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By

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Summary.—This report describes an investigation into the hydrodynamic qualities of a *Sunderland* flying-boat hull, weight 50,000 lb, fitted with a main-step fairing of fairing ratio 17 : 1. The fairing was equipped with ventilating ducts, drawing air at atmospheric pressure through ports on the hull side, and discharging it through exit vents on the afterbody planing bottom. No pumping apparatus was fitted, the airflow being induced by the sub-atmospheric pressures on the fairing.

The main conclusions of the investigation may be summarised in this manner:

(*a*) A highly faired hull of this kind is hydrodynamically satisfactory, with a ventilating area equivalent to $0 \cdot 042$ (beam)^2 placed immediately behind the main-step line.

(*b*) For satisfactory hydrodynamic behaviour, the step line, *i.e.*, the junction between forebody and afterbody must be kept sharp, but only an angular discontinuity in the vertical plane is necessary.

(*c*) Without ventilation, the highly faired hull exhibits severe hydrodynamic instability during take-off and alighting, and the resistance is about 30 per cent higher than the ventilated hull.

(*d*) Pressure measurements on the afterbody indicate that skipping instability is caused by the presence of a region of sub-atmospheric pressure, covering almost the whole afterbody during skipping, and having maximum suctions of up to 4 lb/sq in. occurring at about $0 \cdot 4$ beam lengths aft of the step line.

The general conclusion of the investigation is that successful hulls may be designed without conventional steps, provided that sufficient internal ventilation is provided.

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1. *Introduction.*—The trend towards higher cruising speeds for modern aircraft which followed the advent of jet and propeller-turbine engines has emphasised the necessity for reducing the air drag of seaplane hulls. The principal sources of drag on a contemporary seaplane hull, over the corresponding streamline shape, are the main step, the chines and the hull camber. Of these, the greatest source is the main step, which may account for as much as 25 per cent of the hull drag, compared with 8 per cent for camber and chines[1].

In an effort to eliminate this step drag, without affecting the hydrodynamic qualities of the hull, the Marine Aircraft Experimental Establishment has, within recent years, conducted a series of full-scale tests on hulls having fairings of varying degree over their main step. Because the tests were necessarily limited to existing types of aircraft, no attempt was made to investigate the hydrodynamic consequences of reducing drag from chines and hull camber, and the type of fairing investigated was limited to simple fairings in elevation, as opposed to the streamline fairing[2].

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This report presents the results from the final full-scale tests done on a *Sunderland* flying boat fitted with a fairing having a fairing ratio of 17 : 1, and incorporating varying degrees of afterbody ventilation.

A detailed commentary on the results is given in section 5, but a quick appreciation of the design implications of the investigation may be obtained from sections 10 and 11.

2. *Historical.*—The *Sunderland* tests represent the culmination of a series of full-scale experiments on various aircraft, extending over a period of ten years.

The first full-scale investigation of step fairings was made at the M.A.E.E. on the prototype *Sunderland* during 1940 and 1941[3,4]. These tests showed that when the step was faired by a simple elevation fairing of concave section, a limit was set to the length of fairing by the deterioration in longitudinal hydrodynamic stability during take-off and landing. When the fairing ratio approached 9 : 1, an instability occurred at high planing speeds during which the aircraft was thrown clear of the water in every cycle—the so-called ' bounce porpoise ' or ' skip '. Examination of the possible causes of this unstable motion confirmed that the most likely cause was the presence of sub-atmospheric pressures on the planing bottom afterbody, brought about by the reduced wake clearance of the faired step.

Various investigations suggested that the instability might be overcome by providing apertures in the fairing connected to the outer atmosphere and this scheme was first tried full-scale on an American flying boat which, although not fitted with a faired step, did have dangerous skipping tendencies. The application of internal ventilation to this hull produced disappointing results, probably because the ventilating area was too small.

A systematic series of tests was next undertaken on the *Saro* 37, a small four-engined British flying boat, which was tested with fairings of increasing fairing ratio from 6 : 1 up to 20 : 1. The possibility of using ' forced ventilation ' was first investigated on this aircraft. Instead of being connected to the hull interior, the ventilating apertures on the fairing were supplied with a flow (80 lb/min) of air under pressure, from a centrifugal air compressor. By this means, it was hoped to reduce the planing-bottom ventilating area necessary for a given fairing. However, the investigation showed clearly that a well-designed natural ventilation system was preferable to forced ventilation and that fairing ratios up to 15 : 1 were satisfactory with ventilation[5,6].

Having demonstrated these facts on a small aircraft, the final stage was the design and construction of an extreme step fairing on a large aircraft which would embody all the design experience collected and would enable the effect of such variables as ventilating area, step form and aperture positions to be investigated. A *Sunderland* Mk. 5 aircraft was chosen—being most readily available—and the forward half of the afterbody modified to accommodate a ventilated step fairing of 17 : 1 fairing ratio. The test programme on the aircraft covered the period July 1948 to July 1950.

3. *Description of Fairing and Ventilation System.*—The test aircraft was basically a standard *Sunderland* Mk. 5, the main step and afterbody of which had been modified to incorporate a 17 : 1 step fairing. Figs. 1, 2 and 3 show the modified hull and its relation to the original hull. In order to keep the junction of afterbody and forebody as smooth as possible, a machined light alloy strip was introduced on the original step line, and forebody and afterbody plating butted to it (Fig. 3).

For the greater part of the test programme, the forebody–afterbody junction was ground to an edge, giving a mean forebody–afterbody angle at the step of 12 deg. To check the sensitivity of the hydrodynamic performance to the form of the step junction line, a few tests were made with a circular arc of 12-in. radius replacing the sharp edge.

Refs. 5 and 6 showed that afterbody ventilation has two functions; it must help to separate the flow at the step line when the forebody–afterbody angle is small, and it must provide relief to the afterbody suctions caused by insufficient clearance between the afterbody and the wake from the forebody. Figs. 4 and 5 illustrate the application of these principles to the *Sunderland* fairing. Four ventilating ports (total area 4 sq ft) were placed immediately behind the step line to help breakaway, and four additional ports (total area 4 sq ft) were placed at 0·89 beam lengths aft of the step line, in the region assumed to experience maximum suction.

All the ventilating ports were naturally ventilated, *i.e.*, they relied on the afterbody suctions to provide the necessary ventilating air. The method of construction is illustrated in Fig. 4. Each port was connected to a porthole in the side of the hull by way of a light-alloy duct. The duct inlets were flush with the skin plating, *i.e.*, no use was made of ram pressure to provide additional flow. To enable the effect of varying ventilation area to be investigated, each port was provided with a flush-fitting sealing cover which could be screwed to the afterbody skin plating. The interior ducts on the port side of the hull had provision for measuring the total flow of ventilating air.

4. *Range of Investigation.*—A total number of ten different configurations of ventilating area and step-line form were tested. For ease of reference, these are summarised in Fig. 6. The primary effects of these changes were expected to appear as alterations to the hydrodynamic longitudinal stability in landing and take-off and to the hydrodynamic resistance. Quantitative assessments of these parameters were made. Spray and hydrodynamic directional stability were expected to be but slightly affected and qualitative assessments only were necessary. No attempt was made to measure any alterations in aerodynamic performance which could be attributed to the fairing.

The basic test programme was performed at a weight of 50,000 lb and a c.g. position 3·02 ft forward of the main-step keel. A few tests were performed at 60,000 lb weight, c.g. 2·8 ft forward of step, and at 50,000 lb weight, c.g. 2·5 ft forward of step: these were confined to the hull with step line sharp and all vents open.

4.1. *Take-off and Constant-speed Run Stability.*—Most of the hydrodynamic stability tests under power were done during take-offs with full take-off power. Where the stability was in doubt, the doubtful regions were checked by runs at constant speed, or by reduced power take-offs. During each test run, the elevator position remained constant, a number of runs being made to cover the widest possible elevator range. Zero flap setting was used for all tests except those at 60,000 lb weight, when the flap setting was increased to 8 deg to avoid unduly long runs.

4.2. *Landing Stability.*—The technique employed for assessing landing stability was similar to that described in the reports on the *Saro* 37 tests[5, 6]. The pilot was given only a general instruction before beginning the approach, *e.g.*, ' high-attitude landing ' ' normal landing ', ' stall landing '. He was allowed a free hand on the approach and could use engine if necessary, to put the aircraft into the required position. Immediately on touch-down, the engine power was reduced to idling value and the elevator position fixed. During and after touchdown, the elevators remained in this position and the engines remained at idling power. Using this technique, the rate of descent at touch-down was usually small, about two or three feet per second.

All landings were made with a flap angle of 16 deg.

4.3. *Afterbody Pressure Measurements.*—To substantiate the inferential evidence on the mechanism of skipping and afterbody ventilation drawn from the stability results, direct measurements were made of the pressure distribution over the faired afterbody. A number of strain-gauge type pressure pick-ups were mounted on the starboard afterbody planing bottom and connected by way of a suitable amplifying apparatus to a 15-channel Miller type recording galvanometer (Fig. 7). The pick-ups and recording apparatus are described in detail in Ref. 7. For these tests, pick-ups with a working range of ± 10 lb/sq in. were utilised. Pressure measurements were made for only a limited number of ventilation configurations, principally those with small or zero ventilating area.

4.4. *Tests with the Standard Sunderland Hull.*—To provide a basis for evaluating the operational suitability of the faired hulls, take-off and landing tests were made on a standard Mk. 5 *Sunderland* utilising the same experimental and analytical techniques for assessing the hydrodynamic behaviour. The standard aircraft was tested at weights of 50,000 lb and 60,000 lb, c.g. 3·0 ft forward of step keel.

4.5. *Instruments.*—In addition to the electronic equipment described in section 4.3, the following instruments were employed to obtain quantitative information on the hydrodynamic qualities of the test aircraft.

A Barnes type two-axes accelerometer and gyroscope was used to measure attitude and longitudinal acceleration. This instrument was synchronised with an automatic observer, containing :

four air-speed indicators, recording airflow through the ventilating ducts

two low-reading air-speed indicators, recording aircraft speed—one connected to a pitot in venturi and static reservoir, and the other connected to a pitot in venturi and the aircraft static vent system

four boost gauges and four r.p.m. indicators, recording engine power

a Desynn indicator, recording elevator angle

a Desynn indicator, recording longitudinal acceleration from a Desynn type accelerometer

a Veeder counter operated by the timing system of the two-axes accelerometer and gyroscope, and synchronising these with the automatic observer instruments.

The airflows in the ventilating ducts were recorded by a pitot–static system, consisting of a static-hole in the side of each duct and three pitot-heads, positioned across each duct, such that a mean of their readings gave the mean airflow velocity in the duct.

5. *Longitudinal Hydrodynamic Stability Results.*—5.1. *Full Ventilation, Step Sharp.*—The stability diagram for take-off with full ventilation follows the normal pattern for a hull with good hydrodynamic stability (Fig. 8). Upper-limit porpoising could be achieved only at elevator angles of −10 deg to −15 deg (*i.e.*, elevators fully up), and the maximum amplitude of porpoising never exceeded 2 deg. Porpoising amplitudes of up to 6 deg were achieved in the lower instability region, but then only at extreme elevator positions, about + 15 deg, and porpoising could be checked immediately by an appropriate elevator movement. There was no evidence of the violent type of skipping instability which occurred during the *Saro* 37 tests, neither was there any sign of increased resistance near take-off, owing to undue afterbody wetting (*cf.* Ref. 5, section 6.11). With the elevators fully up, the aircraft left the water in a semi-stalled condition and occasionally made contact after a few seconds of flight. This is predominantly an aerodynamic phenomenon and there was no sign of hydrodynamic skipping, even on the second touch-down.

Landing stability for this configuration was excellent (Fig. 9). The aircraft was alighted over a range of keel-datum attitudes from 5 deg (fast landing) to 10 deg (near stall) without skipping. Near the stall there was a tendency to porpoise after touch-down, with the elevators fully up, but the amplitude was small (maximum 3 deg), and the oscillation damped out after one or two cycles.

5.2. *The Effect of Reduction in Ventilation Area, Step Sharp.*—5.2.1. *Forward outer ducts sealed.*—For these tests, the outlet of each forward outer duct was sealed off by means of a flush-fitting plate (Fig. 2). The stability and trim results for this arrangement are given in Figs. 10, 11 and 29 respectively. There was little or no change in hydrodynamic longitudinal stability in either take-off or landing, but a rather disconcerting motion occurred in the hump region. This appeared in the form of a sudden yaw to port or starboard, at a water speed of 40 to 45 knots, which caused pilots some concern until they became accustomed to it. The phenomenon is probably attributable to some asymmetry in the breakaway of flow behind the main-step line. Some confirmation that this is so is given by the pressure records of Fig. 46.

5.2.2. *All aft ducts sealed.*—In this state, the hull had all the aft ducts sealed off and all the forward ducts open to atmosphere. Landing and take-off stability and trim curves are given in Figs. 12, 13 and 30. Stability during take-off and landing deteriorated, compared with the fully ventilated hull. Mild skipping occurred at high speed (50 to 60 knots) and high attitude (keel attitude = 10 deg) during take-off, and after touch-downs at keel attitudes between 9 and 10 deg. These attitude–speed regions are well beyond those used normally, and pilots were not unduly worried by the skipping when it did occur. Stable landings were occasionally accompanied by some movement in heave after touch-down, which could not be attributed entirely to sea conditions. This motion was never dangerous and, at its worst, only slightly uncomfortable to the occupants of the flying boat.

A check was made of the hydrodynamic stability of this hull configuration in waves of 2 to 5 ft height and 20 to 50 ft length accompanied by a wind of 19 to 20 knots. The water performance was not markedly different from that of a standard *Sunderland* Mk. 5 in similar sea conditions. A heaving motion occurred immediately after hump speed and was probably akin to that noted in calm-water landings—it was not dangerous. Alighting was satisfactory.

5.2.3. *All aft and forward inner ducts sealed.*—Only a few tests were done at this hull configuration ; it was regarded as an intermediate step to tests with no ventilation at all. On take-off, the range of the skipping instability region increased and the motion was more severe than that described in section 5.2.2. (Fig. 14). Skipping was encountered whenever the touch-down attitude was greater than 6 deg, varying in severity depending on the rate of descent at the touch-down point (Fig. 15). The directional instability noted in section 5.2.1 re-appeared in a more severe form, the hull performing a ‘ corkscrewing ’ motion over the hump on occasions.

5.2.4. *All ducts sealed.*—In this state the aircraft was difficult to control during take-off and alighting, and would have been dangerous in the hands of a pilot unused to severe skipping (Figs. 16, 17). Stable take-offs could be made by keeping the elevators down for most of the take-off run and then pulling the aircraft off the water sharply at high planing speed (75 knots). Stable landings could be made by touching down at keel attitudes below 4 deg, with elevator central. Any attempt to stray beyond these limitations caused skipping, severe in take-off and violent in landing. Directional stability during take-off deteriorated further, although it was still controllable by judicious use of asymmetric power.

5.3. *The Effect of Rounding the Step Line.*—For all the tests described in sections 5.1 and 5.2, the junction between forebody and afterbody was ground to an edge and painted. Subsequent painting of the planing bottom reduced the sharp junction to one having a radius of $\frac{1}{4}$ to $\frac{1}{2}$ in. To check the sensitivity of the hydrodynamic performance to the form of the step line, a series of tests was made with a circular arc of 12-in. radius replacing the sharp edge (Fig. 3).

5.3.1. *Full ventilation.*—From the evidence of the first few tests on this configuration, there appeared to be little change in hydrodynamic performance, compared with the sharp step version. However, as the range of investigation widened, certain deteriorations in stability were revealed. At high planing speed (75 to 85 knots), during take-off, a porpoising motion of increasing amplitude occurred when the elevators were more than two-thirds down (Fig. 40b). Although this was indistinguishable in form from normal lower limit porpoising, the unstable region lies well above the normal lower limit (Fig. 18), and the motion, therefore, cannot be attributed entirely to the forebody.

The behaviour in landings was interesting, in that it showed a reversal of the usual stability pattern (Fig. 19). At high touch-down attitudes, about 10 deg, slight porpoising occurred. At lower attitudes, about 7 deg, the touch-down was stable, but the attitude usually increased immediately after touch-down, bringing the hull again into the upper instability region (Fig. 41b). This increase in attitude could be checked by a small forward movement of the control column, and its effects were often masked by involuntary pilot correction. When the touch-down attitude was decreased to 4 or 5 deg, the attitude increase was greater and occurred more violently, resulting in a skipping motion.

5.3.2. *Front duct area halved.*—With the step line still rounded, the front duct area was halved by means of metal liners inserted in all four original ducts (Fig. 5). The liners were designed to reduce the duct area without causing undue restriction to the airflow to the planing bottom.

The result of this modification was a further deterioration in hydrodynamic performance. During take-off the instability occurring at high speeds was extended to all take-off attitudes (Fig. 20), and caused a form of ' bounce porpoising ' at attitudes over 10 deg. At touch-down, skipping and porpoising occurred over the available range of touch-down attitudes, with violent skipping below 5 deg.

This investigation was forcibly abbreviated by damage to an auxiliary float during a skip landing.

5.3.3. *Aft outer ducts sealed.*—For this part of the investigation, the front duct area was restored to its original value and flush-fitting plates fitted over the exits of the two aft outer ducts.

There was little difference in hydrodynamic longitudinal stability compared with that obtained by halving the front duct area. The porpoising region in take-off was confined to higher speeds (Fig. 22), and the severity of skipping in landing was not so great (Fig. 23). The worst skipping after touch-down still occurred at low attitudes. Touch-downs at higher attitudes were usually accompanied by porpoising which persisted down to hump speed. This was of 5 to 7-deg amplitude, but was not dangerous.

5.3.4. *Aft inner ducts sealed.*—This configuration was tested to discover whether there was any significant difference in the contribution of the outer and inner ducts to hydrodynamic stability. Only a few take-offs and landings were made. These confirmed that the hydrodynamic performance was not appreciably different from that with the aft outer ducts blocked.

5.3.5. *All aft ducts sealed.*—With all the aft duct exits closed, the aircraft was dangerously unstable. The porpoising which occurred near take-off speed with one duct closed, deteriorated into skipping (Figs. 24, 40c), and skipping during landing was accompanied by violent porpoising (Figs. 25, 41c), quite beyond the control of the pilot. After a few take-offs and landings, the tests were terminated to avoid damage to the aircraft.

5.4. *The Effect of Weight Increase and C.G. Movement.*—To check the effect of variations in aircraft weight, and c.g. movement, tests were made on the original hull—step sharp, full ventilation—at a weight of 60,000 lb, and at a weight of 50,000 lb, with the c.g. near its aft limit (Table 1).

An increase in weight to 60,000 lb produced the expected raising of the lower stability limit; the upper limits remained unchanged. The aircraft was satisfactory in sheltered water, but the narrow stable band at 35 to 40 knots led to porpoising of 7 deg amplitude in a swell of 1-ft to $1\frac{1}{2}$-ft height. The instability damped out automatically at higher planing speeds. Evidence on the *Solent* flying boat indicates that this narrow stable band would cause porpoising in swells of 150 to 200-ft length, but that this would not be dangerous, provided the acceleration in the critical region was good, *i.e.*, about $0 \cdot 1g$.

Alighting at 60,000 lb was confined to those touch-down attitudes used in normal practice, because of structural limitations. Within this range, no instability was encountered.

Take-off stability at 50,000 lb, c.g. aft, was not different from that with the more forward c.g. position utilised for the rest of the investigation. Control on the approach was more difficult, because of the reduction in aerodynamic static stability, and there was a tendency to balloon when the pilot checked before touch-down. In spite of these difficulties, stable landings were achieved over the available attitude range.

