A PRELIMINARY STUDY OF THE PROBLEM OF BOUNDARY LAYER CONTROL

THESIS

by

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The author wishes to express his sincere appreciation to Dr. Clark B. Millikan for his interest in the problem and his many helpful suggestions as to the course of the research.

He wishes to give special thanks to Mr. Wm. H. Bowen for his valuable advice concerning preparation of the boundary layer model and considerable time spent in working upon it.

Thanks are expressed to Mr. Wm. R. Sears and members of the wind tunnel staff for their capable help in carrying out the tests

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NOTATIONS

α	Angle of attack of model with reference to chord line
α_o	Angle of attack corrected to infinite aspect ratio
b	Wing span
C	Tail Cone
C_D	Drag coefficient
C_D'	Coefficient of drag including the reaction effect = $C_{DR} + C_D$
C_{D_o}	Wing profile drag coefficient
C_{D_P}	Parasite drag coefficient
C_{DR}	Coefficient measuring the drag reaction upon model as a result of flow through it
C_{DS}	Measure of power used to remove Boundary Layer = $\frac{E}{qSV}$
C_L	Lift Coefficient
C_{LR}	Coefficient measuring the lift reaction upon model as a result of flow through it
C_P	Ratio of internal wing pressure to dynamic head = $\frac{P}{q}$
C_Q	Measure of quantity handled per second = $\frac{Q}{SV}$
E	Power supplied by the Boundary Layer Model to air passing through it
F	Flap, - subscript indicates specific flap; exponent indicates flap angle
G	Slot, - subscript indicates specific slot
H	Total energy of flow
θ	Angle of exhaust jet to undisturbed velocity

λ	Fraction of wing chord
ν	Kinematic viscosity
P	Static pressure within the wing referred to free stream conditions
P_1	Static pressure at front static ring
P_2	Static pressure at rear static ring
P_T	Dynamic pressure on Pitot-static rake
q	Dynamic pressure of airstream during test
Q	Quantity of air passing through Boundary Layer model per second
ρ	Density
R	Reynolds number
S	Wing area of model. With subscript, designates a normal configuration of the model
t	Mean aerodynamic chord
V	Undisturbed air velocity of test
W	Wing of Model
X	Fillet

SUMMARY

This thesis presents a study of the problem of securing high lifts by means of boundary layer removal, together with first results of tests on the Boundary Layer Model of the Guggenheim Aeronautics Laboratory, California Institute of Technology (hereinafter called GALCIT). It is divided into two parts: first, a review and discussion of previous work, and second, presentation and development of methods used for carrying out tests upon the GALCIT model, together with experimental results obtained from the tests upon the model.

Previous researches show that boundary layer removal is indeed successful in securing high lift coefficients. Study reveals also that results from one experiment may differ greatly from those of another. Consequently, previous work is of little help in predicting results to be obtained for a design different from the model tested.

Results on the GALCIT model have not been favorable, but it is believed that flow tests have found the difficulty. Consequently, the experimental work has value only for the light it sheds upon the future course of this research at the Institute.

- I -

PREVIOUS WORK

THE BOUNDARY LAYER AND SEPARATION. The idea of controlling the boundary layer is as old as the boundary layer concept itself. This concept dates back to the year 1904 when it was introduced by L. Prandtl at the International Mathematical Congress in Heidelberg. As part of his proof that the retarded air near a surface could be regarded as a separate layer, he presented results of certain simple experiments in removing it to secure potential flow.

The boundary layer is a layer of fluid next a surface past which there is relative flow. This layer is a layer of flow retarded by viscous shearing forces arising from the relative motion between fluid and surface. It has no definite edge since it theoretically extends to infinity, but as Prandtl showed, the layer could be treated as one with a definite bounding surface for all practical purposes. One common definition is that the boundary layer extends to the point where velocities are 99.5% of those given by pure potential flow. Its thickness as thus defined is ordinarily small. Thus, effects of viscous stresses are confined to a region close to the surface causing the layer. Figure 1 illustrates laminar and turbulent boundary layer profiles on a thin plate.

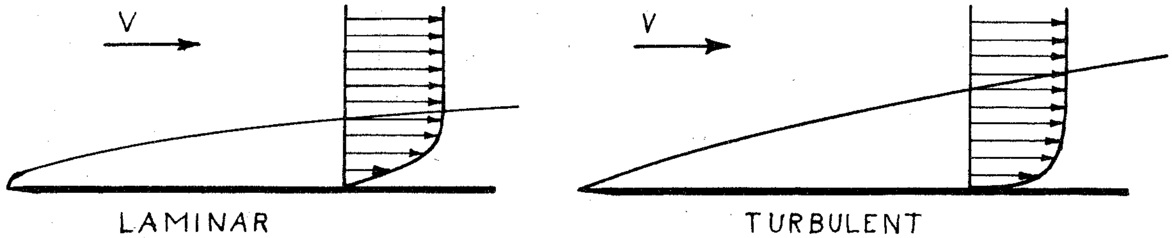


FIG. 1

By controlling the thickness of the boundary layer it is possible, in theory at least, to control the local skin friction coefficient. The possibilities for this use of boundary layer control do not seem great since indications are that any decrease in drag would do little more than make up for power expended in controlling the boundary layer.

By far the most important use for boundary layer control is to prevent flow separation. The mechanics of separation will be illustrated by an example. Consider flow over an airfoil, Figure 2.

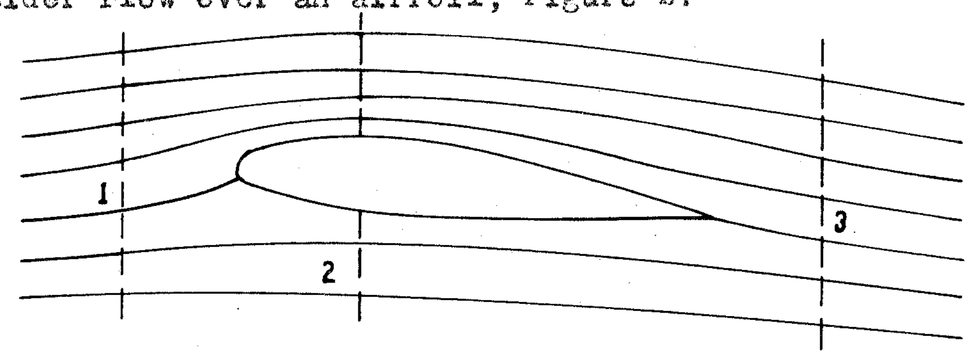


FIG. 2

At (1) the total head in the airstream is $H_1 = p_1 + \frac{1}{2}\rho V_1^2$ Well above or below the airfoil, because there has been nothing to decrease the energy of the air, the total head at (3) is also equal to H. Now consider flow along the upper surface of the airfoil. Due to the shape and angle of attack of the airfoil, pressure falls and velocity rises from values in region (1) to new values in region (2) in accordance with Bernouilli's equation. Next, the fluid must go from (2), a region of low pressure, to (3), a region of high pressure. The transition can be accomplished only by using up the high kinetic energy found at (2). However, if friction retards the flow, insufficient kinetic energy is available. In this case the fluid will proceed as far as it can against the adverse pressure gradient and then follow a line of least resistance, which is a path away from the airfoil. Such a phenomenon is called separation. Thus, separation can occur only when pressures are changing from low to higher values along the streamlines.

Figure 3 is a mechanical analogy of flow over the upper surface of an airfoil. It is obvious from the figure that any friction will prevent the ball from returning to its original level. Flow with separation is illustrated in Figure 4.

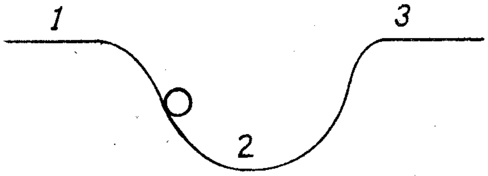


FIG. 3

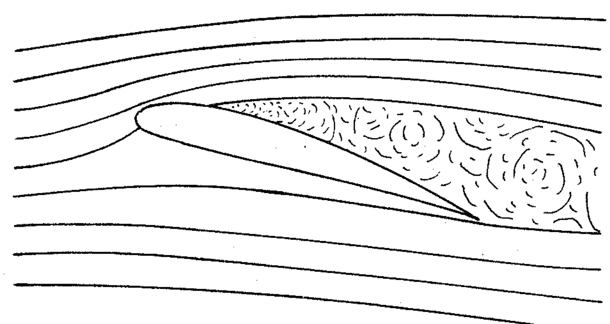


FIG. 4

The only reason there is not separation for all flows against adverse pressure gradients, since friction always exists, is that if the change is gradual enough, energy sufficient to make up for the deficiency can be imparted from the outer, unretarded layers.

CONTROLLING THE BOUNDARY LAYER. Therefore, to prevent separation, it is obvious that there must be some control over this retarded layer. The two most successful methods have been either to reenergize the boundary layer or to suck it off. Either method will delay separation. Reenergizing has been most successfully accomplished by blowing air out of a slot after the method indicated in Figure 5, to speed up the retarded layer. In most tests using this method, air is forced out of the slot at a speed roughly twice free air speed. This method has been found to require considerably more power than the method of boundary layer removal and so will not be considered further.

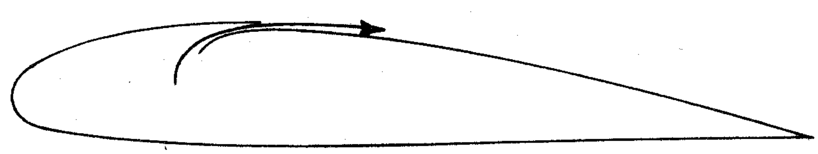


FIG. 5

The usual method of boundary layer removal is indicated by Figure 6. Air is merely sucked in through an opening in the upper wing surface in considerable quantities. Two effects of sucking air through this slot occur. One is that most of the boundary layer is taken inside the wing. However, there is another effect perhaps just as important. Air flowing into the slot creates a change in pressure distribution of the type shown in Figure 7. This change is toward a favorable gradient that helps the flow along, and yet its net effect on lift as given by the integral of the pressure distribution curve is small because the slot is merely a sink. However, there is some question as to whether a sink of this type does not actually change the circulation. A theoretical investigation of this problem could probably be made and would be quite useful.

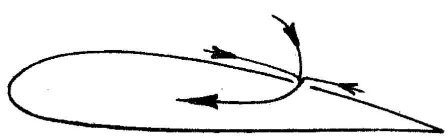


FIG. 6

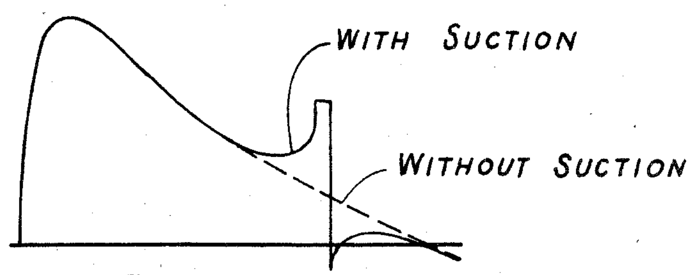


FIG. 7

PRESSURE DISTRIBUTION ON UPPER SURFACE OF A WING

EXPERIMENTS ON WINGS. First attempts at securing high lift coefficients by boundary layer removal were made in Germany in 1922. Since then, considerable work has been done upon this problem by British and American investigators as well as the German scientists. Wings experimented upon have been arbitrarily selected as to airfoil section and plan-form. The purpose in general has been to find the effect of boundary layer removal upon a given wing. Most tests were made upon rectangular airfoils, often of low aspect ratio, using end plates. The NACA and GALCIT are the only organizations experimenting upon a wing of tapered plan-form. Three types of profiles have been tested, - very thick wings, thin wings, and thin wings with flaps. By thin is meant wings of 10% to 15% thickness. For convenience, references to the specific experiments are listed on Page 53.

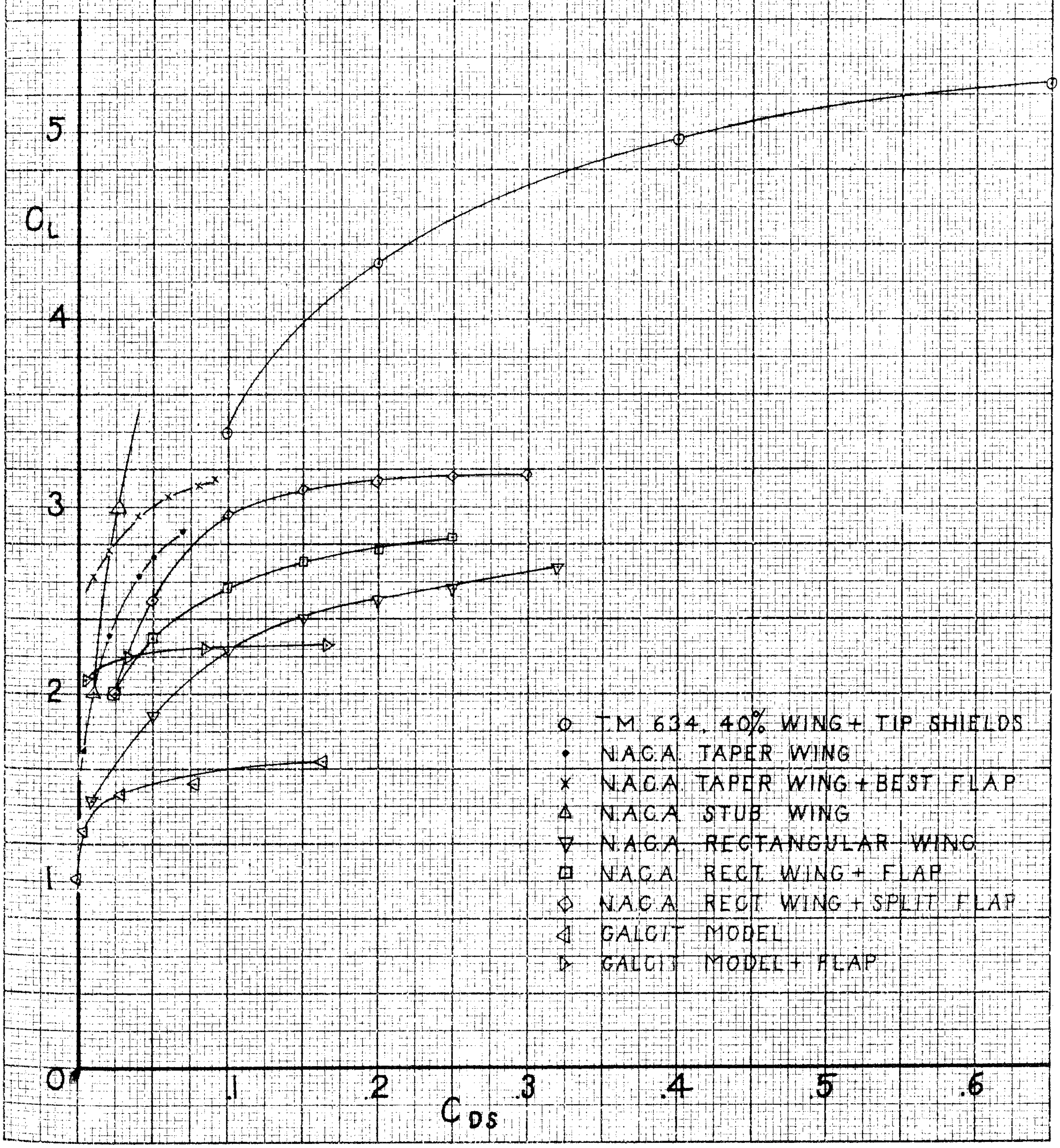
Different types of results have been obtained for nearly every wing tested. But in general it can be said that lift is considerably increased, drag is reduced slightly, slope of the lift curve is increased, and moments are changed somewhat, but in no definite manner. Effects are most marked on very thick wings of 30% to 40% thickness. These develop a great increase in C_L for a small blower power and in addition have considerably reduced drag. Thin wings do not fare so well. Curves of C_L vs C_Q or C_{DS} (cf. Figure 8 or 9) seem to indicate possibility of lift coefficient values of the order of 3 with not too much power. But for higher C_L's power becomes excessive. Drag on thin wings is reduced only slightly. Data indicate that the possibility of considerable drag reduction occurs only when drag on the profile is abnormally high.

