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Investigations on Stalling Behaviour, Rudder Oscillations, Take-off Swing and Flow Round Nacelles on the Tudor I Aircraft

By

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Summary.—During the development of the *Tudor I* aircraft, the Royal Aircraft Establishment co-operated in the flight tests. This report summarises the results, which are felt to be of general interest.

The importance of ' deep tufting ' in leading to an understanding of varied aerodynamic problems has again been forcibly demonstrated; namely in showing that:—

(a) early buffeting of the *Tudor* as the stall is approached was due to a very small airleak around the leading edge of the wing root causing a breakaway of flow, the resultant wake of which hit the tailplane,

(b) early wing-tip stalling was shown to be due to small mal-fitment of the T.K.S. de-icers,

(c) rudder " kicking " arose from flow through the hinge cutouts,

(d) excessive take-off swing was due to poor rudder control as a result of the early rudder stall, and to the fact that the aircraft was stalled in the ground attitude,

(e) the inner nacelle needed considerable lengthening.

1. *Introduction*.—During the development trials on the *Tudor I* aircraft, several troubles were encountered of aerodynamical origin which were difficult to eliminate.

These troubles can be classified under the following headings:—

(a) pre-stall buffeting at a relatively high speed,

(b) violent rudder oscillation at moderate angles,

(c) severe take-off swing,

(d) loss in performance from that estimated,

(e) tendency to bounce on landing.

In view of the importance of this aircraft, the Royal Aircraft Establishment were asked to co-operate with the firm in the development trials. The R.A.E. actually made flight and tunnel investigations in connection with (a), (b), (c) and (d) above, and this report, together with Ref. 1, gives the results obtained. It is felt that the results of these investigations, especially on problems (a) and (b) above, are of such general interest as to warrant publication.

* R.A.E. Report Aero. 2237, received 16th April, 1948.

2. *Stalling Behaviour*.—2.1. *Original Aircraft*.—The original aircraft received at the Royal Aircraft Establishment (G.AGRD) had the following relevant features:—

(a) small flight fillets between the wing and body (*see* Fig. 4),

(b) extended tailplane,

(c) normal wing finish,

(d) T.K.S. type de-icers fitted to the leading edge of the outer wing, tailplane and fin. (It might be explained here that the T.K.S. de-icer consists of a porous metal strip, inserted into the leading edge of a surface, through which de-icer fluid is pumped.)

It had been reported by the Aeroplane and Armament Experimental Establishment in July 1946 that *Tudor I* aircraft in this condition had an exceedingly low $C_{L\,max}$ ($0 \cdot 97$ flaps and u/c up), and that at the stall violent buffeting occurred throughout the whole aircraft with a tendency for the nose to drop accompanied by porpoising (test No. 17, Table 2 gives the measured results).

When G.AGRD was received at the R.A.E., the aircraft was thoroughly 'deep-tufted' (*i.e.*, with tufts placed on masts 3, 6, 9 and 12 in. from the aircraft skin). The areas covered were:—

(1) the whole wing upper surface, port and starboard,

(2) one side of the body from the position of the wing maximum thickness down to the tailplane, including the fin-tailplane junction,

(3) the top and bottom surface of the tailplane and elevator,

(4) one side of the fin and rudder.

A map of the tuft mast positions indicating the density of tufting is given in Fig. 1. The behaviour of the tufts was observed visually mostly through the cabin windows, but a periscope was used for observation of the tailplaine, fin and body tufting.

In addition a trailing static was fitted to the aircraft for all tests made at the R.A.E. and a venturi pitot for all except Test No. 1, Table 1. An approximate correction for pitot errors involved, using the standard pitot head, was made in this one case.

Stalling tests with this deep tufting brought to light the following important points (*see* Table 1, Test No. 1).

(i) The stall previously reported was not the true stall. If the pilot was extremely careful and could prevent the propoising from building up, the speed could be lowered much below the previously reported minimum speeds, through intense and almost dangerous buffeting, until a wing drop occurred. The $C_{L\,max}$ values at this wing drop were reasonable though not high ($1 \cdot 20$ flaps and undercarriage up).

(ii) A diagram of the breakaway of flow observed in flight is shown in Fig. 2. As the pattern of breakaway was almost identical in all cases (*i.e.*, flaps up and down, engines on and throttled), only a general picture is given without any absolute speeds. The measured flight speeds at buffeting and the stall are given in Test 7, Table 1. With engines throttled back the flow picture was roughly symmetrical about the centre line; with engines on the flow was asymmetrical, in that the speeds at which the phenomena happened on each side were different (the starboard wing root breakaway commencing before that on the port wing), though the breakaway picture was similar.

The sequence of events in the airflow, as the stall was approached, was as follows:—

(a) the first sign of bad flow as the flight speed was lowered, was a small breakaway in the wing root fillet. At the same time an area of fairly violent turbulence appeared on top and bottom inboard portions of the tailplane and elevators (*see* Fig. 2). Simultaneously appreciable buffeting was felt on the stick and on the whole aeroplane.

(b) As the speed was lowered a further 2 to 4 knots A.S.I., the breakaway in the wing root fillet spread rapidly forward up to the line CD in Fig. 2. At the same time the turbulence on the tailplane spread out, until at least $\frac{2}{3}$ of the tailplane span was involved, and became extremely violent. This spread of the turbulence was accompanied by extremely violent aircraft buffeting, vicious oscillation of the whole tail end of the fuselage, and increasing nose-down pitch. The aircraft tended to porpoise violently and it was extremely difficult to hold the nose of the aircraft up, though the stick force was not excessive if back elevator trim was used.

(c) A considerable reduction of speed with the conditions as observed in (b) was then made, until the extreme wing tip was seen to be stalling. A wing drop (port) occurred after the speed had been lowered by a further 2 knots, and as the wing dropped the stall spread rapidly to about the half-span point on the dropping wing. The wing dropped up to 30 deg.

(d) As the wing root breakaway spread forwards to the line CD, it was noted that there was considerable spread of the wake upwards, as well as outwards over the tailplane. Fig. 3 shows the area of extreme turbulence of flow as observed by the tufts in side view. The whole of the body flow from the wing back was involved, and the turbulence extended for about $\frac{1}{2}$ to $\frac{2}{3}$ up the fin and rudder.

(iii) From the observations described in (ii) it was clear that the $C_{L\,max}$ values on the *Tudor I* were normal (Ref. 2) though on the low side, and that the severe buffeting, which in practice limited the apparent stall to a very low $C_{L\,max}$, was caused by a deep and violent wing root breakaway, occuring at a very low C_L, the resultant violent wake passing over the tail end of the aircraft. It was fairly evident, therefore, that prevention of the premature wing root breakaway would obviate the early buffeting. There was some possibility that the fairly sharp insweep of the body in both plan and side view just forward of the tailplane position, may have worsened the effect of the wake hitting the tailplane, by causing a further breakaway to occur at the change in body shape; but this would be, clearly, a secondary effect and it was considered that the best dividend would be paid by obviating the wing root breakaway at its source. The first and obvious method of doing this was to improve the wing root filleting. At this time Messrs. A. V. Roe Ltd. had designed a new and larger fillet and were fitting it to *Tudor* G.AGST. Accordingly this aircraft was sent to the R.A.E. for test with the new fillet and the next section describes the results of tests made on this aircraft with this fillet. The drawing of this large fillet is shown in Fig. 4.

2.2. *Aircraft with Large Flight Fillets.*—When the aircraft with large flight fillets (G.AGST) was first received at the R.A.E., brief qualitative tests seemed to indicate that the large fillet had been successful in curing the premature buffeting trouble, in that there was now only a reasonable margin, (2 to 5 m.p.h. E.A.S.) between the onset of buffeting and the stall as indicated by the wing drop. Quantitative measurements, however, showed a very different state of affairs. Though the speed at which buffeting commenced had been lowered considerably, between 14 and 33 m.p.h. E.A.S. compared with the tests on G.AGRD for the various conditions tested (*see* Table 1, Test 2), the stalling speeds had increased up to 10 m.p.h. above those recorded before. The $C_{L\,max}$ flaps and undercarriage up was found to be $1 \cdot 05$. Examination of the wing flow pattern as the stall was approached, showed little difference from that described in section 2.1, except that the wing root stall had not spread fully forward before the wing tip stall occurred. It became clear at this stage that we were dealing with two roughly separate effects in the stalling of this type of aircraft:—

(a) changes in inner wing condition leading to changes in the speeds at which buffeting occurred,

(b) changes in outer wing condition leading to changes in the speed at which the stall occurred, as indicated by the wing drop.

