R. & M. No. 2898
(15,197)
A.R.C. Technical Report

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

The Full-scale Hydrodynamic Performance of a Large Four-engined Flying Boat at Overload in Calm Water and Swell

By

J. A. HAMILTON and R. V. GIGG

LONDON: HER MAJESTY'S STATIONERY OFFICE
1956

PRICE 10*s* 6*d* NET

The Full-scale Hydrodynamic Performance of a Large Four-engined Flying Boat at Overload in Calm Water and Swell

By

J. A. HAMILTON and R. V. GIGG

COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR),
MINISTRY OF SUPPLY

Reports and Memoranda No. 2898*
August, 1952

Summary.—Tests have been made on a large four-engined flying boat (*Solent* Mk. 3), to determine the hydrodynamic performance in sheltered water and in open-sea swells. The sheltered water characteristics were investigated over a range of weights between 72,000 and 84,000 lb. The performance in swell covered weights up to 82,000 lb, and swell heights up to 5 feet. The latter tests were made at Gibraltar in February, 1951.

The main conclusions of the investigation which may be applied generally to hulls similar to the *Solent* can be summarised, as follows:

(*a*) *In Sheltered Water*
  (i) The hydrodynamic longitudinal stability and spray are acceptable in calm water at a $C_{\Delta 0}$ of $1 \cdot 2$ (84,000 lb weight for the *Solent*).
  (ii) Short seas up to 4 feet in height have relatively little effect on hydrodynamic performance.
  (iii) Acceleration through the hump region has a considerable effect on the acceptable amount of porpoising, and the limiting out of wind angle for take-off. For military aircraft, a minimum take-off acceleration of $0 \cdot 1g$ is recommended.

(*b*) *In Ocean Swell*
  (i) Violent porpoising may occur on a normally stable hull, if operated into ocean swells of length greater than the aircraft length, and height greater than 1 to $1\frac{1}{2}$ feet.
  (ii) Swell height does not appear to affect the stability greatly (limits tested, 1 to 5 feet).
  (iii) The porpoising motion is relatively insensitive to weight, but increased take-off acceleration at lower weight reduces the extent of the unstable region.
  (iv) Operation along the swell produces no instability.
  (v) The presence of wind may reduce swell porpoising considerably.

PART I

Tests in Sheltered Waters

1. *Introduction.*—The behaviour of a flying boat when taking off and alighting in ocean swells is a subject of obvious practical interest. Unfortunately, owing to the difficulties and hazards of full-scale experiments in such seas there exists relatively little quantitative full-scale information on the subject. This report presents the results from such a full-scale investigation made

---

* M.A.E.E. Report F/Res/225, received 23rd September, 1952.

on a *Solent* type flying boat at weights up to 82,000 lb. As a preliminary to the swell tests at Gibraltar, corresponding tests were made in sheltered water at Felixstowe. These are interesting in themselves since the investigation covered hull loadings higher than those set by normal practice for the *Solent* type of hull. The results from the sheltered water tests are presented in Part I of the report and those from the open sea tests in Part II.

Details of the aircraft are given in Fig. 1 and Table 1.

2. *Range of Investigation.*—2.1. *Take-off Stability.*—The take-off stability was investigated at weights between 72,000 and 84,000 lb. In order to avoid confusing the main arguments of the report with a plethora of results, only those for 72,000, 82,000 and 84,000 lb have been given. The changes in hydrodynamic qualities over this weight range are relatively small and the results for intermediate weights may be interpolated with little error.

For all take-offs, the cowl gills were closed, the oil-cooling louvres were one-quarter open and one-third flap was used.

2.2. *Landings.*—These were confined to low-attitude touch-downs, and a medium amount of power was used to reduce the rate of descent. A small number were recorded, but no attempt was made to investigate the water stability on landing.

2.3. *Crosswind Take-off Performance.*—The limiting out-of-wind angle and the limiting wind speeds at these angles, on the port and starboard bows, for take-off at 82,000 lb, were determined.

2.4. *Rough Water Performance.*—Take-offs were made to determine the limiting wave height for safe operation in choppy seas.

2.5. *Spray.*—During all take-offs and landings, notes were taken of the spray characteristics, with particular attention to damage to propellers.

2.6. *C.G. Position and Loadings.*—The tests were made at the following c.g. positions,

(*a*) 72,000 lb, 3·21 feet forward of main-step keel,

(*b*) 82,000 lb, 3·21 and 3·22 feet forward of main-step keel,

(*c*) 84,000 lb, 2·28 feet forward of main-step keel.

2.7. *Pilot Technique.*—2.7.1. *Take-offs.*—All take-offs for the purpose of stability determination were made with full-power, fixed elevator, and with one-third flap. The pilot held a pre-selected elevator position unless porpoising developed which he considered dangerous, when he took control.

2.7.2. *Landings.*—All landings were made with two-thirds flap. Approaches were made at high speed, using power. The best approach speed was found to be from 110 to 120 knots E.A.S., using 20-in. boost and 2,400 r.p.m. (approximately 400 b.h.p. per engine). This gave a rate of descent of the order of 100 ft/min. Touch-downs were made at fine attitude, using power to give a minimum rate of descent.

During early landing runs above 78,000 lb, solid water hit the flaps at about 50 knots water speed and the tail-plane at the end of the run, as the bow settled in the water. To reduce damage to the flaps, they were raised immediately after a touch-down. To reduce damage to the tail plane, a burst of power was given on the inner engines as the bow settled.

2.8. *Weather Conditions.*—An attempt was made to confine the calm water tests to days when the wind was less than 8 knots, but this was not always possible. The tests at 72,000 lb and 82,000 lb were all done in wind speeds less than 10 knots and those at 84,000 lb in wind speeds less than 16 knots.

3. *Instrumentation.*—The following quantities were recorded on an automatic observer and photographed by a Bell and Howell 35 mm ciné camera operating at 5 frames per second.

Engine r.p.m.
Air speed from aircraft pitot head and static vent.
Air speed from pitot in venturi and static tank.
Angle of pitch : micro-ammeter indicating keel angle relative to horizontal datum (α_K).
Angle of roll : micro-ammeter indicating angle port or starboard.
} By Anschütz gyroscope.
Aileron force
Elevator force
Acceleration
Elevator movement
} By Desynn type transmitter and indicator.
Run number by Veeder number indicator.
Time by timing Veeder, operated by master contactor, every second.
Course by aircraft gyro-magnetic distant-reading compass.

Angle of pitch was also recorded by a Barnes type recording gyroscope.

4. *Results, Calm Water.*—4.1. *Stability and Attitude on Take-off.*—The stability and attitude curves obtained from take-offs at 72,000, 82,000 and 84,000 lb are compared in Figs. 2 and 3. The individual stability plots are given in Figs. 4, 5 and 6.

The stability runs at 72,000 and 82,000 lb were done in calm or choppy water conditions : those at 84,000 lb were done in some instances with a slight swell running. As is shown in the swell tests (Part II), slight swells may have a marked de-stabilising effect, and in addition, variation of wind speed, up to 16 knots, tends to cause some scatter at this weight. Hence no great reliance can be placed upon these results to give the calm water stability limit accurately. They are included in this report for the sake of completeness. Unstable points, obtained when a slight swell was running, are distinguished by a subscript 's'.

Figs. 7, 8 and 9 show typical take-off runs, elevator central, at 72,000, 82,000 and 84,000 lb. Both the 72,000 and 82,000 lb runs were stable, although that at 82,000 lb showed slight damped oscillations at the hump and between 75 and 95 knots. At 84,000 lb there was slight instability of 1-deg amplitude, between 40 and 60 knots, and a quickly damped oscillation between 80 and 95 knots. Typical fixed elevator take-off runs at an elevator angle of $+ 3 \cdot 5$ deg are shown in Figs. 10, 11 and 12. At 72,000 lb there was a slight oscillation over the hump, building up after 40 knots to an amplitude of just over 2 deg, and damping out at 55 knots. Oscillations built up again from 60 knots and control was taken* at 74 knots. At 82,000 and 84,000 lb there was similarly a slight oscillation over the hump, building up more rapidly after 40 knots to an amplitude between 3 deg and 4 deg. Control was taken in each case at 78 knots.

No upper limit instability was found, the upper take-off attitude being limited by lack of aileron control (*see* section 4.3). At full up elevator, $\eta = - 18$ deg, it is possible that attitudes giving upper limit instability could be attained at low speeds (35 to 45 knots), where lack of aileron control would be troublesome but not dangerous. On the *Seaford* I, the military predecessor of the *Solent* with the same hull form, skipping instability occurred on steady runs at high attitudes (greater than 8 deg) and speeds (greater than 70 knots)[1]. In the present tests, skipping instability occurred infrequently, at attitudes above 9 deg and speeds above 60 knots, and was very slight. It was not possible to define a limit. In tests on the *Sunderland* 3, an upper stability limit was determined and occurred at approximately 1 deg above the lower limit at the hump[2].

---

* Control was taken, *i.e.*, the fixed elevator was abandoned and the take-off completed normally.

The stable elevator ranges for 72,000 and 82,000 lb are tabulated below. These are based on an upper elevator-angle limit of — 12·5 deg, imposed by the lack of aileron control. The differences in stable elevator range at the two weights are not sufficient to affect noticeably the take-off performance.

Water speed (knots)	Stable elevator range (deg)	
	72,000 lb	82,000 lb
40	12	12
50	12	11·5
60	13	11·5
70	13	13
80	13·5	13

The attitude curves for $\eta = 0$ deg, — 12·5 deg and + 3·5 deg for each weight, together with the lower stability limit, are shown in Figs. 13, 14 and 15. — 12·5 deg and + 3·5 deg are the minimum and maximum elevator angles at which fixed-stick take-offs could be done. At $\eta = +5 \cdot 5$ deg, violent porpoising occurred at all weights and control had to be taken at about 60 knots.

The stable attitude range at each weight is plotted against water speed in Fig. 17. At 35 knots, increase of weight raises the attitude curve for $\eta = - 12 \cdot 5$ deg, more than the lower stability limit. Hence the available stable attitude range is increased with increase in weight, being 0·7 deg at 72,000 lb, increasing to 1·0 deg at 82,000 lb and 1·4 deg at 84,000 lb. At 60 knots water speed, increase of weight raises the lower stability limit more than the attitude curve, $\eta = - 12 \cdot 5$ deg, and the available stable attitude range decreases with increase in weight, being 3·9 deg at 72,000 lb, 3·6 deg at 82,000 lb and 3·0 deg at 84,000 lb. At 40 knots, the stable attitude ranges are approximately equal at 1·4 deg.

From the pilot's point of view, the narrow stable attitude range for 72,000 lb at 35 knots is not serious, since porpoising at the hump, if it does occur, is usually innocuous. At the higher weights and speeds the stable attitude ranges, although narrower than at 72,000 lb, are still wide enough to give ample control on take-off in calm water.

4.2. *Elevator Effectiveness.*—The elevator effectiveness at each weight was calculated over a water speed range of 30 to 80 knots and an elevator angle range of + 3·5 deg to — 12·5 deg. A linear efficiency over the range of η was assumed and in Fig. 16 the elevator effectiveness $d\alpha/d\eta$ calculated on this basis is plotted against water speed. Increase of weight from 72,000 to 82,000 lb decreases the elevator effectiveness by 20 per cent between 40 and 60 knots water speed. At 84,000 lb there are further decreases of 20 per cent at 50 knots and 10 per cent at 60 knots.

4.3. *Aileron Control.*—At 75,000 lb on take-offs with an up elevator angle greater than 12·5 deg, aileron control was poor, aileron snatch occurred at water speeds from 65 to 75 knots and the aircraft tended to leave the water at speeds which, combined with lack of aileron control, were dangerous. In flight at low speeds the aileron loads were high.

Increases in the tension of the aileron circuit improved the aileron snatch, but poor lateral control remained the limiting factor in the amount of up elevator which would be applied during take-off.

4.4. *Landing.*—Pilots experienced no difficulty in landing at all-up weights up to 84,000 lb. In order to keep the rate of descent at touch-down low, powered approaches were made using approximately 2,400 r.p.m. and 20-in. boost, giving approximately 400 b.h.p. per engine, at a speed of 110 to 120 knots E.A.S. Power was also used on touch-down to reduce the rate of descent to a minimum. The optimum touch-down speed range was found to be 90 to 95 knots E.A.S. On the few occasions when the rate of descent on touch-down was allowed to rise above 100 ft/min a slight heave resulted.

Fine-attitude landings also gave improved aileron control at touch-down. At the end of the landing run, poor aileron control at low speeds made it difficult to keep the port float out of the water.

4.5. *Spray.*—4.5.1. *Take-off.*—Medium spray was thrown into the inner propeller discs and light spray into outers from 20 to 35 knots water speed on take-off. Duration of damaging spray in propellers during normal take-off at 82,000 and 84,000 lb was 6 to 10 seconds. At planing speeds, the propellers were clear of spray. Spray height was increased only slightly with increase of weight from 80,000 to 84,000 lb. The extent of the damage to the propeller blades after 30 take-offs at 82,000 lb and 46 take-offs at 84,000 lb is shown in Fig. 18. The blades were filed smooth before these tests. The damage to the inner blades consisted of pitting on the leading edge for a distance of about 1 foot from the tip. The outer blades appeared to be completely undamaged. The spray damage is considered acceptable at 84,000 lb.

The spray on the flaps during take-off was appreciable, but not sufficient to cause damage.

During take-offs at weights up to 84,000 lb, the spray was clear of or only just touching the tailplane.

The spray on the propellers and tailplane at 25 knots, during a typical take-off at 80,000 lb, is shown in Fig. 19.

4.5.2. *Landing.*—On landing, solid water struck the flaps at about 50 knots water speed, causing them to vibrate (estimated from the aircraft about 3-in. amplitude). This was noted at an early stage in the tests. For all subsequent landings, the flaps were retracted immediately on touch-down to minimise the damage.

At the end of the landing run, as the bow settled in the water, solid water struck the tailplane. To minimise the damage, a burst was given on the inner engines as the bow settled, with the object of blowing the spray past the tailplane. This technique appeared to be successful and was adopted on all landings.

4.6. *Rough Water Performance.*—At 82,000 lb, take-offs could be made satisfactorily in short chops up to 4 feet in height. In winds of 20 knots, gusting to 27 knots, and a 4-feet chop with distance between wave crests of 40 feet, the take-off time was of the order of 45 seconds, with an unstick speed of about 90 knots E.A.S. Porpoising commenced at 35 knots water speed, but could be damped out by backward movement of the control column. Aileron and rudder control were adequate. A take-off in these conditions is illustrated in Fig. 20. Heavy spray was thrown on to the inner propellers and engines before the hump. Appreciable spray was thrown on to the flaps and tailplane between 35 and 50 knots, but was not heavy enough to cause damage. The floats were clear of heavy spray at all speeds. Solid water was not thrown into the propellers. Hull pounding was heavy, but not excessively so, before the hump, and was slight at planing speeds. Pounding of the floats occurred before the hump, but was light. There was a tendency for the aircraft to become prematurely airborne at 55 to 60 knots, but this could be controlled easily by forward movement of the control column.

The best pilot technique for take-off in rough water appeared to be as follows. The take-off was begun with elevator fully up and the outer engines opened up before the inners. Thus considerable speed was reached before the inner propellers were turning at full speed and this, combined with the high attitude, reduced the spray on the inner propellers considerably. The control column was moved forward to central so that the aircraft started to plane sooner. Any porpoising which occurred just after the hump could be damped quickly by upward elevator movement. At 55 to 60 knots, the aircraft had to be held down to counteract any tendency to leave the water before safe flying speed was attained.

All landings at 82,000 lb were made in more sheltered water to prevent damage to the aircraft, but landings in short chops up to 18 in. in height were made without difficulty.

4.7. *Crosswind Take-off Performance.*—The crosswind take-off performance is affected by two opposing factors. On an into-wind take-off, the aircraft tends to swing to starboard and the starboard float tends to immerse. With the wind on the starboard bow, the aircraft tends to weathercock and the swing to starboard is aggravated, but the wind helps to lift the starboard float and lateral control is improved. Conversely, a wind on the port bow improves directional control, but aggravates immersion of the starboard float.

At 82,000 lb, with the wind on the starboard bow, the limiting out-of-wind angle appeared to be 60 deg, irrespective of wind speed. The limiting wind strength at 60 deg out of wind was 12 knots, giving a crosswind component of 10·5 knots. The limiting wind speeds for other out of wind directions were not established.

At angles out of wind greater than 60 deg, the port outer engine had to be throttled so far that lateral control was lost and there was a danger of a float digging in the water in a rough sea. Also porpoising, if started just after the hump, became uncontrollable, because of the poor acceleration through the hump with one engine throttled, which allowed the amplitude to build up in the unstable region. Several take-offs were abandoned for this reason. On one take-off with a wind of 15 to 20 knots gusting, at 75 deg on the starboard bow, uncontrollable porpoising built up and the take-off was abandoned at 54 knots water speed. As the engines were throttled, the aircraft hit a swell and was thrown off the water, re-landing port wing down and damaging the port main spar. The attitude and control movements on this take-off are plotted in Fig. 21.

In the limiting conditions, coarse use of differential throttle and full port rudder were necessary to maintain a straight heading up to 45 to 50 knots, when full power could be applied. Full aileron was necessary up to 30 knots to keep the port float clear of the water. A take-off in near limiting conditions is shown in Fig. 22.

When the aircraft was fully planing, it was possible to maintain a straight course up to 80 deg out of wind.

Only a small number of take-offs with the wind on the port bow were done. The behaviour was similar to that with the wind on the starboard bow, but the limiting out-of-wind angle was about 50 deg, and the limiting wind speed 12 knots. It was difficult to raise the starboard float, aileron control being poor until full power was applied at about 40 to 45 knots. For the whole of each take-off run about 70 deg of wheel movement (about half full travel) and considerable force were needed to keep the starboard wing up.

