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Tests in the R.A.E. 10-ft × 7-ft High Speed Wind Tunnel on Drop Tanks fitted to Two Swept-Back Wings

PART I

Comparison of Under-Wing and Wing-Tip Installations

By
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PART II

Comparison of Various Under-Wing Drop-Tank Arrangements

By
Staff of R.A.E. High Speed Wind Tunnel

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PARTS I and II

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General Summary.—The report describes tests made in the Royal Aircraft Establishment 10-ft × 7-ft High Speed Wind Tunnel on drop tanks, fitted to two wings, having the same plan-form with a sweepback of 40 deg and an aspect ratio of 3·5, but differing in thickness/chord ratio, being 10 per cent and 8·5 per cent thick respectively.

Part I compares the results obtained with the drop tanks mounted in two alternative positions on the 10 per cent thick wing: under the wing at about mid-semi-span, supported by an 8·5 per cent thick strut or alternatively, at the wing tip in a mid-wing position. Part II compares the results obtained with several different types of under-wing installation, *e.g.*, with different designs of strut or alternatively dispensing with the strut and fitting the tanks directly on to the lower surface of the wing. The latter are referred to as 'nacelle-type' tanks. Most of the tanks had a fineness ratio of 8 : 1.

The original under-wing and tip arrangements gave about the same drag increment for $C_L = 0 \cdot 2$ throughout the Mach-number range; at $M = 0 \cdot 88$ and $R = 2 \cdot 8 \times 10^6$, this was about 20 lb drag at 100 ft/sec for two full-scale tanks. For values of C_L less than about 0·2, the tip installation was superior. The reduction in top speed, owing to the drag of these tanks might amount to about 0·03 to 0·04 in Mach number.

The tip arrangement has several important disadvantages:

(i) it causes appreciable shifts in the aircraft c.g. and neutral point
(ii) buffeting may occur in flight at high Mach numbers and moderate lifts (possibly even under cruising conditions)
(iii) the performance of the basic wing is not quite restored after the tanks have been dropped owing to the substitution of a square for a curved tip—the corresponding reduction in top-speed Mach number is about 0·01.

The last two disadvantages could probably be eliminated by designing a square tip to have a good performance at high speed, *e.g.*, by the introduction of camber and twist there.

Suggestions for improving the tip and under-wing installations are made in sections 6.1.7. and 6.1.5. respectively of Part I. An improved performance would be expected in both cases if the tank were moved so that the upper surface of its nose were faired smoothly into the wing upper surface and its intersections with the lower wing surface were modified to coincide with the streamline over the wing. This suggestion, applied to tanks fitted near mid-semi-span was investigated in the tests reported in Part II with most promising results.

At high Mach number, the loss in performance with the nacelle-type tanks at values of C_L of 0·2 or less was only about half that with the best strut-supported arrangement, *e.g.*, the reduction in drag-divergence Mach number (M_D) was only about 0·025. The gain from shaping the junction to follow the streamline over the wing was not large for the tank tested (90 gallons on a wing of about 35 ft span) but might be greater for a larger store.

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* R.A.E. Report Aero. 2442, received 14th February, 1952. R.A.E. Tech. Note Aero. 2177, received 24th November, 1952.

No definite opinion can be given regarding the scheme in which the tank was held by three small struts instead of a single large strut because of the large scale effect likely with the results on this arrangement.

Part II also includes some measurements of the normal force and pitching moment on the tank itself, when supported by a single strut. The results suggest that for stressing, the effects of Mach number are not as severe as assumed previously but that the nose-down pitching moment at low C_L, which has to be corrected for by jettison fins, increases appreciably with Mach number.

PART I

Comparison of Under-Wing and Wing-Tip Installations

By

D. E. HARTLEY, B.A., and A. B. HAINES, B.Sc.

1. *Introduction.*—The carriage of external stores on the swept wings of present high-speed aircraft introduces some difficult interference problems. In practical cases, the choice of a suitable installation may be restricted, *e.g.*, by wing stiffness, spar position, or the presence of the undercarriage and control surfaces. Nevertheless, there are still a large number of relevant variables and so it is difficult to plan a programme of tests that is both reasonably short and capable of giving enough data on which to base general conclusions. The effects of some of these variables have been investigated[1] in earlier work at low speeds. This work has shown that adverse aerodynamic effects were likely to be observed on swept wings at high speeds with both under-wing and tip installations because :

(i) with the under-wing arrangement, the strut distorts the isobar pattern of the wing lower surface, especially at low incidences, and this, combined with the higher suctions near the junctions, should result in a decrease of the Mach number at which the drag rise begins;

(ii) with the wing-tip arrangement, the tank acts as an endplate, causing an increase in the peak suctions towards the tip. This effect should decrease the induced drag at low incidences and low speeds but at high Mach numbers would be expected to cause an earlier drag rise. Furthermore, the extra lift, produced by the effect of the tank, is aft of the aircraft c.g. and causes changes in trim that vary with Mach number and C_L. Hence it would not be possible to balance the c.g. shift under all flight conditions.

These tests, made at low speeds, have indicated the probable sources of trouble at high speed; the aim of the tests at high Mach number, described in this report, is to show the order of the actual resulting loss of performance—including the effects on drag, lift and effective $C_{L\max}$. These tests, which were made in the R.A.E. High Speed Wind Tunnel, relate to tanks fitted in two positions on a half-model of a 40-deg swept-back wing. The wing was without camber or twist and had an RAE 101 section from root to tip. The tank was either supported under the wing from a strut fitted near to the leading edge at about the mid-semi-span position or was fitted symmetrically at the tip. These installations are almost the same as those on model B of the low-speed tests[1].

The two arrangements tested here are the natural development of typical under-wing and tip installations on unswept wings, having regard to the practical limitations of a representative swept-wing fighter. It was essential to obtain the present results at high Mach number on these relatively simple arrangements before deciding whether it would be really necessary to design alternative schemes which, in most cases, would be more complicated.

The present results apply strictly only to the arrangements tested but they should give a reliable indication of the effects to be expected in similar cases in which the aircraft has swept wings that are symmetrical* and untwisted (as in current designs) and in which no attempt has been made *ab initio* to design the wing and tank as a single unit. It is likely that future swept-wing aircraft may have wings with modifications in section and twist to give the best performance at the design C_L and the present results are not necessarily representative of tip tank installations on such wings.

The opportunity was taken to test the arrangements at low Mach number up to the higher Reynolds numbers (about 9×10^6 on tank length) possible in the High Speed Wind Tunnel with the object of showing whether the earlier low-speed data are subject to serious scale effect.

The report includes the results of some low-speed pressure-plotting tests on a similar swept wing fitted with a tip tank. Modifications to the shape of the tank were made in an attempt to improve the overall performance.

2. *Description of Models Tested.*—Fig. 1 shows the models tested ; Table 1 gives their principal dimensions.

The basic wing is wing No. 1 of the recent research series of swept-back wings[2] having a sweepback of 40 deg on the quarter-chord line, a nominal aspect ratio of 3·5 (*see* below), a taper ratio of 0·4 and a thickness/chord ratio of 10 per cent. The wing is untwisted and has the symmetrical RAE 101 section with its maximum thickness at 0·31*c* from the leading edge.

The basic wing used for the strut tank tests has a curved leading-edge tip designed[3] to improve the performance at high speed. Its gross aspect ratio is 3·53. Since a tip tank could not be carried on a wing tip of this particular shape, a square-cut tip was used for the tests with a tip tank. The wing area is almost unaltered by this change (the difference is only about 1 per cent) but the gross aspect ratio, defined by the span extending to the inboard side of the tank is reduced to 3·32.

The size of drop tank tested represents a 150-gallon tank full-scale fitted to an aircraft wing of about 35-ft span (the model being about 1/7th scale). The tank has a fineness ratio of 8 : 1 and is of circular cross-section. It has an ellipsoidal nose and a pointed rear separated by a cylindrical portion of length equal to the strut chord.

The strut for the under-wing arrangement was mounted at 0·522 of the semi-span (Fig. 1). It is of constant chord equal to 0·24 of the local wing chord and is without sweep-back, taper, camber or twist. Its thickness/chord ratio is 0·085 and its centre-line is at 0·167 of the local wing chord from the leading edge.

The strut is longer than would probably be used in practice because of ground clearance. With the strut used in the present tests, the minimum gap between the tank and wing surfaces is about 0·15*c*. Further tests are now being made in the High Speed Wind Tunnel to check the effect of reducing the gap to about 0·08*c*.

The strut tank is mounted at — 1·5 deg incidence to the wing chord since stores on straight-winged aircraft have usually been set at a slight negative incidence.

In addition to the strut and tip tank installations, tests were also made on two other configurations:

(i) the basic curved-tip wing with strut only, *i.e.*, no tank attached. The full strut was tested and so the part normally buried within the tank was now exposed to the air stream (Fig. 1). Its minimum length is 0·31*c*, *i.e.*, roughly twice the minimum strut length when the tank is present;

(ii) the strut tank installation with 0·183*l* cut off from the nose of the tank, leaving a flat nose. This was intended to represent a rocket battery without its cap and in this report it will be described simply as a rocket battery.

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* With no modification of section shape towards the tip.

3. *Description of Tests.*—The tests in the R.A.E. High Speed Wind Tunnel comprised measurements of lift, drag and pitching moment and observations of tuft behaviour on half-models in the presence of a body not integral with the wing (Fig. 1). A mercury seal (Fig. 1) was used to prevent a flow of air over the wing stub between the working-section and the dead space.

Transition was not fixed on the wing but was fixed on the tank at 0·15 of the tank length, l.

The force and moment coefficients are based on net wing areas, *i.e.*, wing areas excluding the part shielded by the body.

The tests can be considered in four groups:

(i) tests at low Mach number and various Reynolds numbers on the basic wing and on the strut and tip-tank installations;

(ii) tests at constant Reynolds number ($2 \cdot 8 \times 10^6$ on tank length) over a range of Mach numbers on the basic wings and tank installations;

(iii) tests as (ii) but on the subsidiary arrangements—wing with strut and with strut and rocket battery;

(iv) a tufting test on the wing with tip tank.

Tests (i) to (iii) were made during March 1950 and (iv) during June 1950. The following table outlines the range of conditions covered:

Configuration	R based on tank length	M	α (deg)
Tests (i)	$5 \cdot 1 \times 10^6$ $7 \cdot 6 \times 10^6$ $9 \cdot 1 \times 10^6$	0·33 0·22 0·18	−2 to +14
Tests (ii)	$2 \cdot 8 \times 10^6$	0·5 to 0·94	−2 to +14
Tests (iii)	$2 \cdot 8 \times 10^6$	0·5 to 0·94	0, 2, 4
Tests (iv)	$2 \cdot 8 \times 10^6$	0·5 to 0·94	0 to 10

The report also includes the results of some low-speed pressure-plotting tests ($M = 0 \cdot 107$, $R = 1 \cdot 6 \times 10^6$, $\alpha = 0$ deg) made in the R.A.E. No. 1, 11½-ft Wind Tunnel in January 1950 on a tip-tank arrangement.

4. *Interpretation and Presentation of Results.*—Before discussing the results in detail, it is essential that the basis for interpreting the comparison should be made clear. This applies particularly to whether the wing with the square tip or that with the curved tip should be taken as the datum wing for the tests with the tip tank.

It is probable that a fighter, having swept-back wings with symmetrical sections and no twist, will benefit from a tip having a curved leading edge similar to that of the basic wing. The drag increment with any tank installation should be obtained by subtracting the drag of the wing with a curved tip. This implies that in the case of the tip tank there is a loss in performance caused by:

(*a*) the substitution of the square for the curved tip, and

(*b*) the addition of the tank to the square tip.

It should be remembered that the first loss would be still incurred after the tank has been jettisoned. At low C_L, this loss is relatively small; in the present tests, it is slightly affected by the small reduction in aspect ratio. This has however only a small influence on the comparison of the drags under cruising conditions and is only significant for C_L values above 0·3, say, and when making a detailed analysis into endplate effects (*e.g.*, Fig. 4).

When considering the effects on pitching moment, the basis of comparison is different from that used for drag. The most important practical consideration is whether any serious changes in trim or stability occur when the tank is jettisoned. Hence, when comparing C_m vs. C_L curves or values of $(\partial C_m/\partial C_L)$, $(\partial C_L/\partial \alpha)$, etc., the curved-tip wing should be used merely for the effects of the under-wing tank while, in the case of the tip tank, the square-tip wing should serve as the datum*. For the latter case, it is also important to consider any adverse effects introduced by the change of tip shape, *e.g.*, more pronounced instability at high C_L.

There are several ways of presenting the comparative values of drag at high Mach number. The most direct method consists merely of comparing curves of C_D vs. M at constant C_L, *e.g.*, Fig. 8, for the cases with and without a tank. The coefficients C_L, C_D, etc., are based on net wing area—this is almost the same for both square and curved tip wings and so ' constant C_L ' implies almost constant lift.

A second method is to difference these curves (*i.e.*, to find the increment of drag owing to the addition of a tank) and to express it in lb drag full-scale at 100 ft/sec. This increment can be plotted against Mach number at constant C_L as in Fig. 9 or—more graphically—against C_L for various Mach numbers as in Fig. 10. Expressing the drag increment in this way is the usual method for results at low speeds. At high subsonic speeds, however, an appreciable part of the increment may result from an increase of the drag of the wing itself and so this method of presentation which implies that the drag increment is independent of the geometry of the wing may be misleading. Nevertheless, it remains a very clear method of comparing the two arrangements tested and of showing how the results are influenced by increasing Mach number.

There is also a third method of interpreting the results and, in particular, for giving an idea of the effect of the tanks on the top speed performance. It is assumed that the top speed of the basic aircraft roughly corresponds to the Mach number at which the C_D for the wing alone has risen by $0 \cdot 005$ above its low speed value at the same C_L. This particular value of C_D is reached at a lower Mach number when the tanks are fitted and the reduction in Mach number can be taken as giving a rough idea of the loss in top speed. The actual loss in top speed will be rather less than that indicated by this method because the engine thrust does not increase as the square of the speed but is in fact almost constant with changing speed. Therefore a comparison at constant drag would be a closer approximation. This is only a reasonable method of interpreting the high-speed drag results when the increment of drag coefficient owing to the tank is small, relative to $0 \cdot 005$ at low speed. In practice, this means that it should only be used for C_L values less than about $0 \cdot 3$.

Each of these three methods has its merits. For a comparison of two alternative installations, the second is probably the best; while for deciding how much of the advantage of having a fighter with swept-back wings is lost by the addition of a tank, the third is the clearest.

The low-speed data are discussed first in this report because they form the natural connection between the data already issued and the results at high speed given here. The variation of the effects with increasing Mach number is however of greater significance than their magnitude at low speeds.

A discussion of the effects of the installations on cruising and top-speed performance is given in sections 6.1.2 and 6.1.3 respectively. The under-wing arrangement is assessed and possible modifications considered in section 6.1.5 following a detailed analysis of the results in section 6.1.4. The drag of the tip tank is analysed in detail in section 6.1.6 and ways of improvement are discussed in section 6.1.7; reference should also be made to the discussion of the problems of balance and trim in section 6.3.

5. *Results at Low Mach Number : Effect of Reynolds Number.*—Results were obtained at low Mach number ($M < 0 \cdot 5$) at four Reynolds numbers on both the basic wing and with the tip and under-wing installations. The wing with square tip was tested only at the lowest of the four Reynolds numbers and so data for this wing are not included in Figs. 2 to 7 which relate to the low speed effects at high Reynolds number.

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* This is not possible at low Mach number and high Reynolds number for which the square-tip wing was not tested.

5.1. *Lift.*—Mean C_L vs. α curves up to $\alpha = 8$ deg over the four Reynolds numbers of the tests are given in Fig. 2. There is no significant variation with Reynolds number in this incidence range and the differences between the results for the various values of R appear to be due to some experimental scatter*.

The addition of the under-wing strut tank reduces C_L at any moderate incidence by about 0·02 without affecting $(\partial C_L/\partial\alpha)_M$. On the other hand, the tip tank causes an increase of about 6 per cent in the lift-curve slope relative to that of the basic wing. The true effect of the tip tank is obtained after making allowance for the fact that the square-tip wing has a slightly lower aspect ratio. The predicted difference in $(\partial C_L/\partial\alpha)_M$ between the two plain wings is 2 per cent and this is confirmed by the experimental results at moderate Mach numbers. Hence, the real increase in $(\partial C_L/\partial\alpha)_M$ due to the tip tank amounts to about 8 per cent.

This increase is presumably due partly to a redistribution of load over the wing and partly to the actual loads on the tank itself. In magnitude, it is nearly three times the increase that would be predicted[4, 5] by replacing the tank by an endplate in the wing–tank junction (Fig. 3). Although it is in fact almost the same as would be predicted if the wing were assumed to extend to the centre-line of the tank and an endplate fitted there, this comparison is probably unsound, since the loads on the tank should not be represented by an equivalent endplate. Even larger increases in lift have been obtained in tests with other stores at the tip of a swept wing; at present, these effects are not fully understood.

With the strut tank, there is a reduction in effective $C_{L\max}$ of about 0·05 to 0·06. With the tip tank, however, at the highest Reynolds number, the breakaway over the wing-tip sections with the tank present is not serious enough to prevent an apparent improvement of about 0·07 in $C_{L\max}$ compared with the value for the wing with curved tip. However, as indicated below in section 5.2.1, buffeting may occur prematurely at a C_L near 0·6 and so this gain in $C_{L\max}$ may not be usable in practice.

5.2. *Drag.*—The drag increments due to the tip and strut tanks are plotted against C_L for the four test Reynolds numbers in Figs. 4 and 5 respectively. The increments are expressed in lb drag at 100 ft/sec for two full-scale tanks. When making comparisons with the results in Ref. 1, for example, two points should be remembered:

(*a*) the increments are obtained at constant total lift rather than at constant incidence,

(*b*) as explained in section 4, the increments apparently due to the tip tanks include some drag due to the accompanying slight reduction in wing aspect ratio (the difference due to the change in plan shape of the wing tip is probably unimportant at low Mach number). Also given in Fig. 4 is the predicted variation of ΔD with C_L, making allowance for the endplate effect as in Fig. 3a.

5.2.1. *Drag of tip tanks.*—The most important conclusion to be drawn from the results given in Fig. 4 is that the C_L value above which there is a serious increase in ΔD owing to a breakaway of flow in the wing–tank junction becomes much higher as the Reynolds number is increased. For example, this critical value of C_L increases from about 0·2 at $R = 2{\cdot}8 \times 10^6$ to about 0·55 at $R = 9 \times 10^6$. Hence it is apparent that results obtained at the Reynolds numbers of previous low-speed tests[1] can give, in this respect, a very pessimistic idea of the performance with tip tanks. On the other hand, the expected reduction of ΔD with C_L below this critical value of C_L, as a result of the endplate effect, is not realised. A comparison with the predicted curves in Fig. 4 shows that even at the highest Reynolds number of the tests, only about a quarter of the effect is apparently obtained. In view of the observed effect on $(\partial C_L/\partial\alpha)$, the endplate effect on ΔD must be present but is being almost counter-balanced by an increase in the wing-tank profile drag. Fig. 13 shows that even for $C_L = 0$, there is a steep adverse pressure gradient over the wing-tip sections when the tank is present and this would clearly be accentuated by increasing C_L. An increase in wing profile drag could result from the consequent thickening of the boundary layer. A large increase in tank profile drag with incidence has recently been found in

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* Except for an increase in $(\partial C_L/\partial\alpha)_M$ with M; *cf.* the mean values in Fig. 2 and the values for $M = 0{\cdot}5$, $R = 2{\cdot}8 \times 10^6$ in Fig. 17.

some low speed tunnel tests. It is interesting to note from Ref. 1 that with the similar tip-tank installation on model B, only part of the estimated reduction of ΔD with C_L was realised. On the other hand, the full effect was achieved with the arrangement on model A and the reason for the differences in behaviour is not clear. Since the effect is not appreciable at a cruising C_L of $0 \cdot 15$, its importance should not be exaggerated.

The principal conclusions are that with the present tip installation, the drag at low C_L is approximately equal to the total profile drag of the tank, and that at flight Reynolds numbers and low Mach number, the buffeting, probably associated with the increase in ΔD will not occur at values of C_L below $0 \cdot 6$ or $0 \cdot 7$.

5.2.2. *Drag of under-wing strut tanks.*—The values of ΔD for $C_L = 0 \cdot 1$ are plotted against log R in Fig. 6 for comparison with the estimated profile drag of the tank alone and with the previous low-speed results[1] on a similar installation (model B). The agreement between the results of the two sets of tests is fair and it seems that the low-speed interference drag decreases with R. For $R = 10^7$, the full-scale interference drag is about $1 \cdot 8$ lb at 100 ft/sec or about 40 per cent of the estimated drag of the tank alone (compared with 55 per cent at $R = 10^6$).

At high values of C_L, ΔD increases rapidly with C_L (Fig. 5). At the highest Reynolds numbers, this does not occur at a C_L below about $0 \cdot 7$: but for $R = 2 \cdot 8 \times 10^6$ and $M = 0 \cdot 5$*, ΔD for only $C_L = 0 \cdot 6$ is about twice that for $C_L = 0 \cdot 1$. Most of this increase in ΔD at a given C_L results from the loss in C_L at a given incidence near the stall (noted in section 5.1). The relatively small increase in ΔD at a given incidence suggests that no serious breakaway exists in the flow over the wing and hence no buffeting should result in flight. Hence the effect should not be affected appreciably by changes in Reynolds number and the variation shown in Fig. 5 is a function of the Mach number—*see* later in section 6.1.1.

