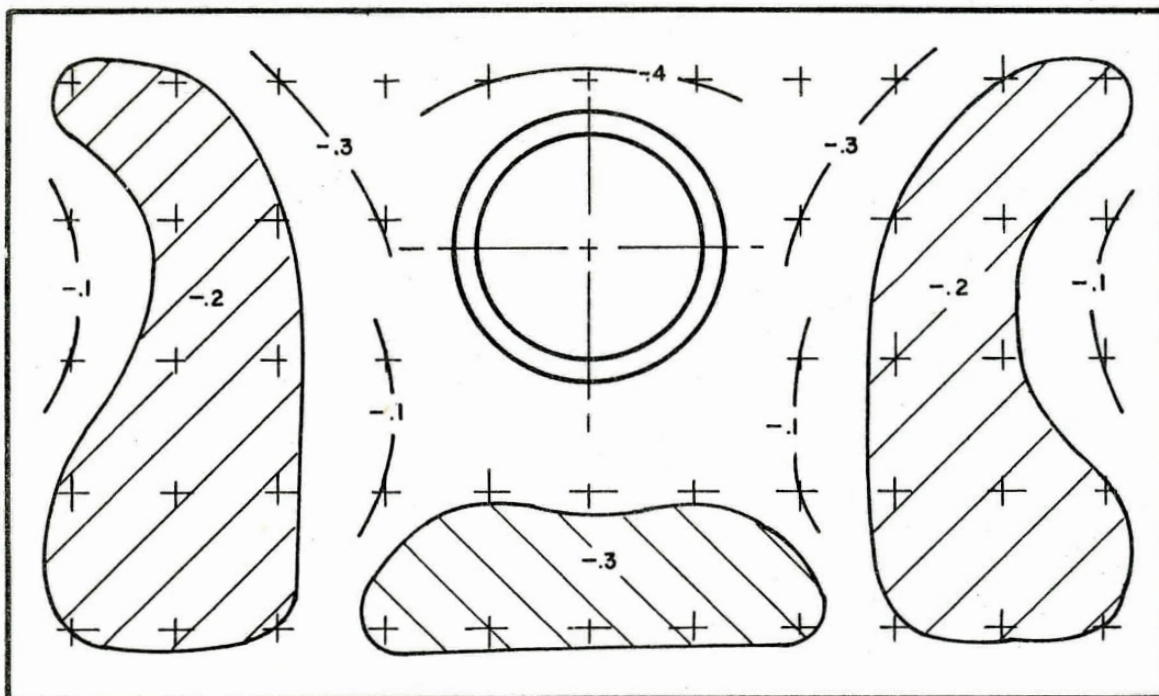


FIG. 13 WING PRESSURE PROFILE CHART—LOWER SURFACE—SERIES NO. 1

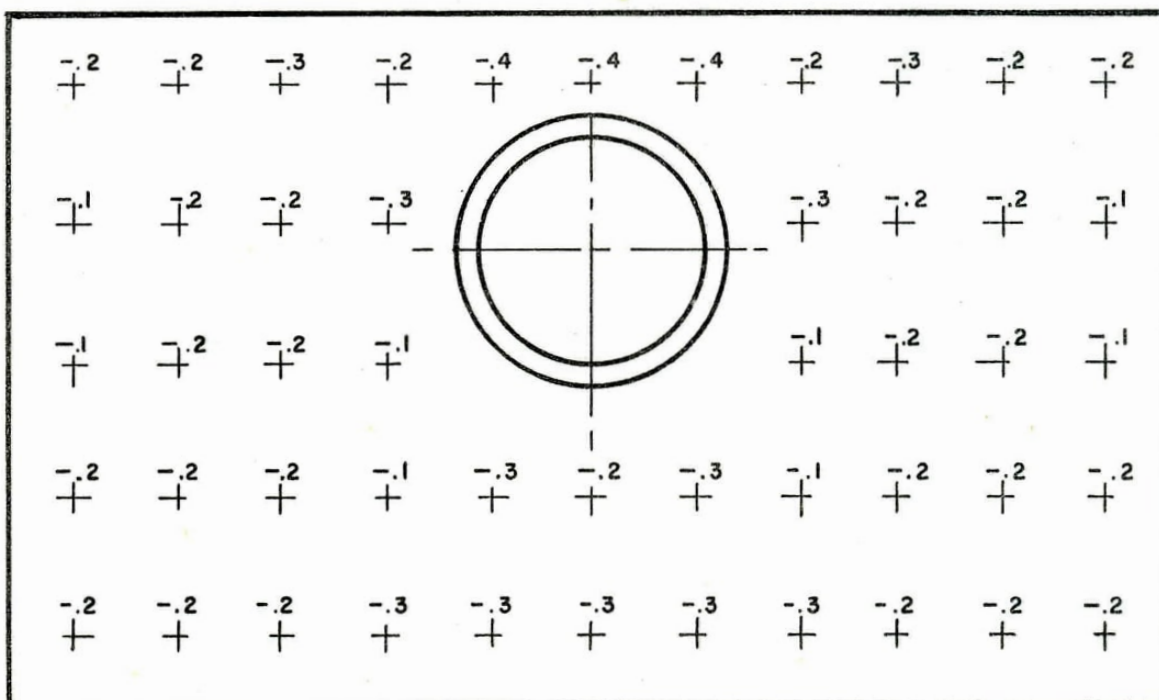


FIG. 13a WING PRESSURE CHART—LOWER SURFACE—SERIES NO. 1

NOTE: LOCAL STATIC PRESSURE DEVIATIONS FROM AMBIENT ARE GIVEN IN INCHES OF WATER

RUN NO. 24/45 R
N_c: 11900 R.P.M.