Good wings show very little decrease in drag with suction. Flap profiles usually stand between results for thick wings and those for normal wings. Normally, flaps reduce power and quantity of air required to reach a given C_L. One of the most useful benefits given by flaps plus suction is that the angle of attack for maximum lift is decreased, thereby decreasing landing gear length.

An attempt to present a graphical comparison between various tests is shown by Figures 8 and 9. Each curve is- in the writer's opinion, typical of the best results obtained from each of several investigations. The curves have no common basis for comparison; each test has been made at a different Reynolds number, and almost every one of these investigations has been made in a different tunnel from all the rest. However, qualitatively the curves serve as a simple comparison between various tests. They show that high lifts have been obtained only with thick wings. It appears from these curves also that for small increases in C_{Lmax} thin wings require less air and power than thick wings. But for C_L's above 3, tests indicate that extreme quantities of air may be required, since several of the C_L vs C_Q or C_{DS} curves appear to run off almost asymptotically to $C_L = 3$. Thick wings curves show no such sudden bending over at the higher C_L's. Curves for

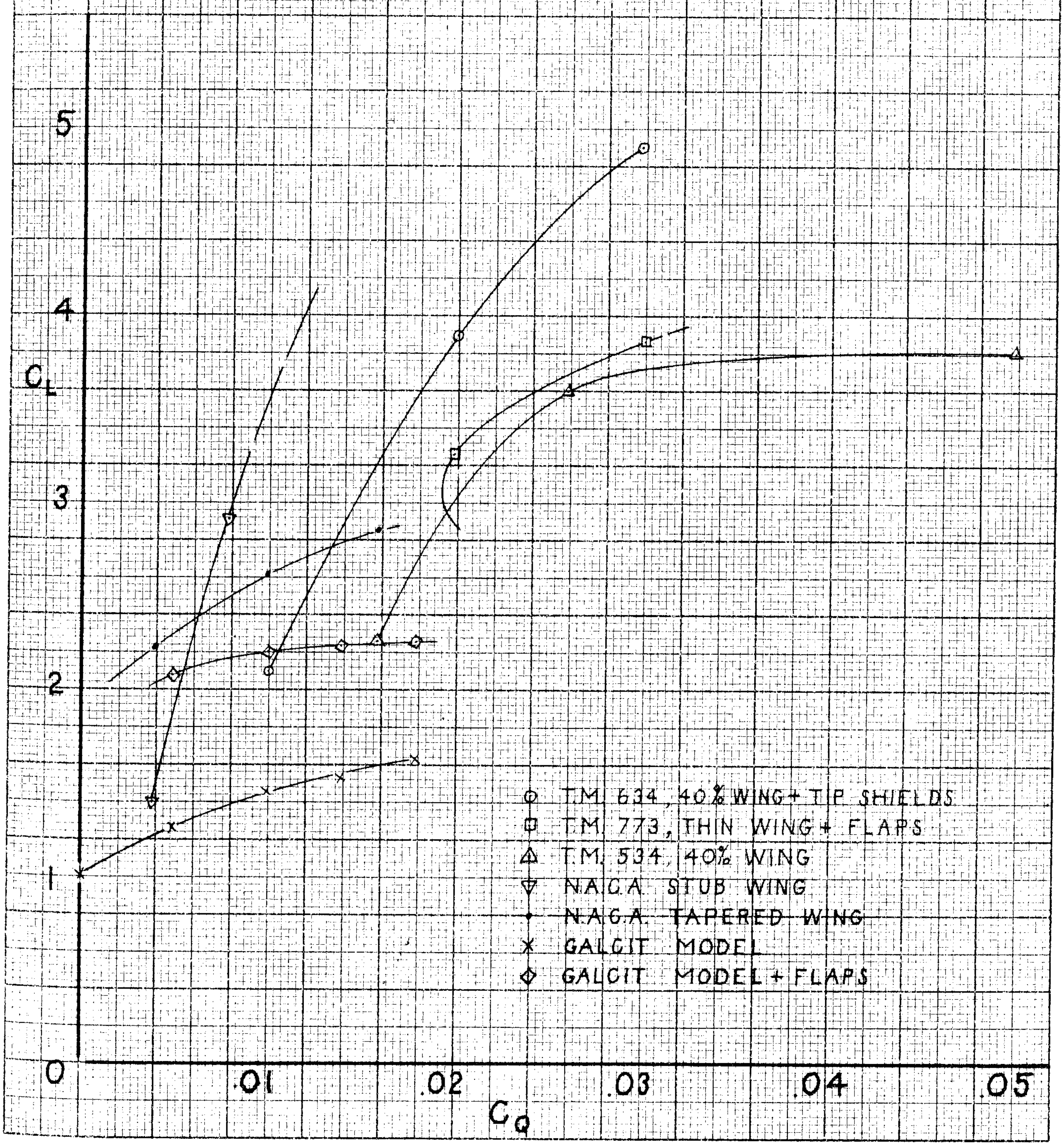
BEST RESULTS OF SEVERAL BOUNDARY LAYER REMOVAL EXPERIMENTS

FIG 8



Best Results of Several Boundary Layer Removal Experiments

Fig. 9



wings with flaps have C_L vs C_Q and C_L vs C_{DS} curves roughly similar to curves for the basic section except that they are displaced upward slightly.

To show where the GALCIT tests fit into this picture, best results so far obtained are also plotted on Figures 8 and 9. GALCIT results are seen to be very poor. Suction increases C_L rapidly up to a certain point, but then the curves bend over suddenly and become almost horizontal. These curves show that if improvement is to be made, something else besides applying more suction must be done.

As important as obtaining the C_L, C_D, C_Q, and C_{DS} values is the part of the investigation determining the best manner of obtaining high lifts. Numerous means of withdrawing air from the boundary layer into the interior of the wing have been tried. Air has been drawn in through a perforated upper wing surface, many types of perforations being used. A very wide slot covered with cheesecloth has been tested. Single slots as well as multiple slots have been tested. The weight of evidence indicates that slots are at least as good as any other method, but whether there should be a single slot or several of them has not yet been decided. Another question comes up in connection with multiple slots. Some tests have indicated that each slot should have its own wing duct, and a suction pressure in the duct adjusted to the position of the slot upon the wing. Other tests indicate that such a refinement is unnecessary, meaning that all slots can just as well admit to a common wing duct. Therefore, the problem is to learn what method is best if multiple slots are used. This much can be said. If the effectiveness of a slot is a function only of quantity of air flowing through it, slot widths can certainly be adjusted to get any rate of flow while exhausting into a common duct.

Possibly the following explains why a slot is as effective as a perforated surface. On first thought the best way of removing the boundary layer would seem to be to remove it continuously as it forms. With a single slot such is impossible. If it is well back, a thick boundary layer builds up ahead of it. If forward, a new boundary layer of considerable thickness can build up behind the slot. However, a slot is as effective as a porous surface. As previously mentioned, the effects of suction are twofold, one effect being boundary layer removal, the other being the creation of a favorable pressure gradient. A slot, due to this favorable pressure gradient, has as large a sphere of influence as a porous surface. Thus, while it removes the boundary layer at only one point, it is speeding it up over considerable wing area. If boundary layer removal were the only function of a slot, it could have no effect upon conditions upstream. Experiments have shown, however, that a slot as far back as 95% of the chord still has considerable effectiveness. It is this sphere of influence then that makes a single slot equal or superior to a perforated surface removing air continuously.

Figure 10 illustrates some of the most common types of slot cross sections tested.

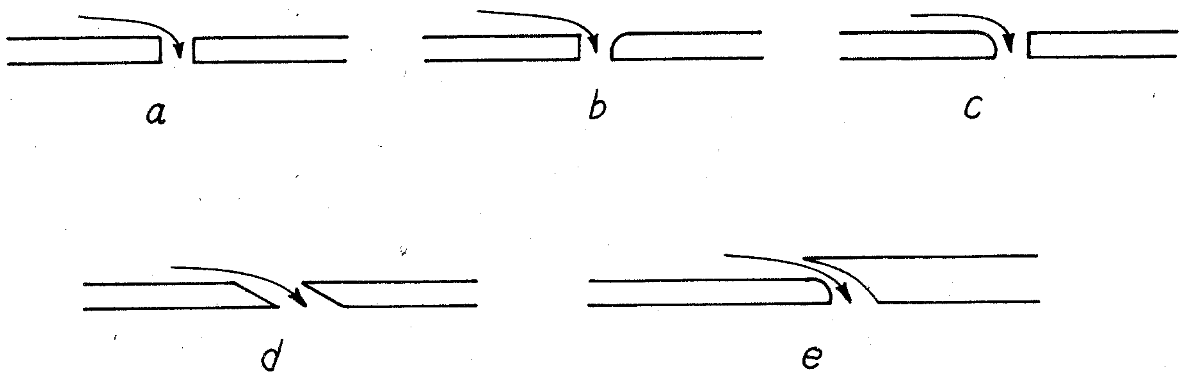


FIG. 10

Type 10a is most common. 10b has the rear face rounded off. Tests indicated no difference between 10b and 10a. 10c has the upstream edge rounded. It permits a greater flow for a given minimum width but shows no improvement upon C_L if C_Q is held constant. Slot 10a has a lower orifice coefficient than 10c. If it is widened to compensate for this decreased coefficient, 10a and 10c give identical results. 10d shows no marked changes. Slot 10e is intended to utilize the dynamic head, thereby decreasing C_{DS} for a given C_Q. Actually, it gives negligible improvement. Numerous other types have been tried but all indicate that slot shape is not important.

The only effect of slot shape seems to be in determining quantity of air flowing through a slot of given minimum width. Slot width seems important primarily as a determinant of power required to move the air. Narrow slots require too much power. Slots 2% of the chord in width appear ample for quantities of air handled to date. Wider slots increase structural complications and create slightly greater drag. Incidentally, if the ratio, slot width to chord width, has the same value as C_Q, air is flowing through the slot with a velocity equal to free stream velocity.

A primary purpose of all investigations has been to determine the optimum slot location. Tests are all in disagreement; some work indicates forward locations, others rearward. Actually, the position appears to depend upon the airfoil section. Thick sections give best results with a slot located at about 70% chord, but thinner ones do best with the slot at about mid-chord. Between the 40% and 70% stations, however, lifts are not far below the optimum.

Such is the nature of all investigations to date. Research upon boundary layer control is begun, any convenient design of wing is used, and then tests are made upon it to determine how C_L varies with the five parameters: slot location, slot size, slot shape, C_Q and C_{DS}. There has been no consistency to results so far obtained. It would be unsafe to try to apply results from these model tests to a full scale airplane. Hardly any conclusions can be drawn from these tests except that boundary layer removal does increase lift. When one thinks of the number of parameters determining results, it is not surprising that nothing checks because all tests have had some of the variables different from those of all other tests. The most important parameters involved in the problem are: (1) slot location, (2) slot size, (3) slot shape, (4) C_Q, (5) C_{DS}, (6) airfoil section, (7) wing plan-form, (8) Reynolds number. The number of these factors shows the complexity of the problem. An examination of the list shows why it has been impossible to check one investigation against another, for none of the wings tested has had common values of the 6th, 7th, and 8th factors given above.

- II -

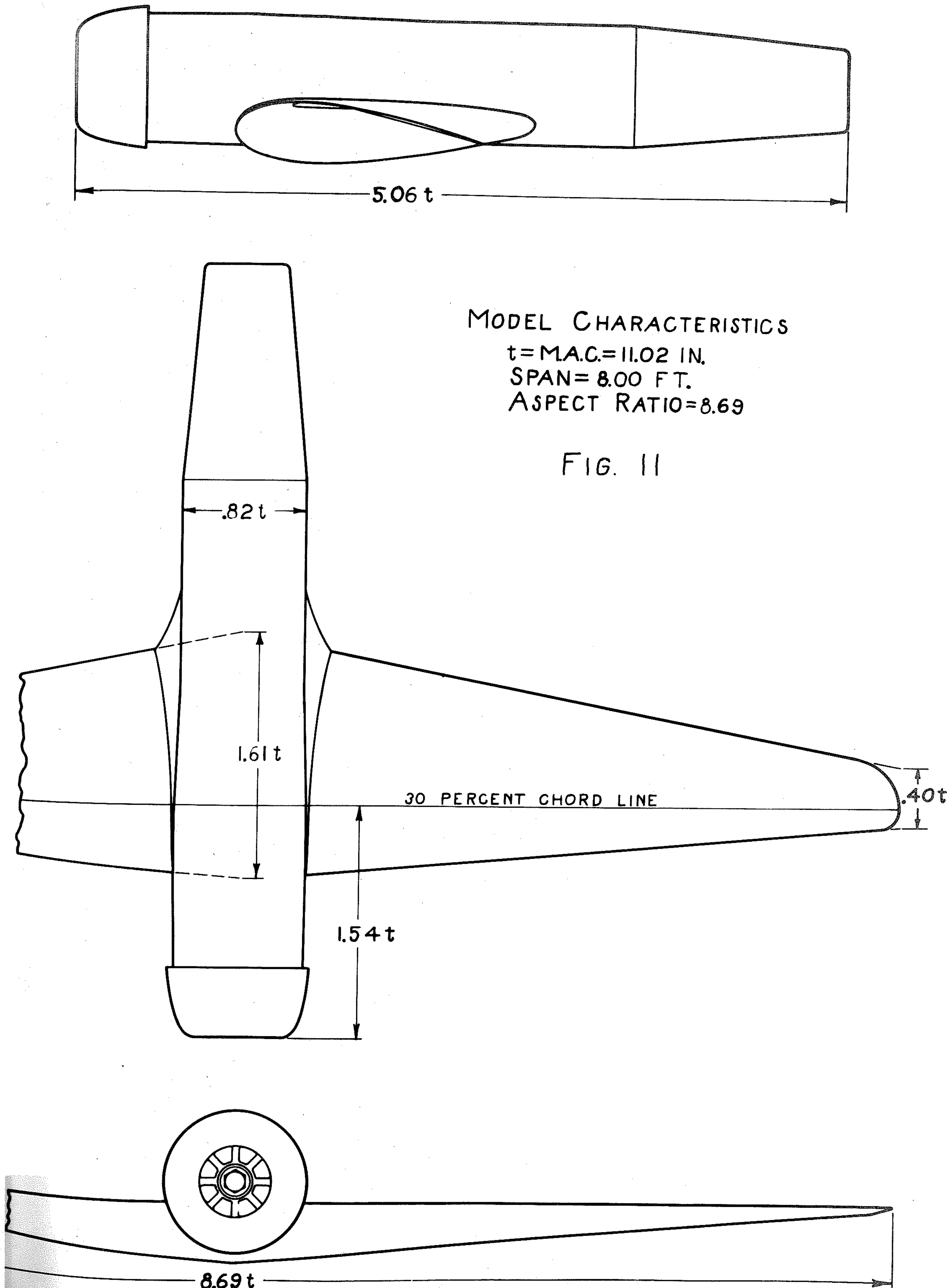
EXPERIMENTAL PROCEDURE AND TESTS ON THE GALCIT MODEL

INTRODUCTION. Part II of this thesis describes the experimental procedure used for tests on the model, corrections of data, and results of tests. Special emphasis is given to the discussion of experimental methods and treatment of the data because this report will probably serve as a guide for further research at the GALCIT upon the boundary layer control problem.

