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ABSTRACT

A four engined turbo-prop flying boat, the PX-S, G.W. 87,000 lbs, with high open ocean capability has been designed and is under construction. The deflected slip stream and BLC are adopted as high lift device. An ASE is included in the fully powered flight control system. A newly developed spray suppressor is applied on the hull forebody. *A dynamically similar flying model, the UF-XS, 75% in linear dimension, was* constructed and flight tested. The results show that: the C_L measured at take off, 40 kts, is 6.9 . Take off run with 18 kt wind is about 400 ft in 10 seconds. The low landing speed, 45 kts, together with an air cushion effect of the BLC near the surface makes the landing shock very small. The flying quality at low speeds with ASE on is satisfactory except a large side slip during approach due to asymmetric force on the nacelles by the like-rotation propellers. This problem was almost solved in the SS-2* design by lowering the nacelle position relative to the wing. The hull has a wide *stable trim range and the spray characteristics is satisfactory. The estimated utili-*zation of the SS-2 through the year in the North Pacific Ocean is 86% days.

* "SS-2" : One of the model numbers

INTRODUCTION

A new STOL flying boat, designated PX-S, with a high open ocean capability has been designed and the prototype is now under construction in Japan under the sponsorship of the Japan Maritime Self-Defence Agency. The maximum gross weight is 87,000 lbs which can be raised up to 99,000 lbs as a growth potential. The engines are four T64-GE-10 (2850 eshp, each) to drive propellers and one T58-GE-8 (1250 shp) to drive a BLC compressor.

The present paper describes the aerodynamic and hydrodynamic aspects of the design of the flying boat, referring to the actual flight test results of a 3/4 scale flying model, designated UF-XS.

BASIC DESIGN CONCEPT

There are many water surfaces everywhere in the world, open oceans, inland seas, bays and lakes, which all have a possibility to be flying boat bases provided the flying boat has a capability of take off and landing on high seas and of short time and run. The open ocean capability, therefore, is the key point to extend the utility boundaries of the flying boat to much wider area than it is to-day.

In order to obtain a high open ocean capability the followings are essential:

(1) Low take off and landing speed and short time and run.

(2) Good flying qualities at low speeds.

(3) Spray-free, stable and low shock hull bottom.

(4) Ample reserve horse-power.

(5) High reliability of all the systems, equipments and structures.

Since the above features must be realized without largely sacrificing the general performances, i.e., range, payload, speed, climb and so on, the following design techniques have been adopted:

(1) The deflected slip stream and BLC system as the high lift device to obtain a usable C_L of 6 to 7 for take off and landing at 45 kts, keeping the wing loading at a moderately high value.

(2) An automatic stabilization equipment (ASE) for use at low speeds is included in a fully powered flight control mechanism with dual independent hydraulic systems.

(3) A high length to beam ratio hull added with a newly developed spray control system [1], the groove type spray suppressor.

(4) Adoption of light weight and powerful turbo-prop engines, four T64-GE-10's, to keep the power loading at a low value, 7.6 lbs/eshp at maximum gross weight without unduely increasing the weight of the power plant.

Wind tunnels, towing tanks, computers and flight simulators can afford the necessary *data for design according to their own abilities, however they are separated.* It is the utmost importance to amalgamate them into a flying boat to achieve a successful design. For this purpose a three quarter scale flying model, the UF-XS, was manufactured and flight tested before the final design of the PX-S was freezed.

HYDRODYNAMICS

The hull has a high length-to-beam ratio of 11.7, dead rise angle of 23.5^{-0-} at the step with warping of 6 degrees per beam. It is provided with a groove type spray suppressor along the chine of the hull forebody from the bow to the propeller-plane. (Figs. 1, 3 and 12). The water coming up along the bottom surface (Fig. 3) continues to cling to it along the rounded corner of the chine, led into the longitudinal groove, flows rearward and is thrown out of the exit (Fig. 12). An almost zero spray condition was realized in the towing tank test. The spray height measured in the actual test on the sea by the UF-XS was not zero but very low (see Fig. 1 (a) and (b), compare the spray with conventional flying boat) . The stable region of the hull is wide enough (Fig. 2) and no porpoising nor skipping was experienced on the UF-XS.

The impact loads on the hull in 10-foot-waves are estimated below 3 g's through water tank tests and UF-XS flight tests (see also Fig. 20). The low shock value is due to the low landing speed 45 to 50 kts (with 20 kt head wind the water speed is 25 to 30 kts), and an air cushion effect of the BLC blowing air near the ground (Fig. 12). No jumping was observed during the flight test. This is because the lift produced by engine power is cut down just after touch down and hence the total lift is reduced rapidly to almost 20% of the airplane weight (Fig. 4).

The tip floats have ample capacity and together with reversible propellers the SS-2 will have satisfactory maneuverability in the open ocean under 25 knots wind, gust 37 kt.

Spray mist appeared at take off run with BLC on (Fig. 12(top)). It disappears when the airspeed reaches about 35 kts. This phenomenon was the one which was unexpected. The cause of the spray mist is understood by Fig. 12 (bottom) which was prepared through a wind tunnel test with ground board and direct observations of the flight test.

AERODYNAMICS

HIGH LIFT DEVICE

A low pressure blowing type BLC was adopted on the UF-XS and the compressed air temperature was kept below about 200° F even in hot days in order to avoid the thermal deformation of the duct system and the adjacent structures. The power plant is two

T58-GE-6 turbo-shaft engines to provide more than enough power for test purpose. Each engine drives an axial flow compressor specially designed for the purpose. Both the flap blowing and the shroud blowing types were tested as shown in table 3 to compare the relative merit of the two types.

The flight test results are:

(1) No thermal deformation observed.

(2) Blowing above the C_μ critical is not worth-while.

(3) Flap blowing type is better both aerodynamically and structurally.

According to the test results of the UF-XS the flap blowing type is adopted for all the surfaces on the SS-2 as shown in table 3 . The values of C_μ in the table correspond to C_μ critical. The power plant is one T58-GE-8 (1250 shp) driving a new axial compressor.

Fig. 6 shows the C_L measured in the wind tunnel with an 8% powered model of the UF-XS. In Fig. 4 a break down of the lift force during take off run for the SS-2 is shown. The estimation was done by using Kuhn's formulas[2] the coefficient of which being modified by the wind tunnel data and the flight test results of the UF-XS. The lift by the deflected slip stream is about 80% to 120% of the propeller thrust from V = 0 to 45 kt.

STABILITY AND CONTROL AT LOW SPEEDS

The root loci of the stability equation of the UF-XS at $C_L = 7.0$ is as shown in Fig. 7. The derivatives used are those estimated before the flight test. The inherent stabilities are negative both longitudinally and laterally as shown by X's in the figures. The period P and the time to half or double amplitude $T\frac{1}{2}$ are added. The very short time to double amplitude (2.5 sec) of the spiral divergence is the main reason to adopt the ASE.

The ASE moves the three control surfaces as the followings:

$$\delta_{e\,ASE} = K_{0e}(\theta - \theta_0) + K_{1e}\dot{\theta} + K_{SC}\delta_{ep}$$

$$\delta_{a\,ASE} = K_{0a}\phi + K_{1a}\dot{\phi} + K_{SC_a}\delta_{ap}$$

$$\delta_{r\,ASE} = K_r\,\delta_{a\,ASE}\;, \quad K_r \simeq -C_{n\delta a}/C_{n\delta r}$$

The thick lines in Fig. 7 show the stabilization by the ASE and the values around the marks shown on the thick lines were tested in the flight tests of the UF-XS, which showed a satisfactory flying qualities with ASE on except a side slip excursion at the turn entry[3].

For the ASE of the SS-2 a rudder movement is added to the δ_{rASE} advised by Mr. C. Holzhauser, NASA. Ames, as a remedy for the side slip excursion:

$$\Delta\delta_{rASE} = -\frac{g}{V_0}\frac{N_r}{N_{\delta r}}\phi + \left(\frac{g}{V_0}\frac{1}{N_{\delta r}} - \frac{N_p}{N_{\delta r}}\right)p$$

The $\Delta\delta_{rASE}$ proved effective as shown in Fig. 8, the pilot rating of the SS-2 by a simulator of the National Aero/Space Laboratory, Japan.

The maximum deflection of the control surfaces is as shown in table 4. The lateral control at STOL configuration is the most effective, because the outboard flaps and the spoilers are located in the slip stream of the outer engines. The maximum value of the rolling moment coefficient is $C_l = 0.232$ as shown in Fig. 10 which gives an angular acceleration of 0.53 rad/sec^2 at 45 kts. The bank angle at one second after the full control movement is 11.2° which is less than the 15° recommended by the NASA TN D-331[4]. There are some arguments that the 15° could be somewhat reduced for STOL airplanes. Our experiences of the flight tests of the UF-XS and the simulator test of the SS-2 indicate that 8° to 10° may be acceptable.