DISC. LOAD : 214 P.S.F.
H/D : 6

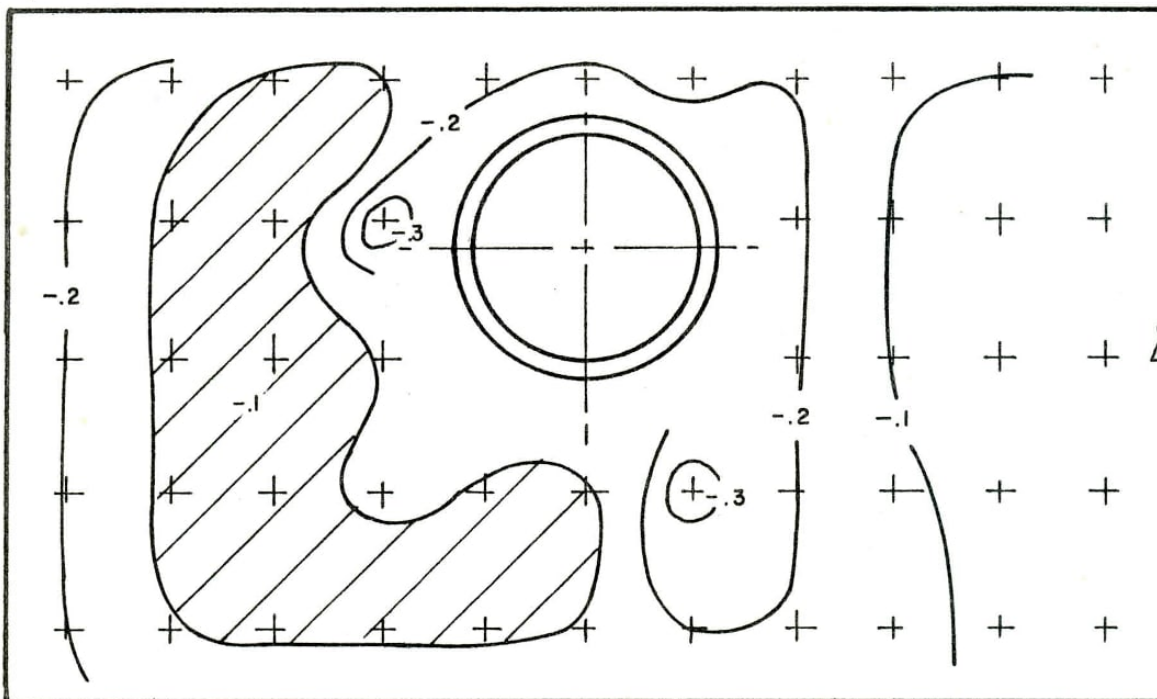


FIG. 14 WING PRESSURE PROFILE CHART-LOWER SURFACE-SERIES NO. 2

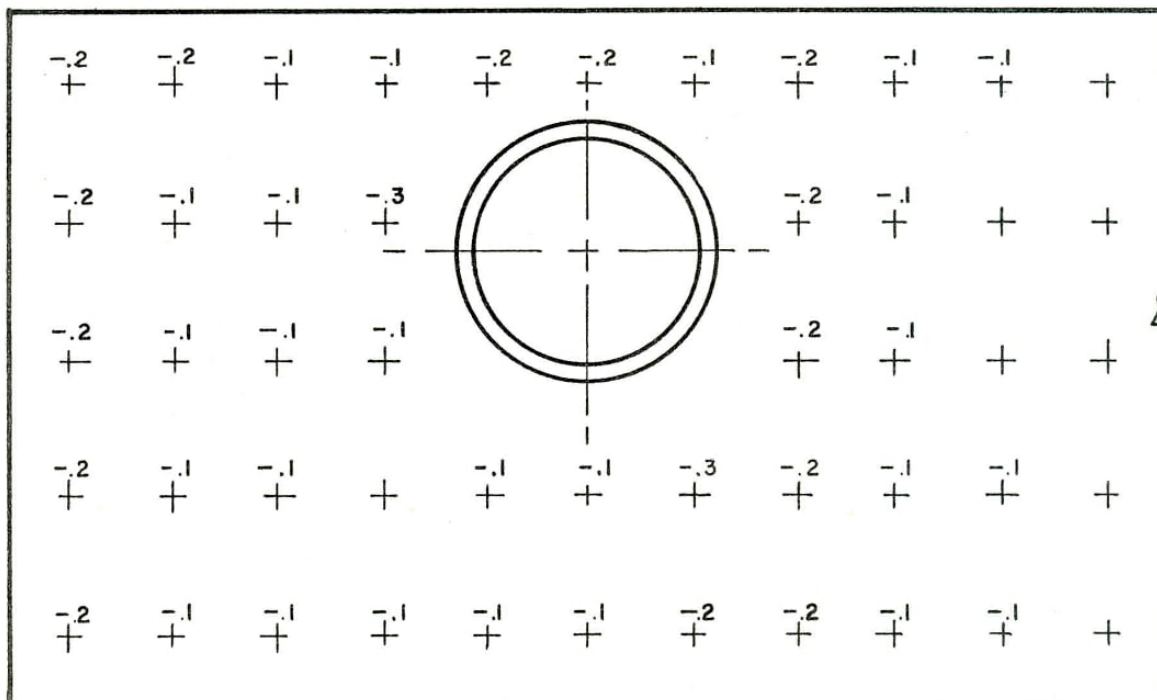


FIG. 14a WING PRESSURE CHART-LOWER SURFACE-SERIES NO. 2

NOTE: LOCAL STATIC PRESSURE DEVIATIONS FROM AMBIENT ARE GIVEN IN INCHES OF WATER

RUN NO. 39/60
N_c: 11900 R.P.M.