THE GALCIT BOUNDARY LAYER MODEL. Figures 11, 12, 13, and 14 show the general appearance of the model. Air is sucked into the hollow wing, flowing into the fuselage and exhausting out the tail. General characteristics are:

Span	6 ft.
M. A. C.	11.02 in.
Taper Ratio	4 to 1
Root Section	NACA 23025
Tip Section	NACA 23009
Aspect Ratio	6.69
Overall Length	55.7 in.

The 30% line on the upper wing surface is straight. Dihedral is given only by thickness taper. There is no twist in the wing. For tests with no suction, the tail is faired with the tail cone of Figure 15.



MODEL CHARACTERISTICS
t = M.A.C. = 11.02 IN.
SPAN = 8.00 FT.
ASPECT RATIO = 8.69

FIG. 11

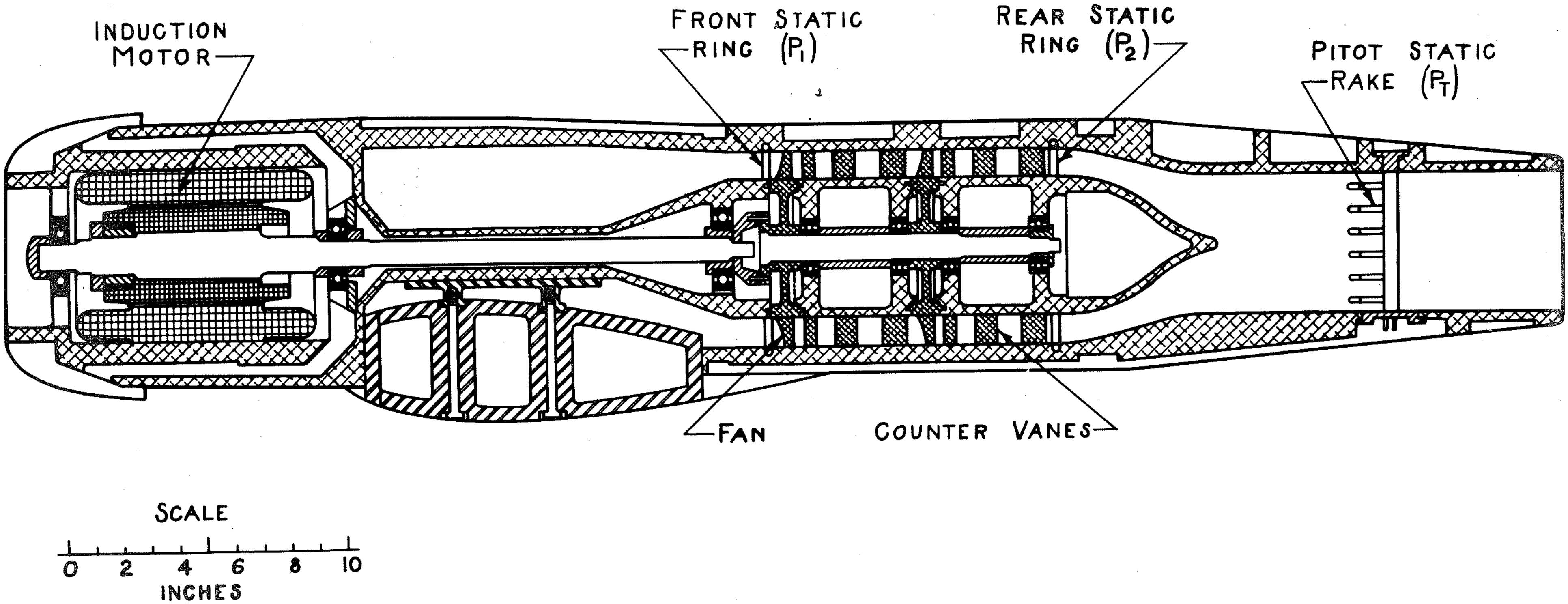

INDUCTION MOTOR
FRONT STATIC RING (P_1)
REAR STATIC RING (P_2)
PITOT STATIC RAKE (P_T)
FAN
COUNTER VANES
SCALE
0 2 4 6 8 10
INCHES

FIG. 12

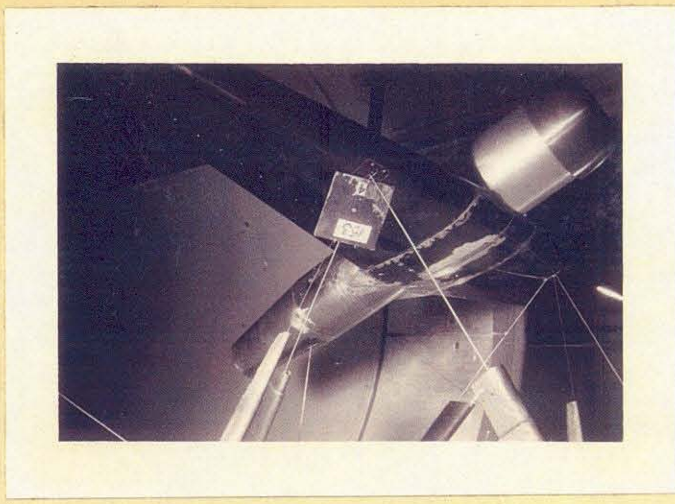


Fig. 13
General View of Model

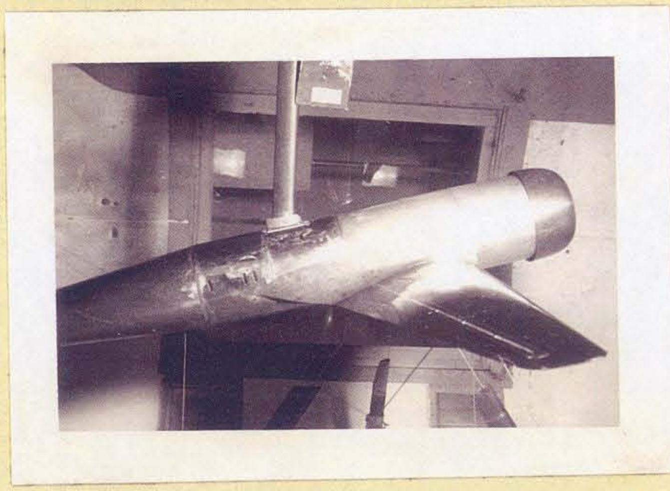
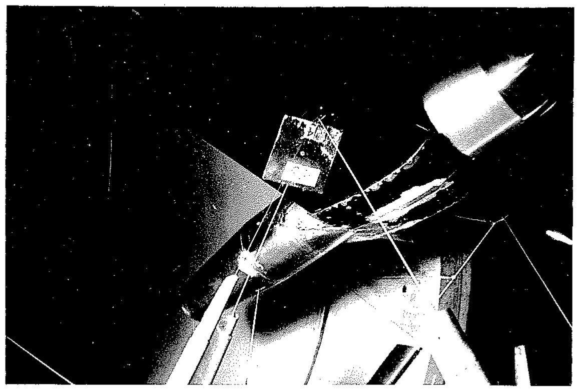


Fig. 14
Another View, Showing Fillet X_3

Fig. 15
Tail Cone used for Power-off Tests



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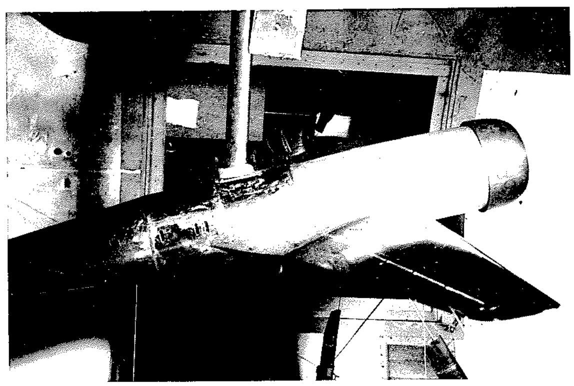

Fig. 14
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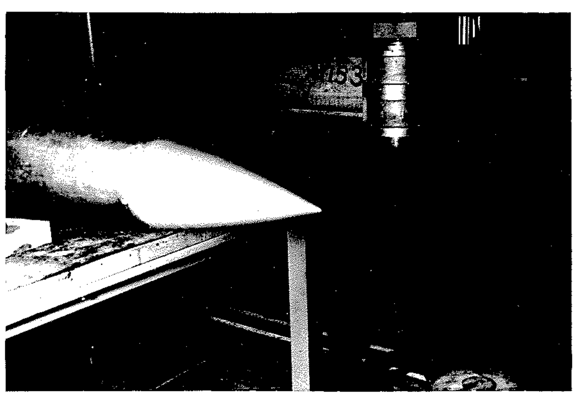

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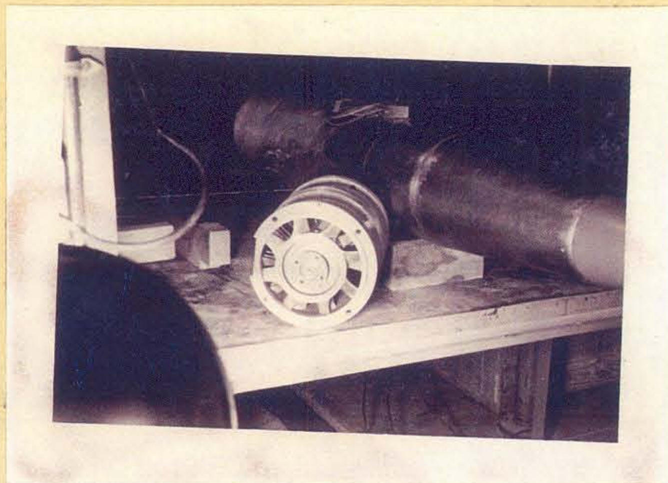
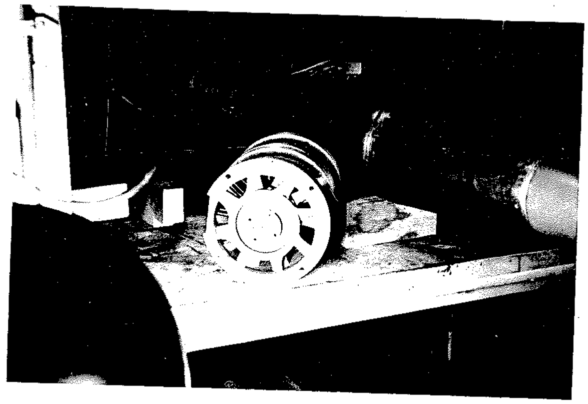


Fig. 16
Fan Unit showing one Fan and Countervanes

Some idea of the internal mechanism is given by Figures 12 and 16. The wing is cast of aluminum with a copper plate in which the slots are cut, forming the upper surface. The rear 20% of this wing is formed of wood.

Figure 12 shows schematically the interior of the cast aluminum fuselage. A 10 h.p., 17,500 r. p. m. induction motor is the driving unit. Speed control comes from a variable frequency power supply that gives the motor a speed range of about 2,000 r.p.m. to 17,500 r.p.m. Cooling is accomplished by air flowing in through the front of the cowling, through the duct areas, and out at the rear of the cowling. Cooling is good. The cowling has no harmful effects on flow.

The fans are driven as shown in Figure 12. Three fan designs were built, fan 1B being the one used upon



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The fans are driven as shown in Figure 12. Three fan designs were built, fan 1B being the one used upon the model. It is two stage, of 7 inches diameter and can be used to deliver about 20 cubic feet of air per second at 60 centimeters of water. For further details of the motor and fans and their characteristics, together with the electrical system used, see Reference 17.

Figure 12 illustrates also how flow conditions are measured. Static pressures ahead and behind the fan are measured by P_1 and P_2. At these stations pressures are obtained from 3/32" brass tube static rings set into grooves as shown. Near the tail of the model a pitot static rake is installed for measuring velocity at the section and hence quantity of air handled. It consists of six pitot static tubes, of as near the standard Prandtl type as possible, spaced at equal intervals. Oddly enough, calibration tests (Reference 17) showed that the rake averages the flow almost perfectly. From slightly ahead of P_1 on back to the exit, the model was so designed that duct area remains substantially constant. Thus, no velocity changes occur. Rubber tubing leads coming from these measuring devices, together with electrical leads, are carried out through the small streamline strut shown in Figure 14. Figure 17 shows the manometers and speed control box.

MEASUREMENTS. Specifically, the pressure measuring arrangement is as follows: (1) P_1 to one side of a U-tube manometer; tunnel static (cf. Figure 18- Verti-

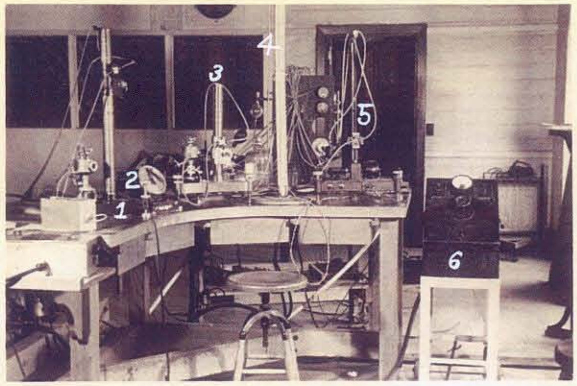
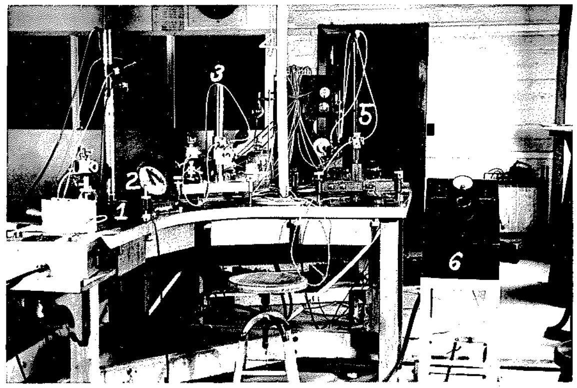


Fig. 17
Control Table
1. Wind tunnel control manometer
2. Selsyn angle of attack indicator
3. P_2 manometer
4. P_1 U-tube manometer
5. P_T manometer
6. Model Speed control

cal section through tunnel) to the other. (2) P_2 to the high pressure side of a GALCIT micro-manometer; tunnel static to the other. (3) P_T total head to the high pressure side of another GALCIT micro-manometer, P_T static to the low pressure side. As the above arrangement shows, all measurements are made with reference to the tunnel static pressure. This system gives the following readings: (1) gives static pressure in the wing. It is only approximate, for it neglects variations in velocity head and pressure drop due to friction losses. However, velocity head is low, the highest velocity head being about 3 gr./cm.^{2} for a pressure head of about 55 gr./cm.^{2}. (2) gives pressure below the fans with reference to tunnel static.