5.2.3. *Comparison of the low-speed drags of strut and tip tanks.*—In Fig. 7, a comparison is made between the values of ΔD due to tip and strut tanks at two Reynolds numbers; the curves are taken or deduced from those in Figs. 4 and 5. The tip tanks give the smaller drag increments at values of C_L below $0 \cdot 2$ and the reverse is true at higher values of C_L. The difference between the drag increments at high C_L should be less marked at flight Reynolds numbers.

6. *Discussion of Results at High Mach Number.*—6.1. *Drag.*—6.1.1. *General characteristics.*—Fig. 8 shows the variation of C_D with Mach number at constant C_L for the wings with tanks and for the basic wing. The drag increments, ΔD in lbs full-scale for 2 tanks at 100 ft/sec, derived from these results, are plotted against Mach number at constant C_L in Fig. 9 and against C_L for $M = 0 \cdot 5, 0 \cdot 8, 0 \cdot 88$ and $0 \cdot 92$ in Fig. 10. The performance of the wings with square and curved tips is compared in Fig. 11.

It is clear from Figs. 8 to 10 that there is a considerable increase with Mach number in the drag due to either installation. Up to $M = 0 \cdot 9$, it remains true, as at low speeds, that the tip tank gives smaller drag increments below $C_L = 0 \cdot 2$ and that the reverse applies for higher values of C_L (at least, up to $C_L = 0 \cdot 4$).

The variation of ΔD with C_L at high Mach number for the under-wing strut tank is similar to that at low speed except that the trends are more marked (Fig. 10). Outside the range of Figs. 8 to 10, ΔD increases rapidly with C_L above $C_L = 0 \cdot 5$ (*cf.* Fig. 5). This effect occurs at about the same value of C_L at all Mach numbers but leads to larger increases of drag at high speeds. The effect remains associated with a loss in lift at a given incidence.

With the tip tank, the serious increase in ΔD with C_L starts at a lower value of C_L as the Mach number is increased (Fig. 10). At the highest Mach numbers, and above $C_L = 0 \cdot 2$, there is even an appreciable increase of drag if the curved tip is replaced by the square tip (Fig. 10). As might be expected, the further additional drag when the tank is fitted is rather less under such conditions than at, say, $M = 0 \cdot 88$, when the change of tip shape has a much smaller effect.

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* A comparison of these results with those obtained for $R = 2 \cdot 8 \times 10^6$, $M = 0 \cdot 65$ casts some doubt on whether, even in this case ($R = 2 \cdot 8 \times 10^6$, $M = 0 \cdot 5$), ΔD rises appreciably until about $C_L = 0 \cdot 55$.

6.1.2. *Effect of tanks on cruising performance.*—For a fighter with this wing design, it is probable that the cruising speed would correspond to about $M = 0\cdot88$. In view of the wider range of possible duties, it is difficult to specify a typical cruising C_L and so results for both $C_L = 0\cdot1$ and $0\cdot2$ are considered.

Fig. 10 shows that for $M = 0\cdot88$, $C_L = 0\cdot2$, either installation gives a drag increment of 20 lb compared with 7 to 8 lb at $M = 0\cdot5$ and the same Reynolds number. This represents a serious increase in the total aircraft drag and suggests that other arrangements for carrying additional fuel externally should be considered—for example, making the tank in the form of a faired underslung nacelle (as with arrangements D and E of Part II).

In the case of the tip tank, there is also a small penalty even after the tank has been jettisoned —in the present case, this amounts to about 3 lb; if the aspect ratio had not been reduced, it would have been about 2 lb. For $M = 0\cdot88$, $C_L = 0\cdot1$, the drag increment due to the strut tanks is 8 lb more than that due to the tip tanks.

Other features to be noted from the results are:

(*a*) *for the strut-tank installation :* If it is assumed that the reduction in ΔD with R is the same at high Mach number as at low speeds, then for $R = 10^7$, the drag increment for $M = 0\cdot88$, $C_L = 0\cdot2$ would be about 18 lb composed of

Low-speed skin-friction drag[6] $= 4\cdot5$ lb.

Low-speed interference drag $= 1\cdot7$ lb.

Additional drag due to effects of increasing Mach number $\simeq 12$ lb.

The relative magnitudes of these component factors show that an appreciable improvement of the cruising performance with a strut-supported tank can only be obtained by modifications in design which reduce the compressibility effects and these should be incorporated even if it is found that they involve slight increases in the low-speed interference drag. This is discussed further in section 6.1.4.

(*b*) *for the tip-tank installation :* From the variation of ΔD with C_L (Fig. 10), it appears that for $M = 0\cdot88$, and $R = 2\cdot8 \times 10^6$, the breakaway of flow over the wing-tip sections is present even near $C_L = 0\cdot1$ At high Mach number, this characteristic may not be subject to the strong favourable scale effect which exists at low speed (Fig. 4). Hence buffeting in flight at high speed may occur not only at high C_L but also under 1*g* cruising conditions. For this reason, the under-wing arrangement may be preferred even if it gives the higher drag as is the case if the cruising C_L is only $0\cdot1$ to $0\cdot15$ rather than $0\cdot2$.

6.1.3. *Effect of tanks on top-speed performance.*—As explained in section 4, the probable reduction in top speed of a fighter with this wing design can be judged by comparing the Mach numbers M' at which a certain value of C_D is reached, tanks fitted or without tanks. The value of C_D chosen is $0\cdot005$ above the low-speed value at the same C_L for the wing alone.

The following table gives the appropriate values of Mach (M'), defined as above and derived from the curves of Fig. 8:

C_L	M'		
	Basic wing	With tip tanks	With strut tanks
0	0·92	0·87	0·80
0·1	0·915	0·87	0·84
0·2	0·91	0·855	0·855
0·3	0·895	0·815	0·84

Therefore, for $C_L = 0 \cdot 2$, the effect of either installation amounts to a loss of about $0 \cdot 055$ in M'. This loss does not entirely arise from compressibility effects—some of it, by definition, is due to the drag increment already present at low speeds. For example, for $C_L = 0 \cdot 2$, the actual increase in ΔD with Mach number accounts for a loss in M' of only $0 \cdot 035$. This value compares with $0 \cdot 01$ for the effect of a tip tank fitted to a wing of small sweepback.

Also, a slight loss in M'—between $0 \cdot 005$ and $0 \cdot 01$ for $C_L = 0 \cdot 2$, *i.e.*, about 5 m.p.h.—remains after the tip tank has been jettisoned because of the poorer performance of the square tip shape (Fig. 11).

If less than half the $0 \cdot 005$ increment in C_D is due to the effects of increasing Mach number, the values of M' not only give an inaccurate idea of these effects but also are pessimistic in terms of the overall performance (*see* also section 4). This is because, in such cases, C_D for the wing-tank combination is probably increasing only slowly with Mach number near $M = M_D$ (Fig. 8). These remarks apply to the strut-tank arrangement near $C_L = 0$ (loss in M' is $0 \cdot 12$ whereas the part of the loss due to compressibility effects is only about $0 \cdot 06$) and to the tip-tank arrangement at and above $C_L = 0 \cdot 3$.

6.1.4. *Analysis of strut-tank results; correlation with low-speed pressure-plotting.*—Pressure distributions at low speed in the strut–wing and strut–tank junctions of a similar configuration (wing $t/c = 8 \cdot 5$ per cent rather than 10 per cent) are given for $C_L = 0$ in Fig. 9 of Ref. 1. The highest local suction occurs in the inner wing–strut junction and amounts to $C_p = -0 \cdot 44$. In the immediate neighbourhood of the strut, the isobars are probably unswept and so, on this perhaps pessimistic assumption, the local critical Mach number (M_{crit}) for this junction is about $0 \cdot 72$*. With the 10 per cent thick wing of the present tests, the corresponding value may be taken as $0 \cdot 71$. The values of M_{crit} for the other junctions, also assuming zero sweepback, are:

Outer wing–strut junction: $0 \cdot 77$
Inner strut–tank junction: $0 \cdot 77$
Outer strut–tank junction: $0 \cdot 75$.

To obtain an idea of the sources of drag with the strut-tank installation, C_D vs. M curves are given in Fig. 12 for the wing and strut alone† for comparison with the results for the wing alone and for the full arrangement. At $C_L = 0$, the drag increment for the strut alone increases above about $M = 0 \cdot 77$, *i.e.*, a Mach number about $0 \cdot 05$ higher than the estimated M_{crit} in the junction, but the rate of increase is slow and suggests that the effect of the strut on the wing isobar pattern is still fairly localized.

The addition of the tank to the strut gives a further drag increment that does not vary significantly with Mach number below about $M = 0 \cdot 83$; this is about $0 \cdot 06$ higher than the value for the start of the drag rise due to the strut. This difference appears to correspond with the difference between the values of M_{crit} for the two junctions. Above $M = 0 \cdot 89$, a very rapid increase in the tank drag occurs; this may be partly caused by a shockwave from the lower wing surface reaching the tank and causing a breakaway of the flow over the tank.

As C_L is increased, the local velocities below the wing are reduced and so, as would be expected, the low-speed drag due to the strut is less and its increase with Mach number is delayed—by about $0 \cdot 05$ in M for $C_L = 0 \cdot 2$. The tank drag is sensibly unaffected except that the final rapid rise occurs at a rather higher Mach number.

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* This estimate is a mean of values derived using the Glauert and Weber[7] relations.

† The low-speed drag of the strut will be greater here than in the actual strut-tank arrangement, because then part of the strut tested here will be contained within the tank.

For the cruising conditions discussed above ($M = 0{\cdot}88$), an approximate drag analysis is as follows:

C_L	0·1	0·2
Total drag increment (lb at 100 ft/sec)	21·2	20
Proportion from	(per cent)	
(i) drag due to strut at $M = 0{\cdot}7$*	14	12
(ii) tank drag at $M = 0{\cdot}7$*	31	36
(iii) increase with Mach number in drag due to strut	31	27
(iv) increase with Mach number in additional drag due to tank	24	25

There may be a favourable end interference on the strut drag when no tank is attached and so some of the quoted increase in tank drag with M (iv) should probably be debited to item (iii).

6.1.5. *Assessment of strut-tank installation and methods of improvement.*—There is a considerable loss in performance with the strut-tank although the installation was favourable in two respects:

(*a*) the relatively small value for the ratio (strut chord)/(local wing chord). It is possible that to ensure satisfactory jettisoning of a single strut installation, the value of this ratio might have to be increased from $0{\cdot}25c$ to about $0{\cdot}35c$ and the strut would then have a more pronounced effect on the wing isobar pattern,

(*b*) the far forward position chosen for the strut. A farther back position would lead to lower values of M_{crit} in the junction and also to a steeper rise in drag at higher Mach numbers. (This assertion is based on some pressure-plotting results on a rectangular wing fitted with a strut which showed that after the appearance of shockwaves, one of the principal effects of a strut is to cause a large increase in pressure over the wing surface ahead of it.)

Despite these favourable features in the present installation, it still seems that the interference of the strut on the flow over the lower wing surface is the most important source of trouble. There are several ways by which this interference might be reduced:

(i) using *several small struts* instead of a larger single strut (this idea has been tested as arrangement C in Part II). Particularly if the struts are tapered, having a smaller chord at the wing end, the area of contact with the wing and hence the effect on the wing isobar pattern would be reduced. This scheme would probably be effective only if it is possible to retain a small thickness/chord ratio and a fairly forward position on the wing for the rear strut.

(ii) *by cambering and twisting the strut* so that the surface formed by the centre-lines of the sections coincides with the estimated stream surface of the flow at cruising speed and incidence. If this were done, use of a thin strut of large chord would be beneficial.

(iii) *by moving the installation close to the wing root* in order that the strut should benefit from the low velocity region ahead of the maximum thickness. This is probably impossible on existing designs because of the presence of the undercarriage (and engine entries). Future designs will probably include modifications to the wing and body shapes to eliminate the root kink effect (and thus increase the local velocities ahead of the maximum thickness). At zero lift, the velocities near the root would also be reduced by the effect of the wing taper but for a wing of the plan-form† considered here, it is doubtful whether this advantage would still be present on the lower surface at a typical cruising lift.

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* Increases in tank drag between $M = 0{\cdot}5$ and $0{\cdot}7$ should not be caused by the growth of any supersonic regions of flow and so choice of $M = 0{\cdot}7$ should give a fairer division of the drag contributions.

† These conclusions do not necessarily apply for a highly tapered wing.

The additional drag due to adding a tank to the strut might be reduced by:

(a) *moving the tank forward* with respect to the wing, possibly by the use of swept struts. In practice, this may be found necessary so that the tank may clear the flaps, when down.

(b) *decreasing the strut thickness/chord ratio* so as to improve the poor M_{crit} values in the strut–tank junction.

The performance would probably be affected slightly by changes in other variables, *e.g.*, wing–tank gap, tank yaw and incidence.

It is probable that an appreciable loss in performance would occur with even the best strut-supported installation. Tests are therefore to be made on an underslung nacelle type of tank, faired into the wing, thus dispensing with the strut. The junctions between the tank and lower wing surface are designed to follow the estimated streamline over the wing for the cruising Mach number and C_L and hence it may be hoped that with such an arrangement, the isobar pattern over the wing will not be seriously disturbed.

6.1.6. *Analysis of tip-tank results—correlation with low-speed pressure measurements.*—Some pressure measurements were made in the No. 1, 11½-ft Low Speed Wind Tunnel on the tip-tank installation at zero incidence. These were done by means of creepers and the results are shown in Fig. 13. Chordwise pressure distributions are given for the top centre-line and the outer edge of the tank, for the wing–tank junction and for two other spanwise positions along the wing. For the latter stations, measurements were also made on the wing alone.

The outstanding features of the results are:

(i) there is a large suction peak, $C_p = -0{\cdot}7$, in the wing–tank junction at about 4 per cent chord,

(ii) the addition of the tank increases the peak suction at A—A ($0{\cdot}213 \times$ tip chord inboard of the junction) by $-0{\cdot}1$ in C_p but has no effect on its chordwise position, and

(iii) the velocities over the tank centre-line section and outer edge are higher by about $-0{\cdot}1$ in C_p than the estimated[8] value for the tank alone.

In order to extrapolate the curves to high Mach number and to interpret them, two criteria will be used. It is emphasized that although the implications of both these criteria are fairly well known for two-dimensional flows, their application to complex three-dimensional problems such as the present is difficult and uncertain.

The table which follows contains values for the various positions of M_{crit} and M_d where M_{crit} is the estimated free-stream Mach number at which the velocity in a direction perpendicular to the maximum velocity line first reaches sonic value and M_d is the estimated free-stream Mach number at which sonic velocity is attained at the crest of the aerofoil in a direction perpendicular to the isobar passing through the crest*.

The values of both M_{crit} and M_d given for the wing (including the wing–tank junction) are a mean of those obtained assuming the local velocities vary with Mach number according to either the simple Glauert rule or that suggested[7] by Miss Weber. The variation of the tank velocities with Mach number has been assumed to be a mean between the $1/(1 - M^2)^{1/2}$ and $1/(1 - M^2)^{1/4}$ rules (*see* Ref. 8). The use of M_d for the sections on the tank is of uncertain validity but values are quoted for the sake of completeness.

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* This original criterion proposed[6] by Nitzberg and Crandall for two-dimensional flows appears to give reasonable agreement with the drag divergence Mach number, as defined in America, *i.e.*, the Mach number for a rate of increase of C_D with M at constant α of $0{\cdot}01$. It has been supported by experimental results[10] from the National Physical Laboratory and theoretical work[11] done in U.S.A.

TABLE

Position	M_{crit}	M_d
Wing alone, B—B	0·91	0·91
Wing alone, A—A (basic wing I with curved tip) ..	0·935	0·935
Tank alone (velocities estimated by Ref. 8)	0·93	0·93
Wing with tank, B—B	0·91	0·91
Wing with tank, A—A	0·87	0·89
Junction of wing and tank (assuming no sweep here) ..	0·65	0·81
Tank centre-line	0·87	0·88
Tank outer edge	0·865	0·90

The differences shown above between M_{crit} and M_d are small (about 0·02) with the notable exception of the wing--tank junction where M_{crit} is seriously reduced by the large front peak suction. In such a case, under two-dimensional conditions, the drag rise is delayed well beyond M_{crit} and occurs near M_d—hence it seems reasonable to ignore M_{crit} in favour of M_d in the present case, also.

The values of M_{crit} and M_d quoted for section A—A may be optimistic. The sweepback was assumed to be equal to the geometrical value but it is probable that at high speeds, the sweepback of the isobars will be reduced owing to the spread of the 'tip' effects along the wing (a slight tendency for this is apparent even in the low-speed results of Fig. 13). An extreme lower limit for M_{crit} and M_d at this section A—A can be found by assuming zero sweepback giving $M_{crit} = 0·75$ and $M_d = 0·76$. It is suggested that the true values of M_{crit} and M_d for this section probably lie between 0·80 and 0·86 and that it is not possible to make a more definite prediction.

On the basis of the above, an increase with Mach number in the section drags would be expected to start

in the junction near $M = 0·81$,

at A—A between $M = 0·80$ and 0·86,

at B—B (unaffected by the tank) near $M = 0·91$,

and on the tank near $M = 0·88$ to 0·90.

No precise idea can be obtained from these values of the effect of the tank on the overall drag characteristics, particularly in view of the uncertainties that have been noted. Fig. 9 shows that the actual extra measured drag due to the tip tank at $C_L = 0$ increases rapidly above about $M = 0·84$ which lies within the range of values quoted.

Although the high peak suction in the junction does not dictate a very early drag rise with Mach number, the steep adverse gradient behind it may have serious practical consequences. Even at zero incidence, it probably causes a thickening of the boundary layer towards the rear (*cf.* the suction values for $x/c = 0·9$ in Fig. 13). As the incidence is increased, the adverse gradient becomes more severe and, judging from the drag results of Fig. 4, it is probable that it induces a flow separation near $C_L = 0·2$ for $M = 0·5$, $R = 2·8 \times 10^6$. The tuft photographs of Fig. 14a show the extent of the wing affected at C_L's of 0·4, 0·55 and 0·685 at $M = 0·5$; the disturbance appears to originate near the wing leading edge. At $M = 0·80$, the breakaway occurs at a lower C_L and from Fig. 14b it can be seen that the flow at the rear of the section is affected more than at low speed. It also seems that by $C_L = 0\cdot48$, the flow is disturbed over the rear of the tank and so there is a chance that the performance might be improved by a forward movement of the tank.

At high Mach numbers, when the separation in the junction is associated with a shockwave, it is less likely to be subject to such a favourable scale effect as at low speed (Fig. 4). Experience in the case of a tip-tank installation on a less swept wing suggests that the presence of an area of disturbed flow in the tunnel tests may indicate the possibility of buffeting in flight at high speed.

6.1.7. *Methods of improving tip-tank installation.*—As explained in the introduction, the tip-tank installation tested was a relatively simple arrangement but it was not a good design. Appreciable improvements could be obtained by modifications to reduce the high suctions near the tank-wing junction. There are three possible ways of doing this:

(i) Modification of the tank shape.

(ii) Modification of the wing design near the tip.

(iii) A change of tank position relative to the wing.

Considering these in turn:

(i) *Tank shape.*—During the low-speed tunnel tests, attempts to modify the flow in the junction were made by yawing the tank outwards by 5 deg and by changing the tank shape near the junction on the basis of Refs. 12 and 13. The results of these tests are shown in Fig. 15. The 5 deg yaw had no appreciable influence on the suctions in the junction but the most effective changes in tank shape reduced the suction peak from $C_p = -0\cdot7$ to $-0\cdot32$. The change in shape necessary to do this was however large (Mod. III, Fig. 15) and is unlikely to be acceptable in practice (such a tank would probably have to be retained permanently).

(ii) *Wing design.*—Three cases can be distinguished:

(*a*) a symmetrical, untwisted wing such as in the present tests

(*b*) an ' optimum ' wing design in which the tip sections have the small amount of camber, negative twist and the correct shape required to maintain straight isobars along the wing at the design Mach number and C_L with the tank absent. (In this case, the wing could have a square-cut tip)

(*c*) a wing having more extreme modifications designed to achieve the same aim as (*b*), but with the tank present, *i.e.*, in this case, the tank and wing have been designed from the start as a single unit.

Of these, (*c*) is the only sure way of avoiding large increases in drag due to the tank or possible buffeting under cruising conditions. Nevertheless, it should be realised that the drag increments in case (*b*) should be less than for (*a*) because the twist and camber on the wing should reduce the suctions over the wing even when the tank is present. For example, it is conceivable that the drag increment at $C_L = 0\cdot2$, $M = 0\cdot88$ for a tank fitted to the ' optimum ' wing (*b*) might be about the same as that for $C_L = 0$, $M = 0\cdot88$ in the present tests, *i.e.*, 12 lb rather than 20 lb for 2 tanks, full-scale.

Centrally fitted tip tanks would therefore appear more promising on such ' optimum ' wings—particularly as the performance after jettisoning would be as good as if the tanks had never been fitted—in contrast to the present tests where there is a loss due to the substitution of a square for a curved tip. Another solution must be sought to obtain a better tip-tank arrangement on aircraft already designed to be of the type (*a*).