DISC. LOAD 214 P.S.F.
H/D: 1

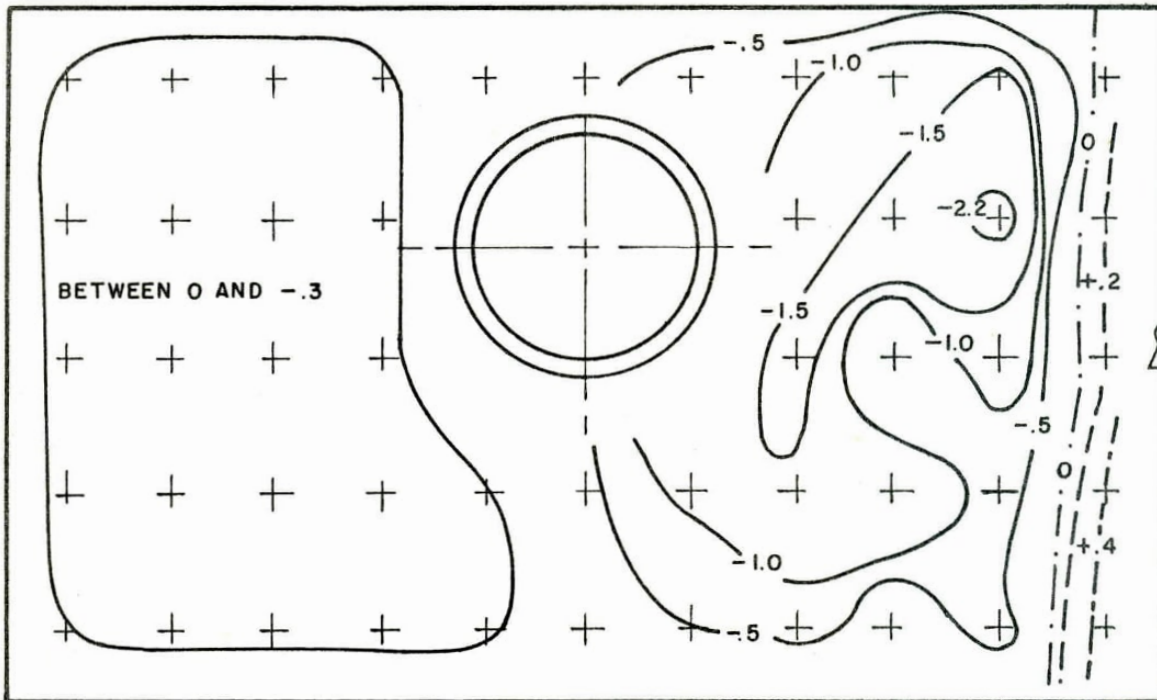


FIG. 15 WING PRESSURE PROFILE CHART-LOWER