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FLIGHT MEASUREMENTS OF THE LOW-SPEED CHARACTERISTICS OF A 35° SWEPT-WING AIRPLANE WITH BLOWING-TYPE BOUNDARY-LAYER CONTROL ON THE TRAILING-EDGE FLAPS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Tests have been conducted to determine the flight characteristics of an F-86 airplane equipped with a blowing-type boundary-layer-control installation on the trailing-edge flaps. Included in this study are the pilots' evaluation of the operational use of the boundary-layer-control system. The effectiveness of the flap was determined in conjunction with slatted leading edges, and an inflatable rubber boot on the leading edge. Measurements were made of the lift, drag, and flow requirements. Performance computations were made for take-off, climb, and landing. The results of the flight tests are compared with those of full-scale wind-tunnel tests of a similar type installation, and with those of flight tests of a wing-shroud blowing system of an F9F-4 airplane.

The results showed that blowing air over the flap deflected 55° for the landing-approach condition (11° angle of attack, 80-percent engine rpm) increased the lift coefficient from 1.02 to 1.37 over that obtained with the standard slotted flap deflected 38°. Maximum lift coefficient was increased from 1.40 for the 38° slotted flap to 1.68 for the 66° flap deflection with blowing at maximum engine power. Improvements in performance were indicated for landing, field take-offs, and catapult-type take-offs. The pilots' evaluation of the operational use of the blowing flap showed reductions in average landing-approach speeds of as much as 12 knots.

INTRODUCTION

As has previously been reported, boundary-layer control (BLC) is a promising means of improving flap lift at low speeds. One application of boundary-layer control by suction through a porous material near the

flap leading edge has been flight tested on an F-86A airplane (ref.1). Another application, which utilizes a high-velocity air jet directed over the flap, has become feasible with the advent of the high pressure ratio jet engine affording relatively large bleed-air flow quantities. Initial flight-test experience was gained with a type of blowing boundary-layer control where the air was ejected from the wing shroud ahead of the flap (ref. 2).

In an effort to reduce the momentum requirements for the blowing system, tests were conducted in the Ames 40- by 80-foot wind tunnel (ref. 3) of a YF-86D airplane where the air was ejected from the leading edge of the flap itself.

Because the wind-tunnel tests could provide only a portion of the information desired, the flight investigation reported upon herein was undertaken on an F-86F airplane. The following items were investigated: (1) the lift increments due to blowing; (2) the effect of the boundary-layer control on the flying qualities and operation of the airplane; and (3) the manner in which the pilot utilizes the additional lift gains.

The blowing flap was tested in conjunction with various wing leading-edge devices. From the lift and drag data obtained, computations were made of the landing and take-off performance. Comparisons are made of flight results on the F-86F with the wind-tunnel results of the YF-86D (ref. 3). In addition, the flight characteristics are compared with those obtained in flight on the straight-wing F9F-4 airplane of reference 2.

NOTATION

b	wing span, ft
C_D	drag coefficient, $\frac{\text{drag}}{qS}$
C_L	lift coefficient, $\frac{\text{lift}}{qS}$
ΔC_L	increment of lift coefficient due to flaps
$C_{L_{max}}$	maximum lift coefficient
C_μ	momentum coefficient, $\frac{w/g}{qS} V_j$
g	acceleration of gravity, 32.2 ft/sec^2
N	engine speed, rpm
p	free-stream static pressure, lb/sq ft

p_d total pressure in flap duct, lb/sq ft

p_t total pressure at engine compressor outlet

P_d duct pressure coefficient, $\frac{p_d - p}{q}$

q dynamic pressure, lb/sq ft

S wing area, sq ft

V_i indicated airspeed, knots

V_j velocity of blowing jet expanded to free-stream static pressure, ft/sec

V_s velocity at stall, knots

V_{s_G} velocity at stall in glide condition, knots

w bleed air flow, lb/sec

$\frac{W}{S}$ wing loading, lb/sq ft

δ ratio of total pressure at compressor to static pressure at sea level

δ_f flap deflection, deg

θ ratio of total temperature at compressor to total temperature at sea level

EQUIPMENT AND TESTS

The installation of the blowing-type boundary-layer control was made on the flaps of an F-86F airplane. A two-view drawing of the test airplane is shown in figure 1. Pertinent dimensions of the airplane are given in table I. A general view of the airplane and a close-up of the flap are presented in figures 2 and 3, respectively. The blowing system consisted of a manifold to collect air from the last stage of the engine compressor of the J-47GE-27 engine, a butterfly valve controlled by the pilot, and a 3-inch-diameter ducting to each flap. The ducting was mounted on the underside of the fuselage to facilitate installation.

The flap used for the blowing system was a plain type made by reworking the nose section of the slotted flaps normally used on the airplane. The flap tracks were removed and external hinge brackets were installed on the undersurface of the wing, allowing flap deflections up to 66°. A rotating O-ring-type seal was used to supply air to the flap at a point

on the center of flap rotation. A sketch of the flap cross section is given in figure 4. A photograph showing the flap ducting details is given in figure 5. All parts of the air-supply system were made of steel. The nozzle block was made in two parts, the lower part of steel welded to the 3-inch-diameter tubing, the upper part forming the nozzle exit of 2024-T aluminum, fastened by screws to the steel nozzle block. Spacers were used at 3-inch span intervals to provide a 0.020-inch nozzle gap. The area of the nozzle was 0.0221 square feet.

The weight of the boundary-layer control equipment for this research-type installation was 175 pounds. In a production-type installation a considerable savings in weight should be possible.

The amount of engine bleed air used at various engine speeds is presented in figure 6. These values of bleed air correspond to approximately 3.5 percent of the primary engine air flow. The bleed flow quantity was calculated from one-dimensional flow equations using measured values of pressure, temperature, and nozzle area. The variation of static thrust (measured on a thrust stand) with percent engine speed is presented in figure 7 with and without bleed air extraction. It can be noted that for the blowing-on case there was a reduction in static thrust of approximately 5 percent. The variation of pressure ratio with percent engine speed is presented in figure 8. It will be noted that sonic flow would occur in the nozzle exit at approximately 63-percent rpm.

Standard NACA instruments were used to record airspeed, altitude, acceleration, duct pressures, and angle of attack. Values of airspeed, altitude, and angle of attack were measured approximately 8 feet ahead of the fuselage nose. Duct pressures in the flaps were measured at the midspan station of the flaps.

The flight tests were conducted with a number of wing leading-edge devices. These included an F-86D-type slat, a 6-3 slat, and an inflatable rubber boot on a 6-3 leading edge. The latter leading edge could be inflated to cover a range of leading-edge radii and amounts of camber by adjusting the internal pressure. For these tests an internal pressure of 10 pounds per square inch gage was used which gave a leading-edge radius of 1.57-percent chord. A sketch of the cross section of each leading-edge device is shown in figure 9. The majority of data presented herein are for the 6-3 slat, since this is the leading edge currently used with F-86F type airplanes.

Tests were conducted at sea level and 5,000 feet over a speed range from 170 knots to the stall. An average wing loading of 45.5 pounds per square foot was used with the take-off center of gravity at 24.1 and 26.6-percent mean aerodynamic chord for the airplane with the F-86D slatted

leading edge and 6-3 leading edge, respectively.[1] The engine rpm was held fixed for a given series of test runs. Tests were conducted at trailing-edge flap deflections of 38°, 45°, 55°, 60°, and 66°.

RESULTS AND DISCUSSION

Airplane with 6-3 Slatted Leading Edge

Lift.- Lift data are presented in figure 10(a) for various flap deflections with blowing on and off for 100-percent engine rpm, in figure 10(b) for 80-percent rpm, and in figure 10(c) for various percent engine rpm for 60° flap deflection. For comparative purposes, data are shown in figure 11 for the standard 38° slotted flap, normally used on the airplane. The equations used to determine C_L and C_D are discussed in Appendix A of reference 2. The data in figure 10 indicate substantial increases in lift resulting from the application of blowing at all flap deflections. It will be noted that the angle of attack for maximum lift coefficient decreases with the application of blowing, with increase in flap deflection, and with amount of blowing. The effect of various leading-edge devices on the lift will be discussed later.

The improvement in flap lift for the case with blowing on over that obtained with the standard 38° slotted flap can be seen by comparing the data in figures 10 and 11; with the 55° flap deflection there was an increase in C_L from 1.02 to 1.37 at the landing-approach attitude ($\alpha = 11^\circ$, 80-percent rpm) and with the 66° flap deflection an increase in $C_{L_{max}}$ from 1.40 to 1.68 at maximum engine power.

It can be observed from the data in figure 10 that the magnitude of the flap lift increment due to blowing varies over the angle-of-attack range. The variation of flap lift increment with angle of attack for various flap deflections is presented in figure 12. It is noteworthy that maximum flap lift occurs in the angle-of-attack range (10° to 12°) for the landing approach. These results are similar to those obtained on the F9F-4 airplane (fig. 10 of ref. 2).

Drag.- The drag results presented in figure 10 indicate that at low lift coefficients blowing caused an increase in drag at a given flap deflection (at a constant C_L). Thus, although the profile drag must be reduced by blowing, the induced drag has increased sufficiently to raise the total drag values. This increase in induced drag is a result of the increased distortion in span loading occurring with the relatively short-span, high-lift flap. It can be noted that the drag values are reduced near $C_{L_{max}}$ by blowing. Similar results concerning drag were obtained in other boundary-layer control investigations (refs. 1, 2, and 3).

[1]The designation "6-3" refers to a full-span chord extension of 6 inches at the wing root and 3 inches at the wing tip.

Effect of momentum coefficient, C_μ, on lift.- The variation of lift coefficient with momentum coefficient is presented in figure 13 at various flap angles and for angles of attack of 8°, 12°, and that corresponding to $C_{L_{max}}$. These data indicate that as the momentum coefficient was increased, the lift first increased rapidly and then increased more slowly. Wind-tunnel tests of reference 3 indicated that the initial increase in lift was associated with control of the boundary layer on the flap. The continued increase in lift is due to an increase in circulation induced by the jet flow over the flap. It can be observed from the data in figure 13 that most of the increase in lift occurs in the C_μ range up to 0.005. It is shown by the data in figure 14 that a C_μ of 0.005 is obtained for an engine rpm of approximately 60 percent. The C_μ variation with C_L is presented along with the lift data of figure 10.

One item to be noted in the data of figure 13 is the fact that for a given C_μ range and at a constant α the change in lift with change in C_μ is greater for the larger values of flap deflection. It is also shown that less change in lift for a given C_μ range is obtained at the higher angles of attack. This latter effect is believed to be due to the presence of a thicker boundary layer ahead of the flap at the higher angles of attack. A compensating effect with this blowing boundary-layer control system is the fact that larger values of C_μ are available as the angle of attack is increased in steady straight flight (i.e., as the airplane slows down).