5. *Discussion of Results.*—The outstanding feature of the test results at overload is the satisfactory spray and stability performance of this hull in sheltered water, at weights up to 82,000 lb. This weight corresponds to a static beam loading coefficient of 1·17, a value well above that generally considered satisfactory for a hull of *Solent* forebody length/beam ratio (3·33).

The hydrodynamic stability is acceptable, mainly because the rise in the lower stability limit is counterbalanced by a corresponding rise in the attitude curves, and because the upper limit lies well beyond the available range of attitude. Thus, the elevator ranges for stable take-off are hardly changed between 72,000 and 82,000 lb weight.

Paradoxically, the main deterioration in longitudinal stability with increased weight arises not from the movement of the stability limit, but from the decrease in longitudinal acceleration.

This effect is most marked during periods of instability, when the greater time in the unstable region leads to a higher amplitude of porpoising. The following table indicates the order of the time increase.

Water speed range	72,000 lb		82,000 lb	
	Stable	Porpoising	Stable	Porpoising
20 to 40 knots	11 sec	12 sec	$15\frac{1}{2}$ sec	18 sec
40 to 60 knots	9 sec	10 sec	14 sec	14 sec

At 72,000 lb, with an elevator angle of $+3 \cdot 5$ deg, the porpoising amplitude is about 2 deg. At 82,000 lb and the same elevator angle, the amplitude is between $3 \cdot 5$ deg and 4 deg.

It is difficult to determine how much of the rise in lower limit between 82,000 and 84,000 lb is due to the influence of swell, and how much to a continued deterioration in stability. Assuming that the effect of swell predominates, there is no reason why the present *Solent* hull should not be satisfactory at weights up to 86,000 lb, provided the engine power is increased to maintain a sufficiently high value of longitudinal acceleration—at least $0 \cdot 1g$.

The effect of spray at the higher weights is surprisingly small, considering that the acceleration in the damaging region is low, and that no attempt was made to nurse the inner propellers by throttling these engines at the start of take-off. These results suggest that the k factor*, put forward by Parkinson as a criterion of spray behaviour, is unduly pessimistic[3]. He quotes a value of $k = 0 \cdot 0975$ for excessive spray, based on the maximum beam and the forebody length to the step at the keel. The *Solent,* at 82,000 lb, has a k factor of $0 \cdot 194$, based on the beam at the step and forebody length to step centroid. A possible weakness in the use of the k factor as a criterion of spray characteristics is the fact that it depends on the static beam loading, $C_{\Delta 0}$, and makes no reference to the beam loading at the spray damaging speeds, which is affected by wing lift.

A report[4] on steady-run spray tests at 80,000 lb on a *Seaford* estimates the number of take-offs for critical damage†. The *Seaford* has the same hull form as the *Solent,* with consequently the same spray/propeller interference, enabling a comparison to be made with the present tests. The report estimates that for the *Seaford,* with hot water quenched blades, at 80,000 and 90,000 lb, respectively 85 and 21 normal‡ take-offs can be made before critical damage occurs. An interpolation of these figures gives approximately 40 take-offs for critical damage at 84,000 lb. This is considerably less than that obtained on the *Solent,* as is shown by Fig. 18, which shows the damage occurring after 46 normal take-offs at 84,000 lb and 30 normal take-offs at 82,000 lb.

On the *Seaford,* the blades were all of the same material, but some were oil quenched and the remainder were hot water quenched after heat treatment ; the report demonstrated that the hot water quenched blades were much more resistant to erosion than the oil quenched. On the *Solent* of the present report, all the blades were the same material as on the *Seaford,* but were cold water quenched after heat treatment. It has been found that cold water quenching gives greater resistance to erosion than hot water quenching, and it is considered that this is the main

---

* k is defined by the expression

$$C_{\Delta 0} = k\left(\frac{L_F}{b}\right)^2 .$$

† Critical damage is defined as that which demands removal of the propeller for re-balancing.

‡ Normal, *i.e.*, full power, not using the optimum technique as suggested in Ref. 4.

reason for the decreased damage on the *Solent* from that predicted from the *Seaford* tests. This view is supported by the results of overload tests done at the Marine Aircraft Experimental Establishment on a Tasman *Solent* Mark 4 fitted with cold water quenched blades. After 60 take-offs at 79,000 lb and many more at 70,000 lb, the propeller tips of this aircraft were not eroded, apart from isolated pin-sized cavities. The propellers on the *Seaford* would have been eroded to a depth of $\frac{1}{16}$-in. to $\frac{1}{8}$-in. at the tips after a similar number of take-offs. Although the engines are of greater power on the *Solent* 4 (2,000 b.h.p., *cf.* 1,680 b.h.p. on the *Seaford*) and the spray damaging time is therefore reduced, this difference alone is not sufficient to explain the large reduction in damage.

Another possible source of error in estimating the spray damage at 84,000 lb from Ref. 4 lies in the extrapolation of results to 90,000 lb. This is based on the increased damaging time on take-off and the increased blister height. The damaging times (4·8 sec at 80,000 lb, 11·1 at 90,000 lb) agree with those found on the present tests (6 to 10 sec at 82,000 and 84,000 lb); the extrapolation of blister height to 90,000 lb, however, may be erroneous. Although no quantitative measurements of spray height were made in the present tests, it appeared from visual observations that increase of weight up to 84,000 lb had but small effect on the spray height.

The worst characteristic of the aircraft at high all-up weights is its cross-wind performance. By contemporary standards this is poor, though there is no doubt that the low power available is again the limiting factor, rather than the inherent stability characteristics of the hull. With more powerful engines, the time spent in the porpoising region would be reduced, greater directional control would be available by use of asymmetric power, and the limiting wind speeds and out-of-wind direction would probably be increased.

6. *Conclusions.*—(*a*) With flying boats of similar hull form to the *Solent*, increase of weight up to a $C_{\Delta 0}$ of 1·2 has only a small direct effect on the take-off stability and spray characteristics.

(*b*) Decreased acceleration through the hump region at high all-up weights increases the porpoising, increases the duration of damaging spray in the propellers, and decreases the limiting out of wind angle for take-off. At 82,000 lb this limiting angle is between 50 deg and 60 deg coupled with a limiting crosswind component of 9 to 10 knots. For military aircraft, a minimum take-off acceleration of $0 \cdot 1g$ is recommended.

(*c*) Short seas up to 4 feet in height have relatively little effect on hydrodynamic performance.

(*d*) Landings up to a $C_{\Delta 0}$ of 1·2 are possible in sheltered waters.

PART II

Tests in Ocean Swell

1. *Introduction.*—Although the stability limits of the *Solent* appeared to be little affected by increases in weight, the reduction in acceleration and elevator efficiency gave rise to doubts about the performance in sea swells, where the uncontrollable external disturbance might cause porpoising beyond the limits of attitude regulation available to the pilot.

Unfortunately, the coastal waters around the Marine Aircraft Experimental Establishment are subject principally to short steep seas, and the long swells, most likely to cause dangerous instability, occur infrequently. A temporary test base was therefore established at Gibraltar, where swells are known to occur on most days of the year. Owing to the needs of other units at Gibraltar, the test period was limited to three weeks during February, 1951, and only a small variety of sea conditions could be investigated.

2. *Test Areas.*—Gibraltar Bay is sheltered from the ocean swells coming into the Mediterranean from the Atlantic and at no time during the test period was there a swell of suitable length in the Bay itself. The areas employed for take-off and alighting tests are indicated in the sketch map of Fig. 23. For westerly swells, the coastal area off Tangier was ideal, being directly exposed to the Atlantic and yet having a bay sheltered from the swell area, suitable for safe landing at high weight. A few tests were made off Gibraltar where the swell is shorter and steeper than at Tangier.

3. *Scope of Tests.*—The weight range covered was from 62,000 to 82,000 lb. Tests at the lower end of the weight scale were made to refresh the pilots' rough water handling techniques and to give a preliminary assessment of the aircraft's performance in swell. Most of the recorded results apply to the weight range between 74,000 and 82,000 lb.

Since the primary function of the tests was to establish the take-off behaviour, most of the recorded results are of take-offs. Wherever possible, landings were made in calmer water because of the danger of structural damage when alighting at overload. A few landings were made in swells at the lighter weights.

The sea conditions investigated included swells varying in length from 50 to 170 feet, and in height 0·5 to 5·0 feet. Wind strengths varied from zero to 15 knots. A summary of the conditions applicable to each test series is given in Table 2.

In contrast with the calm water test technique, pilots were not instructed to hold the elevator angle constant during take-off and landing runs. Use of differential power was allowed to maintain a straight course during take-off, and use of power was allowed to adjust the flight path during a landing approach.

Swell dimensions were estimated visually by independent observers on the aircraft and the stand-by launch. The lengths were checked by comparing the swell length against the length of the launch from the air. Estimated errors in assessment of swell dimension are ± 20 per cent for height and length. These errors are not unduly high when one considers that the swells were never of a simple sinusoidal shape, but varied in length and were often complicated by minor cross-swells and by wind waves.

4. *Results.*—Owing to the shortness of the test period available, an exhaustive survey of the effect of various parameters such as swell height, swell length, aircraft weight and wind velocity on the hydrodynamic stability was not possible. There is, however, a sufficiently wide range of conditions to allow the deduction of some generalisations on seaplane performance in sea swell.

4.1. *Comparison Between Take-off in Calm Water and Swell.*—The worst combination of circumstances for swell stability is that of high weight, zero wind and swell length sufficient to give resonance with the natural porpoising motion of the aircraft in the critical stability region. Such a combination occurred during one set of tests off Tangier. The aircraft weight was 82,000 lb, the wind strength between 0 and 4 knots and the swell length 100 to 170 feet.

Behaviour during a take-off into* a swell height of 0·5 to 1·0 feet is shown in Fig. 24. Porpoising started at 38 knots, built up to a maximum amplitude of 4 deg at 45 knots, and the aircraft stabilised itself at 54 knots. At 70 knots instability reappeared, but damped out after two oscillations. When the swell height increased to 1 to 2 feet, a similar train of events occurred, but the maximum amplitude increased to 10 deg and, as there was no sign of the motion being damped at 60 knots, the take-off had to be abandoned (Fig. 25). A similar take-off in calm water showed no sign of instability.

4.2. *The Effect of Swell Length.*—Figs. 26 and 27 illustrate the sensitivity of the hydrodynamic instability to swell length. The take-offs shown were made at a weight of 74,000 lb. The first was made into a swell of length 30 to 50 feet and height 2 feet. There was no pitching instability

---

* Throughout this report 'into swell' implies a take-off run perpendicular to the swell crests and against the direction of swell travel: 'along swell' a take-off run parallel to the swell crests.

and only slight movement in heave. The second take-off run was made during the same test series, but into a swell of length 80 to 100 feet and height 2 feet. Violent porpoising occurred from 30 to 60 knots, damping out automatically as the speed increased from 60 knots to take-off at 85 knots. These examples should be compared with Fig. 25 which refers to a swell length of 150 feet. Unfortunately, the latter comparison is obscured by the effect of increased weight.

4.3. *The Effect of Swell Height.*—Swell height appeared to have little influence on hydrodynamic instability. Provided the length was above the critical, all swells of over 1 foot in height produced violent instability. Below 1 foot, the instability was present but the porpoising amplitudes were reduced (Fig. 28).

4.4. *The Effect of Aircraft Weight.*—The effect of weight changes on the calm water hydrodynamic stability has been discussed in the first part of this report. For the open-sea trials, the aircraft was not equipped with means for changing the weight quickly, and tests at different weights had to be done on different days. Thus, changes in take-off weight were inevitably accompanied by changes in sea conditions and the effect of weight change is difficult to isolate.

However, some inferences on the effect of weight may be drawn from the evidence available. In Fig. 29 are plotted three take-offs. The first was made at a weight of 82,000 lb, swell 150 × 2 feet and zero wind, the second at a weight of 74,000 lb, swell 80 × 2 feet and wind 5 knots, and the third in the same conditions as the second, but with a wind speed of 12 knots.

Comparing the first two, and ignoring for the moment any effects due to the difference in swell length, there was an apparent amelioration in stability with reduction in weight. The rate of increase of amplitude with speed (Fig. 30) and the maximum amplitude were similar. But at 82,000 lb, the aircraft took 34 seconds to go from 30 knots to 62 knots, whereas at 74,000 lb this time was reduced to 20 seconds, and it was this greater time spent within the danger region which caused the pilot to abandon the take-off at the high weight but continue at the light weight. Thus, a reduction in weight of 10 per cent does not measurably improve stability in swell, but reduction of the time spent in the instability region caused an apparent improvement in the take-off behaviour.

A direct comparison of the performance at two weights may be obtained from take-offs B and C, where the wind has effectively reduced the weight in the unstable region, without altering the time spent in that region. Here there is a noticeable improvement but the weight reduction is large (equivalent weight at 50 knots = 63,000 lb). However, this does indicate the help which may be expected from take-offs into wind.

4.5. *The Effect of Take-off Direction Relative to the Swell Motion.*—The technique of taking-off in a direction parallel to the swell crests as a palliative for hydrodynamic instability has been known for some years. Its efficacy was demonstrated in a series of tests made by the United States Coastguards off the Californian coast[5].

For the *Solent,* the technique was equally effective. Of the take-offs shown in Fig. 31, the first was made into a swell of length about 150 feet and height $1\frac{1}{2}$ to 3 feet and had to be abandoned owing to severe porpoising; the second, made immediately afterwards, parallel to the crests of a swell of similar length but 3 to 4 feet in height, produced no instability.

4.6. *Alighting in Swell.*—Owing to the greater risk of structural damage during landing in swell compared with take-off, only a few landings were attempted in swell.

One landing made into a swell of 4 to 5 feet in height and 100 to 150 feet long is illustrated in Fig. 32. The violent movement in pitch was accompanied by an equally violent movement in heave, which caused the aircraft to be thrown clear of the water after the first touch-down. Although the landing was made into a wind of 14 knots, large aileron movements were needed to keep the wing-tip floats clear of the water. During the landing run, the tailplane leading edge was damaged (Fig. 33). Part of a typical landing run into a swell, showing heavy spray on the tailplane, is illustrated in Fig. 34. During a take-off made into the same swell, a divergent pitching oscillation occurred but the take-off run was short—owing to the wind—and the motion relatively innocuous. Pilots thought that take-off would be possible into such a swell, but landing hazardous.

No attempt was made to land into a swell at 82,000 lb weight. Landings made along the swell were completely satisfactory, even with swell heights of 3 to 4 feet.

4.7. *Lateral and Directional Stability.*—During into wind take-offs in swell, the lateral and directional stability appeared to be satisfactory, though large aileron deflections were necessary to keep the aircraft level. In landings, there was a tendency for the port wing to drop uncontrollably at a relatively high speed (about 35 knots), and if cross-wind landings are to be made it appears necessary to have the wind always on the port beam. Only a few cross-wind take-offs were made during the swell tests, the greatest cross-wind component was one of 15 knots on the port beam at an all-up weight of 65,000 lb. During this take-off, considerable differential throttling was necessary to maintain a straight path and the aileron control was such that the starboard float could not be raised from the water until a speed of 45 knots had been achieved.

4.8. *Spray.*—A qualitative assessment was made of the spray formation during rough-water take-offs and landings. The spray entering propellers did not appear to be much greater than that encountered during calm-water take-offs, and examination of the propellers before and after the tests showed no evidence of excessive spray damage.

However, the tailplane was subject to considerable impact, not only from spray but from green water, particularly during rough-sea landings where pitching occurred. This water impact was sufficient in the present tests to damage the leading edge of the port tailplane for a length of 3 to 4 feet (Figs. 33, 34). During subsequent into swell take-offs, the temporary repair to this damage showed signs of additional distortion owing to water impact.

The floats appeared to be quite clear of any spray during take-off and landing. The port float sustained one or two heavy impacts at speeds between 30 and 40 knots in landing, but showed no signs of damage. The present length of float struts is satisfactory for calm-water and rough-water operation.

5. *Discussion.*—If operated into an ocean swell of length greater than 50 to 70 feet and height greater than 1·0 to 1·5 feet, the *Solent* may porpoise violently from 40 to 60 knots. Swell height does not appear to affect the performance between the minimum critical height of 1·0 to 1·5 feet and the maximum height encountered, 5 feet. The motion is relatively insensitive to weight between the limits tested, *i.e.*, 72,000 and 82,000 lb, but the increased acceleration at 72,000 lb reduces the extent of the unstable region. Wind may reduce the severity of porpoising appreciably. Operation along the swell produces no instability in swells up to 200 feet long and 4 feet high.

Discussion of these results may be conveniently divided into three parts :

(i) general comments on swell stability

(ii) the relationship between model- and full-scale swell tests

(iii) design criteria for good behaviour in swell.

5.1. *General Comments on Swell Stability.*—The difficulty of isolating the effect of any specific parameter on swell stability by means of full-scale tests makes an accurate analysis of the problem impossible. However, one or two relationships are clear.

The swell length is of primary importance, in that below a certain length, approximating to the length of the hull, there is no tendency to pitch to the waves and the aircraft behaves very much as in calm water, with additional movement in heave depending on the height of the swell. As the swell length increases from this minimum critical value, the aircraft tends to pitch to the waves until a combination of swell length and height is reached, which is sufficient to disturb the aircraft into a region of cyclic instability, thereby triggering the onset of severe swell porpoising. This reasoning suggests that once above the triggering length, swell porpoising will occur whatever the swell length. However, the amplitude of the instability will obviously depend on the relationship between the frequency of the calm-water porpoising oscillation and the rate of striking swells. A crude analysis of the problem suggests that the severe instability will occur when the swell length is such that disturbance frequency is equal to the calm water porpoising frequency in a speed range where the calm water stability limits are close together. For example, on the *Solent,* this speed range is from 40 to 60 knots water speed and the calm porpoising period is 2 to $2\frac{1}{2}$ seconds, giving dangerous swell lengths of 130 to 250 feet. Severe instability certainly occurred on the *Solent* when operating in swells of this length, but the maximum swell length tested was 170 feet and there is, therefore, no full-scale information on the behaviour as the swell length increases beyond the danger lengths.