The rudder is effective as shown on Fig. 11 for the whole range of deflection (45-o-, Table 4) at C_μ of 0.03 for the SS-2 (Table 3).

PITCHING MOMENT

Fig. 9 showes the pitching moment coefficient Cm at Zero elevator angle vs. lift coefficient C_L on the UF-XS. The flight tests show nose-up moment equivalent to an elevator deflection of about 13-o- compared with the wind tunnel results. The wind tunnel used was 8 feet diameter open section type and most tests were made at 28 feet per second wind speed. The model with BLC and running propellers had a span of 80% of the tunnel diameter. No wall correction was applied to the results.

The discrepancy is considered due mainly to the wall effect.

ASYMMETRIC CHARACTERISTICS

Fig. 13 shows the side-force coefficent $C_Y = Y/qS$ vs. lift coefficient $C_L = L/qS$ for the UF-XS. The agreement between wind tunnel and flight test is good. To investigate the cause of this phenomenon a pressure distribution survey was made in the wind tunnel and it was found that the main portion contributing to the side-force is nacelles (Fig. 15). This pressure distribution on the nacelles is understood by the combination of clock-wise

circulation around the nacelle (viewed from behind) due to like-rotation propellers with a strong up wash flow in front of the wing.(Fig. 12).

In the SS-2 design nacelles were lowered relative to the wing (Fig. 14) in the sense that the nacelle side area above the extension of the wing chord line is mainly generating the side force. The wing was raised relative to the hull to keep the propeller tip clearance above the water. The wind tunnel tests show that this modification resulted in a remarkable decrease in the side force (Fig. 14) as well as the nose-down pitching moment at take off configuration. A Nacelle fence which was set on the nacelle longitudinally at ten-o'clock position (viewed from behind) was very effective (Fig. 14 (3) and (4)) to cancelle the side-force in the wind tunnel. But this is considered unnecessary for the SS-2.

Fig. 16 shows the improvement in the lateral characteristics ----- left-ward roll and yaw tendency is also improved.

AILERON DROOP AND SPOILERS

The aileron droop originally adopted in the UF-XS was cancelled because of the poor effectiveness for the lift augmentation. The spoilers just ahead of ailerons on the UF-XS showed also very little effectiveness and, for the SS-2 design, they were shifted inward to the position in the outboard propeller slipstream. Wind tunnel test results (Fig. 10) show a remarkable contribution of the spoilers to the control effectiveness without adverse yaw penalty.

PERFORMANCE

The take off and landing performance is stated in Table 2 together with that of a typical conventional flying boat of similar size. The lift due to propeller slipstream reaches almost 50% of the total lift of the SS-2 (Fig. 4) and at the sametime the induced drag due to the above mentioned slipstream lift cancels the total thrust by about one half (Fig. 5). This means that a considerable thrust is necessary also for landing. Figs. 17 (a) and (b) show the slow speed performance of the UF-XS predicted by wind tunnel (no wall correction) together with the flight test data (through inter-and extrapolation). The difference of the angle of attack between the two is from 2 to 4 degrees, which is attributed to the tunnel wall effect.

Fig. 18 shows the measured take off speed vs. applied power of the UF-XS and the predicted value. The flight tests show lower speeds which may be due to wind tunnel wall effect including the ground effect and the pilot take off technique. Fig. 19 is the measured take off speed and time vs. take off weight for the UF-XS together with the calculated values of which the formulae were modified taking account of the flight test results. The weight corresponding to the SS-2 open ocean gross weight is marked on the figure.

OPEN OCEAN CAPABILITY

Among several factors essential for the open ocean capability the slow speed with good flying qualities, impact load, spray, control effectiveness, tip float capacity, longitudinal trim stability and so forth have been proved satisfactory as described in the preceding chapters. On this back ground the one remaining important factor, the jumping ----- thrown up by waves, digging into wave crests or hard impact, was taken as a criterion for the open ocean capability. The towing tank tests in waves show that "no jumping" is the sufficient condition for take off and landing capability and that whether a hull jumps or not under a given sea condition is predicted by a comparatively simple theory. *

As for the structural strength the water loads were estimated by water tank tests and theoretical calcutations assuming 12 feet waves with length-to-height ratio from 20 to 40 and take off and landing speed of 45 kts under wind speeds up to 25 kts. The structural strength thus decided was checked over the whole sea state range where the operation is capable (according to the "jump" criterion mentioned above i.e., utilizable area in Fig. 20).

Fig. 20 is one of the figures prepared from the observed sea state data reported by ships and accumulated for four years in a sea area shown in table 1.

In this figure is shown the relative occurence probability, by shaded area, of a sea state (wave height and wave length or period) under the wind speed of 15-20 kts. The figure shows that a wave height between 3 to 7 feet accompanied by a wave length of 100 to 300 feet will most frequently occur at this wind speed range.

* The theory assumes that a seaplane jumps when the binding force necessary to keep the seaplane mass along the contour of a wave exceeds the load-on-water (weight minus air lift).

In the same figure utilizable envelopes, showing the limit line of possible jumping, for the SS-2 and for a conventional flying boat (Table 2) are drawn. The utilization is counted on the graph to be 87.9% and 25.4% respectively for the specific wind speed range of 15 - 20 kts. The large difference between the two is due to (1) difference of water speed (Table 2):

	SS-2	Conventional Flying Boat
Head wind	20 kts	20 kts
Take off air speed	45	72
Take off water speed	25	52
Landing air speed	45	85
Landing water speed	25	65

and (2) difference of lift produced by propeller (L_o in Table 2) which is to vanish after touch down, as mentioned in "Hydrodynamics".

The utilization limit lines for other wind speeds were obtained by the same procedure. Table 1 shows the total utilization, Fig. 20 being an example for the wind speed class of 15 - 20 kts of which the frequency is 19.94%. The utilization through the year comes out to be 86.7% for the SS-2 and 45.7% for the conventional flying boat.

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REFERENCES

1) Kikuhara, S., A Study of Spray Generated by Seaplane Hulls, Journal of the Aero/Space Sciences, Vol. 27, pp. 415-428, June 1960.

2) Kuhn, R. E., Semi-empirical Procedure for Estimating Lift and Drag Characteristics of Propeller-Wing-Flap Configurations for Vertical-and-Short-Take-Off-and Landing Airplanes, NASA Memo. 1-16-59L, February 1959.

3) Holzhauser, C. A., Innis, R. C. and Vomaske, R.F., A Flight and Simulator Study of

the Handling Qualities of a Deflected Slipstream STOL Seaplane Having Four Propellers and Boundary Layer Control, NASA TN D-2964, June 1965.

4) Anderson, S. B., An Examination of Handling Qualities Criteria for V/STOL Aircraft, NASA TN D-331, July 1960.

SYMBOLS

C_L	=	lift coefficient
C_ℓ	=	rolling moment coefficient
Cm	=	pitching moment coefficient
Cn	=	yawing moment coefficient
$Cn_{\delta a}$	=	$\frac{\partial C_n}{\partial \delta_a}$
$Cn_{\delta r}$	=	$\frac{\partial C_n}{\partial \delta_r}$
C_Y	=	side-force coefficient
C_μ	=	blowing momentum coefficient
D	=	drag
g	=	gravity acceleration
Im	=	imaginary part of the root
Ksc	=	stick canceller constant
K_o, K_1	=	ASE gain
L	=	lift
L_o	=	lift produced by slip stream
N_p	=	yawing moment due to roll rate
Nr	=	yawing moment due to yaw rate
$N_{\delta r}$	=	yawin moment due to rudder deffection
P	=	period
Δp	=	static pressure increment
q	=	dynamic pressure
Re	=	real part of the root
S	=	wing area
T	=	wave period

T'c	=	(thrust) ÷ (qs)
$T\frac{1}{2}$	=	time to half amplitude (negative means double)
V	=	speed
W	=	airplane weight
w	=	nozzle width
α	=	angle of attack
β	=	angle of side slip
γ	=	path angle
δ	=	surface deflection
θ	=	pitch attitude
$\dot{\theta}$	=	pitch rate
ϕ	=	roll attitude
$\dot{\phi}$	=	roll rate

SUBSCRIPT

a	=	aileron
ASE	=	automatic stabilization equipment
e	=	elevator
f	=	flap
H	=	hull
p	=	pilot
r	=	rudder
w	=	wind
o	=	reference
∞	=	general flow

TABLE I CALCULATED UTILIZATION

WIND SPEED KT.	FREQUENCY %	UTILIZATION (%) IN EACH WIND SPEED CLASS		UTILIZATION (%) IN YEAR	
		SS-2	CONVENTIONAL FLYING BOAT	SS-2	CONVENTIONAL FLYING BOAT
CALM	0.83	100.00	100.00	0.83	0.83
0-5	9.97	97.56	89.57	9.72	8.93
5-10	27.34	94.38	71.08	25.83	19.44
10-15	20.85	89.49	46.04	17.67	9.62
15-20	19.94	87.91	25.44	17.54	5.08
20-25	10.30	87.64	17.90	9.03	1.84
25-30	6.66	91.08	0	6.07	0
30-40	3.48	0	0	0	0
40-	0.63	0	0	0	0
TOTAL	100.00			86.69	45.74