Comparison of flap lift with theory.- In order to assess the lift effectiveness of a flap it is convenient to compare with the lift predicted by inviscid flow theory, in which, of course, no flow separation is assumed. Values of flap lift increment for various flap deflections are presented in figure 15 for blowing on and off at various values of angle of attack. Results for the configuration with the gear up are included in this figure in order to more closely approximate the theoretical conditions. The theoretical lift values were calculated using reference 4 with a correction for pitching moment obtained from reference 5. The results in figure 15 for 55° flap deflection indicate that for blowing off, flap lift effectiveness is considerably below theory at all values of angle of attack. Applying blowing increased flap lift beyond the theoretical value at the two lower values of α.

An examination of the data in figure 15 for the gear-down condition at various flap deflections discloses that increases in lift with increase in flap deflection were still being obtained up to the highest flap deflection tested. It is felt, however, that lift obtained at flap deflections beyond 66° would not be useful for the test airplane due to the associated drag increase. (See Pilot Evaluation of the Use of Boundary-Layer Control.)

Airplane With Various Leading-Edge Devices

One of the factors influencing the utility of the lift gains of a boundary-layer control flap is the wing leading-edge stall. As mentioned previously, the effect of applying boundary-layer control to the flap was to cause a stall at a lower angle of attack. This shift in angle of attack is felt to result from a stall at the wing leading edge induced by the increase in lift due to the flap. If a powerful leading-edge protection were used, considerable gain in maximum lift would be forthcoming with blowing on. Extending the lift to higher angles of attack can be accomplished by the use of various devices such as slats or camber in the forward portion of the airfoil combined with a large leading-edge radius.

The effect of the F-86D slats and the inflatable leading edge on the lift and drag characteristics is indicated by the data in figure 16 for a flap deflection of 55° at 80-percent rpm. First, it can be seen that the inflated leading edge provided leading-edge protection to the same angle of attack for trailing-edge flap blowing on or off. Similar protection was obtained with a nose flap on the F9F-4 airplane (ref. 2). As a point of interest, it can be noted (fig. 16(a)) that with the F-86D slats open no increase in $C_{L_{max}}$ occurred with blowing on although the stalling characteristics were made tolerable and the lift was extended to a higher value of angle of attack with the slats open. No runs were made with the 6-3 slats closed. It can be inferred, however, by comparing maximum lift values with the 6-3 slats operating (fig. 10(b)) with those obtained with the leading-edge boot deflated (fig. 16(b)) that relatively large improvements in $C_{L_{max}}$ result when using the 6-3 slat in conjunction with the blowing over the trailing-edge flap.

With the inflated leading edge the highest $C_{L_{max}}$ value was attained, although the maximum lift would have to be compromised somewhat for more desirable stall characteristics. The stall was characterized by an abrupt roll-off which was not mitigated appreciably by the installation of the standard 6-3 leading-edge fence. Further tailoring to find a more satisfactory fence configuration was not carried out due to difficulties experienced in bonding the rubber boot to the wing skin.

A summary of the maximum lift characteristics for the various leading-edge devices is presented in the following table. The stalling speed values were based on a wing loading of 45 pounds per square foot, 80-percent engine rpm, and 55° flap deflection.

Leading edge configuration	Blowing	$C_{L_{max}}$	V_S, knots
F-86D slats			
Open	On	1.61	88.6
Open	Off	1.43	93.5
Closed	On	1.60	94
Closed	Off	1.33	97.5
Inflatable boot			
On	On	1.67	87
On	Off	1.37	96
Off	On	1.37	97
Off	Off	1.18	104
6-3 slats			
Open	On	1.59	89.4
Open	Off	1.42	94.3

The variation of stalling speed with gross weight is presented in figure 17 for the 6-3 slatted leading edge and various flap deflections and engine rpm. These data indicate that the largest percentage reduction in stalling speed due to blowing occurs at the lowest gross weights for a given engine power. This is due to the fact that for a given engine power smaller C_μ values are available at the higher gross weights.

As another point of interest, the flap lift increments over the angle-of-attack range from 0° to that corresponding to $C_{L_{max}}$ are presented in figure 18 for the various leading-edge devices and $\delta_f = 55^\circ$ at 80-percent rpm. From an inspection of these data it can be observed that there are only small differences in magnitude of the flap lift increment at a given angle of attack for the various leading edges. Thus it would appear that the flap lift increment was insensitive to the fact that the slats did not extend to the inboard edge of the leading edge. In this regard the area-suction flap discussed in reference 6 was noted to have suffered a reduction in lift due to a vortex shed from the inboard edge of the slat.

Figure 19 shows a comparison between flight and wind-tunnel results for the F-86D slatted leading edge with the flap deflected 60°. The flight results are presented for the gear-up condition to correspond with the tunnel tests (ref. 3). These data show reasonably good correlation between the wind-tunnel results and the flight results over the C_μ range tested.

Operational Characteristics

In the evaluation of the performance of the airplane, actual measurements of landing and take-off distances, climb, and catapult launching were not made; but by the use of the lift and drag data obtained with the 6-3 slatted leading edge and engine thrust, computations have been made of the

performance. The methods used for computing performance are contained in the appendix of reference 1 and are felt to be adequate for comparative purposes.

Landing performance.- The landing distance over a 50-foot obstacle and the ground roll distance were computed for the landing configuration using the average approach speeds selected by the pilots and are presented in figure 20 for flap deflections of 55° and 66°, blowing on and off. For comparison purposes the computed distances for the normal 38° slotted flap deflection are also presented in figure 20. These data indicate that a reduction of approximately 30 percent in total distance would be realized using the 66° flap deflection with blowing on at an airplane gross weight of 14,000 pounds.

Take-off performance.- In the computations for take-off and climb, account is taken of the thrust loss incurred as a result of extracting air from the engine compressor. In order to operate the engine within the allowable tailpipe temperature when extracting air for boundary-layer control, a reduced value of rpm is used. The thrust reduction was approximately 270 pounds at maximum power.

In considering a catapult type take-off this reduction in thrust is not too significant, since take-off acceleration is provided principally by the catapult itself. It is required, however, that sufficient engine thrust be available to accelerate the airplane after launch with a minimum longitudinal acceleration of approximately 0.065g.[2] Lift-off speed is selected as the speed at 0.9 $C_{L_{max}}$ or at the maximum ground attitude. The results of computations of the take-off speeds at the end of the catapult run as a function of gross weight for various flap deflections with blowing on and off are presented in figure 21. Indicated on this figure are the H8-catapult characteristics. The results indicate significant improvements in performance with blowing on. Compared to the 38° deflection of the slotted flap, the 66° deflection of the flap with boundary-layer control would allow an 8-knot reduction in catapult take-off speed at a gross weight of 16,000 pounds. At this gross weight the longitudinal acceleration would be approximately 0.15g.

With regard to a field take-off, the assumption is made that the airplane accelerates on the ground in a level attitude, and at take-off speed the airplane is rotated to the angle of attack corresponding to a velocity of 1.2 V_{stall}. For the transition distance, it is assumed that the airplane is in a steady rate of climb at the value for the 50-foot-height point. The results of the computations presented in figure 22 indicate small improvements in total distance over a 50-foot obstacle with blowing on for the 45° flap deflection compared with the standard 38° slotted flap. The take-off performance was computed with the maximum possible C_{μ}

[2]Assumed minimum acceleration value used to assure that the airplane does not sink after launch.

available. Reducing the air flow to the flaps to reduce the thrust loss and thus operate at a lower C_μ made a further improvement in the take-off performance. By waiting until take-off speed is reached before turning on the boundary-layer control, a 6-percent reduction in total distance would be realized over the standard technique.

Climb characteristics.- The rate of climb after a catapult take-off ($1.05\ V_{stall}$) is presented as a function of gross weight in figure 23. Although the rate of climb is reduced when blowing is used, it should be kept in mind that due to the lower stalling speed it is possible to climb at a lower airspeed with blowing on.

Pilot Evaluation of the Use of Boundary-layer Control

A total of 48 flights were made by four Ames pilots, a number of company test pilots, and service pilots to evaluate the airplane with and without boundary-layer control. In particular, it was desired to know the effect of BLC on the landing-approach speeds, take-off characteristics, and flying qualities.

Approach speeds.- The landing-approach speeds chosen by the NACA pilots for a carrier-type approach at 12,850 pounds, the stalling speeds, and the stalling characteristics are presented in table II for the airplane with various leading-edge devices for 55° flap deflection. Included in the table for comparison are the values for the slotted flap ($\delta_f = 38°$).

These data indicate that substantial reductions in approach speed are realized with the boundary-layer control operating. For the normal type slatted leading edge, a 12-knot reduction in average approach speed over the slotted flap was obtained, while a 9-knot reduction was obtained with the 6-3 slatted leading edge. The variation of average approach speed with gross weight with the 6-3 leading edge for the 55° flap deflection, blowing on and off, and the slotted flap is presented in figure 24. These data were computed on the assumption that the pilot would approach at the same angle of attack regardless of gross weight.[3]

The reasons given by the pilots for selecting a minimum comfortable approach speed changed in most cases from the ability to arrest a sink rate or to control altitude without boundary-layer control to proximity to the stall with boundary-layer control on. The relationship between the pilots' selected approach speeds on the lift curves with the 6-3 slatted leading edge is given in figure 25. These data indicate that the pilots did not make approaches at the same angle of attack with blowing on and off. Although the pilots felt that the ability to control altitude

[3]Several pilots commented on the improvement in turning performance during landing approach by noting an increase in attainable angle of bank or normal acceleration with blowing on.

while maintaining a desired approach airspeed was greatly improved with blowing on, a reduction in angle of attack was necessary to maintain a safe margin below maximum lift.

Each pilot also made carrier approaches with the flaps deflected 66°. In this case the increased lift resulted in only small (1 to 2 knots) reductions in approach speed. The 66° flap deflection was not felt to be desirable for carrier approaches because of the increased drag causing poorer wave-off performance.

The foregoing discussion has been concerned with carrier-type approaches which are made at essentially constant altitude with power for level flight. For normal field operation, a sinking-type approach is used at reduced engine powers. Because engine power has a direct effect on the amount of flap lift produced with blowing on, as well as affecting the steepness of the glide path, the approach speeds selected in a sinking-type approach will vary, depending on the amount of power used. The effect of engine power on flap lift increment is indicated by the data presented in figure 26 for a 55° flap deflection. The data show a smooth variation of flap lift with rpm. Figure 27 shows the variation of approach speed chosen with engine rpm for a 55° flap deflection with boundary-layer control on and off. These approaches were made at constant power and constant airspeed with the throttle retarded after the flare (except for idle condition). Although an appreciable amount of lift due to blowing is present even at idle power, the data in figure 27 indicated that if the entire approach is made near idle power little or no reduction in approach speed would be realized. In order to get the maximum utilization of the boundary-layer control for a sinking-type approach, the NACA pilots modified their approach and used low power to reduce airspeed and lose altitude in the early part of the landing pattern, and then increased power in the last part of the final approach, with a cut in power after the flare. Final approach speeds for landings made in this manner could be as slow as those obtained in the carrier-type approaches. In an approach where 70-percent rpm was maintained until the landing flare was initiated, due to wind-milling action, the engine rpm dropped off only 55 percent. For the sinking-type approach some pilots preferred a 66° flap deflection since the added drag permitted higher engine rpm and resulted in improved engine response and increased lift due to blowing.