5.5. *Standard Sunderland Hull.*—At a weight of 50,000 lb, the standard hull had longitudinal stability properties very similar to those of the fully faired hull with ventilation from the forward ducts only (Figs. 12, 26). Qualitative impressions from pilots and observers suggest that, when skipping did occur, the heaving motion was more severe for the fully faired hull, but that otherwise the two were equally good.

Comparison at 60,000 lb weight is difficult because of the paucity of results from the fully ventilated, faired hull. At 40 knots water speed, the faired hull appeared to have a smaller stable region than the standard hull. Too much emphasis should not be placed on this comparison, because the results for the faired hull were obtained while taking-off outside the sheltered water test base and a slight swell was running during the tests.

6. *Take-off Trim Results.*—Care should be taken when examining the take-off trims not to read too much significance into them. Trim is affected by a number of interdependent factors, and the most obvious interpretation of a given effect may not be the correct one.

However, one or two trends are clearly defined. The trims for the fully ventilated hull are similar to those for the standard *Sunderland* hull at the hump speed, but during planing the two sets of curves diverge by as much as 2 deg over the whole elevator range. The faired hull gives the higher trims (Figs. 28, 37).

Reasons for the characteristic kinks in the trim curves with the forward outer vents sealed have been discussed elsewhere in the report (section 10.3). These kinks in the curves also occur with all vents closed and, to a lesser degree, with the forward inner vents closed. Sealing the aft vents appears to have little effect on trim (Figs. 30 to 32).

When the step is rounded, large trim changes occur, particularly at positive elevator positions. The elevator effectiveness from elevator central to elevator 12 deg down is reduced by about 30 per cent, compared with the corresponding sharp-step hull, and the minimum planing angle with 12 deg of down elevator is 6 deg, compared with 3 deg, for the basic hull (Fig. 33). At negative elevator angles, greater than 5 deg, the trim curves for basic and rounded-step hulls agree.

7. *Resistance Results.*—In Figs. 42 and 43 are compared the longitudinal accelerations during take-offs with varying amounts of ventilation. With elevators central, the fully ventilated and half ventilated hulls have similar acceleration curves. Reducing the ventilation area to zero causes a marked increase in resistance, which is at a maximum at 40 knots. The sudden change in acceleration occurring at this speed should be compared with the trim changes of Fig. 32. Rounding the step also increases the resistance and, at 40 to 50 knots, there is $0 \cdot 05g$ difference between the curves for rounded and sharp-stepped hulls.

At the increased trims corresponding to 10 deg of up elevator, the rounded hull has as small a resistance as the ventilated sharp-step hull, but the unventilated hull retains its increased resistance (Fig. 43).

No reliable acceleration results were available for the standard *Sunderland* at -10 deg elevator angle, but comparison with the fully ventilated hull at 0 deg and -5 deg reveals that no apparent increase in resistance is caused by the greater fairing (Figs. 44, 45).

8. *Afterbody Pressure Measurements.*—Pressure measurements were obtained with two configurations :

(*a*) step sharp, all vents sealed

(*b*) step sharp, aft vents sealed.

The results have been presented in a fashion which illustrates three aspects of the flow over the afterbody, *viz.*, the variation in pressure during a complete take-off and landing, the build-up of a single pressure wave across the afterbody, and the instantaneous distribution of pressure over the afterbody.

The first of these aspects is illustrated in Figs. 46 and 47. The pressure variations during take-off (Fig. 46) throw an interesting light on the cause of the sudden changes in attitude, resistance and directional stability which occurred at speeds of about 45 knots on the unventilated hull. Up to this speed, there appears to be a region of suction on the fore part of the afterbody keel (pick-up D), followed by a region of pressure due to wake impact (pick-ups F and J). At 45 knots (30 to 31 seconds), the wake adhesion disappears suddenly bringing about the attitude and resistance changes noted earlier. The directional instability at this speed probably results from asymmetric breakdown of the adhesion on either side of the afterbody. At 53 knots water speed, the pressures and suctions accompanying skipping instability spread rapidly across the afterbody, pressure and suction waves occurring each time the aircraft touches the water and causing repeated skips until the aircraft reaches flying speed.

A more detailed picture of one such wave is given in Fig. 48. This shows that during stable planing, there are small suctions over part of the fairing. When the attitude falls below 9 deg at a speed of 52 knots, a sudden burst of suction, sometimes led by high pressures, occurs, starting at the keel and spreading in about 0·5 sec to the chine. When the attitude has decreased to 7 deg, the whole afterbody is restored to atmospheric pressure.

The landing example (Fig. 47) illustrates the type of landing described as a ‘ delayed skip ’, during which the aircraft planes stably for several seconds after first impact, before being thrown violently off the water. During the stable planing period, appreciable suctions occur near the afterbody keel (pick-ups D, F and J), and near the sealed after ducts (pick-up H). As the speed decreases and attitude increases, these suctions become greater, until at 52 knots there occurs the characteristic dip in the attitude curve, followed by a suction wave over the afterbody and a skip. The process is illustrated more fully in Fig. 49.

With the forward vents open, the evidence of wake adhesion at speeds below 45 knots disappears. When the aircraft approaches the skip instability limit of Fig. 12, a rapid suction wave spreads across the afterbody, causing instability (Figs. 50, 52). The form is similar to that for the unventilated hull, but the intensity of pressure is less. At attitudes between the skip limit and the trim curve for elevator central, there is a relatively slow increase in suction, as the speed increases beyond 60 knots. The intensity never exceeds 0·4 lb/sq in., and no instability results. At attitudes below those corresponding to zero elevator angle, no measurable suction appears.

Similar processes to those just described take place during an alighting with the forward vents open. Fig. 51 shows the pressure results from a ‘ borderline ’ landing, *i.e.*, one in which some heave occurred, but none sufficient to throw the aircraft clear of the water. At attitudes higher than those for this landing, the suctions are greater and skipping occurs, and at lower attitudes the suctions are too small to cause appreciable motion of any kind.

The sequence of events during an unstable run is most clearly illustrated in Fig. 52. Starting with the aircraft completely airborne, the first impact is made on the rear step at about 12-deg keel attitude. No suctions are recorded until the main-step impact at 9-deg attitude, when they spread rapidly across the afterbody. The keel attitude continues to decrease for 0·2 to 0·3 seconds, before the suctions have their full effect and an increase starts. At 9·5 deg the afterbody suddenly rides clear of the wake, the attitude continuing to increase, until at 12 deg the whole aircraft becomes airborne.

Probably the most significant information for design is the instantaneous distribution of pressure over the afterbody. Typical contour diagrams for the ventilated and unventilated hulls are given in Figs. 53 to 56. A feature common to all the distributions is the presence of a ridge of low pressure midway between keel and chine. For the unventilated hull, this ridge resolves itself into a region of low pressure at a position about half-a-beam width aft of the step. The low pressure region is less well defined when the front vents are open.

The greatest differences between ventilated and unventilated hulls lie in the extent of the sub-atmospheric pressure region, and in the intensity of these pressures. The atmospheric pressure contour lies very close to the chine for the unventilated hull, and is markedly inboard for the ventilated hull: the maximum suctions average 4 to 5 lb/sq in. for the unventilated hull, and less than half of this value for the ventilated hull.

Thus, although the ventilation source is confined to the area immediately behind the step, its effect is brought about by a change in flow conditions for the whole afterbody.

9. *Airflow Results.*—The take-off airflows followed the pattern indicated in the *Saro* 37 tests. With the step sharp, all the ducts appeared equally effective, apart from the forward outer which invariably gave lower airflows than the other three. In spite of this, there was a marked increase in airflow through the remaining ducts when the forward outer was sealed. No further increase occurred as the other ducts were sealed.

When the step line was rounded, the airflows with all ducts open increased, compared with the corresponding sharp-step hull, the forward outer duct still giving the lowest flows. Sealing the aft inner duct reduced the effectiveness of the forward ducts appreciably, and increased that of the aft outer slightly. With both aft ducts sealed, these forward duct airflows remained at their reduced value.

The landing results confirm the trends indicated during take-off. All the ducts gave similar flows, apart from the front outer, which appeared to be relatively ineffective. When the step was rounded, there was an increase in maximum flows of about 1,000 cu ft/min.

10. *Discussion.*—10.1. *Hydrodynamic Stability.*—In this investigation, there are two effects to be considered; the effect of reducing ventilation area on stability, and the effect of modifications to the step line.

With the step line sharp, there occurred a deterioration in stability as ventilation was reduced very much as indicated by earlier tests. One or two aspects are worth detailed explanation. For example, although sealing of the forward outer vents had little effect on stability—and this might have been expected from the airflow results—the ' corkscrew ' motion which was induced at 40 knots water speed made this reduction in ventilation area unacceptable. A similar motion occurred when the forward inner ducts were sealed. It is undoubtedly linked with the breakdown of the small suction area which exists near the afterbody keel at speeds up to 40 knots (Fig. 46). Owing to slight asymmetry in the wake flow, this breakdown probably occurs earlier on one side of the afterbody than on the other, thus causing momentary directional instability.

Pilots who flew the aircraft considered that, with both aft ducts sealed, its hydrodynamic performance equalled that of the standard Mk. 5 *Sunderland*. The skipping instability during take-off occurred at attitudes much higher than those used for normal operation and, even when encountered, the mildness of the motion rendered it relatively innocuous. The mild skipping which took place during high-attitude alightings did so almost entirely in heave and required no undue piloting skill to correct. When both aft and the forward inner vents were sealed, the aircraft became unacceptable once more, not only because of the increased instability regions and increased skipping severity, but also because of the re-appearance of directional instability near the hump speed.

Whereas the instability with the step sharp was predominently a movement in heave, with the step rounded the pitching motion was more noticeable. Cursory examination of the stability limits (Fig. 18) suggests that this is due to a raising of the normal lower limit, but the process is not so simple as this. The instability that occurs at keel attitude of 7 deg and water speeds between 60 and 80 knots is probably a modified form of two-step porpoising. Without pressure measurements or direct observation, one can only speculate on the flow conditions round the afterbody, but one explanation of this low-angle two-step porpoising is that at 7-deg keel attitude the forebody wake is not completely separated from the afterbody by the rounded step, and there is thus insufficient clearance between forebody and afterbody to avoid instability. As the keel attitude increases, the wake begins to clear the afterbody because of improved flow separation at the main step, and instability ceases. With decreasing ventilation area, the attitude range for wake clearance decreases, and then disappears, giving a band of instability over the whole available attitude range (Fig. 24). Whatever the explanation, the effect is to make the hull with step rounding unacceptable, even with full ventilation.

To sum up: the hull with sharp step line and full ventilation is as good as the best contemporary conventional hulls; when the ventilation area is halved, the hull is still acceptable, if the area is provided immediately behind the step line; the hull with rounded step and full ventilation is unacceptable.

10.2. *Resistance.*—Little need be said about the resistance measurements; the increases in resistance are self-explanatory. Note that there is equality in planing efficiency between the standard *Sunderland* design and the faired hull with adequate ventilation and a sharp step line.

10.3. *Afterbody Pressure Distribution.*—The afterbody pressure distributions confirm the contention, made from earlier qualitative results, that there are two speed regions in the take-off run where ventilation is necessary. These are,

(*a*) at low speed where flow separation at the step is about to start

(*b*) at high speed where there is a danger of skipping instability.

Delay in the achievement of flow separation at the step results in increased hump resistance, and the transition period may be marked by directional instability, owing to the asymmetric breakdown of regions of sub-atmospheric pressure on the afterbody. The cure is the provision of ventilating areas immediately behind the step line.

At speeds near take-off, the achievement of a critical combination of speed, draft, and attitude produces a critical clearance between afterbody and forebody wake, and results in a sudden wave of sub-atmospheric pressure across the afterbody. The manner in which this wave proceeds from keel to chine suggests that the first result is an increase in draft, followed by a large nose-up moment as the forebody is immersed, and then by the skip. Thus, the forebody design may have an influence on the angular movement which usually accompanies skipping and which is its most dangerous feature.

Although the pressure distributions indicate that the region of lowest pressure is about half a beam aft of the step line, ventilating ducts away from this region are effective in reducing skipping, *e.g.*, the aft ducts on the *Sunderland.*

If the ventilating area is sufficient to keep the maximum afterbody suction below 0·5 lb/sq in. then only mild skipping will occur. Violent skipping is associated with suctions of 2 to 4 lb/sq in. spread over two-thirds of the afterbody area.

10.4. *General Discussion.*—The *Sunderland* investigation has proved that a highly faired hull, having no step in the accepted sense, can be made hydrodynamically satisfactory, with the addition of relatively small amounts of ventilating area to the afterbody planing bottom.

From these tests, certain general design principles for highly faired hulls may be deduced. Of primary importance is the condition of the step line. This must be kept sharp, and sharp for the *Sunderland* means a maximum radius of $\frac{1}{2}$-in. Some of the area required for ventilation must be placed immediately behind the step line. The area will depend on the general afterbody design, but as a first approximation, for afterbody angular breaks exceeding 9 deg—the *Sunderland* heel-to-heel angle—the *Sunderland* value of $0 \cdot 084(\text{beam})^2$ may be used. Whether or not more ventilating area is necessary will depend on the degree of fairing employed. This leads directly to the question—how much fairing is necessary to eliminate step drag ?

The only quantitative information on this subject comes from some National Advisory Committee for Aeronautics wind-tunnel tests, which indicate that there is no gain in air drag obtained by going from a 9 : 1 straight fairing to a complete main-step-to-rear-step fairing[8]. For a 9 : 1

fairing, $0 \cdot 042(\text{beam})^2$ ventilation immediately behind the step line should be adequate. For a complete fairing, the full *Sunderland* ventilation area should be sufficient (Fig. 57). The disposition of the additional area does not appear to be critical. Pressure records show that a ventilating area immediately behind the main step causes a general reduction in suctions over the whole afterbody. However, assuming that the area of maximum suction represents the optimum position, additional ventilation should be placed near the keel and between half-a beam and one-beam length aft of the step line.

A complete analysis of the influence of ventilation and afterbody design is beyond the scope of this report, but one or two trends are clear. The normal two-step upper-limit instability was very little affected by the addition of a 17 : 1 fairing to the *Sunderland*, even when the ventilation area was zero. This suggests that existing criteria for the value of the heel-to-heel angle will still apply to highly faired hulls. This must be qualified by the statement made earlier that, if a main-step-to-rear-step straight fairing is used, and the heel-to-heel angle falls below the *Sunderland* value, a ventilating area greater than $0 \cdot 042(\text{beam})^2$ may be needed behind the step line. The deadrise distribution for the fully faired afterbody will follow from the front-step and rear-step deadrise angles. The range of front-step deadrise angles utilised in main-step design is small, and the *Sunderland* value of 26 deg is still representative of present-day practice. Efforts to reduce the rear-step impact loads and pitching in waves has led to the adoption of rear-step deadrise angles slightly higher than the *Sunderland's*. Thus, there should be little danger of ventilating area greater than the *Sunderland's* being necessary on modern hulls owing to a more adverse afterbody deadrise distribution.

Nothing has been said so far on the relative merits of ventilated fairings and streamline fairings. For moderate degrees of fairing, the straight fairing shows a marked decrease in air drag over its streamline counterpart (Fig. 58)[1], but the latter does not have the added weight and complication of internal ducting. This suggests that the ultimate low-drag hulls—of conventional shape otherwise—could be achieved by combining the two conceptions to give an extreme streamline fairing, needing only a little added ventilation to make it hydrodynamically satisfactory.

11. *Conclusions.*—11.1. *Experimental.*—(*a*) A *Sunderland* fitted with a main-step fairing of fairing ratio 17 : 1 shows little deterioration in hydrodynamic qualities, compared with a standard *Sunderland* (6 : 1 fairing), provided a ventilating area of 4 sq ft, *i.e.*, $0 \cdot 042(\text{beam})^2$, is placed immediately behind the step line.

(*b*) With an additional 4 sq ft of ventilation area at 7·5 ft, *i.e.*, 0·8(beam) behind the main step, the highly faired hull has superior hydrodynamic stability compared with the standard hull, and is equal to the best modern hull designs.

(*c*) When the ventilation area is reduced to zero, the highly faired hull exhibits severe skipping instability and high hydrodynamic resistance.

(*d*) Any attempt to reduce the forward ventilating area results in directional instability at about 40 knots water speed. This is disconcerting, but not dangerous, provided the pilot is aware of its presence beforehand. The directional instability is a result of the asymmetric breakdown of flow adhesion on the afterbody, brought about by inefficient afterbody ventilation.

(*e*) If the step line is rounded to a radius of 12 in., the hydrodynamic instability characteristics are unacceptable, even with full ventilation. Porpoising occurs with elevator positions below central during take-off, and skipping at keel attitudes below 5 deg on landing.

(*f*) Skipping instability is initiated by the occurrence of a region of sub-atmospheric pressures on the afterbody. These pressures reach a maximum at 0·3 to 0·5-beam lengths aft of the step line, and fall off gradually towards the rear step and the chine. The maximum suctions are about 4 lb/sq in. below atmospheric pressure for the hull with zero ventilation, and about 1·5 lb/sq in. for the hull with the forward ducts open.

11.2. *Design.*—(*a*) With the use of afterbody ventilation, the step on a conventional hull can be reduced to a change in angle between afterbody and forebody, without unsatisfactory hydrodynamic behaviour.

(*b*) For hulls of the *Sunderland* type, a ventilating area of 0·04(beam)^2 is sufficient for a step fairing extending to half-way along the afterbody. For a complete fairing extending from front step to rear step, 0·08(beam)^2 of ventilating area may be necessary.

(*c*) At least half of the ventilating area must be placed immediately behind the step line. The remainder should lie between 0·5 and 1-beam lengths aft of the step line. The ventilating ducts should extend from the keel to a position 0·8 of the half-beam width on either side of the keel.

(*d*) The step-line junction between forebody and afterbody must be kept sharp.

(*e*) For forebody/afterbody angular breaks of less than 10 deg, a ventilating area of more than 0·08(beam)^2 may be necessary.

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2	D. I. T. P. Llewelyn-Davies	Tank tests on a hull with the main step faired in plan-form and elevation. R. & M. 2708. May, 1945.
3	G. J. Evans, A. G. Smith, R. A. Shaw and W. Morris.	Water performance of *Sunderland* K.4774 with step fairing. R. & M. 2868. April, 1941.
4	G. J. Evans and R. A. Shaw	Water performance of *Sunderland* K.4774 with a 1 : 6 step fairing. R. & M. 2868. April, 1941.
5	J. A. Hamilton	An investigation into the effect of forced and natural afterbody ventilation on the hydrodynamic characteristics of a small flying boat (*Saro* 37) with a 1 : 15 fairing over the main step. R. & M. 2463. December, 1946.
6	J. A. Hamilton	An investigation into the effect of forced and natural afterbody ventilation on the hydrodynamic characteristics of a small flying boat (*Saro* 37) with a 1 : 20 fairing over the main step. R. & M. 2714. November, 1947.
7	J. W. McIvor	Full-scale measurements of impact loads on a large flying boat. Part I. Description of apparatus and instrument installation. C.P. 182. March, 1950.
8	J. M. Riebe and R. L. Naeseth ..	Effect of aerodynamic refinement on the aerodynamic characteristics of a flying-boat hull. Report No. N.A.C.A. Tech. Note 1307. June, 1947.