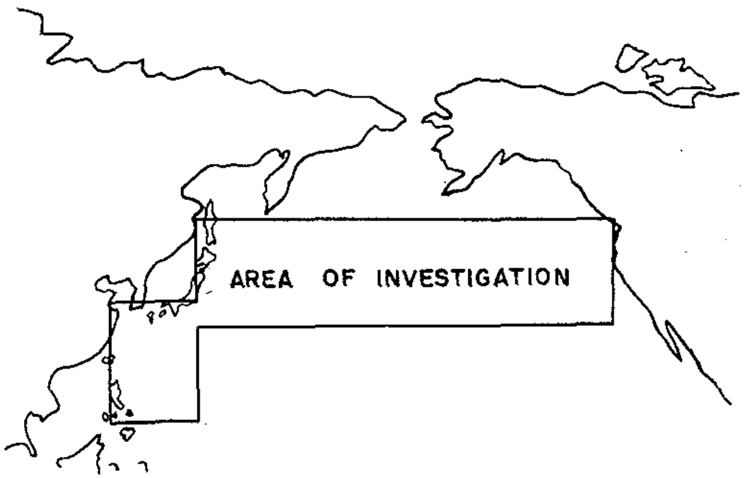


TABLE 2 TAKE OFF AND LANDING PERFORMANCE

		SS-2	Conventional Flying Boat
Take off:	speed (kts)	45	72
	L_o/W*	0.50	0.28
	time (sec)	12	35
	run (ft)	300	1800
Landing:	speed (kts)	45	85
	L_o/W	0.50	0.05
	time (sec)	12	
	run (ft)	430	2300
Wing loading (lbs/sq.ft.)		50	55
Power loading (lbs/hp)		6.3**	12

* L_o : Lift due to propeller slip stream

W : airplane weight

** : corresponding to open ocean G. W.

TABLE 3 C_μ AND NOZZLE WIDTH

	SS-2		UF-XS	
	C_μ***	ω	C_μ	ω
Inboard flaps	0.10	0.07"(F)	0.15	0.15"(F)
Outboard flaps	0.10	0.07(F)	0.15	0.10(S)
Ailerons	--**	---	0.06	0.03(S)
Elevators	0.05	0.04(F)	0.15	0.07(S)
Rudder	0.03	0.04(F)	0.04	0.96(F)
Pressure Ratio *	1.85		1.60	

$C_\mu = \dfrac{\text{Jet momentum}}{q_\infty \times \text{area concerned}}$, at 45 kts.

ω: nozzle width in inches

F: flap blowing type

S: shroud blowing type

*: at compressor exit

**: not applied because the aileron drooping was cancelled by the flight test results.

***: correspond to C_μ critical

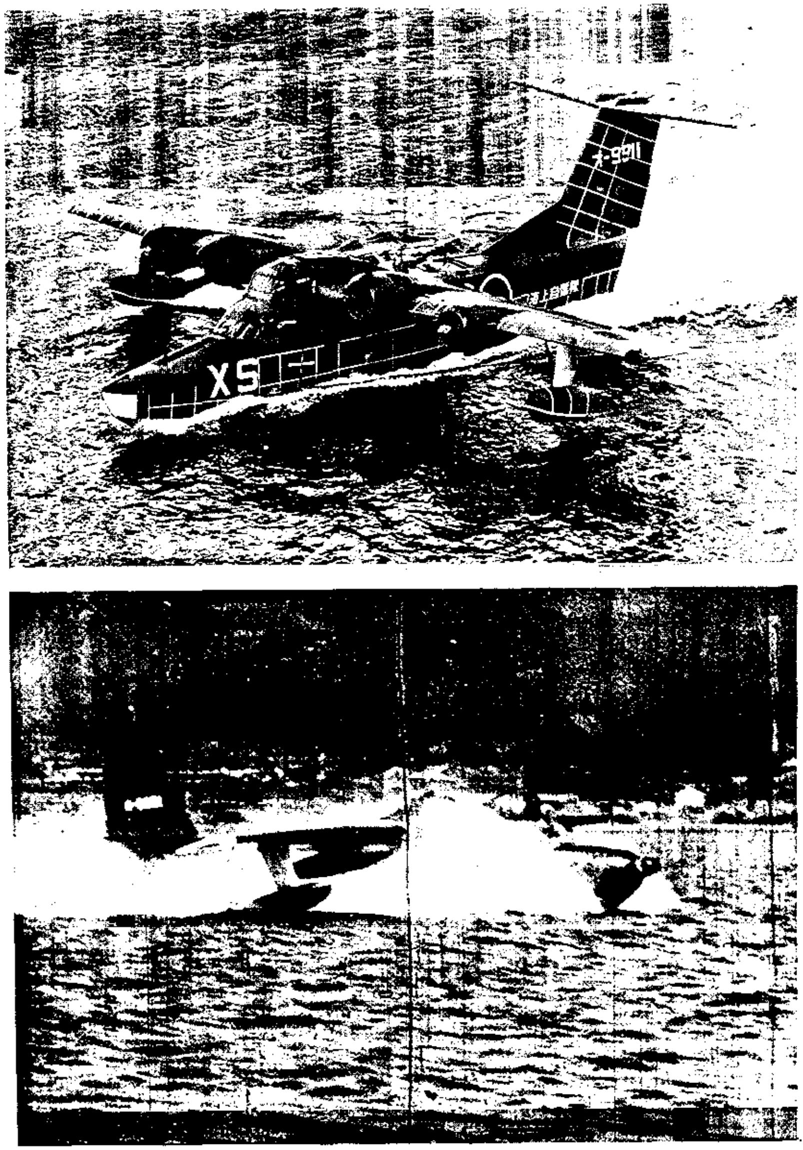


FIG 1 (a) top, UF-XS, WITH SPRAY SUPPRESSOR
(b) bottom, UF-2, WITHOUT SPRAY SUPPRESSOR

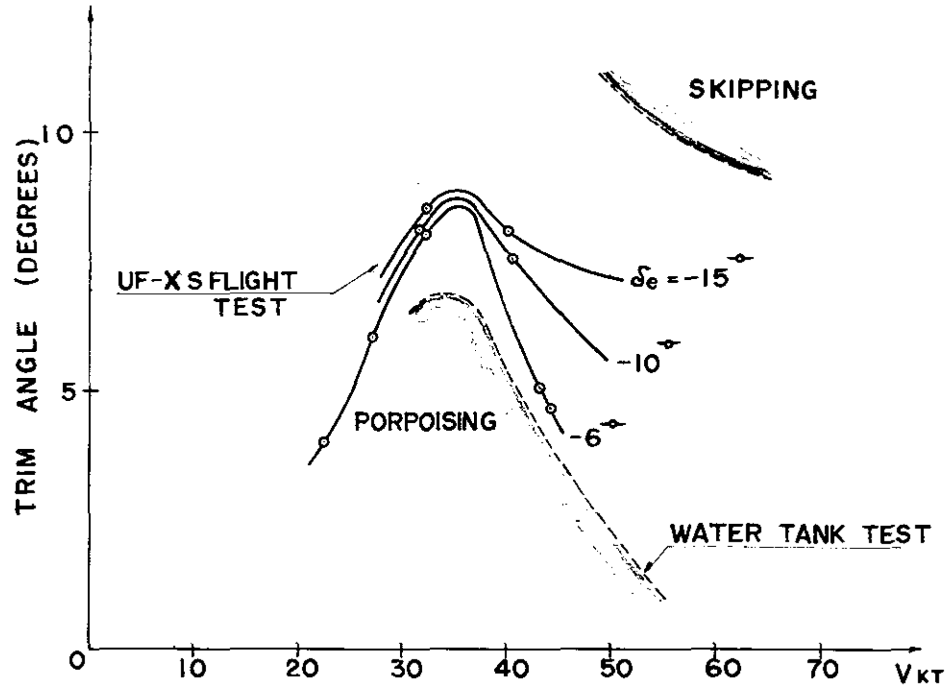


FIG 2 STABILITY LIMIT OF TRIM
FLAP ANGLE = 20-15°, BLC OFF, CG = 24% MAC

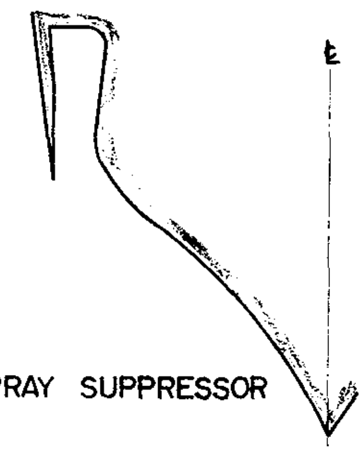


FIG 3 SPRAY SUPPRESSOR

TABLE 4 CONTROL SURFACE DEFL

		Deflection in degrees	
		SS-2	UF-XS
low speed	Outboard flaps*	up 27 dn 18	up 25 dn 20
	Ailerons	up 27 dn 18	up 25 dn 20
	Spoilers	0 - 60	0 or 60
	Elevators	up 60 dn 25	up 45 dn 20
	Rudder	± 45	± 45
cruise	Outboard flaps	—	—
	Ailerons	up 27 dn 18	up 25 dn 20
	Spoilers	—	—
	Elevators	up 30 dn 12.5	up 22.5 dn 10
	Rudder	± 22.5	± 22.5