(iii) *Tank position.*—So far only ' mid-wing ' tip tanks have been considered. From work[14] on bodies situated asymmetrically with respect to a wing, it is known that the suctions obtained in the upper junction of a high wing arrangement are much smaller than for the corresponding mid-wing combination. Thus a simple downwards movement of the tank should be beneficial, especially at incidence, and this is the most promising suggestion for improving on the present installation. Three extreme cases can be noted: in the first (Fig. 21a), the tank is fitted as an underslung nacelle with the upper surfaces of tank and wing faired into each other; in the second (Fig. 21b), the tank is moved backwards as well as down and its shape is modified so that its outer edge coincides with the curved tip of the wing whilst its top surface still fairs into the wing upper surface; and in the third (Fig. 21c), the tank is supported under the wing by a short strut. The third alternative may avoid some of the troubles of the present tip installation at the expense of introducing other problems and is only mentioned as a possibility in case neither of the first two suggestions can be adopted in practice.

In the first two cases the lower-wing tank junction could be modified to follow the wing streamline with advantage.

Tunnel tests are necessary to show the magnitudes of any improvements to be obtained from the various schemes.

6.1.8. *Drag of rocket battery.*—The results are plotted in Fig. 12 and may be summarized as follows:

(*a*) at low Mach number, the battery gives a drag increment of between three and four times that of the strut tank installation

(*b*) the Mach number at which its drag increment starts to rise is not appreciably different from that for the strut tank

(*c*) the initial drag rise with Mach number is not as steep as with the tank installation.

6.2. *Lift.*—Throughout the Mach number range of the tests, the addition of the under-wing strut tank to the basic wing has little effect on $(\partial C_L/\partial \alpha)_M$ at low and moderate values of C_L. The reduction in C_L at a given incidence rises from $0 \cdot 025$ at low speed to about $0 \cdot 05$ near $M = 0 \cdot 9$. At high C_L, the strut tank gives a larger loss of lift which results in an increase in the drag increment for a given C_L(*see* section 6.1.1). If the effective $C_{L\max}$ is defined as the value of C_L at which there is a marked change in $(\partial C_L/\partial \alpha)_M$, then it is reduced by about $0 \cdot 06$ by the strut tank, irrespective of the Mach number.

C_L vs. α curves for four Mach numbers are given in Fig. 16 for the two basic wings and for wing II with tip tank. Values of $(\partial C_L/\partial \alpha)_M$ have been derived for $C_L \simeq 0 \cdot 1$ and $0 \cdot 4$ and are plotted against Mach number in Fig. 17. At low speed and $C_L \simeq 0 \cdot 1$, as discussed in section 5.1, the presence of the tip tank increases $(\partial C_L/\partial \alpha)_M$ by about 6 per cent. With increasing Mach number, this effect at first becomes more marked until for $M \simeq 0 \cdot 8$, the increase in $(\partial C_L/\partial \alpha)_M$ is about 14 per cent but at higher Mach numbers the effect dies out until, at $M = 0 \cdot 92$ $(\partial C_L/\partial \alpha)_M$, is unaffected by the addition of the tank. It seems reasonable to assume that these changes with Mach number are related principally to the development of the pressure distributions over the wing-tip sections after the appearance of a local region of supersonic flow. The most important practical conclusion from the results is that the endplate generalization of the low-speed results, suggested in section 5.1, may not represent the worst stressing case and allowance should actually be made for a larger outwards shift of the centre of lift. The problem of obtaining a satisfactory balance between the lift and gravitational forces due to the tank is discussed below in section 6.3.

At higher values of C_L, *e.g.*, $0 \cdot 4$, the tank has a much smaller effect on $(\partial C_L/\partial \alpha)_M$ and above about $M = 0 \cdot 77$ it becomes quite negligible. It is interesting that the endplate effect and the lift on the tank are still sufficient to balance the effect of the disturbed flow over the tip sections.

6.3. *Trim and Longitudinal Stability.*—For C_L values below about $0 \cdot 3$, the addition of the under-wing strut tank, which is mounted near the aircraft c.g., gives a small forward shift of the aerodynamic centre of about $0 \cdot 01\bar{c}$ at Mach numbers below about $M = 0 \cdot 85$; above $M = 0 \cdot 9$

it gives a small positive C_{m0} ($0 \cdot 01$ by $M = 0 \cdot 92$) and an associated increase in $(-\partial C_m/\partial C_L)_M$ (Fig. 18a). However, the effects of this installation on trim and longitudinal stability are small enough to be neglected.

The tip tanks, on the other hand, have serious effects. They are mounted far behind the aircraft c.g. and it is estimated that for a small day fighter, having this wing design, the addition of two 150 gallon tanks at the tips would move the c.g. aft by about $0 \cdot 11\bar{c}$, tanks full or $0 \cdot 02\bar{c}$, tanks empty. The change in stability or manoeuvre margin* is, in general, less than this; Fig. 18b shows that the extra lift due to the tank causes an aft movement of the aerodynamic centre. As suggested in section 4, the square-tip wing—being the configuration left after the tank has been jettisoned—should be taken as the datum here. Under cruising conditions ($M = 0 \cdot 88$, $C_L = 0 \cdot 1$ to $0 \cdot 2$), the increase in $(-\partial C_m/\partial C_L)_M$ due to the tanks amounts to about $0 \cdot 06\bar{c}$. This figure is sensitive to Mach number and C_L. It may be noted, however, that although the increase in $(-\partial C_m/\partial C_L)_M$ due to the tanks dies out as M is increased above $0 \cdot 88$ and also as C_L is increased at a given Mach number, these changes are not so important because, in both cases, the basic $(-\partial C_m/\partial C_L)_M$ for the wing alone increases.

From the values quoted above, it appears that under cruising conditions, (i) with the tanks full, the reduction in manoeuvre margin is about $0 \cdot 05$ and there is a progressive increase of $0 \cdot 09$ as the tanks are emptied. Neither of these values would probably be acceptable and so another fuel tank ahead of the c.g., say, in the nose, would be required for balance. It might be sufficient if the weight of fuel in the forward tanks were only about half that in the tip tanks. The moment due to the weight of the tip tanks would be reduced if the tanks were moved forward relative to the tips but this would not necessarily improve the overall stability because the lift increment might also be reduced, and (ii) the change in manoeuvre margin on jettisoning the tanks would amount to a reduction of about $0 \cdot 04$, *i.e.*, for $C_L = 0 \cdot 2$, a change in C_m of about $0 \cdot 008$ would have to be corrected by the trimming control.

Also, in the case of the tip tanks, the square-tip wing left after the tank has been jettisoned has not such good pitching-moment characteristics as the original curved-tip wing. The C_L vs. α curves suggest a poorer effective $C_{L\max}$.

The effects on balance and trim are the chief disadvantages of the use of the tip position for tanks of the size tested here. The difficulties would be much less serious for lighter objects, *e.g.*, 90 gallon tanks, and so the tip position should not necessarily be rejected on this score. It may also be noted that with the revised tip arrangements suggested under (iii) in section 6.1.7, the effects of the tank on lift and neutral point should be less marked.

6.4. *Effective Centre of Pressure of Tip Tank.*—For use in flutter calculations, etc., the chordwise position of the effective centre of pressure of the tank has been derived, using the square wing as the datum. The values are termed ' effective ' because they include not only the force and moment on the tank itself but also the changes over the wing-tip sections. The values, relative to the tank nose, are plotted against Mach number for constant C_L in Fig. 19. For all values of C_L, the position remains fairly constant up to $M = 0 \cdot 85$ but at higher Mach numbers it moves back rapidly.

7. *Summary of Conclusions of Part I.*—The under-wing strut tank and tip-tank installations tested give about the same drag increments at $C_L = 0 \cdot 2$ throughout the Mach number range. For this value of C_L and with $R = 2 \cdot 8 \times 10^6$, the increase in cruising drag ($M = 0 \cdot 88$) is about 20 lb at 100 ft/sec for 2 tanks, full-scale. The loss in top speed is considerable, *e.g.*, the reduction in the Mach number corresponding roughly to the wing drag coefficient at top speed is about $0 \cdot 05$. Particularly at high Mach number, the strut tank gives the larger increase in drag at lower values of C_L, *e.g.*, by 8 lb for $C_L = 0 \cdot 1$, $M = 0 \cdot 88$.

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* This is given closely by the change in the value of $(-\partial C_m/\partial C_L)_M$ about the c.g.

Tip installations, in general, suffer from the consequent effects of changes in aircraft c.g. and neutral point, *e.g.*, with the present arrangement, the manoeuvre margin is reduced by about 0·05, tanks full or increased by about 0·04, tanks empty—the latter change occurring when the tanks are jettisoned.

The present tip arrangement has two other important disadvantages:

(*a*) Buffeting may be present in flight at high Mach numbers and at moderate C_L values and possibly even under cruising conditions. This conclusion is supported by American flight experience.

(*b*) The basic wing performance is not quite restored after the tanks have been dropped owing to the substitution of a square for a curved tip, *e.g.*, there is a loss of top-speed Mach number of about 0·01.

Some suggestions are made in section 6.1.7 for designing a better tip installation that does not possess these two disadvantages and which would give smaller drag increments at moderate values of C_L. It seems that with existing swept aircraft designs, the tank should be moved downwards if possible. A better performance would be obtained if the wing itself were designed to have straight isobars over the tip sections. The inherent c.g. problem would still remain.

The under-wing strut arrangement could probably also be improved and suggestions for this are made in section 6.1.5. This forms the subject of Part II for this report.

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* Material from Refs. 3, 7, 12 and 13 is included in R. & M. 2908.

TABLE 1

Model Dimensions

	Curved leading-edge tip	*Square tip*
Half wings		
Section	RAE 101	
Thickness/chord ratio	0·10	
Sweepback: leading edge	43·9 deg	
quarter-chord line	40 deg	
trailing edge	25·3 deg	
Span (gross)	31·50 in.	30·34 in.
Centre-line chord	25·68 in.	
Root chord	24·02 in.	
Tip chord	—	10·89 in.
Mean chord (gross)	17·81 in.	18·29 in.
Aspect ratio (gross)	3·53	3·32
Taper ratio (gross)	—	2·36
Area (gross)	3·90 sq ft	3·85 sq ft
Area (net)	3·31 sq ft	3·27 sq ft
Tank		
Cross-sections—circular		
Fineness ratio	8·0	
Length	25·35 in.	
Maximum diameter	3·16 in.	
Length of ellipsoidal nose	9·51 in.	
Length of central cylindrical portion	4·24 in.	
Length of rear portion	11·60 in.	
Tank mounted on strut		
Distance outboard of centre-line	—	16·46 in.
Distance of nose aft of leading edge centre-line chord	—	7·16 in.
Wing chord at strut position	—	17·65 in.
Incidence relative to wing chord	—	— 1·5 deg
Strut		
Thickness/chord ratio	—	0·085
Chord	—	4·24 in.
Sweepback	—	0 deg
Minimum distance between tank and wing surface	—	2·70 in.
Exposed length of strut centre-line tank mounted	—	2·84 in.
Exposed length of centre-line in strut alone test	—	5·54 in.
Distance of leading edge behind local wing leading edge	—	0·82 in.
Tank mounted on tip		
Distance outboard from centre	—	31·92 in.
Distance of nose behind leading edge, centre-line chord	—	21·66 in.
Incidence relative to wing chord	—	0 deg

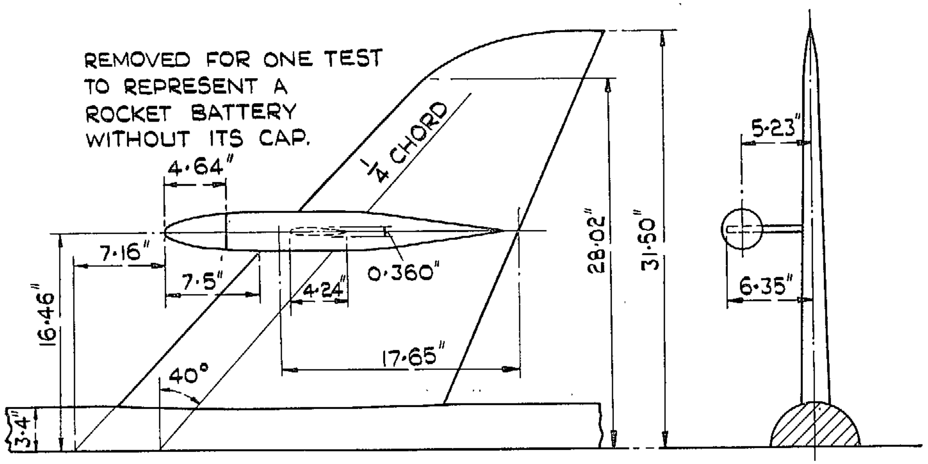


FIG. 1a. Wing (curved tip) with strut tank.

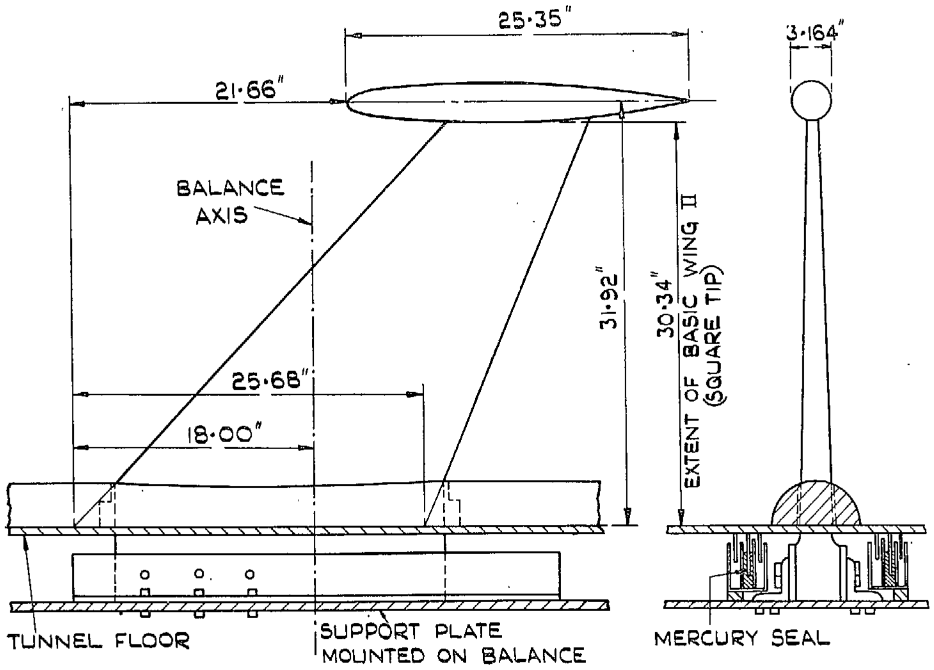


FIG. 1b. Wing (square tip) with tip tank.

FIGS. 1a and 1b. General arrangement of strut and tip-tank installations.

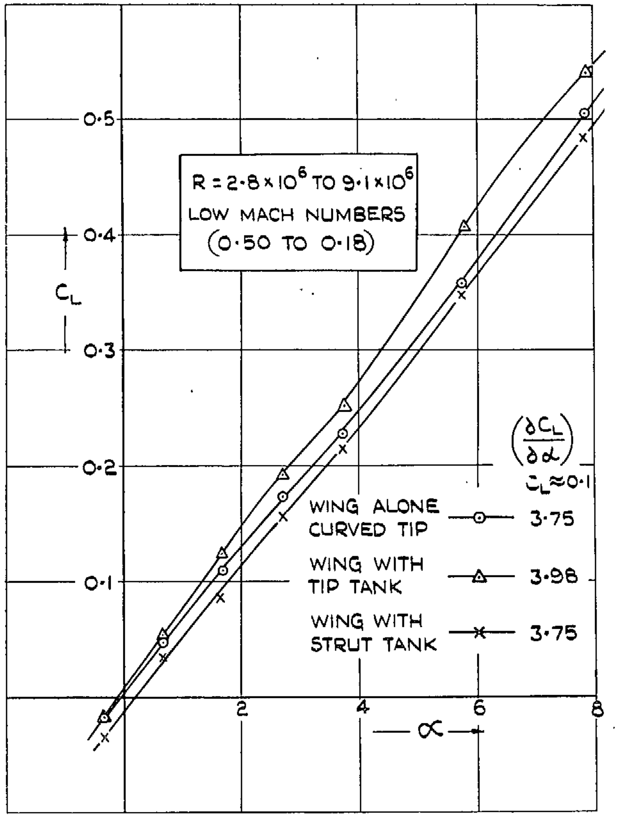
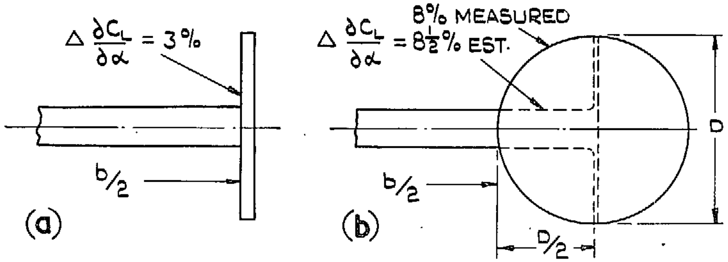


FIG. 2. Lift curves at low Mach number: mean of four Reynolds numbers.



FIGS. 3a and 3b. Wing tip with endplates and tank.

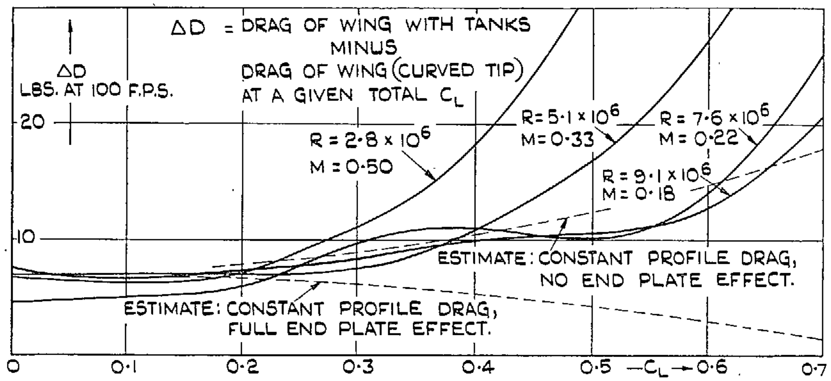


FIG. 4. Drag increment due to two 150-gallon tip tanks: effects of Reynolds number and lift at low Mach numbers.

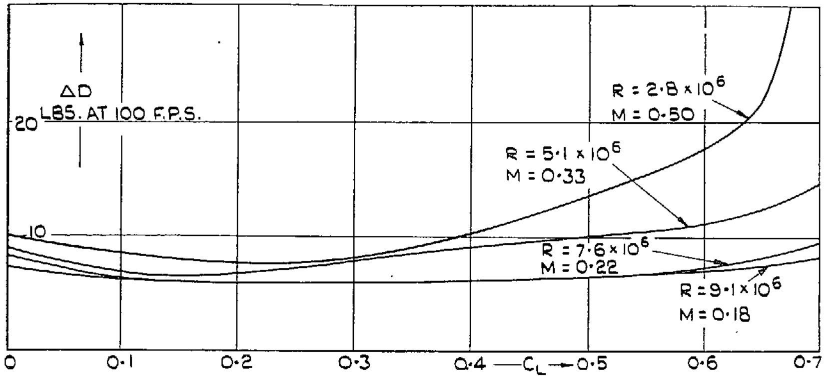


FIG. 5. Drag increment due to two 150-gallon strut tanks: effects of Reynolds number and lift at low Mach numbers.

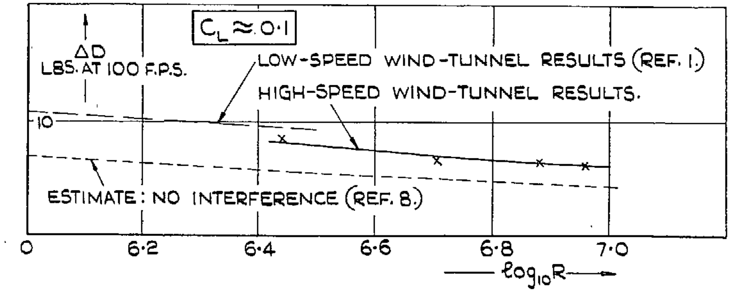


FIG. 6. Drag increment due to two 150-gallon strut tanks: comparison of results with those from low-speed wind tunnels.