TABLE 1

Sunderland Mk. 5

Data

Hull

Beam (max.)	9·79 ft
Length	62·12 ft
Length: beam ratio	6·35
Forebody length	32·94 ft
Afterbody length	29·18 ft
Unfaired step depth	0·74 ft
Forebody keel—hull datum angle	3 deg
Heel-heel angle	9·3 deg
Forebody keel—afterbody keel angle	7·5 deg
Mean forebody—afterbody angular break at step	12 deg
Forebody deadrise at step	26 deg
Main-step fairing ratio	17 : 1

Wings

Area (gross)	1,687 sq ft
Span	112·8 ft
Incidence to hull datum	6·15 deg
Section	Göttingen 436 modified

Flaps

Type	Gouge
Area	286 sq ft
Angle 1/3 out	8 deg
2/3 out	16 deg

Tailplane

Area (including elevators)	205 sq ft
Elevator area (including tabs)	84·5 sq ft
Elevator movement	16·5 deg up and down

Engines

4 Pratt and Whitney Twin Wasp R.1830–90B giving 1,200 b.h.p. at 2,700 r.p.m. and + 9 lb/sq in. boost for sea-level take-off.

Loading

At 50,000 *lb weight*

C.G. ' normal ' is 3·02 ft forward of main step at keel, parallel to hull datum line.

C.G. ' aft ' is 2·53 ft forward of main step at keel, parallel to hull datum line.

$$C_{\Delta 0} = 0{\cdot}833 .$$

At 60,000 *lb weight*

C.G. is at 2·81 ft forward of main step at keel, parallel to hull datum line.

$$C_{\Delta 0} = 1{\cdot}00 .$$

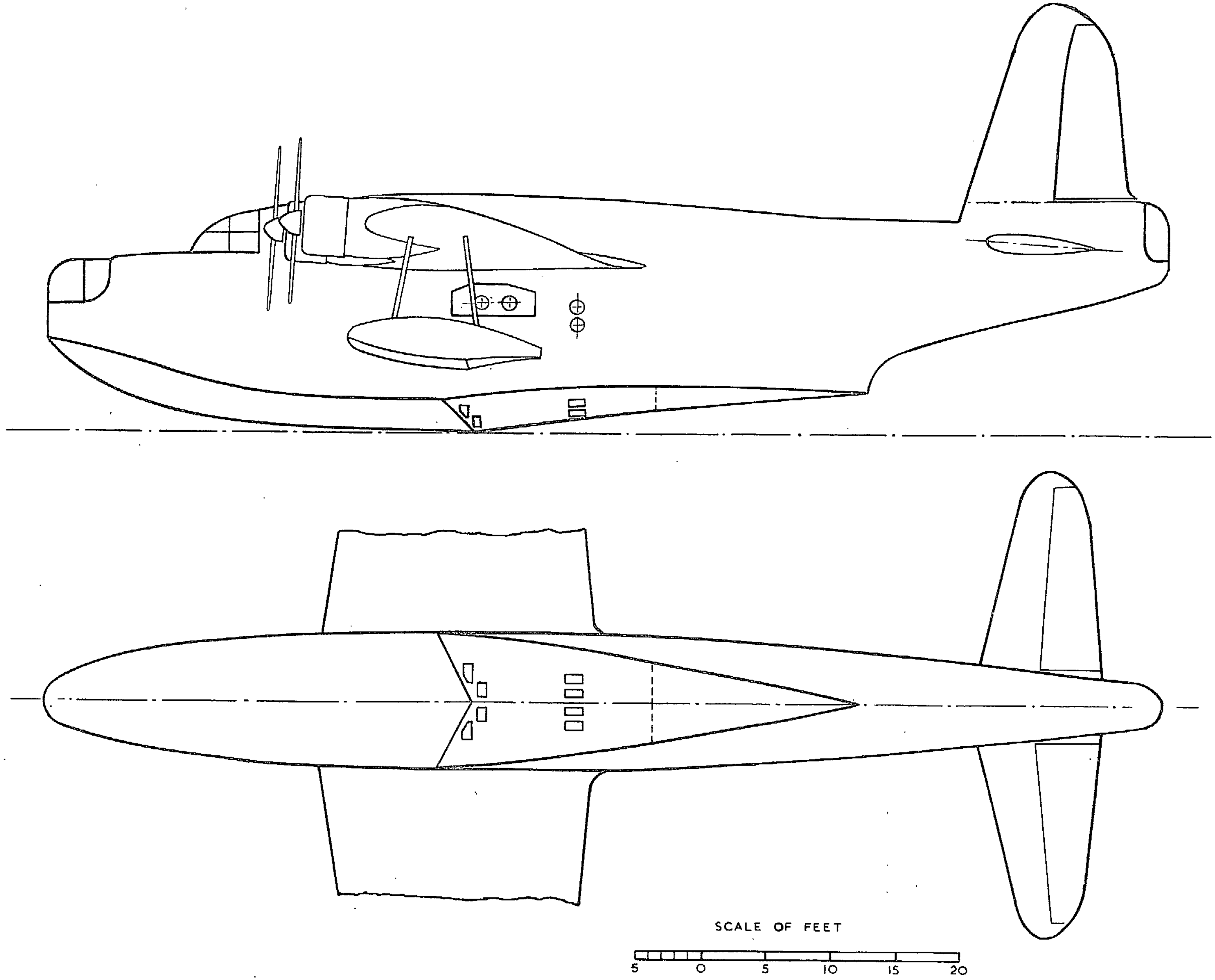


FIG. 1. *Sunderland* with ventilated step fairing. Fairing ratio 17 : 1.

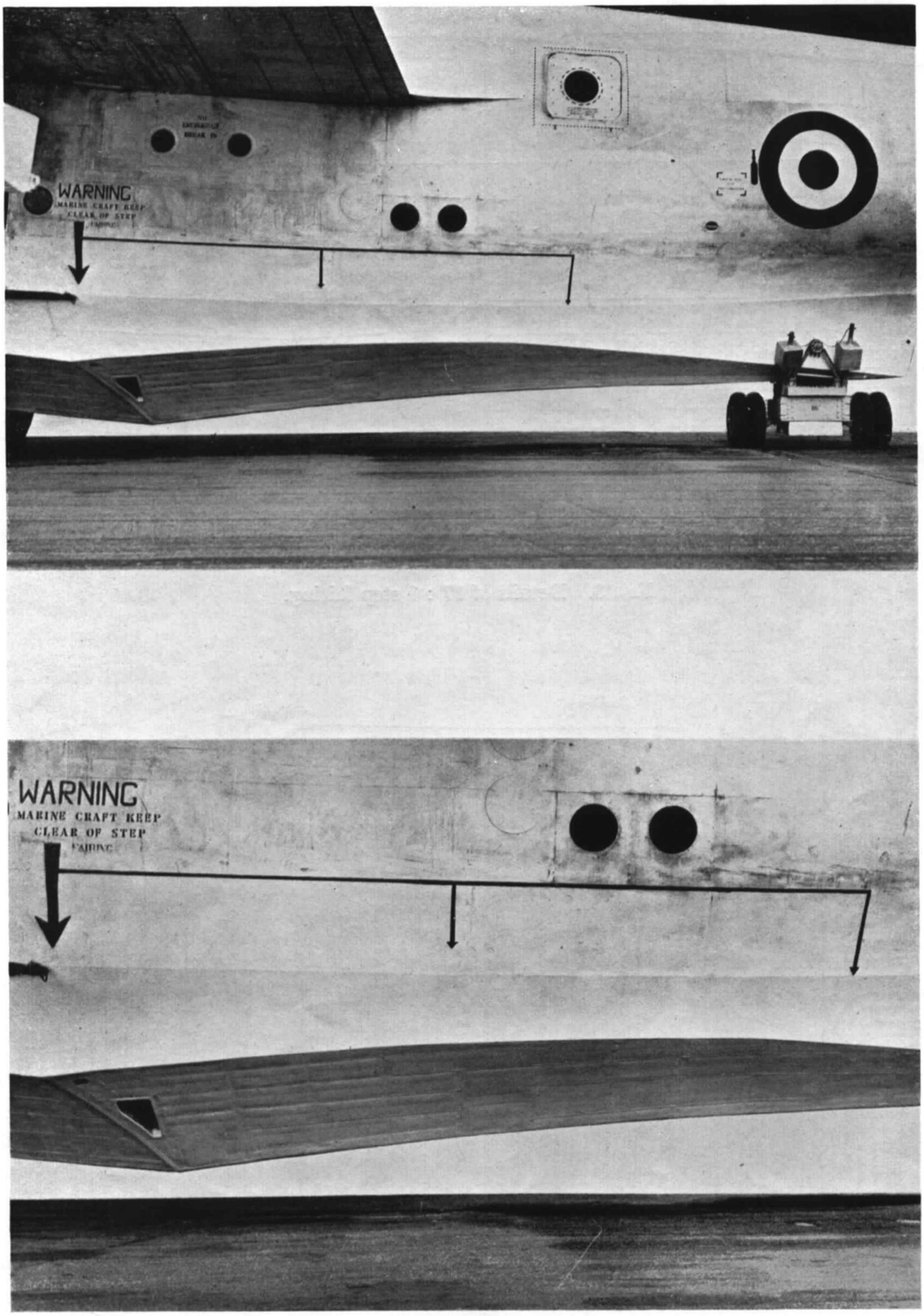
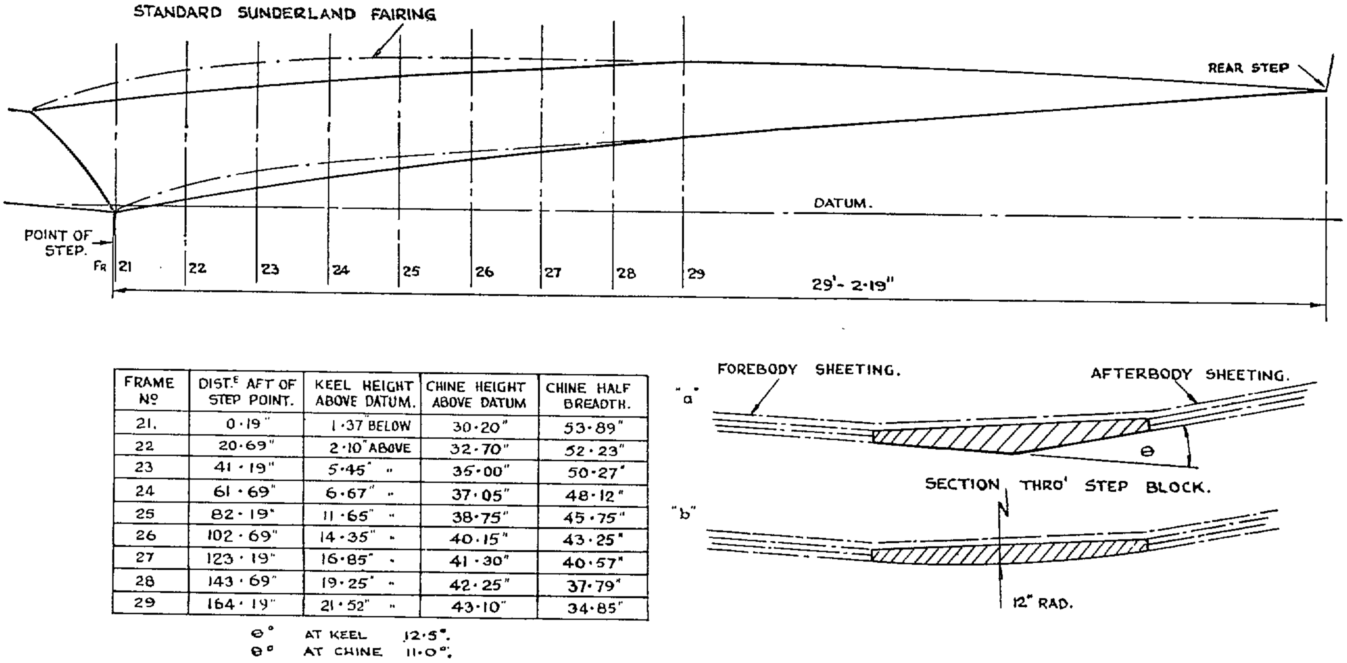


FIG. 2. Extreme fairing with all aft and forward inner vents sealed.



FRAME Nº	DIST.ᴱ AFT OF STEP POINT.	KEEL HEIGHT ABOVE DATUM.	CHINE HEIGHT ABOVE DATUM	CHINE HALF BREADTH.
21.	0·19"	1·37" BELOW	30·20"	53·89"
22	20·69"	2·10" ABOVE	32·70"	52·23"
23	41·19"	5·45" "	35·00"	50·27"
24	61·69"	6·67" "	37·05"	48·12"
25	82·19"	11·65" "	38·75"	45·75"
26	102·69"	14·35" "	40·15"	43·25"
27	123·19"	16·85" "	41·30"	40·57"
28	143·69"	19·25" "	42·25"	37·79"
29	164·19"	21·52" "	43·10"	34·85"

θ° AT KEEL 12·5°.
θ° AT CHINE 11·0°.

FIG. 3. Details of 17 : 1 step fairing.

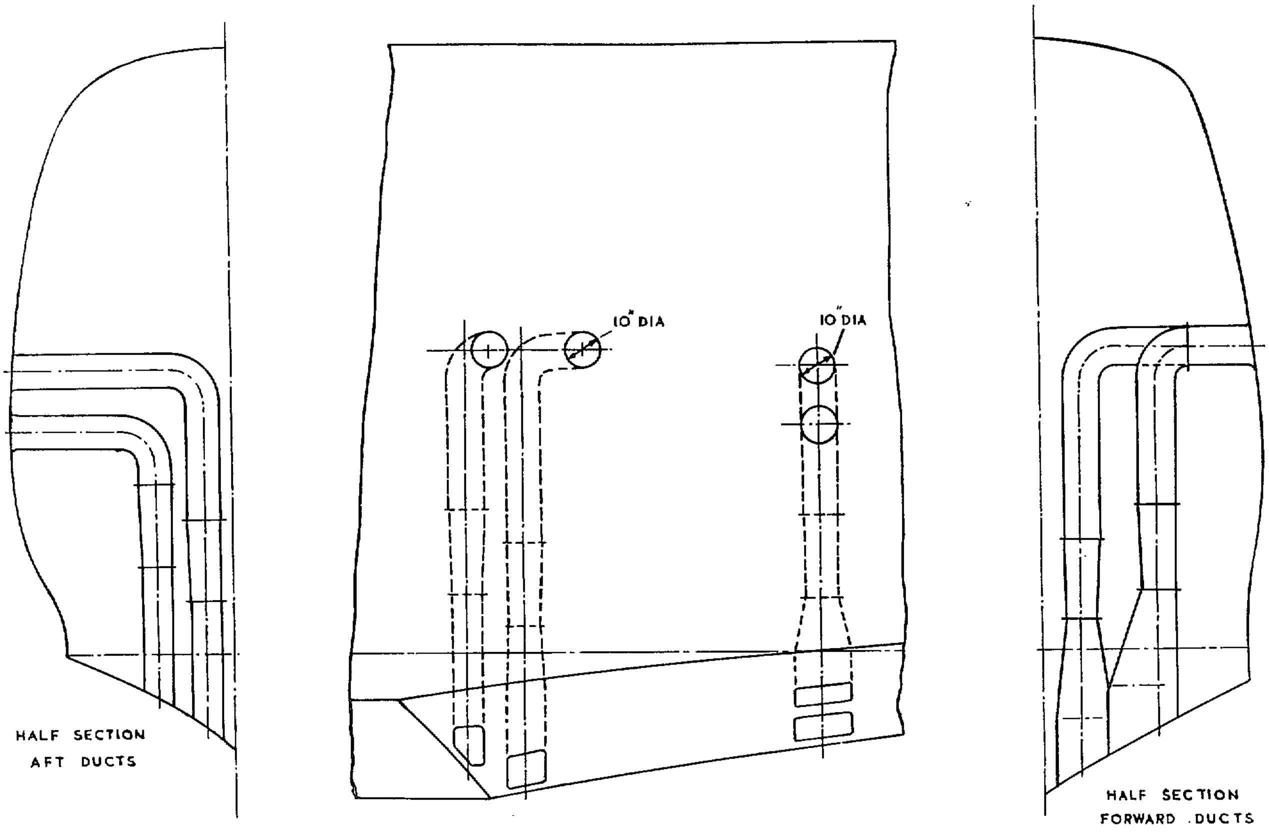


FIG. 4. Ventilating duct installation.

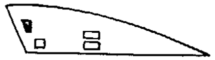
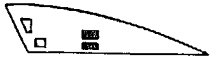
CONFIGURATION	SYMBOL
STEP LINE SHARP	
ALL VENTS OPEN	
FORWARD OUTER VENTS SEALED	
AFT VENTS SEALED	
ALL AFT AND FORWARD INNER VENTS SEALED	
ALL VENTS SEALED	
STEP LINE ROUNDED	
ALL VENTS OPEN	
FORWARD VENT AREA HALVED	
AFT OUTER VENTS SEALED	
AFT INNER VENTS SEALED	
ALL AFT VENTS SEALED	

FIG. 6. Summary of ventilation configurations tested.

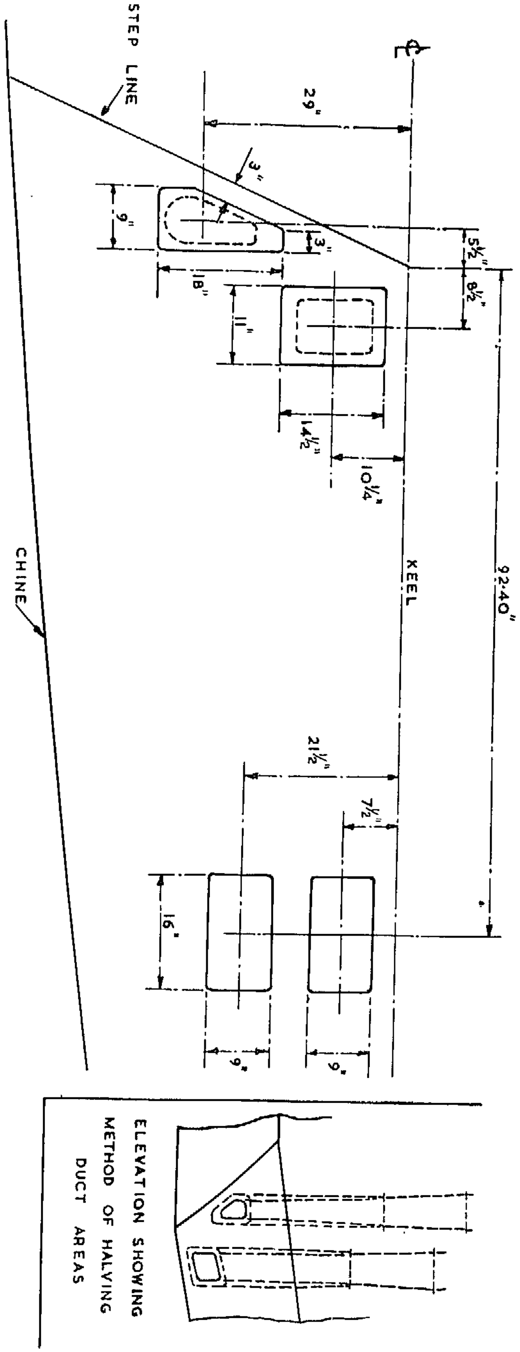


FIG. 5. Details of duct exits in planing bottom.

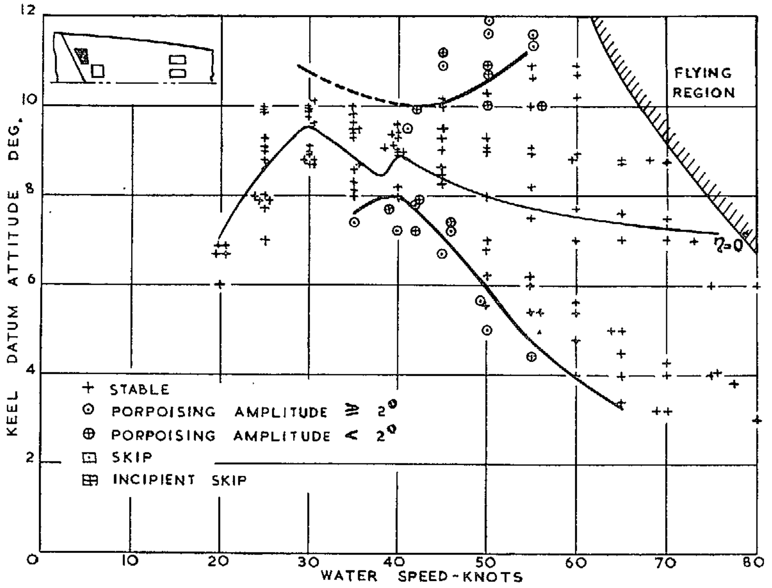


FIG. 10. Take-off stability. Step sharp. Forward outer vents sealed.