engaged with aileron movement

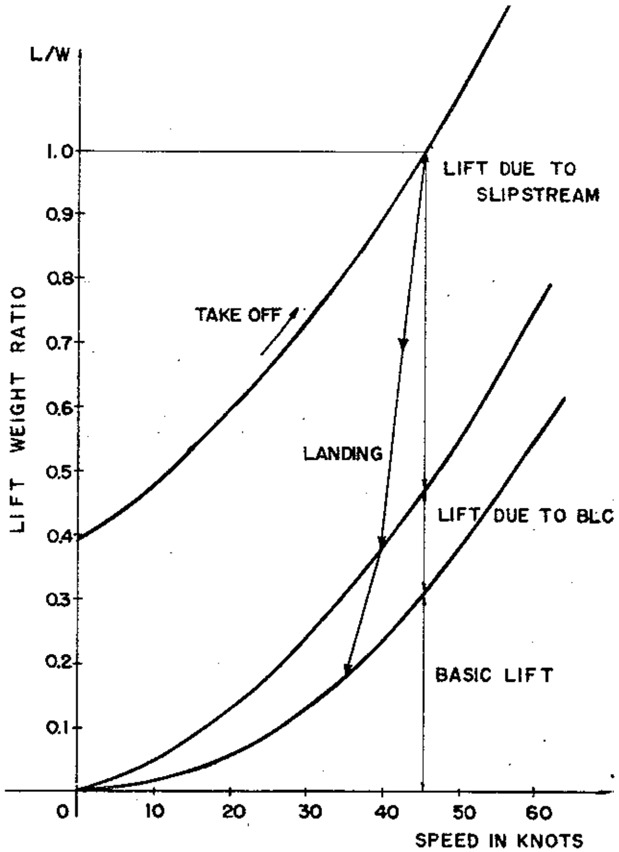


FIG 4 BREAK DOWN OF LIFT
FLAP ANGLE = 60-45-0°, HULL ATTITUDE = 7°
WING SETTING ANGLE = 5°

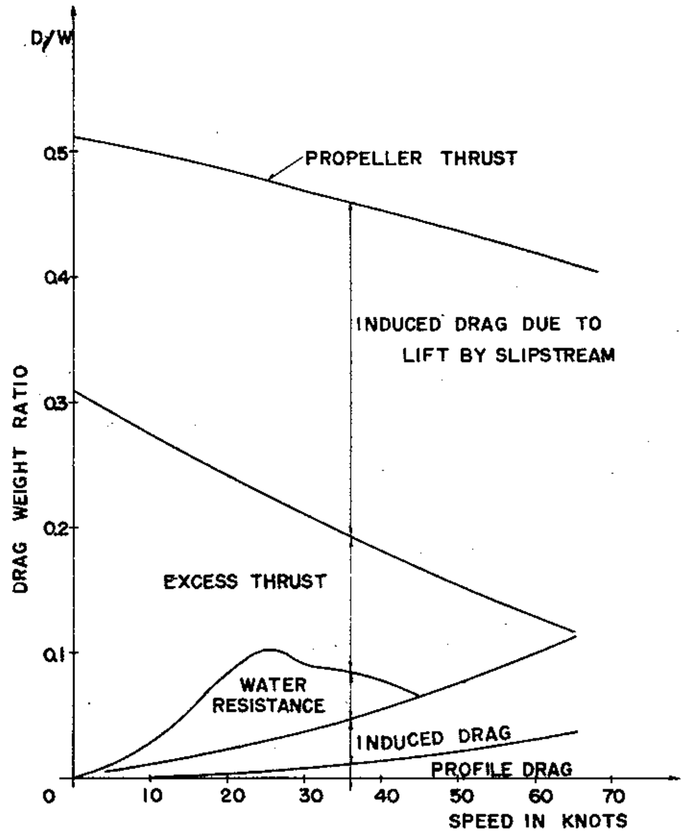


FIG 5 DRAG BREAK DOWN
FLAP ANGLE = 60-45-0°
TAKE OFF SPEED = 45 kt

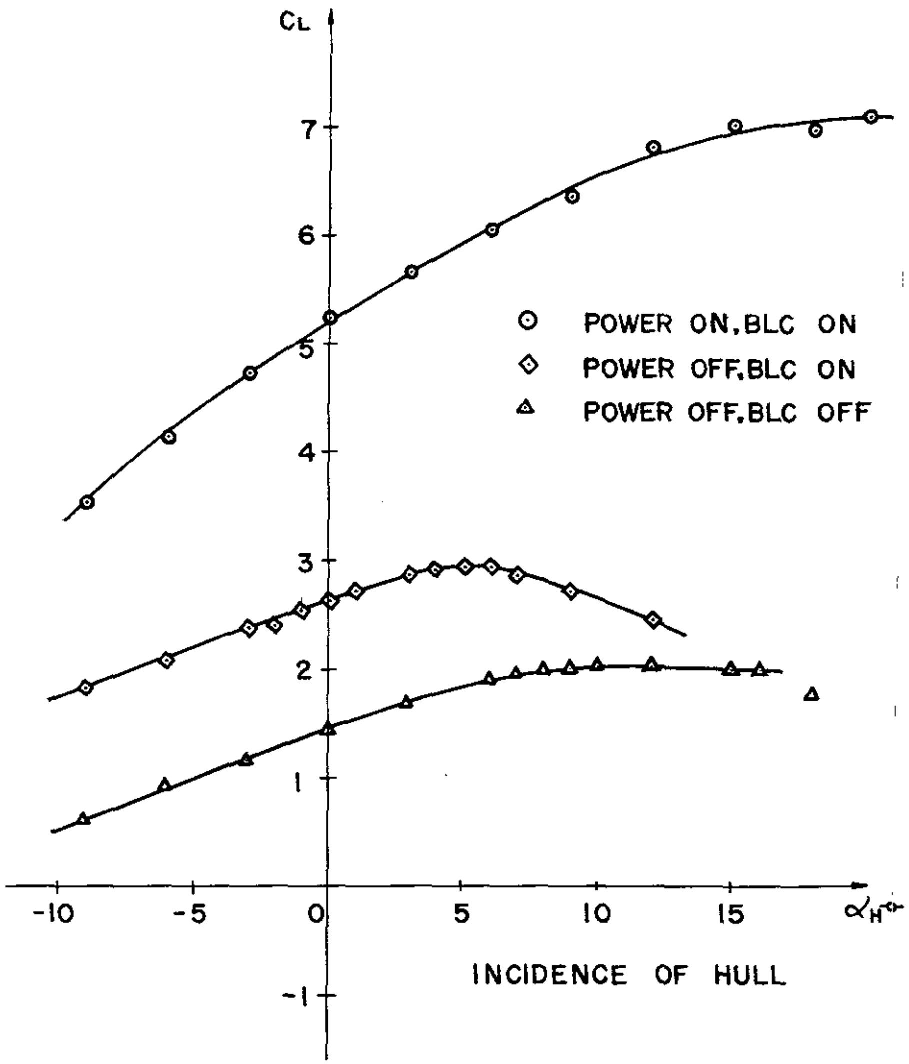


FIG 6 LIFT AT TAKE OFF CONFIGURATION (WIND TUNNEL TEST OF UF-XS)

FLAP ANGLE = 60-45-30° (WING SETTING ANGLE = 5°)