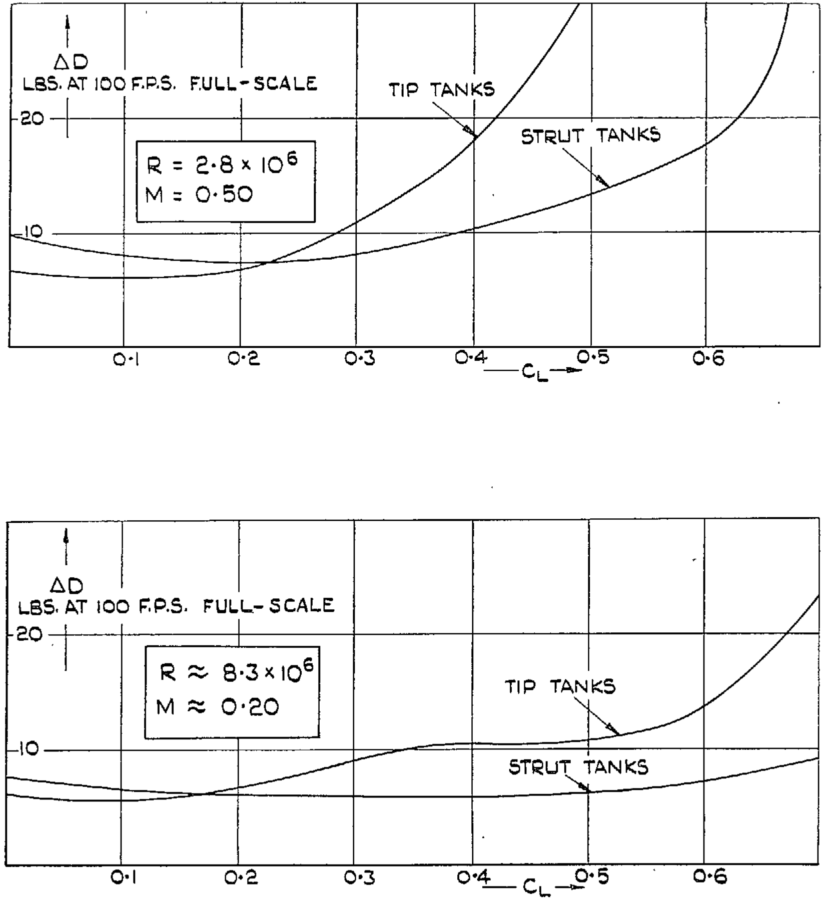


FIG. 7. Comparison of drag increments due to tip and strut tanks for two Reynolds numbers at low Mach number.

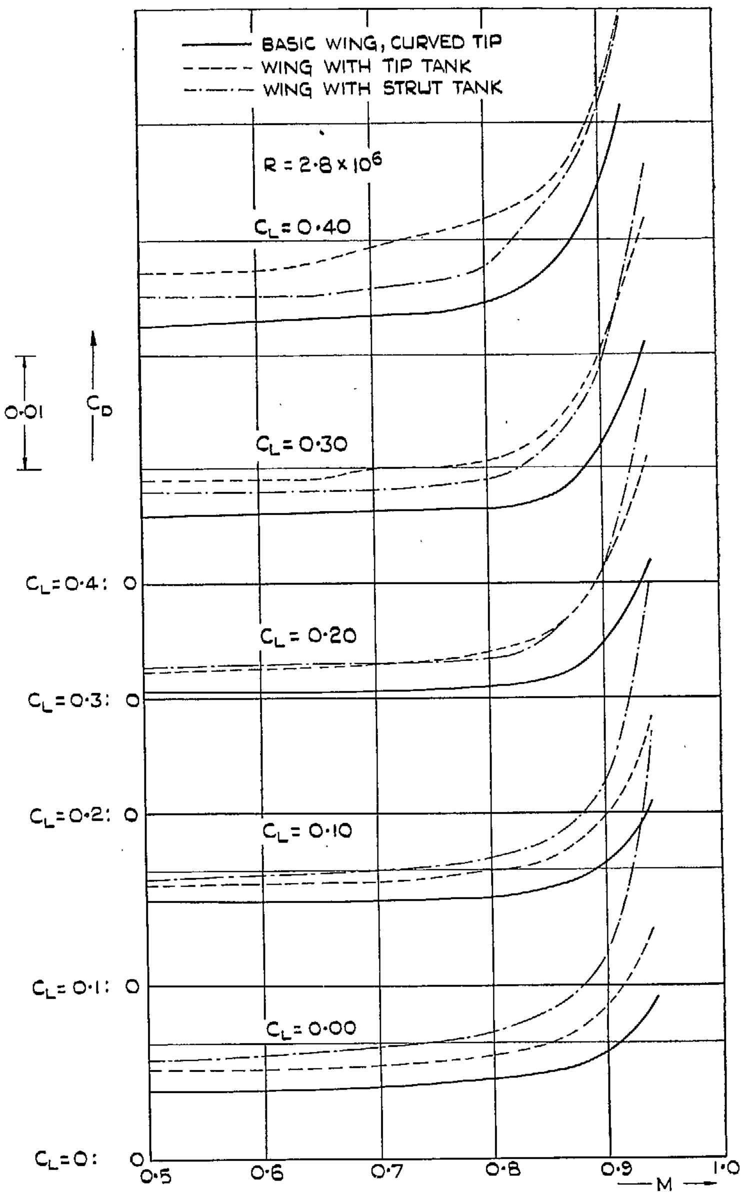


FIG. 8. Drag coefficient against Mach number for basic wing alone and with strut and tip tanks.

ΔD = DRAG OF WING WITH TANKS INSTALLED MINUS DRAG OF THE BASIC WING WITH CURVED LEADING-EDGE TIP.

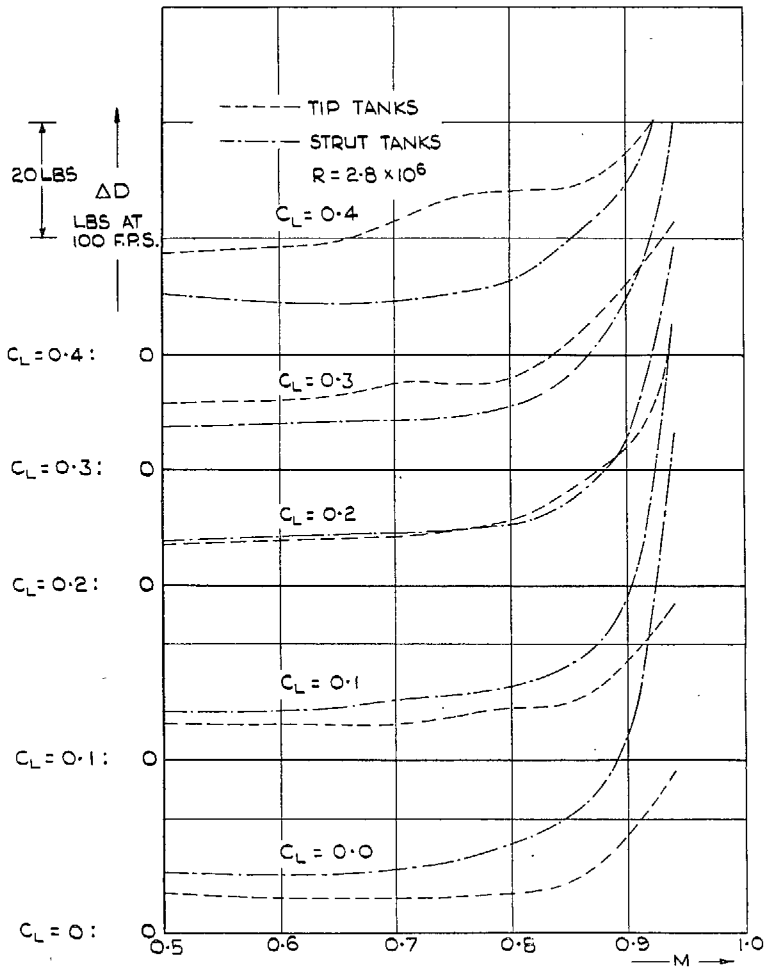


FIG. 9. Variation with Mach number of the drag increment due to two 150-gallon tanks.

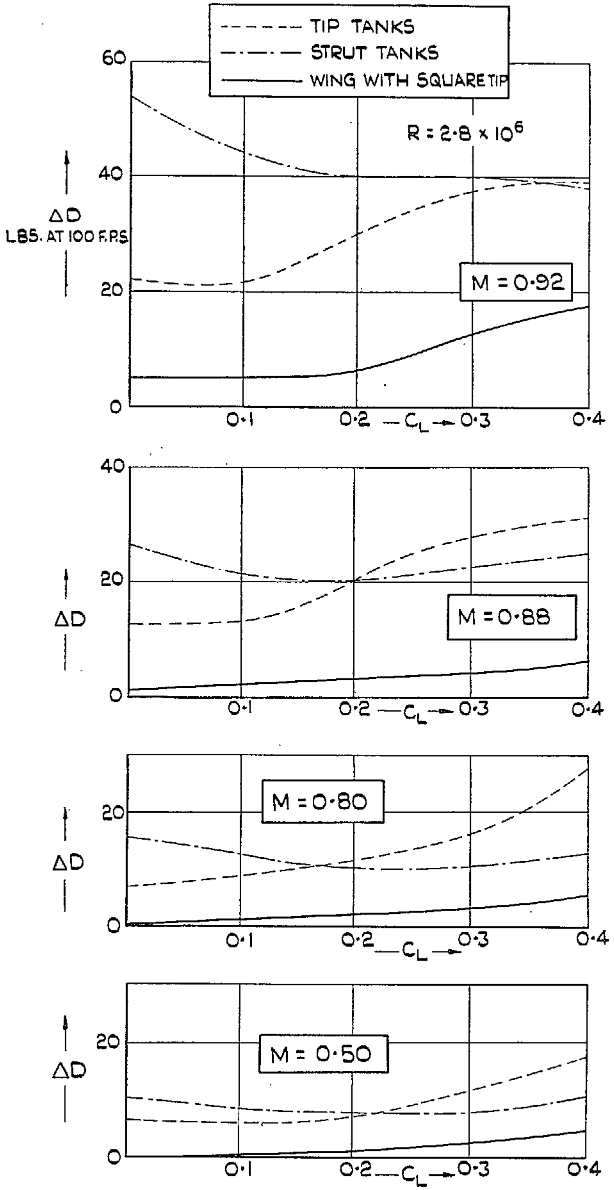


Fig. 10. Variation with lift coefficient of the drag increment due to two 150-gallon tanks.

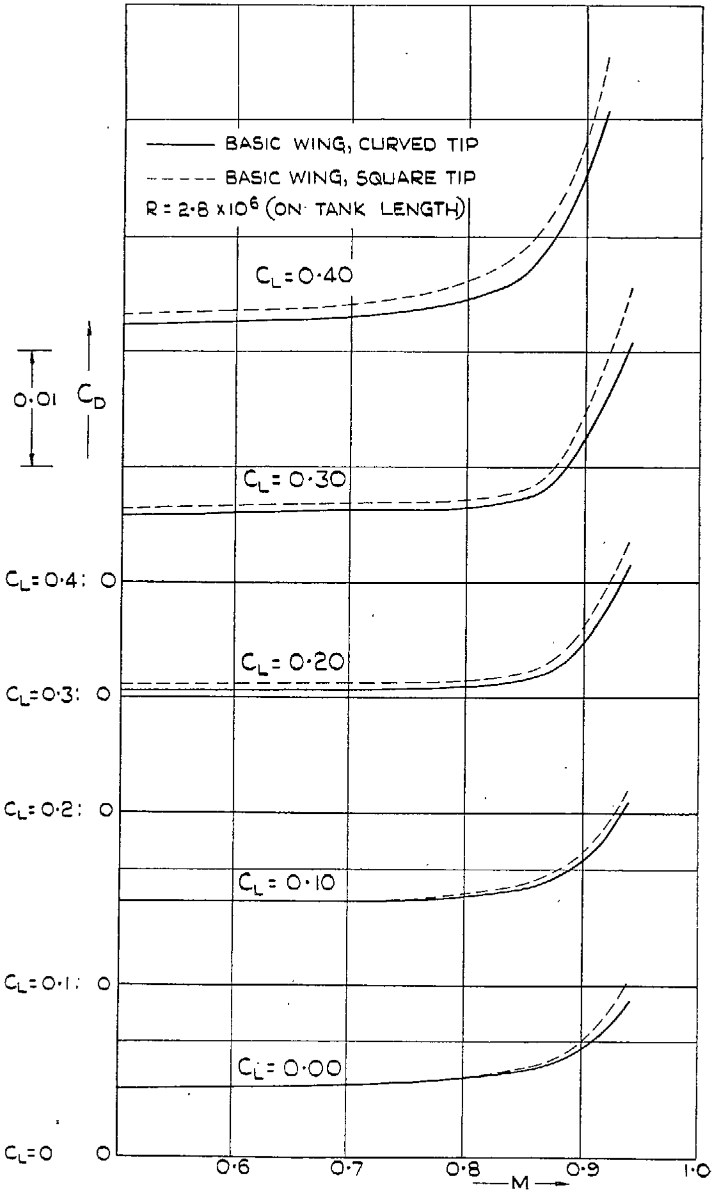


Fig. 11. Drag coefficient against Mach number for the two basic wings.

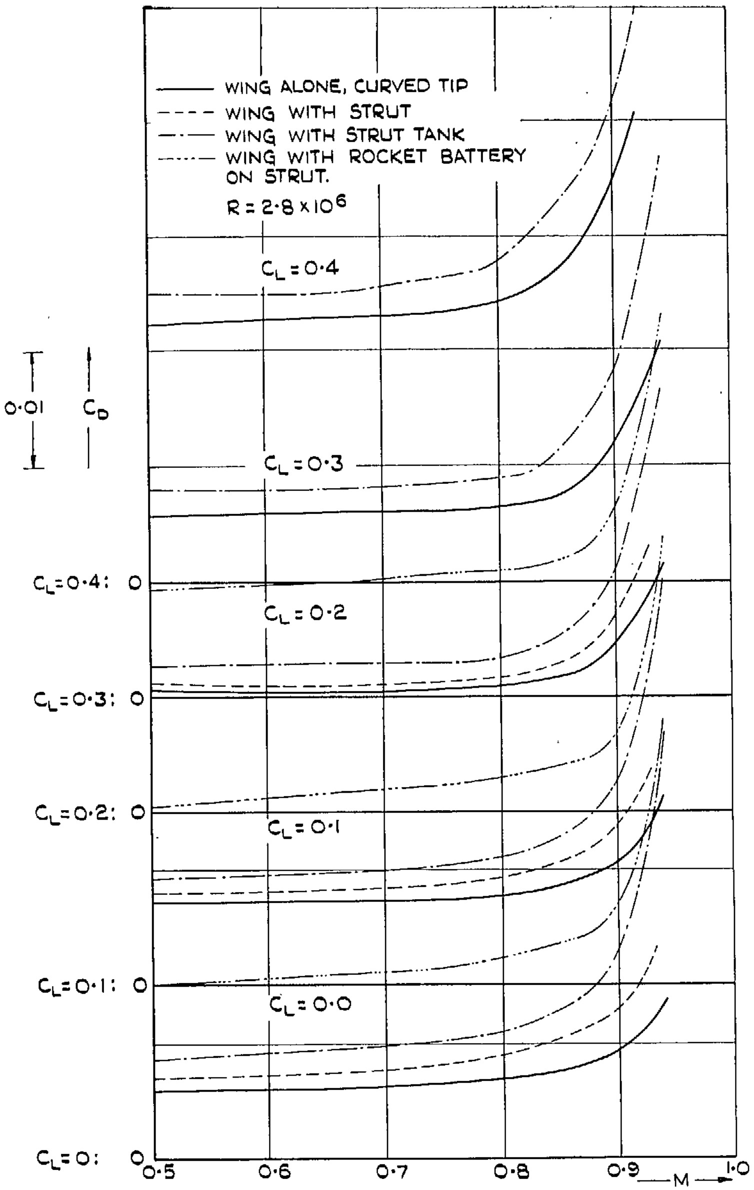


FIG. 12. Drag coefficient against Mach number for wing alone, wing with strut, wing with strut tank and wing with rocket battery on strut.

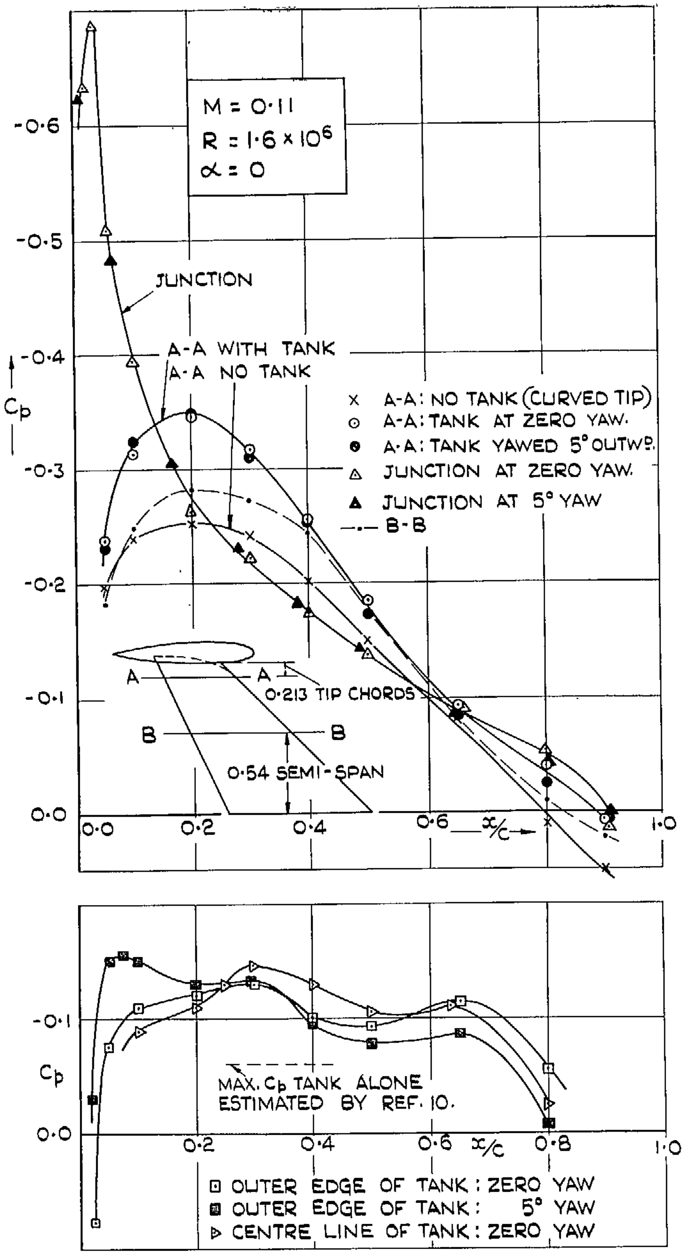


FIG. 13. Pressure measurements at low Mach number on basic wing and wing with tip tank.

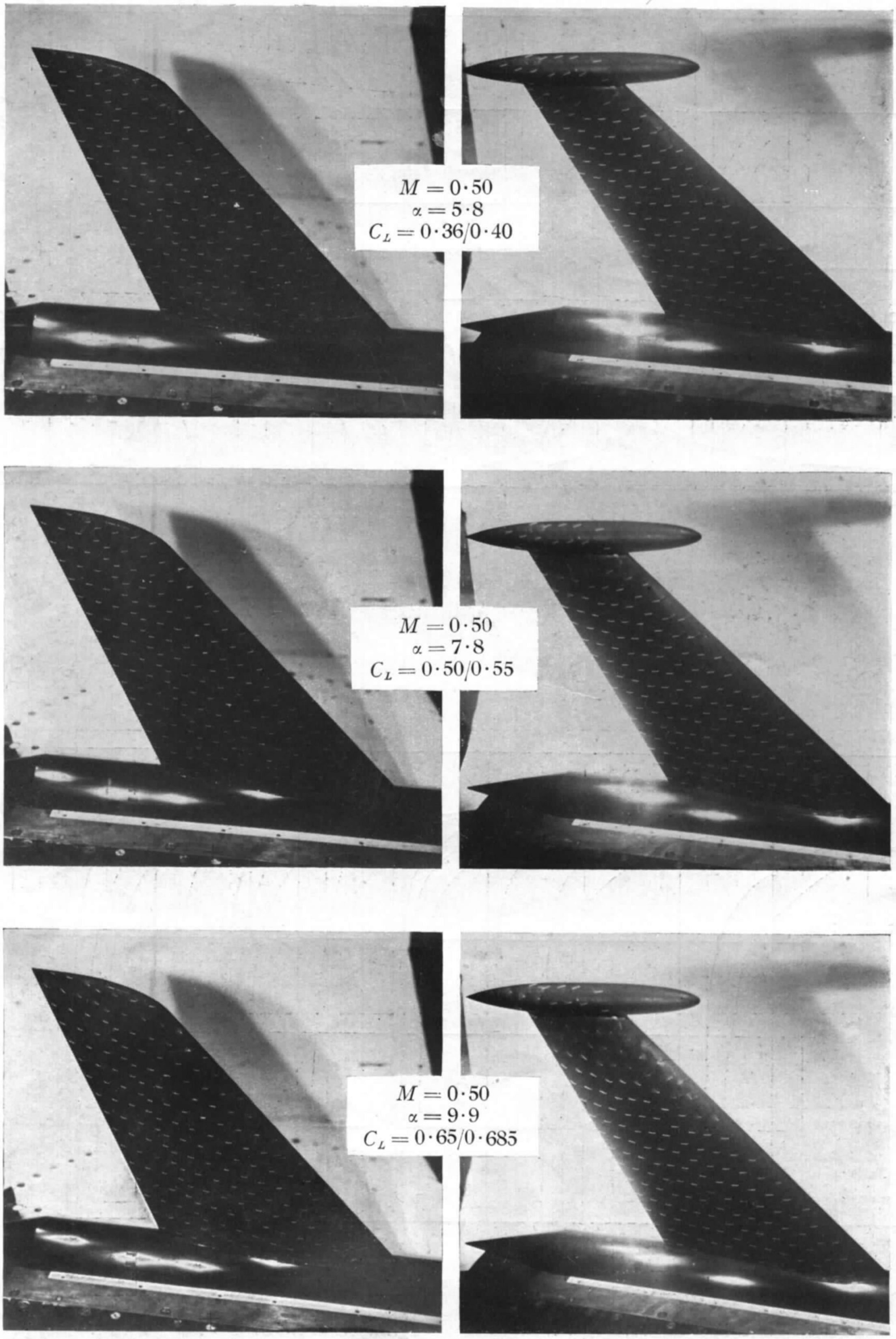


FIG. 14a. Effect of tip tank on flow over wing tip sections as shown by surface tufts. $M = 0 \cdot 5$, $R = 2 \cdot 8 \times 10^6$.