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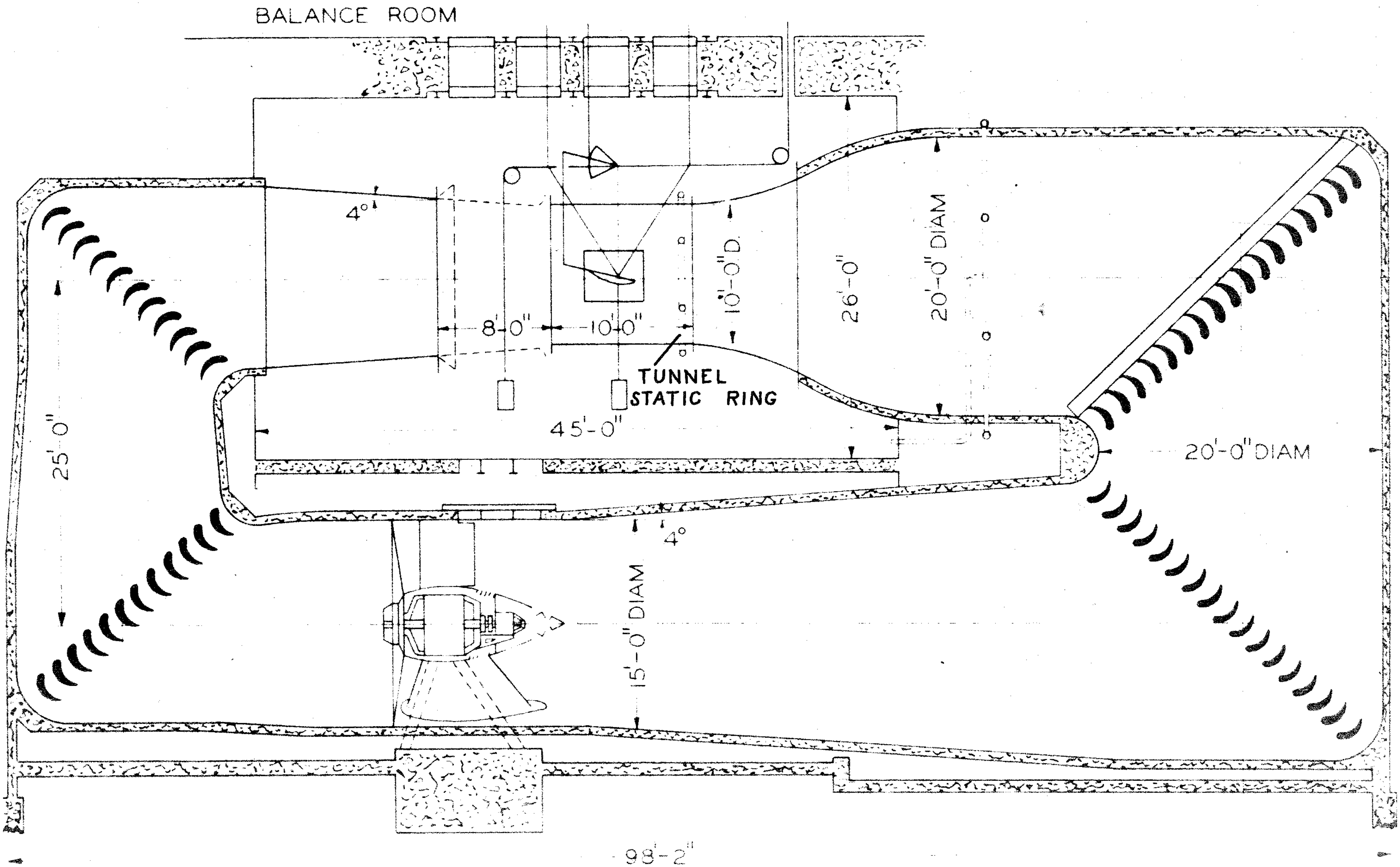
VERTICAL SECTION THROUGH 10 FT. WIND TUNNEL

GUGGENHEIM AERONAUTICS LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA



It is not used alone but only to get pressure rise across the fans by subtracting it from (1). Hence, three quantities are obtained from the above measurements: (a) Static pressure within the wing; (b) Power put into air calculated from flow rate and pressure rise; (c) Quantity of air handled.

COMPUTATIONS AND CORRECTIONS. Testing a boundary layer model in the wind tunnel gives rise to several new quantities and corrections which are to be explained in this section.

One is a coefficient measuring quantity of air taken in through the wing. It is:

$$C_Q = \frac{Q}{VS} \tag{1}$$

where Q = quantity of air handled per second.

V = Tunnel velocity (or velocity of flight)

S = Wing area

For a given model, C_Q can be varied by changing either tunnel speed or Q. C_Q is the ratio of volume of air taken in to the volume that would be swept out by an outline of the wing plan-form set at 90^o to the airstream. For such a hypothetical case at $\alpha = 90^o$

$$C_{Q\,90} = \frac{Q}{VS} = \frac{V \cdot S}{VS} = 1 \tag{1a}$$

C_P is a measure of pressure in the wing. It is given by

$$C_P = \frac{P}{q} \qquad (2)$$

where

P = static pressure within the wing with reference to free stream conditions.

q = dynamic pressure of free stream.

C_P, together with wing static pressure, slot size, and slot orifice coefficient, determine quantity of air flowing through a slot. C_P has only a vague significance. Whether C_P helps control the effectiveness of boundary layer removal is not definitely known. In all work to date, C_P has been of use only as an indication of interior wing pressure. Ordinarily, it is measured only at one point; hence, if pressures vary with spanwise location, it is possible that the C_P manometer may not measure pressures even close to the average for the entire wing. Moreover, model dimensions can change it slightly. Consider the GALCIT model, Figure 12. If the duct area at P_1 were increased considerably, velocities would decrease, causing the negative value of P_1 to decrease also. Because of these effects of model dimensions and duct shape tare runs have been taken outside the tunnel to determine P_1 for various C_Q values.

C_{DS} is a measure of power supplied to the air. By definition

$$C_{DS} = \frac{E}{qSV} \tag{3}$$

Where E = power supplied to the air. For any pump

$$E = Q\,\Delta H = Q(H_2 - H_1) \tag{4}$$

But

$$H_1 = P_1 + \tfrac{1}{2}\rho V_1^2$$
$$H_2 = P_2 + \tfrac{1}{2}\rho V_2^2$$

For the GALCIT model $V_2 = V_1$. Therefore

$$\Delta H = Q(H_2 - H_1) = P_2 - P_1 \tag{5}$$

Substituting in (3)

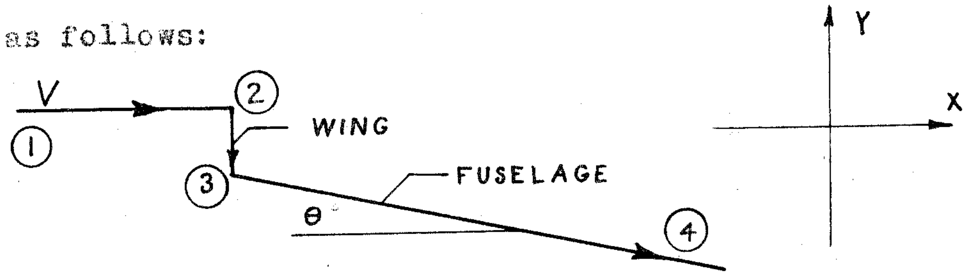
$$C_{DS} = \frac{Q\,\Delta P}{qSV} \tag{6}$$

but $\frac{Q}{SV} = C_Q$ Then (6) becomes

$$C_{DS} = C_Q \frac{\Delta P}{q} \tag{7}$$

Hence, this method of defining C_{DS} gives a measure of energy supplied to the air but says nothing about gross power required. C_{DS} varies somewhat with the exit velocity of the air. Minimum total drag, considering C_{DS} as an additional drag, occurs when exit velocity equals free stream velocity, (Reference 11). Therefore, in actual practice, the exit area should be designed to give such a condition. Such is very nearly true at high C_Q values on the GALCIT model.

Another drag term arises on any model having air flowing through it. It is one resulting from change in momentum of this air. Reaction values are found as follows:



SCHEMATIC PATH OF AIR THROUGH MODEL
Fig. 19

Consider Figure 19. Reaction equals the change in momentum between points 1, the undisturbed velocity, and 4, the exit velocity.

Mathematically, the reaction is

$$\overline{R} = \rho Q \, \Delta \overline{V} \qquad (8)$$

where $\overline{V}$ = vector velocity and $\overline{R}$ = reaction.

The above reaction can be divided into two components since the Z component is zero.

$$R_X = \rho Q \, \Delta V_X \qquad (a)$$

$$R_Y = \rho Q \, \Delta V_Y \qquad (b) \qquad (9)$$

R_x is the drag reaction, R_y the lift reaction.

From Figure 19

$$\Delta V_X = V - V_4 \cos \theta \qquad (a)$$

$$\Delta V_Y = V_4 \sin \theta \qquad (b) \qquad (10)$$

Consequently,

$$R_X = \rho Q(V - V_4 \cos \theta) \qquad (a)$$

$$R_Y = \rho Q\, V_4 \sin \theta \qquad (b) \qquad (11)$$

Dividing by $\frac{1}{2}\rho V^2 S$ will put equation (11) into the coefficient form

$$C_{DR} = \frac{R_X}{\frac{1}{2}\rho V^2 S} = \frac{\rho Q(V - V_4 \cos \theta)}{\frac{1}{2} \rho V^2 S}$$

$$C_{LR} = \frac{R_Y}{\frac{1}{2}\rho V^2 S} = \frac{\rho Q V_4 \sin \theta}{\frac{1}{2} \rho V^2 S}$$

Using the relation $C_Q = \frac{Q}{VS}$ the above can be put in the following form

$$C_{DR} = 2\, C_Q\left(1 - \frac{V_4}{V} \cos \theta\right) \qquad (12)$$

$$C_{LR} = 2\, C_Q \frac{V_4}{V} \sin \theta \qquad (13)$$

C_{DR} can be either negative or positive, depending upon quantity of air flowing through the model and angle of departing air. Contrary to what might be thought, reaction drags on the GALCIT model are positive throughout nearly the entire range of C_Q and θ values. C_{DR} is a correction of considerable value, a maximum positive value of .0098 being reached on the GALCIT model. The lift correction is smaller in quantity, and in addition is a correction to a larger quantity. Hence, it is a correction that can in general be neglected. A moment reaction also arises because entering air is not taken in on the center line of the departing air, Figure 12.

Other coefficients and tunnel corrections are those made on any normal model tested in the GALCIT wind tunnel.

This research is being done on a small scale model. The question comes up as to whether or not the model results are applicable to full scale aircraft. In general, the answer is that they are. Certain corrections can be made that make model results correlate very well with full scale results. Thus, tests on the GALCIT model can be used, with corrections, for predictions of full scale results for all usual quantities. But in this work, two basically new coefficients enter, C_P and C_Q. C_P is not affected by the scale of the model. However, with C_Q it may be different.

By definition, $C_Q = Q/VS$. What determines the value of Q required to prevent separation at a given lift coefficient? The answer is not well-known. It is known that it is at least a function of the energy deficiency in the boundary layer because of the fact that boundary layer removal experiments are successful. The boundary layer thickness is proportional to this energy deficiency. Then, for the sake of seeing what happens, let it be assumed that a given lift coefficient will be attained if C_Q is just large enough to suck off the boundary layer corresponding to this C_L. Let δ = boundary layer thickness, b = wing span = length of slot, V = free stream velocity. Then

$$Q = K \delta V b \tag{14}$$

where K is a factor of proportionality. In general, the boundary layer will be turbulent. Very little is known about turbulent boundary layer thickness for curved flow with pressure gradient. Therefore, to carry out the problem let us use the semi-empirical formula for a flat plate [1]

$$\delta = .375 \left(\frac{\nu}{V}\right)^{\frac{1}{5}} x^{\frac{4}{5}} \tag{15}$$

in which x is the distance back from the leading edge. Substitute (14) and (15) in C_Q and let $x = \lambda t$, where t is the average wing chord. Then

$$C_Q = \frac{.375 K \left(\frac{\nu}{V}\right)^{\frac{1}{5}} V b (\lambda t)^{\frac{4}{5}}}{V S} \tag{16}$$

Cancelling V, putting S = bt, and re-writing

$$C_Q = \frac{.375 K \left(\frac{\nu}{V t}\right)^{\frac{1}{5}} b \lambda^{\frac{4}{5}} t}{b t}$$

[1] Eq. 23.4, Durand Aerodynamic Theory. Vol. III.

This reduces to

$$C_Q = \frac{A\,\lambda^{\frac{4}{5}}}{R^{\frac{1}{5}}} \tag{17}$$

in which $A = .375K$ and $R = \frac{Vt}{\nu}$ = wing Reynolds number. Now assume results are known for a model and are to be extrapolated to full scale. Then λ and A are the same for both model and full scale. Find the ratio of C_Q's. Let $(\ )_1$ = model value; $(\ )_2$ = full scale value. The ratio becomes

$$\frac{C_{Q2}}{C_{Q_1}} = \left(\frac{R_1}{R_2}\right)^{\frac{1}{5}} \tag{18}$$

As the problem was stated, C_Q measures the flow just necessary to suck off the boundary layer at a given C_L. (18) means that in order to get the same C_L at full scale as for the model, the flow required is reduced by the factor $\left(\frac{R_1}{R_2}\right)^{\frac{1}{5}}$. If the above demonstration holds, it means full scale results are much better than model results. Consider the GALCIT model. Tests on it are made at a Reynolds number of 590,000. Reynolds number for a large airplane at landing speed is about 12,500,000. Then, in this case

$$\left(\frac{R_1}{R_2}\right)^{\frac{1}{5}} = 0.55$$

which means C_Q and, hence, C_{DS} are reduced to 55% of the model value to get a given C_L.

The above is based on so many assumptions that it cannot prove anything specifically, but it does have value in indicating that there may be a marked Reynolds number effect.

Tests should be made to find out if there is indeed a variation with Reynolds number.

TESTS ON THE GALCIT BOUNDARY LAYER MODEL. Tests on the GALCIT model have been carried out in a manner similar to that used for ordinary models in the GALCIT wind tunnel. Wing alone was first tested, then effects of fuselage, fillets, and tail cone were obtained by adding these parts to the wing. In all tests in which the effect of suction was being determined, tests were made at five values of C_Q spaced at about equal intervals from $C_Q = 0$ to nearly the maximum obtainable. All suction tests have been made treating C_Q as the independent variable. Hence, the model was run and held at a pre-determined C_Q by controlling its fan speed to maintain a constant reading upon the P_T manometer. Thus, the method is identical in principle with that used for operating the wind tunnel itself.

Characteristics of wing alone are shown by Figures A1, A2, A3. (Note: Large figures are segregated at the end of this thesis and are indicated by a prefix "A".) Tests were made at five speeds to determine Reynolds number effect as well as the usual characteristics measured at a q of 35 gr./cm.^{2}. The wing is slightly below average as compared with normal wings, but for one as thick as it is, its minimum C_{DP} is good. Maximum lift coefficient is about normal. The only unusual quality of the wing is that it has a reverse Reynolds number effect; drag increases with Reynolds number. There is no great interest in moments in this entire investigation, and so all moments are taken about the trunnion axis to reduce computation.

Mounting the fuselage on the wing was found to have a bad effect on lift and drag characteristics. Separation occurred at the fillet. The original metal fillet X_1, Figure 27, was found to be very poor. Consequently, a short fillet investigation was made. Results are shown by Figure A4. Data on fillets X_1 and X_2 were incomplete and so are not plotted. However, both these fillets were inferior to any of the others tried.

The method of test was to make fillets expanding from a given radius at the leading edge to another radius at the trailing edge. The last fillet, X_6, was very large, larger than X_3. Fillet X_3 was finally chosen as being the best one and was used in all the latter tests. No drawing of it is given, but it can be seen in Figures 14, 20, and 21. This fuselage-wing combination is very bad. The model is a low wing type with a fuselage that rapidly narrows down towards the trailing edge of the wing. Because of such a wing fuselage junction, it was found impossible to make a fillet that would eliminate local separation.