SURFACE-SERIES NO. 2

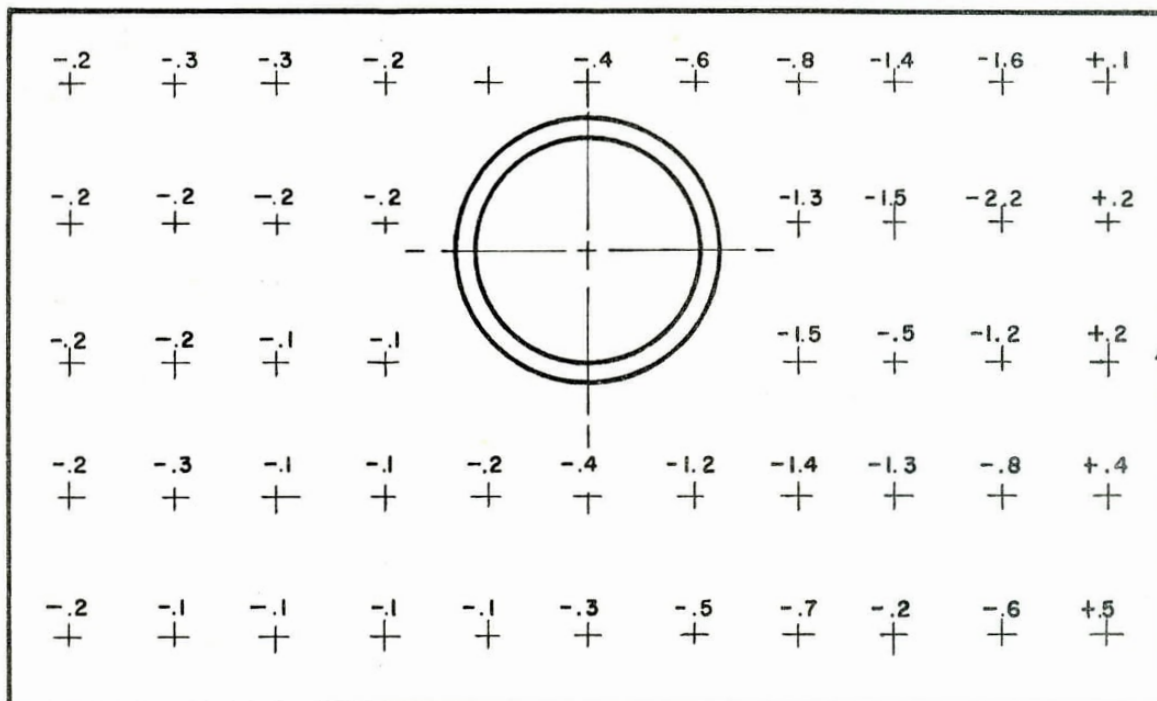
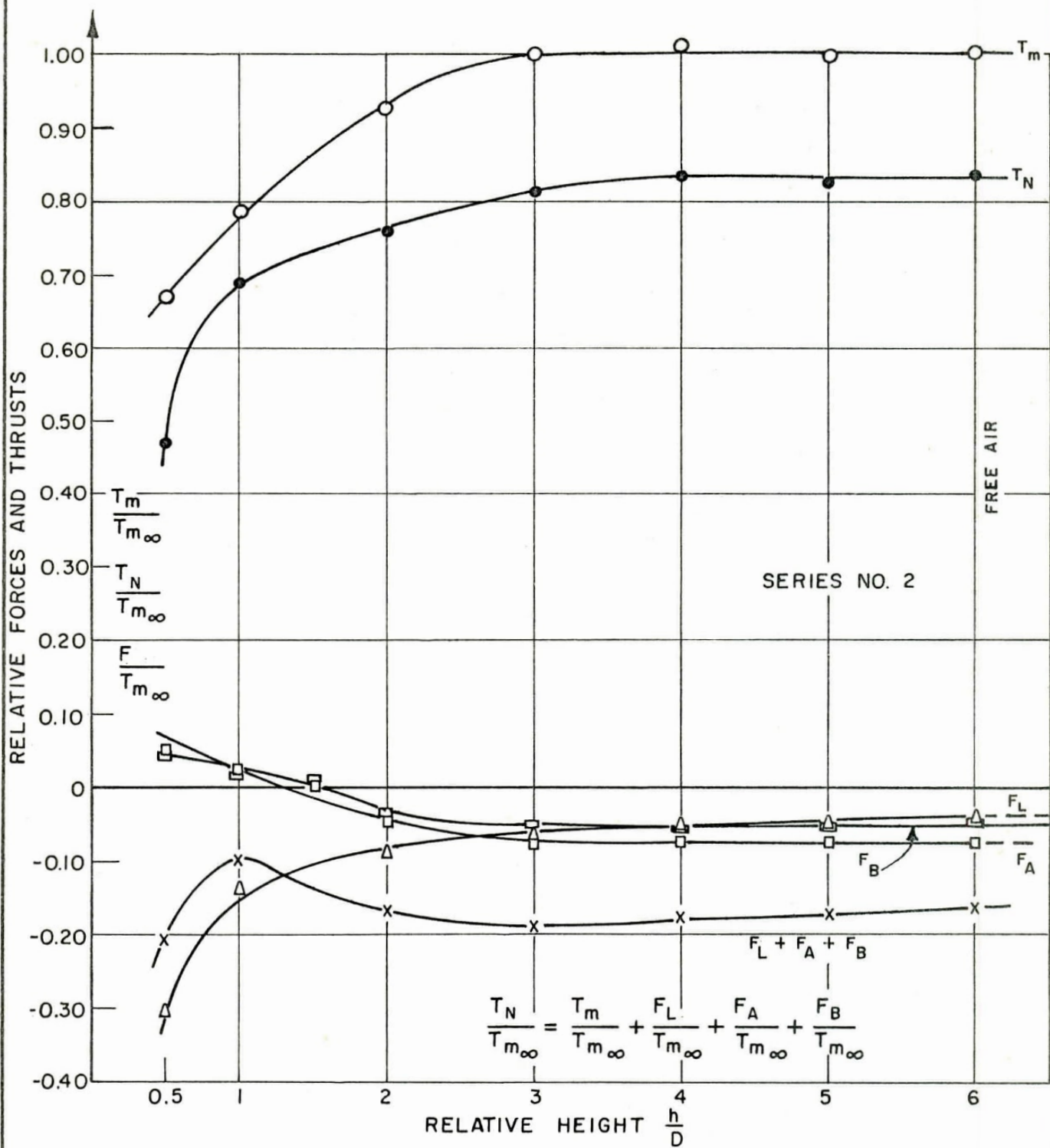