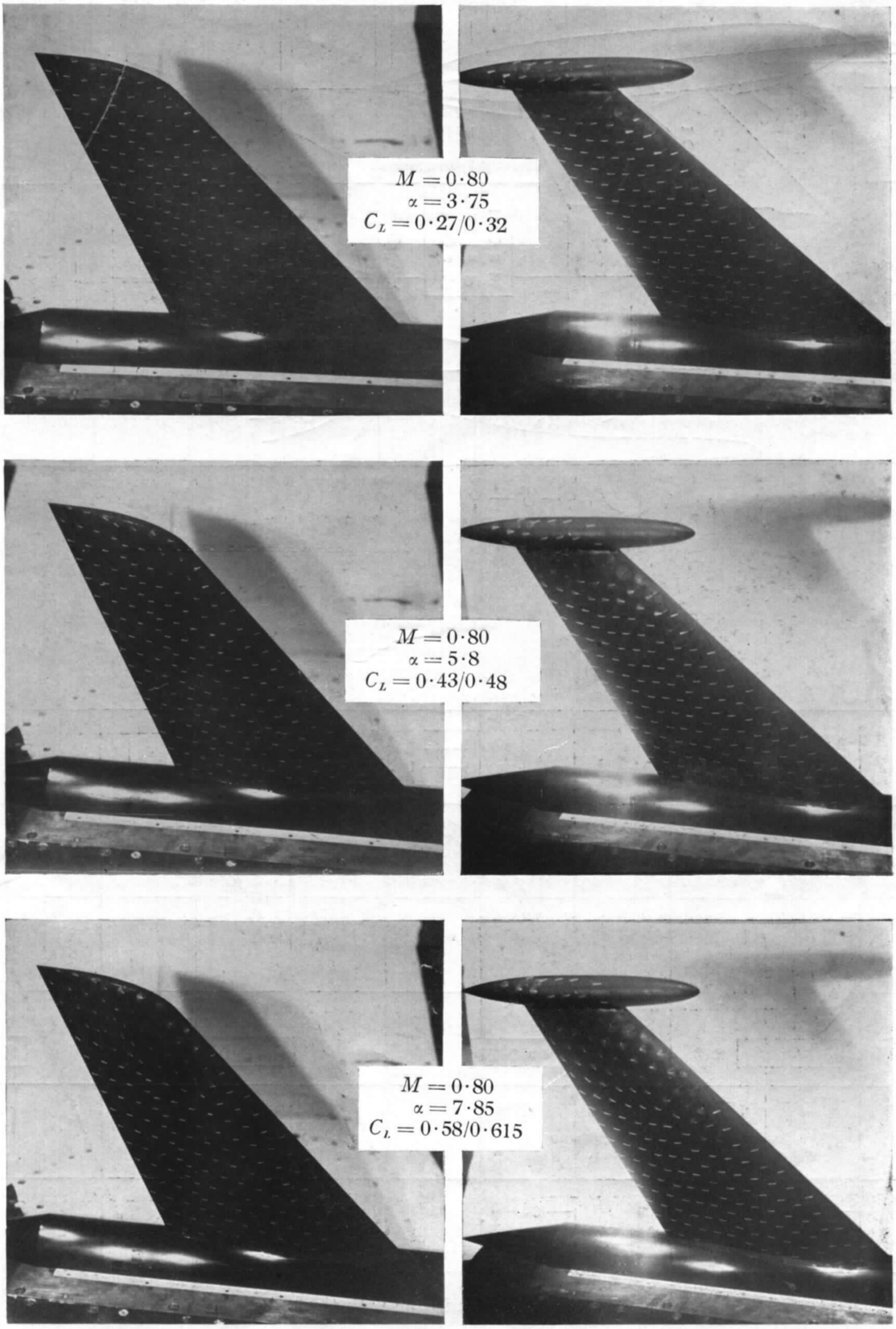


FIG. 14b. Effect of tip tank on flow over wing tip sections as shown by surface tufts. $M = 0\cdot8$, $R = 2\cdot8 \times 10^6$.

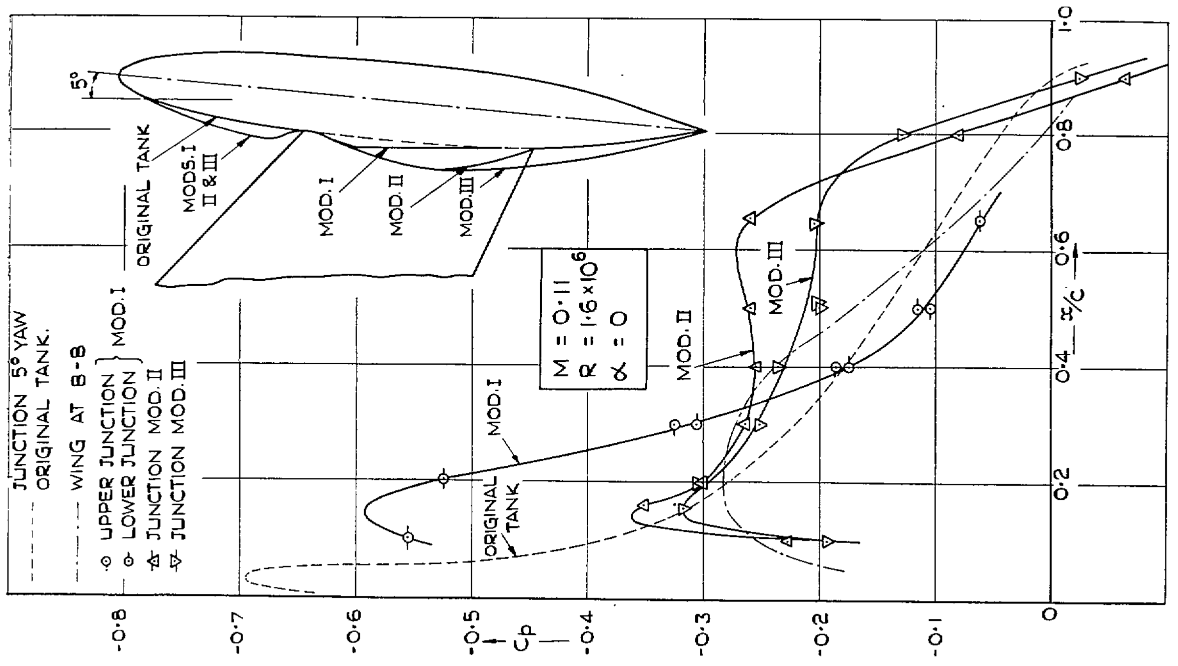


Fig. 15. Effect of modifications to tip-tank shape on junction pressure distribution at low Mach number.

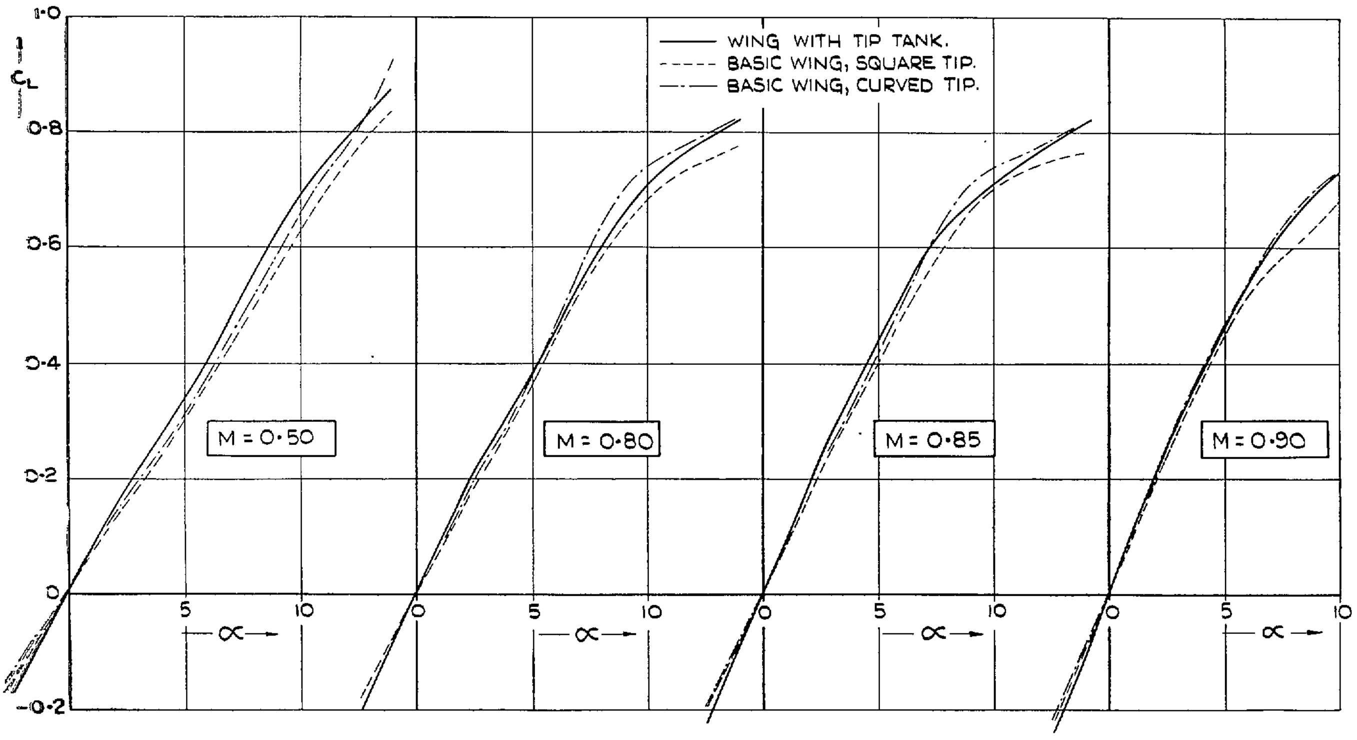


Fig. 16. Lift curves for basic wings and wing with tip tank. $R = 2{\cdot}8 \times 10^6$.

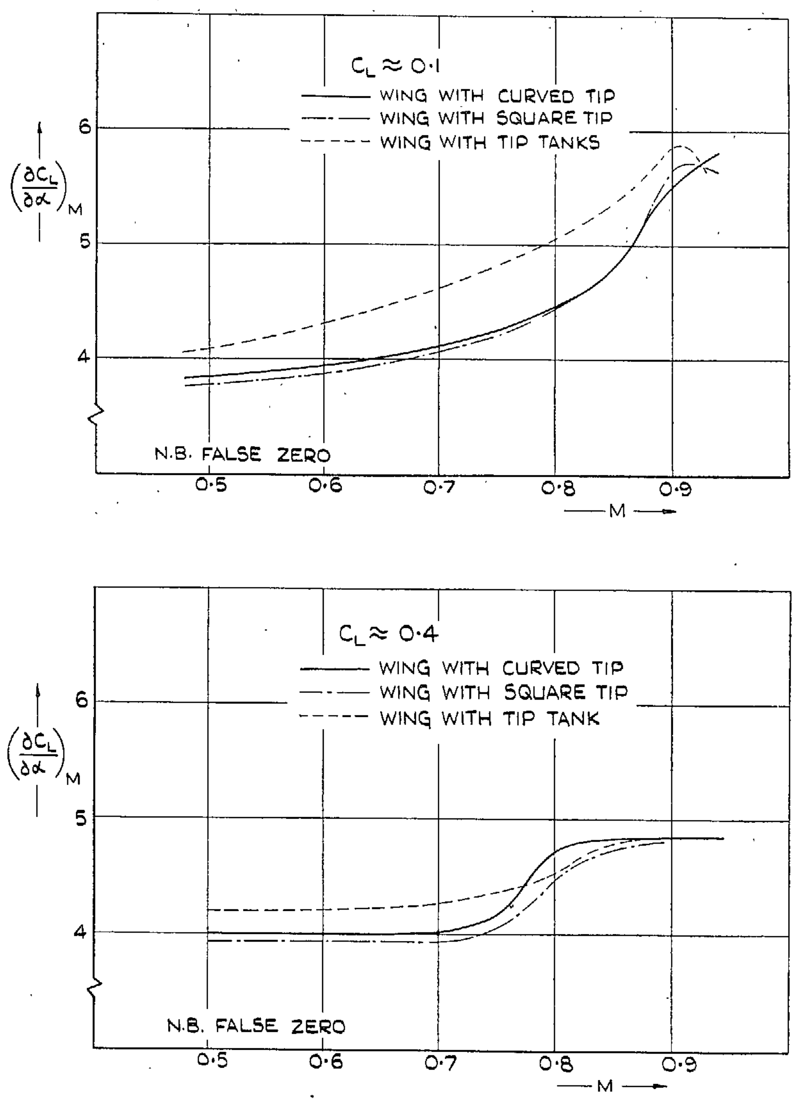


FIG. 17. Lift-curve slopes for wing alone and wing with tip tank. $R = 2{\cdot}8 \times 10^6$.

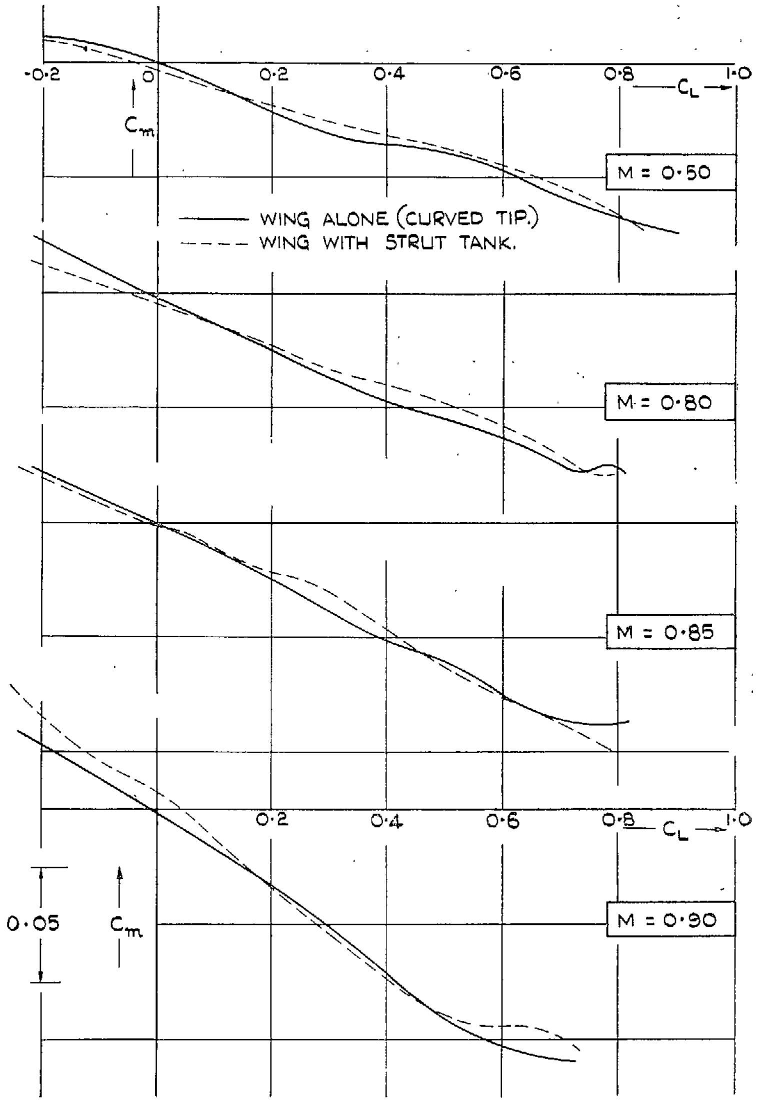


FIG. 18. C_m vs. C_L curves at constant Mach number for wing alone and with strut tank. $R = 2{\cdot}8 \times 10^6$.

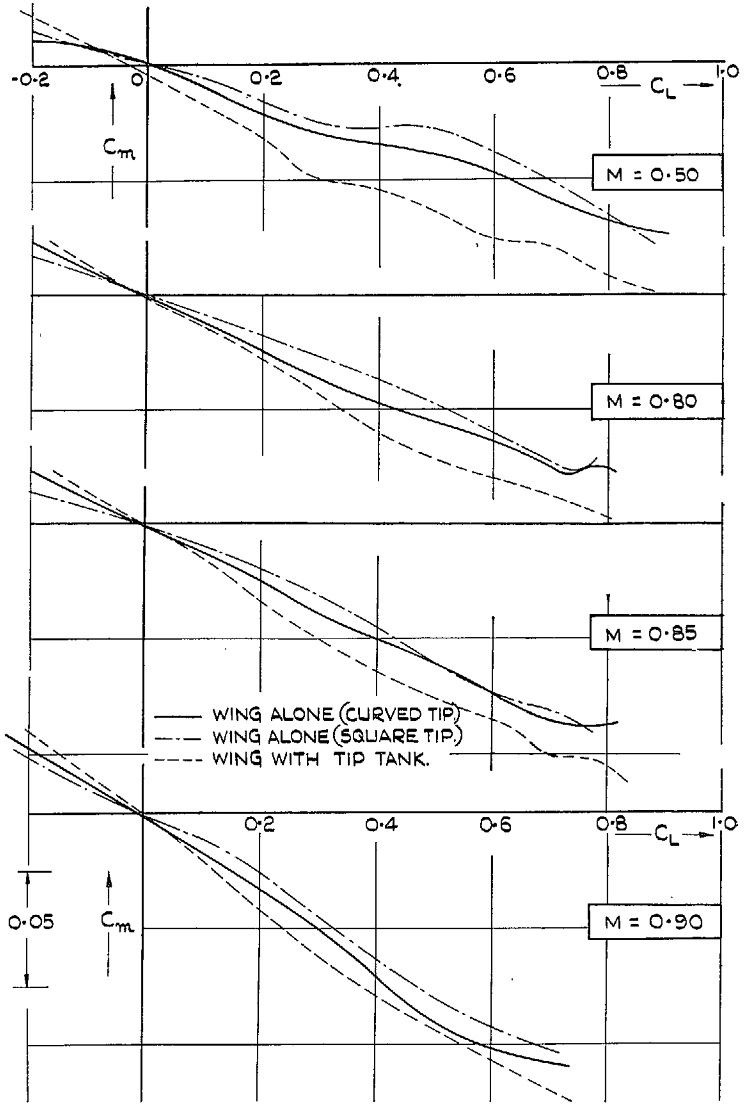


FIG. 19. C_m vs. C_L curves at constant Mach number for basic wings and wing with tip tank. $R = 2 \cdot 8 \times 10^6$.

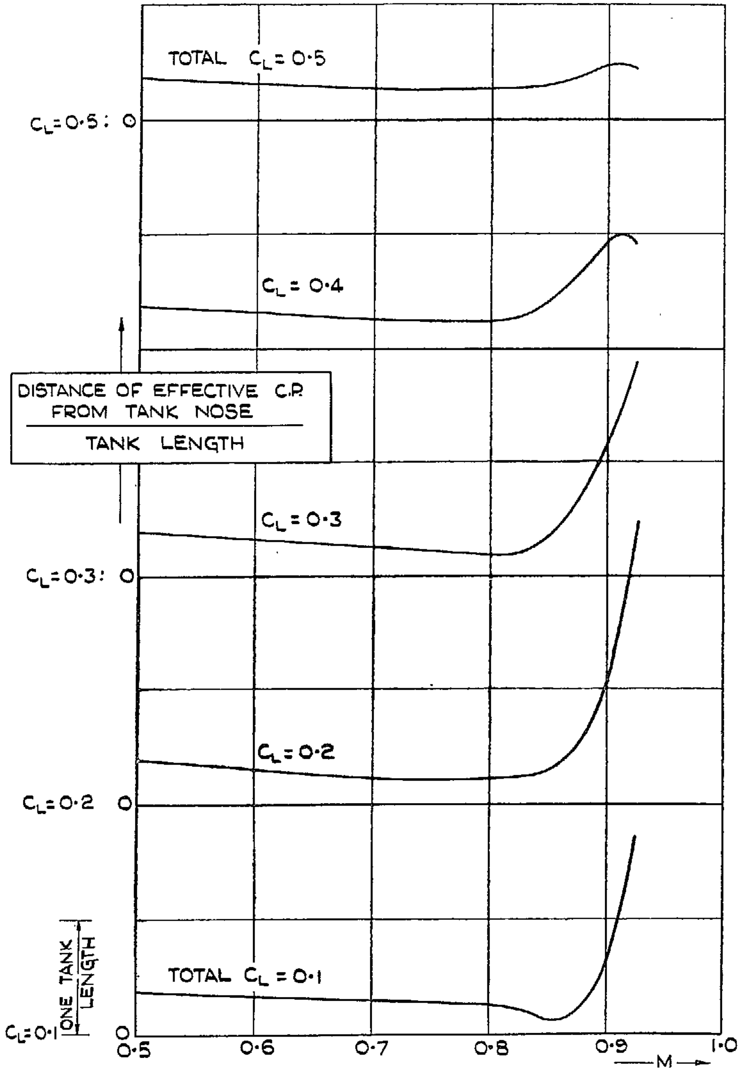
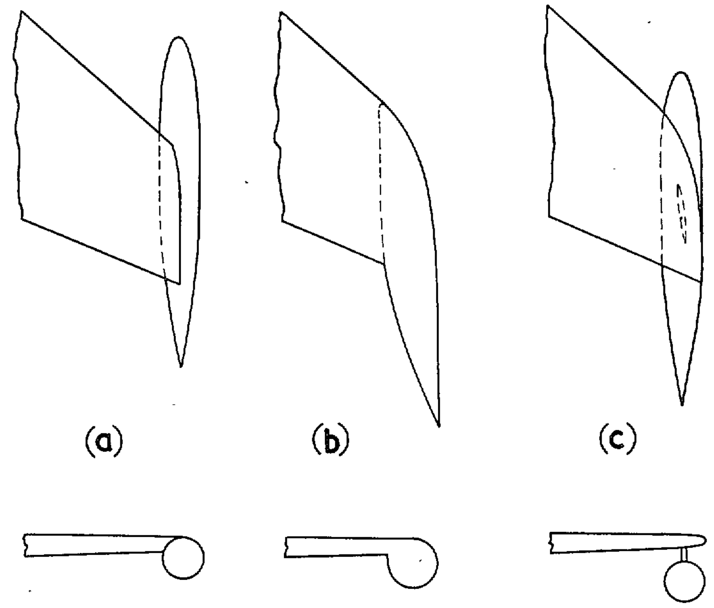


FIG. 20. Variation with Mach number of the position of the effective centre of pressure of the tip tank. $R = 2 \cdot 8 \times 10^6$.