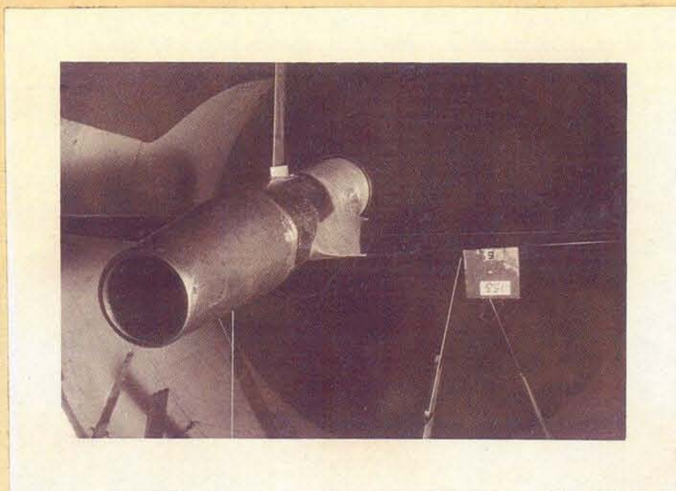


Fig. 20
Rear View of Fillet X_3

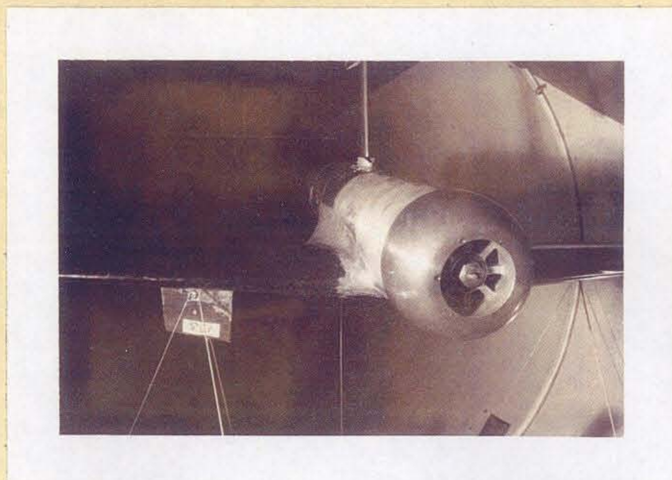


Fig. 21
Front View of Fillet X_3

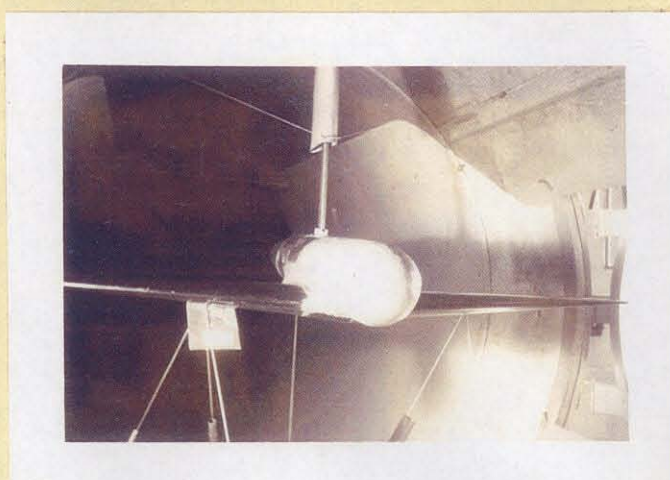


Fig. 22
Fillet X_6 and Cowl Replaced by Wax Nose - Front View

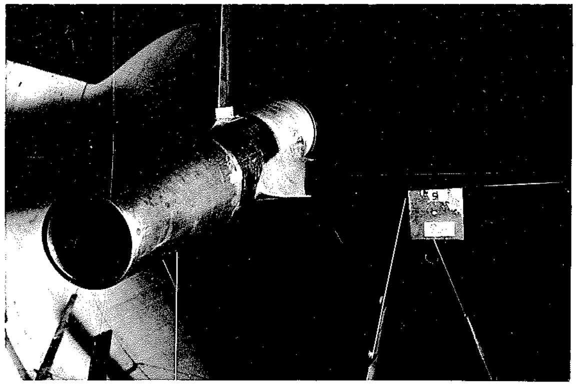


Fig. 20
Rear View of Fillet X_3

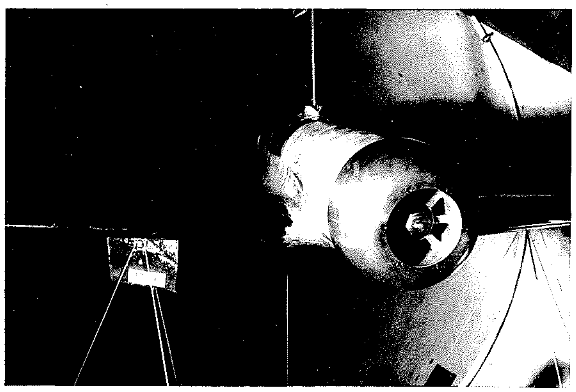


Fig. 21
Front View of Fillet X_3

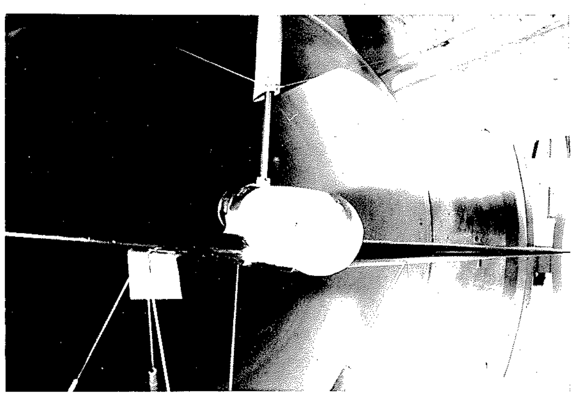


Fig. 22
Fillet X_6 and Cowl Replaced by Wax
Nose - Front View

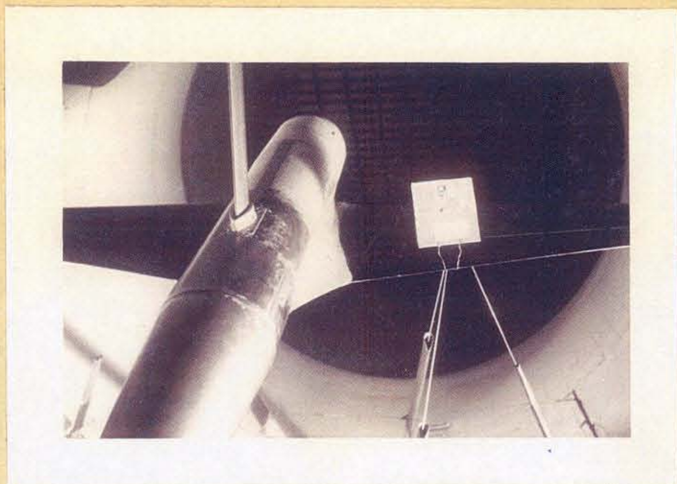


Fig. 23
Fillet X_6 and Cowl Replaced by Wax Nose
Rear View

Another minor investigation was made to determine the effect of an open slot and the effect of the large blunt tail. Four tests were made; with tail cone in place, slot open and closed; with tail cone removed, slot open and closed. Results are plotted in Figures A5 and A6. The slot tested was G_2, Figure 24.

Results are somewhat interesting. Minimum drag is obtained by having the tail cone on and slot covered with cellophane tape, Figure A6. However, drag increases only slightly if the slot is uncovered while the tail cone is left on. Such a drag increase is what would occur due to slotting a wing if some sort of valve were installed in the exhaust duct to prevent any net flow out of the slot. The difference between runs 35 and 37 represents the effect of the tail cone. It is considerable. Run 38 compared with

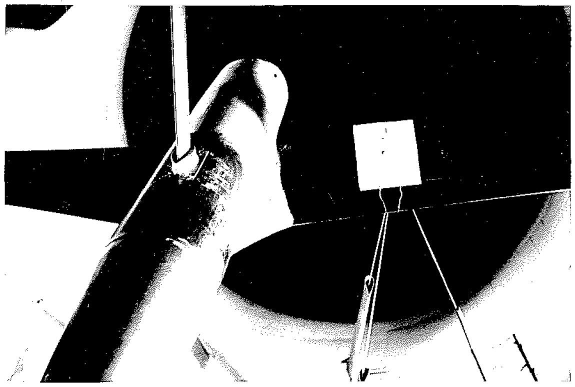


Fig. 23
Fillet X_6 and Cowl Replaced by Wax Nose
Rear View

Another minor investigation was made to determine the effect of an open slot and the effect of the large blunt tail. Four tests were made; with tail cone in place, slot open and closed; with tail cone removed, slot open and closed. Results are plotted in Figures A5 and A6. The slot tested was G_2, Figure 24.

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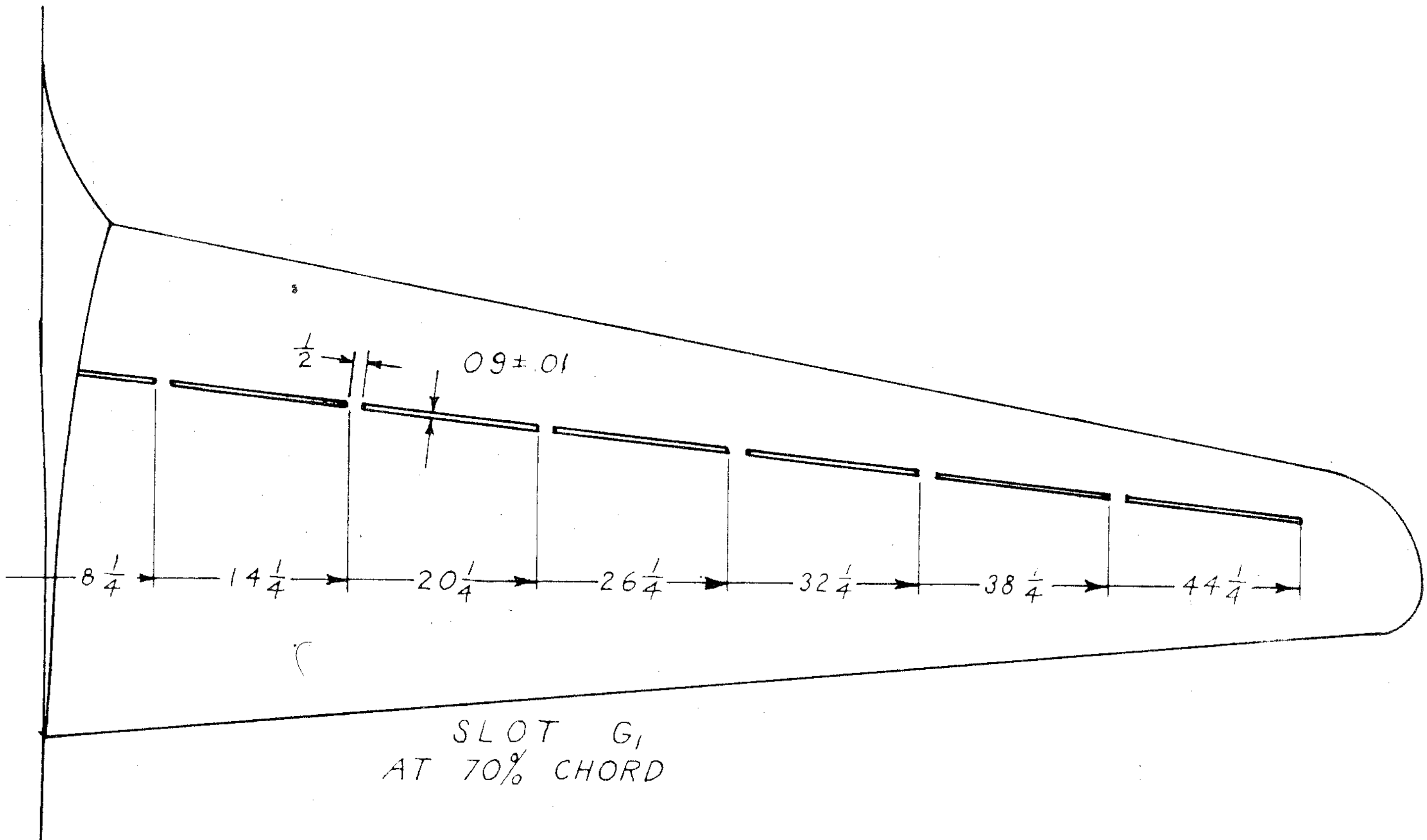
37 shows the effect of a slot on drag when there is net flow through the slot. In this case drag increases considerably.

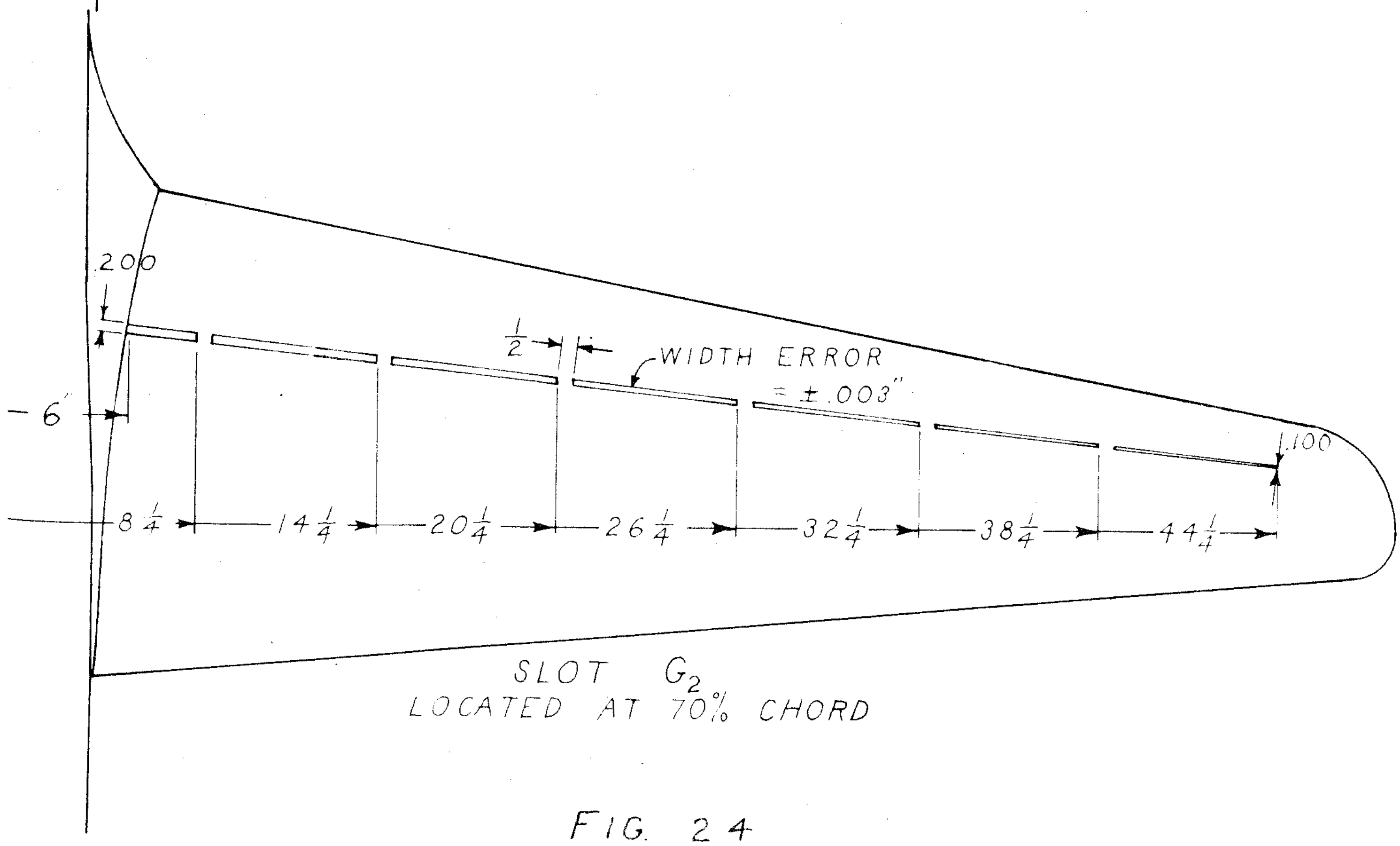
Highest C_L before stalling is given by the slot closed condition, but it is highest by only a trifle. In fact, the open slot seems to have no deleterious effect upon the maximum C_L for the normal wing.