FIG. 15a WING PRESSURE CHART-LOWER SURFACE - SERIES NO. 2

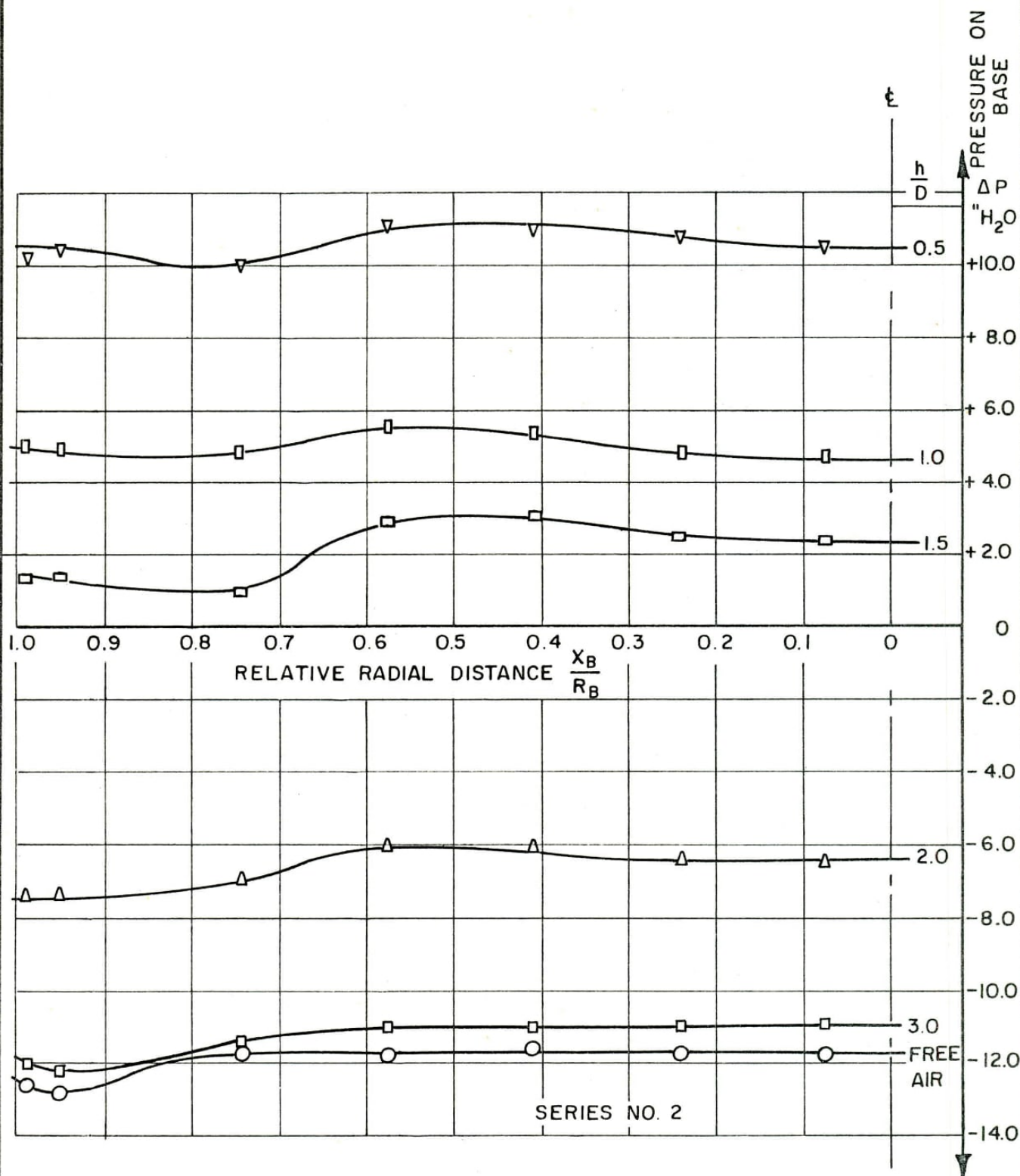
NOTE: LOCAL STATIC PRESSURE DEVIATIONS FROM AMBIENT ARE GIVEN IN INCHES OF WATER