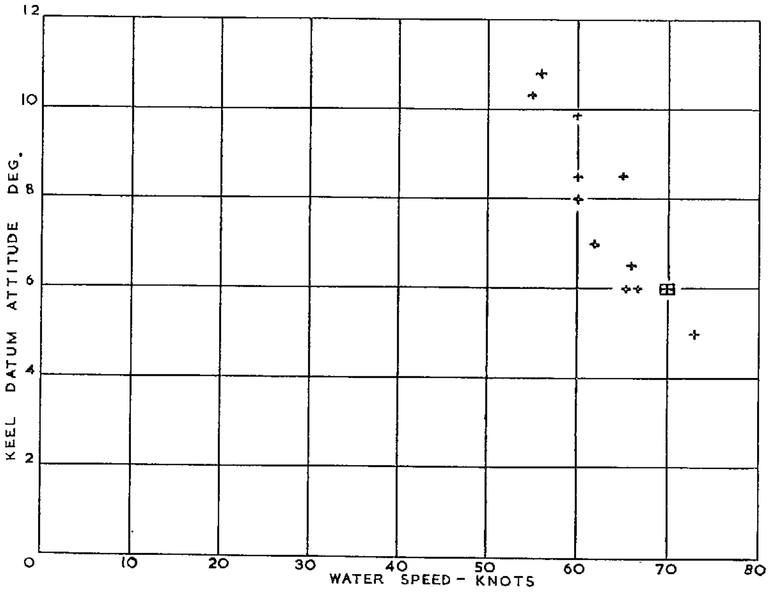


FIG. 11. Landing stability. Step sharp. Forward outer vents sealed.

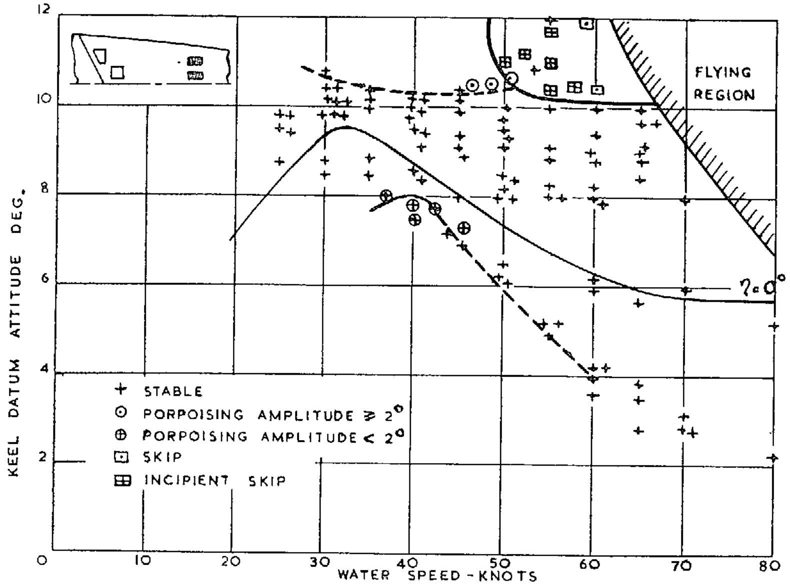


FIG. 12. Take-off stability. Step sharp. All aft vents sealed.

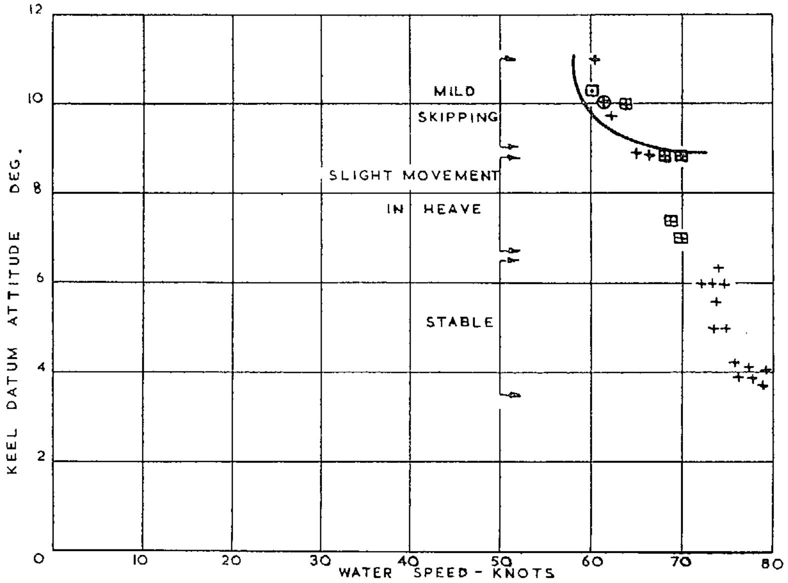


FIG. 13. Landing stability. Step sharp. All aft vents sealed.

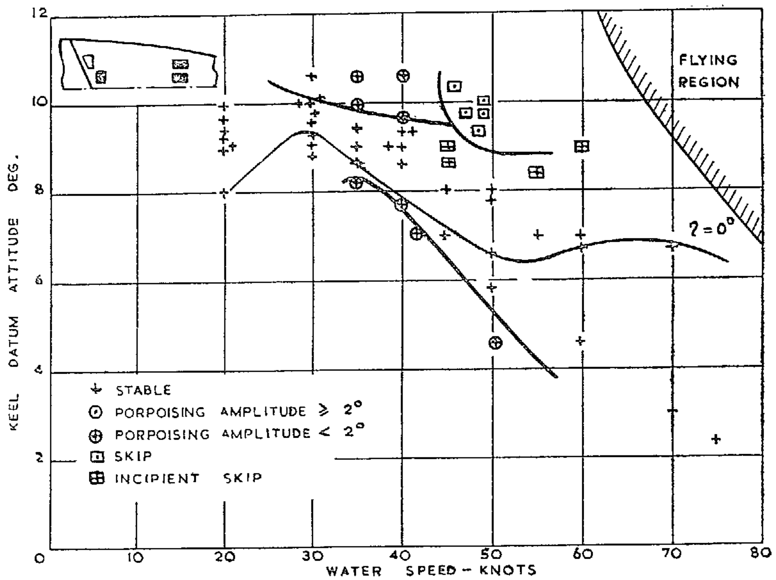


FIG. 14. Take-off stability. Step sharp. All aft and forward inner vents sealed.

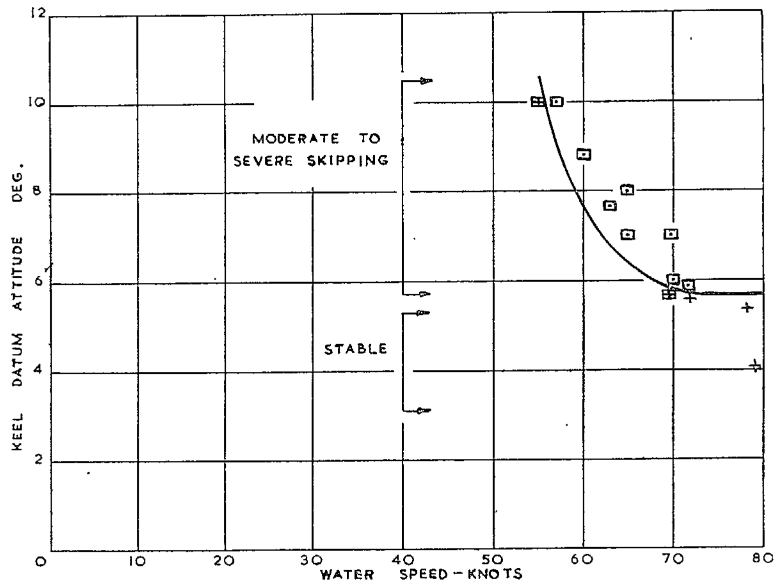


FIG. 15. Landing stability. Step sharp. All aft and forward inner vents sealed.

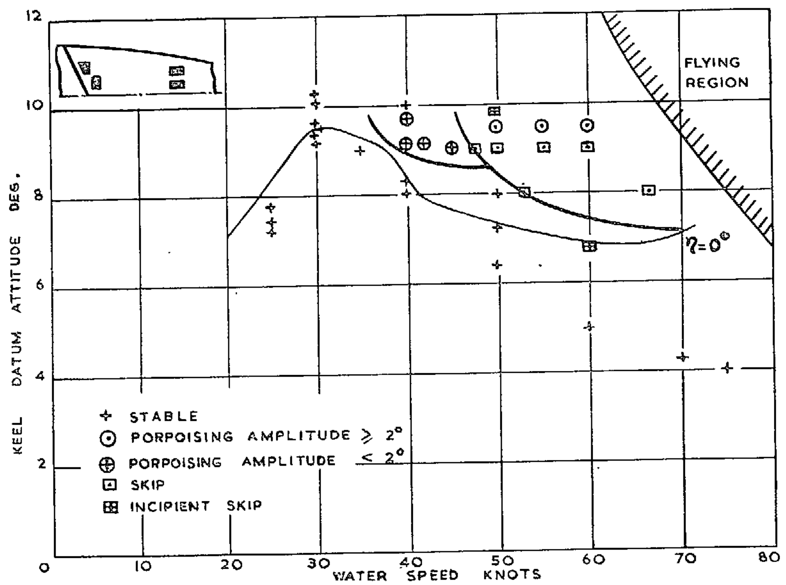


FIG. 16. Take-off stability. Step sharp. All vents sealed.

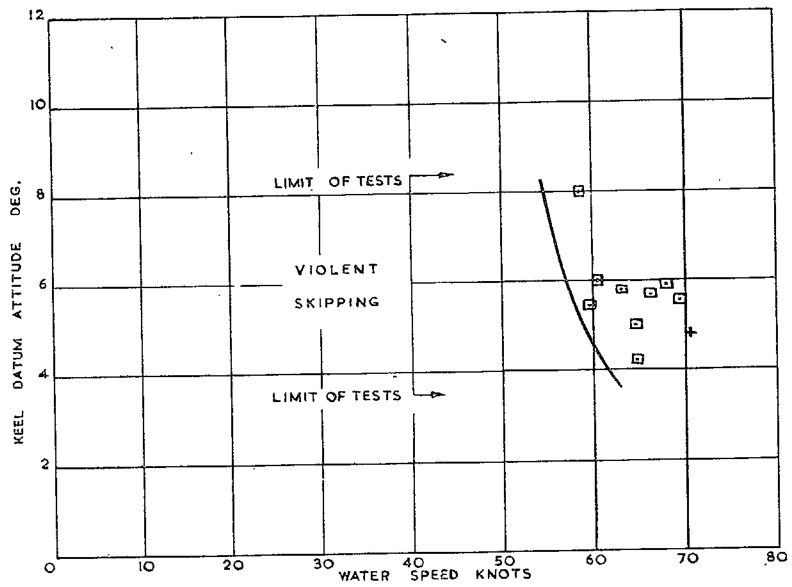


FIG. 17. Landing stability. Step sharp. All vents sealed.

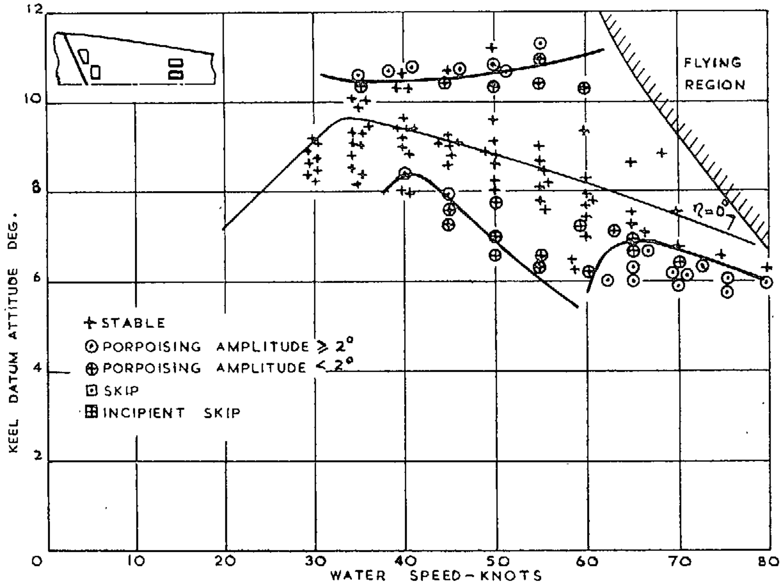


Fig. 18. Take-off stability. Step rounded. All vents open.

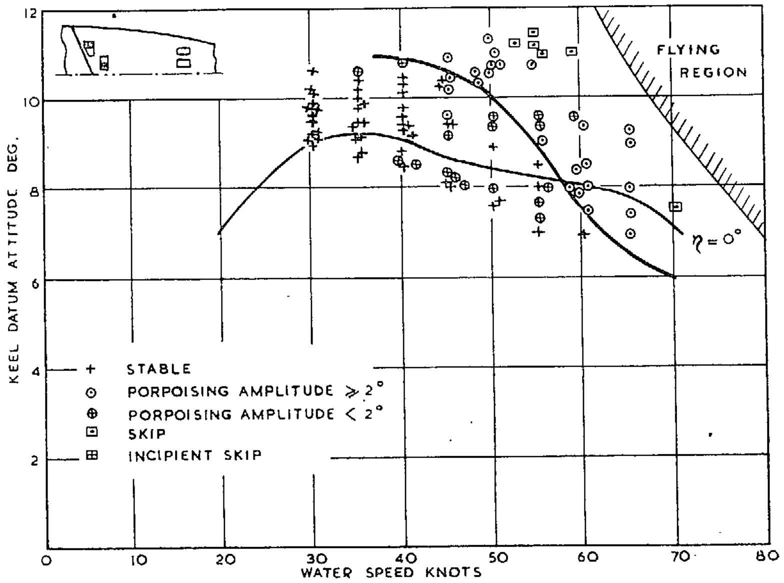


Fig. 20. Take-off stability. Step rounded. Forward vent area halved.

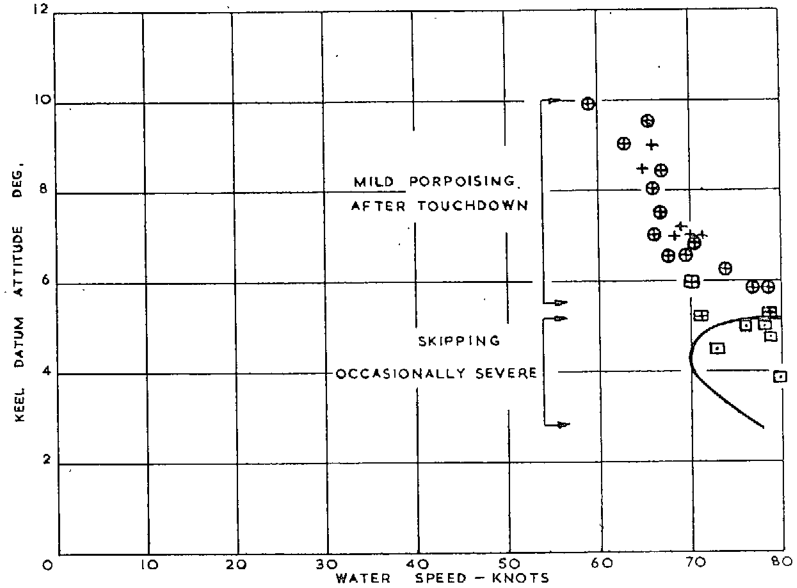


Fig. 19. Landing stability. Step rounded. All vents open.

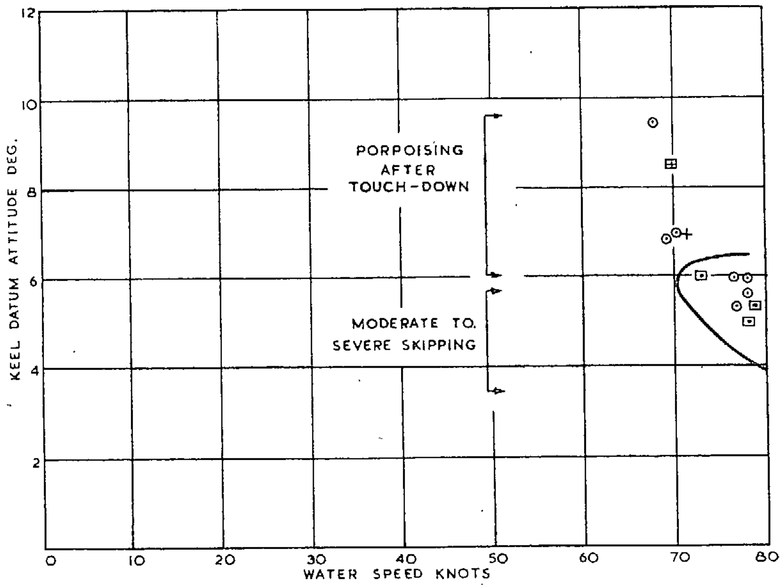


Fig. 21. Landing stability. Step rounded. Forward vent area halved.

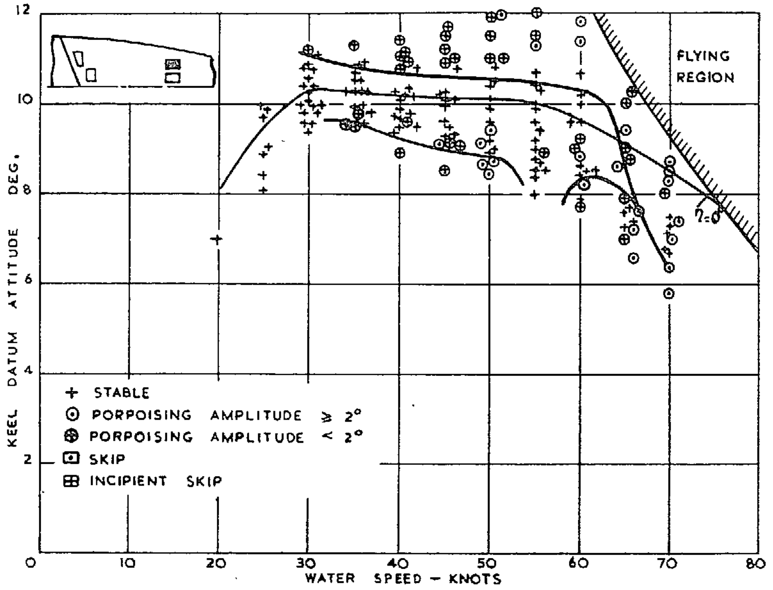


FIG. 22. Take-off stability. Step rounded. Aft outer vents sealed.