Tests with suction on the plain wing using slot G_1 are shown by Figure A7. C_{Lmax} is increased by approximately 50%, but its value is still only $C_L = 1.52$. Small amounts of suction have considerable effect, but larger amounts do not increase C_L in proportion. $C_Q = .011$ was the highest value possible with slot G_1. One of the most noticeable effects of suction is the much higher L/D ratio at high C_L values. Another is that the C_L vs α curve is steepened and offset, thereby decreasing the angle of attack for C_{Lmax}. On these tests the fillet is bad, but suction holds the flow down until the stall is reached so that curves with suction are typical of those for an excellent wing-fuselage intersection. Moments are changed also, due to the air reaction in passing through the model.

One run was made at $q = 25$ gr./cm.^{2} instead of the usual $q = 7$. Results as seen from the figure



SLOT G_1
AT 70% CHORD



SLOT G_2
LOCATED AT 70% CHORD

FIG. 24

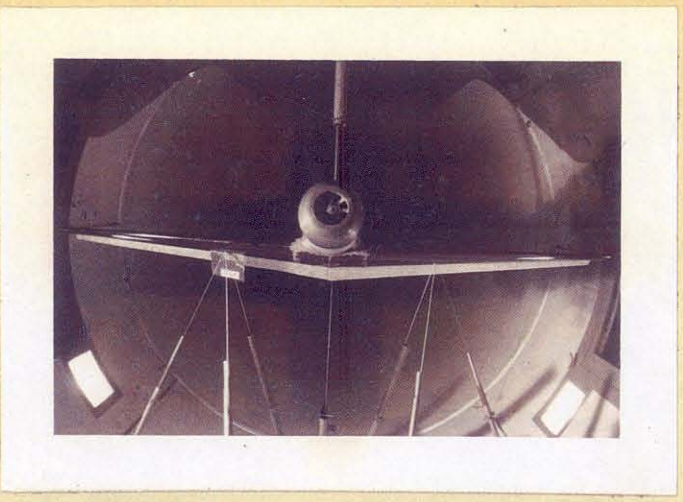


Fig. 25
Flap F_1^{45} front view

Fig. 26
Flap F_1^{45} side view

Fig. 27
Fillet X_1

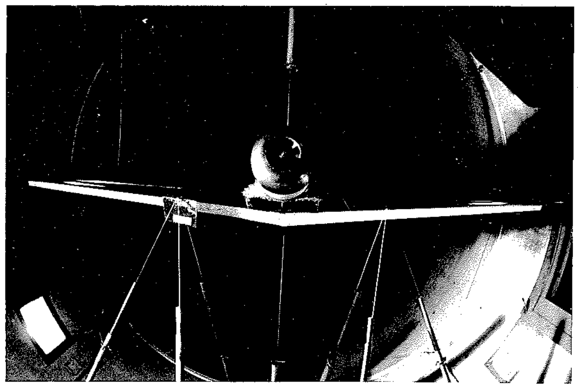


Fig. 25
Flap F_1^{45} front view

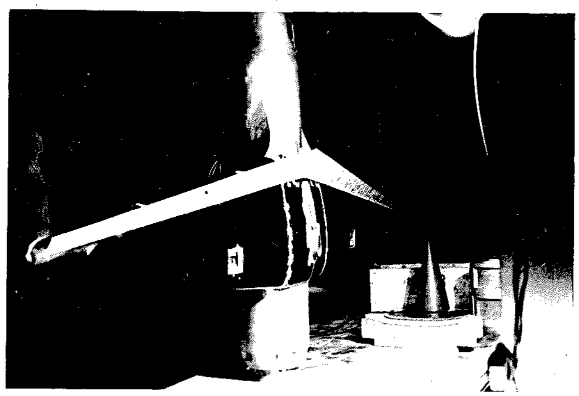


Fig. 26
Flap F_1^{45} side view

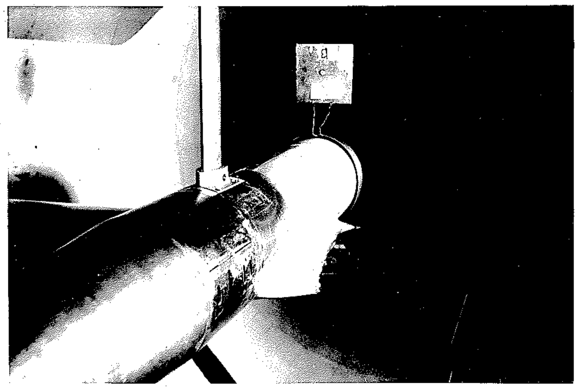


Fig. 27
Fillet X_1

are much more favorable. At q = 25, almost the same lift is obtained with C_Q = .005 as with C_Q = .008 for q = 7. This indicates there may be the marked Reynolds number effect already mentioned. Unfortunately, no other Reynolds number tests were made because the possibility of such an effect had not yet been realized.

Only one type of flap has so far been tried. It was a 25% split flap, covering 88" of the 96" span. Only one setting, 45°, was used in these tests. Figures 25 and 26 are two views of this flap. It is designated as F_1^{45}.

Tests with this flap and G_1 give good C_L values, but only because of the flap itself. Suction had little effect. Figure A8 gives a false idea of the effect of suction. Run 26 is with slot open. Comparing it with Run 43, Figure A11, where the slot is closed, shows that an open slot with flaps down is quite harmful in contrast with the effect on the normal wing. Consequently, to get a true picture, compare Runs 27 and 28 with Run 43. The net gain in C_{Lmax} is only 0.1. However, flaps decrease the angle of attack for a given C_L by about 10°.

Other tests were made using slot G_1 with the poor original fillet, X_1 of Figure 27. Results are much worse than with the better fillet, X_3. This information indicates that an important reason for the poor results is that the wing fuselage junction is causing trouble, since a better fillet raises C_{Lmax} considerably.

The next tests were on slot G_2, Figure 24. Both slots G_1 and G_2 have the cross section illustrated in Figure 10a. Slot G_2 has 70% more area than G_1. Thus, higher C_Q values could be reached.

Tests on the plain wing are shown in Figure A10. C_{Lmax} has been increased from 1.52 with G_1 to 1.64 with G_2. Otherwise, results are similar to those of previous tests. On two of these runs readings were taken going down from the maximum angle to find if there was a sort of hysterises effect. The curves of Runs 39 and 41 show there was indeed such an effect.

As with the plain wing, a slightly higher C_{Lmax} with flaps is obtained with G_2 than with G_1.

Figure A12 has been made solely to give a rough comparison of drags of various configurations with that of wing alone. The most interesting curve is that for Run 22, showing the effect of boundary layer removal. Parasite drag remains low, well up through $C_L = 1.4$.

Comparisons of the two slots are indicated by Figures 28 and 29. For the plain wing the narrow slot produces higher C_L's for a given C_Q, but power

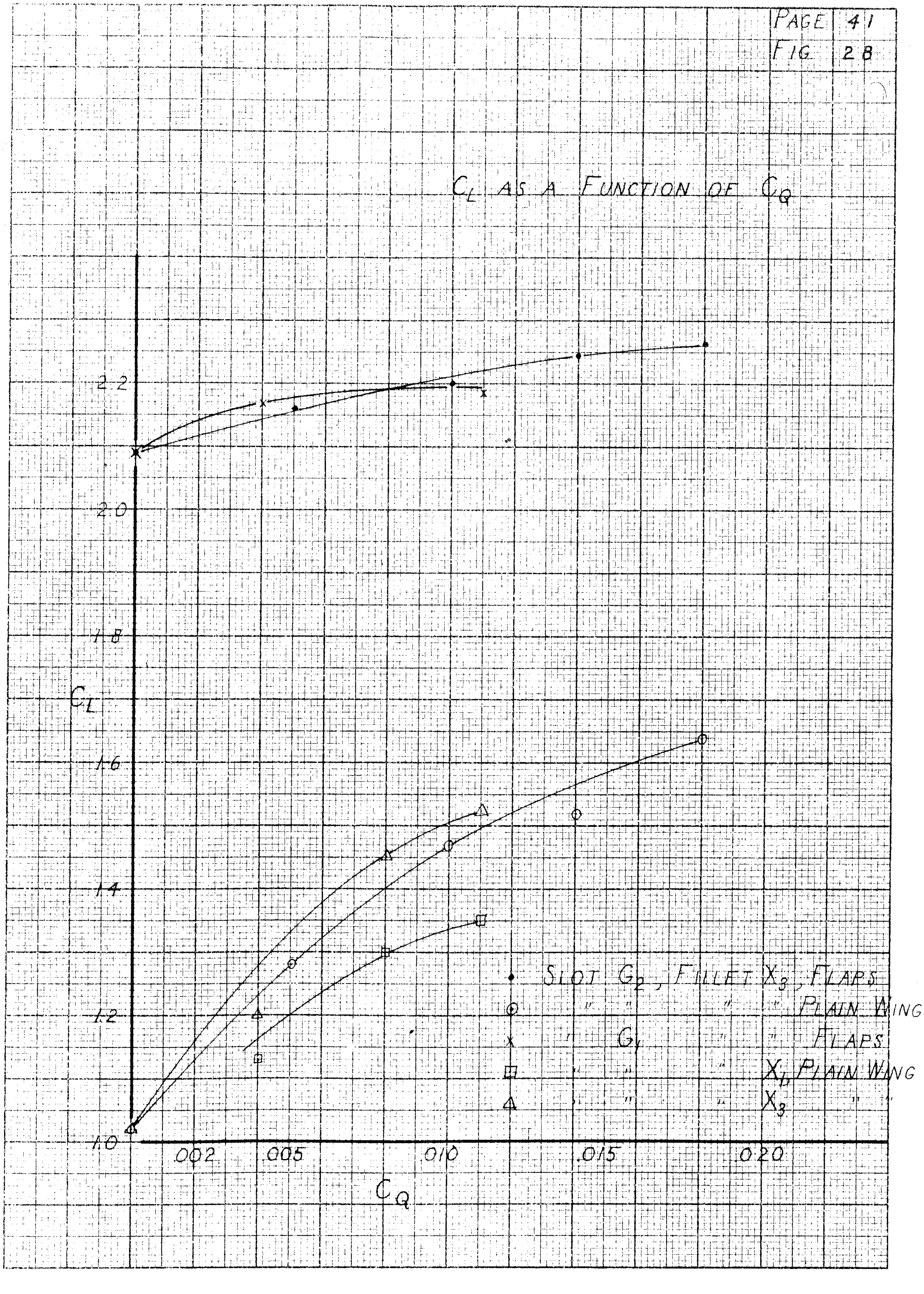
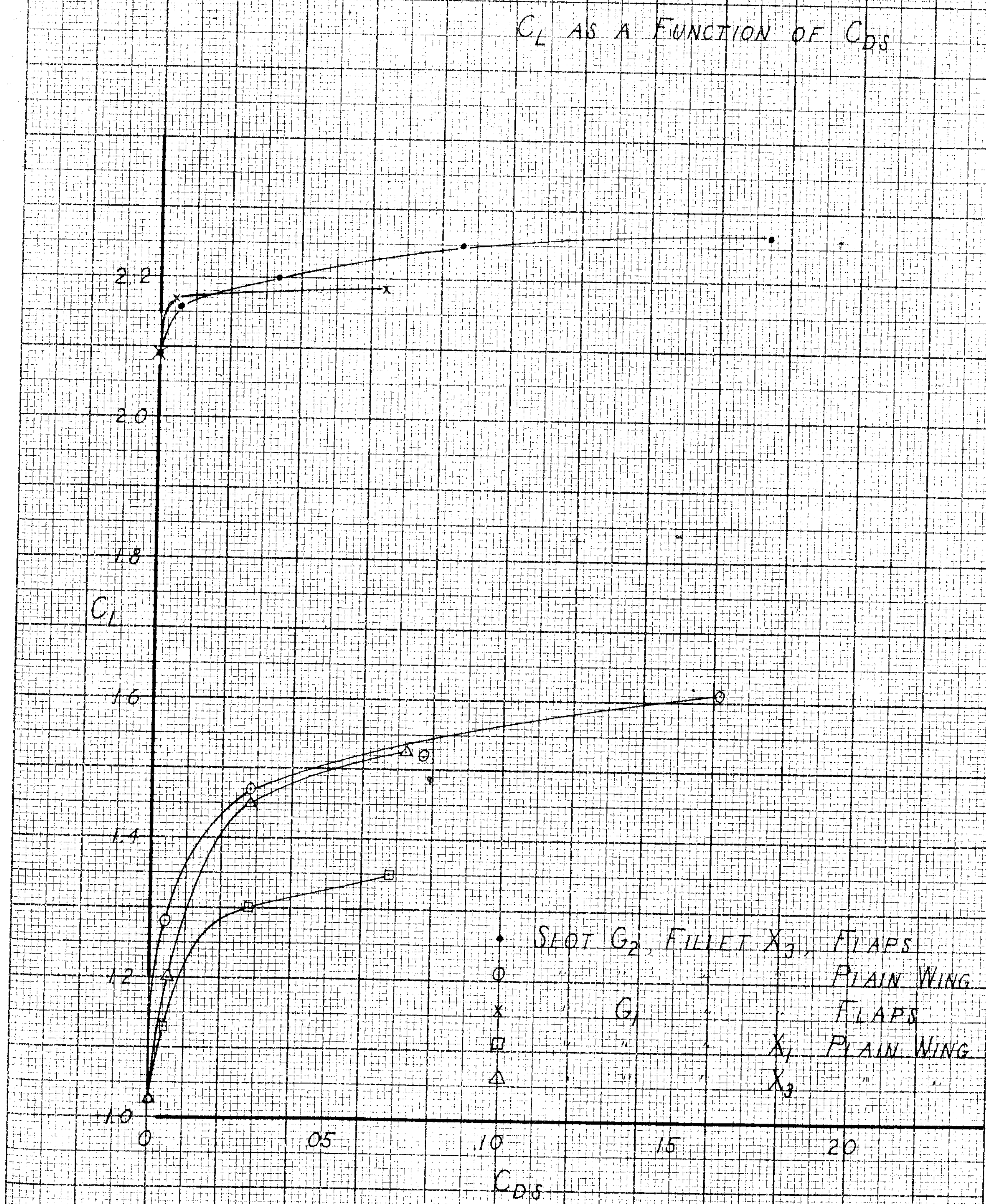


FIG 28
C_L AS A FUNCTION OF C_Q
2.2
2.0
1.8
C_L
1.6
1.4
1.2
1.0
.002
.005
.010
.015
.020
C_Q
• SLOT G_2, FILLET X_3, FLAPS
○ " " " " PLAIN WING
× " G_1 " " FLAPS
□ " " " X_b PLAIN WING
△ " " " X_3 " "