In regard to instrument-type landings several pilots commented that with blowing on the airplane was held more easily at a desired approach speed. This effect is presumably tied in with the increased slope of the $C_L - C_D$ curve with blowing on which results in smaller drag changes for a given lift change.

In order to investigate further the action of boundary-layer control in sinking-type approaches, several GCA (ground control approach) approaches were made using the Moffett Field GCA facilities. The pilot's comments were as follows:

"The first approach was made attempting to use the technique described in the pilot's handbook (i.e., power constant at 78 percent, 150 knots, on level portion of final approach, and upon reaching glide slope, opening speed brakes which is supposed to result in 500 feet per minute rate of descent at 150 knots). The flaps were set at 38°, blowing off. Altitude control was good; however, it seemed rather difficult to maintain the desired airspeed and a number of power corrections had to be made. Even so, rather large excursions from the desired airspeed occurred (10 to 15 knots). The second approach was made with 55° flap deflection with boundary-layer control off. The entire approach was made at 130 knots which seemed quite comfortable. Power required was about 80 percent, speed brakes were opened upon reaching the glide slope. In general, it seemed easier to hold close to the desired airspeed. Altitude control again was good. Two approaches were then made with the boundary-layer control on. On the first the flap deflection was left at 55° throughout the approach and the speed brakes were opened to start the rate of descent. On the second, 55° flap deflection was used to the glide slope, at which point the flaps were lowered to 66°, leaving the speed brakes retracted. This latter procedure seemed the most effective in commencing the 500 feet per minute rate of descent. The desirable approach speed seemed to be 115 knots which required about 83-percent rpm. Speed control with boundary-layer control on is excellent. Glide slope corrections were easily made with little effort, requiring only slight changes in power. Once the correct power and rate of descent were established the airplane seemed to ride down the glide slope as if it were on a track."

Other pilots made comments relative to the take-off characteristics. The fact that additional lift was available with no change in attitude when the blowing was turned on was appreciated by some pilots and was felt to be desirable for instrument-type take-offs. It was also noted that the climb-out angle was increased with the blowing on. However, because of the high drag above 110 knots a modified climb-out technique was used to get maximum performance (i.e., climb initially at 100 to 110 knots, then turn boundary-layer control off before accelerating).

Flying qualities.- The following discussion will cover those items on which boundary-layer control had an effect. All other flying qualities were unaffected by boundary-layer control operation.

The longitudinal trim changes due to the operation of the boundary-layer control system on this airplane were considered to be excessive by the pilot. The measured control forces are presented in the following table for the pertinent conditions outlined in Air Force Specification MIL F-8785 (ASG), reference 7.

Longitudinal stick force, lb	Initial trim condition					Configuration change	Parameter to be held constant
	Speed, knots	Gear	Flaps	Power, percent	BLC		
0	140 ($1.4 V_{S_G}$)	Down	Up	80	Off	---	---
7 pull	140	Down	55° down	80	Off	Flaps down	Altitude
18 pull	140	Down	55° down	87	On	BLC on	Altitude
0	140	Up	55° down	100	On	---	---
15 push	---	Up	55° down	100	Off	BLC off	Rate of climb
24 push	---	Up	Up	100	Off	Flaps up	Rate of climb

Although the trim changes noted in the table exceed the allowable 10-pound push or pull value of reference 7, it is not felt that the boundary-layer control operation in itself would represent a serious trim change problem. It can be noted that large trim changes were encountered in operation of the flaps alone and result from the type of force feel system (irreversible control system with a bungee-fixed spring gradient picked on the basis of high-speed flight) employed on this airplane. It is of interest to note that the pitching-moment change with the application of blowing measured for the airplane in reference 3 was in an opposite direction to that measured in flight in the present investigation. The reason for this is felt to be due to the difference in horizontal tail geometry between the two airplanes.

The effect of the boundary-layer control on the stalling characteristics was dependent somewhat on the type of leading-edge device employed with it. For the 6-3 slats and the slotted flap ($\delta_f = 38^\circ$) the stall was characterized by a mild pitch-up coupled with a lateral unsteadiness which was controllable. The pitch-up was followed by a pitch-down. There was no stall warning. The stall in this configuration was considered satisfactory. With the plain flap deflected 55° and boundary-layer control off, the pitch-up was more pronounced. Applying boundary-layer control tended to increase the pitch-up and the stall itself was considered marginal to unsatisfactory due chiefly to the poor stall recovery characteristics. In order to recover from the stall, large forward stick displacements were necessary and the associated stick forces were objectionable. The pitch-up at the stall and the poor stall recovery characteristics were aggravated by the extreme rearward center-of-gravity location (approximately 27 percent) with the 6-3 slats installed. With the F-86D slats, the stall was considered satisfactory for all conditions; however, the application of boundary-layer control tended to reduce the stall warning and render it marginal to unsatisfactory. With the rubber-boot leading edge inflated the stall was unsatisfactory, both with boundary-layer control off or on, due to a pitch-up and an abrupt roll-off. With the boot deflated and boundary-layer control off, the roll-off was slower and somewhat controllable. As mentioned previously, the addition of the standard 6-3 leading-edge fence did not alter the stalling characteristics appreciably.

CONCLUSIONS

The following conclusions are based on measurements of the flight characteristics of an F-86F airplane equipped with blowing-type boundary-layer control:

1. Blowing air over the flap deflected 55° resulted in an increase in lift coefficient from 1.02 to 1.37 for the landing-approach configuration (11° angle of attack, 80 percent engine rpm) over that obtained with the standard slotted flap deflected 38°. Maximum lift was increased from 1.40 for the slotted flap to 1.68 for the deflected 66° flap with blowing at maximum engine power.

2. Comparison with theoretical flap effectiveness indicated that the flap lift increments predicted by linear, inviscid fluid theory of reference 4 were attained.

3. Most of the increase in flap lift due to blowing occurred in the C_μ range up to 0.005 with a steady increase in lift with increase in C_μ up to the largest C_μ values tested.

4. Of the various leading edges tested, the inflated rubber boot produced the highest value of $C_{L_{max}}$; however, the stalling characteristics were considered unsatisfactory. The 6-3 slatted leading edge was considered by the pilots to be the best leading edge for landing approach, resulting in the lowest approach speed (96 knots) in spite of the objectionable pitch-up characteristics noted at the stall. The type of leading edge had only a small effect on the lift increment due to blowing at a given angle of attack below $C_{L_{max}}$.

5. In regard to performance, use of blowing at a flap deflection of 66° reduced the calculated landing distance by 30 percent compared to the standard 38° slotted flap. In take-off performance, the catapult end speed at a given gross weight was reduced by 8 knots due to blowing. For a field-type take-off, 45° flap deflection was optimum for the case with blowing on; however, these gains were relatively small.

6. The use of blowing with the 55° flap deflection reduced the average approach speed by as much as 12 knots in a carrier-type approach compared to the slotted flap deflected 38°. In sinking-type approaches smaller reductions in speed were realized; the flatter the approach angle with a resultant increase in approach power, the greater the speed reduction.

7. Improvements were noted by the pilots in control of the airplane glide path with blowing on. Improvements were noted also in take-off since the airplane would tend to fly off without as much rotation in attitude required.

8. The longitudinal trim changes due to flap deflection and application of blowing were considered excessive by the pilots.

9. In some cases the stalling characteristics were made less desirable with blowing on.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., July 30, 1956

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2. Rolls, L. Stewart and Innis, Robert C.: A Flight Evaluation of a Wing-Shroud-Blowing Boundary-Layer-Control System Applied to the Flaps of an F9F-4 Airplane. NACA RM A55K01, 1956.

3. Kelly, Mark W., and Tolhurst, William H., Jr.: Full-Scale Wind-Tunnel Tests of a 35° Sweptback Wing Airplane With High-Velocity Blowing Over the Trailing-Edge Flaps. NACA RM A55I09, 1955.

4. DeYoung, John: Theoretical Symmetric Span Loading Due to Flap Deflection for Wings of Arbitrary Plan Form at Subsonic Speeds. NACA Rep. 1071, 1952. (Formerly NACA TN 2278)

5. James, Harry A., and Hunton, Lynn W.: Estimation of Incremental Pitching Moments Due to Trailing-Edge Flaps on Swept and Triangular Wings. NACA RM A55D07, 1955.

6. Cook, Woodrow L., Holzhauser, Curt A., and Kelly, Mark W.: The Use of Area Suction for the Purpose of Improving Trailing-Edge Flap Effectiveness on a 35° Sweptback Wing. NACA RM A53E06, 1953.

7. Anon.: Military Specification - Flying Qualities of Piloted Airplanes. MIL-F-8785(ASG), Sept. 1, 1954. (Amendment 1, Oct. 19, 1954)

TABLE I.- DIMENSIONS OF TEST AIRPLANE

Wing	
Total area, sq ft (with F-86D-type slats)	287.9
Total area, sq ft (with 6-3 leading edge)	302
Span, ft	37.12
Aspect ratio	4.79
Taper ratio	0.51
Mean aerodynamic chord (wing station 98.7 in.), ft	8.1
Dihedral angle, deg	3.0
Sweepback of 0.25-chord line, deg	35.23
Geometric twist, deg	2.0
Root airfoil section (normal to 0.25-chord line)	NACA 0012-64 (modified)
Tip airfoil section (normal to 0.25-chord line)	NACA 0011-64 (modified)
Wing area affected by flap, sq ft	116.6
Horizontal tail	
Total area, sq ft	35.0
Span, ft	12.7
Aspect ratio	4.65
Taper ratio	0.45
Dihedral angle, deg	10.0
Mean aerodynamic chord (horizontal-tail station 33.54 in.) ft	2.9
Sweepback of 0.25-chord line	34.58
Airfoil section (parallel to center line)	NACA 0010-64
Vertical tail	
Total area, sq ft	34.4
Span, ft	7.5
Aspect ratio	1.74
Taper ratio	0.36
Sweepback of 0.25-chord line, deg	35.00
Flap	
Total area, sq ft	23.7
Span (from 13.4 to 49.5-percent semispan), ft	7.27
Chord (constant), ft	1.67

TABLE II.- PILOTS' OBSERVED STALLING AND APPROACH CHARACTERISTICS FOR VARIOUS FLAP AND LEADING-EDGE DEVICES.