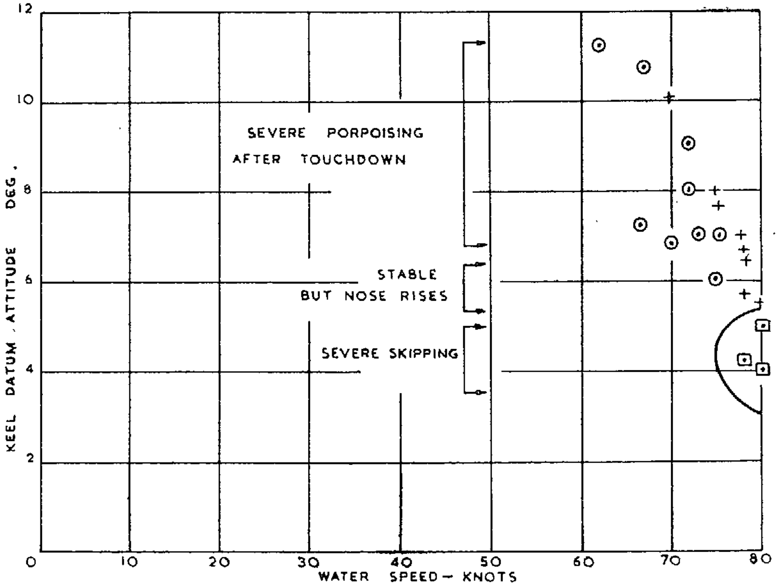


FIG. 23. Landing stability. Step rounded. Aft outer vents sealed.

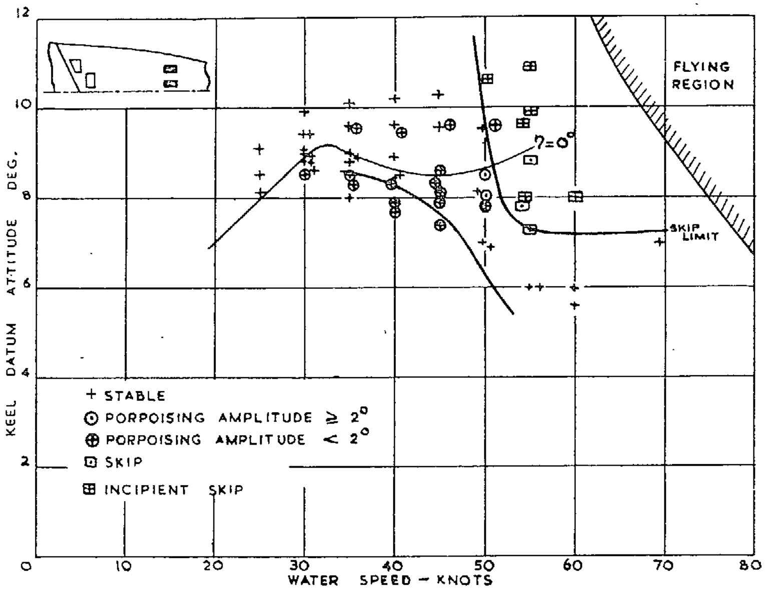


FIG. 24. Take-off stability. Step rounded. All aft vents sealed.

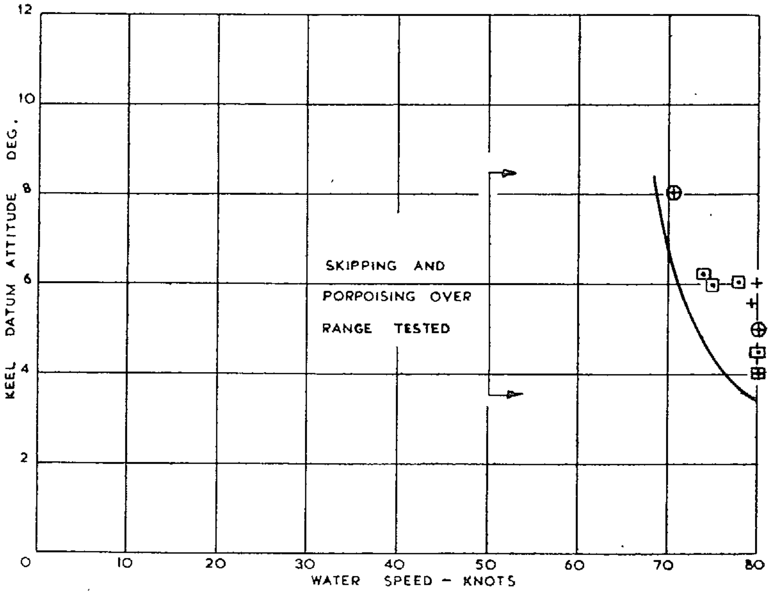


FIG. 25. Landing stability. Step rounded. All aft vents sealed.

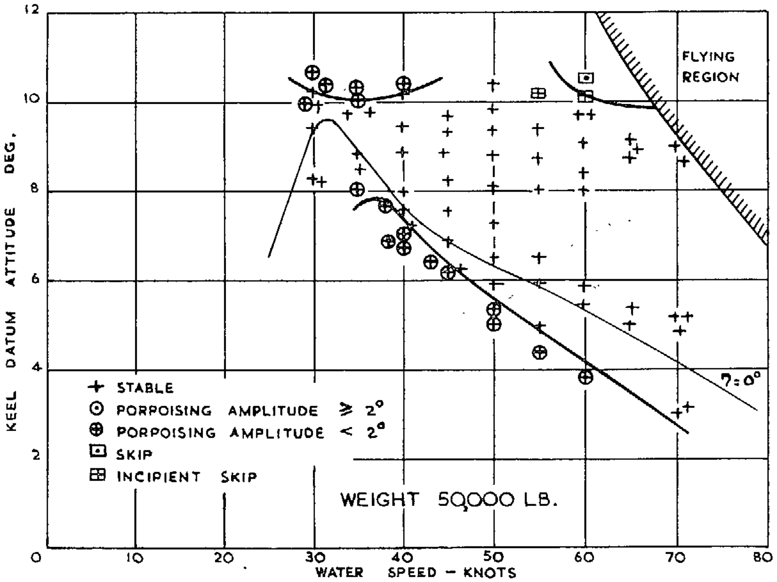


FIG. 26. Take-off stability. Standard *Sunderland* Mk. 5.

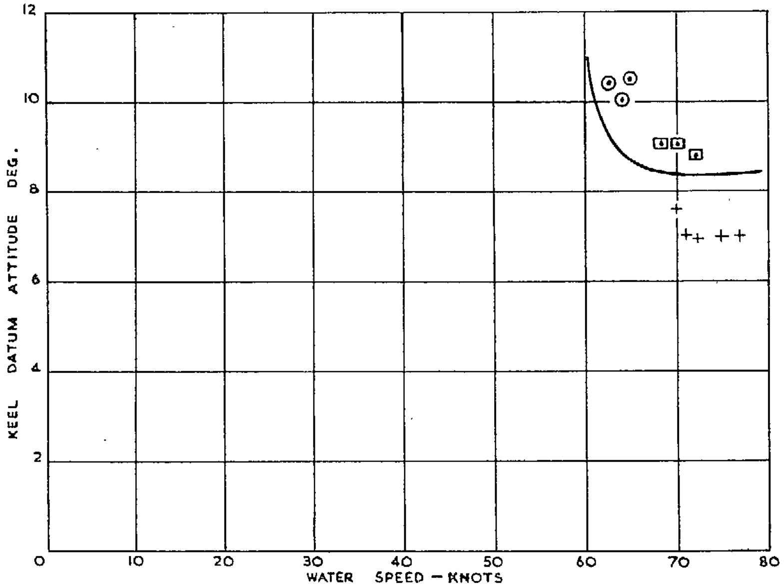


FIG. 27. Landing stability. Standard *Sunderland* Mk. 5.

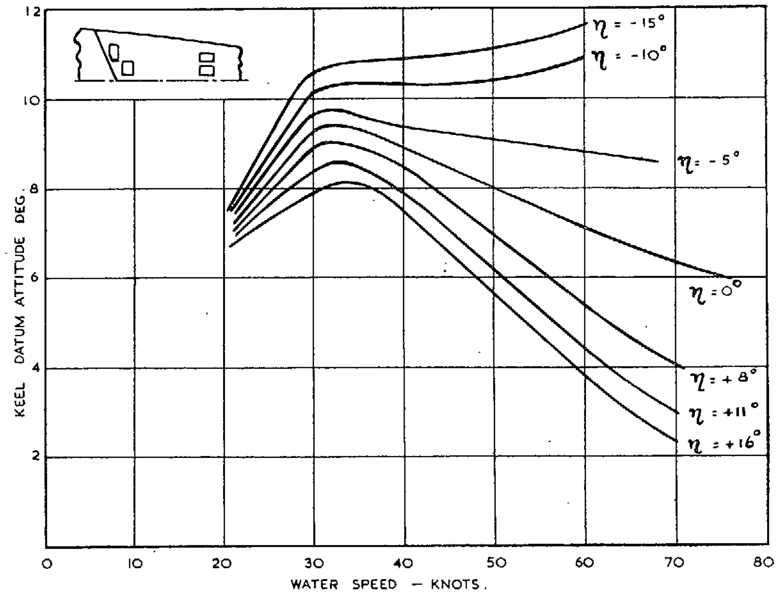


FIG. 28. Take-off Trim. Step sharp. All vents open.

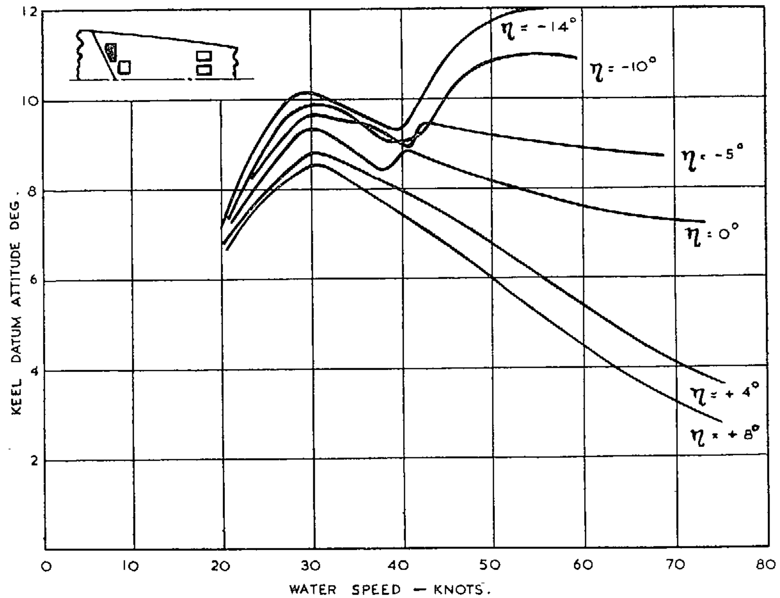


FIG. 29. Take-off trim. Step sharp. Forward outer vents sealed.

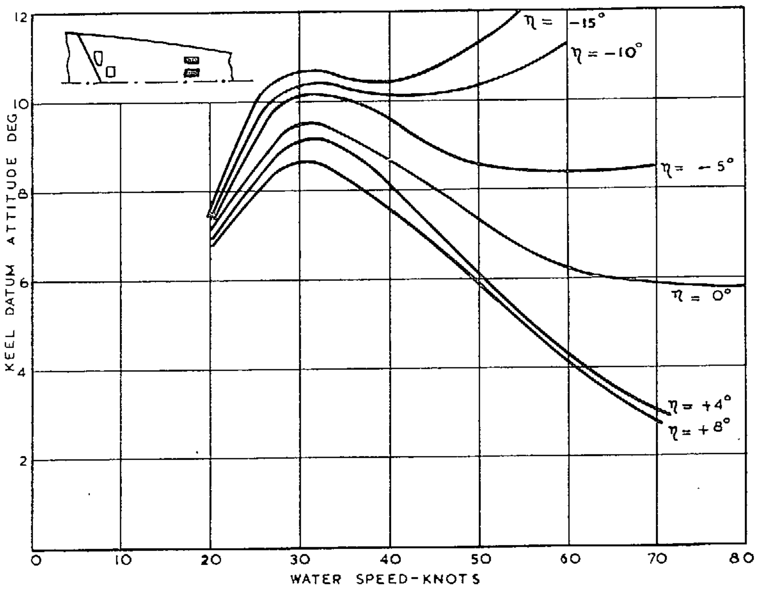


FIG. 30. Take-off trim. Step sharp. All aft vents sealed.

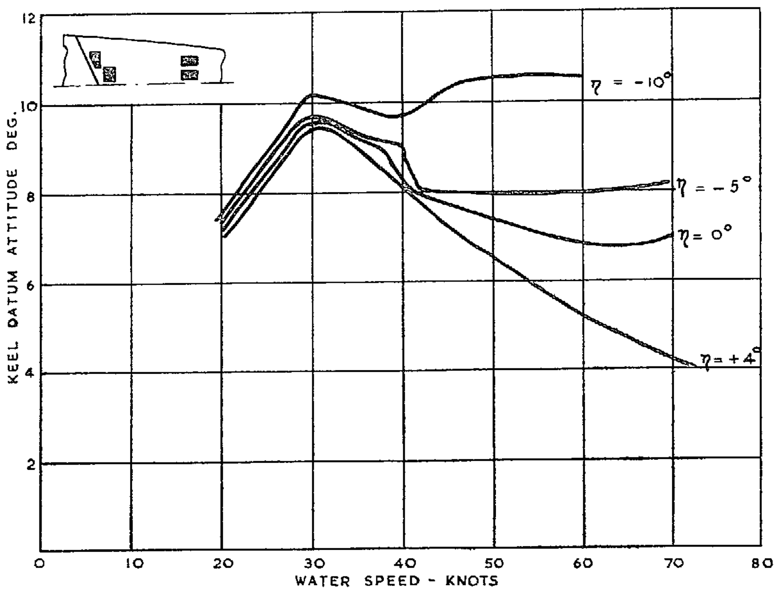


FIG. 32. Take-off trim. Step sharp. All vents sealed.

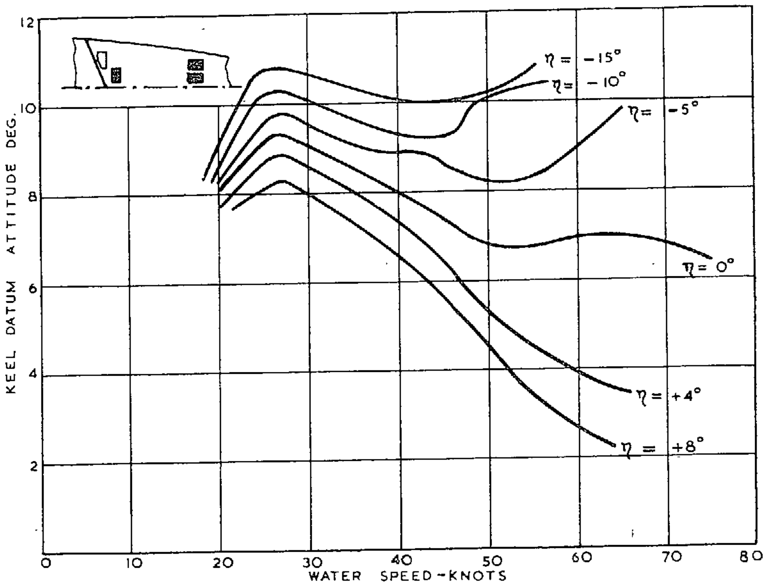


FIG. 31. Take-off trim. Step sharp.
All aft and forward inner vents sealed.

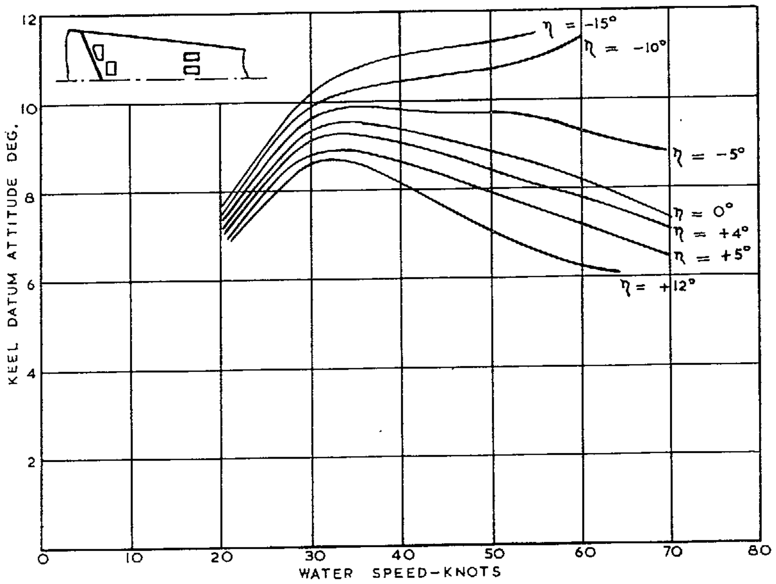


FIG. 33. Take-off trim. Step rounded. All vents open.

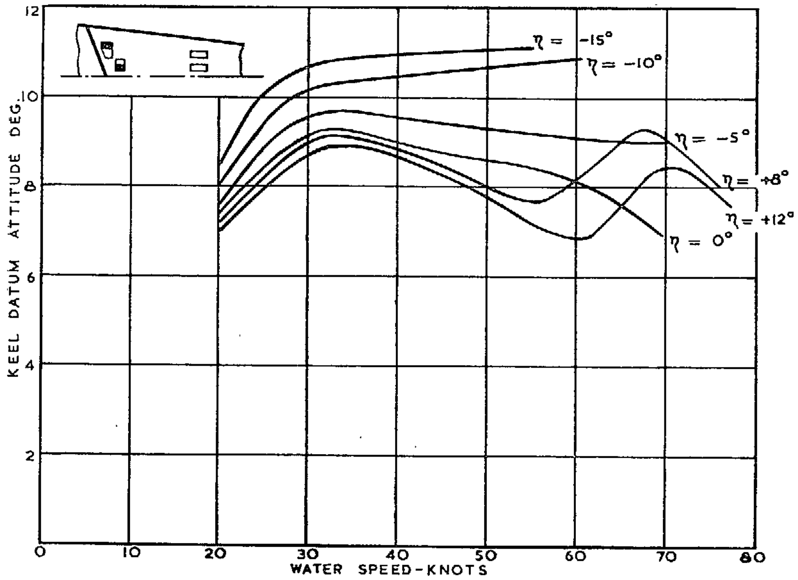


FIG. 34. Take-off trim. Step rounded. Forward vent area halved.

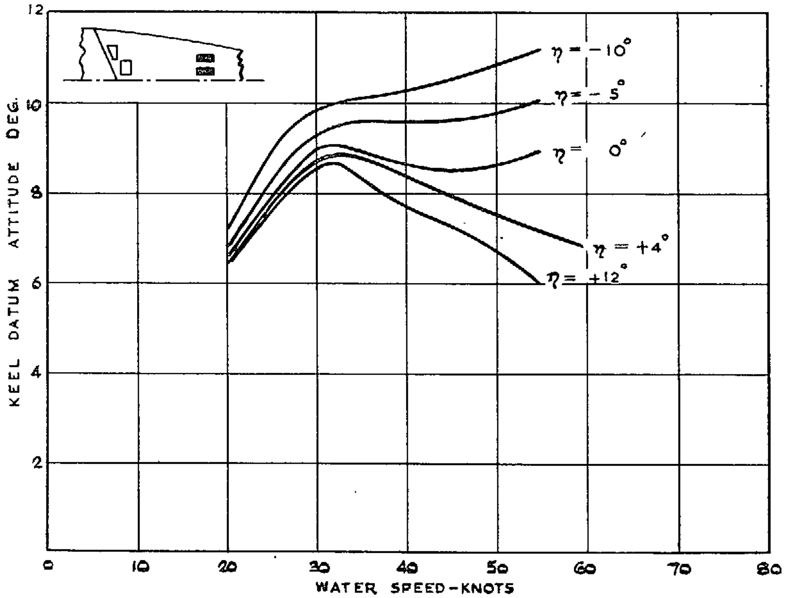


FIG. 36. Take-off trim. Step rounded. All aft vents sealed.