FIG. 29



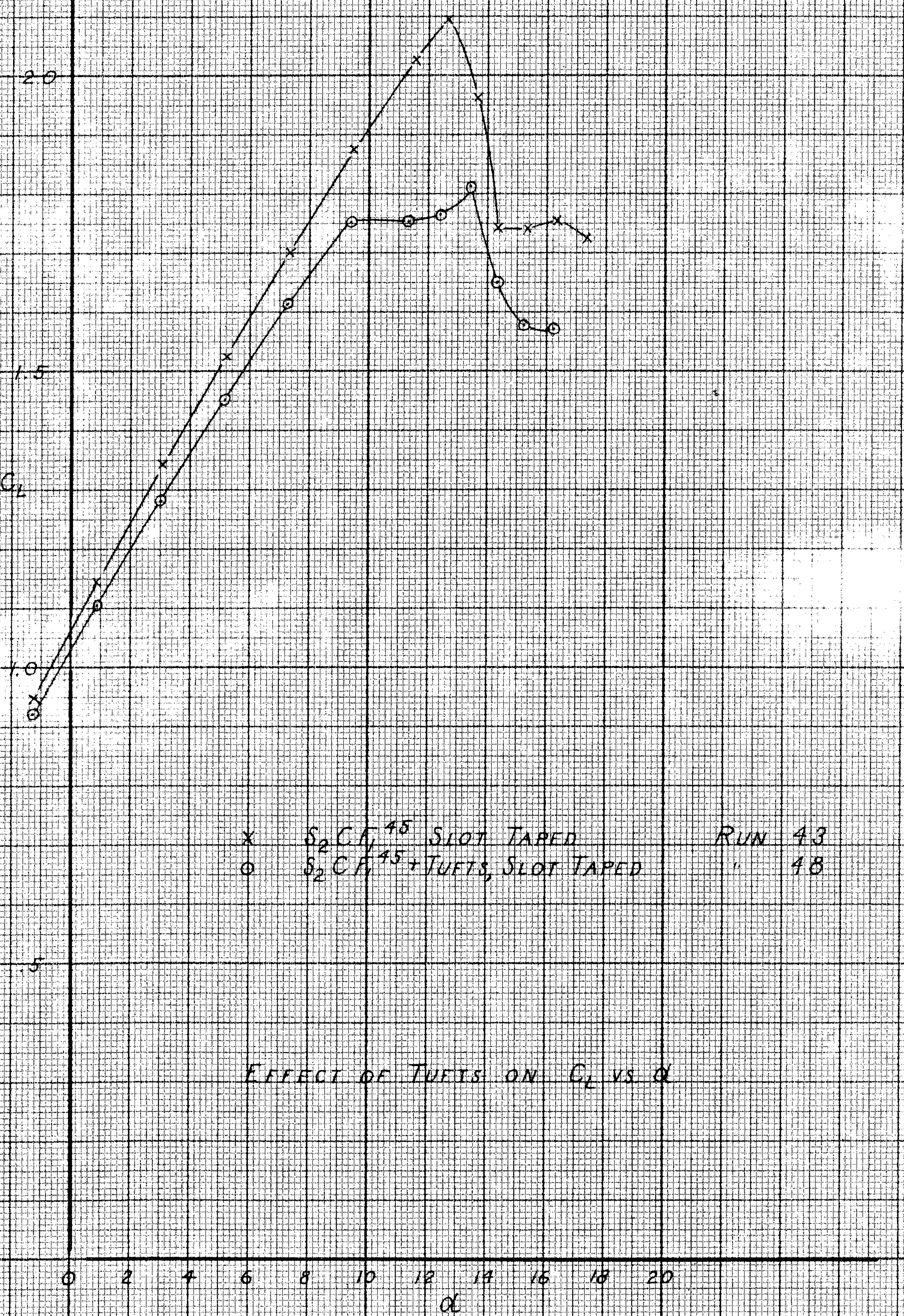
C_L AS A FUNCTION OF C_{DS}
2.2
2.0
1.8
1.6
1.4
1.2
1.0
C_L
0
.05
.10
.15
.20
C_{DS}
SLOT G_2, FILLET X_3, FLAPS
" " PLAIN WING
G_1 " FLAPS
" " X_1 PLAIN WING
" " X_3 " "

required for a given C_L is slightly higher also. The case with the bad fillet, X_1, is much worse, either for C_Q or C_{DS}. For the normal wing, the C_L vs C_Q curve is not flattening off so rapidly that higher C_L values could not be obtained with higher C_Q values, but at the same time C_Q would have to be extremely high because of the poor type of results in general.

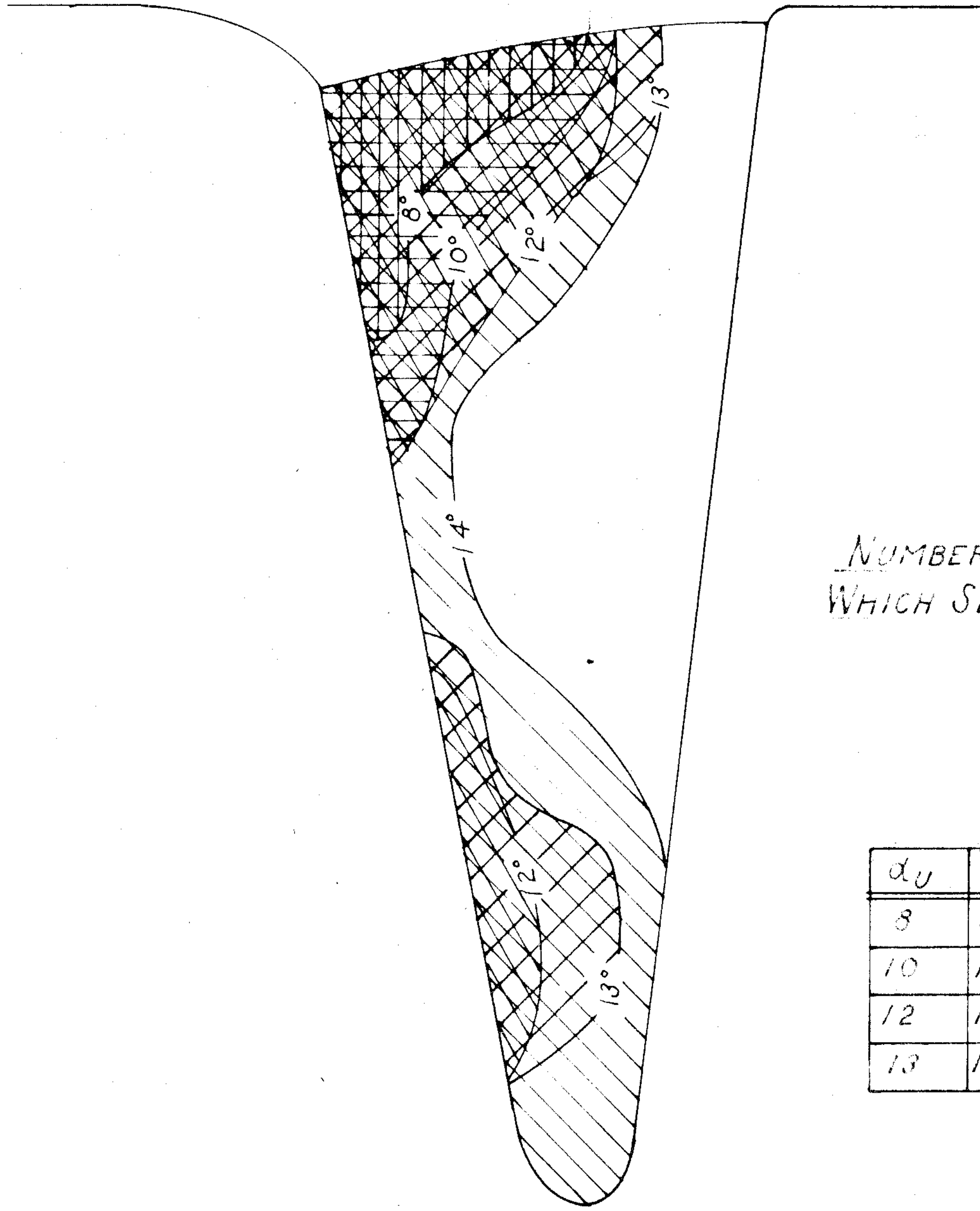
It is difficult to tell which slot is more effective with flaps because the data are too meager. Probably, however, the wide slot will give a certain C_L with less power but slightly more air than the narrow one. Points for these curves have considerable scatter. (Figures 28 and 29). Tests were made in the normal manner to obtain maximum lift by taking readings at one d degree intervals. Such a procedure is satisfactory for most tests but for work in which C_{Lmax} is to be plotted against other functions, this method is insufficiently accurate, leading to appreciable scatter of points. For future work, every C_{Lmax} should be found by more careful exploration of the region near the stall.

FLOW VISUALIZATION EXPERIMENTS. Maximum lift coefficient values on this model have been very poor. Therefore, steps were taken to find the reason for this by means of flow visualization experiments, using tufts of silk floss glued to the upper wing surface. Observation of these showed where flow separation occurred. Results are shown by Figures 30 to 35. It was felt that the wing-fuselage junction was the worst offender, and so tufts were placed upon the fillet and fuselage as well as wing. Tufts were known to make fillets stall early, but since this was the region of most interest, they were placed in that region, notwithstanding. Figures 30, 32, 34 indicate the effect of tufts. They show it to be considerable. Hence, these tests cannot be taken as indicating the exact angles at which separation over the wing and fuselage occurs, but still they show qualitatively what is happening.

Figures 31, 33, and 35 indicate the separation contours. Through an oversight, pictures for the normal wing with suction were not made. However, its results were observed by eye to be similar to those of the other three tests. All three figures show that in every case there is bad and early separation at the fuselage intersection. All stalling spreads from this location. It appears that otherwise the wing has good characteristics, with little signs of tip stall. There was no indication that the four inches of unslotted tip had a harmful effect. Neither were the 1/2" bridges over the slot harmful in the least.



EFFECT OF TUFTS ON C_L VS α



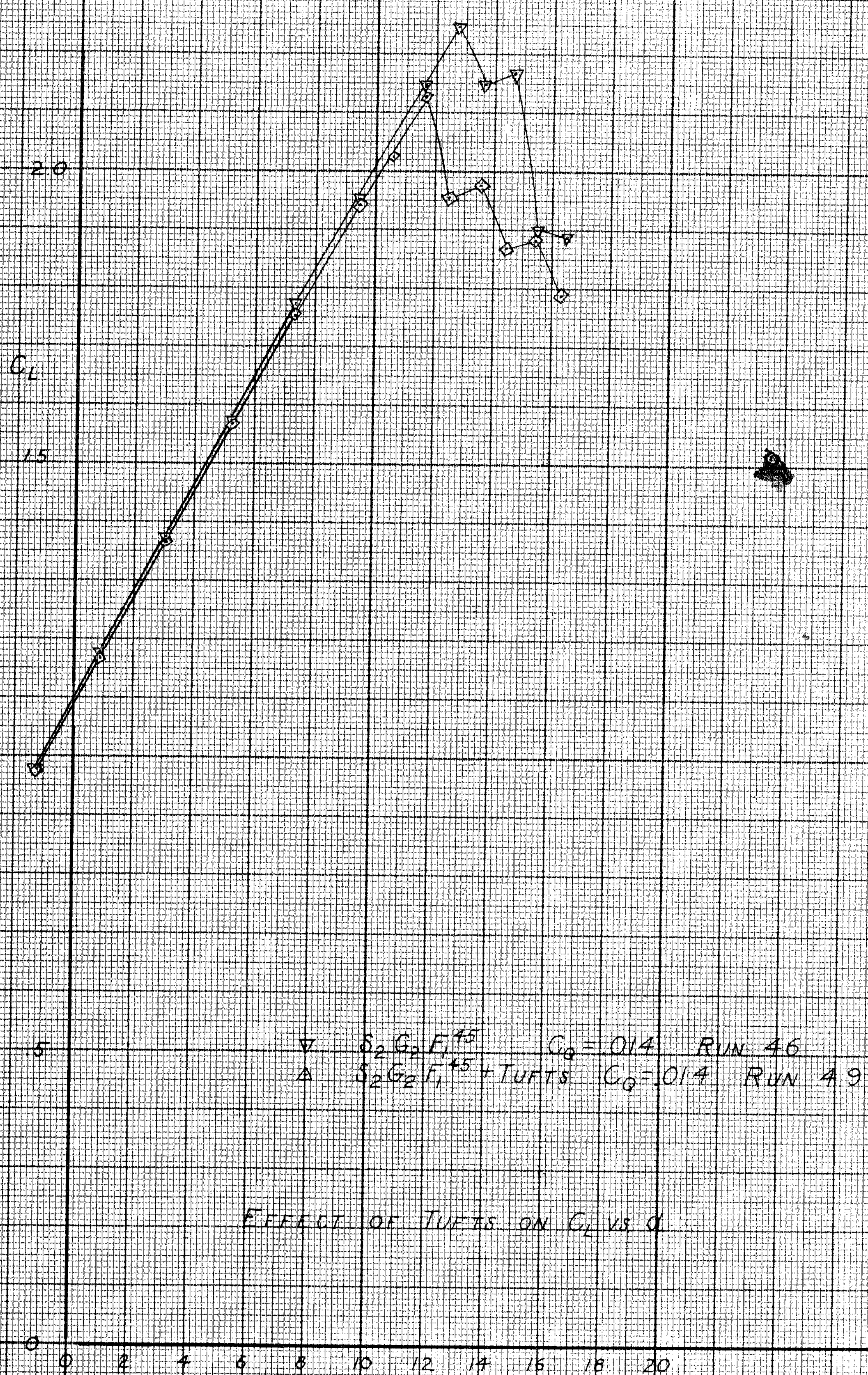
NUMBERS INDICATE α_U AT WHICH SEPARATION OCCURS