Assuming that there is some relationship between the region of cyclic swell instability and the calm-water instability regions, there ought to be a speed during take-off at which the swell porpoising stops, or is reduced in amplitude corresponding to the divergence of the calm-water limits. Fig. 27 illustrates effectively that this does occur. From 40 to 60 knots there is severe instability which stops suddenly at 60 to 65 knots. One could argue that this stabilising effect was due to the changing ratio of disturbance to natural frequencies as the forward speed increases, but this ratio changes slowly over the relevant speed range and would be most unlikely to cause the rapid damping of oscillation shown.

The full-scale tests show clearly that the minimum height of swell required to initiate severe swell instability is very small, 1 to 1·5 feet. Increase in height above this increases the movement in heave and may increase the speed at which porpoising ceases. There was, however, no evidence of this latter effect in swells up to 5 feet high.

The effect of aircraft weight in swell performance is linked to the effect of weight on the position of the calm water stability limits. This appears to be relatively small for the *Solent* and weight should not, therefore, have much effect on swell performance for this aircraft. There is, of course, a marked improvement with lower weight in practice, because of the increased acceleration through the danger region.

If the wind is blowing with the swell, then an into-wind take-off will improve the swell performance by virtue of the decreased loads at any one water speed. The advisability of taking-off into wind in such a combination of wind and swell direction must be considered in relation to the very effective elimination of swell instability achieved by taking-off parallel to the swell crests.

5.2. *The Relationship Between Model- and Full-scale Swell Tests.*—The most recent model tests in swell available in the United Kingdom are those given in Ref. 8. These tests were made primarily to furnish information on the swell behaviour of the *Princess* class flying boats. To establish a norm, tests were first attempted on models of the *Sunderland* and *Solent.* Unfortunately, these hulls exhibited such severe instability at about half take-off speed that continuation of the tests was not possible. Tank tests do simulate the worst conditions encountered full-scale, take-off into swell with zero wind, but even allowing for this, the results from the *Solent* seem pessimistic when compared with the full-scale behaviour.

However, tests were made on *Shetland* and *Princess* models and the results from these provide an enlightening background to the full-scale results.

The effect of swell length is given in Figs. 35 to 37 (swell height 3 feet, speed constant at 67 knots, both to *Princess* scale). For the *Princess,* once the triggering length of 160 to 170 feet has been reached (hull length, 121 feet), there is no great variation in porpoising amplitude with swell length. The calm-water porpoising period of the *Princess* is 3·5 seconds, giving a resonance at a swell length of 430 feet, but there is no untoward increase in instability at this wave length.

The *Shetland* has a triggering length of 120 feet (equivalent length 114 feet) and fairly well defined peaks of porpoising amplitude at 270 and 520 feet, neither of which is very near the critical length for 67 knots (340 feet) (Fig. 35). But a few accelerated runs were made on the *Shetland*, and these show a most marked increase in porpoising amplitude at the critical length (Fig. 37).

During the *Shetland* tests, wave heights of 2·25 feet and 3·0 feet were applied, without producing any apparent change in behaviour.

Thus, it appears that for accelerated runs, the model tests indicate the same trends as are deduced from the full-scale results, though they may be more pessimistic in their absolute assessment of swell instability.

5.3. *Design for Good Performance in Swell.*—The foregoing discussion has indicated a relationship between the stability in calm water and that in swell, but it has also shown that once swell instability has been triggered the behaviour in swell is more a function of the dynamic stability qualities than of the static stability limits. In this respect, the high length/beam ratio hulls developed in the United States have shown themselves superior to hulls of *Solent* design[6]. All the evidence obtained so far is from model tests. If the trend is confirmed full-scale, then length/beam ratios of 10 or 15 appear to be advisable ; the lower figure for aircraft operating infrequently in swell, *e.g.*, civil aircraft, the higher for rescue aircraft and any others expected to operate regularly in ocean swell.

A further improvement in hydrodynamic design may be obtained by utilising the afterbody design criteria of Tomaszewski and Smith[7], which should produce an improvement in the calm-water stability limits, and increased afterbody damping.

The most important requirements in aerodynamic design are good lateral and directional control down to stalling speed on landing, and at as low a water speed as possible during take-off. If the take-off is to be made along the swell, it may also be crosswind, and this suggests that for civil aircraft a straight take-off course should be possible, with a crosswind of 10 knots at right-angles to the take-off path ; for military aircraft, this wind speed should be 15 knots, and for rescue aircraft 20 to 25 knots. The straight path would have to be maintained between speeds of, say, two-thirds hump speed and unstick speed, thus allowing the take-off to be *started* into wind. For into-swell take-offs, good lateral control is needed, down to hump speed, in order to keep the auxiliary floats clear of the water if porpoising starts.

Probably the most important requirement for into-swell take-offs is adequate acceleration through the danger region, where the stability limits are closest. For the *Solent*, the danger region is between 40 and 60 knots and, assuming that no more than five oscillations are permissible within this region, the mean acceleration should not be less than 0·10*g*. The usefulness of rocket assistance was clearly demonstrated in the U.S. Coastguards' tests, and for aircraft to be used in open-sea operations some form of assisted take-off is essential.

For into-swell alighting, lateral control must be good down to the stall, and the stalling speed should be as low as possible. However, unless the crosswind is high (above 20 knots) or space restricted, an into-swell alighting is most unwise, since the pilot has no control, if porpoising does start. For alightings along the swell, the design requirements are similar to those for take-off, *i.e.*, a straight path to be maintained with a beam crosswind of 10 knots for civil aircraft, 15 knots for military aircraft and 20 to 25 knots for rescue aircraft. The straight path should be maintained between touch-down speed and hump speed.

The problem of satisfactory crosswind performance is closely linked to the hydrodynamic and structural design of the wing-tip floats. For good swell performance, the wing-tip floats should not tend to dive, even when fully immersed, and structural design should be such that, for military aircraft at least, full immersion at the aircraft stalling speed does not cause undue structural damage. For civil aircraft, this might be relaxed to a speed equivalent to 0·7 of the stalling speed.

One possible method of reducing the damaging time in an into-swell landing is to increase the deceleration by means of reversing pitch propellers. There are drawbacks to the use of such a procedure. The principal one is that the pilot is committed to riding out the landing, once he has selected reverse pitch.

6. *Conclusions.*—(*a*) Flying-boat hulls of similar form to the *Solent* will porpoise, if taken off or landed into swells having lengths greater than the length of the hull, and heights greater than 1 to $1\frac{1}{2}$ feet. This applies, even if the hull is stable in sheltered water.

(*b*) Swell height does not affect the unstable motion appreciably.

(*c*) Variations in weight do not affect swell stability greatly of themselves. In practice, there is an improvement with decrease in weight, because of the smaller time spent in the unstable region.

(*d*) Wind strength reduces swell porpoising considerably, if the take-off is made into swell and wind.

(*e*) Take-offs and landings may be made parallel to the swell crests without any instability.

(*f*) The most desirable design features for good swell performance are as follows :

- (i) Adequate lateral and directional stability and control at low speeds, including good crosswind control and satisfactory float design.
- (ii) Ample acceleration in the initial stages of planing ; at least $0 \cdot 1g$ is suggested.
- (iii) Adequate hydrodynamic damping in pitch.

LIST OF SYMBOLS

α_K	Keel datum attitude—angle between tangent to forebody keel at step and horizontal
b	Hull beam, feet
C_Δ	Beam loading coefficient (Δ / wb^3)
$C_{\Delta 0}$	Static beam loading coefficient
Δ	Load on water, lb
Δ_0	Static load on water, lb
w	Density of sea-water (64 lb/cu ft)
k	Parkinson's spray coefficient $\left[C_{\Delta 0} = k\left(\frac{L_F}{b}\right)^2\right]$
L_F	Forebody length from bow to step, feet
η	Elevator angle

LIST OF REFERENCES

No.	*Author*	*Title, etc.*
1	J. Stringer	Full-scale water stability tests with special reference to hull pounding, *Seaford* I. M.A.E.E. Report F/Res/205. A.R.C. 10,851. July, 1947. (Unpublished.)
2	P. E. Naylor	The effect of weight variation on the water stability, trim and elevator effectiveness of a *Sunderland* 3 aircraft during take-off and landing. M.A.E.E. Report H/Res/171. February, 1944.
3	John B. Parkinson	The design of the optimum hull for a large long-range flying boat. N.A.C.A. Advanced Restricted Report No. L4I12. Wartime Report L-282. A.R.C. 8,523. September, 1944.

REFERENCES—*continued*

No.	*Author*	*Title, etc.*
4	J. E. Allen	Full-scale spray tests of a four-engined flying boat (*Seaford*) with a special reference to propeller damage. M.A.E.E. Report F/Res/207. A.R.C. 11,237. December, 1947. (Unpublished.)
5	—	Open-sea seaplane operations conducted by the U.S. Coast Guard. Air Sea Safety. Vol. I, No. I. November, 1946.
6	Arthur W. Carter	Effect of hull length/beam ratio on the hydrodynamic characteristics of flying boats in waves. N.A.C.A. Tech. Note 1782. January, 1949.
7	K. Tomaszewski and A. G. Smith	Some aspects of the flow round planing seaplane hull or floats and improvement in step and afterbody design. M.A.E.E. Tech. Memo. 5. A.R.C. 14,376. July, 1951. Paper given at Congress of Applied Mathematics, London, 1948.
8	T. B. Owen and D. F. Wright	Comparative model tests of *Princess* and *Shetland* flying boats in waves. R.A.E. Tech. Note Aero. 2166. A.R.C. 15,496. May, 1952. (Unpublished.)

TABLE 1

Aircraft Data

Hull	
Maximum beam	10·75 ft
Beam at step chine	10·3 ft
Forebody length :	
Front perpendicular to step at chine	36·1 ft
Front perpendicular to step centroid	34·2 ft
Afterbody length, front step at keel to aft step at keel	34·8 ft
Hull overall length	89·6 ft
Ratio $\frac{\text{Forebody length to step}}{\text{Maximum beam}}$	3·35
Ratio $\frac{\text{Forebody length to step centroid}}{\text{Beam at step}}$	3·33
$C_{\Delta 0}$ based on maximum beam	
72,000 lb	0·906
82,000 lb	1·03
84,000 lb	1·06
$C_{\Delta 0}$ based on beam at step	
72,000 lb	1·03
82,000 lb	1·17
84,000 lb	1·20
Forebody keel—hull datum angle	2 deg 12 min
Afterbody keel—hull datum angle	4 deg 14 min
Wings	
Gross area	1,687 sq ft
Span	112·8 ft
Aspect ratio	7·54
Incidence to hull datum	6 deg 9 min
Aileron movement (measured)	17·2 deg up 17·5 deg down

TABLE 1—*continued*

Tailplane	
Area excluding elevators and tabs	163·5 sq ft
Span	42·43 ft
Incidence to hull datum	4 deg
Elevator area including tabs	102·3 sq ft
Elevator movement (measured)	17·5 deg up 18 deg down
Fin and Rudder	
Area of fin, excluding rudder	112·82 sq ft
Rudder area, including tabs	82·18 sq ft
Rudder movement (measured)	±15·5 deg
Flaps (Gouge Type)	
Total area	286·24 sq ft
⅓rd deflection	7 deg 30 min
⅔rd deflection	16 deg 30 min
Increase in wing area, ⅓rd deflection	34·6 sq ft
Increase in wing area, ⅔rd deflection	50·2 sq ft

Engines

4 Hercules 637, giving 1,690 b.h.p. at 2,800 r.p.m. and + 8·0 lb/sq in. (46·25 in. Hg) boost pressure for take-off at sea-level.

Propellers

4-bladed left-hand tractor

Type : de Havilland No. CD 108/446/1

Diameter	12·75 ft
Solidity, at 0·7 radius	0·1405
Gear ratio	0·444

Material : Aluminium alloy to Specification D.T.D. 150, cold-water quenched.

TABLE 2

Wind and Water Conditions for Tests in Swells

(*See* also Fig. 23)

Test series No.	Test	Aircraft weight (lb)	Wind speed (knots)	Sea conditions	
				Swell height (ft)	Swell length (ft)
1	Pilot familiarisation. Take-offs and landings	65,000	5 – 9	1 – 2 (Chop)	—
2	Pilot familiarisation. Take-offs and landings	65,000	8 – 17	2 With 18-in. chop	40 – 50 increasing to 100
3	Take-offs and landings into swell	72,000	13 – 15	3 – 5 With 18-in. chop	100 – 170
4	Take-offs and landings into and along swell	82,000	0 – 6	0 – 3	140 – 160
5	(*a*) Take-offs and landings into and along swell (*b*) Take-offs and landings into swell	74,000	(*a*) 2 – 4 (*b*) 5 – 14	(*a*) 1 – 2 (*b*) 3	(*a*) 30 – 50 (*b*) 80 – 100

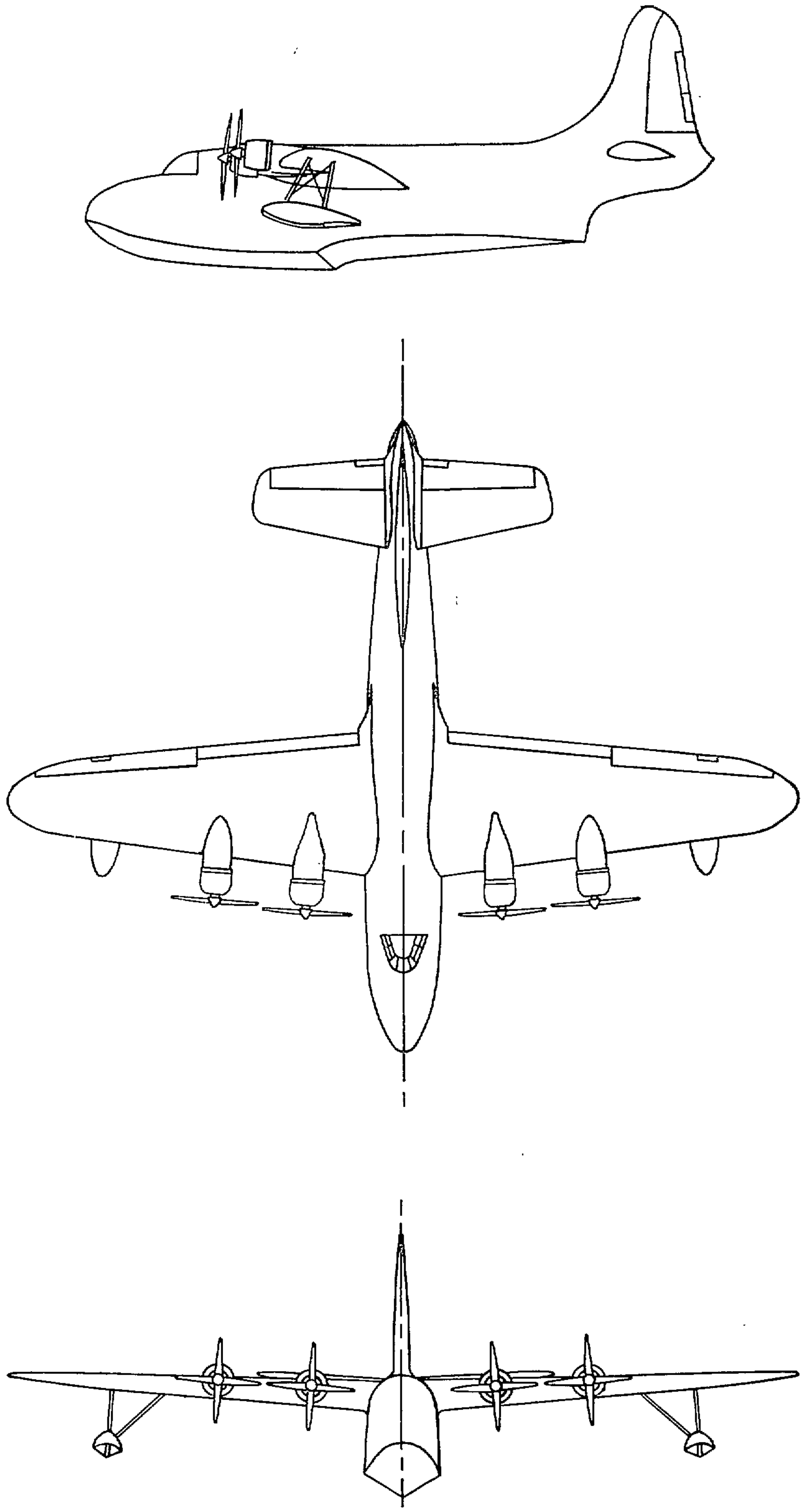


FIG. 1. *Solent* Mk. 3. General arrangement.

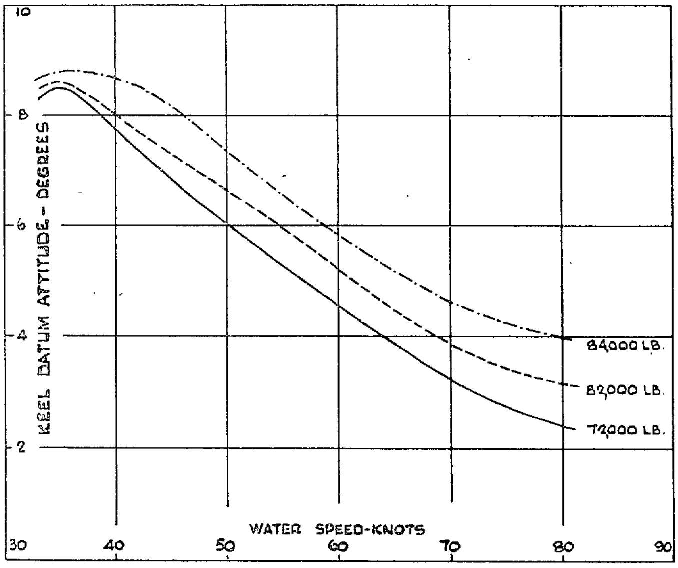


FIG. 2. Calm-water take-off stability.
Lower limits. 72,000, 82,000 and 84,000 lb.