2.3. *Effect of Inner Wing Condition on Buffeting Speeds.*—A series of flight tests were now made on *Tudor I* G.AGST, in which various minor modifications to the inner wing were made and their effects observed. These modifications were:—

(a) wing joint sealed with fabric strip doped to the aircraft skin (*see* Fig. 5),

(b) cooler intake for cabin, open, closed and faired over with a metal sleeve (*see* Fig. 5),

(c) wing root fillet edges sealed (*i.e.*, junctions between fillet and wing and body surface sealed with fabric strip doped to the aircraft skin),

(d) extension of the inner nacelles.

The results of these tests are shown in Table 1, Tests 2 to 8. It should be borne in mind that the tendency of the aircraft to porpoise during the buffeting will cause some scatter of the readings, and that the general changes for all four conditions will give a better estimation of the effect of any modification. It was found that the only really significant change in buffeting speed was obtained by sealing the wing root fillets, roughly about a 6 m.p.h. E.S.A. lowering in the speed at which the buffeting started being observed. A further test in which the T.K.S. de-icer inserts on the tailplane were smoothed over with Plasticene and then fabriced over, showed an inconclusive effect on the buffeting speed as a reduction in A.S.I. (about 3 knots) was recorded but none in E.A.S. readings.

Notwithstanding these reductions in the buffeting speeds, however, the aircraft was still not satisfactory, for a substantial reduction in stalling speed (*see* section 2.4) had widened the gap between buffeting and stalling speeds, and the intensity of buffeting as the stall was approached had become very severe again.

At this juncture the tunnel tests reported in Ref. 1, had been started, to determine, if possible, the size of wing root fillet that was necessary to prevent the wing root breakaway completely until a sufficiently high C_L was reached. These tests, which were made on a 1/12 scale model at a Reynolds number of $1 \cdot 1 \times 10^6$ based on the mean wing chord, indicated that a considerable gain in C_L, at which the wing root breakaway began, could be made by a severe and impractical increase in fillet size, *but* the tests failed to show the rapid spread forward of the breakaway in the wing root and only showed a normal rate of spread forward, of the breakaway.

It was not clear, therefore, that the observations based on the tunnel tests were useful. It was in an attempt to explain the difference in flow between tunnel and flight, that we directed our attention in flight to the leading edge hinged door inspection panel, which extends almost the whole spanwise distance between the body and the inner nacelle. This inspection door (*see* Figs. 1 and 5) consists of the whole aerofoil section up to the 12 per cent chord line, hinged at the top surface, and is used to facilitate inspection of the engine controls *etc.* out to the inboard engine. The hinge on the top surface is by no means flush, projections of up to $0 \cdot 45$ in. above the wing contour have been measured, and attention was drawn to the possibility that this hinge projection might be causing the breakaway in flight at large incidences and thus account for the difference between flight and tunnel breakaway patterns. Support for this view was forthcoming from Refs. 3 and 4. (Attention had not been drawn to this door and hinge before, because the *Lancaster*, *Lincoln* and *York* aircraft all have this same feature, and there has been no suggestion at all on any of these aircraft, of premature prestall buffeting.) Accordingly, the further tunnel tests described in Ref. 1 were made with wires to represent the hinge interference, and similar flow changes to those reported in flight were then obtained in the tunnel, and early breakaways from the wing root observed, the sensitivity to the interference getting less as fillet size increased.

The next step was to test this in flight. Accordingly, *Tudor I*, G.AGRD was sent to the R.A.E., and after making a control test in the original condition (Test No. 10, Table 1), a metal glove was fitted over the whole inboard leading edge section (*see* Fig. 5). It was found that the severe buffeting was completely eliminated, and only slight buffeting occurred just before the stall (Test No. 11, Table 1). At the same time as this was proceeding, Messrs. A. V. Roe had designed a new fillet, the 'aerofoil' fillet, so-called because its chordwise section right up to the body junction was of aerofoil shape. This tested in the tunnel showed no marked advantage over the large flight fillet, but when tested on *Tudor I* G.AGRC (Tests 22 and 23, Table 2) at Messrs. A. V. Roe, showed a complete elimination of the buffeting up to the stall ($C_{L\,max}$ flaps up, 1·35). On examination, this fillet was found, however, to extend so far forward that it was covering over about 2 ft of the inboard end of the leading edge door hinge, and it was thought this fillet's action was to smooth over the hinge projection at the most sensitive position. Simultaneously, however, flight tests were made, both at the R.A.E. on the aircraft with the gloved inner wing leading edge, and at Messrs. A. V. Roe on the aircraft with the aerofoil fillet, with cords placed on top of these fairings at the same chordwise position as the hinge of the leading edge door. Both these series of tests (the R.A.E. results are given in Tests No. 11, 12, 13, Table 1) gave the very important answer that these spanwise cords at 12 per cent of the wing chord, caused little measurable change in the breakaway conditions in the wing root and therefore in the buffeting speeds. There was, therefore, a serious contradiction in results between tunnel and flight.

It was fairly clear as a result of these last tests, that the important action of the fairings was to seal the gaps around the leading edge door rather than to fair its irregularities. Tests without the fairings, and with the large flight fillet with various combinations of sealing, showed that it was only necessary to seal the chordwise gap at the inboard end of the leading edge inspection door (AB in Fig. 5) to get the optimum effect, that is the minimum buffeting speed (*see* Tests No. 14, 15 and 16, Table 1). This gap on G.AGRD was 24 in. long chordwise and only $\frac{1}{16}$ in. wide and was already roughly sealed by an internal baffling. Subsequent tests made by Messrs. A. V. Roe (*see* Tests No. 25 and 26, Table 2) showed that even with the small flight fillet very satisfactory buffeting qualities could be obtained at the stall even with a $C_{L\,max}$ flaps up of 1·50, providing the inboard gap was sealed.* This showed another important contradiction between flight and tunnel, as the tunnel tests indicated that the small flight fillet was quite inadequate even with a smooth and leakless wing. It is of interest to note here that on the *Lancaster, Lincoln* and *York* aircraft, the leading edge inspection door abutts up against the side of the fuselage, and a vertical fairing attached to the door effectively provides a seal or baffle, besides the fact that the leak is well inside the boundary layer of the fuselage. This fact alone would explain the difference in behaviour at the stall between the *Tudor I* in its original condition, and the other aircraft mentioned, besides the increased sensitivity of the low wing arrangement on the *Tudor*.

2.4. *Effect of Outer Wing Condition on Stalling (i.e., Wing Dropping) Speeds.*—As related in section 2.2, flight tests on *Tudor I* G.AGST, as first received with the large fillets, showed extremely poor $C_{L\,max}$ figures (1·05 flaps up undercarriage up). Examination of the outer wings suggested that the only possible cause of the early wing tip stall was the fitting of the T.K.S. de-icers to the wing leading edge. The fit was not bad, though not good, irregular projections of up to 1/20 in. from the aerofoil contour were observed. It was decided to try the effect of improving the contour on the outer wing by fairing in these de-icer strips. Firstly the leading edges were roughly faired by doping over with fabric, and an appreciable drop in stalling speeds was recorded (6 to 11 knots A.S.I. (*see* Tests No. 4 and 5, Table 1)). Further more elaborate smoothing with plasticene and fabric which produced a better smoothness of the leading edge, though the finish was still not good, resulted in a further drop in stalling speed (*see* Tests No. 7 and 8, Table I), and an overall drop in stalling speed from the original outer wing condition of from 9 to 22 m.p.h. E.A.S.; $C_{L\,max}$ flaps up was now 1·24. Tests made later by Messrs. A. V. Roe on *Tudor* G.AGRC showed that by changing the outer wings to *Lincoln* wings with no T.K.S. de-icers, a further substantial drop in stalling speed, was obtainable (*see* Tests No. 23

* Tests made by Messrs. A. V. Roe Ltd. since the completion of this work, have shown that increase in the buffeting speeds and stalling speeds can arise due to deterioration in the sealing of the small fillet between the wing and fuselage around the nose of the wing, even with the inspection door leak fully eliminated. These tests also showed that the major portion of this loss could be made good by resealing the fillet, but tests with a nose fillet produced the same or perhaps slightly greater recovery of buffeting and stalling speeds, possibly due to covering over the leak.

and 24, Table 2), $C_{L\,max}$ flaps up 1·50. With the *Lincoln* outer wings the stall also became much milder in that the wing drop was almost absent, and the stall became very similar to a *Lancaster* or *Lincoln*, the final stall consisting of a gentle nose drop.