Pilot	Configuration			Stall			Carrier approach 12,850 lb	
	Leading edge	Flap	BLC	Indicated air speed, knots	Gross weight, lb	Characteristics	Indicated air speed, knots	Reason for limiting approach speed
A	6-3 slat	38° slotted	None	89	12,750	Warning: Unsatisfactory Stall: ---	105	Inadequate longitudinal control and visibility
	6-3 slat	55°	On	85	12,630	Warning: None - unsatisfactory Stall: Marginal - satisfactory	95	Proximity to stall, inadequate altitude control
	6-3 slat	55°	Off	90	12,720	Warning: None - unsatisfactory Stall: Marginal - satisfactory	103	Proximity to stall, inadequate altitude control and visibility
	F-86D slat	38° slotted	None	96	14,200	Warning: Satisfactory Stall: Satisfactory	106	Inadequate longitudinal control and visibility
	F-86D slat	55°	On	88	12,860	Warning: 93 knots, less than with BLC off Stall: Satisfactory	98	Proximity to stall
	F-86D slat	55°	Off	93	12,860	Warning: 103 knots, satisfactory Stall: Satisfactory	111	Inadequate longitudinal control and ability to arrest sink.
B	6-3 slat	38° slotted	None	90	12,470	Mild pitch-up with roll-off	103-108	Proximity to pitch-up and roll-off
	6-3 slat	55°	On	86-88	12,860	Warning: Unsatisfactory Stall: Marginal, stall recovery unsatisfactory, mild pitch-up with lateral instability at $C_{L_{max}}$	93-98	Proximity to pitch-up
	6-3 slat	55°	Off	93	12,860	Warning: Unsatisfactory Stall: Marginal, satisfactory	98-103	Proximity to pitch-up
	F-86D slat	38° slotted	None	92	12,860	Warning: Satisfactory Stall: Satisfactory	103	Ability to arrest rate of sink, visibility
	F-86D slat	55°	On	88	12,860	Warning: 91 knots, satisfactory Stall: Satisfactory	96-98	Ability to control rate of sink
	F-86D slat	55°	Off	92	12,860	Warning: 96 knots; very mild; unsatisfactory Stall: Satisfactory	108-113	Ability to control rate of sink
C	6-3 slat	38° slotted	None	92	13,310	Smooth to 100 knots; yaw to left at 98 knots and fall through at 94 knots	106	Inadequate altitude control and proximity to stall
	6-3 slat	55°	On	86	12,860	Warning: Unsatisfactory Stall: Unsatisfactory due to pitch-up	97	Proximity to pitch-up
	6-3 slat	55°	Off	92	12,860	Warning: Unsatisfactory Stall: Marginal due to pitch-up	110	Ability to arrest rate of sink
	F-86D slat	38° slotted	None	98	14,300	Warning: Satisfactory Stall: Satisfactory	110	Ability to control rate of sink
	F-86D slat	55°	On	88	12,860	Stall: Satisfactory	98-106	Proximity to stall
	F-86D slat	55°	Off	92	12,860	Stall: Satisfactory	110-113	Ability to control altitude
D	F-86D slat	55°	On	90	12,960	Warning: 98 knots, unsatisfactory, light pitch-up Stall: Satisfactory	98	Inadequate altitude control
	F-86D slat	55°	Off	96	13,660	Warning: 99 knots, unsatisfactory Stall: ---	108	Slow longitudinal control of flight path visibility

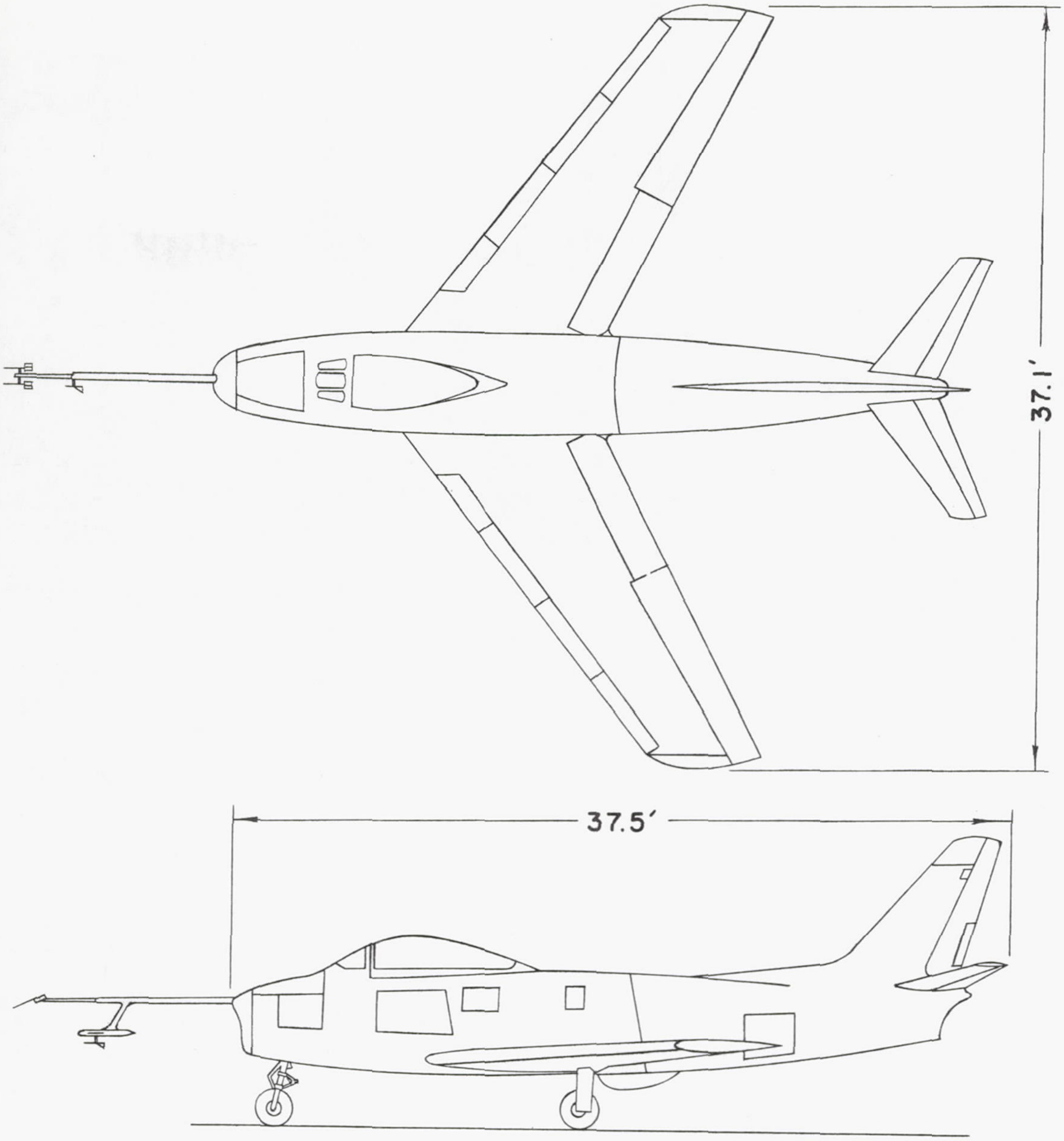
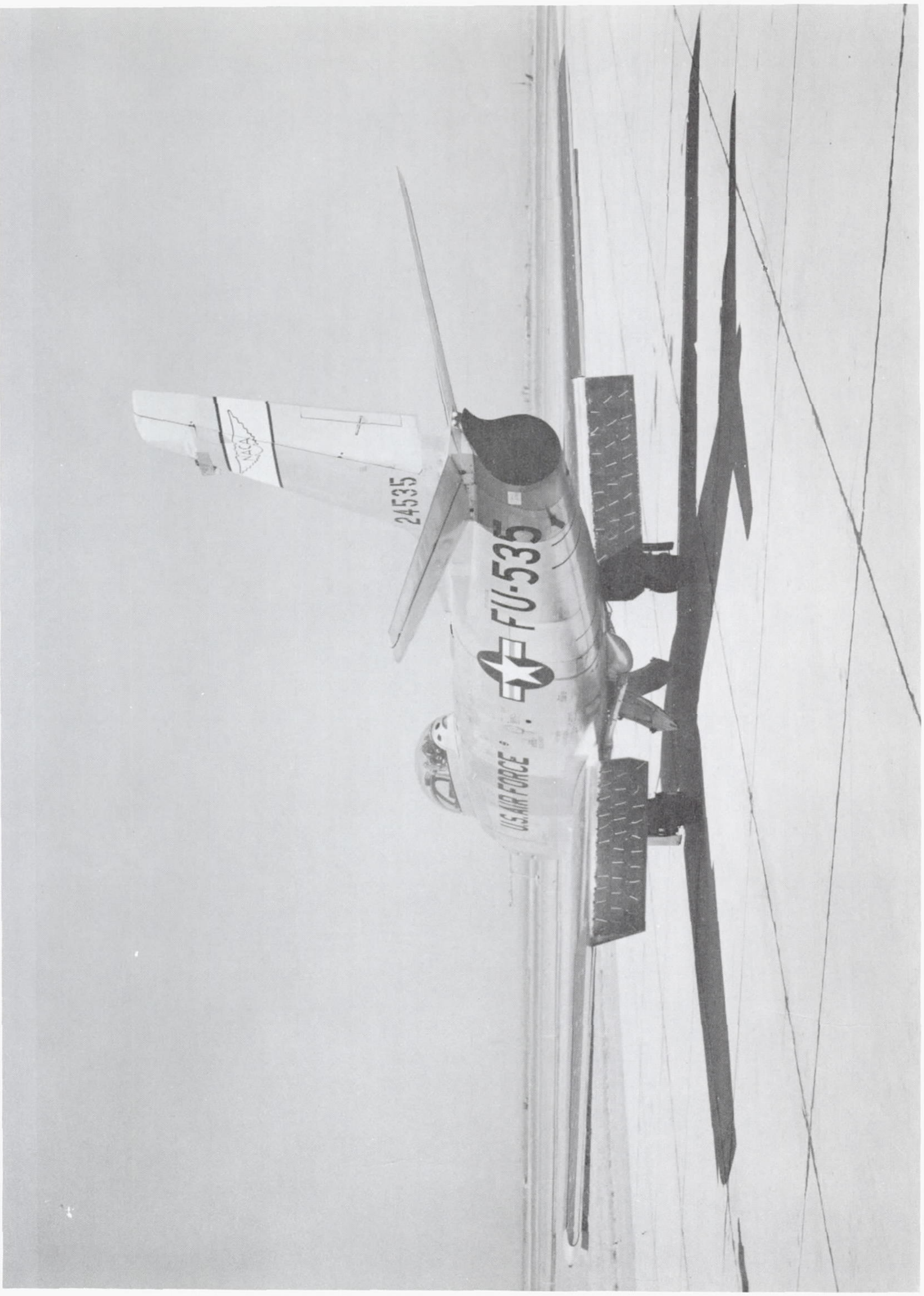
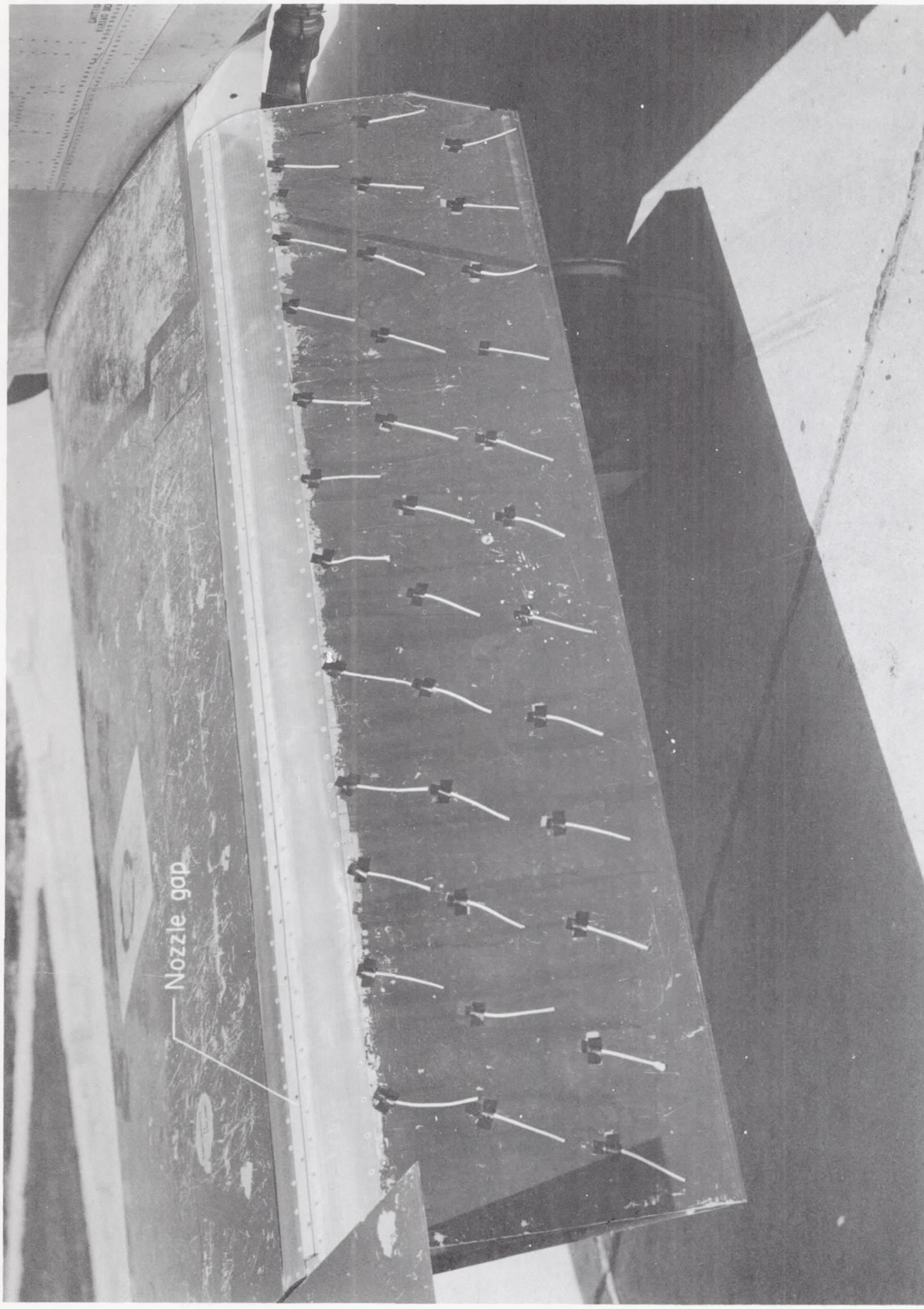