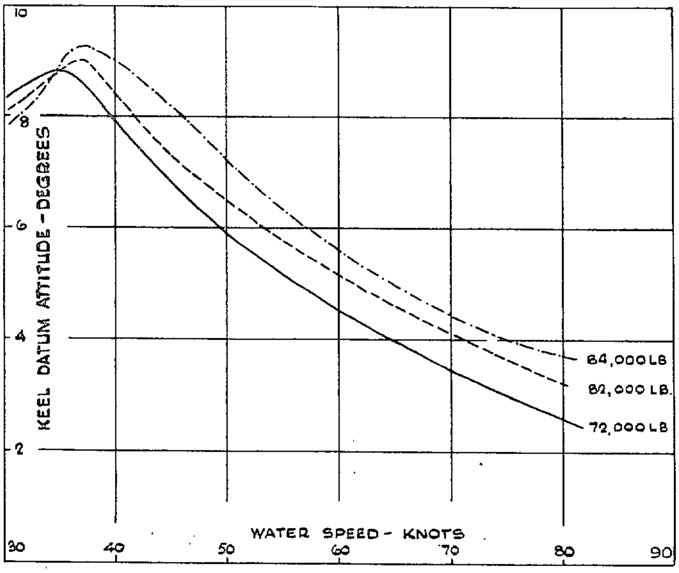


FIG. 3. Attitude curves on take-off in calm water.
72,000, 82,000 and 84,000 lb. Elevator central.

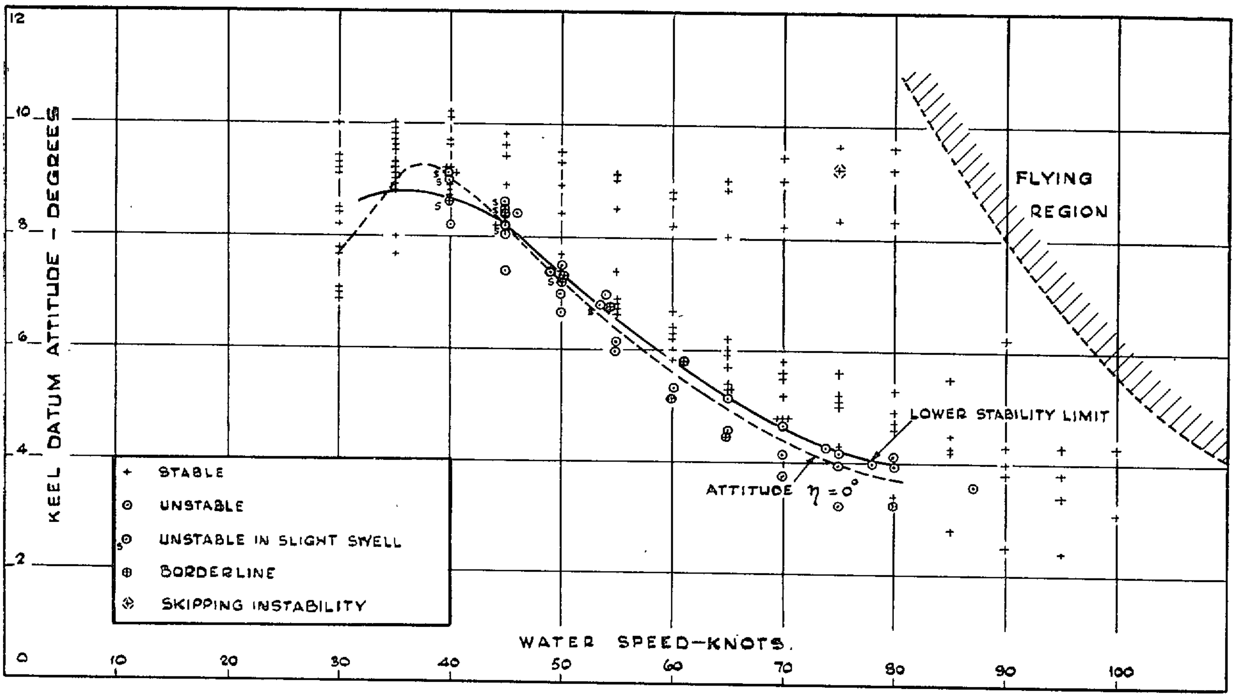


FIG. 6. Calm-water take-off stability. 84,000 lb.

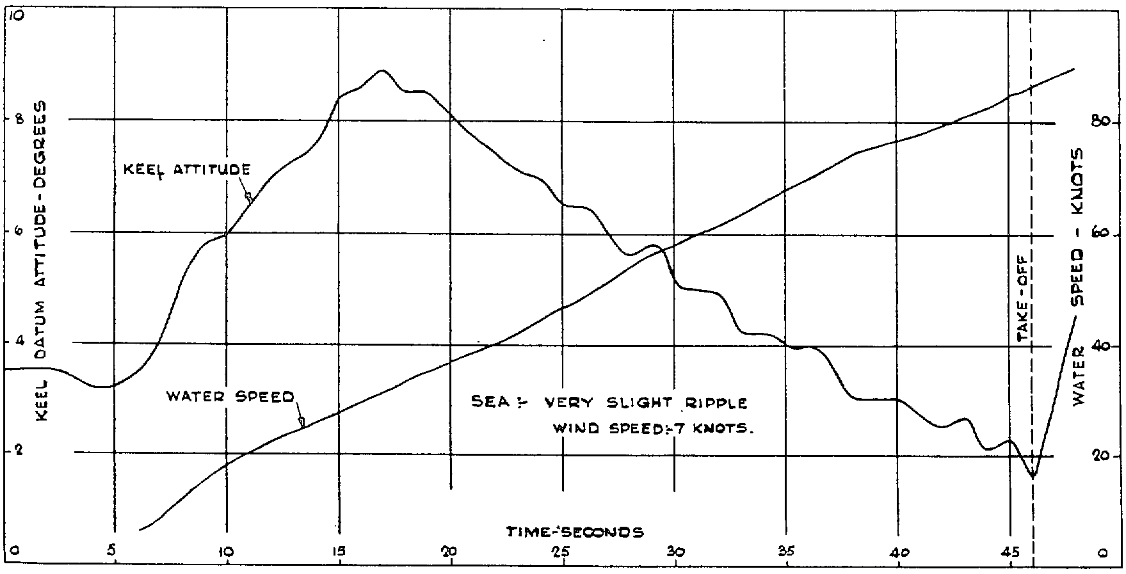


FIG. 7. Time history of take-off. Weight 72,000 lb. Elevator central.

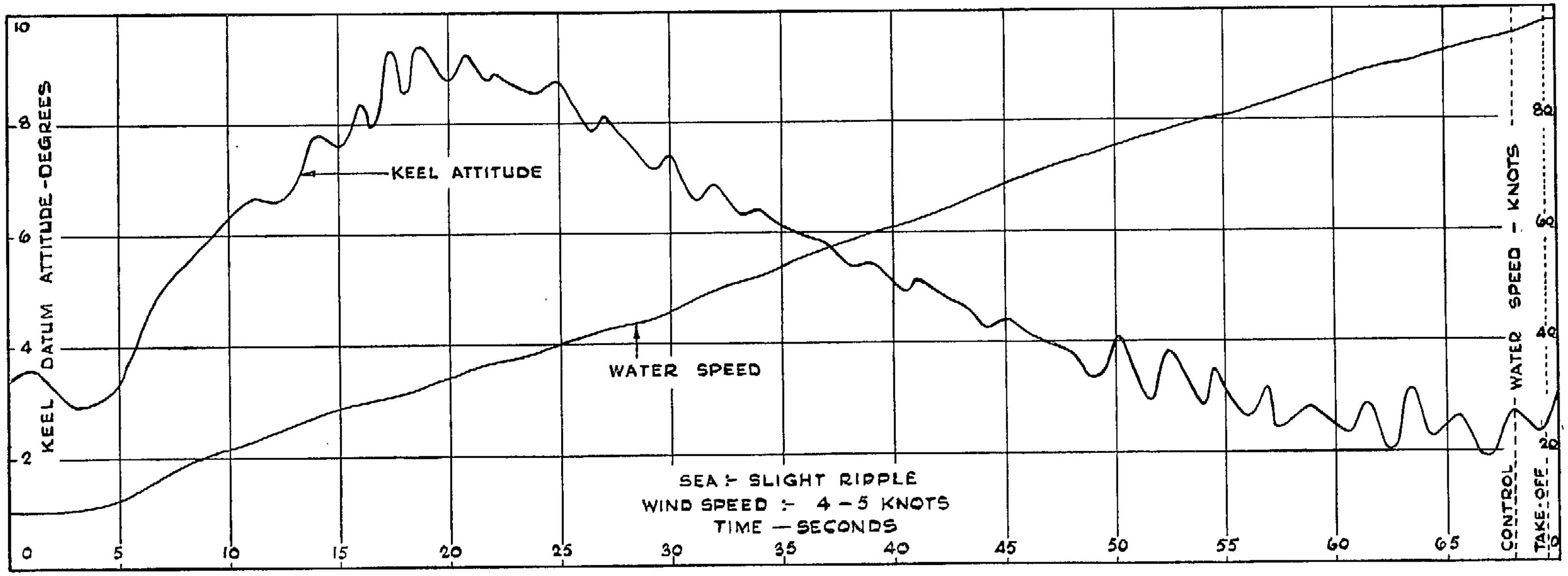


FIG. 8. Time history of take-off. Weight 82,000 lb. Elevator central.

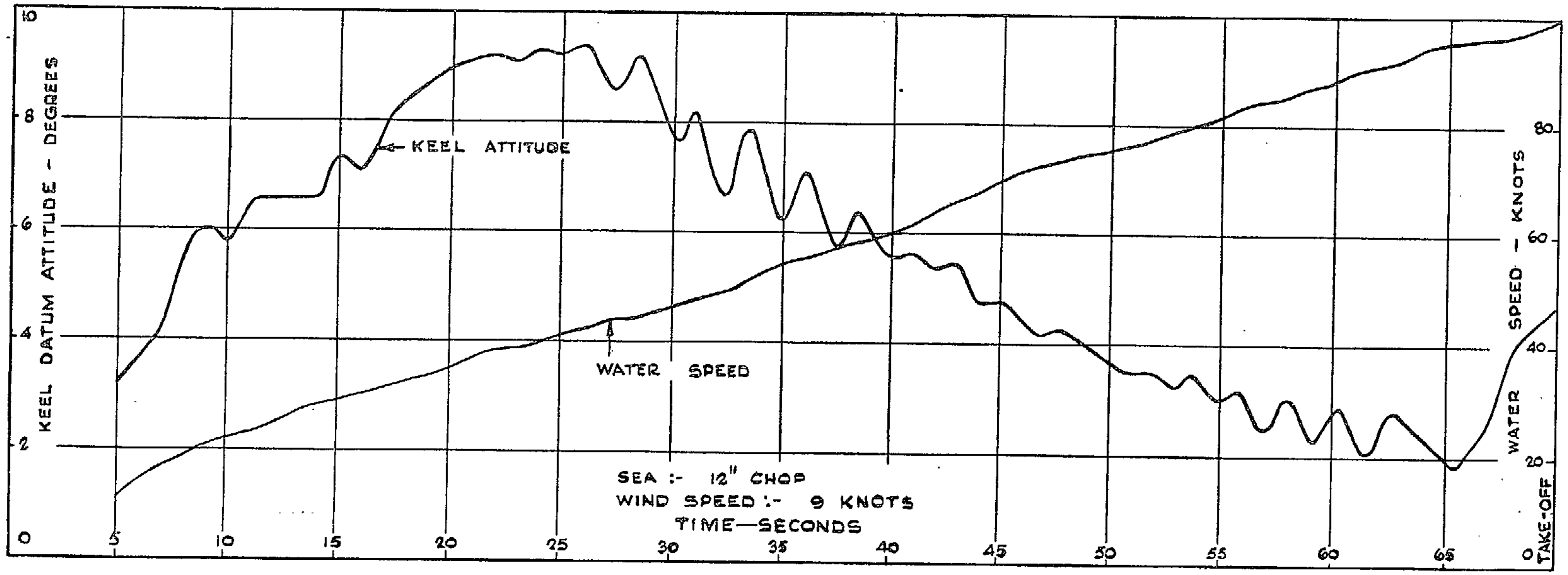


Fig. 9. Time history of take-off. Weight 84,000 lb. Elevator central.

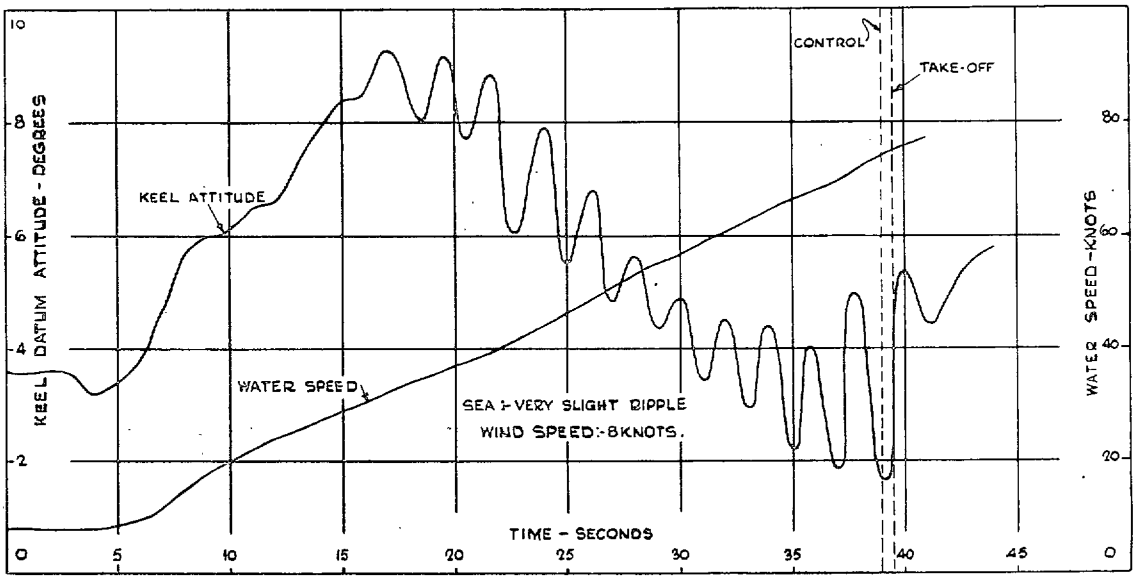


FIG. 10. Time history of take-off. Weight 72,000 lb. Elevator down, $\eta = +3\cdot5$ deg.

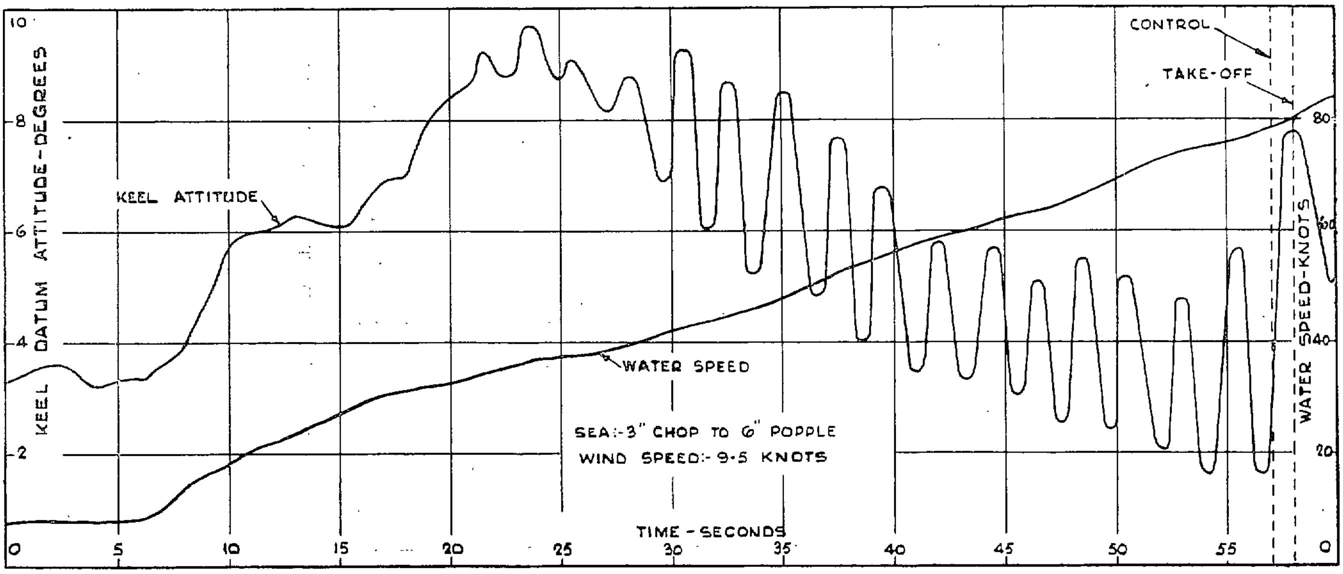


FIG. 11. Time history of take-off. Weight 82,000 lb. Elevator down, $\eta = +3\cdot5$ deg.