IN(b) TANK NOT INTENDED TO BE JETTISONABLE.

Fig. 21. Suggestions for tip installations.

PART II

Comparison of Various Under-wing Drop-Tank Arrangements

By

Staff of R.A.E. High Speed Wind Tunnel*

1. *Introduction.*—The results given in Part I showed that the performance of a 40-deg swept-back wing was seriously affected at high Mach numbers by the addition of a drop tank supported on a strut below the wing at about mid-semi-span. Although these results were considered fairly representative, they applied strictly only to the particular arrangement tested. It was thought that some improvement might be achieved by detailed changes in design but that to obtain a really satisfactory result, a radical change such as dispensing with the strut would probably be required.

Tests have since been made in the R.A.E. 10-ft × 7-ft High Speed Wind Tunnel on another four under-wing drop-tank arrangements for wings having 40-deg sweep on the quarter-chord line. The first of these arrangements is basically similar to the strut-support design tested earlier but differs from it in various detailed respects ; in the second, the single strut is replaced by three smaller struts ; while in the other two schemes the strut is eliminated completely and the tank is fitted directly on to the wing lower surface like an underslung nacelle. These last two arrangements differ merely in the shape of the intersection line between the tank and the wing lower surface

The results with all five under-wing installations are compared here, the results for the original scheme being repeated briefly for the sake of convenience. The measurements on the new single-strut arrangement include not only the effects on overall performance but also the normal force and pitching moment on the tank itself. These data are needed to confirm or otherwise the semi-empirical rules which have generally be used for stressing purposes.

2. *Description of the Models.*—Two half-model wings were used for these tests. One wing is the same as that used for the tests reported in Part I while the other only differs from the first in that its thickness/chord ratio is 0·085 rather than 0·10. The principal dimensions of the wings are given in Table 1. The thinner wing was made of compressed wood. Details of the models and their mounting were otherwise as in Part I.

All the model tanks tested were to about 1/7th scale, if it is assumed that the full-scale tanks were fitted to an aircraft wing of about 35-ft span. The capacity of the full-scale tanks was not the same in all cases, as indicated below. The principal dimensions of all the tanks and supporting struts are given in Table 1 and the ordinates of the tanks in Table 2.

The two tanks supported by a single strut were fitted to the 10 per cent thick wing. These tanks are shown as A and B in Fig. 1 ; the results on tank A were given previously in Part I. For tanks A and B, the strut was mounted at 0·52 of the wing semi-span with its centre-line at 0·167 of the local wing chord behind the leading edge; the strut thickness/chord ratio was 8·5 per cent and the strut chord was 0·24 of the local wing chord. Both tanks had a fineness ratio of 8 : 1. The principal differences between the two arrangements were:

(*a*) length of strut: the minimum gap between the tank and lower wing surfaces was only $0{\cdot}08c$ for tank B, compared with $0{\cdot}13c$ for the original tank A, where c is the local wing chord

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* The tests were made by L. N. Holmes, D. E. Hartley and K. W. Newby, and this part of the report was written by A. B. Haines.

(*b*) size of tank: assuming that the models were about 1/7th full-scale, the full-scale capacity of tank A would be 150 gallons and, to the same scale precisely, tank B would have a capacity of 114 gallons

(*c*) shape of tank: both tanks have a parallel cylindrical portion inserted in the basic ellipsoid but this ellipsoid is 5·4 : 1 for tank B compared with 6 : 1 for tank A

(*d*) since the nose of each tank was placed the same distance ahead of the leading edge of the local chord, the tail of tank B is about 0·15*c* farther forward than that of tank A.

Tank C (Fig. 1, Table 2) was held by three small struts to the 8·5 per cent thick wing. This arrangement is partly in accordance with a suggestion made in Part I. All three struts are tapered with their smaller chord at the wing end, so reducing the area of contact with the wing in an effort to prevent serious distortion of the isobar pattern on the wing lower surface. The principal dimensions of the scheme are given in Table 1 but certain features should be noted in particular. For example, the thickness/chord ratio of the very small front struts varied from 21·6 per cent at the tank end to 31·2 per cent at the wing end; their section was basically rectangular with rounded leading and trailing edges. The rear strut was 15 per cent thick and its centre-line was at 0·535*c* behind the wing leading edge. The tank had a fineness ratio of 6·25 : 1; it again had a parallel portion but was not symmetrical fore-and-aft. Model C represents a tank with a full-scale capacity of only 90 gallons.

The two nacelle-type tanks (D and E, Fig. 2) were tested on the 8·5 per cent thick wing. The junctions of tank E with the wing lower surface were shaped to follow the estimated streamline over the wing at zero incidence at $M = 0{\cdot}9$. The junction shape was not quite the same as for the tank tested at low speed because of the different wing-section shape. The junctions of tank D were symmetrical about the free-stream direction, and hence tank D would be simpler to manufacture than tank E. Both tanks also differed from those tested at low speed in the direction of the knife edge at the rear; in the present tests, the intersection with the lower surface of the wing was at right-angles to the free-stream direction. Models D and E both represent 90-gallon tanks.

All the tanks were made of teak with a Phenoglaze finish. All the struts were made of steel except for the rear strut of scheme C, which was made of Tufnol.

3. *Details of Tests and Corrections Applied to Results.*—The tests were made at a Reynolds number of 2×10^6, based on the wing mean chord; based on the length of tank, the Reynolds number varied from $2{\cdot}8 \times 10^6$ for A to 2×10^6 for E. The Mach number was varied from 0·5 to 0·93 or 0·94.

Lift, drag and pitching moment were measured by the mechanical balance. Their coefficients have been based on the net wing area since the forces measured did not include those on the body.

In the case of tank B, the normal force and pitching moment on the tank itself was measured by a strain-gauge balance mounted inside the tank. The coefficients have been based on the tank maximum frontal area and tank maximum diameter. The tank pitching-moment coefficients are given about an axis 0·49 of the tank length aft of the nose.

In all cases, transition was fixed on the tanks at either 0·15 or 0·2* of tank length behind the nose of the tank. In general, transition was not fixed on the wing except for one test with tank D when it was fixed at 0·1*c*. This point should be important only for the nacelle tanks (*see* the discussion below in section 5).

Corrections were applied to the results for blockage and to the drag to allow for tunnel constraint and sidewash.

The tests were made in March, 1950, February, March and July, 1951, and February, 1952.

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* 0·2 for tank B only.

4. *Performance with Strut-supported Drop Tanks.*—4.1. *Single-strut Arrangements* (*A*, *B*).—C_D vs. M curves at constant C_L for the 10 per cent thick wing with and without the two single-strut tank arrangements A and B are given in Fig. 3. The drag increments due to the tanks expressed as lb drag full-scale for 2 tanks at 100 ft/sec E.A.S. are plotted against Mach number at constant C_L in Fig. 4 and against C_L at constant M in Fig. 5.

The most significant differences between the results for the two installations occur at high C_L where the new arrangement B is superior. The improvement is most marked at high Mach number, *e.g.*, for $M = 0{\cdot}88$ (a typical cruising Mach number for an aircraft with this wing design), the drag increment for $C_L = 0{\cdot}3$ is reduced from over 22 lb for A to only 14 lb for B. It seems that the increase of ΔD with C_L at moderate values of C_L which was found with tank A has been eliminated or postponed to a higher value of C_L. It was explained in Part I that this effect was associated largely with a reduction in the overall C_L at a given incidence and hence may be caused by the tank having a spoiling effect on the flow over the lower surface of the wing. If this is so, then the factor that has probably given the improvement with arrangement B, is the further forward position of the tail of the tank relative to the wing (Fig. 1). The other changes in design listed in section 2 including the change in the length of the strut have probably only a secondary influence.

At low C_L and for Mach numbers below about $0{\cdot}8$, the drag with arrangement B is slightly higher than with A, despite the reduction in size of both the tank and the strut. This is presumably because at low C_L, the tank is in a region of higher local velocities with arrangement B (short strut) and also because of increased mutual interference effects. However, even at low C_L, the variation of the drag increment with Mach number is rather less for B. Hence the small disadvantage present at low speeds has disappeared by the cruising Mach number of $0{\cdot}88$ and at higher speeds there is a gain in performance with B.

Summarizing the relative performance, it seems that arrangement B would be definitely superior for say, a bomber cruising at values of C_L of the order of $0{\cdot}3$ and would also be slightly better than A for the case of a high-speed fighter cruising near $C_L = 0{\cdot}2$: the drag increment under cruising conditions would be about 17 lb rather than 20 lb and the drag divergence Mach number would be almost exactly the same in the two cases.

Neither installation had any serious effect on the C_m vs. C_L curves and so these are not reproduced. Addition of either tank results in a forward shift of the aerodynamic centre of about $0{\cdot}01\bar{c}$.

4.2. *Three-strut Arrangement* (*C*).—The drag increments with the three-strut arrangement (C) are also given in Figs. 4 and 5, and the C_D vs. M curves at constant C_L for the wing alone and with tank are shown in Fig. 6.

For Mach numbers below $0{\cdot}92$, the measured drag increment with this arrangement (C) is appreciably higher than for either of the single strut schemes (particularly remembering that tank C represents a capacity of only 90 gallons, compared with 150 gallons for tank A). This would not necessarily be true at flight Reynolds numbers since the present results on C are probably subject to serious scale effect because of the very low Reynolds number on the front struts. This is illustrated by the results at low speed: an additional test with tank C was made at $M = 0{\cdot}18$, $R = 3{\cdot}45 \times 10^6$ (based on the tank length) and the drag increments under these conditions are compared with those for $M = 0{\cdot}5$, $R = 2{\cdot}08 \times 10^6$ at the bottom of Fig. 5. At $C_L = 0$, for example, the value of ΔD decreases from 15 lb to 12 lb for the increase in Reynolds number from $R = 2{\cdot}08 \times 10^6$ to $R = 3{\cdot}45 \times 10^6$, whereas the estimated drag for the tank alone decreases from $4{\cdot}4$ lb to 4 lb. Hence the total strut plus interference drag decreases from about 230 per cent to 195 per cent of the tank drag. Even at the higher Reynolds number, the value of R for the front struts at the wing-end is only $0{\cdot}65 \times 10^4$ which is probably below the critical value. Hence it is not pessimistic to assume that the interference drag would at least decrease at the same rate as the Reynolds number is further increased up to say 10^7 on the tank length. The drag increment would then be only about $7{\cdot}5$ lb or about half that at $R = 2{\cdot}08 \times 10^6$.

For tank A, on the other hand, ΔD only decreases by about 2 lb for this change in Reynolds number (*see* Part I) and so, for a more realistic comparison between schemes A and C, the values of ΔD shown for C in Figs. 4 and 5 should be reduced by at least 5 lb.

Because of this general uncertainty regarding scale effect, it is not possible to make a sound quantitative assessment of scheme C in comparison with A and B. However, it appears that the drag increment increases with Mach number, particularly above $M = 0 \cdot 7$ and so the single-strut arrangements are probably superior up to about $M = 0 \cdot 85$ to $0 \cdot 88$. At the highest test Mach numbers, the three-strut support scheme gives the lower drag increments and these results apparently confirm the earlier suggestion that a scheme such as this would improve the high-speed performance because, with the smaller tapered struts, the interference to the isobar pattern over the wing lower surface is less serious. The increase in ΔD with Mach number at moderate Mach numbers may be caused by an increase in the interference effects at the low scale of the tests but it is more likely that it follows an early breakdown of flow near the rear strut-wing junction. This strut is 15 per cent thick and it is also fairly far back (near $0 \cdot 5c$) and so is in a region of relatively high local velocities at low values of C_L. Some support for this explanation is provided by the fact that the effect dies out with increasing C_L until, for $C_L = 0 \cdot 4$ (Fig. 6) the installation compares favourably with the single-strut schemes even if no allowance is made for any scale effect.

C_m vs. C_L curves for the wing with and without tank C are given in Fig. 7. Up to about $M = 0 \cdot 85$, there is a nose-up kink in the C_m vs. C_L curves with tank near $C_L = 0 \cdot 3$ so that at higher values of C_L, the tank installation contributes a nose-up moment. The explanation of this effect is not clear; however, it is possible that the apparent agreement at low values of C_L is coincidental, *i.e.*, that in the absence of any serious breakaway, the tank would give a nose-up moment as at high C_L but that this is modified at low C_L by the breakaway of flow which must be present in view of the large drag increments (Fig. 6). The characteristic may therefore again be subject to scale effects. With increasing Mach number above $M = 0 \cdot 85$, the effects of the tank on the C_m vs. C_L become less marked.

Summarizing, no definite judgment on this three-strut type of installation is possible until flight evidence is available. It seems probable, however, that to make it satisfactory it is important to keep the rear strut as thin and as far forward as possible.

5. *Performance with Nacelle-type Drop Tanks* (*D, E*).—The drag increments with the 'symmetrical' underslung tank D are given in Figs. 4 and 5. These values were obtained up to $M = 0 \cdot 9$ with transition fixed on the tank at $0 \cdot 15l$ and on the wing at $0 \cdot 1c$. The values quoted for Mach numbers above $0 \cdot 9$ are with transition free on both the wing and tank but as can be seen from the comparison in Fig. 9, fixing transition has little significant effect on the drag increments near $M = 0 \cdot 9$.

The drag increments at low speed are much lower than for the strut-supported installations and are in good agreement with those found for the streamline tank in the tests in the No. 1 11½-ft Wind Tunnel. Near $C_L = 0 \cdot 2$, the drag increment ΔD for 2 tanks at $M = 0 \cdot 5$ amounts to about 4 lb which is roughly the same as the estimated drag of the tanks alone, *i.e.*, the interference drag is negligible.

The increase in the drag increment with Mach number is also slower than for the strut-supported tanks—the really steep increase is delayed till near $M = 0 \cdot 9$, *i.e.*, to near the Mach number for the rapid drag rise on the wing alone (Fig. 8). At high Mach number, the drag increments are affected only slightly by C_L except below $C_L = 0 \cdot 1$; near $C_L = 0$, the values of ΔD are somewhat higher as would be expected.

The further effect resulting from shaping the junction between the tank and wing lower surface to follow the estimated streamline as with tank E is shown in Fig. 9. These comparative values of ΔD were obtained with transition free—this should not affect the comparison at high speeds (*cf.* the curves in Fig. 9 for the symmetrical tank). Up to $M = 0 \cdot 8$, there is no difference between the results for tanks D and E, but at higher Mach numbers tank E gives the lower drag increments. Again, as would be expected, the improvement is most noticeable near $C_L = 0$ and at $C_L = 0{\cdot}2$ it only amounts to 2 lb at the most, even at high Mach numbers.

Since the performance of the strut arrangements, particularly tank B, improves considerably with C_L, the relative advantage of these nacelle tanks is more marked for the case of a fighter flying at say, $C_L = 0{\cdot}15$ than for a bomber, cruising at say, $C_L = 0{\cdot}3$. A quantitative comparison may be slightly misleading because the nacelle tanks were fitted to a thinner wing but this should not affect the general picture which can be summarized in the table below, which refers to a representative value of $C_L = 0{\cdot}2$. For the purposes of this comparison, the values of ΔD are quoted for 100-gallon tanks in all cases. These values have been derived from the experimental results on the basis that the size of tank affects only the low-speed skin-friction drag of the tank alone, *i.e.*, that it has no effect within these limits (90 gallons to 114 gallons) on the interference drag or on the increase of drag with Mach number.

Arrangement	Tank B (Strut-supported)	D (Nacelle, symmetrical)	E (Nacelle, streamline)
ΔD for 2 × 100 gallon tanks, lb $M = 0{\cdot}85$ ..	13·4	8·5	7·9
$0{\cdot}90$ ..	21·2	12·7	10·7
Reduction in Mach number for $\Delta C_D = 0{\cdot}005$, wing alone.	0·052	0·027	0·022

[$M = 0{\cdot}90$ is probably a typical cruising Mach number for an aircraft with this 8·5 per cent thick wing.]

It seems therefore that the penalty at high speeds arising from fitting an under-wing drop tank can be decreased considerably by eliminating the strut and fitting the tank directly onto the wing lower surface. In practice, it may be considered that the further gain from shaping the junction as in E is not sufficient to justify the additional complication but this may not be true for a larger store, or for a store on a more highly tapered wing.

C_m vs. C_L curves for the wing alone and with tanks D and E are given in Fig. 10. The addition of the tanks results in:

(i) a nose-down change in C_{m0} of about 0·005

(ii) a forward shift of the neutral point of about $0{\cdot}02\bar{c}$ at moderate values of C_L for Mach numbers up to about 0·88

(iii) for Mach numbers up to about 0·85, an apparent improvement in the usable C_L of about 0·1, if this limit is set by longitudinal instability.

At high Mach numbers, *e.g.*, 0·90, the only effect of the tanks on C_m is a change of trim, corresponding to the change in C_{m0}.

6. *Normal Loads on a Strut-supported Tank* (*B*).—The variation of the tank normal force and pitching-moment coefficients with incidence is shown for the various test Mach numbers in Figs. 11 and 12. These results can be related to the overall C_L by means of the C_L vs. α curves given in Fig. 13.

The results at $M = 0{\cdot}5$ are shown to be in good agreement, particularly as regards pitching moment (Fig. 12) with values deduced from the low-speed pressure-plotting measurements reported in Refs. 1 and 2. The latter values were derived from the results on the '8 : 1 inboard central' arrangement of Ref. 1 which was similar to the present tank B except that the tank axis was parallel to the wing chord instead of being set at $-1{\cdot}5$ deg. It was assumed, on the basis of Ref. 2, that the effects of the change of setting on C_{NT} and C_{mT} are merely equivalent to the effects of this incidence on C_{NT} and C_{mT} for an isolated tank.

The changes in $C_{N\,T}$ with Mach number are less regular than those in $C_{m\,T}$ indicating, as would be expected, that the principal changes in the flow over the tank at high Mach number occur near the strut–tank junction, where the local M_{crit} is probably only about 0·75. Even by $M = 0 \cdot 80$ and to a greater extent at higher Mach numbers, both the upward load at low incidence and the downward load at high incidence are smaller than at low Mach number. This can be explained qualitatively as follows. As shown in Ref. 1, at low Mach number the upward force on the tank near $C_L = 0$ is mostly concentrated near the strut and the net decrease in load with incidence results from the fact that the load near and behind the strut decreases more than the increase occurring over the nose of the tank. At high Mach number, after the flow has become supersonic in the strut-tank junction, a shock-wave forms off the tank and moves back with increasing Mach number, being probably slightly farther back on the upper than on the lower surface. The local Mach numbers ahead of the shock would not increase on either surface above a value between about 1·4 and 1·5 and so the local lift on the tank near and just behind the strut would tend to disappear with increasing Mach number, thus producing the observed changes in $C_{N\,T}$.

In view of this evidence, it is clearly pessimistic to assume as in Ref. 3 that, for stressing purposes, the normal force, estimated for low Mach number, should be increased by a factor, such as $1/\sqrt{1 - M^2}$ for operation at high Mach number. The stressing criterion should rather be the low Mach number values themselves.

The values of $C_{m\,T}$ are less affected by the changes in flow near the strut-tank junction and depend more on the flow over the nose and tail of the tank and hence on the general flow field round the wing. Consequently, the variation of $C_{m\,T}$ with Mach number is fairly regular throughout the test range but, again, it cannot be expressed by a simple factor. A good approximation is afforded by the following semi-empirical rule : the value of $C_{m\,T}$ for $\alpha_T = 0$ deg should be assumed to vary as $1/\sqrt{(1 - M^2)}$* but $(\partial C_m/\partial \alpha_T)_M$ taken as independent of the Mach number.