Figure 1.- Two-view drawing of the test airplane.



A-20518

Figure 2.- General view of test airplane.



A-20519.1

Figure 3.- Close-up of flap.

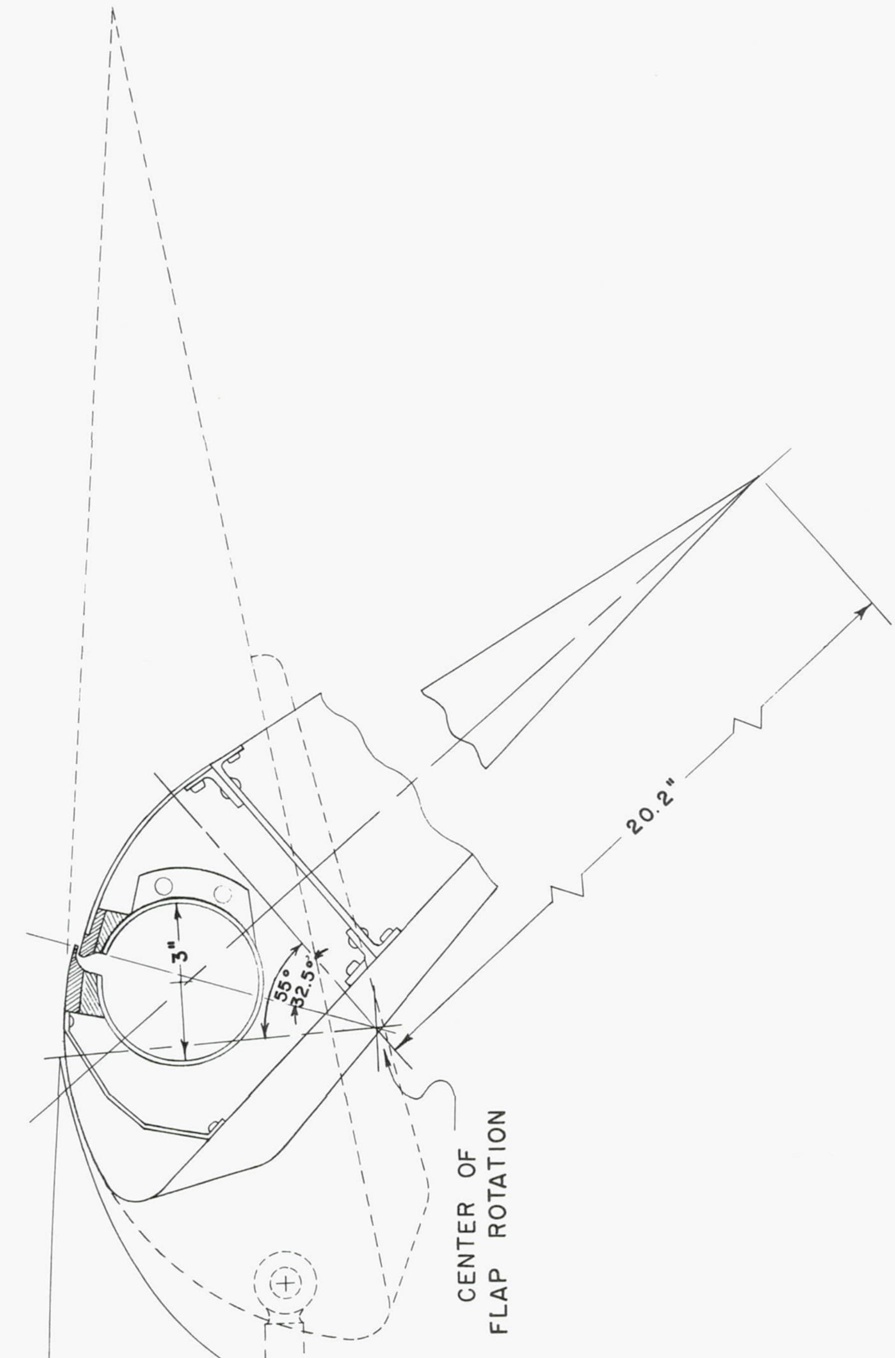
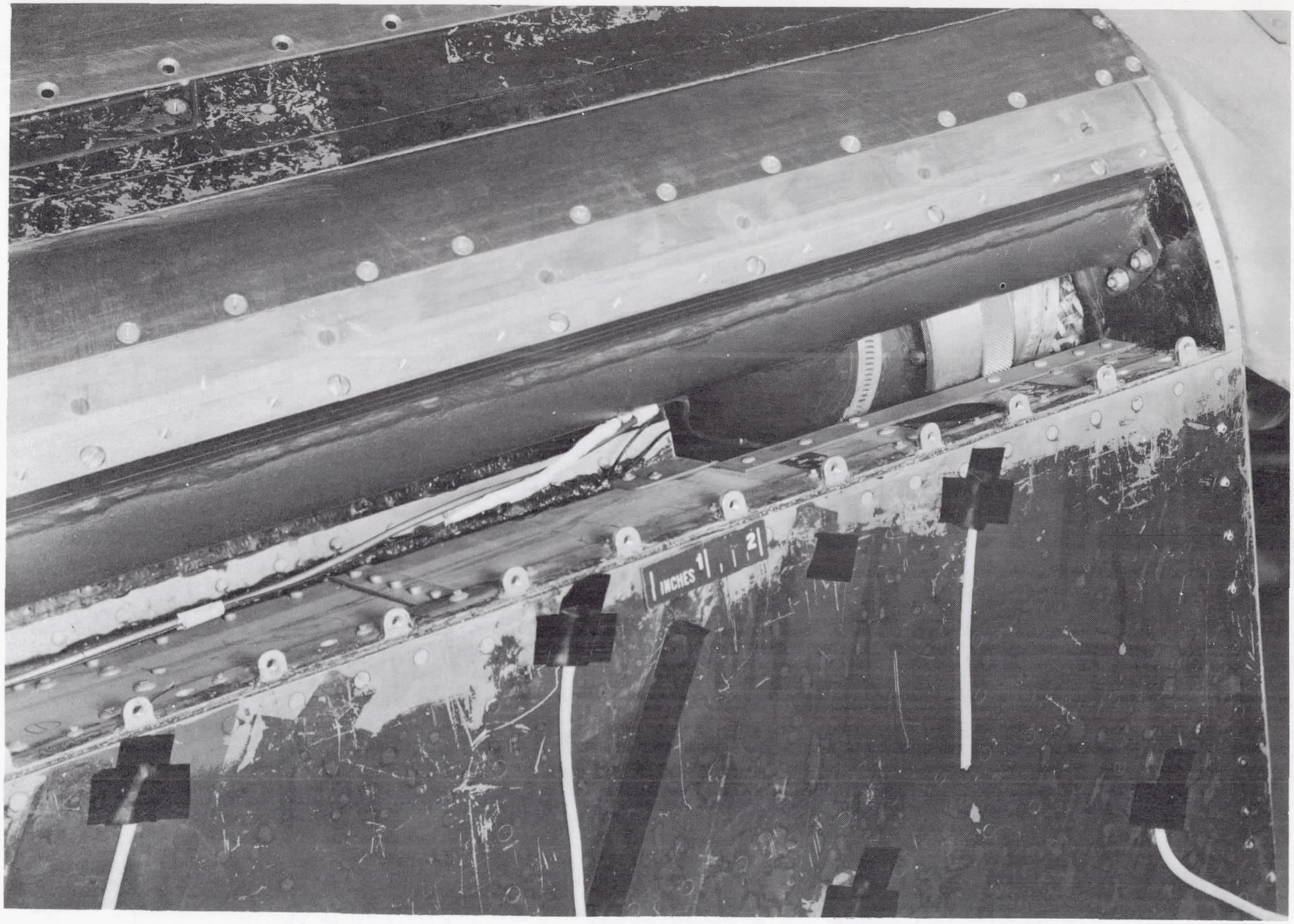


Figure 4.- Typical cross section of flap.