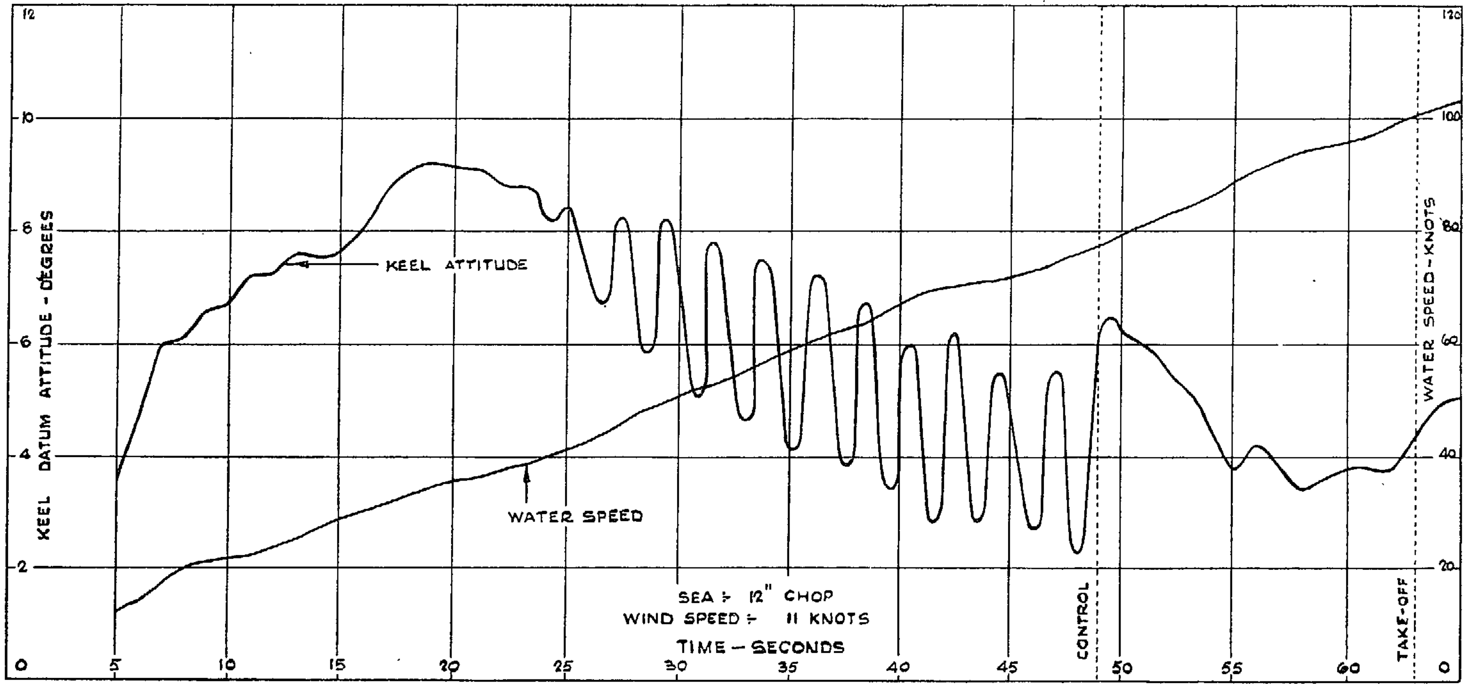


FIG. 12. Time history of take-off. Weight 84,000 lb. Elevator down, $\eta = +3 \cdot 5$ deg.

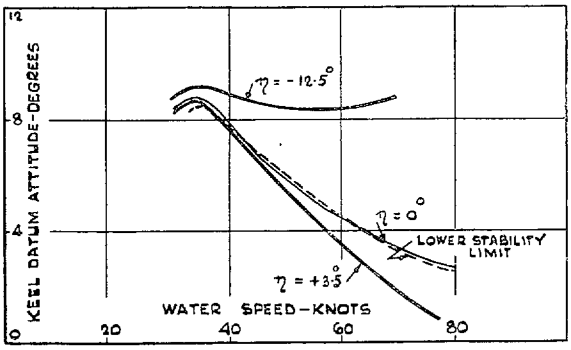


Fig. 13. Attitude curves and lower stability limit. 72,000 lb.

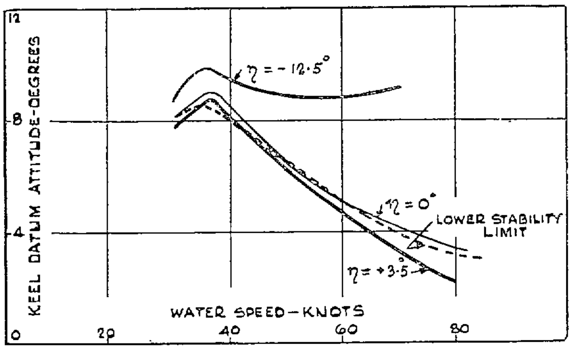


Fig. 14. Attitude curves and lower stability limit. 82,000 lb.

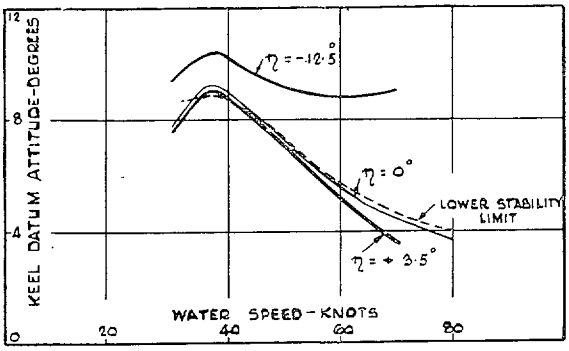


Fig. 15. Attitude curves and lower stability limit. 84,000 lb.

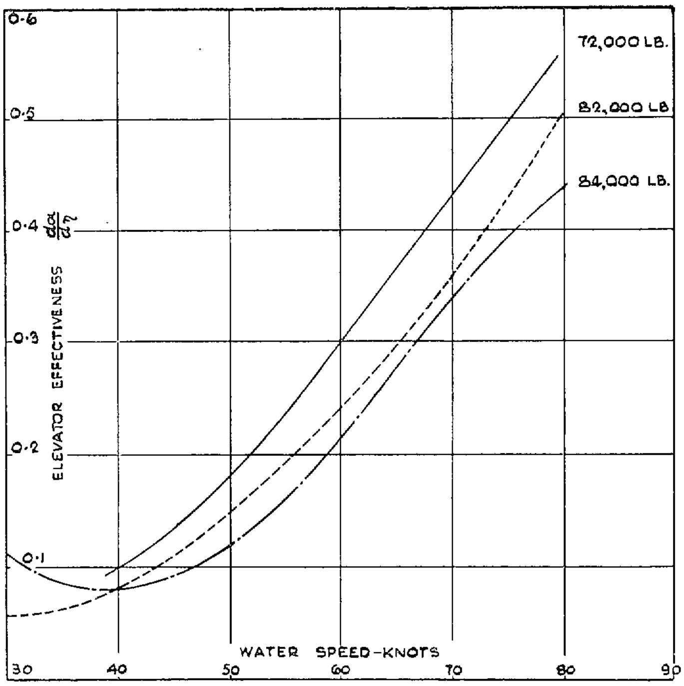


Fig. 16. Comparison of elevator effectiveness. 72,000, 82,000 and 84,000 lb.

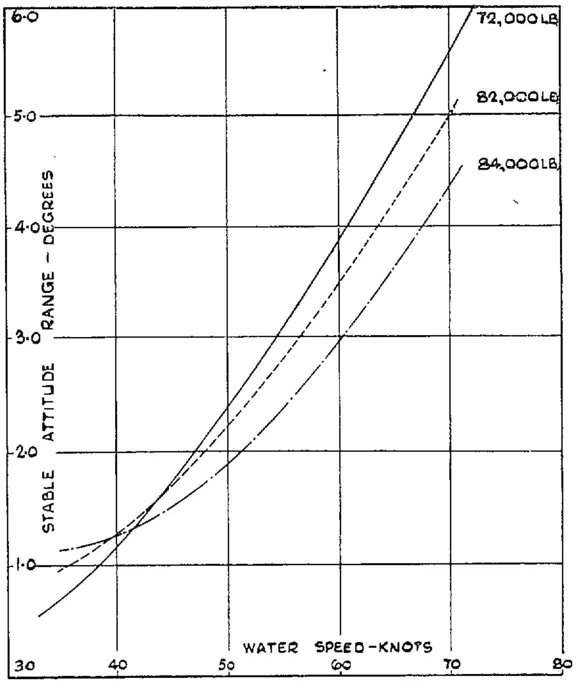


Fig. 17. Comparison of stable attitude ranges. 72,000, 82,000 and 84,000 lb.

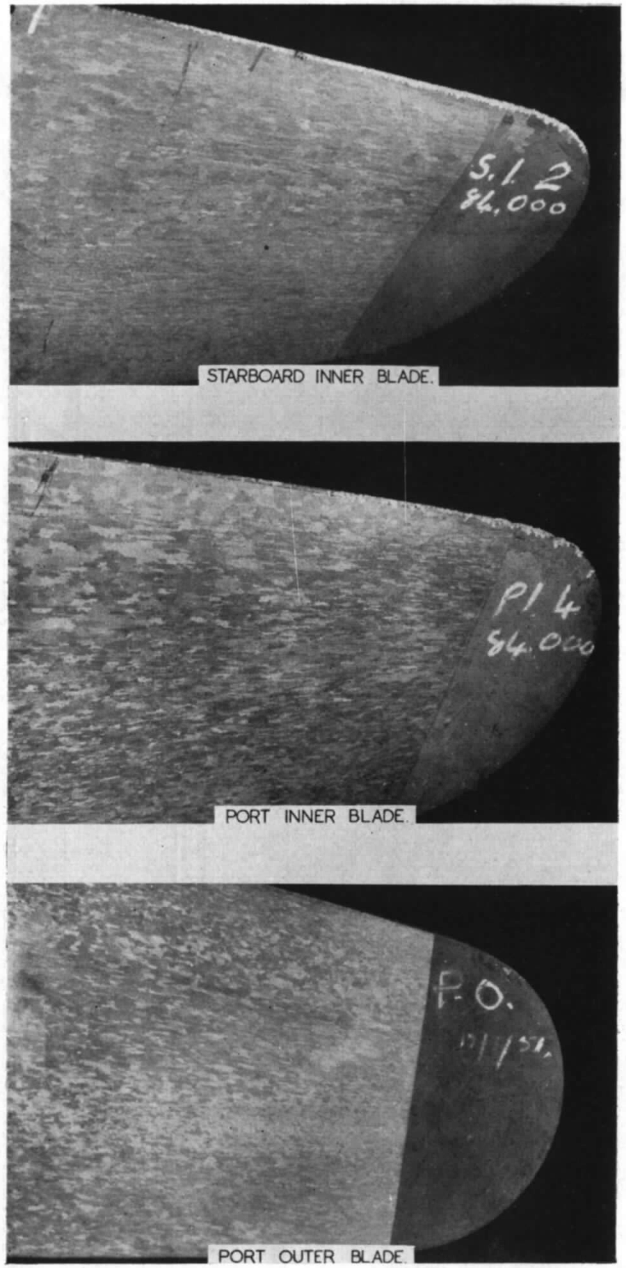
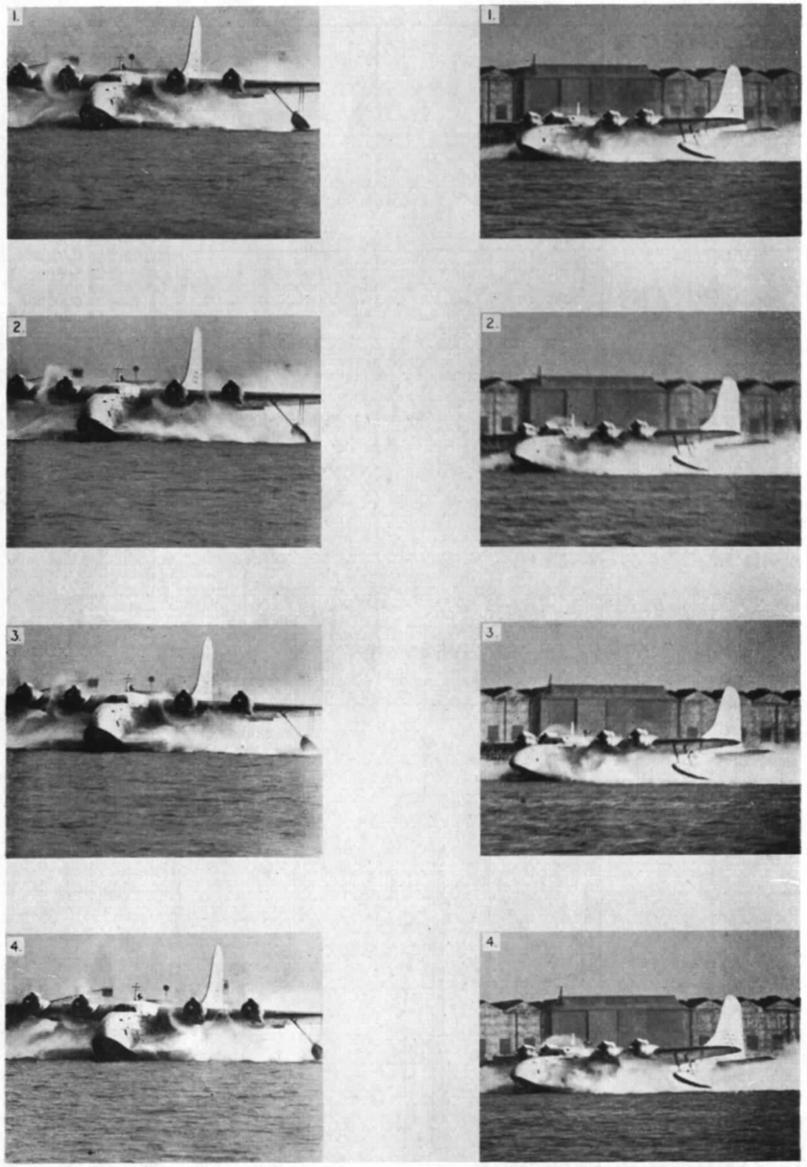


FIG. 18. Propeller damage after 30 take-offs at 82,000 lb. and 46 take-offs at 84,000 lb.



A. Spray in propellers.
Sea : 4-in. chop.
Wind speed : 12 knots.

B. Spray on tail.
Sea : 4-in. to 6-in. chop.
Wind speed : 14 knots.

FIG. 19. Spray during take-off. Weight : 80,000 lb. Water speed : approximately 25 knots. Interval between frames $\frac{1}{6}$ sec.

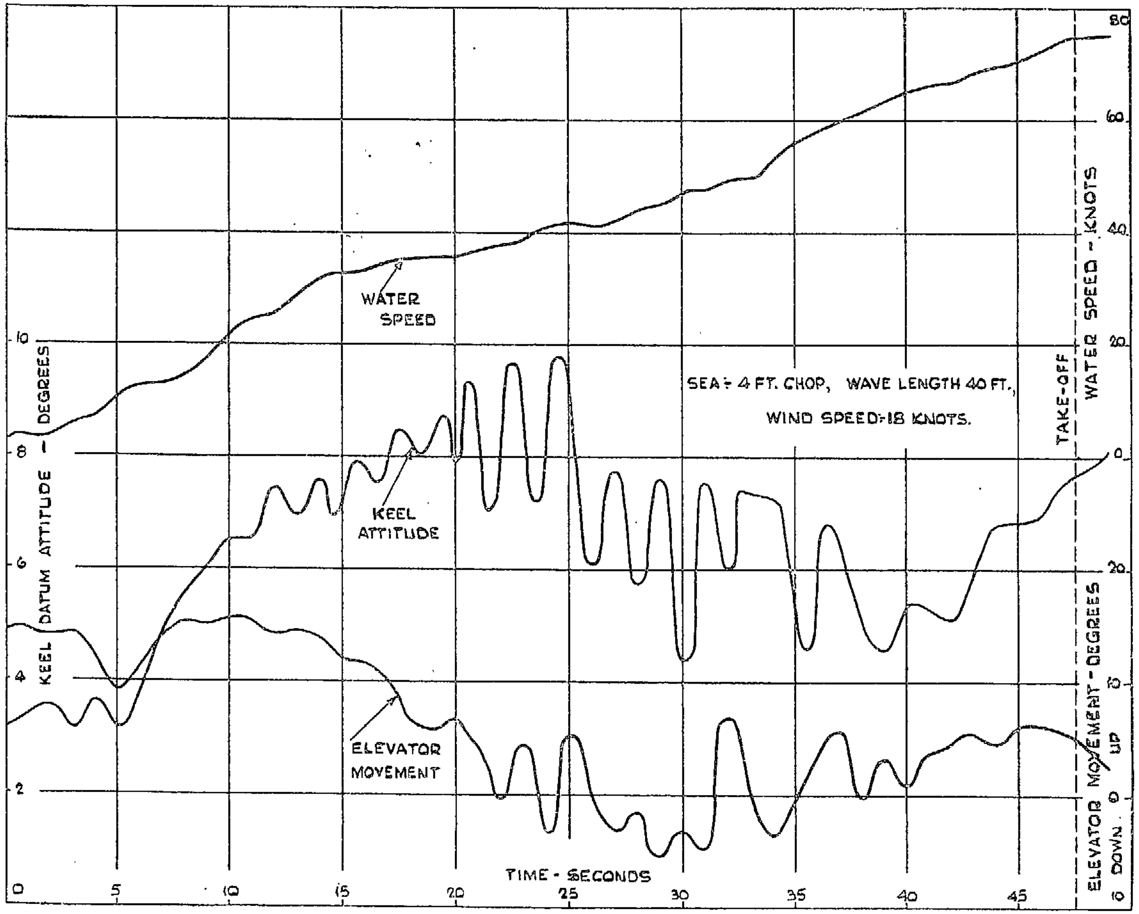


FIG. 20. Time history of rough-water take-off. Weight 82,000 lb. Elevator free.