It was clear, therefore, that to obtain the maximum possible C_L at the stall on this aircraft it was essential to obtain really smooth conditiong on the leading edge of the aerofoil contour, especially on the outer wing sections which are of reasonably small thickness chord ratio (t/c has an average value of 12 per cent on the wing outboard of the outboard engines). Any interference to the leading edge shape caused by such equipment as the T.K.S. de-icer system is inherently bad from this viewpoint and should be avoided if possible. The effect on other aircraft of the T.K.S. de-icer system in the wing has not been measured as far as is known, but there seems no reason to believe that their effect would not be deleterious; if for instance, the *Tudor I* G.AGST with relatively badly fitted T.K.S. inserts had not been stalled with a trailing static, the effect would perhaps never have been noted and maximum C_L values of 1·2 to 1·3 been accepted on the *Tudor* as normal.

2.5. *Variation of Stalling Characteristics Between Aircraft.*—In the normal condition in which most of the *Tudor I* aircraft were first flown (with large wing root fillets and normal wing surface conditions, with no sealing but with T.K.S. de-icing inserts), the variations of buffeting speed and stalling speed between aircraft were extremely large (*see* Tests No. 2, 10, in Table 1, and Tests No. 18, 22, 27 and 29 in Table 2 for results on six aircraft). Buffeting speeds varied between 105 and 118 knots A.S.I. at 64,000 lb flaps and undercarriage up, and stalling speeds between 89·5 and 112 knots A.S.I. for the same conditions ($C_{L\,max}$ varied as far as evidence is known between 1·05 and 1·37 approx.). These variations are clearly due respectively, to variation of the sealing of the inner wing and variation of the fit of the T.K.S. de-icer in the outer wings.

With standard sealing of the vital leak on the inner wing, the variation in buffeting speed has been reduced to between 86 and 95 knots A.S.I. flaps and undercarriage up (*see* Test No. 16, Table 1 and Tests No. 20, 26, 28, 30, Table 2), with one exceptional buffeting speed registered on the A.A.E.E. aircraft G.AGPF of 103·5 knots A.S.I. In this last case, however, there is some reference in the letter from which it was extracted, to the difficulty experienced in maintaining the sealing strips in place during flight, and this probably explains the difference from the general run of aeroplanes. The final production modification to eliminate the leaks in the inner wing, is the elimination of the leading edge hinged inspection door altogether, so that the variation in the flight speeds at which the buffeting commences may become even smaller.

The variation of the stalling speeds and $C_{L\,max}$, when the inner wing is sealed, can still be large due to the variation in the fitting of the T.K.S. de-icer inserts in the outer wing. An attempt is being made to produce a really smooth insertion of the de-icer in production, but it must be realized that the highest $C_{L\,max}$ values measured, 1·50 flaps and undercarriage up (*see* Test No. 24, Table 2) must be obtained in practice, otherwise some aircraft with very good inner wing conditions will stall with a wing drop before any buffeting warning is given of the approach of the stall. In other words, the aircraft buffeting which, in too severe a form and occurring too far from the true stall is extremely objectionable, must be retained in a mild form, if no other form of stall warning is present.

3. *Rudder Oscillation at Large Angles.*—3.1. *Description of Trouble and Effect on Aircraft.*—The rudder oscillation phenomenon was first experienced during tests to determine the adequacy of the directional control in the engine cut condition, on the aircraft with the original small fin and rudder (not illustrated in this report). As however, these tests indicated that the control was inadequate with this small fin and rudder, immediate steps were taken to increase the fin and rudder area to that shown in Fig. 1, and the rudder oscillation problem was shelved. Tests with the larger fin and rudder showed, however, that the oscillation was still present. It was

found that, as the rudder angle was increased especially when trimmer was wound on to trim out the rudder pedal loads, at a certain rudder angle violent kicking occurred on the rudder pedals. Both the rudder and rudder circuit were involved in this low frequency oscillation, and violent shaking was felt at the rear of the aircraft. Though rudders with various balance arrangements had been flown on the *Tudor*, this rudder kicking had been consistently present throughout. It was apparent, therefore, that the nose balance present on the rudder in its last and standard form could not be held responsible for the trouble. The overall effect on the aircraft was to raise the engine-out safety speed, as rudder angles above those at which kicking started could not be used. The maximum usable angle was quoted by Messrs. A. V. Roe at about 12 deg, an extremely low figure.

3.2. *Tuft Investigations and Wind Tunnel Tests*.—When the *Tudor I* G.AGRD was first sent to the R.A.E., the whole side of the fin and rudder was covered by ' deep tufting ' in order to determine, if possible, the flow conditions that were causing the trouble. During flight tests in which these tufts were observed the following points were noted (no instruments were used to measure the rudder angles and these are only approximate):—

(a) with symmetric or asymmetric power the rudder angle at which kicking commenced was roughly the same,

(b) no kicking occurred up to full pedal travel if zero trimmer were used, but some stretch was observed in the circuit. The rudder angle was then about 11 to 12 deg,

(c) as trimmer was wound on with the pedal at full travel, the rudder angle was observed to increase, and violent kicking began. (The maximum angle available at this time with the rudder against its stop was 14 deg),

(d) the minimum speed at which the aircraft could be held straight and level with the port outer engine throttled back and propeller windmilling with climbing power on the other engines was 120 knots A.S.I.,

(e) though bad flow always present in the tailplane-fin junction spread upwards as rudder was applied, the changes in the turbulence in this area did not tie-up well with the sudden onset of kicking on the rudder,

(f) in every case, however, as rudder kicking commenced, a bad stall of the flow was observed in the centre of the rudder on the suction side (*see* Fig. 6), and it was concluded that this stall must be the cause of the kicking. The stall appeared to be similar to the usual control stall at large angles but it was, of course, occurring at an exceedingly low rudder angle.

It was not apparent why this stall was occurring at so low a rudder angle, so wind-tunnel tests were started to see if any light could be thrown on the matter. The variables that it was intended to test were:—

(1) effect of dorsal fin changes,

(2) effect of sideslip and rudder angle combinations,

(3) effect of change in rudder geometry.

The model used was again 1/12 scale complete model at a Reynolds number of $0 \cdot 7 \times 10^6$.

It was found that a stall in the centre of the rudder could be made to occur at the low rudder angles, *only* if an impracticable combination of sideslip and rudder angle was used; *i.e.*, with sideslip angle and rudder angle applied in the same sense. It was further shown that the position of the junction of the dorsal fin and the normal fin determined the position of the stall on the rudder, and that reduction of rudder chord made no improvement. It was then decided to try the effect of representing, on the model, the cutout which is made in the rudder on the full-scale aircraft to accommodate the hinges. The cutout made on the model was equivalent to a cut 3 in. wide and extending 12 in. back from the leading edge of the rudder in full-scale dimensions. It was found that this cutout promoted a stall in the centre of the rudder with practical combinations of rudder angle and sideslip angle at a rudder angle of 10 to 15 deg compared with 25 deg without the cutout. Considerable improvement was shown in the rudder angle obtained before the stall, by preventing the flow through the gap. (Stalling angle then between 15 deg and 20 deg.)

3.3. *Tests of Hinge Cutout Modifications.*—Close examination of the hinge cutouts on the full-scale aircraft (G.AGST), showed that, besides the existence of the large area through which air could flow, a sharp edge at the rear of the cutout projected out into the airstream as rudder was applied (*see* Fig. 7a). A preliminary modification was made at the R.A.E. by filling in the cutout by a fairing attached to the fin and by fitting suitably curved plates to this fairing to cover the projection on the rudder when rudder was applied (*see* Fig. 7b). Flight tests with all three cutouts modified in this way, showed that the kicking had been eliminated up to $\pm$ 16 deg rudder angle. The aircraft was then returned to Messrs. A. V. Roe for a production hinge cutout fairing to be incorporated; the production modification is the local formation of a concentric nose at the hinge cutout, so that the fairing block attached to the fin can be extended right up to the concentric nose, and only a very small leak is left (*see* Fig. 7c). In this condition there was only minute kicking up to $\pm$ $18\frac{1}{2}$ deg of rudder angle. The rudder pedal forces were then adjusted by means of the gearing of the geared tab, until full rudder could be obtained at low flight speeds with reasonable foot loads. It was clear, therefore, that bad flow initiated by the hinge cutouts was solely responsible for the rudder kicking at low rudder angles on the *Tudor*, and that the wind tunnel tests had rightly predicted this. Previous wind-tunnel tests[5] had shown the bad effect of hinge cutouts on the hinge moment characteristics of controls.