The present results also help to show whether the conclusions obtained from jettisoning tests at low Mach number remain valid at high Mach number. The following table compares the values of $C_{N\,T}$ and $C_{m\,T}$ at $M = 0 \cdot 5$ and $0 \cdot 9$ for $C_L = 0 \cdot 1$ and $0 \cdot 2$:

M	$C_L = 0 \cdot 1$		$C_L = 0 \cdot 2$	
	$C_{N\,T}$	$C_{m\,T}$	$C_{N\,T}$	$C_{m\,T}$
0·5	0·04	−0·46	−0·03	−0·16
0·9	0·03	−0·87	0·04	−0·72

The nose-down moments on the tank at a given C_L are appreciably larger at high Mach numbers and so the moment required from jettison fins will also be greater. This conclusion should apply generally to any fairly similar single strut arrangement since it is not closely associated with the flow conditions in the strut-tank junction.

7. *Conclusions of Part II.*—The underslung-nacelle tanks are markedly superior to the strut-supported arrangements, particularly at low values of C_L, and their advantage increases with Mach number. For a typical cruising C_L ($M = 0 \cdot 9$, $C_L = 0 \cdot 2$), the drag increment for two tanks full-scale at 100 ft/sec is 12 lb (symmetrical junctions) or 10 lb (streamline junctions) compared with 22 lb for the best strut arrangement. The reduction in the drag divergence Mach number is of the order of 0·025 for the nacelle-type tanks, compared with 0·05 for the strut-supported tanks. The essential features are the elimination of the strut and the adoption of the

---

* This seems reasonable because, for $\alpha_T = 0$ deg, $C_{m\,T}$ is associated principally with the loading over the front part of the tank and the local velocities due to the wing should vary in this region roughly as $1/\sqrt{(1 - M^2)}$.

faired shape; any further gain obtained from shaping the junctions to follow the streamline is probably not sufficient to justify the additional complication for the tank tested but this may not remain true for a larger store, or for a store on a more highly tapered wing.

From the measurements of normal force and pitching moment on the tank itself in scheme B, it follows that:

(i) the assumptions previously used to allow for compressibility effects were too severe: for stressing purposes, the low Mach number values of C_{NT} should be used and for C_{mT}, the value for $\alpha_T = 0$ deg should be scaled up by the factor $1/\sqrt{(1 - M^2)}$ and $(\partial C_{mT}/\partial \alpha_T)_M$ left independent of Mach number,

(ii) the nose-down pitching moments on the tank at low C_L, that have to be corrected for by jettison fins, increase appreciably with Mach number.

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No.	*Author*	*Title, etc.*
1	R. A. Fail and J. F. Holford ..	Preliminary note on low-speed tunnel model tests of pressure distribution and jettisoning of strut tanks on a 40-deg swept-back wing. R.A.E. Tech. Note Aero. 2095. A.R.C. 14,128. March, 1951. (Unpublished.)
2	J. F. Holford	Addendum to Technical Note Aero. 2095. Further pressure-plotting data. R.A.E. Tech. Note Aero. 2095b. A.R.C. 15,262. (Unpublished.)
3	N. K. Walker	The estimation of the aerodynamic loads on external stores. R.A.E. Tech. Note Aero. 1715. A.R.C. 9502. January, 1946. (Unpublished).

TABLE 1

Leading Dimensions of the Wings and Tanks

Wing Dimensions	
Gross area of wing (from centre-line chord to tip)	3·94 sq ft
Net area of wing (from root chord to tip)	3·355 sq ft
Centre-line chord	25·68 in.
Root chord	24·02 in.
Standard mean chord (gross wing)	18 in.
Span	31·5 in.
Aspect ratio	3·5
Taper ratio (with square tip)	0·4
Sweep-back of quarter-chord line	40 deg
Wing section	Symmetrical, RAE 101
Distance of pitching-moment axis aft of wing apex	18 in.

TABLE 1—*continued*

Tank Dimensions

	Tank A	*Tank B*	*Tank C*
Length	25·35 in.	22·68 in.	18·7 in.
Maximum diameter	3·17 in.	2·83 in.	1·50 in.
Fineness ratio	8 : 1	8 : 1	6·25 : 1
Capacity (full-scale)	150 gallons	114 gallons	90 gallons
Incidence of tank relative to wing chord	—1·5 deg	—1·5 deg	—1·5 deg

Struts for Tanks A and B

Spanwise distance of chord of struts from centre-line of wing	16·46 in.
Wing chord at strut position	17·65 in.
Chord of strut	4·24 in.
Distance behind local wing leading edge of leading edge strut	0·82 in.
Thickness/chord ratio of strut	8·5 per cent
Minimum gap between wing lower surface and tank A	2·3 in.
Minimum gap between wing lower surface and tank B	1·44 in.

Struts for Tank C

Spanwise distance from centre-line of wing to rear strut	17·92 in.
Wing chord at rear strut position	16·96 in.
Chord of rear strut at wing	1·45 in.
Chord of rear strut at tank	2·42 in.
Length of rear strut along mid-chord line	2·30 in.
Thickness/chord ratio of rear strut	15 per cent
Thickness/chord of front struts	21·6 per cent at tank end to 31·2 per cent at wing end
Distance from wing leading edge to leading edge of rear strut	8·37 in.
Distance between front struts at wing	2·82 in.
Chord of front struts at wing	0·35 in.
Chord of front struts at tank	1·96 in.
Gap between tank and wing lower surface at front strut position	1·71 in.
Chordwise distance between mid-chord front struts and mid-chord rear strut	6·09 in.
Distance from nose of tank to mid-chord front struts	8·78 in.

Tanks D and E

Length of tank D	18·78 in.
Length of tank E	18·53 in.
Distance of nose of tank D ahead of local wing leading edge	6·60 in.
Distance of nose of tank E ahead of local wing leading edge	6·25 in.
Incidence of tanks D and E relative to wing chord	—3 deg 42 minutes

TABLE 2

Ordinates of Tanks

Tank A

$\frac{x}{l}$	$\frac{r}{l}$
0	0
0·062	0·035
0·125	0·045
0·188	0·054
0·25	0·059
0·312	0·061
0·375	0·0625
0·437	0·0625
0·500	0·0625
0·542	0·0625
0·605	0·061
0·667	0·059
0·730	0·054
0·792	0·045
0·830	0·039
0·875	0·031
0·917	0·023
0·958	0·012
1·0	0

Tank B

$\frac{x}{l}$	$\frac{r}{l}$
0	0
0·037	0·029
0·075	0·039
0·150	0·052
0·225	0·059
0·300	0·062
0·337	0·0625
0·400	0·0625
0·500	0·0625
0·588	0·0625
0·625	0·062
0·700	0·059
0·775	0·052
0·813	0·047
0·850	0·040
0·925	0·022
0·963	0·013
1·0	0

Tank C

$\frac{x}{l}$	$\frac{r}{l}$
0	0
0·009	0·016
0·030	0·029
0·065	0·042
0·087	0·048
0·109	0·053
0·130	0·057
0·174	0·064
0·260	0·073
0·347	0·078
0·390	0·080
0·433	0·080
0·477	0·080
0·520	0·078
0·607	0·073
0 695	0·064
0·850	0·040
0·962	0·018
1·0	0

Tank D

$\frac{x}{l}$	$\frac{d}{l}$
0	0
0·052	0·079
0·104	0·108
0·208	0·143
0·353	0·167
0·391	0·171
0·468	0·173
0·507	0·173
0·699	0·173
0·892	0·173
1·00	0·173

Tank E

$\frac{x}{l}$	$\frac{d}{l}$
0	0
0·053	0·080
0·105	0·110
0·211	0·146
0·337	0·162
0·417	0·167
0·498	0·194
0·576	0·197
0·732	0·191
0·888	0·184
1·00	0·181

l is the length of the tank.
x distance aft of the nose.
r radius.
d diameter in plan-view.

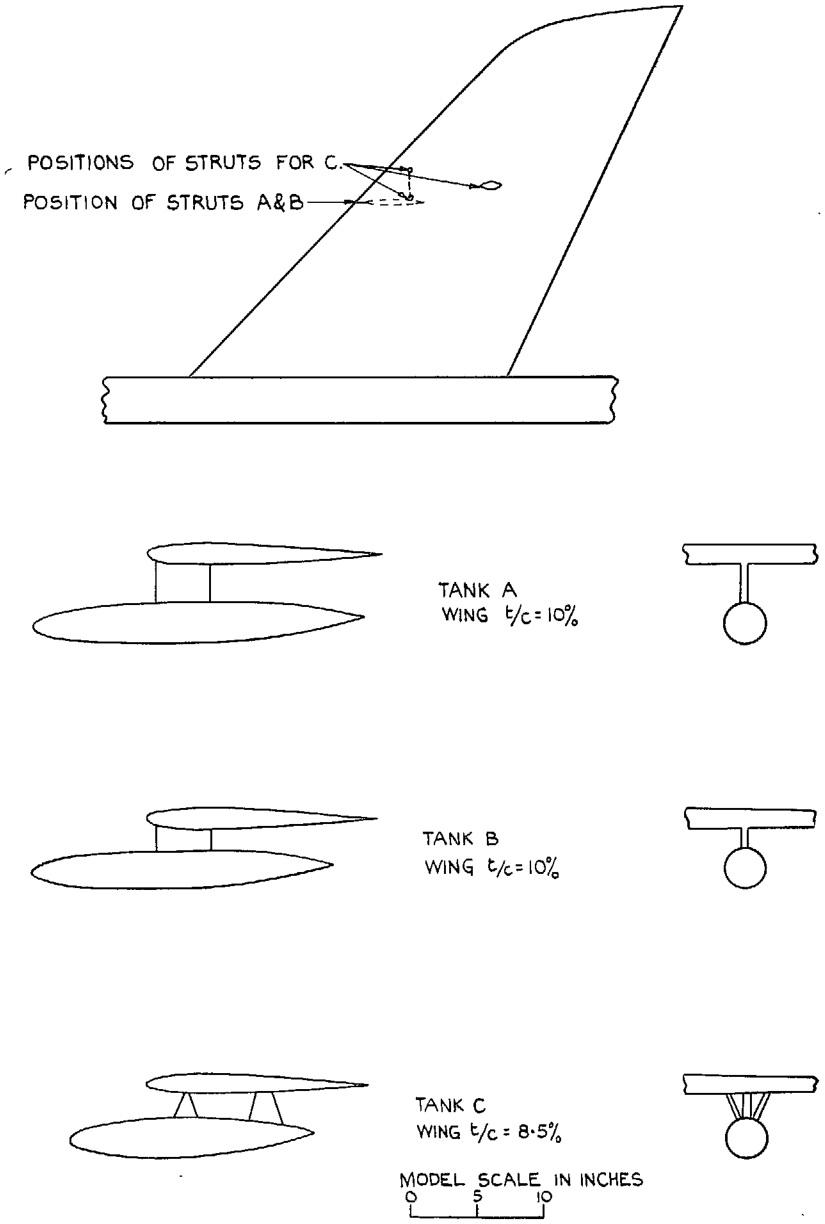

FIG. 1. Details of the strut-supported tank installations.

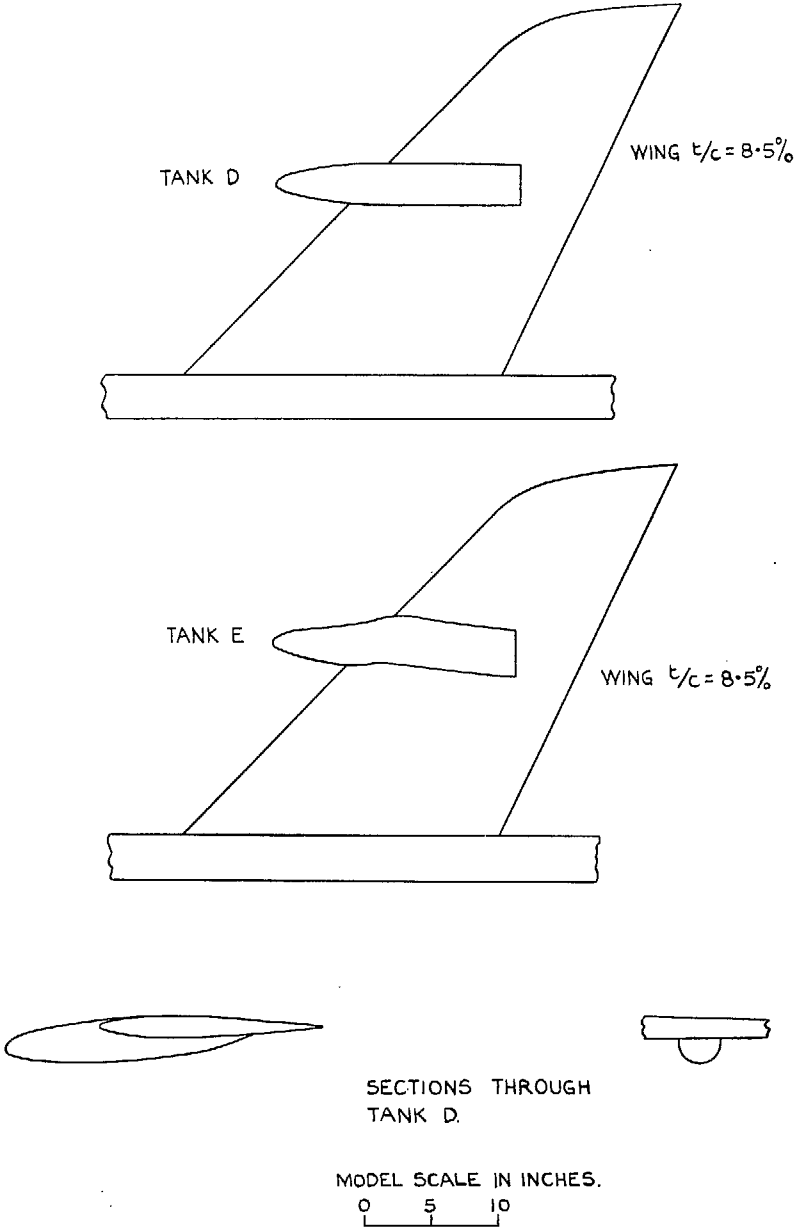

FIG. 2. Details of the nacelle-type tanks.

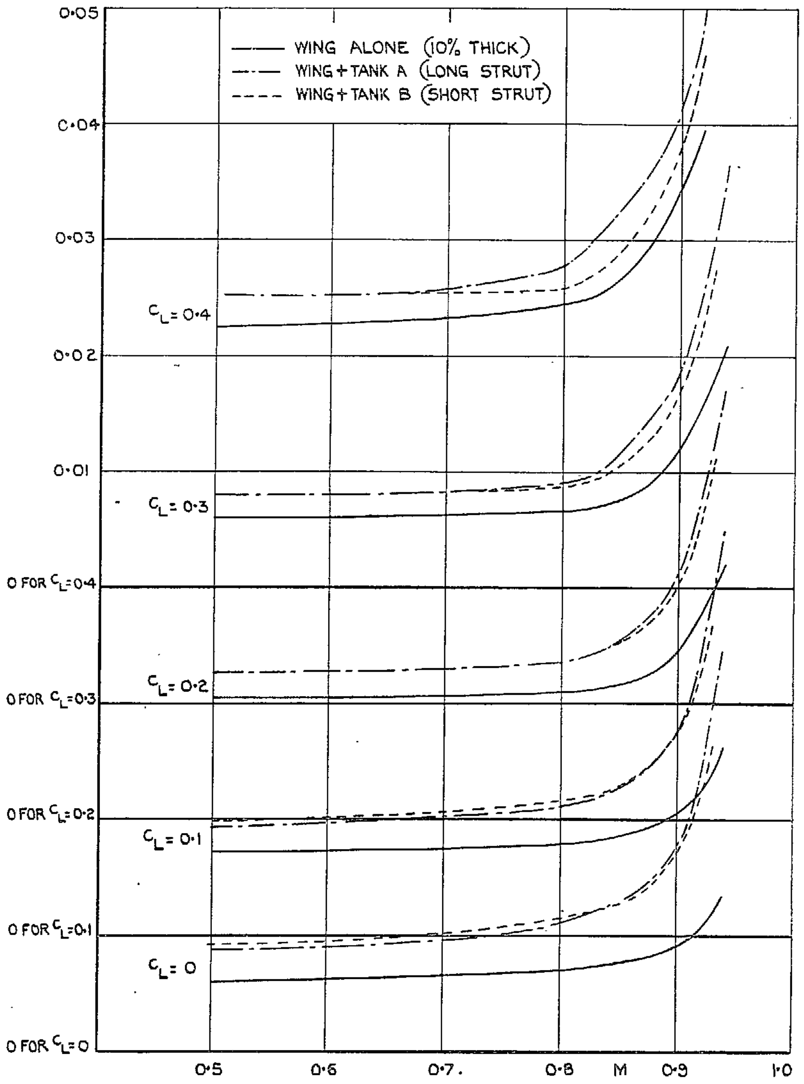

FIG. 3. C_D vs. M at constant C_L for tanks A and B on single struts.

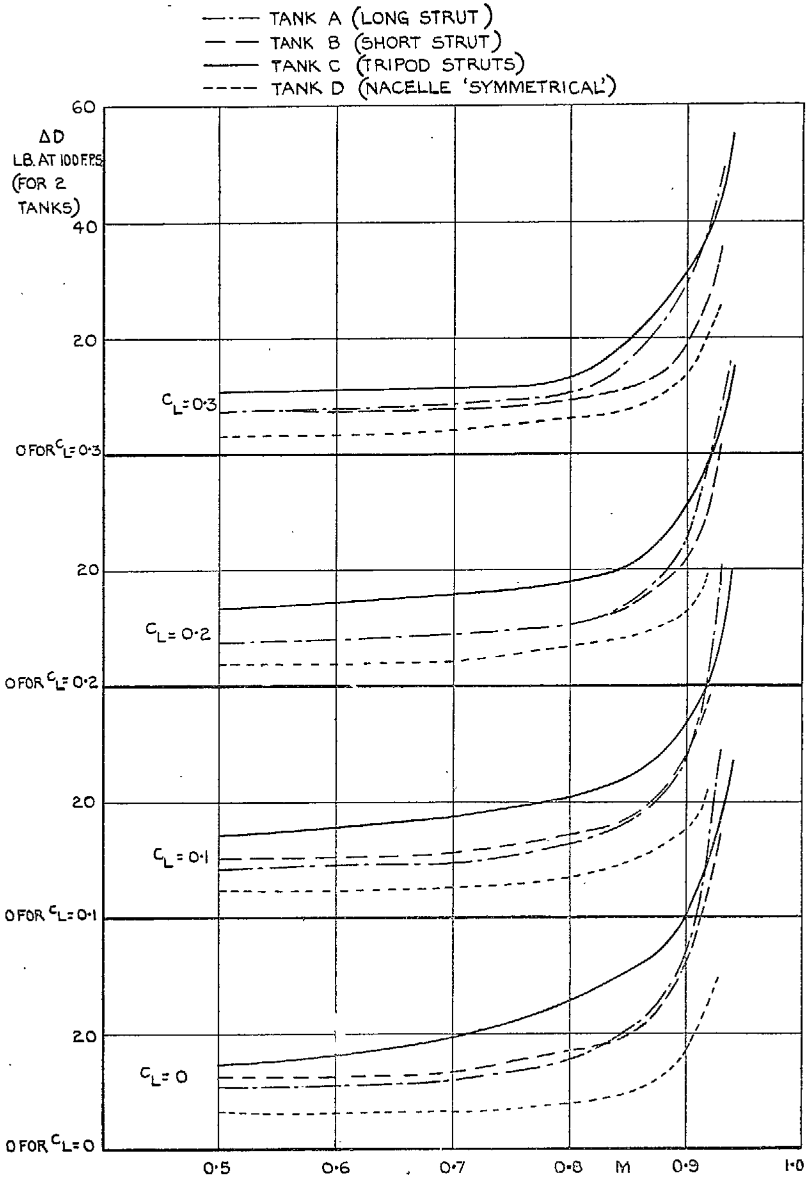

FIG. 4. Increments in drag due to two tanks, for under-wing installations.