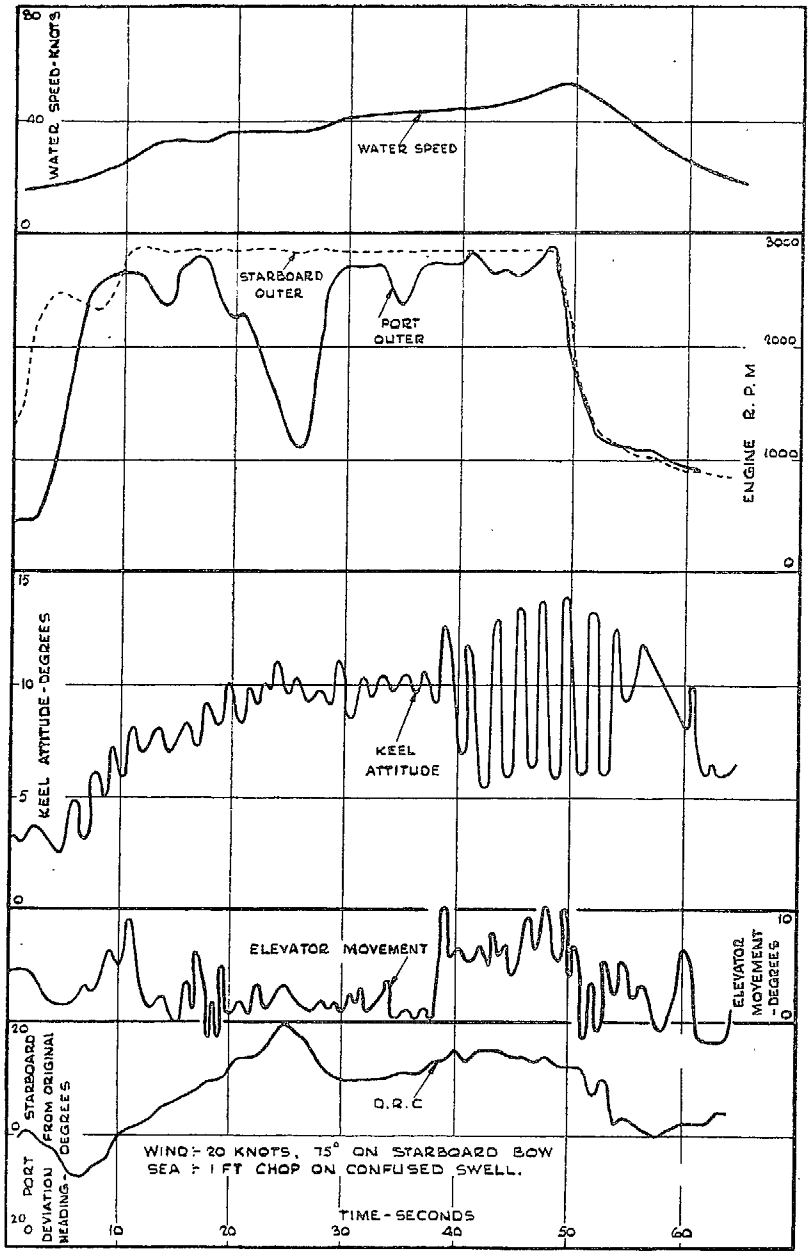


FIG. 21a. Time history of abandoned cross-wind take-off. 82,000 lb.

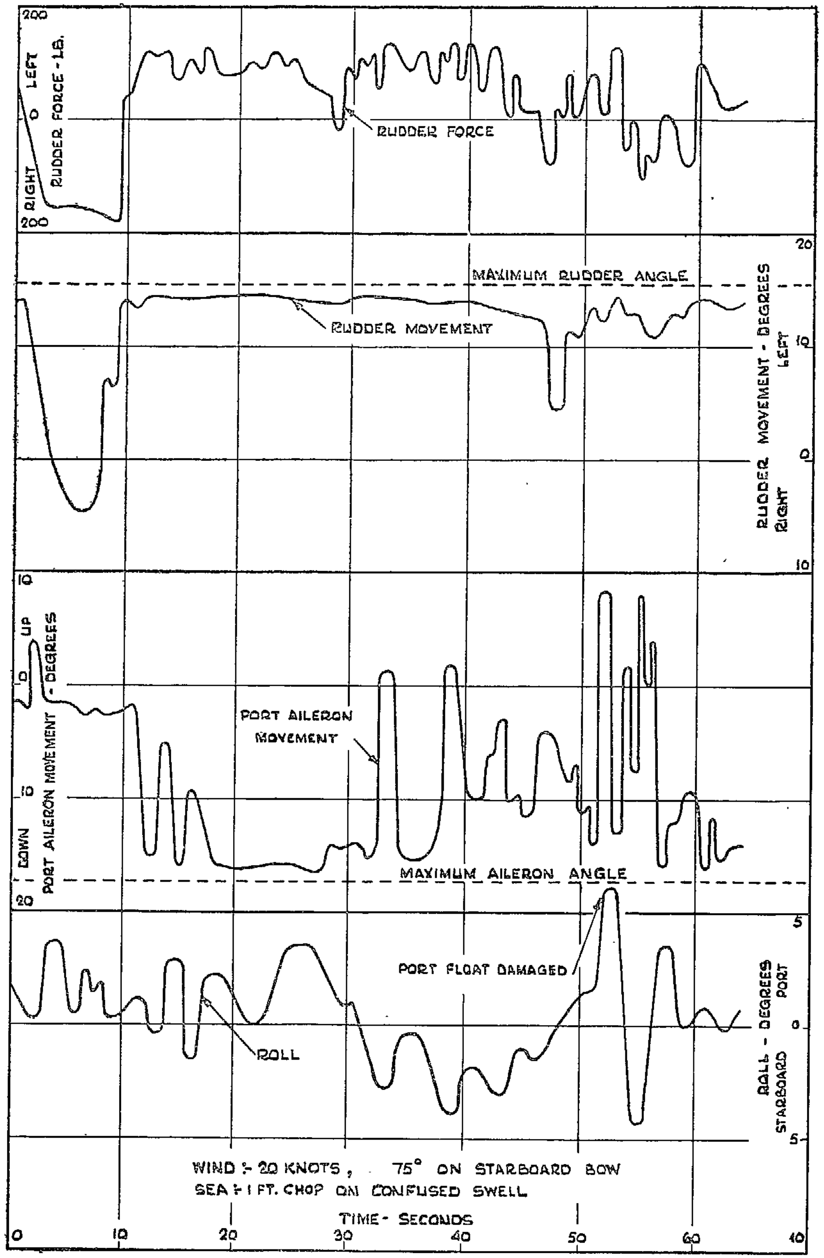


FIG. 21b. Time history of abandoned cross-wind take-off. 82,000 lb.

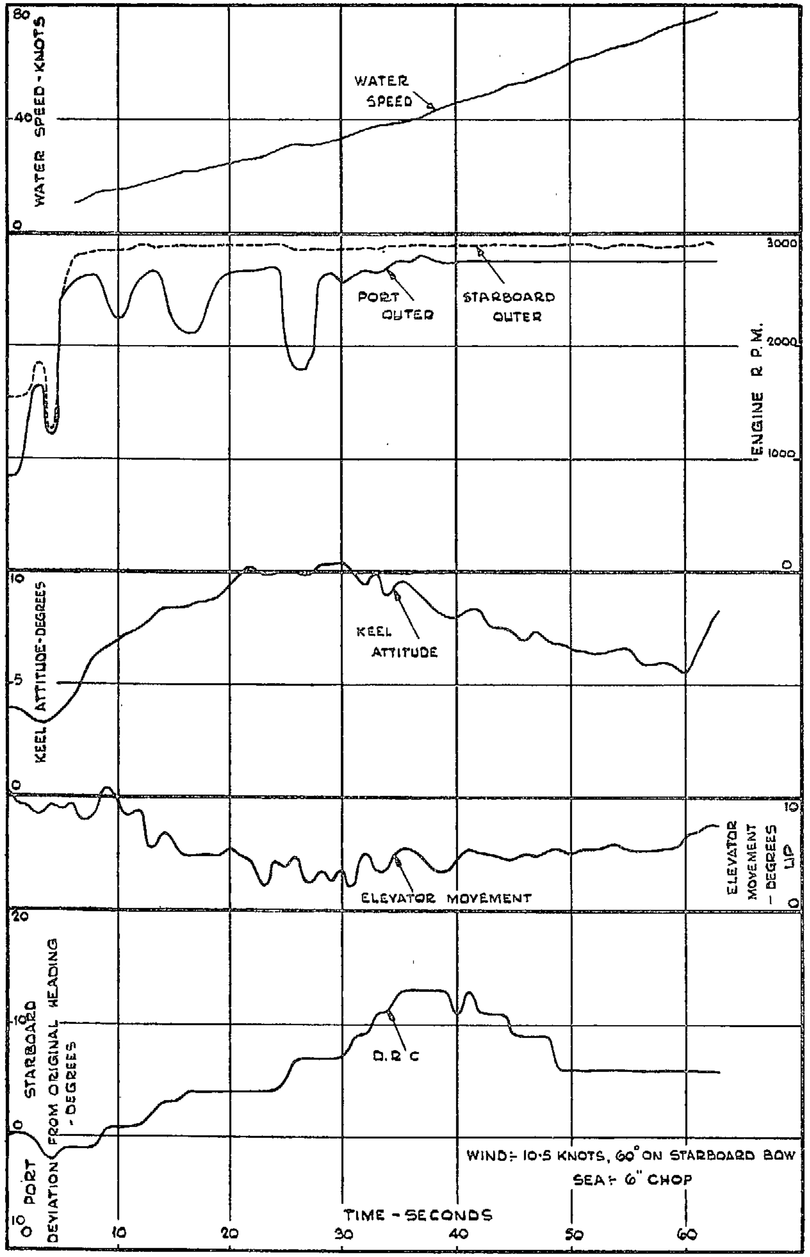


Fig. 22a. Time history of marginal cross-wind take-off. 82,000 lb.

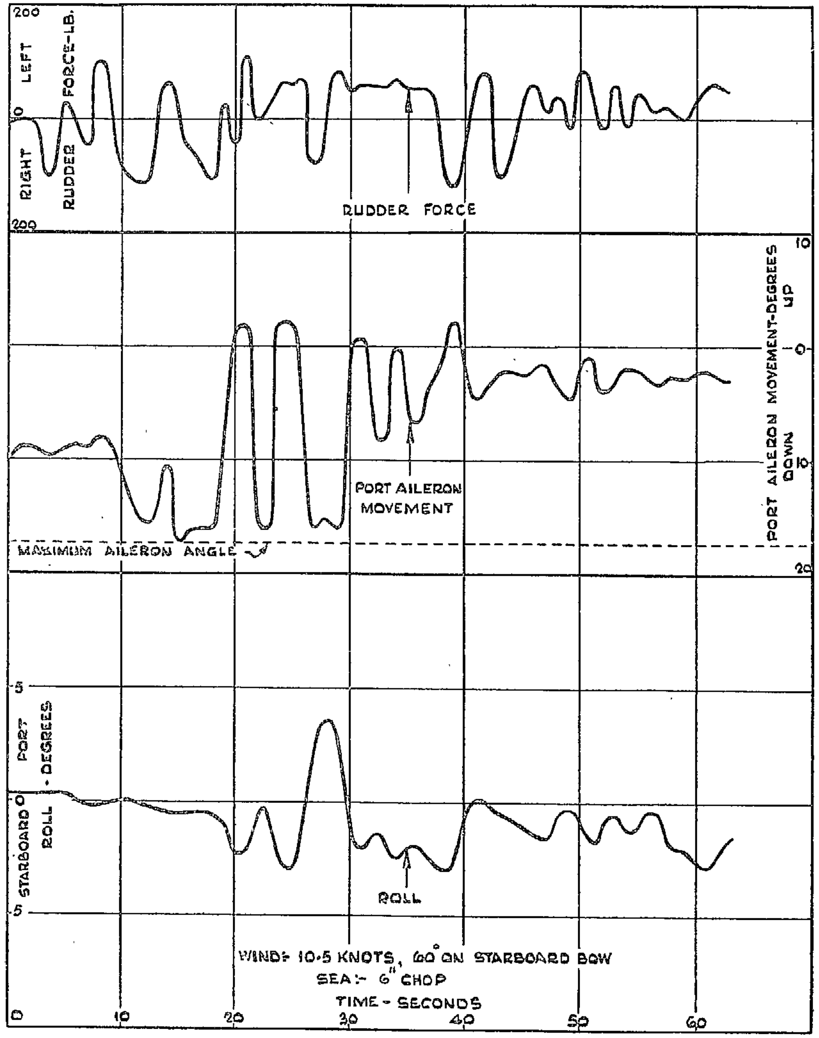


Fig. 22b. Time history of marginal cross-wind take-off. 82,000 lb.

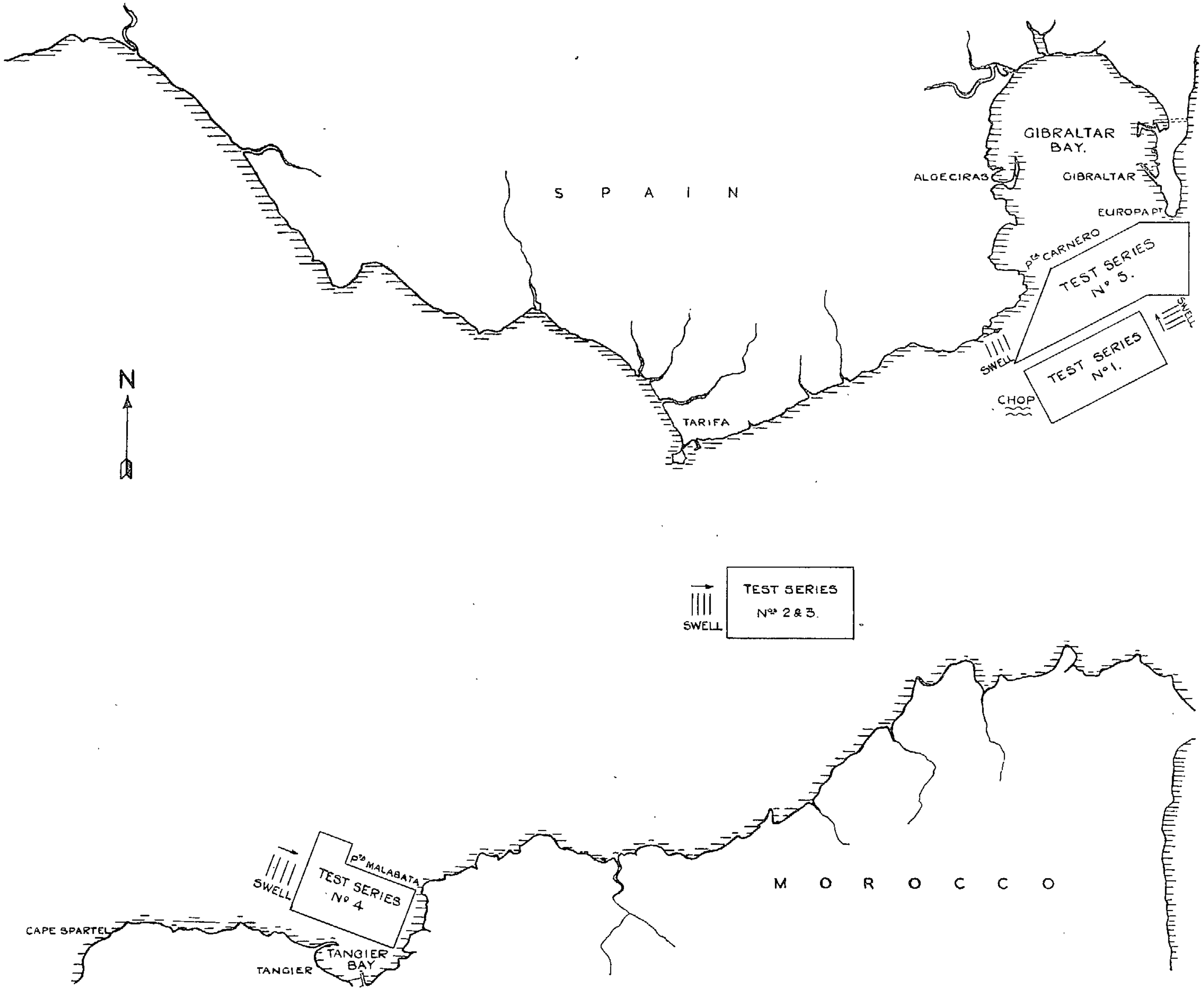


FIG. 23. Sketch map of Gibraltar and Tangier showing take-off and alighting areas (*see* also Table 2).