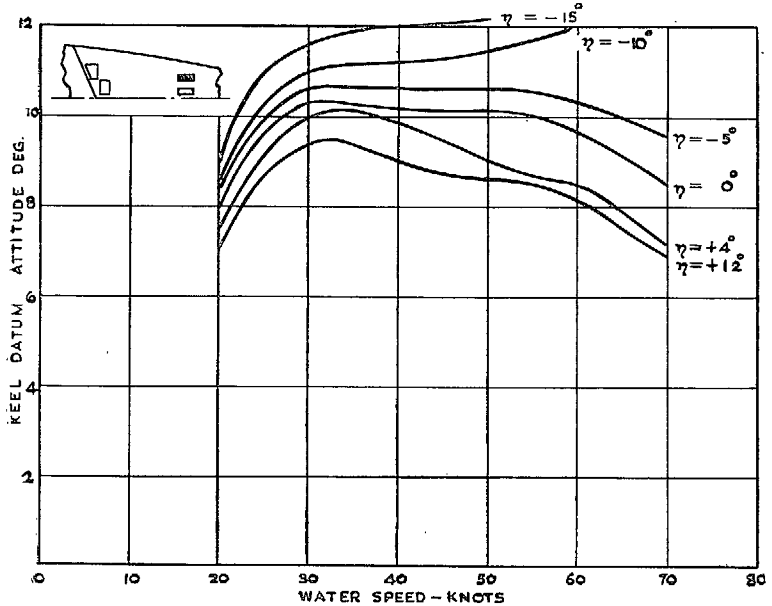


FIG. 35. Take-off trim. Step rounded. Aft outer vents sealed.

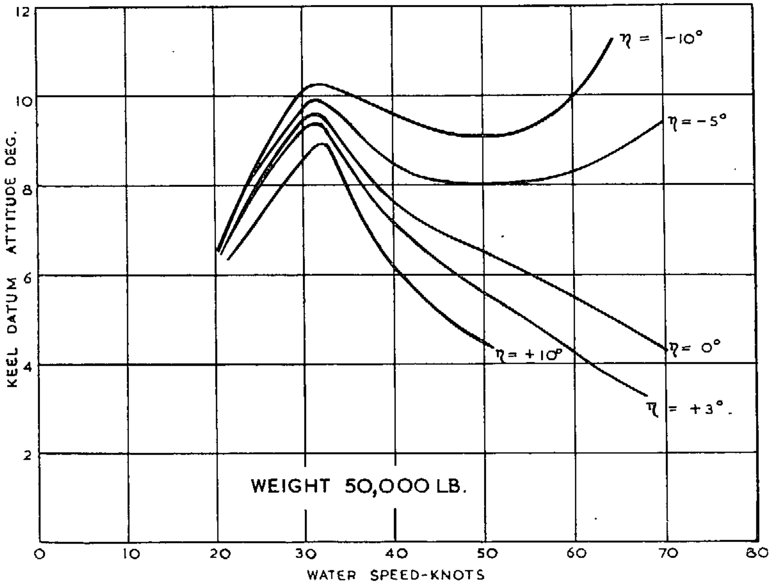


FIG. 37. Take-off trim. Standard *Sunderland* Mk. 5.

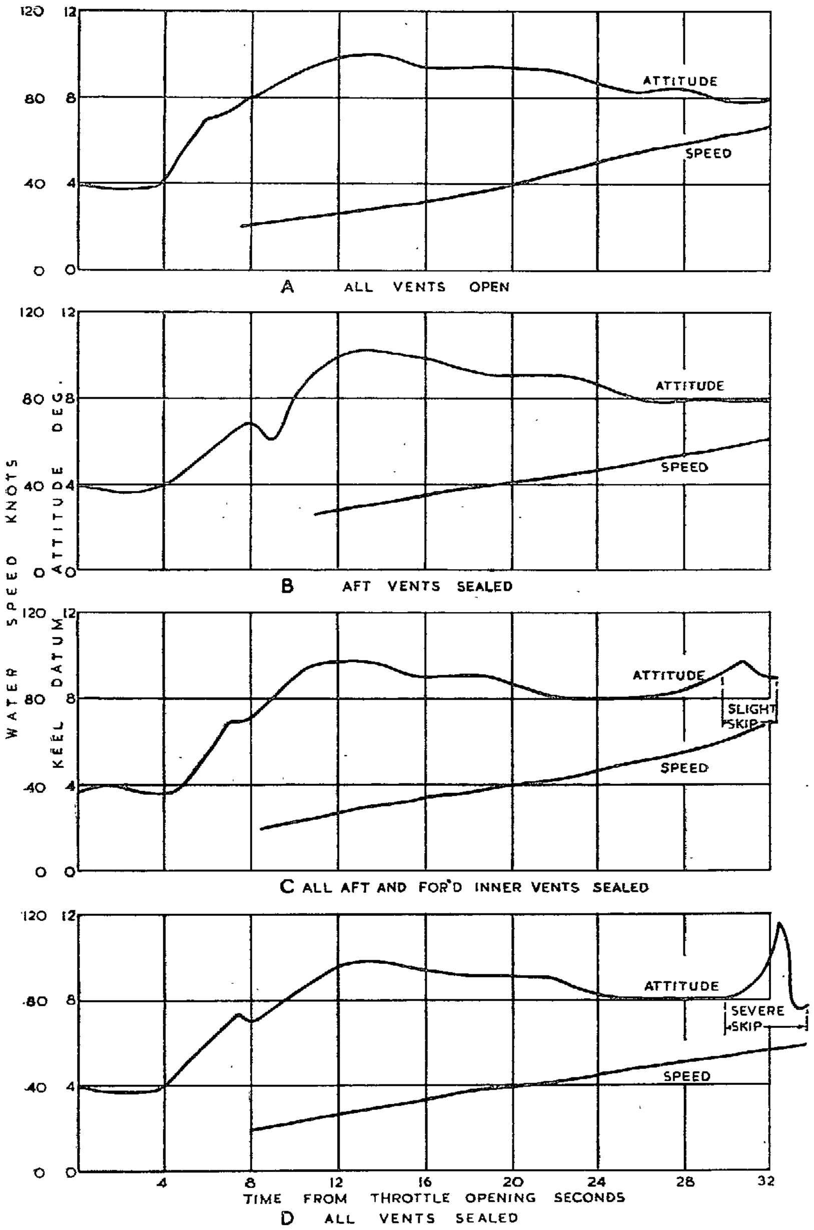


FIG. 38. The effect of ventilating area on take-off stability. Step sharp. Elevator angle — 5°.

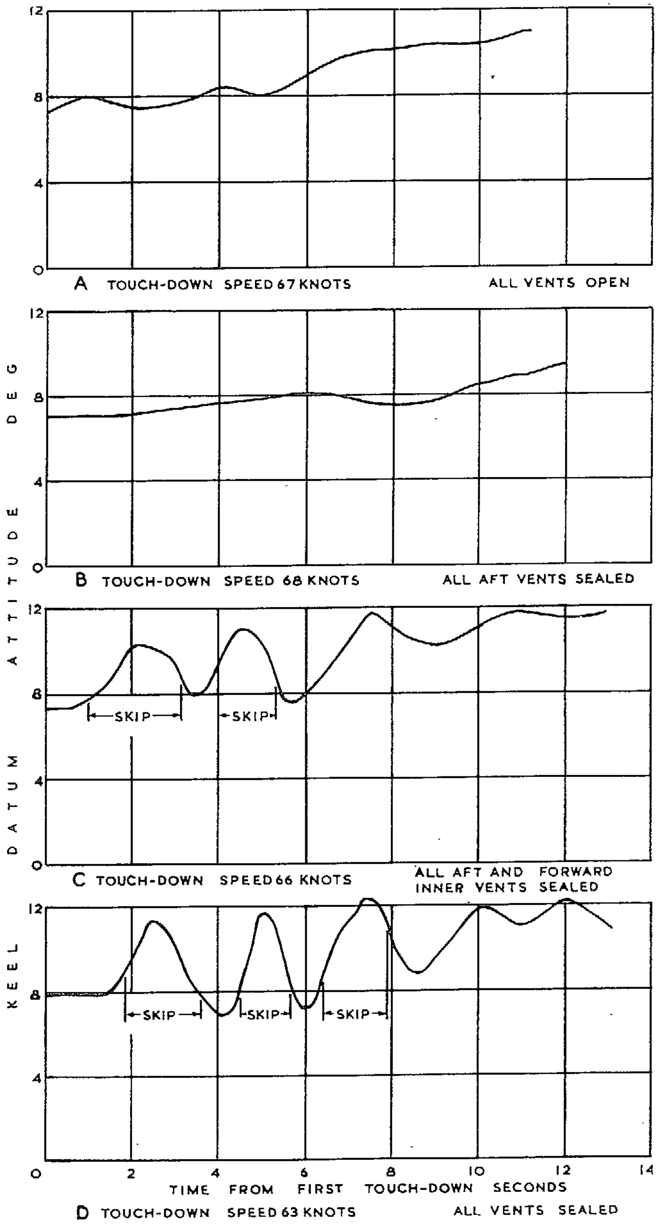
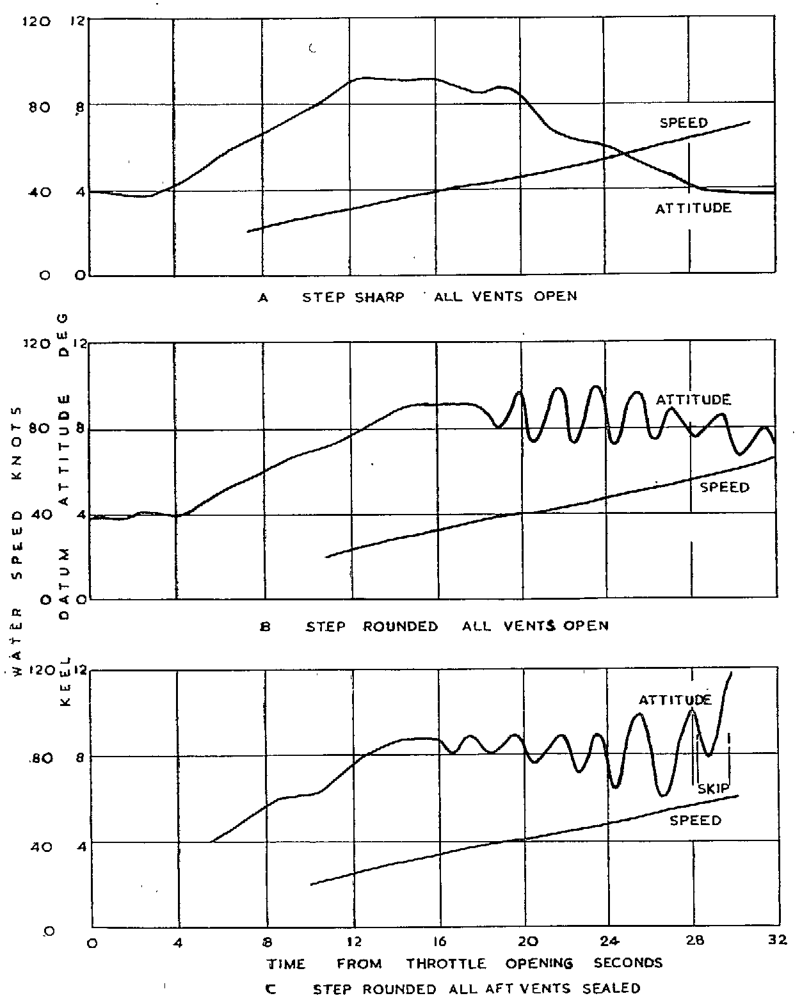


FIG. 39. The effect of ventilating area on landing stability. Step sharp.

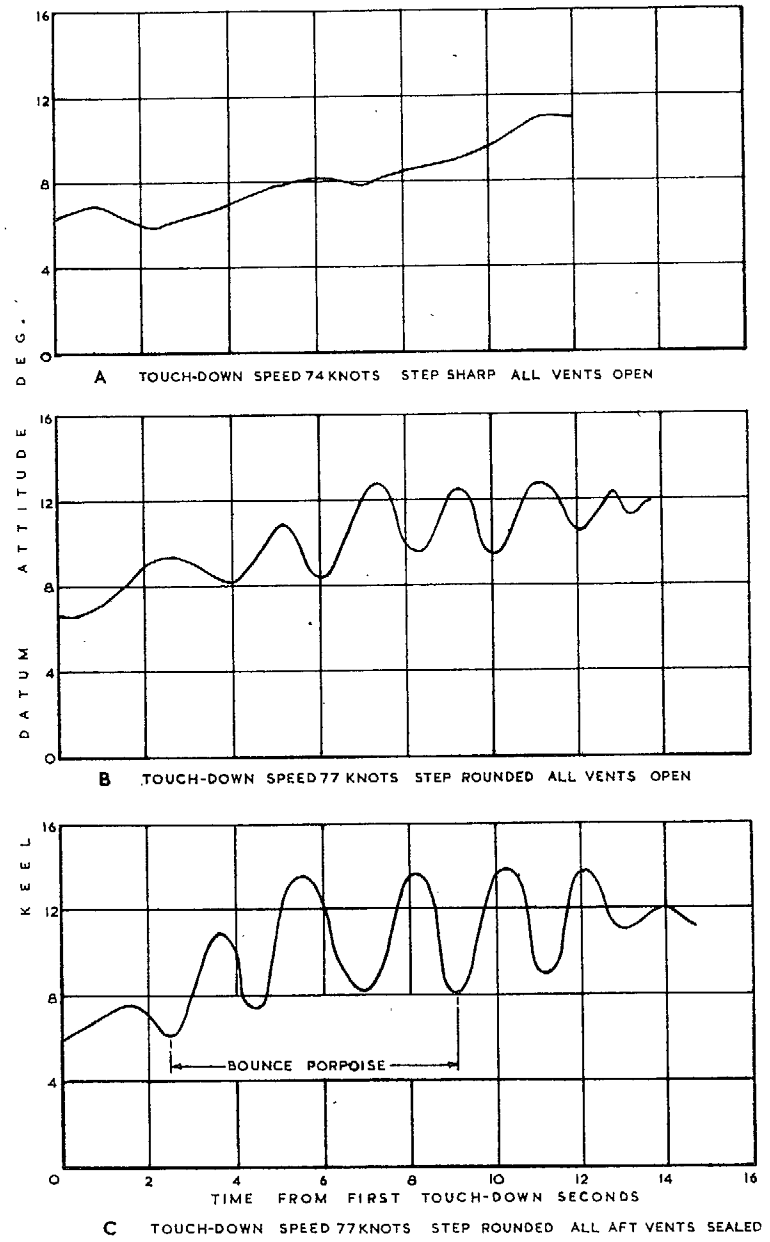


A STEP SHARP ALL VENTS OPEN

B STEP ROUNDED ALL VENTS OPEN

C STEP ROUNDED ALL AFT VENTS SEALED

FIG. 40. The effect of step rounding on take-off stability. Elevator angle + 8°.



A TOUCH-DOWN SPEED 74 KNOTS STEP SHARP ALL VENTS OPEN

B TOUCH-DOWN SPEED 77 KNOTS STEP ROUNDED ALL VENTS OPEN

C TOUCH-DOWN SPEED 77 KNOTS STEP ROUNDED ALL AFT VENTS SEALED

FIG. 41. The effect of step rounding on landing stability.

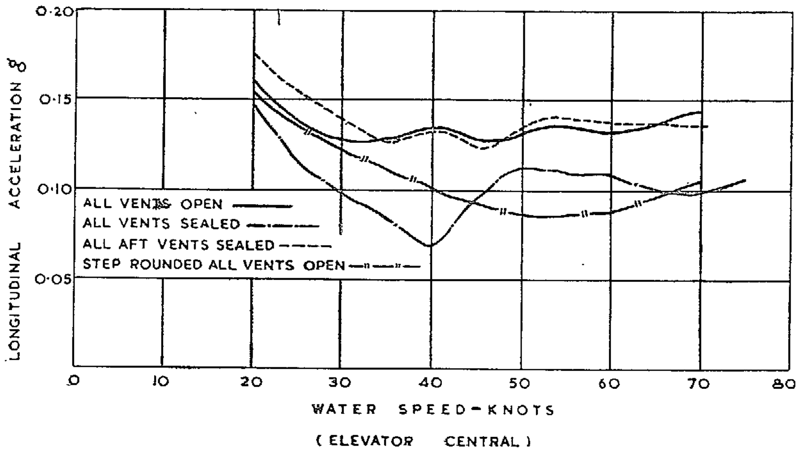


FIG. 42. The effect of planing-bottom modifications on longitudinal acceleration during take-off.

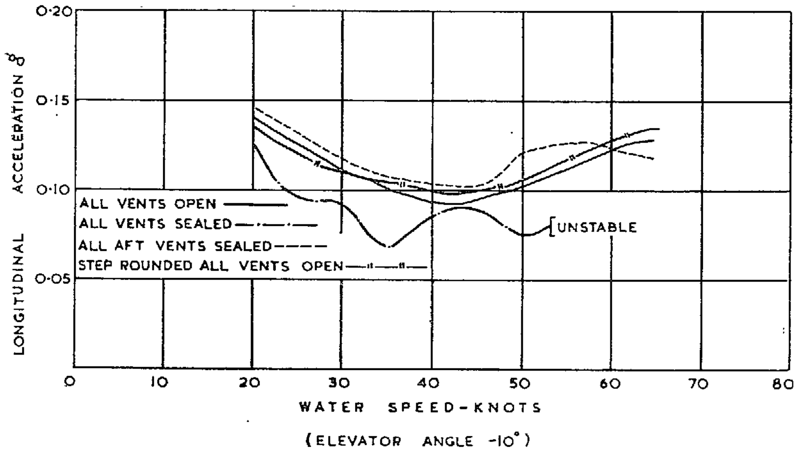


FIG. 43. The effect of planing-bottom modifications on longitudinal acceleration during take-off.

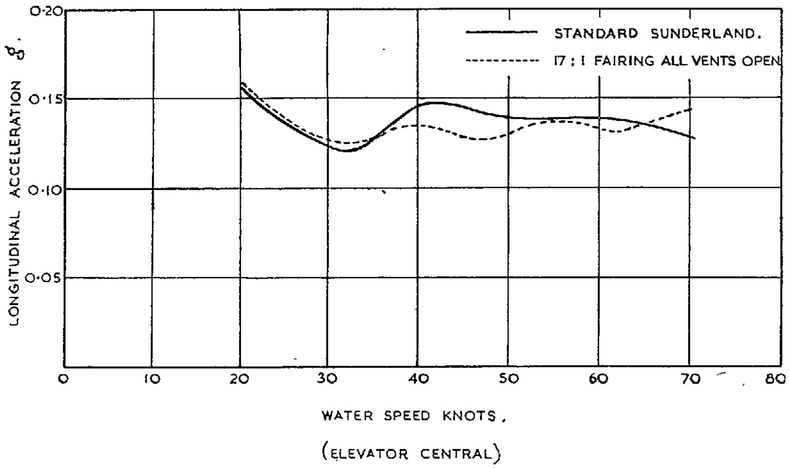


FIG. 44. The effect of a 17 : 1 ventilated fairing on longitudinal acceleration during take-off.

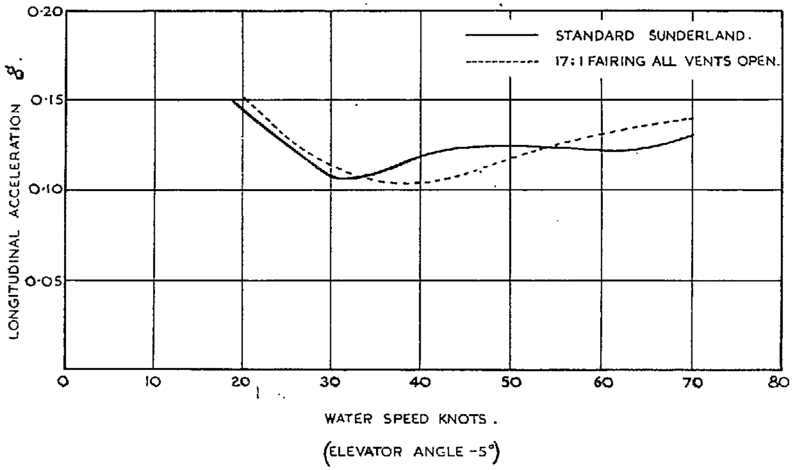


FIG. 45. The effect of a 17 : 1 ventilated fairing on longitudinal acceleration during take-off.