3.4. *Effect of Rudder Modifications on Engine Cut Safety Speeds.*—During these tests the efficacy of the rudder alterations had also been roughly tested by measurements of the minimum speed at which the aircraft could be held straight, with wings level, with the port outer engine cut (the port engine cut produces the worst effect on the *Tudor*). The minimum speed obtained in this way, with the remaining three engines at take-off power, gives a very rough measure of the minimum speed at which an engine cut can be controlled during take-off; the actual conditions are complicated, of course, by the variation of the bank angle etc. during an actual engine cut, but the figures thus obtained in the various conditions will form a reliable basis of comparison.

As related in section 3.2 above the minimum speed obtained in the original condition with *climbing power* only, was 120 knots A.S.I. The first R.A.E. modification of the hinge cutouts with $\pm$ 16 deg of rudder angle available, dropped this figure immediately to 100 knots A.S.I. with climbing power, and 105 with take-off power. The Avro production hinge cutout modification produced a further drop to 92 knots A.S.I. *with climbing power* with a rudder angle of $\pm$ 16 deg, and when the rudder angle available was increased to $\pm$ $18\frac{1}{2}$ deg, the minimum speed was below the violent longitudinal pre-stall buffeting speed then present on the aircraft ($<$ 92 knots A.S.I.) with climbing power, and was 95 knots with take-off power. It was found necessary, of course, during this sequence of tests to lighten off the rudder pedal loads by increase of the rudder tab gearing (*see* section 3.3), the figures quoted in all cases refer, however, to full rudder pedal movement, without retrimming from the symmetrical power case. Later more accurate tests at A.A.E.E. of actual conditions during a take-off with an engine cut, showed that the safety control speed is about 100 knots A.S.I. at 80,000 lb A.U.W. with the rudder in the fully modified condition.

It appears, therefore, that a reduction of approximately 30 knots has been made in the minimum forward speed necessary to be able to hold an engine cut, merely by these hinge cutout modifications. This reduction would appear greater than would be expected from the increase in available rudder travel only, and suggests that some increase in rudder effectiveness was also obtained by the modification.

4. *Take-off Swing.*—4.1. *Behaviour During Take-off in the Original Condition.*—The main facts about the swinging on the *Tudor I* during take-off in its original condition (*i.e.*, small wing

root fillets and large fin and rudder), that can be deduced from the pilots' reports, are as follow:—

(a) there was a tendency for the aircraft to swing when the wind was directly down the runway, but the tendency was not excessive for an aircraft with a 'conventional' undercarriage. Correction of this tendency was very difficult, however, as little rudder power seemed to be available,

(b) evidence of the sensitivity of the aircraft to small effects was shown by tests at the A.A.E.E., where cross gradients of 1/70 across the runway were sufficient either to counteract the tendency to swing in a straight wind, or to approximately double the effect according to the direction of the slope. (N.B. It can be shown that there is a tendency for the conventional undercarriage to turn uphill.)

(c) the swing developed dangerously in cross-wind conditions, especially when the cross-wind came from the port. Very little cross-wind from that direction was necessary before a take-off became impossibly difficult for the pilot, even with coarse use of differential throttles and rudder,

(d) the consensus of pilots opinion suggested that considerable improvement in the ability to control the swing was noticed as the tail was lifted off the ground; though satisfactory control of the aircraft could not be obtained without differential use of the throttles to a very high speed, even with the tail up,

(e) it was noticed that the initial period of take-off run, during which most of the difficulty with swing occurred, was long due to poor acceleration. Aileron snatch and elevator buffet also occurred.

Examination of the deep tufting on the aircraft during a take-off run showed clearly that the *whole wing* was completely stalled in the ground attitude; the ground incidence was $14\frac{1}{2}$ deg. As in the stalls in the air, the breakaway on the wing was accompanied by violent turbulence of flow over the whole rear body extending $\frac{1}{2}$ to $\frac{2}{3}$ the way up the fin and rudder (*see* section 2.1 and Fig. 3). The flow did not clear up until the tail had been lifted some distance from the ground. These flow conditions explained satisfactorily both the poor initial ground acceleration, and the poor rudder control with the tail on the ground, and accounted for the improvement in the ability to hold the swing as the tail was lifted from the ground. It was concluded from these recorded facts that the aircraft showed no unusual tendency to swing, taking into account the conventional undercarriage layout and the large directional stability, but that the root cause of trouble was in insufficient rudder power available for corrective action, this being especially low when the tail was down. Differential engine throttling on the outer engines only, provided ample yawing moment to correct the swinging moment in a cross wind, but control on the throttles alone was, as would be expected, unsatisfactory because of the time lag between the throttle opening and the development of power. It was clear that at the best, with an undercarriage of conventional form, there would always be a need for differential throttling, and that the only complete cure would be the fitting of an undercarriage of tricycle form; the best lines of attack with the conventional undercarriage appeared to be:—

(a) decrease of wing incidence on the ground, and delaying of wing root breakaway to a higher incidence,

(b) increase of rudder power,

the former to tackle the problem of clearing up the air flow over the fin and rudder when the tailwheel is in contact with the ground by eliminating the wing root stall in the ground attitude, and the latter to provide a general improvement for the whole of the take-off run.

As described in section 2 the wing root stall has been delayed until a satisfactory wing incidence in flight by sealing of the wing root leaks, and, in addition, the ground wing incidence has been reduced to the lowest practical, $13\frac{1}{2}$ deg, by a shortened undercarriage. Though we have not had the opportunity of investigating by 'deep-tufting' the airflow over the wing root and fin and rudder in this latest configuration, it is still considered that the wing stall will have occurred before the full ground attitude is reached, and it is clear from pilots' reports, that the control during the period when the tail is on the gound is still not quite as good as it might be for a conventional undercarriage layout, especially at heavy A.U.W., when the tail cannot be raised for a long period. Suggestions have been made that a tail-wheel lock would improve the control during this period. A tail-wheel lock would have reduced the swing whilst the tail-wheel was on the ground, but as it is necessary on this aircraft to raise the tail as soon as possible to unstall the wing this modification would not have produced as much overall improvement in take-off characteristics as on some other aircraft.

4.2. *Effect of Improved Rudder Control.*—With the success of the rudder modifications described in section 3.3, and the increase in rudder travel made possible by these modifications, the improvement in the ability to control the swing became very apparent. There was considerable benefit felt both in the tail-down and the tail-up attitude, and at light weights (64,000 lb) it became possible in small cross-winds to perform take-offs without differential throttling. It became clear during the rudder development trials at the R.A.E. that the lightness of the rudder control played a considerable part in the directional control during take-off, and the optimum condition from the pilots' viewpoint was the attainment of the lightest rudder forces without tendency to overbalance at large angles. (N.B. There is a limit to the practicable lightness due to the need for the avoidance of overbalance due to ice formation on the leading edge of the fin. Current Paper 66[6]).

Tests made by A.A.E.E. at the maximum A.U.W. (80,000 lb) with the latest rudder modifications, have indicated that the swing during take-off is now fairly normal for a type with conventional undercarriage layout, and that at this weight, differential throttling is usually necessary.

5. *Nacelle Design.*—5.1. *Flow Tests on Original Inner Nacelle.*—The original inner nacelle shape is shown in Fig. 8a. It was not the first type flown on the *Tudor*, but a compromise arrived at after the *Lancaster* type nacelles had given vibration troubles during early development tests at the firm. Shortening the nacelle to finish at the flap hinge had eliminated a periodic shake felt on the whole aircraft.

Because of the loss in performance from that estimated, attention was drawn by the R.A.E. to the probability that the flow round the rather bluff ends of the inner nacelles was bad. Flow observations in flight by means of ' deep-tufting ' showed clearly that a complete breakaway of flow was occurring behind the nacelle over the whole speed range, slight improvement only being noticed as the stall was approached. It was also noted that the flow could be cleared up completely by lowering the flaps through a small angle (10 to 15 per cent of maximum travel), and that as the flow breakaway was stopped by this means a good deal of the continuous vibration felt on the aircraft ceased at the same time. The poor inner nacelle shape was, therefore, producing both drag and vibration. Clearly lengthening of the inner nacelle rear fairing was required, and both because of the previous trouble experienced by the firm, and of evidence produced by wind tunnel tests that the optimum nacelle design was not obtained by the nacelles finishing at the trailing edge (R. & M. 2406[7]), it was considered that the nacelle should extend some 18 in. to 2 ft behind the trailing edge. As an interim step, however, the *Lancaster* type nacelle was refitted.