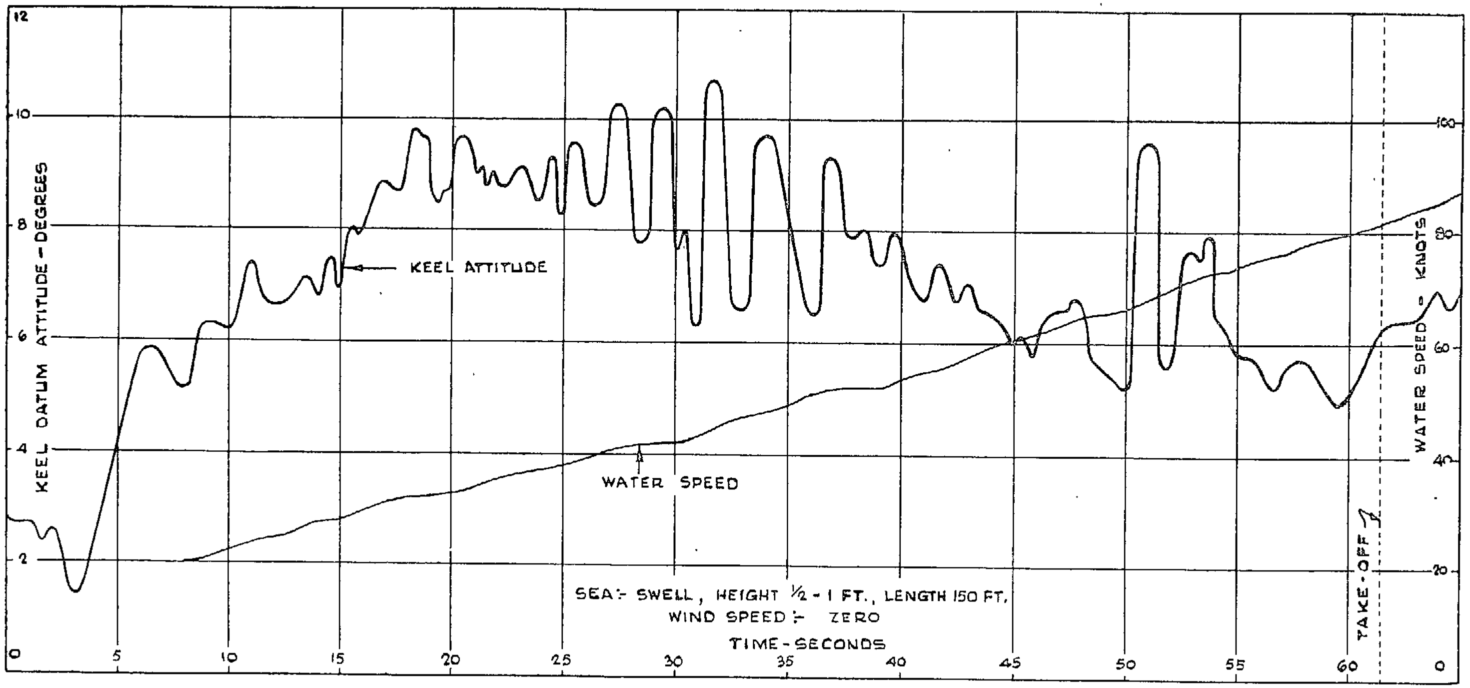


FIG. 24. Take-off into swell. Weight 82,000 lb. Elevator free.

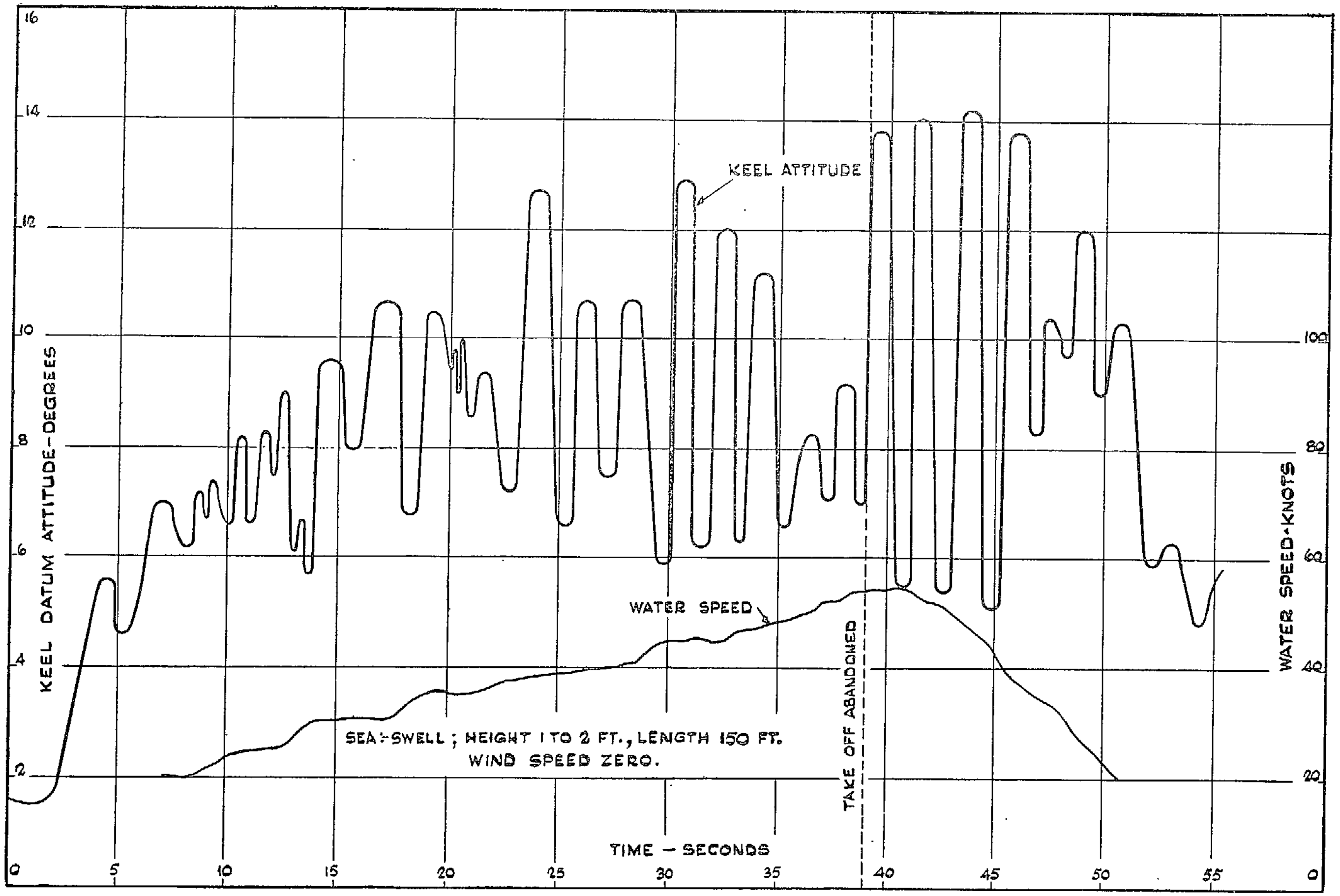


FIG. 25. Take-off into swell. Weight 82,000 lb. Elevator free.

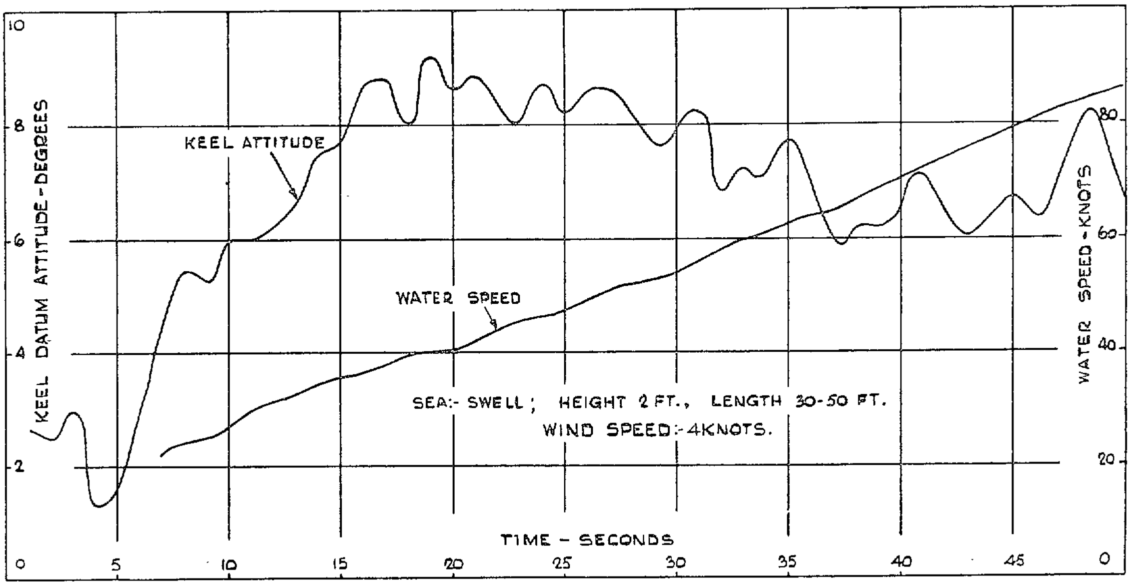


FIG. 26. Take-off into swell. Weight 74,000 lb. Elevator free.

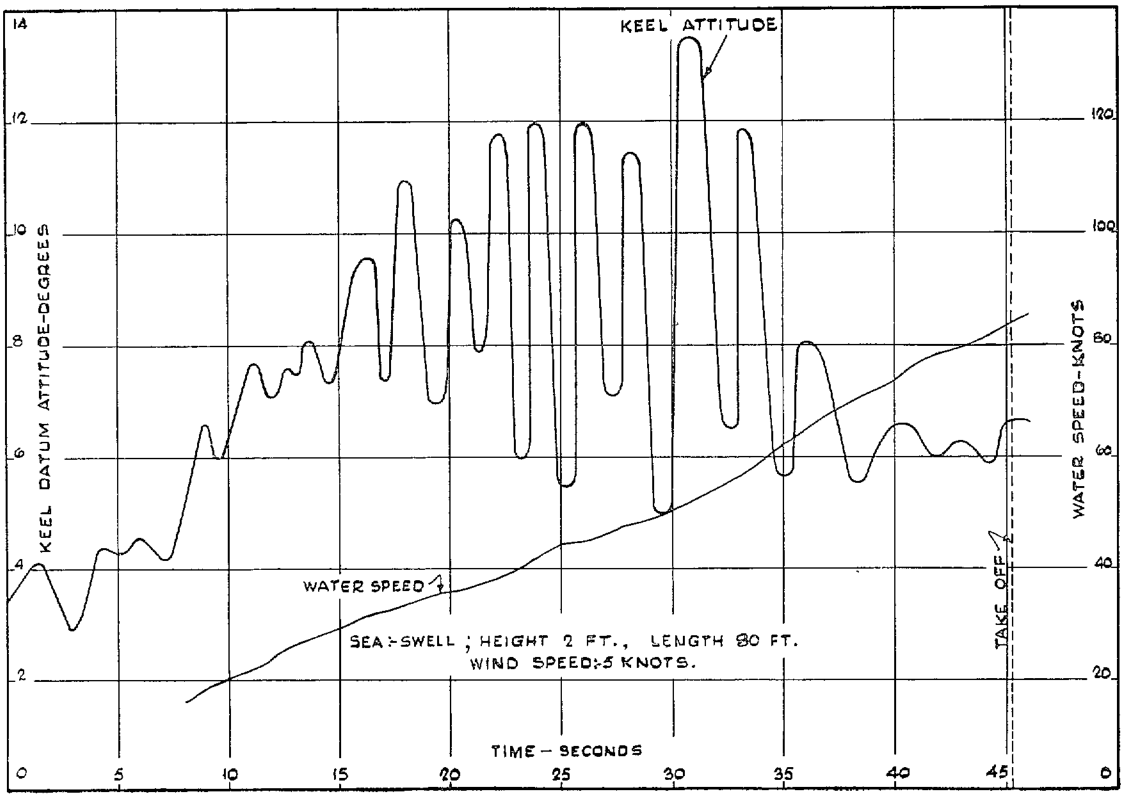
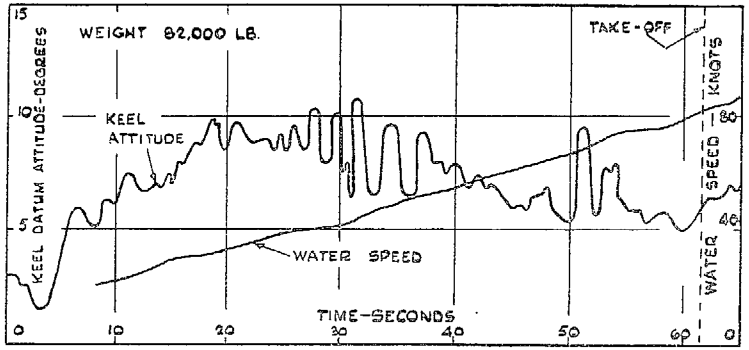
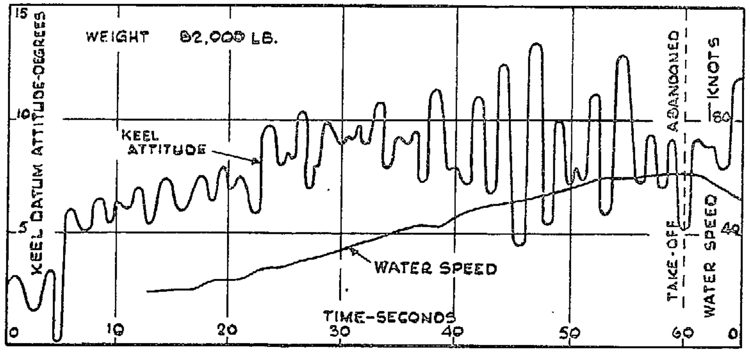


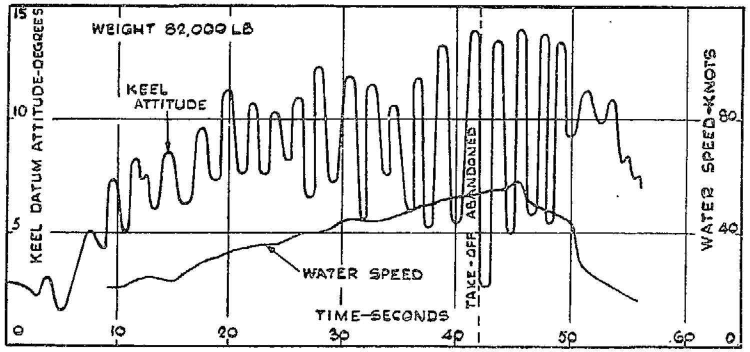
FIG. 27. Take-off into swell. Weight 74,000 lb. Elevator free.



A: SWELL HEIGHT ½-1 FT., LENGTH 150 FT.; WIND SPEED ZERO.

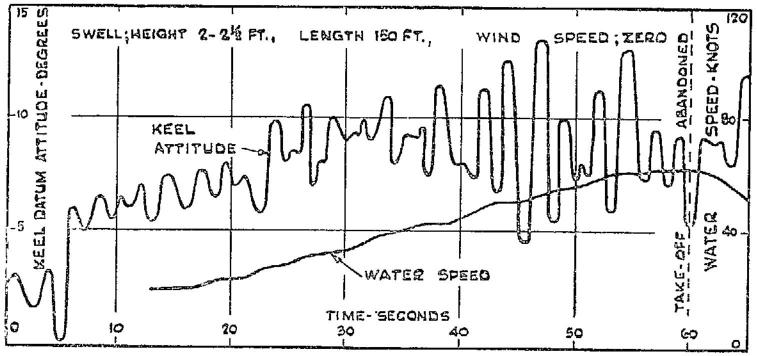


B: SWELL HEIGHT 2-2½FT., LENGTH 150 FT.; WIND SPEED ZERO.

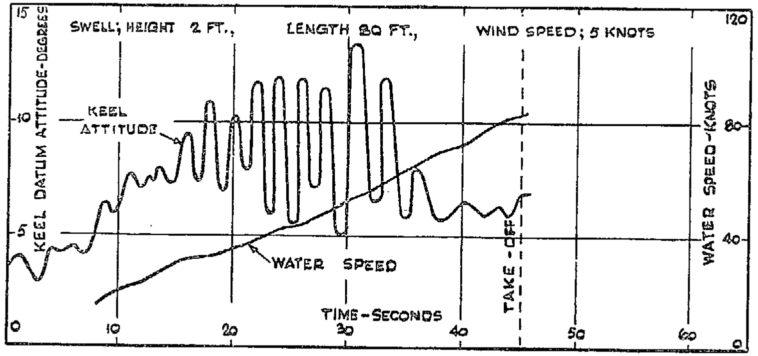


C: SWELL HEIGHT 1½-3FT., LENGTH 150FT.; WIND SPEED 2 KNOTS.

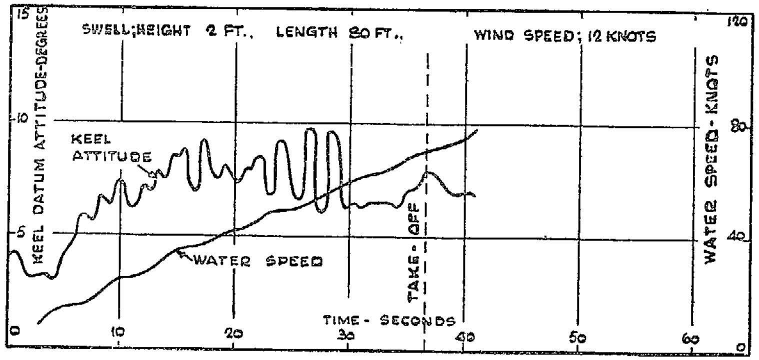
Fig. 28. Effect of swell height on porpoising amplitude.



A: WEIGHT 82,000 LB.

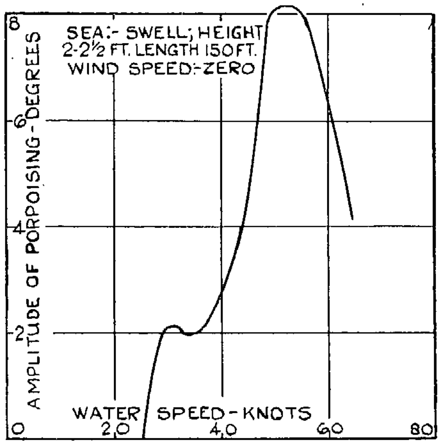


B: WEIGHT 74,000 LB.