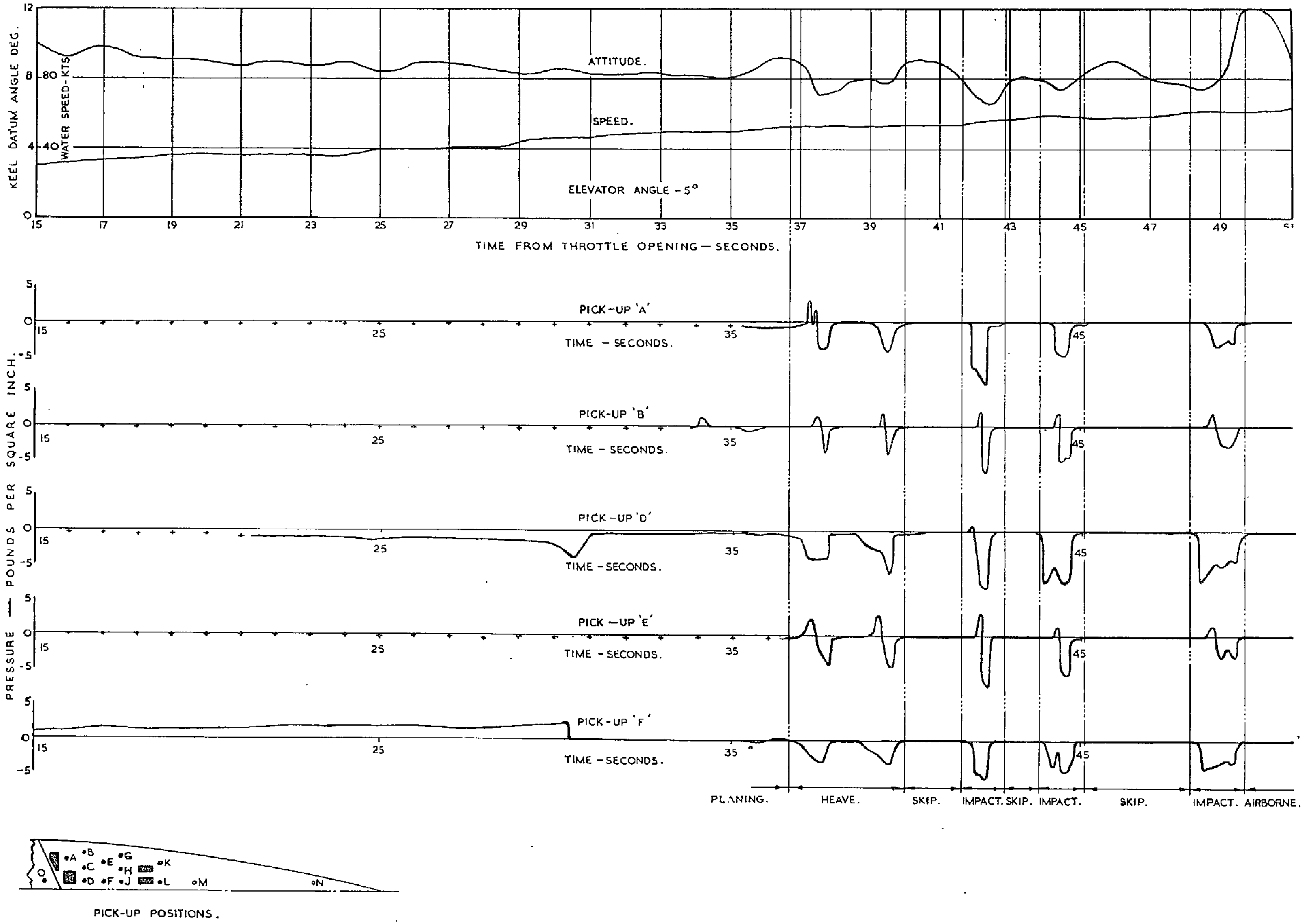


Fig. 46a. Afterbody pressure variation during take-off. Step sharp. All vents sealed.

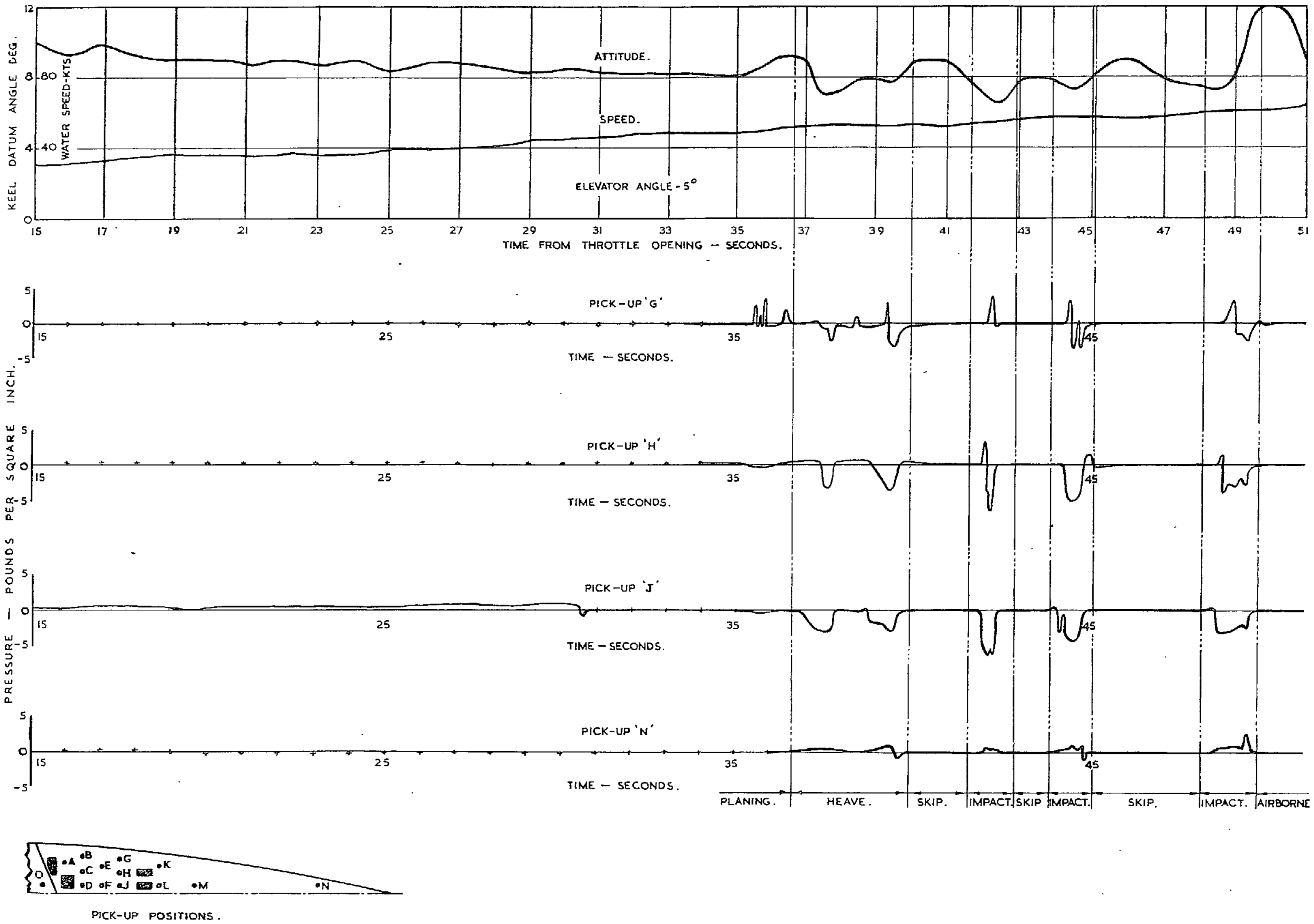


FIG. 46b. Afterbody pressure variation during take-off. Step sharp. All vents sealed.

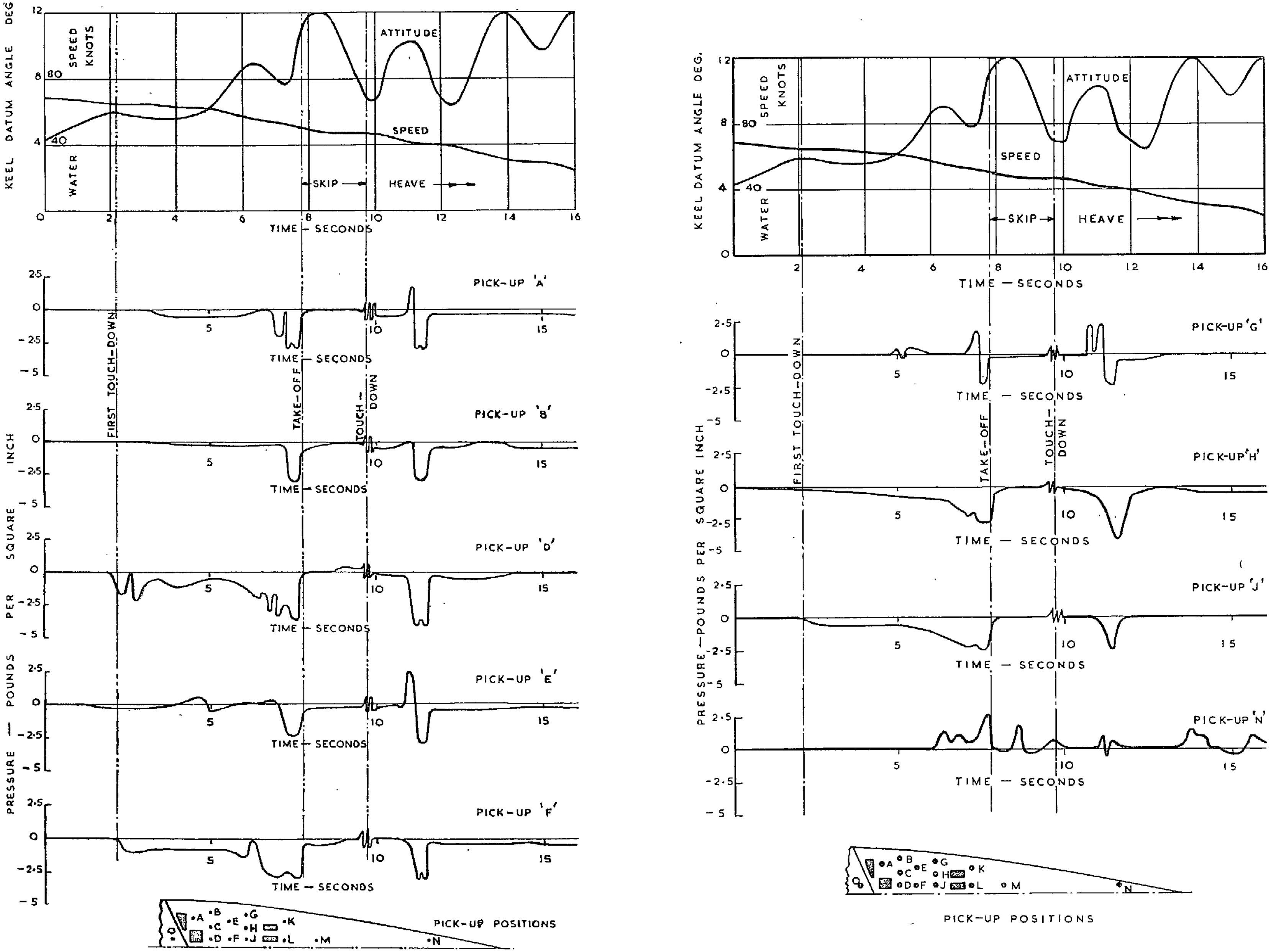


FIG. 47. Afterbody pressure variation during landing. Step sharp. All vents sealed.

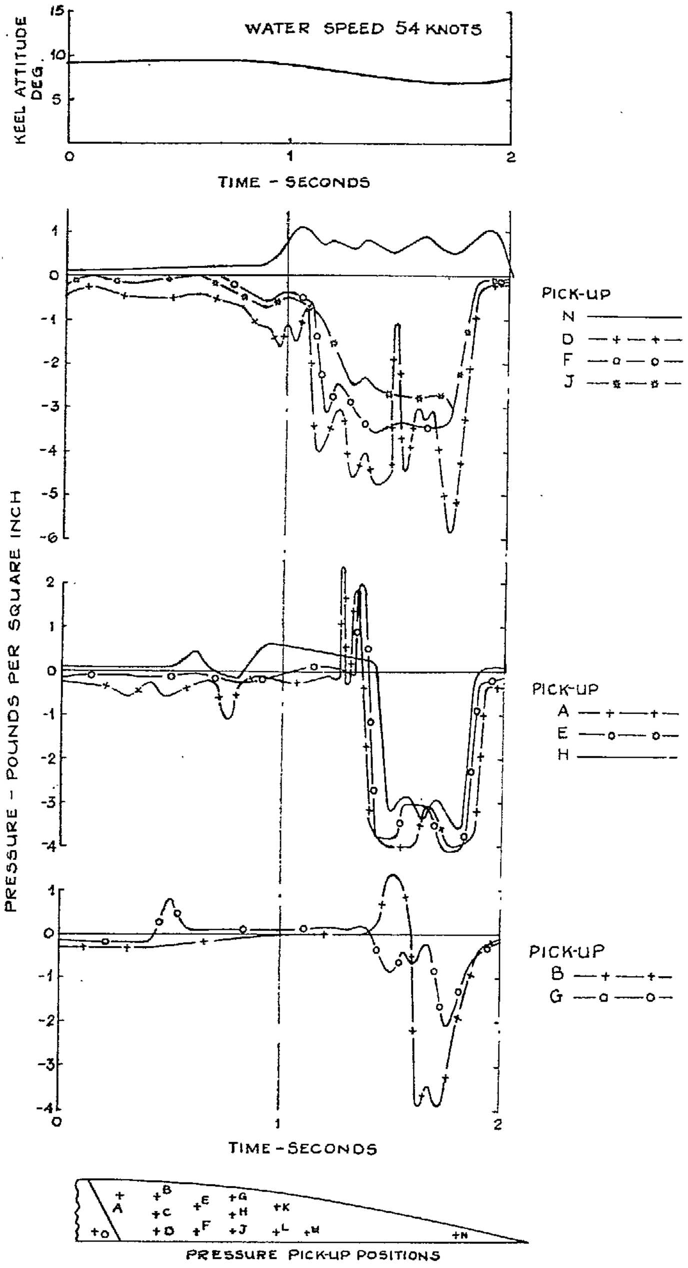


FIG. 48. A typical pressure wave during take-off. Step sharp. All vents sealed.

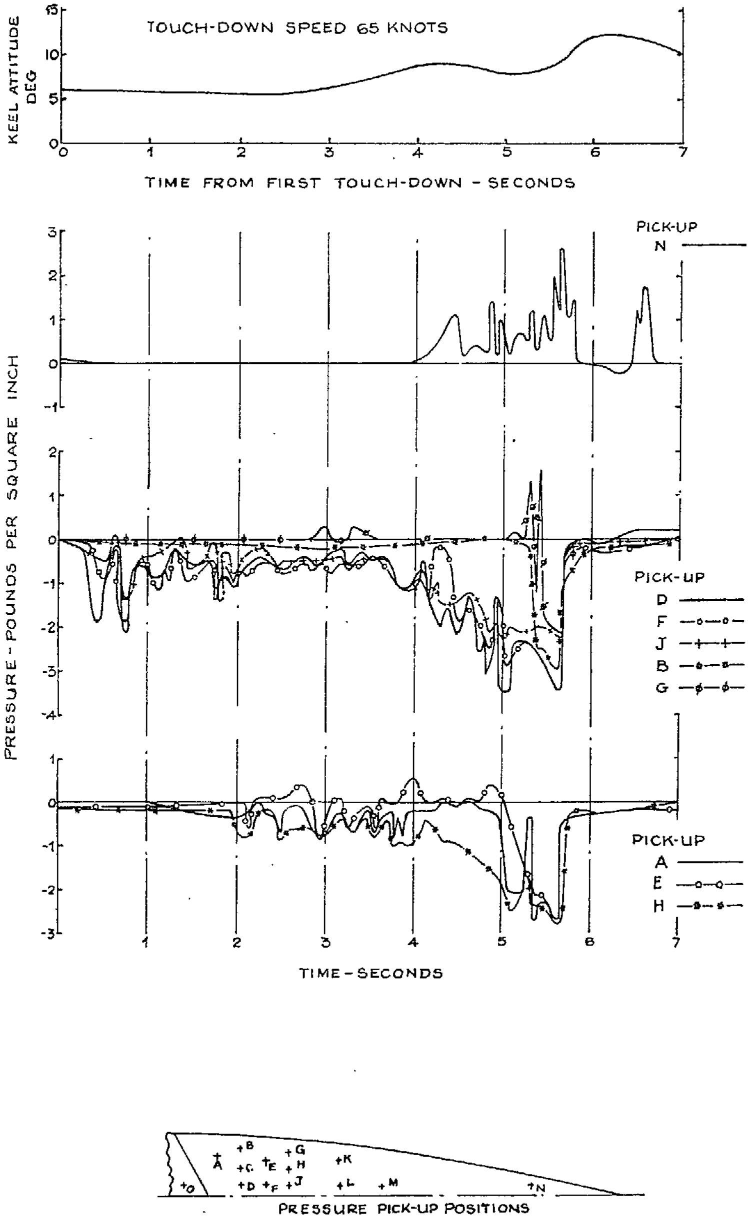


FIG. 49. A typical pressure wave during landing. Step sharp. All vents sealed.

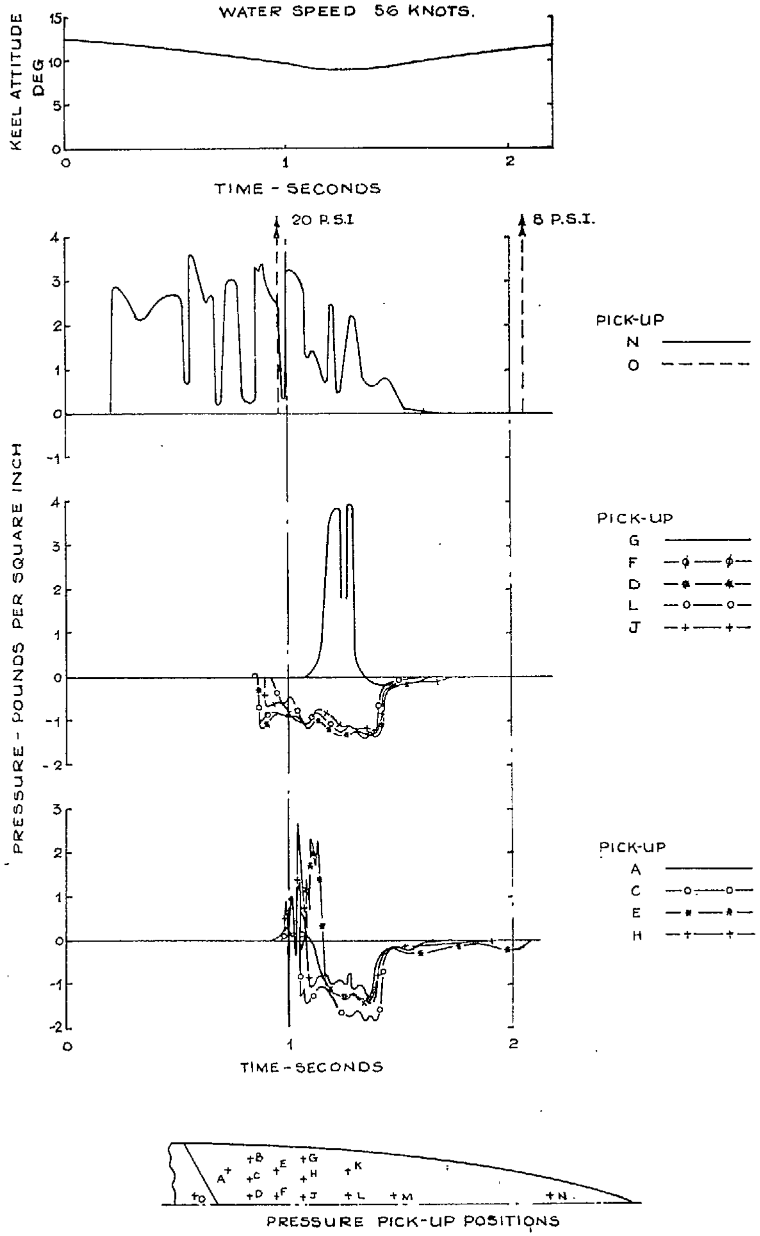


FIG. 50. A typical pressure wave during take-off. Step sharp. All aft vents sealed.