5.2. *Flow Tests on Lancaster Type Inner Nacelle.*—A sketch of this nacelle shape is given in Fig. 8b.

Deep-tufting tests showed that while the breakaway in flow behind the nacelle had been reduced to about $\frac{1}{3}$ of that previously noted, there was still sufficient breakaway to cause concern about the drag resulting from it. Also the vibration experienced on the aircraft as a whole had changed character. Instead of the continuous vibration noted with the ' original ' inner nacelle, there was now a periodic and more violent shake on the aircraft, as had been reported previously by the firm. Smaller flap angles were now needed to clear up the breakaway and this periodic shake (5 to 10 per cent of full flap travel).

5.3. *Flow Tests on Extended Type Inner Nacelle.*—A sketch of the extended inner nacelle is given in Fig. 8c. Deep-tufting tests showed no signs of any flow breakaway round the nacelle over the speed range from slow cruising to top speed; at low speeds the flow over the top of the nacelle rear fairing became confused with the wing root breakaway. The vibration level of the aircraft with the extended nacelles, flaps up, was lowered appreciably from either of the other two cases.

6. *Summary of Conclusions.*—(i) The value of flow observations by deep-tufting methods in leading to an understanding of varied aerodynamic problems, has been demonstrated again very forcibly. It should again be emphasised here, that surface tufting (*i.e.*, flow observations by tufts fixed only to the surface of the aircraft) is liable to lead to a completely misleading interpretation of the flow conditions.

(ii) The action of small air leaks into critical regions of flow producing severe flow breakaway has been shown clearly. The apparent minuteness of such leaks compared with the size of the aircraft is apt to delay recognition of their effect.

(iii) Hinge cutout design, which leaves large spaces for the air to flow through from one side of the control surface to the other, and/or causes sharp lips to project into the airstream and act as spoilers, has been shown to produce early stalling of the control. (It should be noted that previous wind-tunnel and flight tests have shown such design to lead to adverse effects on the balance of the control surface.)

(iv) It is clear from the tests on the *Tudor* aircraft that conclusions based on wind tunnel tests, in conditions in which breakaway of flow are occurring, must be treated with reserve if the model tests are at low Reynolds number. The low Reynolds number favours an early stall; and though model tests may indicate a region, which is still in flight susceptible to breakdown of flow, a more drastic disturbing factor may be needed at the higher Reynolds number. It appears undoubtedly that, in this case, wind-tunnel tests gave wrong indications of the effects of modifications on the wing root stall (both in quality and in magnitude); in the case of the rudder stall, on the contrary, they undoubtedly reproduced the flight effects completely.

(v) The effect of the T.K.S. de-icer inserts in the leading edge of the wings in producing early stalls, indicated very clearly that the wing contours should not be interfered with by such, or similar equipment, if at all possible, and that every effort be made to stow the de-icer equipment internally without interference with external shape.

(v) The action of surface irregularity on the stalling of an aerofoil section is not clear. On the outer wings of the *Tudor*, very small surface irregularity certainly produced extremely early stalling, but on the inner wing quite large cords produced little effect in a region in which tunnel tests both in America[3,4] and Britain[1] would forecast large effects. In the two cases in flight, there was certainly a difference in position of the irregularity (on the leading edge of the outer wing, and about 10 per cent back from the leading edge on the inner wing), and the outer wing might be expected to be more sensitive because of the thinner section (11 to 12 per cent over the section concerned as against 18 per cent at the root); the effect of the root junction however, in effecting the sensitivity of the inner section might be expected to be large. It would appear worthwhile when the opportunity arises to carry this work further.

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3	E. N. Jacobs	Airfoil Section Characteristics as Affected by Protuberances. N.A.C.A. Report No. 446. 1933.
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5	J. Nivison	Effect of Hinge Gaps on Control Characteristics. R.A.E. Technical Note No. Aero. 983. July, 1942.
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TABLE I

BUFFETTING SPEED, STALLING SPEED AND $C_{L\,max.}$ MEASUREMENTS ON TUDOR I AIRCRAFT AT R.A.E.

NOTE:- ALL SPEEDS PERTAIN TO AN AU.W. OF 64,000 lb.

V_B IS SPEED AT WHICH MARKED BUFFETTING COMMENCES

V_S IS STALLING SPEED (TAKEN AS SPEED AT WHICH WING DROP OCCURS)

WHERE MIN. IS USED AFTER V_S SPEED THIS INDICATES NO UNCONTROLLABLE WING DROP

TEST No.	AIRCRAFT No.	CONDITION OF AIRCRAFT: WING FILLET SEE FIG.4.	CONDITION OF AIRCRAFT: INNER WING CONDITION	CONDITION OF AIRCRAFT: OUTER WING CONDITION	CONDITION OF AIRCRAFT: OTHER RELEVANT CONDITIONS	MEASUREMENT	TRUE E.A.S. (M.P.H.) GLIDE FLAPS UP	TRUE E.A.S. (M.P.H.) GLIDE FLAPS DOWN	TRUE E.A.S. (M.P.H.) ENGINES ON 2300RPM+3½lb/in² FLAPS UP	TRUE E.A.S. (M.P.H.) ENGINES ON 2300RPM+3½lb/in² FLAPS DOWN	PILOTS A.S.I. (KNOTS) GLIDE FLAPS UP	PILOTS A.S.I. (KNOTS) GLIDE FLAPS DOWN	PILOTS A.S.I. (KNOTS) ENGINES ON 2300RPM+3½lb/in² FLAPS UP	PILOTS A.S.I. (KNOTS) ENGINES ON 2300RPM+3½lb/in² FLAPS DOWN
1	G.AGRD	SMALL	AS RECEIVED NO SPECIAL SEALING	AS RECEIVED WITH T.K.S. TYPE DE-ICERS	EXTENDED TAILPLANE SHORT NACELLES	V_B	147	145	144	132	127	127	124	116
						V_S	122	106	113·5	91·5	102	90	89	79
						C_L MAX.	1·20	1·56	1·37	2·16	—	—	—	—
2	G.AGST	LARGE	AS RECEIVED NO SPECIAL SEALING	AS RECEIVED WITH T.K.S. TYPE DE-ICERS	LANCASTER TYPE NACELLES	V_B	133	112	126	102	118	98	110	89
						V_S	130	109	124	97	112	92·5	105	82
						C_L MAX.	1·05	1·48	1·16	1·88	—	—	—	—
3.	"	"	AS 2 BUT WITH WING JOINT SEALED (SEE FIG.5) COOLER INTAKE FLAP CLOSED	"	"	V_B					112	94	113·5	87
						V_S					109	90	103	76
						C_L MAX.					—	—	—	—
4	"	"	AS 3. BUT WITH COOLER INTAKE FLAP OPEN	"	"	V_B					112	—	111	—
						V_S					110	—	101	—
						C_L MAX.					—	—	—	—
5	"	"	AS 3	T.K.S. DE-ICERS ROUGHLY FAIRED OVER WITH FABRIC	"	V_B					115	95	110	—
						V_S					104	82min.	90	72
						C_L MAX					—	—	—	—
6	"	"	AS 3 BUT WITH INTAKES COMPLETELY FAIRED OVER	"	"	V_B					114	95	112	88
						V_S					105	92	90	72
						C_L MAX.					—	—	—	—
7	"	"	AS 6 BUT WITH WING ROOT FILLETS SEALED	"	"	V_B	126	108	120	96	111	90	105	82
						V_S	121	106	112	91	102	84	91	76
						C_L MAX.	1·20	1·56	1·40	2·12	—	—	—	—
8	"	"	AS 7	T.K.S. DE-ICERS WELL SMOOTHED OVER WITH PLASTICENE AND FABRIC	EXTENDED INNER NACELLES	V_B	130	104	123	96	112	88	109	85
						V_S	119min.	96min.	101	88	101	82	84	69
						C_L MAX	1·24	—	1·72	2·26	—	—	—	—
9	"	"	"	"	AS 7 WITH FAIRED OVER T.K.S. DE-ICER ON TAILPLANE NOSE	V_B	126	106	125	95	107	87	105	80
						V_S	—	—	103	88	97min.	83min.	82	65
						C_L MAX.	—	—	1·66	2·26	—	—	—	—
10	G.AGRD	"	AS 2	AS 2	AS 8	V_B	133	110	118	96	114	90	100	78
						V_S	116	100min.	118min.	88·5	89·5	77·5	80·5	66
						C_L MAX.	1·31	1·75	—	2·24	—	—	—	—
11	"	"	INNER WING L.E. BETWEEN FUSELAGE AND INNER NACELLE GLOVED OVER WITH METAL FOR 3·1 FT. CHORD TOP SURFACE.	"	"	V_B	115	103	103·5	93	92·5	75	81·5	74
						V_S	115min.	103min.	103·5	91	92·5min.	75min.	81·5	65
						C_L MAX.	—	—	1·64	2·12	—	—	—	—
12	"	"	AS 11 BUT WITH ⅛" CORD FIXED OVER METAL GLOVE AT LOCATION OF WING L.E. HINGE	"	"	V_B	115·5	99·5	109	91·5				
						V_S	115·5	99·5	107	89				
						C_L MAX.	1·32	1·77	1·54	2·22				
13	"	"	AS 12 BUT ¼" DIA. CORD	"	"	V_B	116·5	102	109	92·5	95	80	88	75
						V_S	—	99	106	91·5	94min.	77·5	84·5	69
						C_L MAX.	—	1·78	1·56	2·10	—	—	—	—
14	"	"	AS 10 BUT WITH ALL GAPS IN INNER WING L.E. SEALED WITH FABRIC (SEE FIG 5)	"	"	V_B	112	97·5	104	88	88	74·5	83·5	68
						V_S	112	—	102	88	88	—	79	65
						C_L MAX.	1·40	—	1·70	2·27	—	—	—	—
15	"	"	AS 14 BUT WITH OUT-BOARD CHORDWISE SEALING STRIP REMOVED	"	"	V_B	113	99	105	91·5	86·5	74·5	83·5	72
						V_S	—	—	—	—	—	—	—	—
						C_L MAX	—	—	—	—	—	—	—	—
16	"	"	AS 15 BUT WITH SPAN-WISE SEALING STRIP OVER L.E. HINGE REMOVED	"	"	V_B	110	97·6	103	90	86	75	83	71
						V_S	—	—	—	—	—	—	—	—
						C_L MAX.	—	—	—	—	—	—	—	—