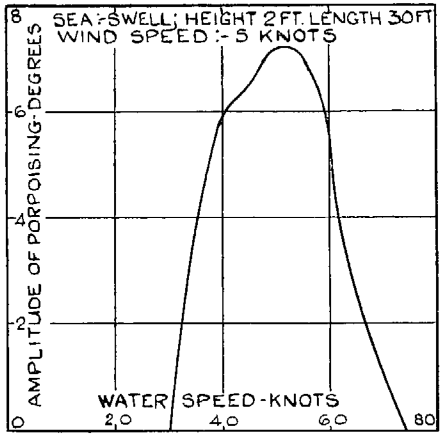


C: WEIGHT 74,000 LB.

Fig. 29. Effect of weight on take-off stability in swells.

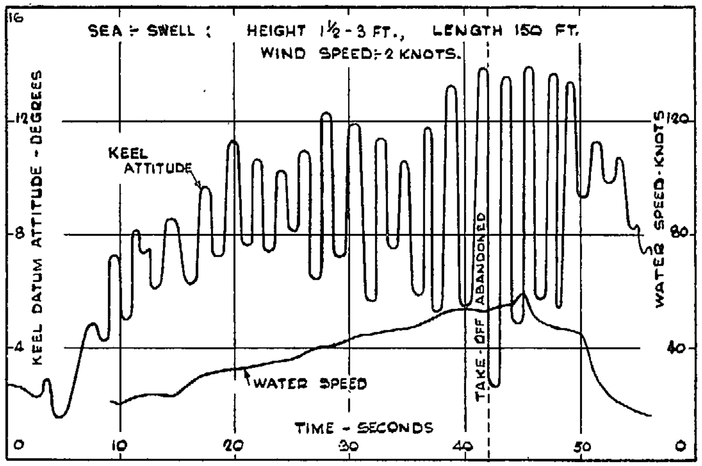


A: WEIGHT 82,000 LB.

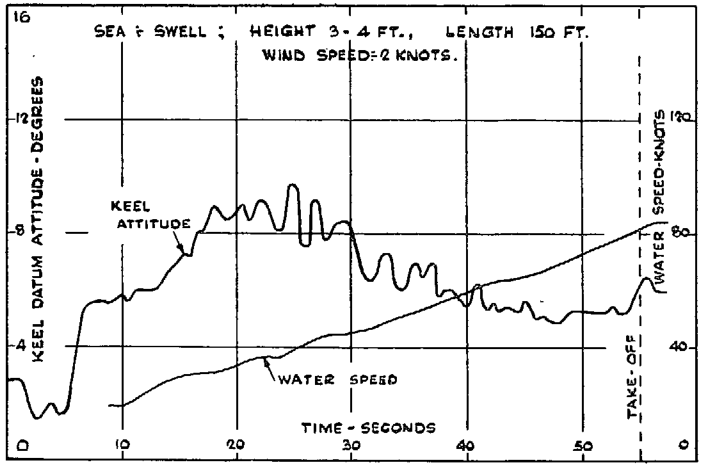


B: WEIGHT 74,000 LB.

FIG. 30. Amplitude of porpoising plotted against water speed.



A: TAKE-OFF INTO SWELL
WEIGHT 82,000 LB.



B: TAKE-OFF ALONG SWELL
WEIGHT 82,000 LB.

FIG. 31. Effect of take-off direction relative to the swell motion.

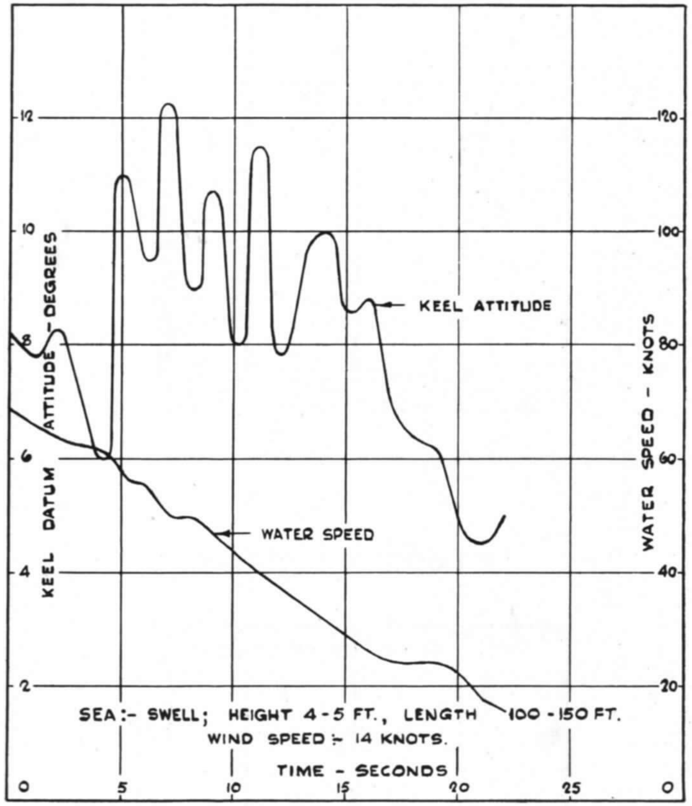
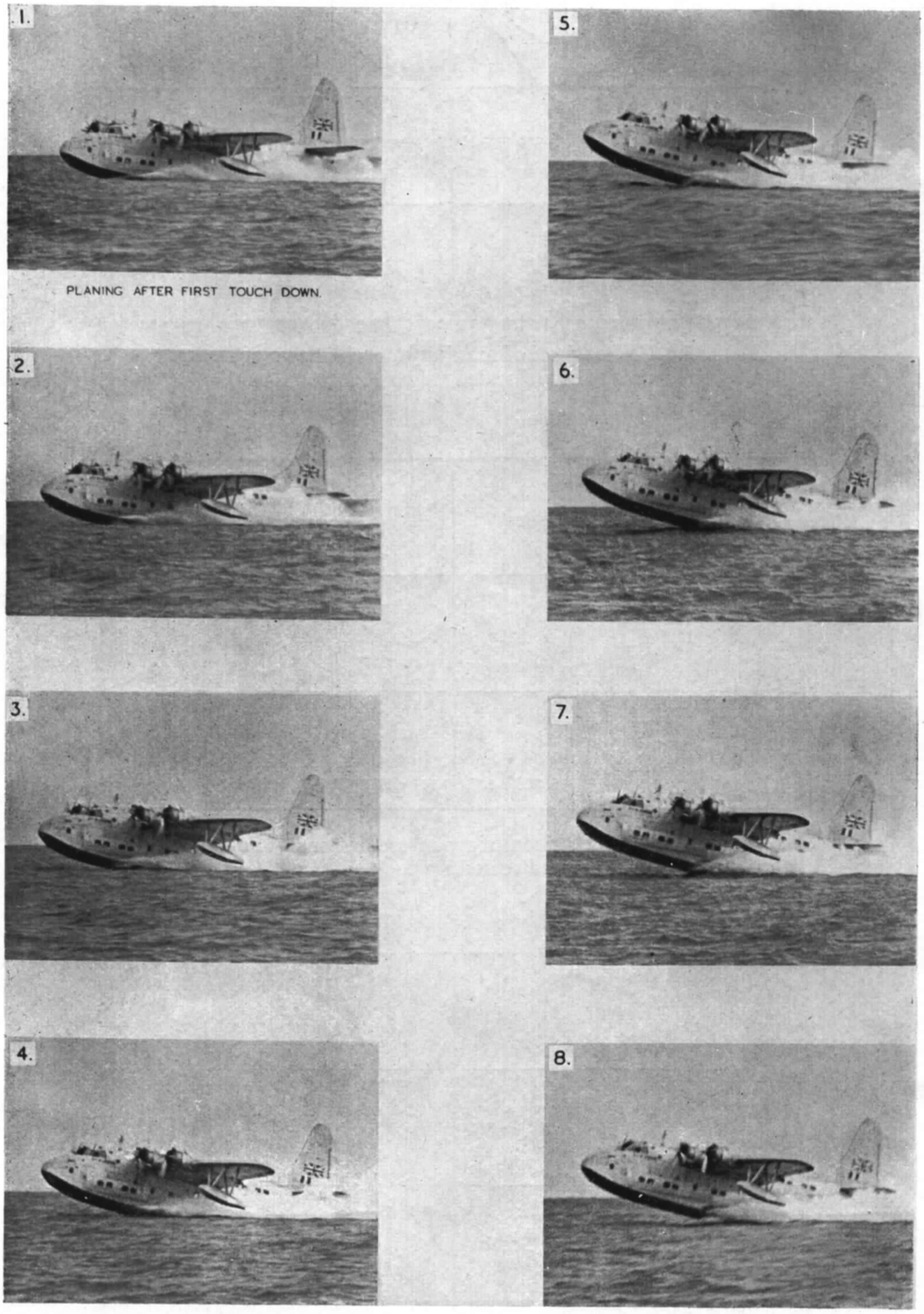


FIG. 32. Landing into swell. Weight 72,000 lb. Elevator free.

FIG. 33. Tailplane damage after landing in swell.



Swell height : 2 ft with 18-in. chop. Swell length : 50 ft. Weight : 65,000 lb.
Wind speed : 11 knots. Interval between frames : $\frac{1}{8}$ sec.

FIG. 34. Spray on tail during landing into swell.

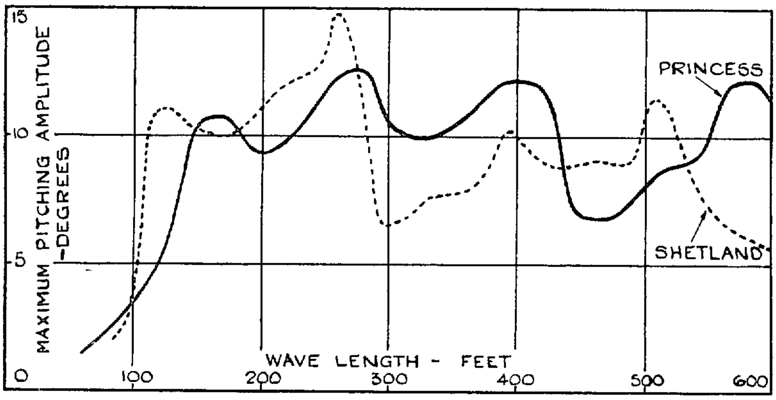


FIG. 35. Comparison of maximum oscillations of *Princess* and *Shetland* scaled up to *Princess* size.

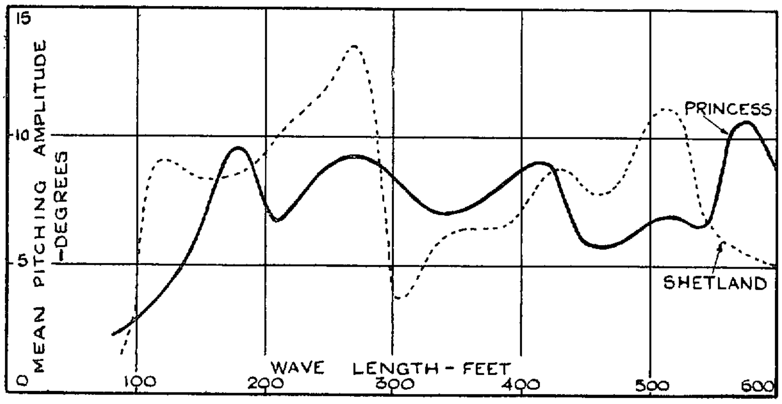


FIG. 36. Comparison of mean oscillations of *Princess* and *Shetland* scaled up to *Princess* size.

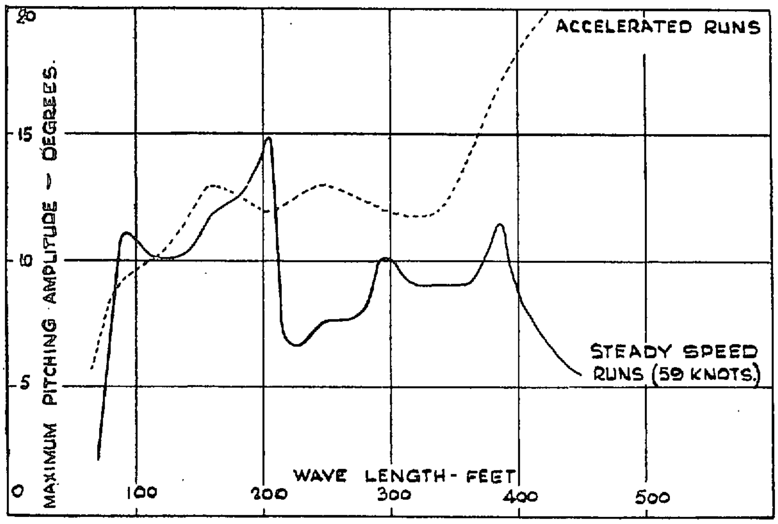


FIG. 37. Maximum pitching amplitudes for *Shetland* in 2·25-ft high waves.

J4334 18/9296 K7 2/56 D&Co. 34/263

PRINTED IN GREAT BRITAIN

R. & M. No. 2898

Publications of the Aeronautical Research Council

ANNUAL TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL (BOUND VOLUMES)

1938 Vol. I. Aerodynamics General, Performance, Airscrews. 50*s.* (51*s.* 8*d.*)
Vol. II. Stability and Control, Flutter, Structures, Seaplanes, Wind Tunnels, Materials. 30*s.* (31*s.* 8*d.*)

1939 Vol. I. Aerodynamics General, Performance, Airscrews, Engines. 50*s.* (51*s.* 8*d.*)
Vol. II. Stability and Control, Flutter and Vibration, Instruments, Structures, Seaplanes, etc. 63*s.* (64*s.* 8*d.*)

1940 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Icing, Stability and Control, Structures, and a miscellaneous section. 50*s.* (51*s.* 8*d.*)

1941 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Stability and Control, Structures. 63*s.* (64*s.* 8*d.*)

1942 Vol. I. Aero and Hydrodynamics, Aerofoils, Airscrews, Engines. 75*s.* (76*s.* 8*d.*)
Vol. II. Noise, Parachutes, Stability and Control, Structures, Vibration, Wind Tunnels. 47*s.* 6*d.* (49*s.* 2*d.*)

1943 Vol. I. Aerodynamics, Aerofoils, Airscrews. 80*s.* (81*s.* 8*d.*)
Vol. II. Engines, Flutter, Materials, Parachutes, Performance, Stability and Control, Structures. 90*s.* (91*s.* 11*d.*)

1944 Vol. I. Aero and Hydrodynamics, Aerofoils, Aircraft, Airscrews, Controls. 84*s.* (86*s.* 9*d.*)
Vol. II. Flutter and Vibration, Materials, Miscellaneous, Navigation, Parachutes, Performance, Plates and Panels, Stability, Structures, Test Equipment, Wind Tunnels. 84*s.* (86*s.* 9*d.*)

ANNUAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL—

1933–34	1*s.* 6*d.* (1*s.* 8½*d.*)	1937	2*s.* (2*s.* 2½*d.*)
1934–35	1*s.* 6*d.* (1*s.* 8½*d.*)	1938	1*s.* 6*d.* (1*s.* 8½*d.*)
April 1, 1935 to Dec. 31, 1936	4*s.* (4*s.* 5½*d.*)	1939–48	3*s.* (3*s.* 3½*d.*)

INDEX TO ALL REPORTS AND MEMORANDA PUBLISHED IN THE ANNUAL TECHNICAL REPORTS, AND SEPARATELY—

April, 1950 - - - - - -	R. & M. No. 2600.	2*s.* 6*d.* (2*s.* 7½*d.*)

AUTHOR INDEX TO ALL REPORTS AND MEMORANDA OF THE AERONAUTICAL RESEARCH COUNCIL—

1909–January, 1954 - - -	R. & M. No. 2570.	15*s.* (15*s.* 5½*d.*)

INDEXES TO THE TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL—

December 1, 1936 — June 30, 1939.	R. & M. No. 1850.	1*s.* 3*d.* (1*s.* 4½*d.*)
July 1, 1939 — June 30, 1945. -	R. & M. No. 1950.	1*s.* (1*s.* 1½*d.*)
July 1, 1945 — June 30, 1946. -	R. & M. No. 2050.	1*s.* (1*s.* 1½*d.*)
July 1, 1946 — December 31, 1946.	R. & M. No. 2150.	1*s.* 3*d.* (1*s.* 4½*d.*)
January 1, 1947 — June 30, 1947. -	R. & M. No. 2250.	1*s.* 3*d.* (1*s.* 4½*d.*)

PUBLISHED REPORTS AND MEMORANDA OF THE AERONAUTICAL RESEARCH COUNCIL—

Between Nos. 2251–2349. - -	R. & M. No. 2350.	1*s.* 9*d.* (1*s.* 10½*d.*)
Between Nos. 2351–2449. - -	R. & M. No. 2450.	2*s.* (2*s.* 1½*d.*)
Between Nos. 2451–2549. - -	R. & M. No. 2550.	2*s.* 6*d.* (2*s.* 7½*d.*)
Between Nos. 2551–2649. - -	R. & M. No. 2650.	2*s.* 6*d.* (2*s.* 7½*d.*)

Prices in brackets include postage

HER MAJESTY'S STATIONERY OFFICE

York House, Kingsway, London W.C.2; 423 Oxford Street, London W.1 (Post Orders: P.O. Box 569, London S.E.1);
13a Castle Street, Edinburgh 2; 39 King Street, Manchester 2; 2 Edmund Street, Birmingham 3; 109 St. Mary Street,
Cardiff; Tower Lane, Bristol 1; 80 Chichester Street, Belfast, *or through any bookseller*

S.O. Code No. 23-2898

R. & M. No. 2898