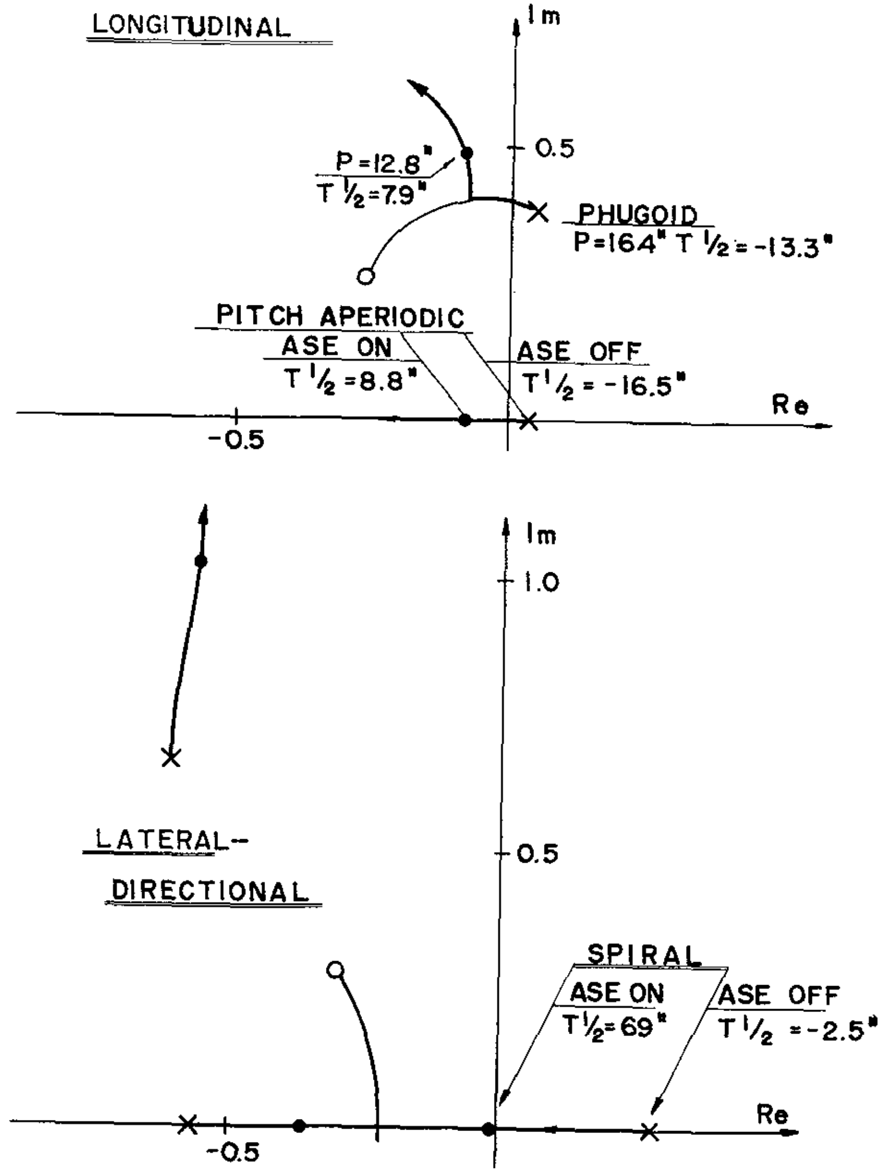


FIG 7 STABILITY AUGMENTATION

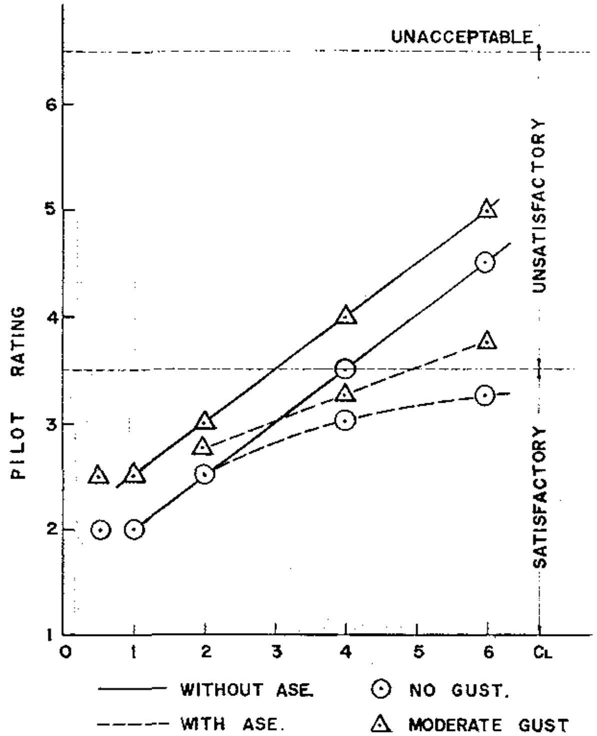


FIG 8 SS-2 FLIGHT SIMULATOR PILOT RATING

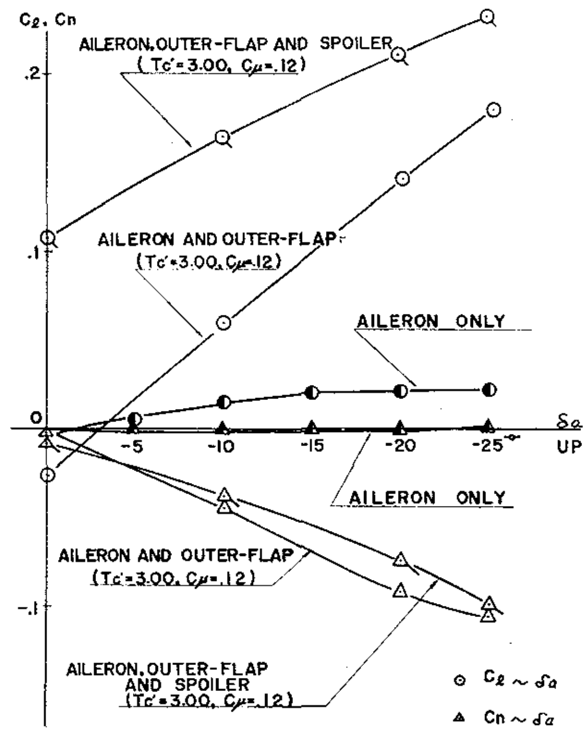


FIG 10 AILERON EFFECTIVENESS

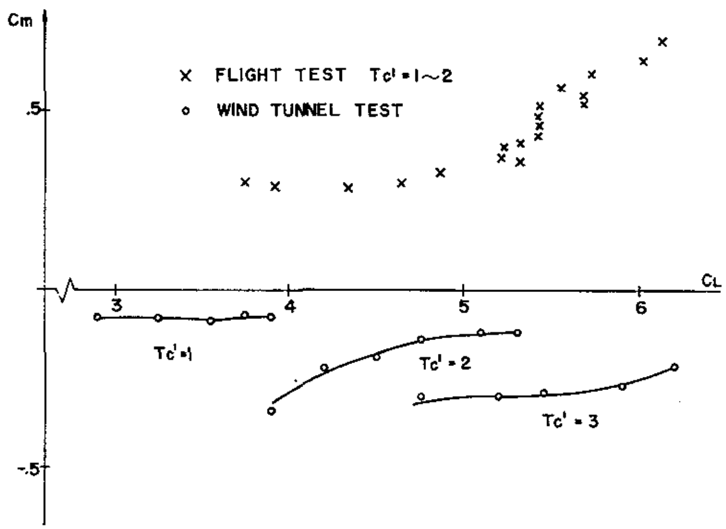


FIG 9 PITCHING MOMENT DISCREPANCY BETWEEN FLIGHT- AND WIND TUNNEL- TEST

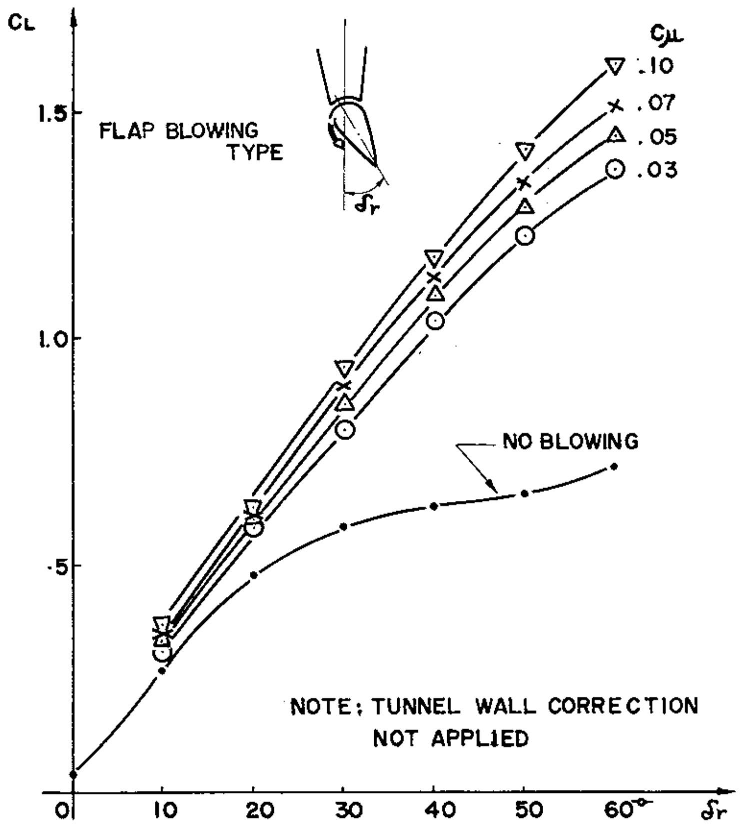


FIG 11 LIFT PRODUCED BY RUDDER
(WIND TUNNEL TEST)