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TABLE II

BUFFETTING SPEED, STALLING SPEED AND C_L MAX. MEASUREMENTS ON TUDOR I AIRCRAFT OTHER THAN AT R.A.E.

NOTE:- ALL SPEEDS PERTAIN TO AN A.U.W. OF 64,000 lb. V_B IS SPEED AT WHICH MARKED BUFFETTING COMMENCES
V_S IS STALLING SPEED (TAKEN AS SPEED AT WHICH WING DROP OCCURS) WHERE MIN. IS USED AFTER V_S SPEED THIS INDICATES NO UNCONTROLLABLE WING DROP

*DEDUCED FROM P.E. CURVES, NOT ACCURATE

TEST No.	AIRCRAFT No.	CONDITION OF AIRCRAFT: WING FILLET (SEE FIG 4)	CONDITION OF AIRCRAFT: INNER WING CONDITION	CONDITION OF AIRCRAFT: OUTER WING CONDITION	CONDITION OF AIRCRAFT: OTHER RELEVANT CONDITIONS	PLACE OF MEASUREMENT	MEASUREMENT	GLIDE: TRUE E.A.S. (m.p.h.) FLAPS UP	GLIDE: TRUE E.A.S. (m.p.h.) FLAPS DOWN	GLIDE: PILOTS A.S.I. (KNOTS) FLAPS UP	GLIDE: PILOTS A.S.I. (KNOTS) FLAPS DOWN
17	G.AGPF	SMALL	NORMAL AS 1. IN TABLE I	NORMAL WITH T.K.S. DE-ICERS ON L.E.	EXTENDED TAILPLANE SHORT NACELLES	A.A.E.E.	V_S	135 min.	116 min.	118 min.	101 min.
							C_L MAX.	0·97	1·32	—	—
18	"	LARGE	"	"	AS 17 BUT WITH LANCASTER INNER NACELLES	A.A.E.E. BY R.A.E.	V_B	122·5 *	102·5 *	105	87
							V_S	113 *	97 *	95·5	82
							C_L MAX.	1·37 *	1·86 *	—	—
19	"	"	"	"	AS 18 BUT WITH EXTENDED INNER NACELLES	A.A.E.E.	V_B	122·5	104	102	87·5
							V_S	122·5 min.	—	98 min.	
							C_L MAX		—		
20	"	"	SEALED L.E. GAPS AS 14 IN TABLE I	"	"	"	V_B	121	104	103·5	87·5
							V_S	118	101	98	82
							C_L MAX.			—	—
21	G.AGRI	"	"	"	"	"	V_B			—	—
							V_S			93	80
							C_L MAX.			—	—
22	G.AGRC	"	AS 17	"	"	A.V. Roe	V_B	125	104		
							V_S	114	101		
							C_L MAX.	1·35	1·72		
23	"	AEROFOIL	INNER CHORDWISE GAPS COVERED BY AEROFOIL FILLET	"	"	"	V_B	—	—	—	—
							V_S	114	101	100	86
							C_L MAX.	1·35	1·72	—	—
24	"	"	"	LINCOLN OUTER WINGS WITH NO T.K.S. DE-ICERS FITTED	"	"	V_B	112	98·5		
							V_S	108·5	98·5		
							C_L MAX.	1·50	1·81		
25	"	SMALL	AS 17	"	"	"	V_B			106	90
							V_S			104·5 min.	88 min.
							C_L MAX.			—	—
26	"	"	SEALED INBOARD CHORDWISE GAP	"	"	"	V_B			90	82·5
							V_S			87	80
							C_L MAX.			—	—
27	G.AGNH	LARGE	AS 17	AS 17	AS 19	"	V_B			111·5	96
							V_S			90	81·5
							C_L MAX.			—	—
28	"	"	AS 26	"	"	"	V_B			90	79·5
							V_S			86	70
							C_L MAX.			—	—
29	G.AGRI	"	AS 17	"	"	"	V_B			113	—
							V_S			111	—
							C_L MAX.			—	—
30	"	"	AS 26	"	"	"	V_B			95	—
							V_S			90	78·5
							C_L MAX.			—	—

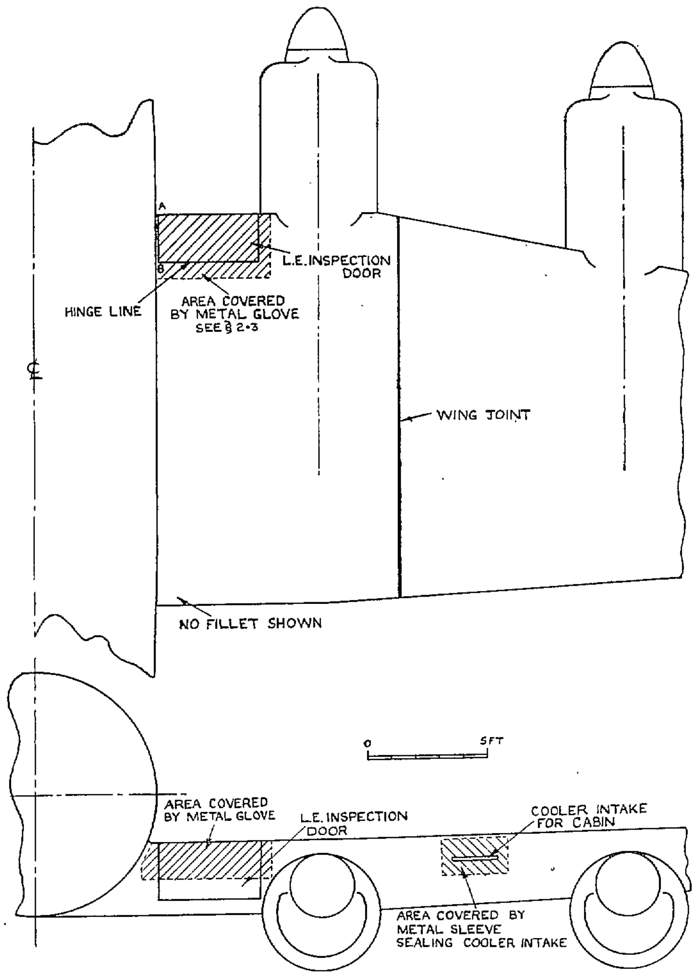


FIG. 5. Sketch of inner wing.