A-20520

Figure 5.- Close-up showing flap ducting details.

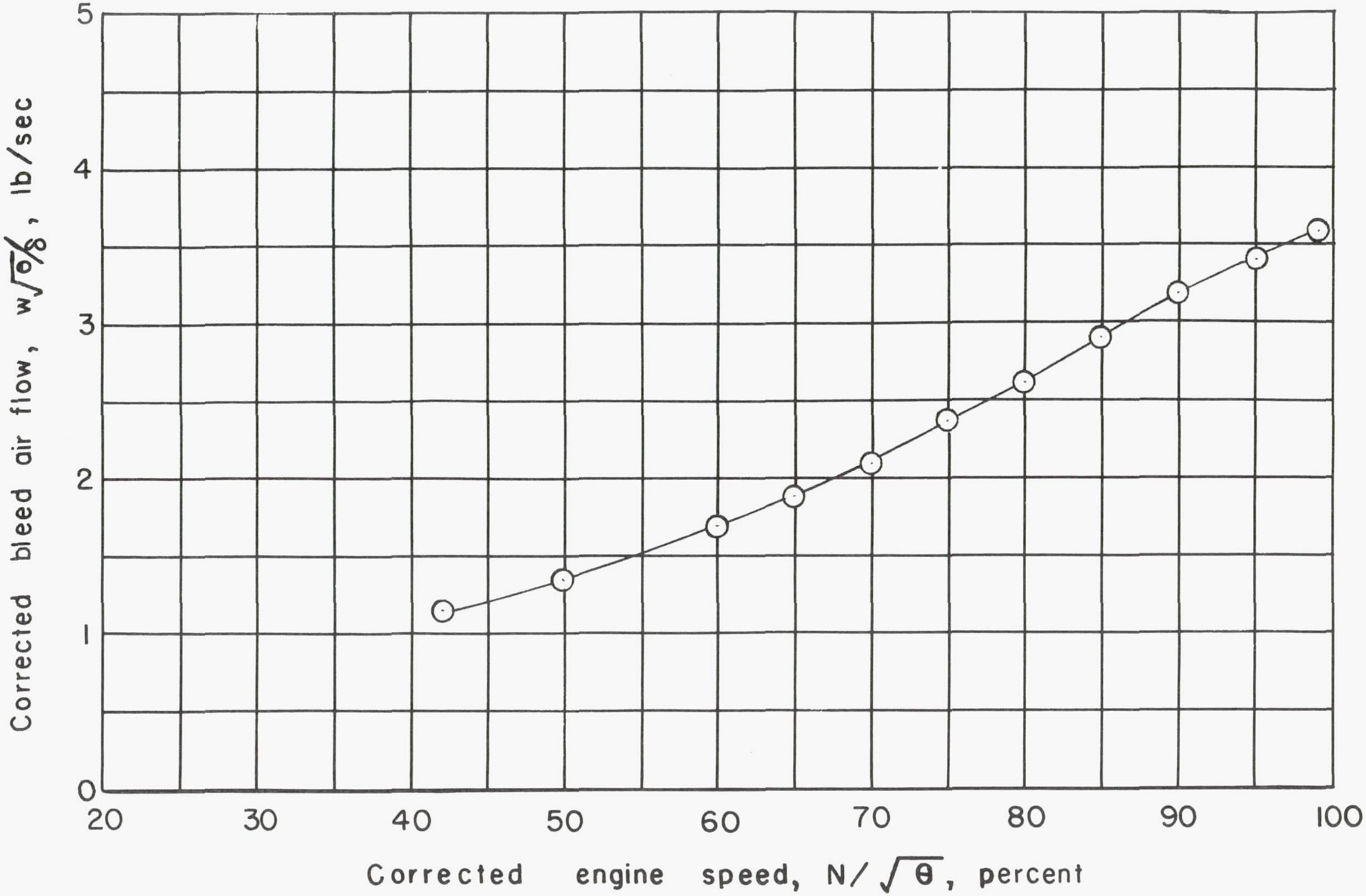


Figure 6.- Variation of engine bleed air with engine speed; sea level.

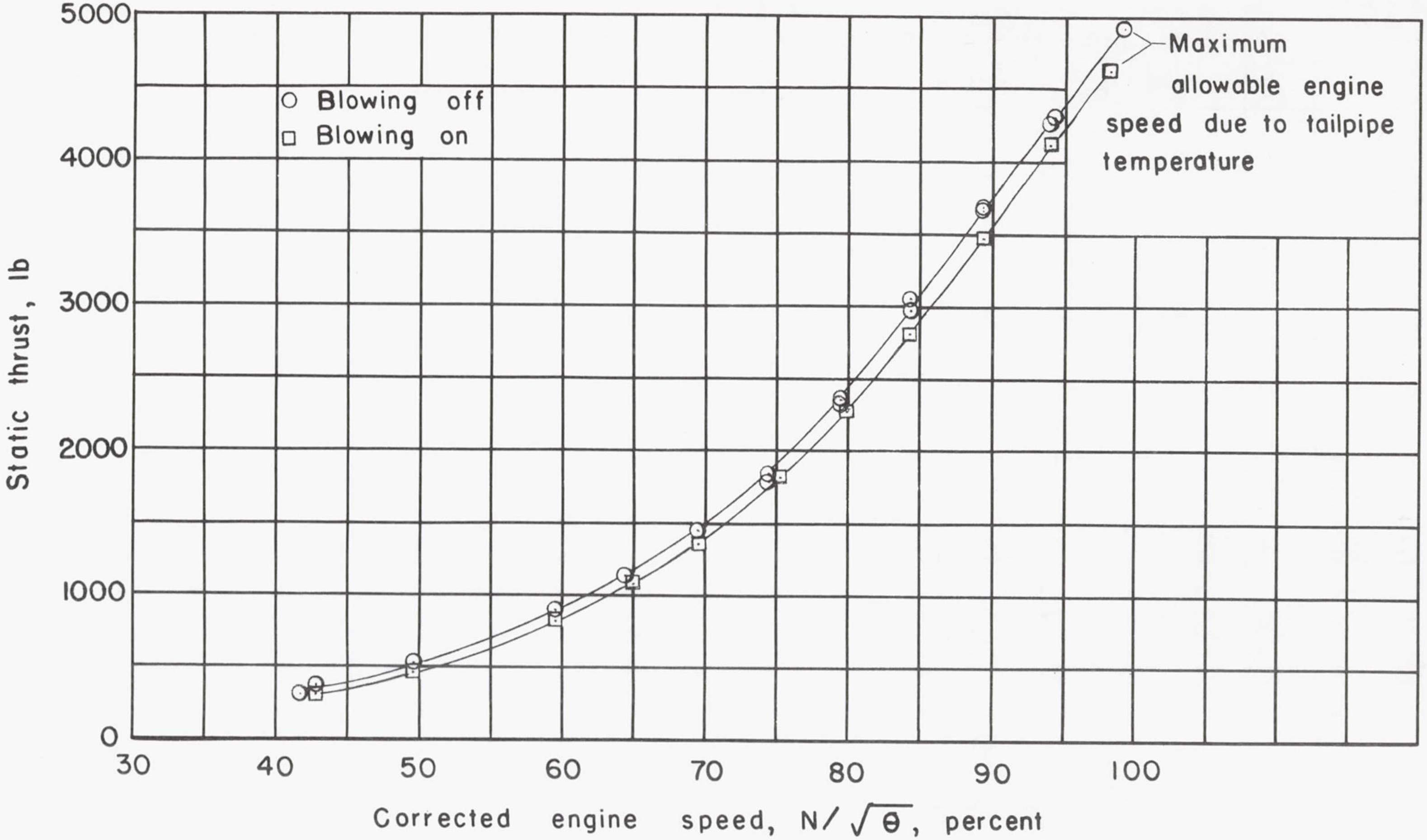


Figure 7.- Variation of static thrust with engine speed for blowing on and off; sea level.