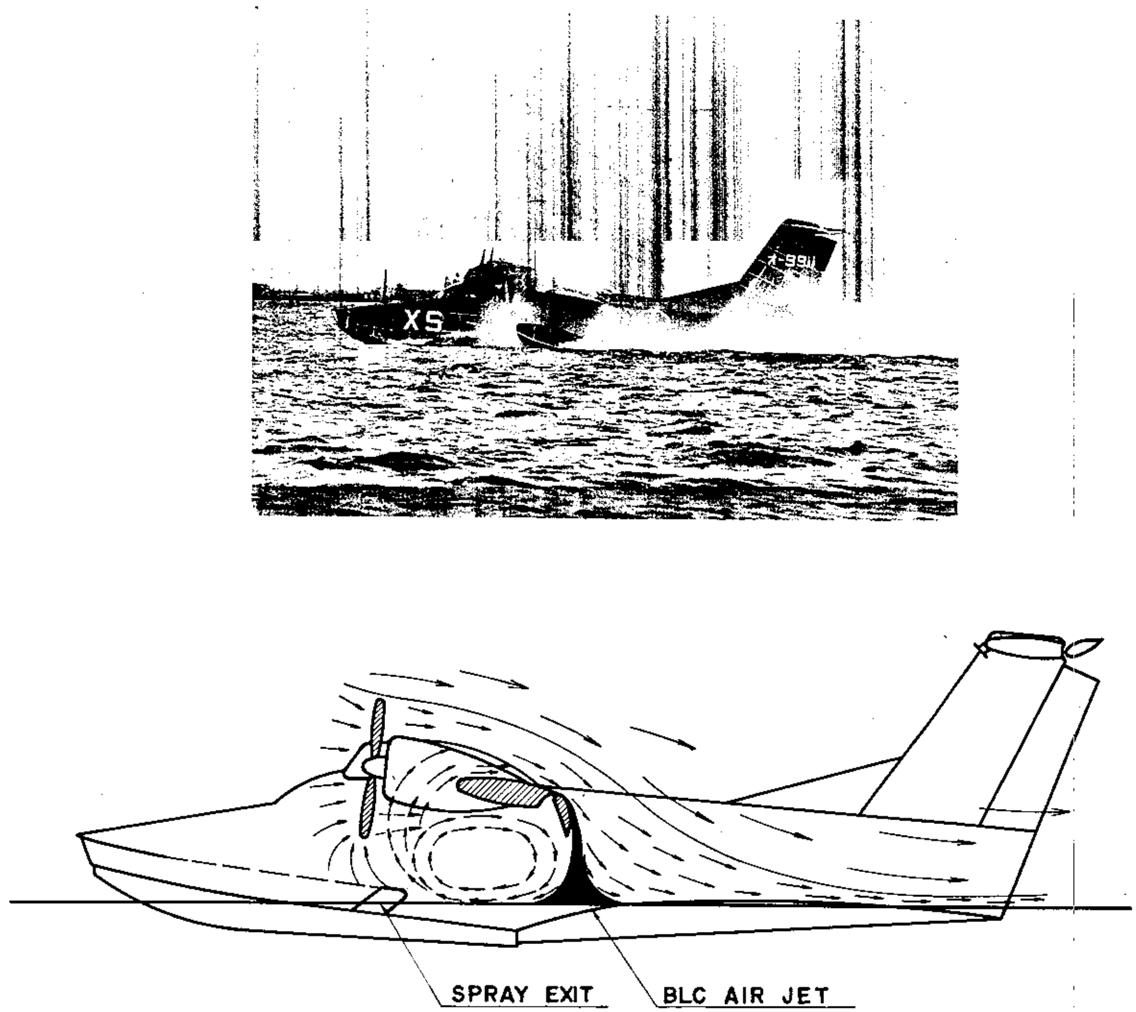
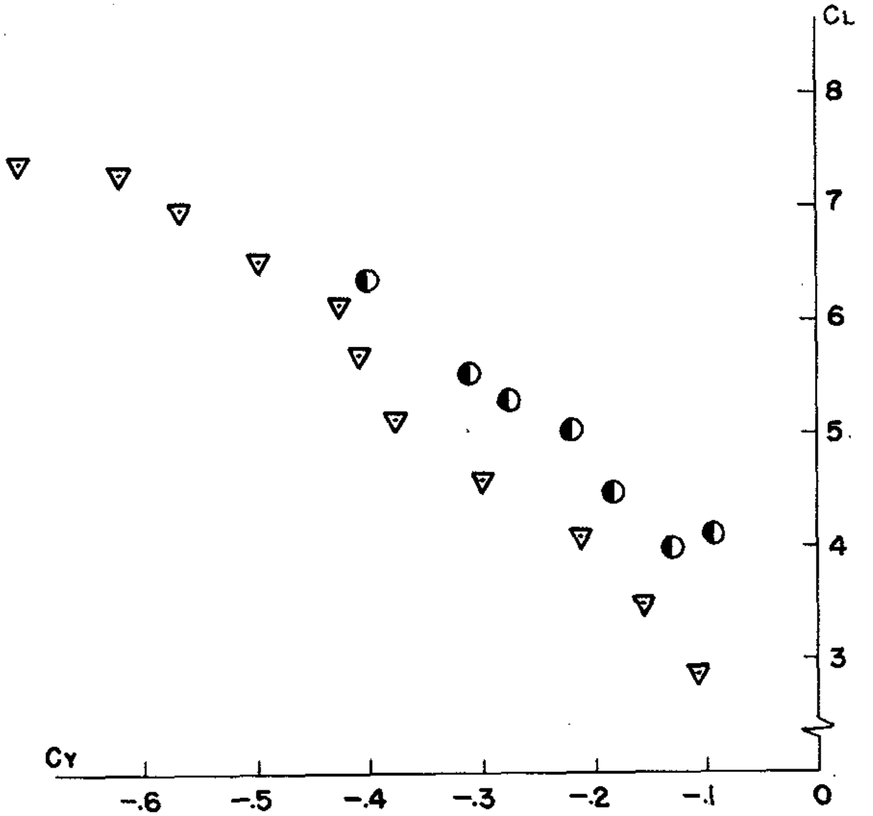


FIG 12 FLOW PATTERN DURING TAKE-OFF, UF-XS

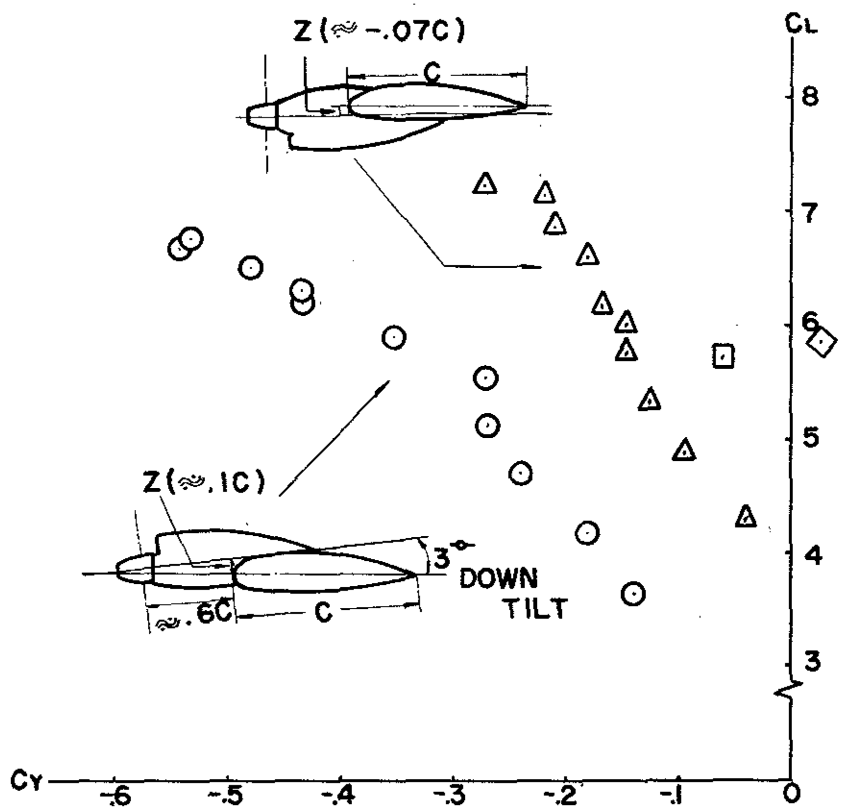


δ_f	T_c'	C_μ	
◐ 55-45-0°	1~2	0.10~0.18	FLIGHT TEST
▽ 60-45-0°	3.0	0.18	WIND TUNNEL TEST

FIG 13 $C_Y \sim C_L$

UF-XS WIND TUNNEL TEST

AND FLIGHT TEST



	Z/C	DOWN TILT	REMARKS
⊙	≈.10	3°	① ORIGINAL DESIGN
△	≈-.07	0°	② REVISED DESIGN
⊡	〃	〃	③ ② PLUS NACELLE FENCE 4.5% PROP DIA.
◇	〃	〃	④ 7.5% 〃 〃