FIG. 16
MET-369

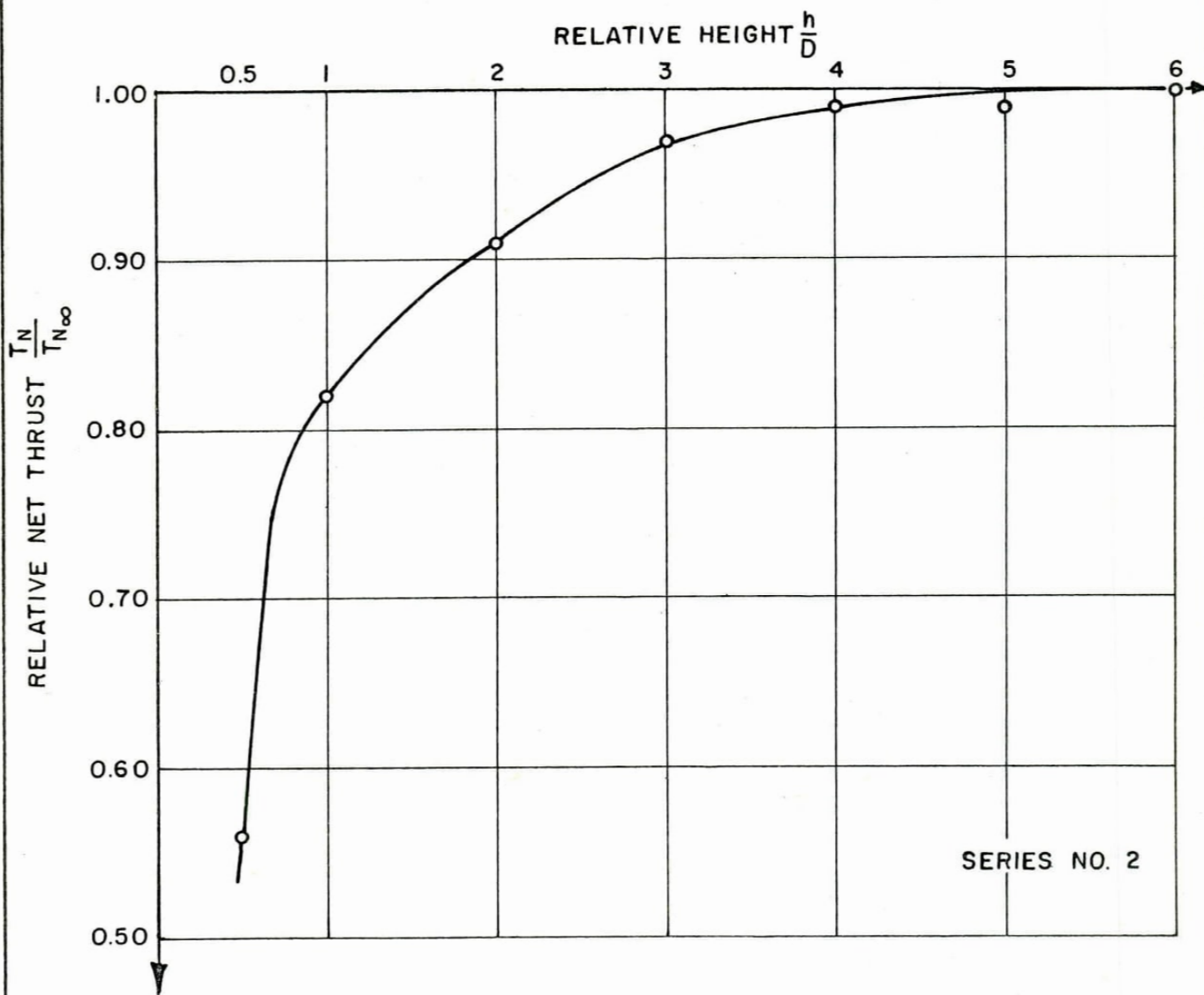


VARIATION OF NET THRUST AND ITS COMPONENTS WITH HEIGHT

FIG. 17
MET-369



PRESSURES ON FAN BASE
 N_c 11900 RPM



RELATIVE NET THRUST VS. RELATIVE HEIGHT

$$\frac{T_N}{T_{N\infty}} \text{ vs. } \frac{h}{D}$$