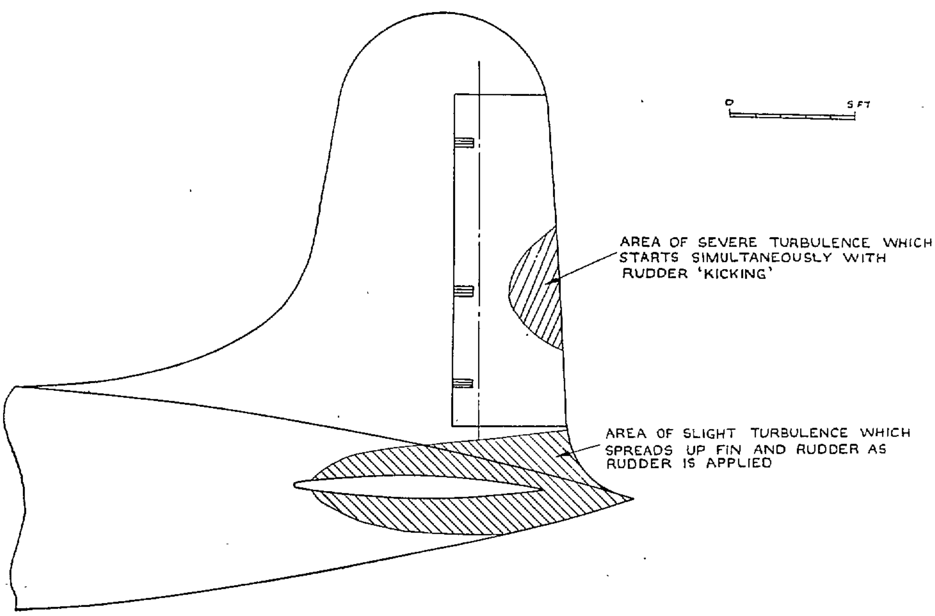
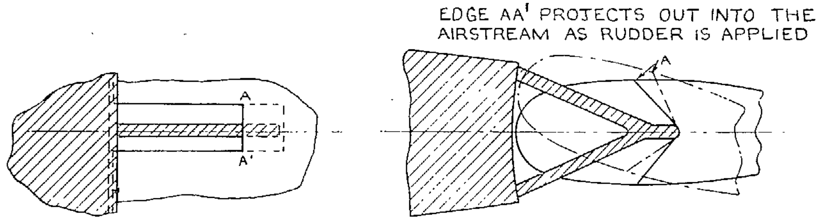
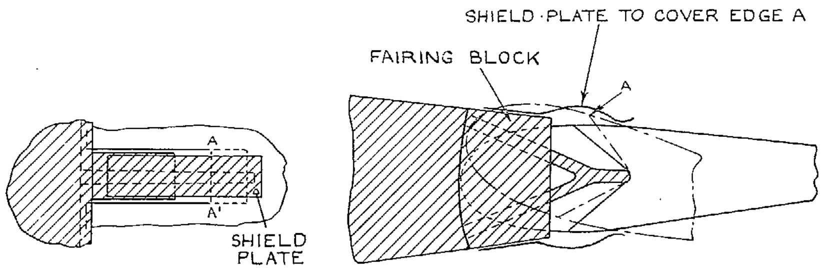


FIG. 6. Sketch illustrating flow breakaway in the rudder region.

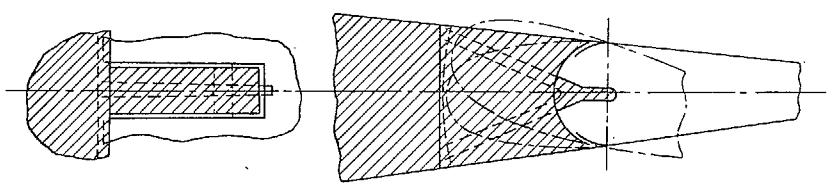


(a) ORIGINAL UNMODIFIED HINGE CUTOUT

ALL SHADED PORTIONS
ARE ATTACHED TO FIN

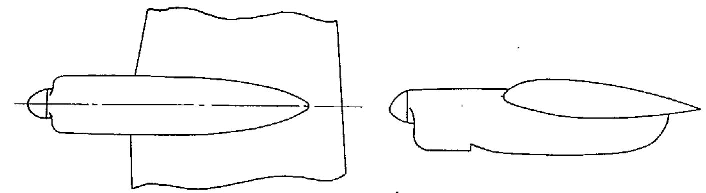


(b) R.A.E. MODIFIED HINGE CUTOUT (TEMPORARY)

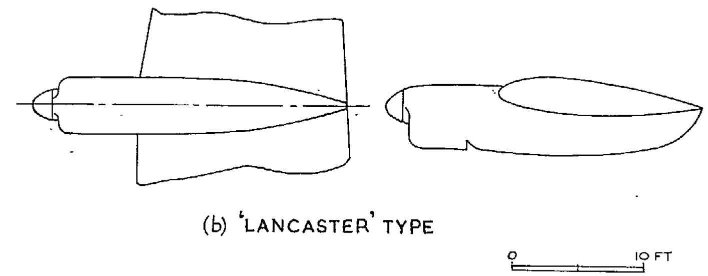


(c) PRODUCTION MODIFICATION OF HINGE CUTOUT

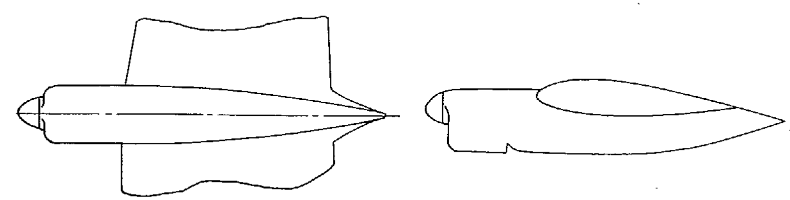
FIG. 7. Hinge cutout modifications on the rudder.



(a) ORIGINAL TYPE (17·7·46)



(b) 'LANCASTER' TYPE



(c) EXTENDED TYPE

FIG. 8. Sketches of inner nacelle shapes.

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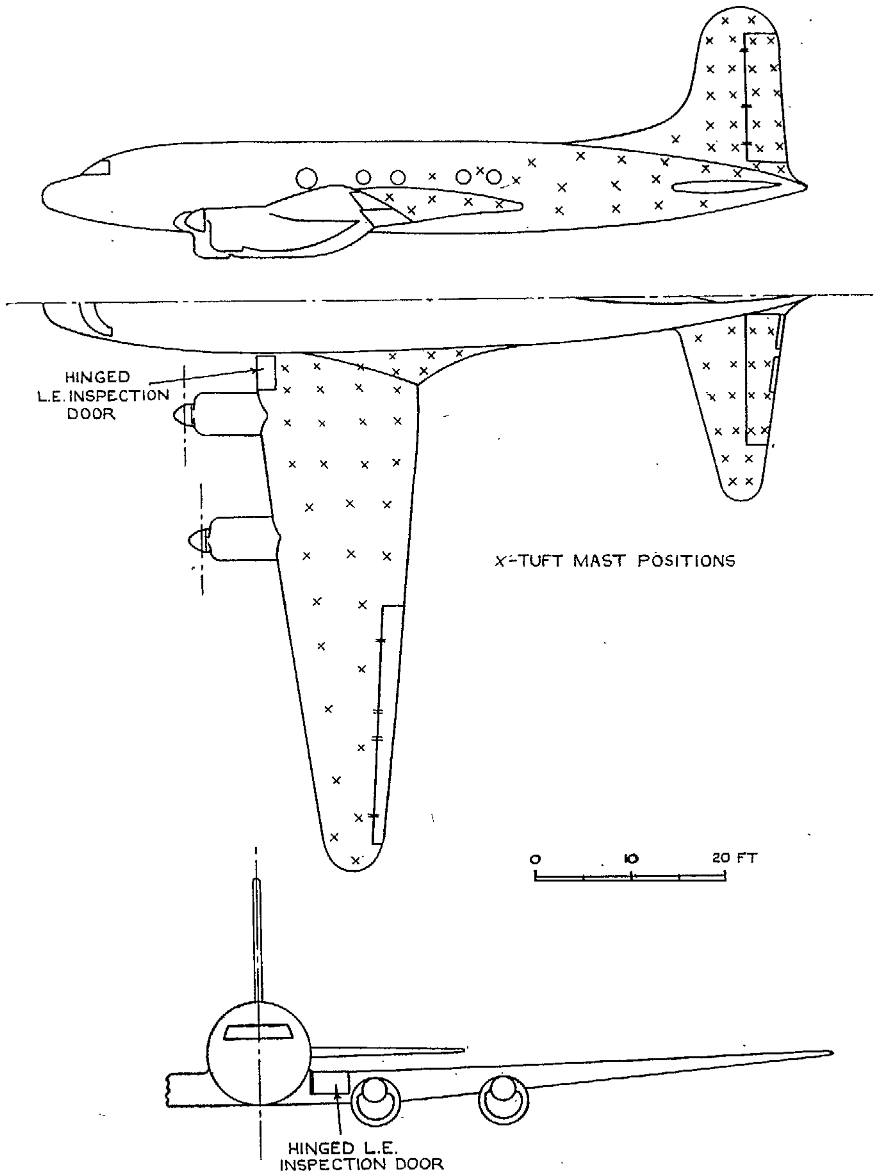