FIG 14 $C_Y \sim C_L$ SS-2 WIND TUNNEL TEST (TAKE-OFF CONFIGURATION)

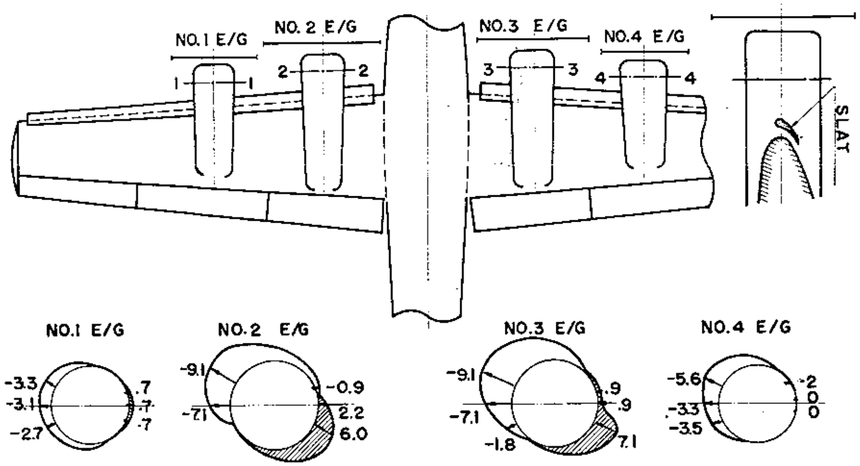


FIG 15 PRESSURE DISTRIBUTION ($\Delta p/q_\infty$) ON NACELLES
T_c' = 3.0 (TAKE-OFF), UF – XS