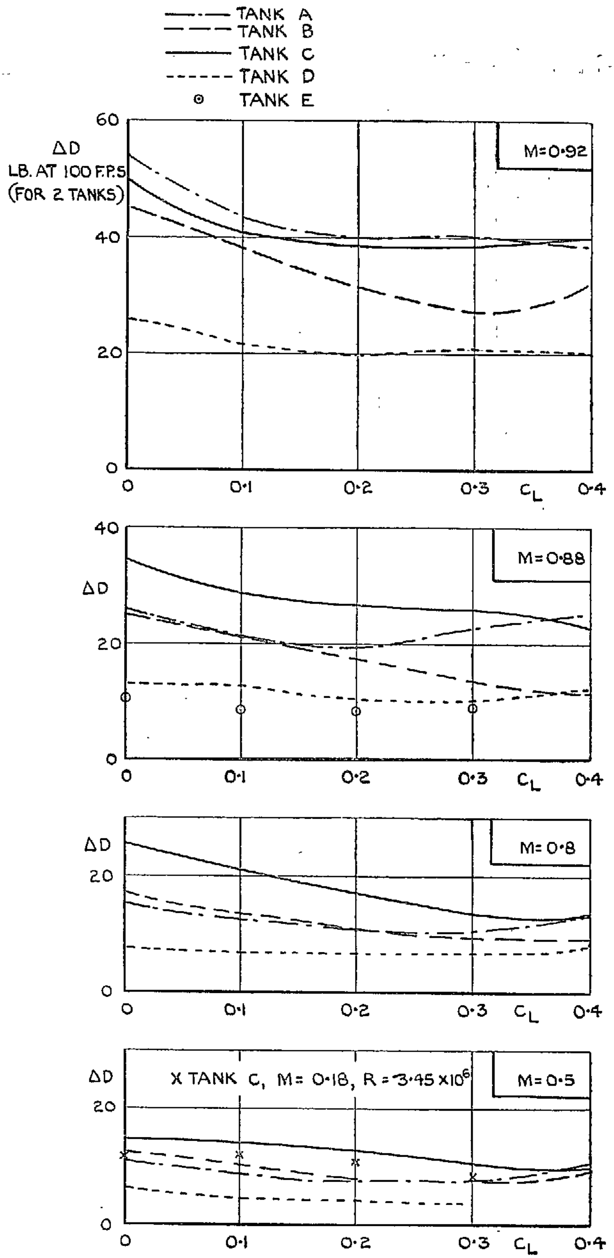

FIG. 5. Increments in drag due to two tanks, for under-wing installations.

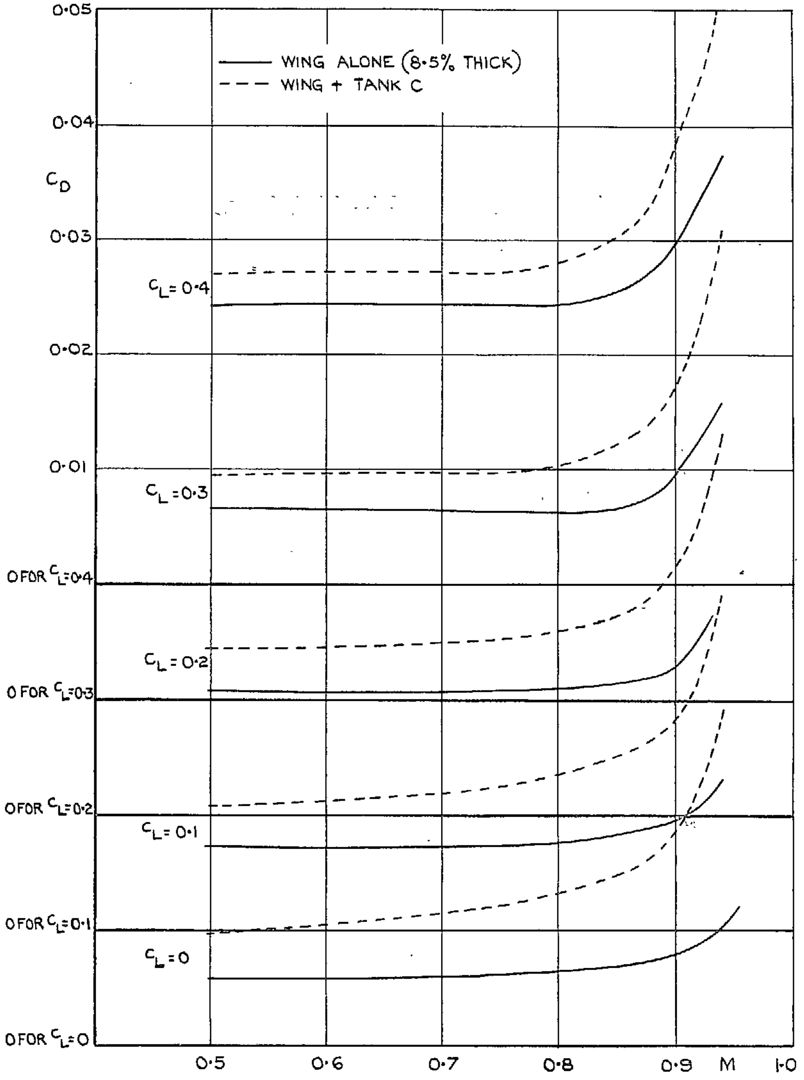

FIG. 6. C_D vs. M at constant C_L for the three-strut-supported tank C.

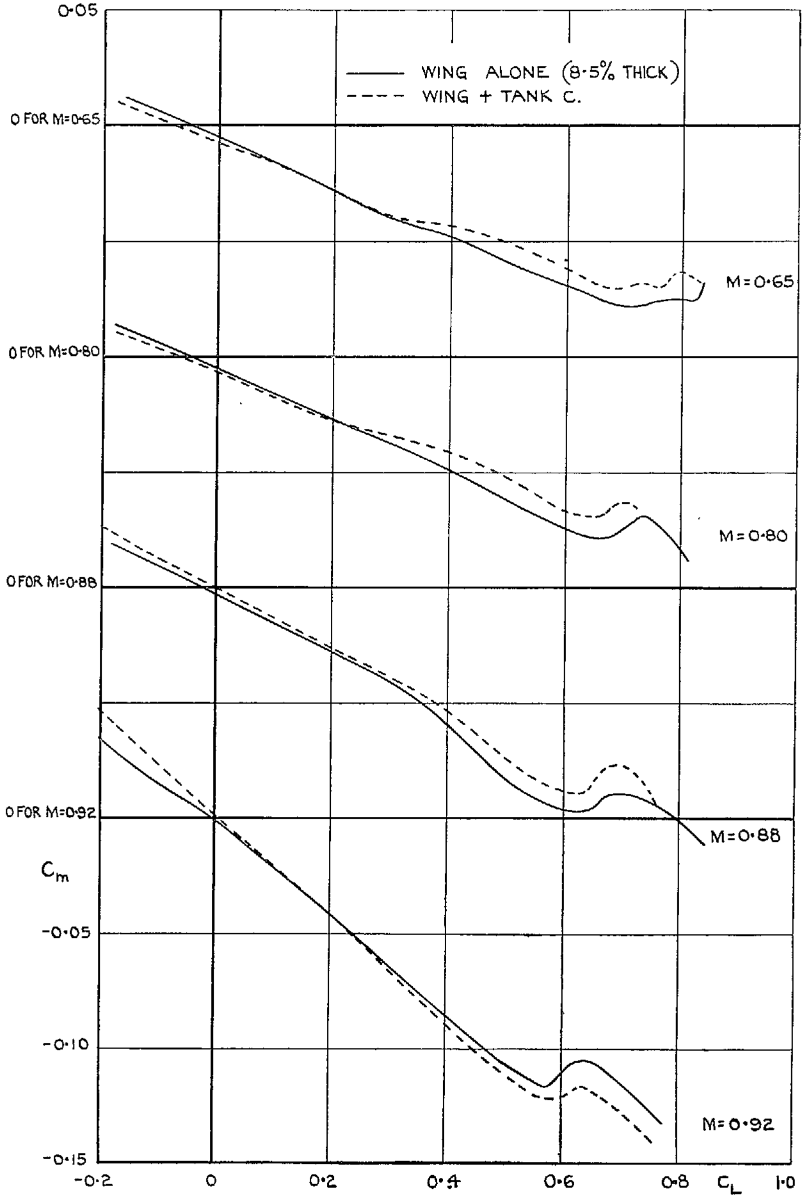

FIG. 7. C_m vs. C_L curves with three-strut-supported tank C.

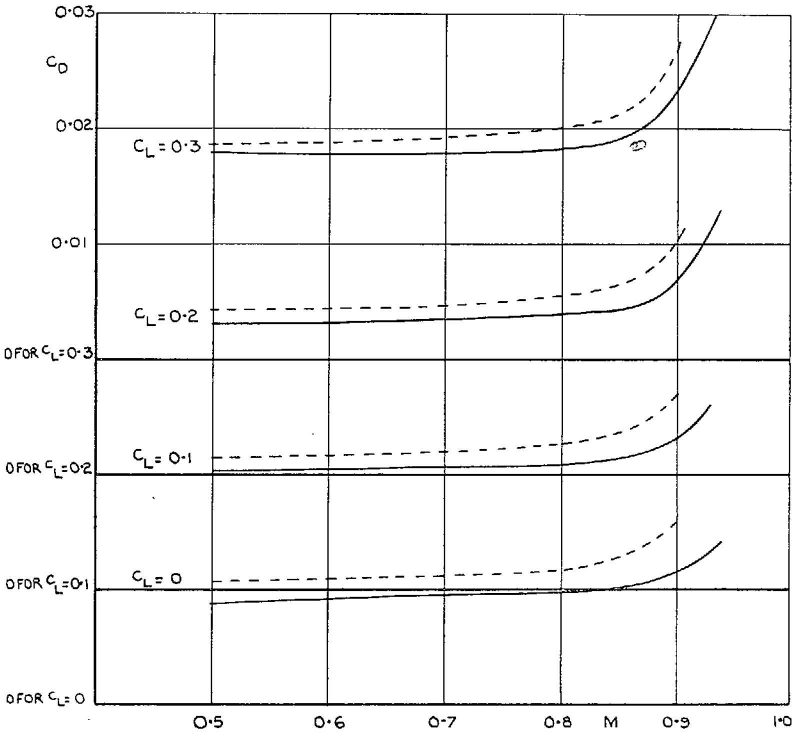

FIG. 8. C_D vs. M at constant C_L for the nacelle-type tank D.

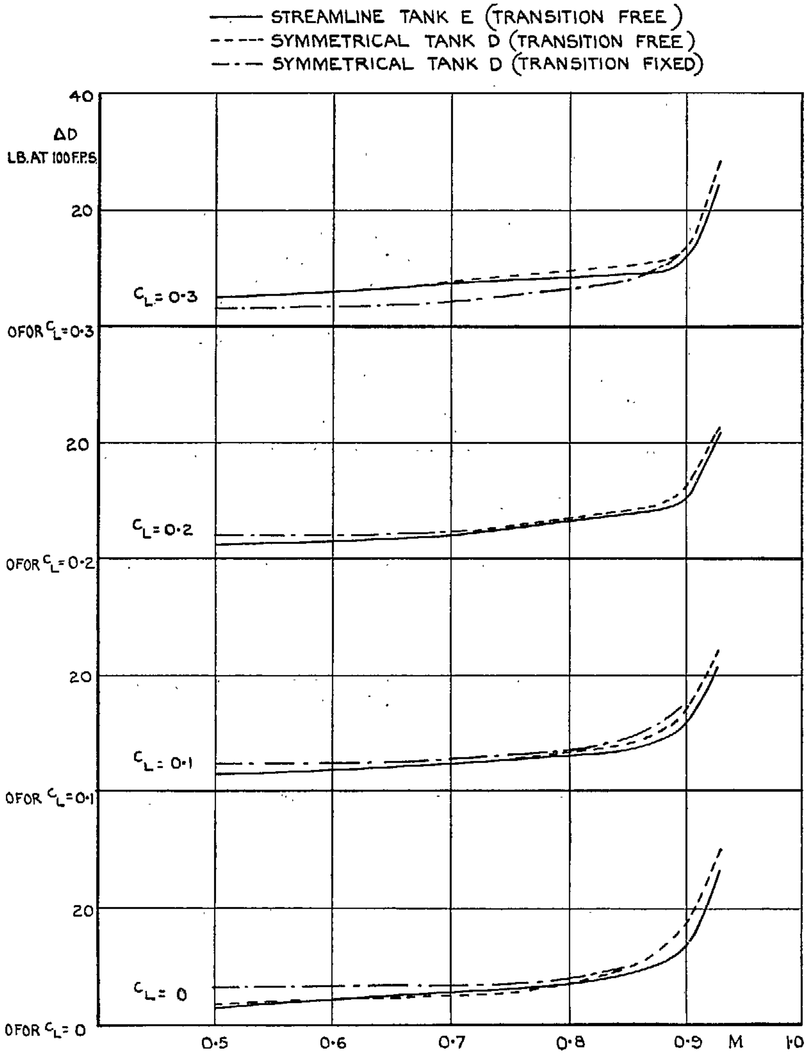

FIG. 9. Increments in drag due to two tanks, for both nacelle-type tanks D and E.

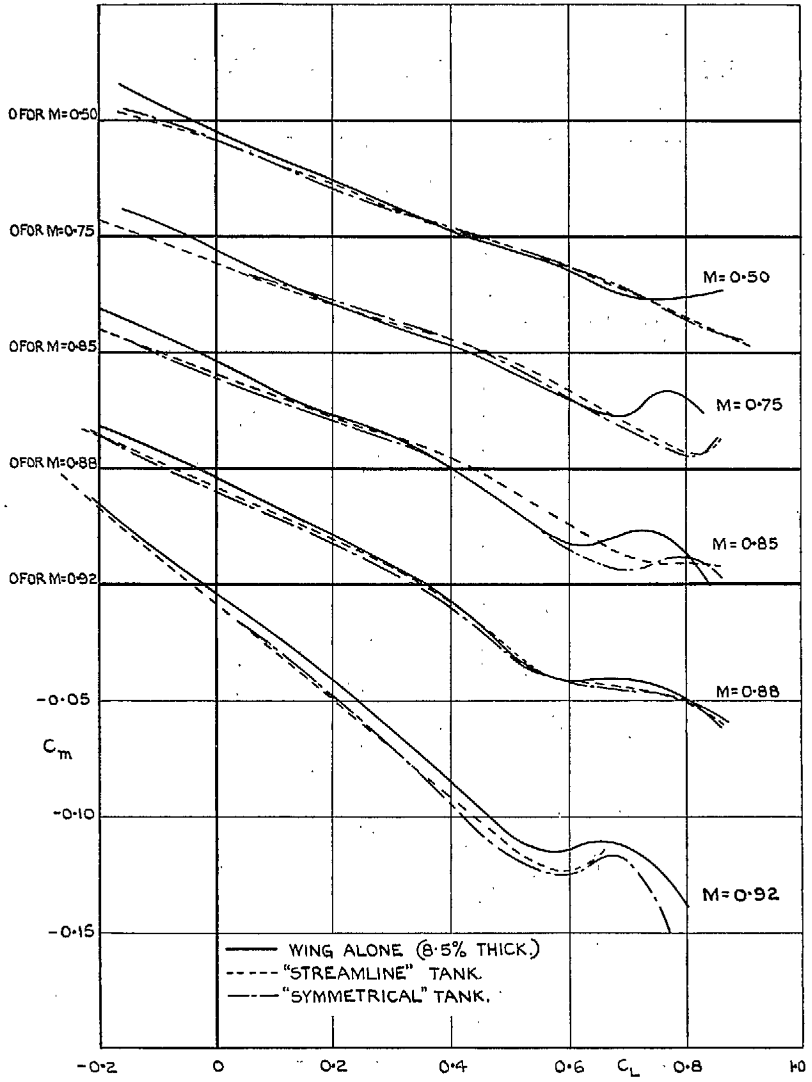

FIG. 10. C_m vs. C_L curves, showing the effects of fitting nacelle-type tanks.

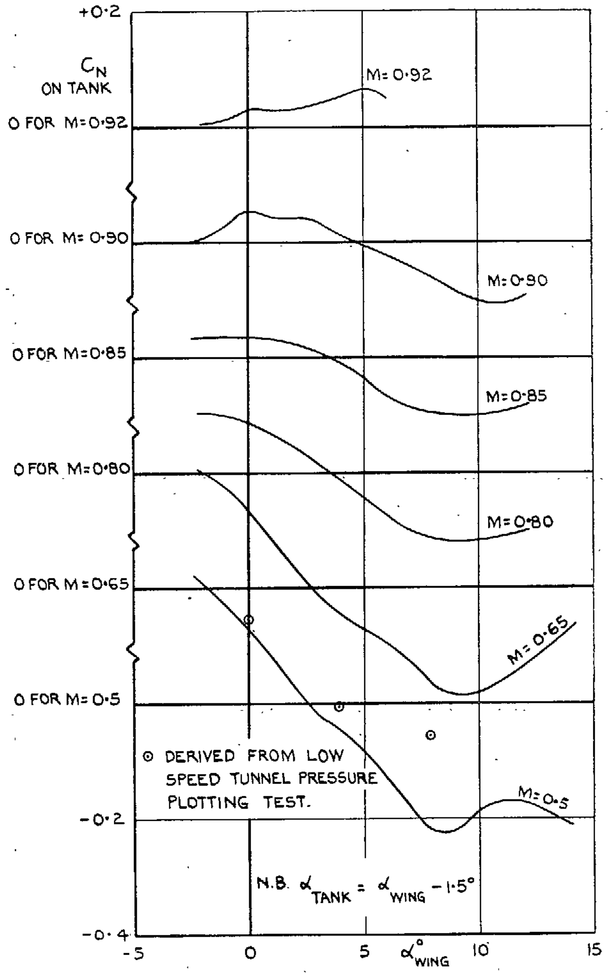

FIG. 11. Variation of tank normal force with incidence and Mach number. Tank B.

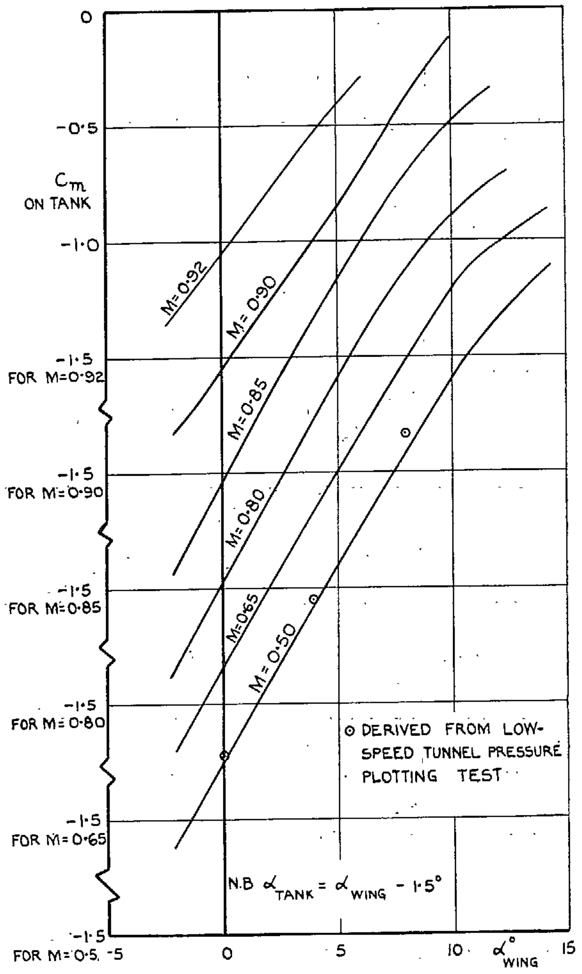

FIG. 12. Variation of tank pitching moment with incidence and Mach number. Tank B.

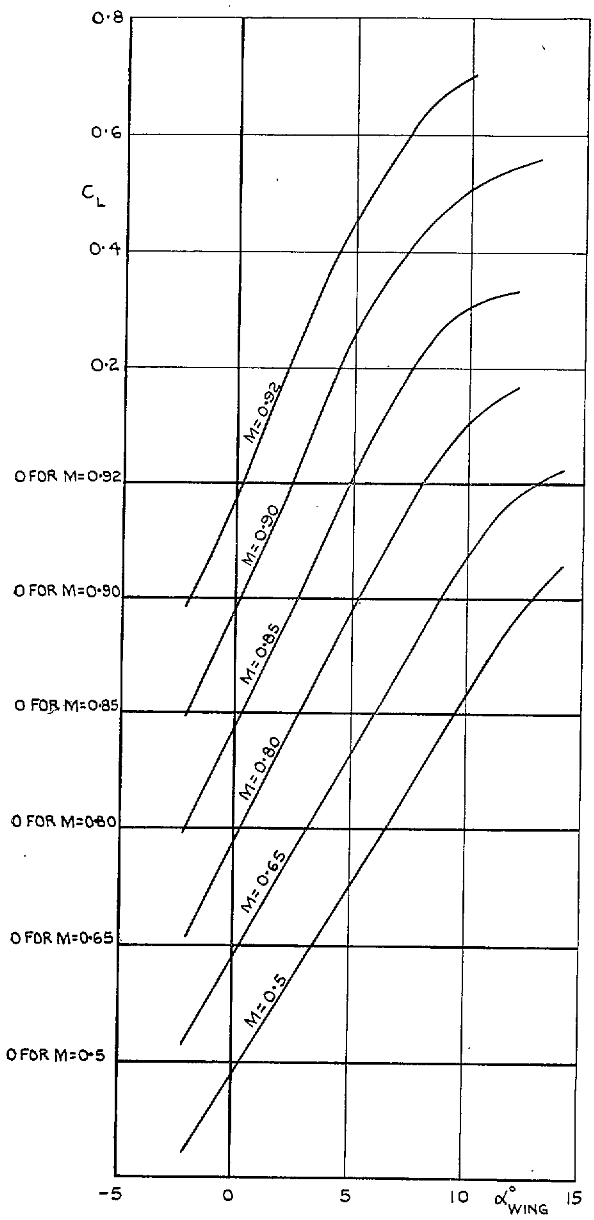

FIG. 13. C_L vs. α curves for wing + tank B.

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