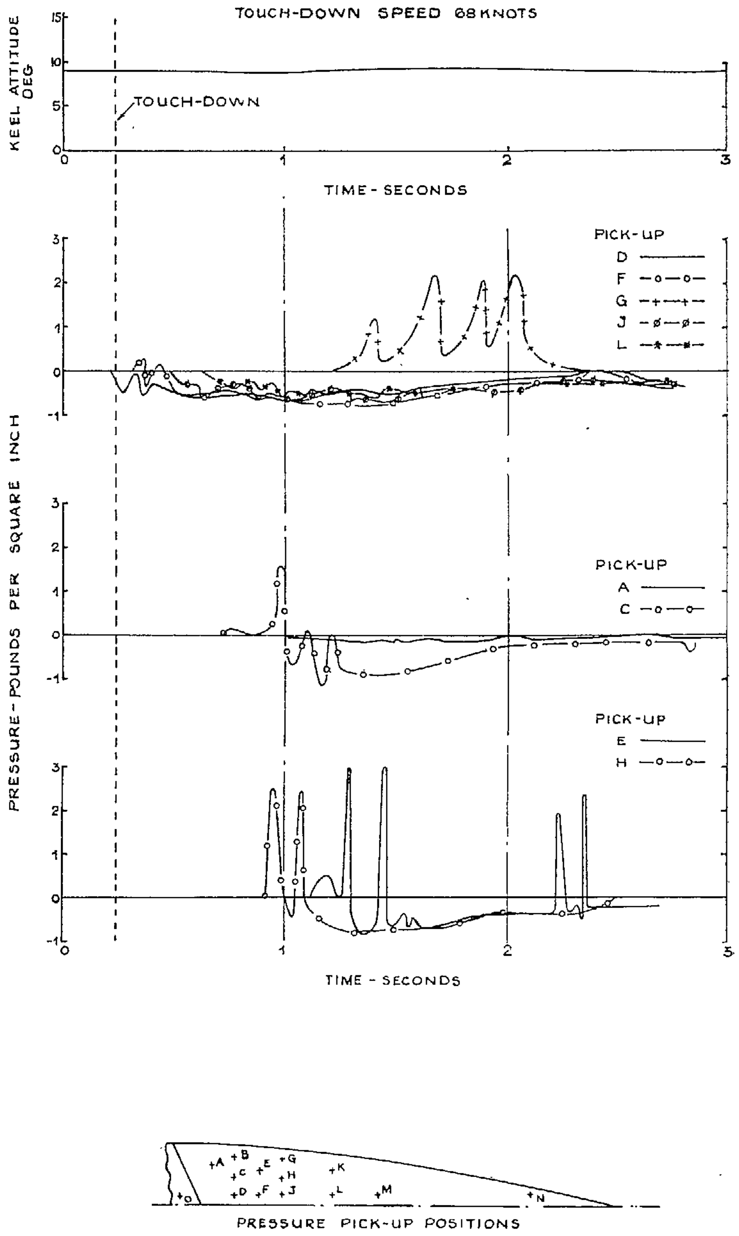


FIG. 51. A typical pressure wave during landing. Step sharp. All aft vents sealed.

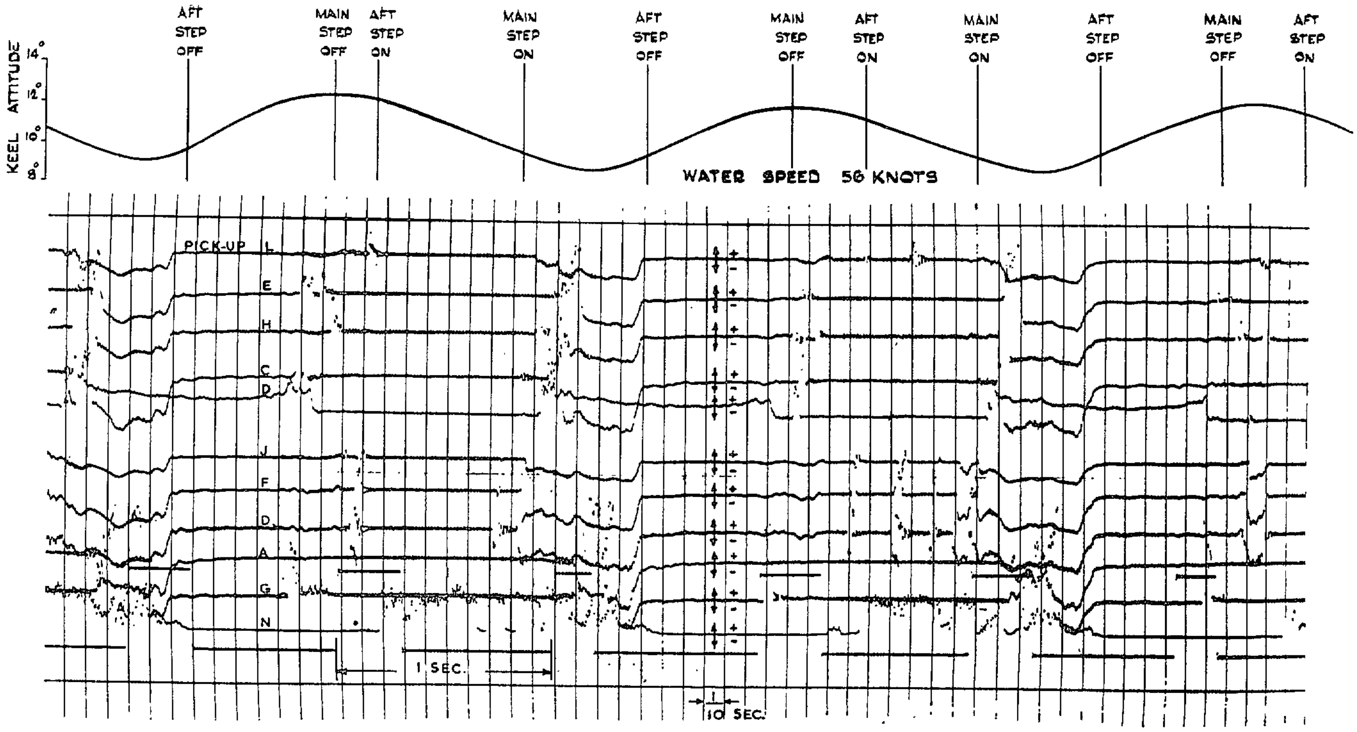


FIG. 52. A typical record of skipping at constant speed. Step sharp. All aft vents sealed.

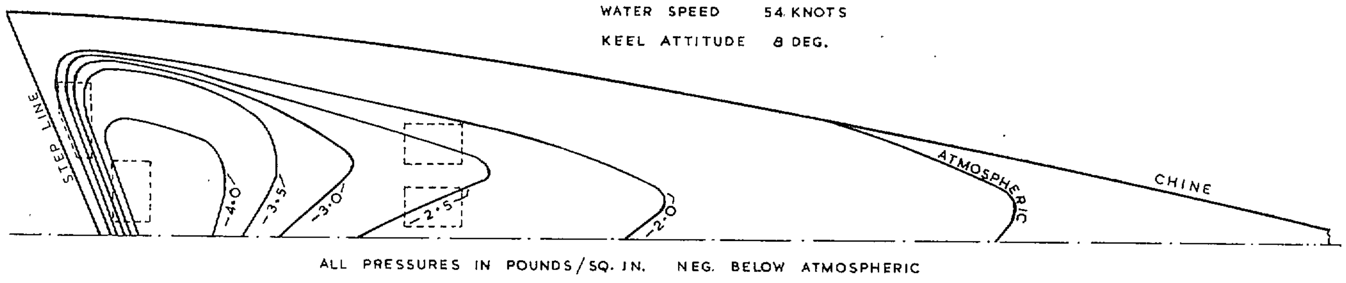


FIG. 53. Afterbody pressure distribution during a take-off skip. Step sharp. All vents sealed.

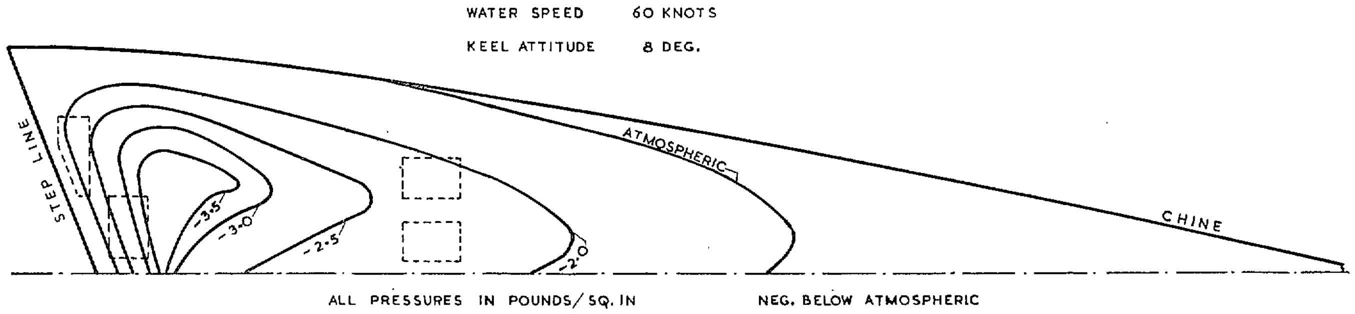


FIG. 54. Afterbody pressure distribution during a landing skip. Step sharp. All vents sealed.

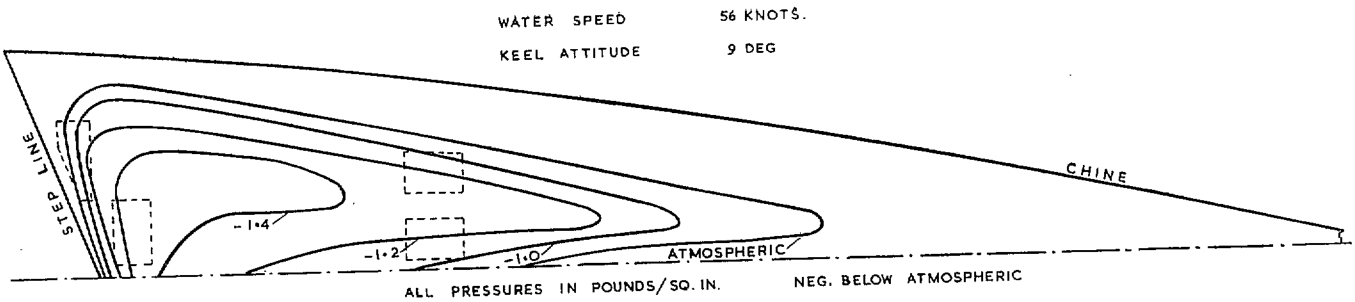


FIG. 55. Afterbody pressure distribution during a take-off skip. Step sharp. All aft vents sealed.

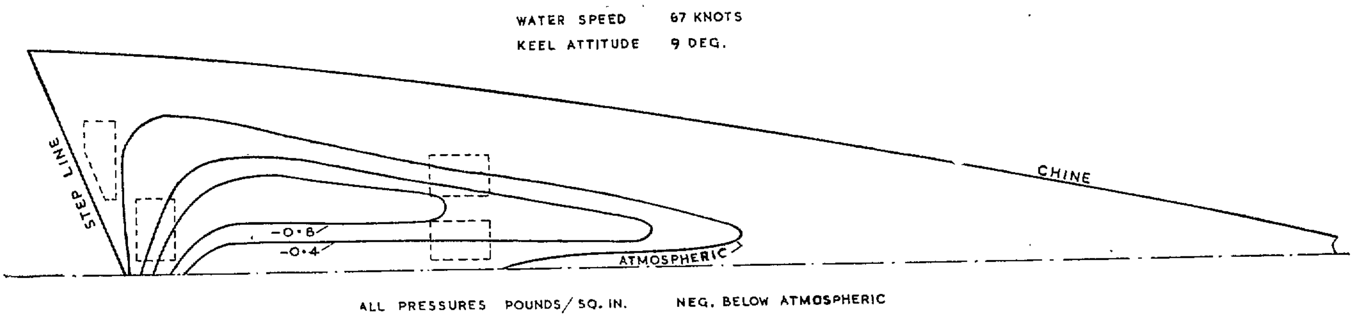


FIG. 56. Afterbody pressure distribution during a borderline landing. Step sharp. All aft vents sealed.

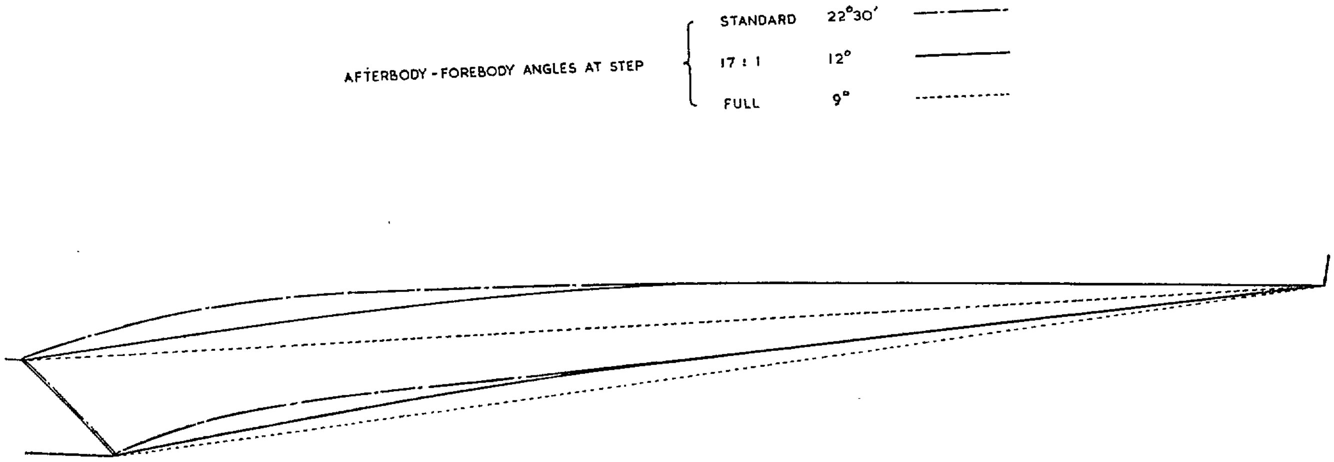


FIG. 57. Comparison of fairings on *Sunderland* afterbody.

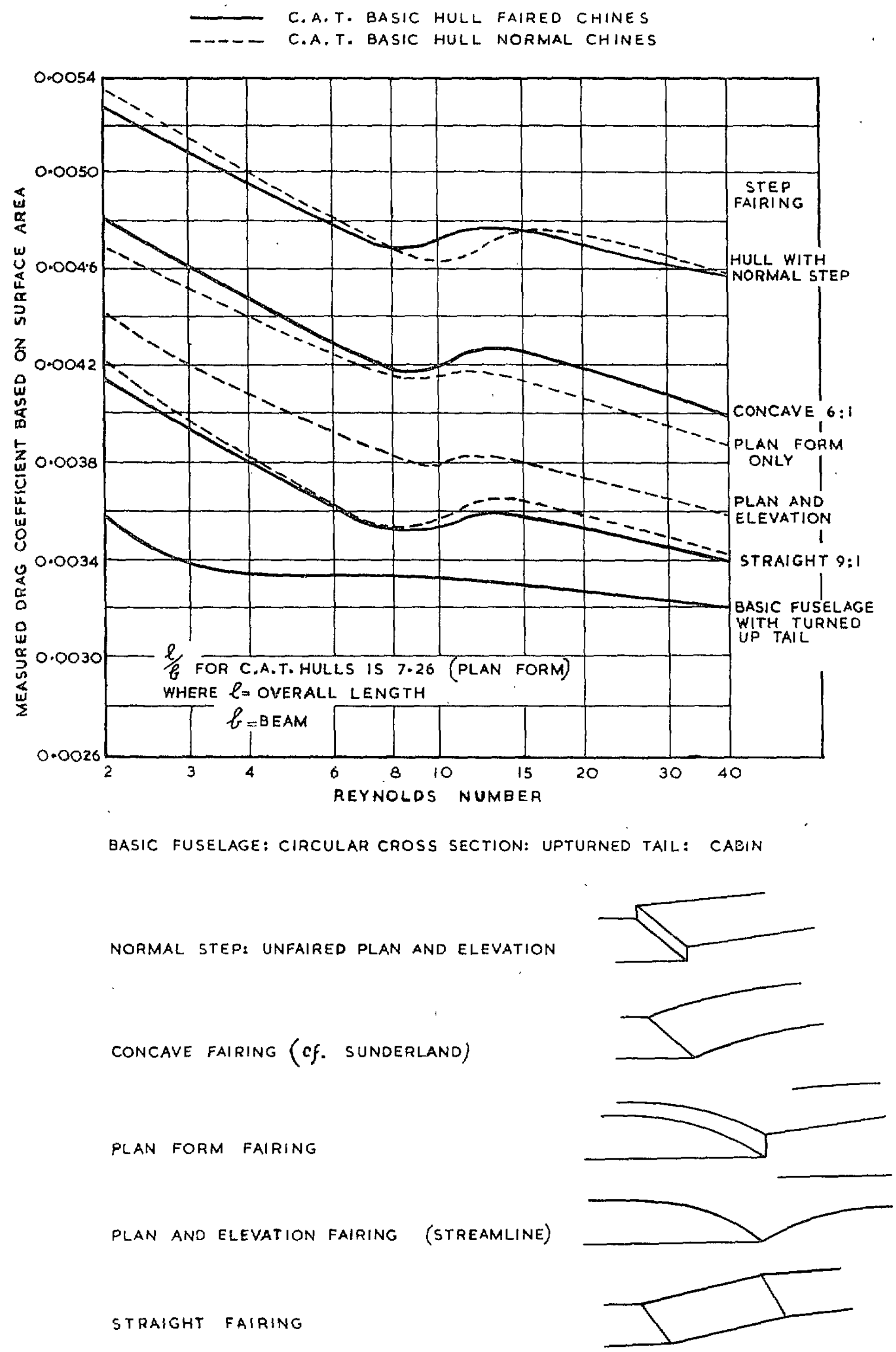


FIG. 58. Effect of various step fairings on hull air drag.
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