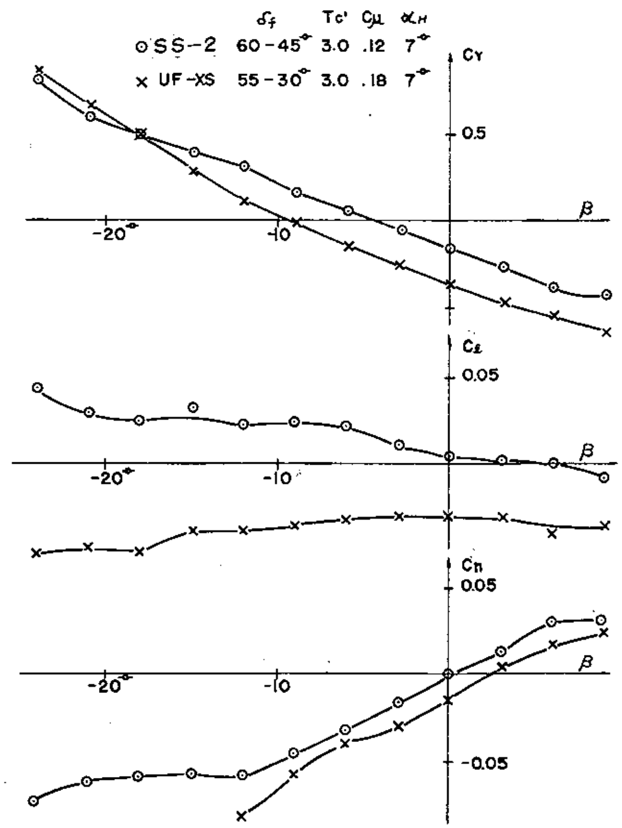


FIG 16 LATERAL CHARACTERISTICS

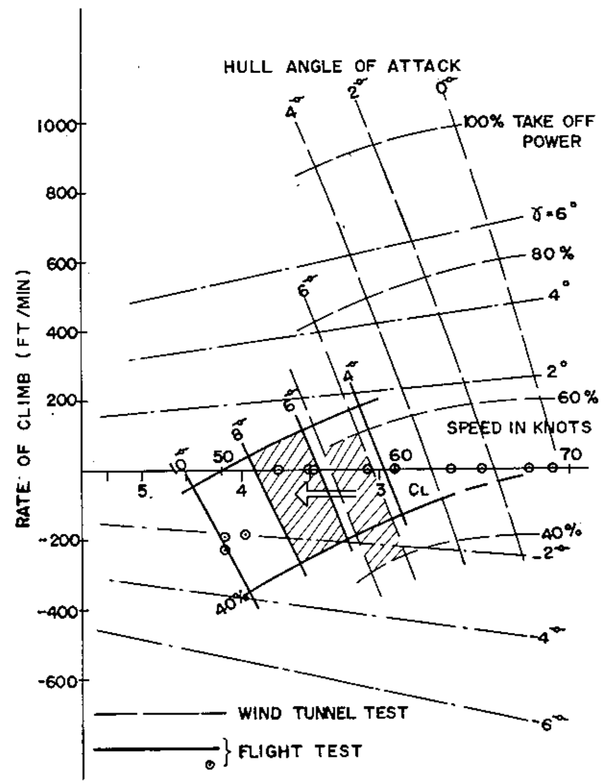


FIG 17 FLIGHT PERFORMANCE OF UF-XS
(a) δ_f = 40-30-0°
W = 30,000 LBS. SL. ISA

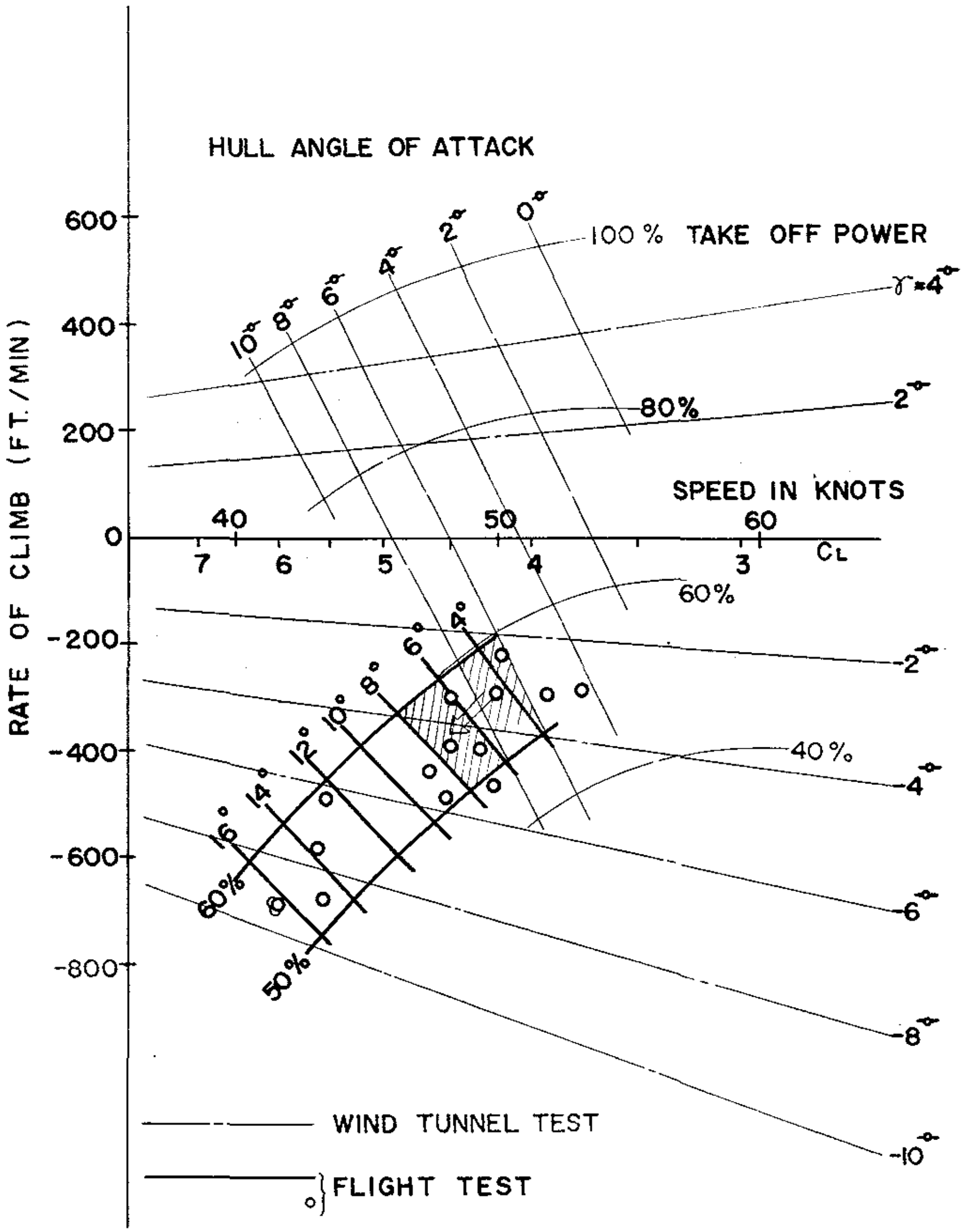


FIG 17 CONCLUDED
(b) δ_f = 60-45-0°
W = 30,000LBS. SL. I.S.A

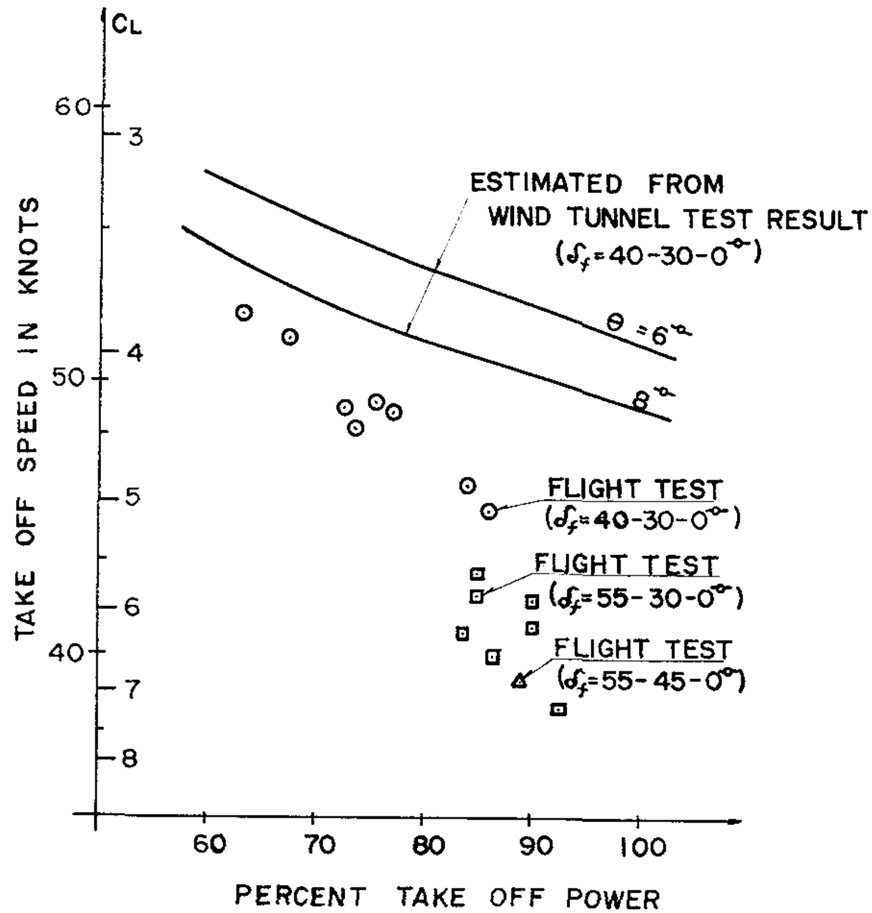


FIG 18 TAKE OFF PERFORMANCE OF UF-XS
REDUCED TO W = 30.000 LBS ISA

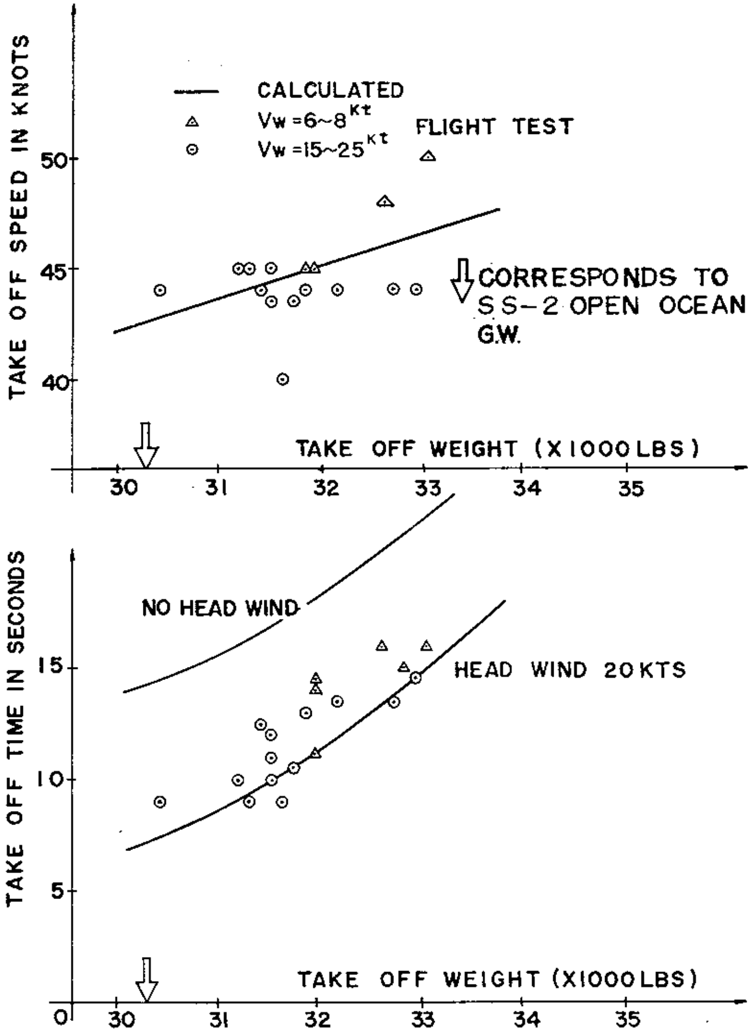


FIG 19 TAKE OFF PERFORMANCE OF UF-XS
FLAP ANGLE = 55-30-0°

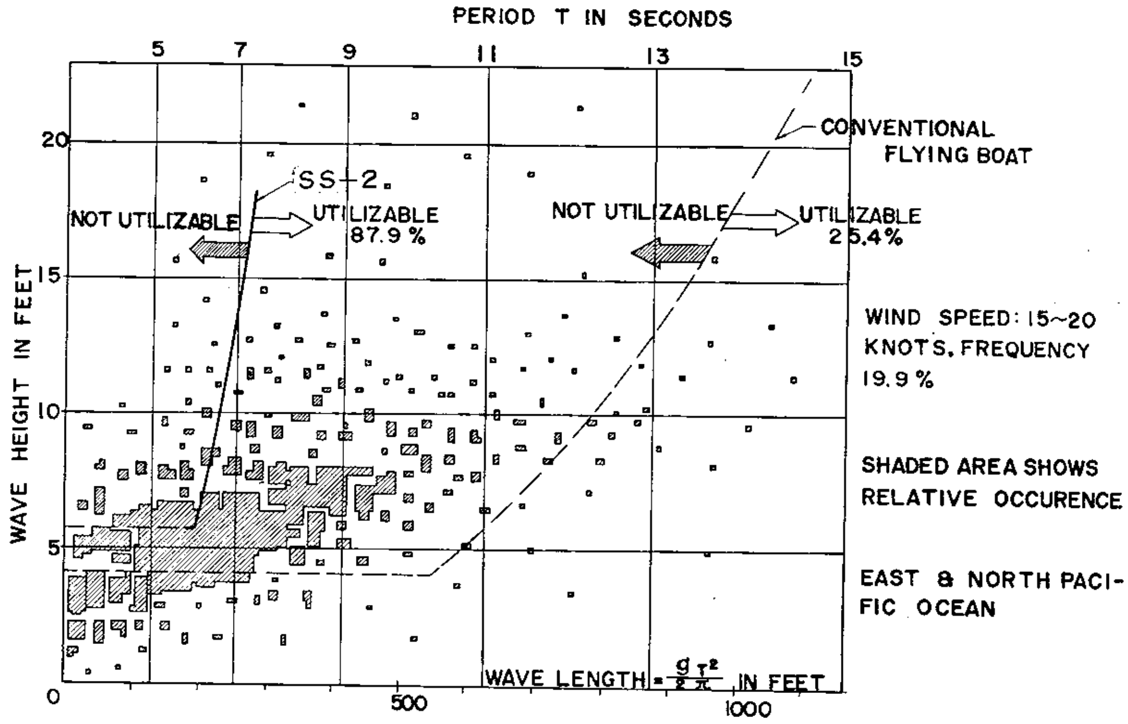


FIG 20 OCCURENCE PROBABILITY OF SEA STATE IN 15~20 KNOTS WIND AND UTILIZABLE ENVELOPE FOR TAKE OFF AND LANDING