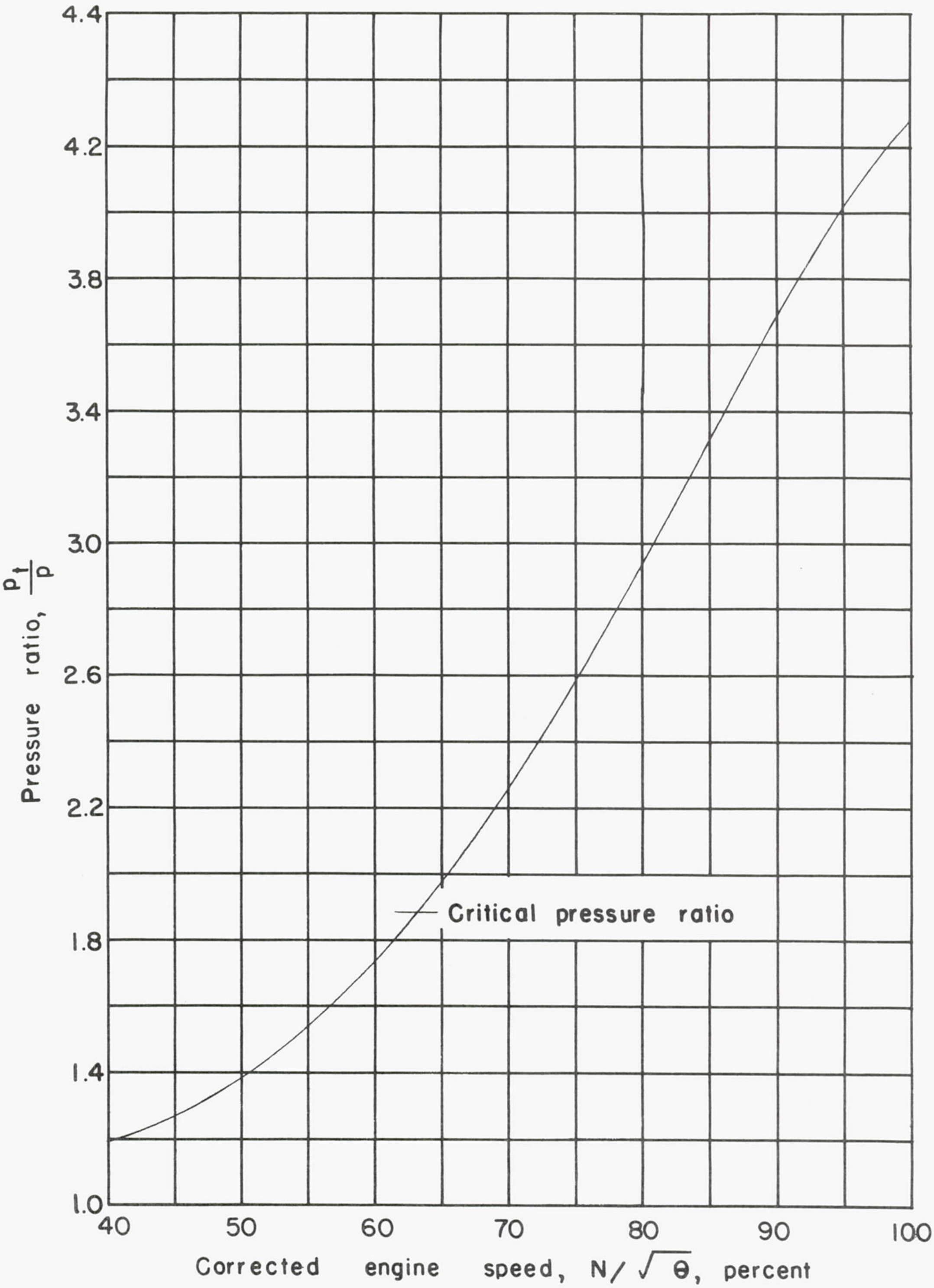


Figure 8. - Variation of pressure ratio with engine speed; sea level.

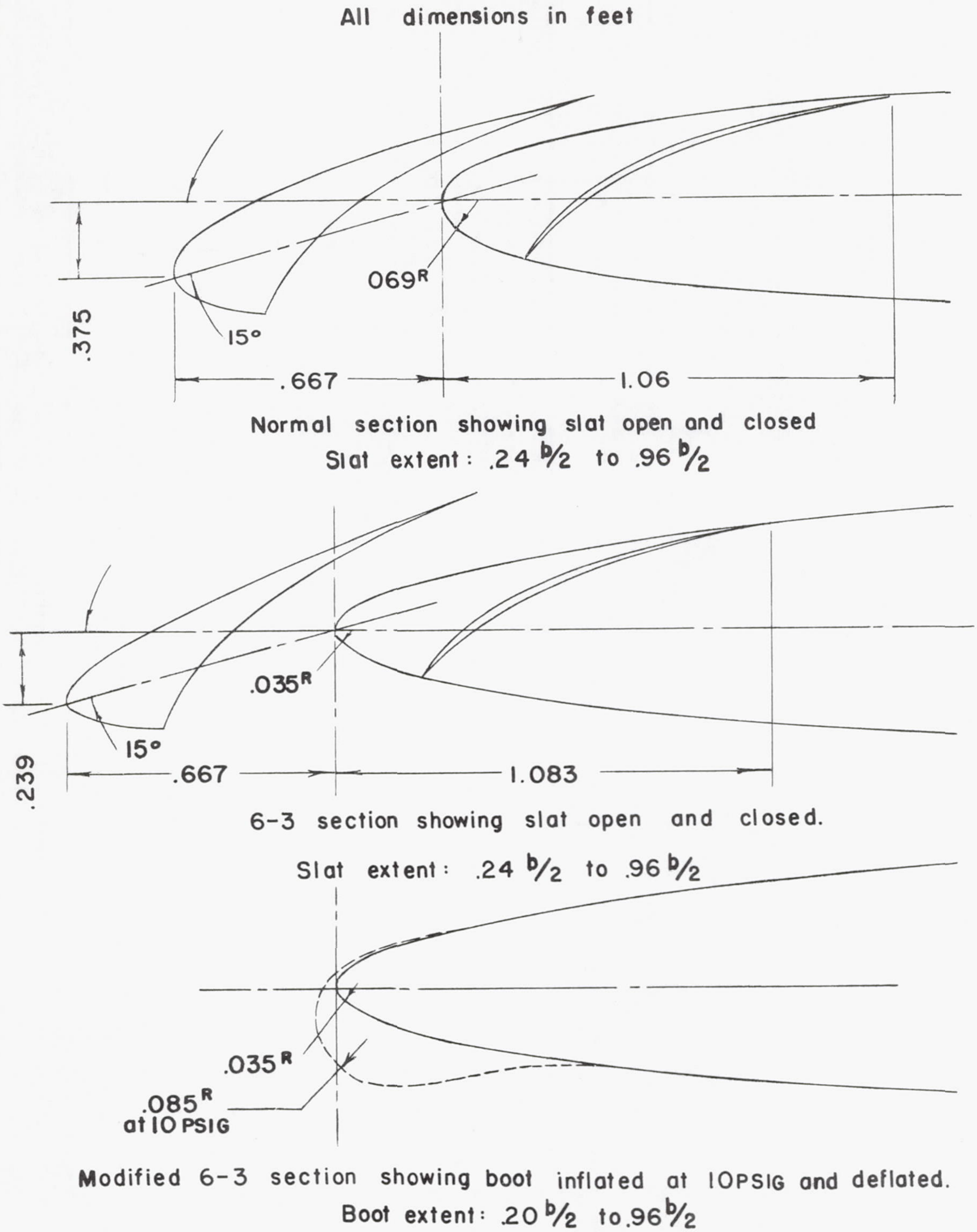
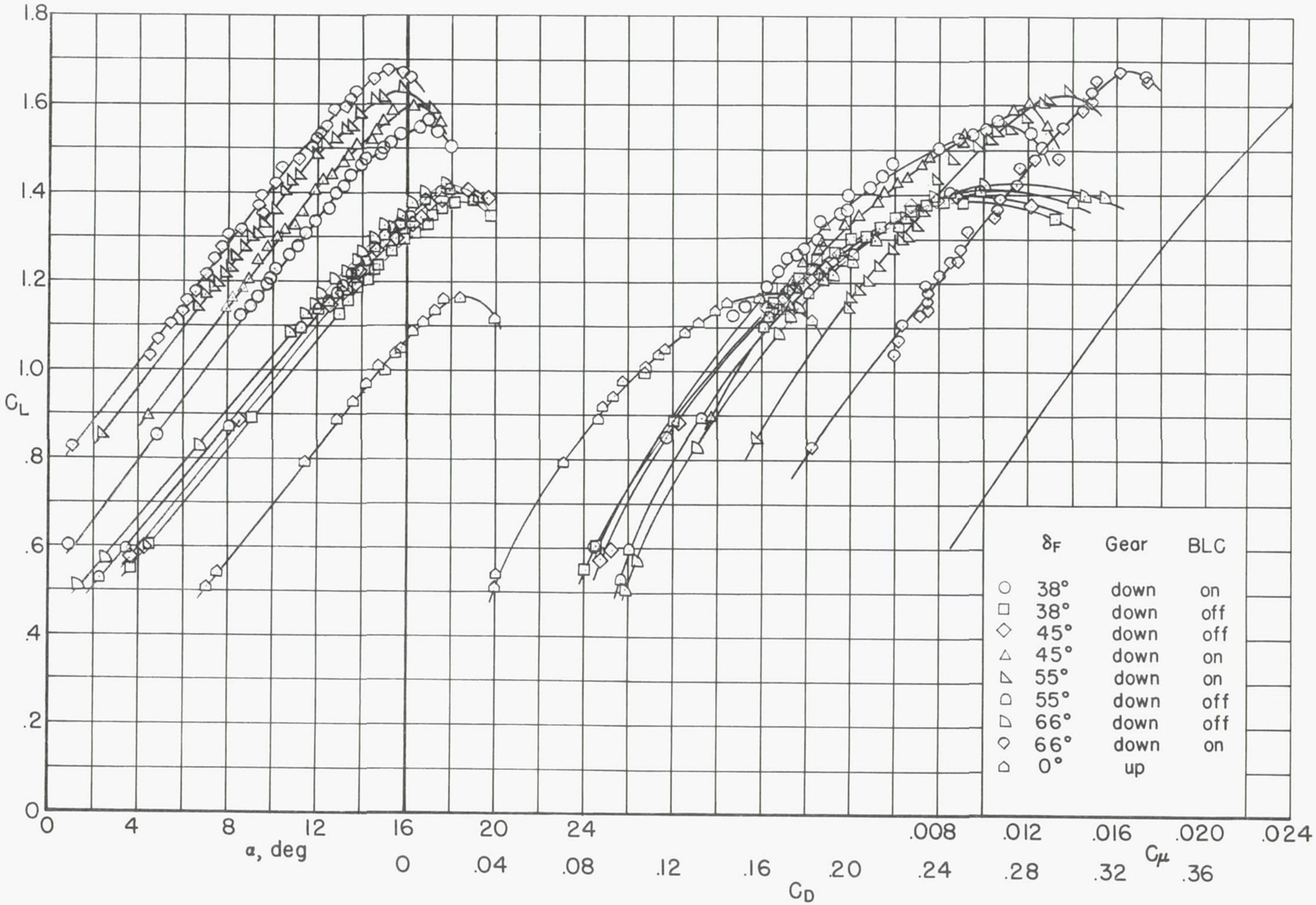
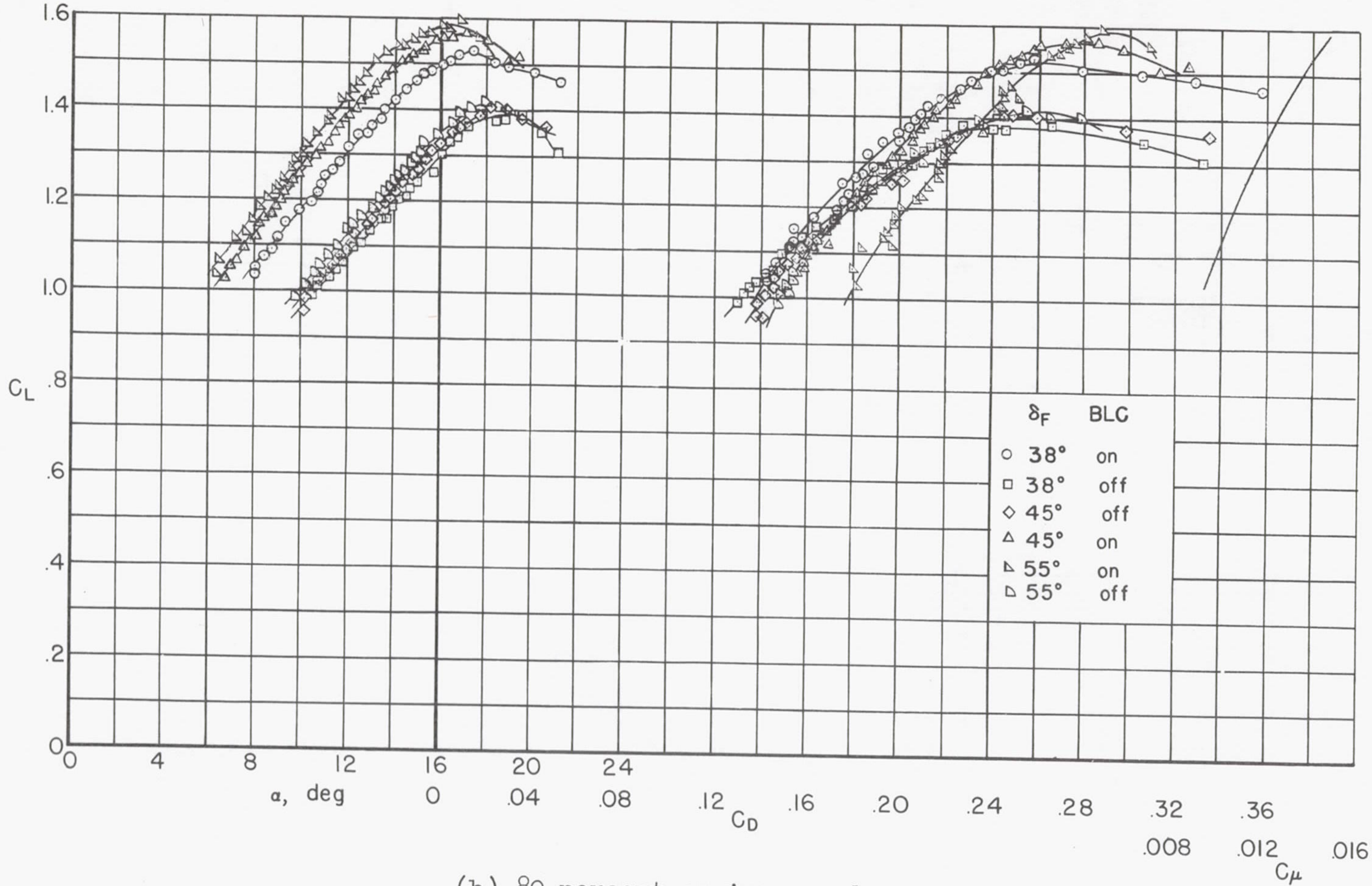