FIG. 1. Three-view general arrangement drawing of *Tudor I* with large fillets showing deep-tufting positions.

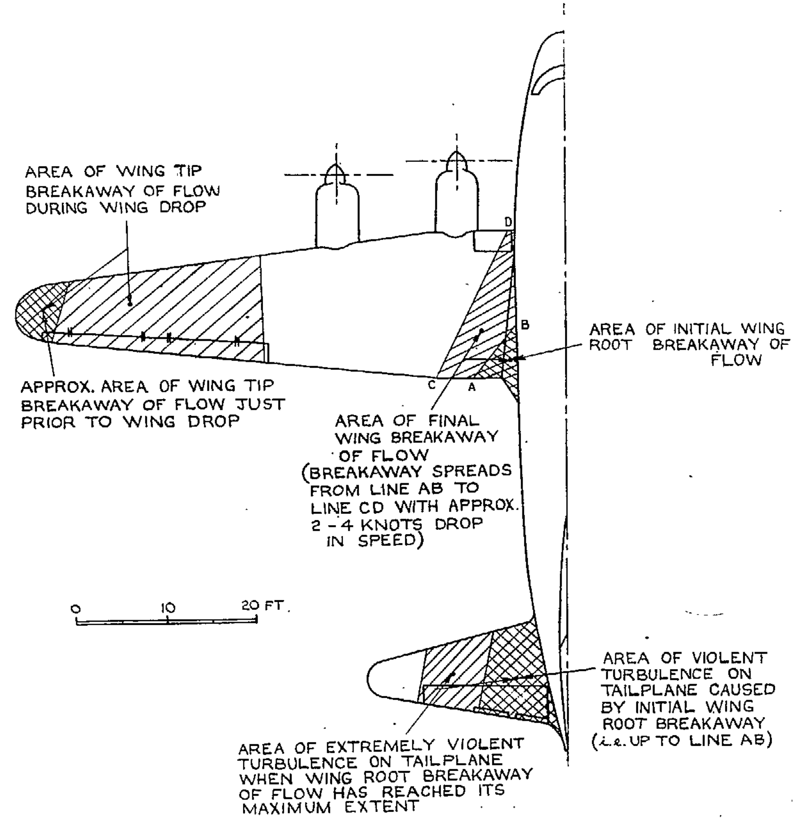

FIG. 2. Sketch illustrating flow breakaway on wing and tailplane of aircraft at the stall (engine on or glide, flaps up or down) as shown by ' deep-tufting.' (Small wing root fillets.)

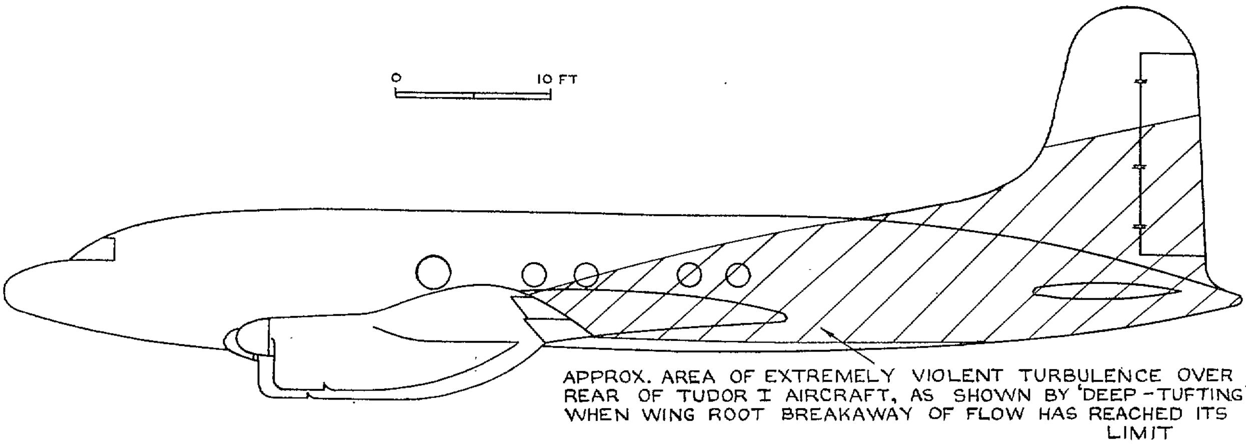

FIG. 3. Sketch illustrating flow breakaway over fin and rudder at the wing root stall.

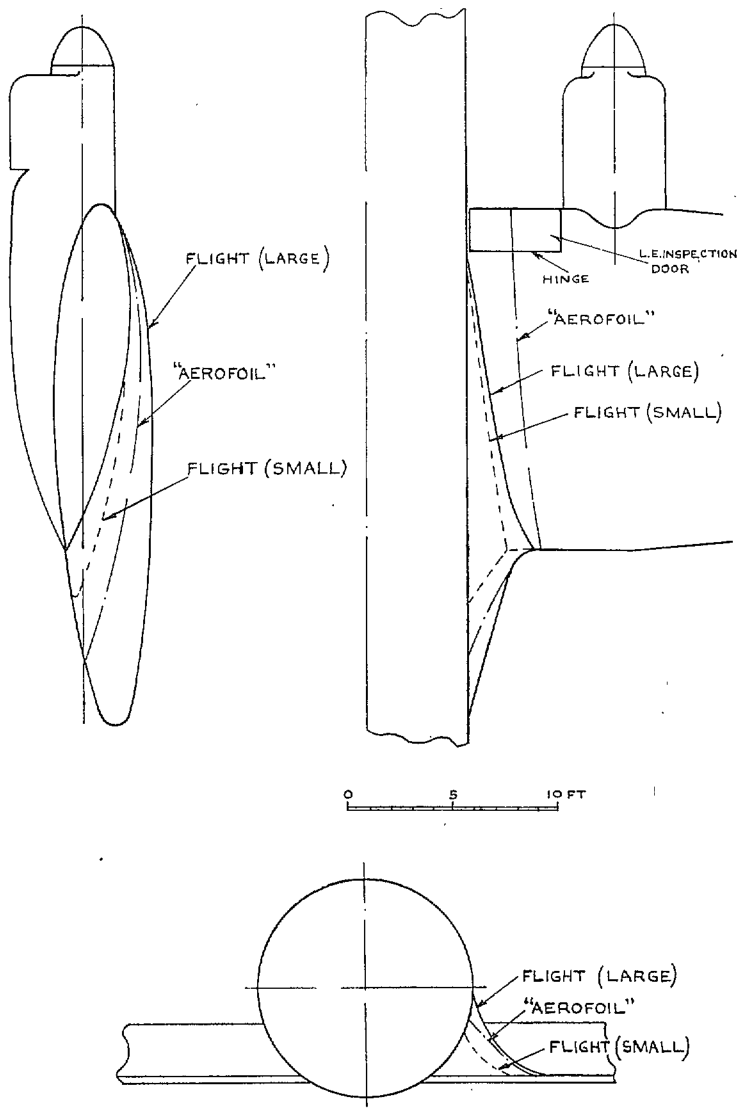

FIG. 4. Sketches of wing root fillets flown on the aircraft.

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