α_U	α	C_L
8	9.35	1.753
10	11.35	1.753
12	13.40	1.813
13	14.27	1.651

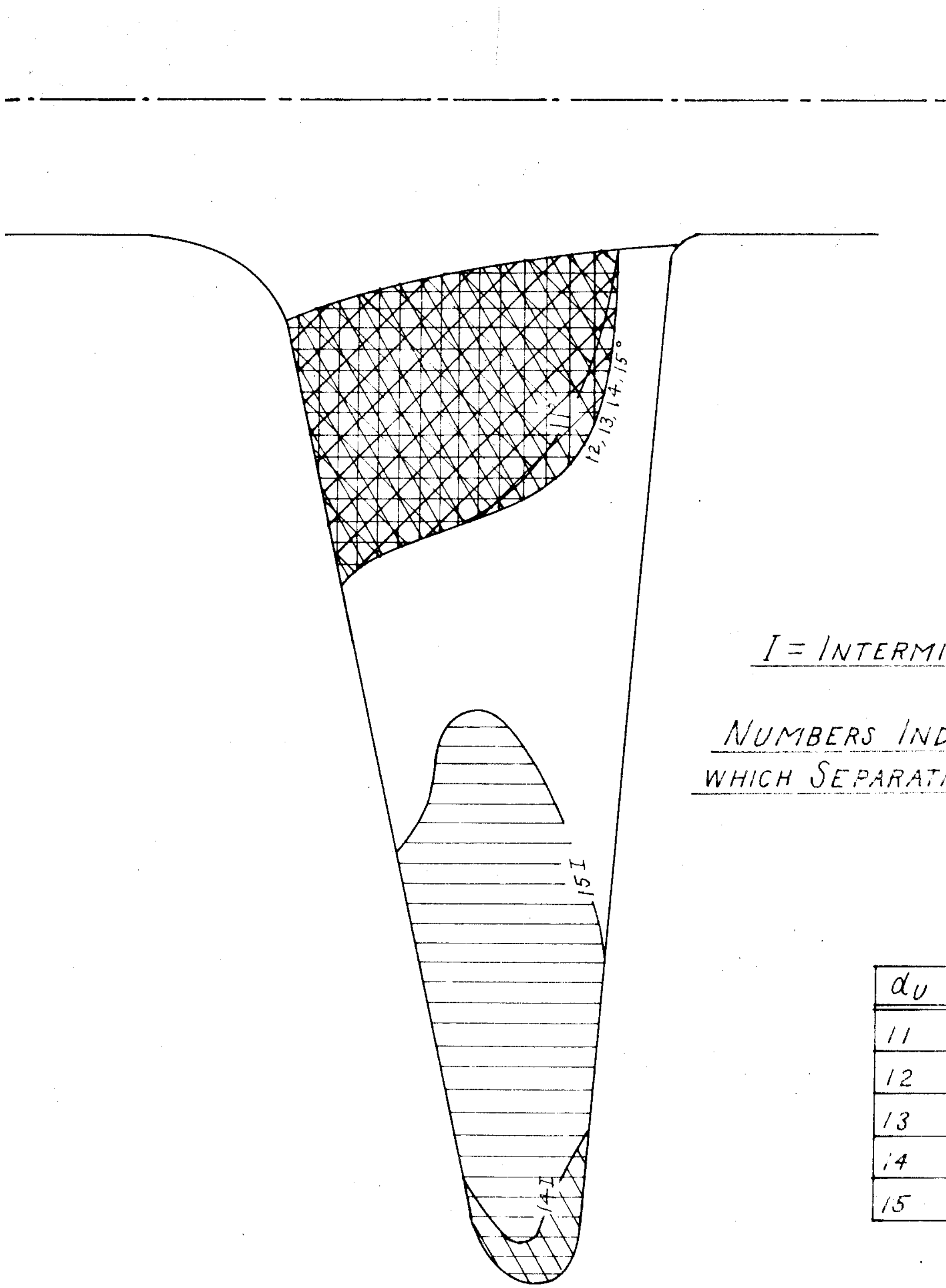
$S_2 C F_1^{-4.5}$ SLOT TAPED. RUN 45

CONTOURS SHOWING APPROXIMATE LINES OF FLOW SEPARATION

FLAPS DOWN $C_Q = 0$



EFFECT OF TUFTS ON C_L VS α



I = INTERMITTENT STALL

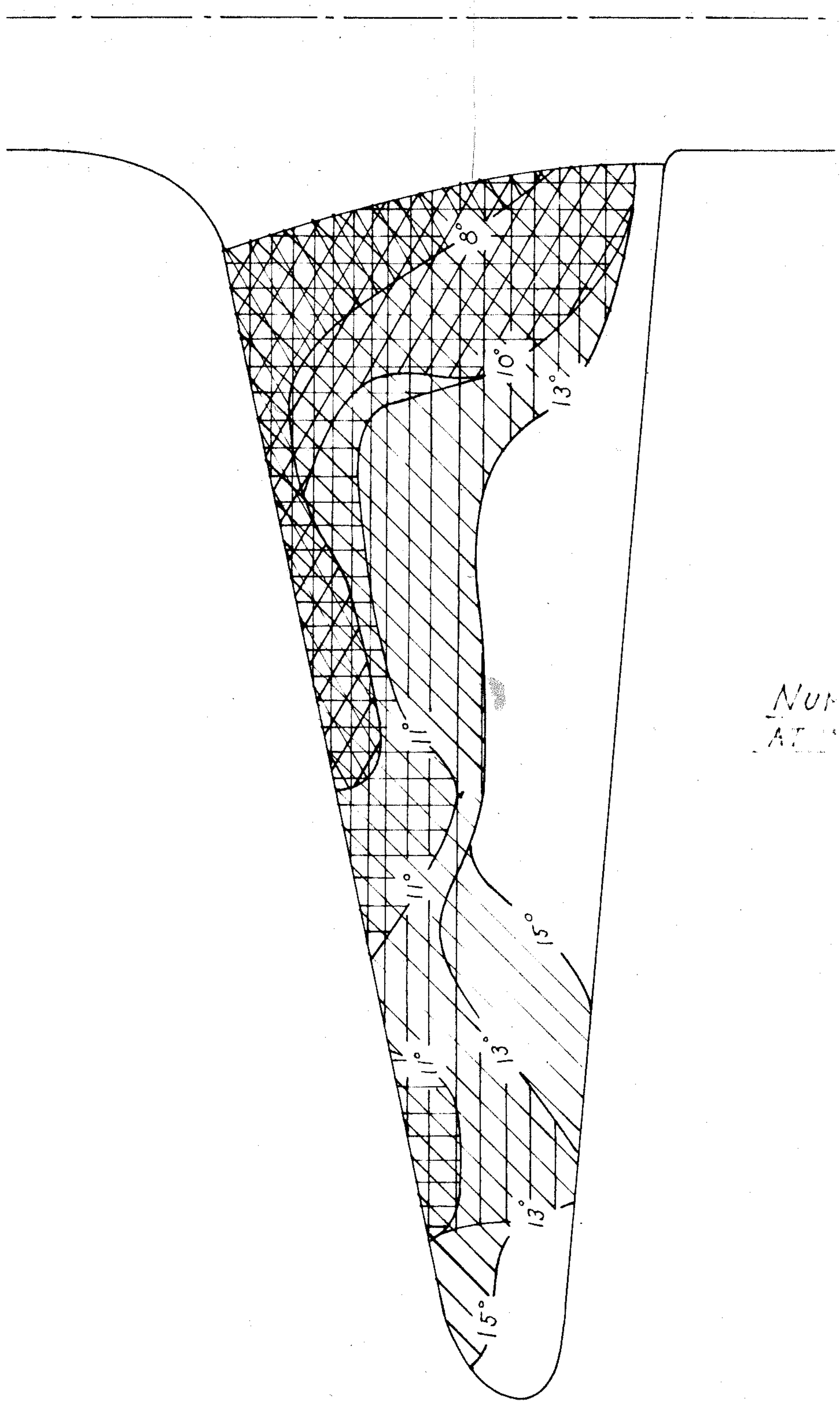
NUMBERS INDICATE α_U AT WHICH SEPARATION OCCURS

α_U	α	C_L
11	12.51	1.955
12	13.52	1.975
13	14.44	1.868
14	15.45	1.881
15	16.38	1.790

$S_2\ G_2\ \Gamma_1^{4.5}$ RUN 49

CONTOURS SHOWING APPROXIMATE LINES OF FLOW SEPARATION

FLAPS DOWN $C_Q = .014$



NUMBERS INDICATE α_U AT WHICH SEPARATION OCCURS

α_U	α	C_L
8	8.48	.625
10	10.54	.725
11	11.59	.767
13	13.66	.862
15	15.72	.935

S_2C SLOT TAPED, RUN 50

CONTOURS SHOWING APPROXIMATE LINES OF FLOW SEPARATION

FLAPS UP $C_Q = 0$

CONCLUSION. These tuft tests concluded the writer's experiments. If success is judged by the value of maximum lift coefficients obtained, the work has been a failure. Nevertheless, more is known now than before the start of the work. One reason for the trouble encountered has been found to be in the wing-fuselage intersection. One of three paths for remedying this trouble lies open: (1) Expand the fuselage toward the trailing edge of the wing. (2) Slot the fillet and use suction to prevent separation on it. (3) Turn the wing over and use the model as a high wing. This third method is recommended for the present. A high wing should be easier to work with and should always give optimum results because the slot is so easily extended entirely across the span. Then, if satisfactory results are obtained as a high wing model, it may be converted back to a low wing type and special investigations made to remedy the disadvantages inherent in a low wing model. In such a case, the high wing experiments should serve both as a guide and as a goal.

The author has not done enough work with the model to be sure of any definite method of attack for getting best results but would use the following method unless a better solution develops. Try several slot locations to see the effect of location, and for every slot location, set out to develop the best lift possible.

In all boundary layer control experiments the flow is being held on artificially. Experience with flow breakdown at the fillet and experience with trying to control the flow after it has separated indicate that flow can be maintained for only a few degrees after initial separation occurs. In other words, it seems to the writer that the effectiveness of boundary layer control in preventing separation is only as great as at its weakest point.

With such a working theory in mind, flow visualization tests should be made with each slot to see where stalling begins. The slot should then be re-designed to prevent stalling in that portion. Then test again and re-design anew until an optimum is approached.

Results so far have been negative, but it is hoped that this thesis presents information that may be of use in the future study of the problem of boundary layer control.

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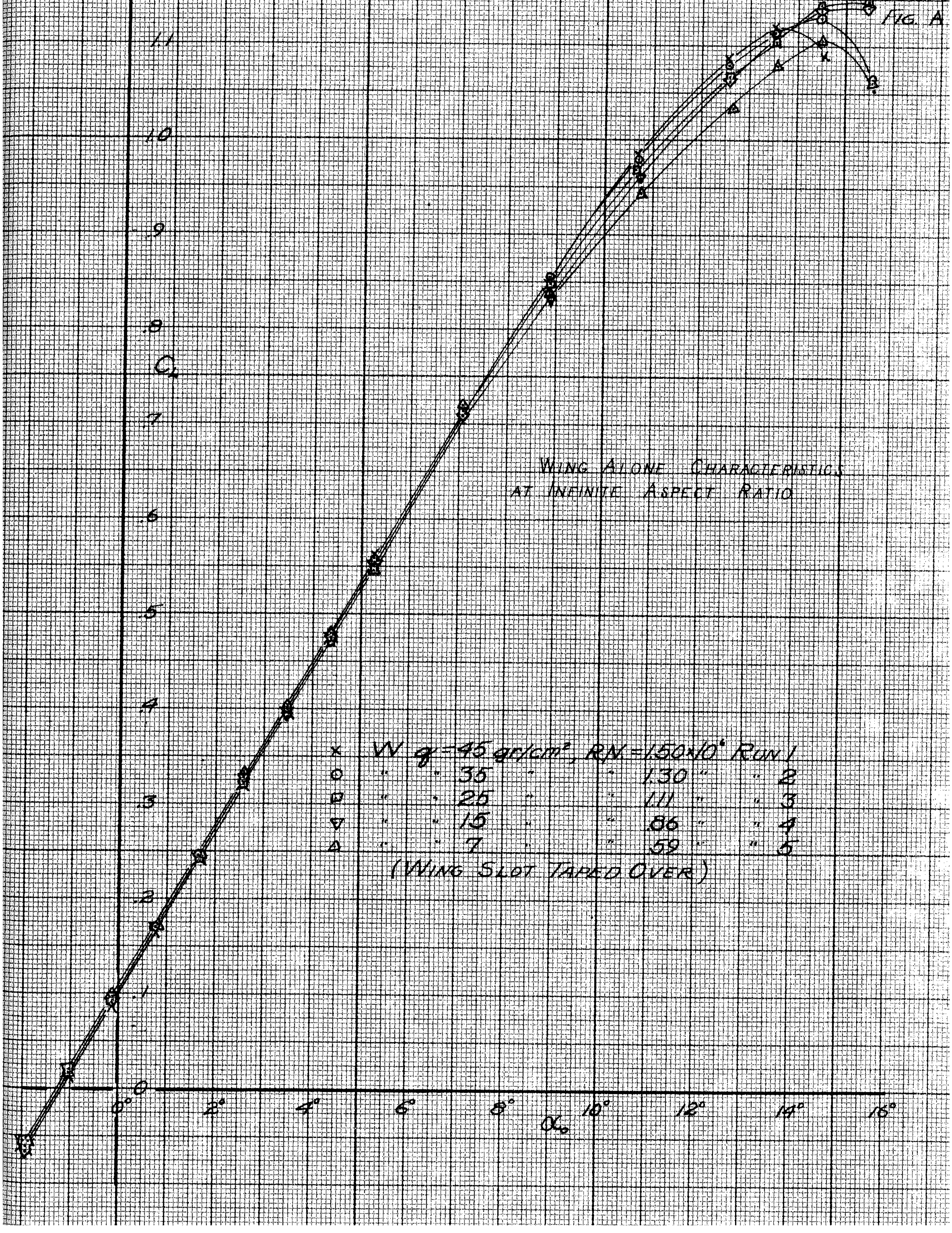
FIG. A


1.1
1.0
.9
.8
C_L
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.4
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0
0°
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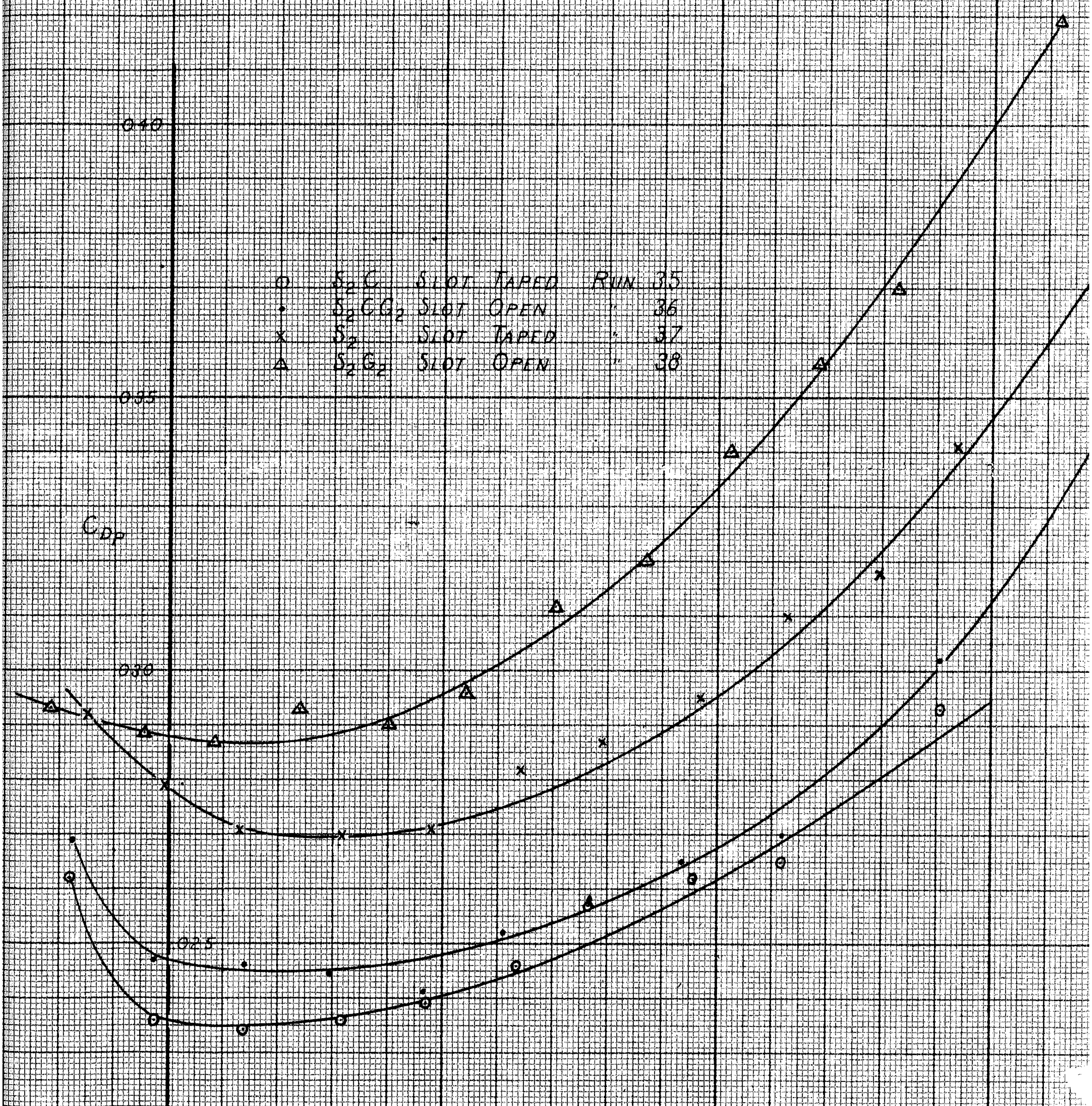
4°
6°
8°
10°
12°
14°
16°
α_o
WING ALONE CHARACTERISTICS
AT INFINITE ASPECT RATIO
× W/q = 45 gr/cm², R.N. = 1.50×10⁶ Run 1
○ " " 35 " " 1.30 " " 2
□ " " 25 " " 1.11 " " 3
▽ " " 15 " " .86 " " 4
△ " " 7 " " .59 " " 5
(WING SLOT TAPED OVER)



EFFECT OF G_2 AND TAIL CONE ON DRAG