Figure 9.- Cross sections of various devices normal to the wing leading edge; wing station 0.857 b/2.



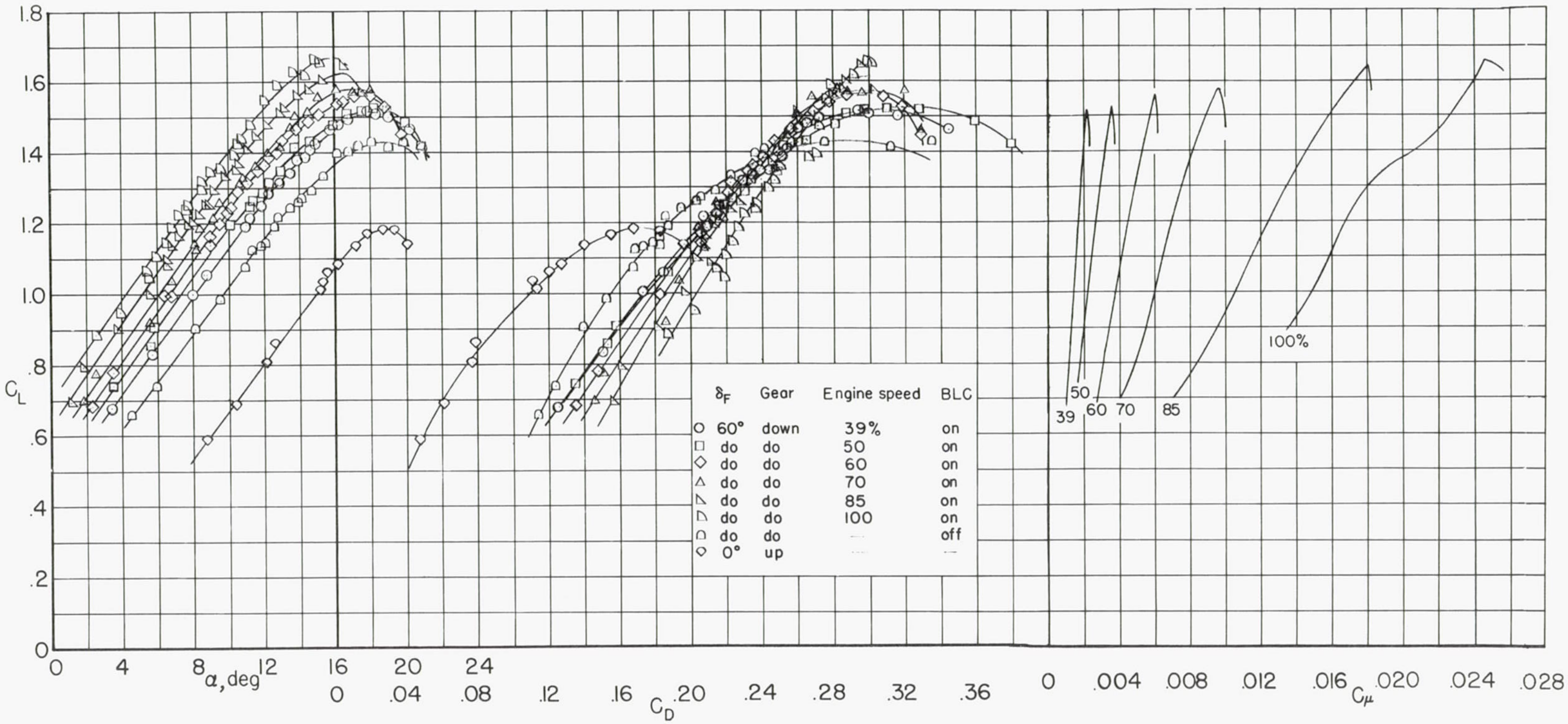
(a) 100-percent engine speed.

Figure 10.- Lift, drag, and momentum-coefficient curves for various flap deflections; 6-3 slatted leading edge.



(b) 80-percent engine speed.

Figure 10.- Continued.



(c) $\delta_f = 60^\circ$; various rpm.

Figure 10.- Concluded.

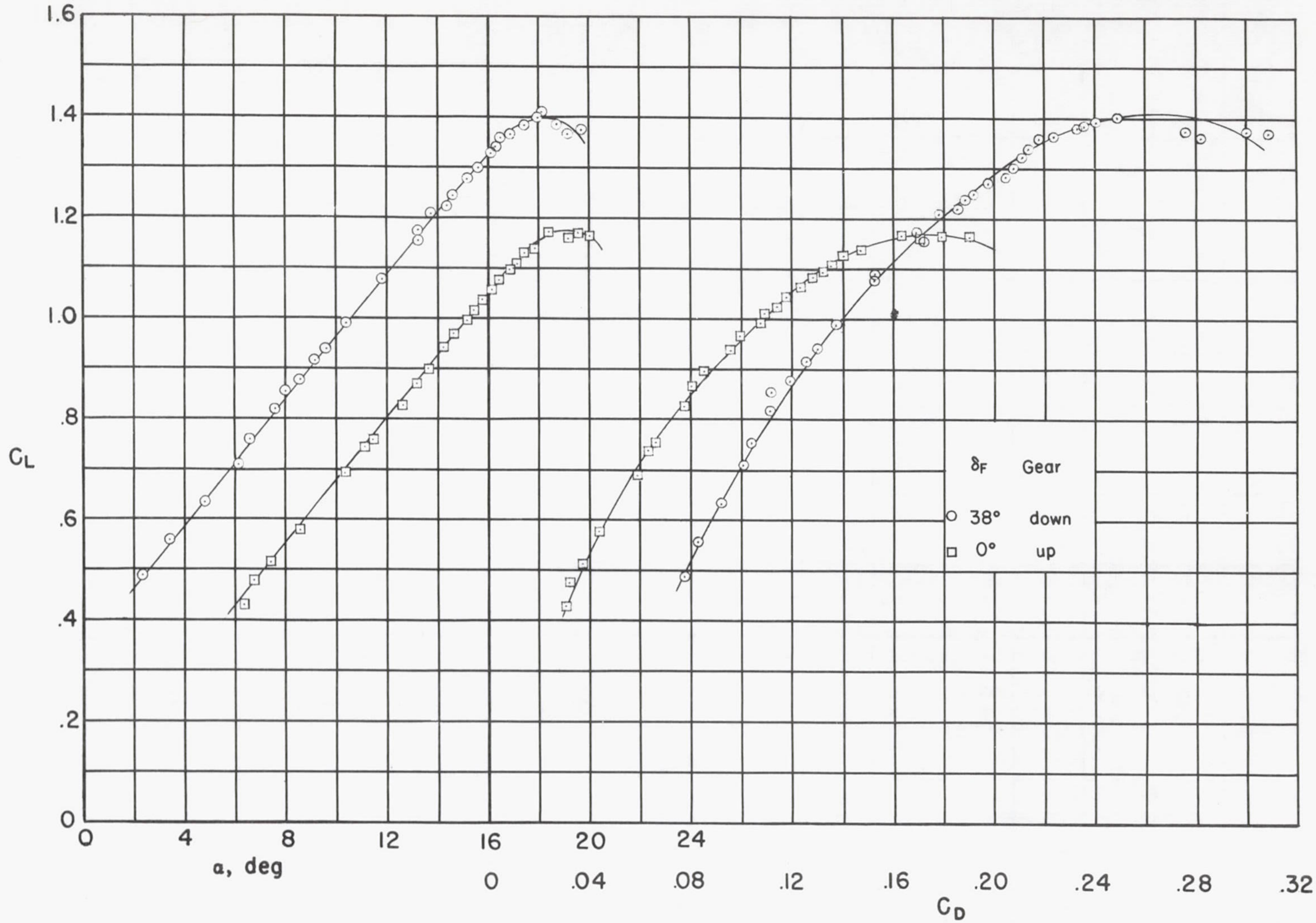


Figure 11.- Lift and drag curves for slotted flap; 6-3 slatted leading edge.

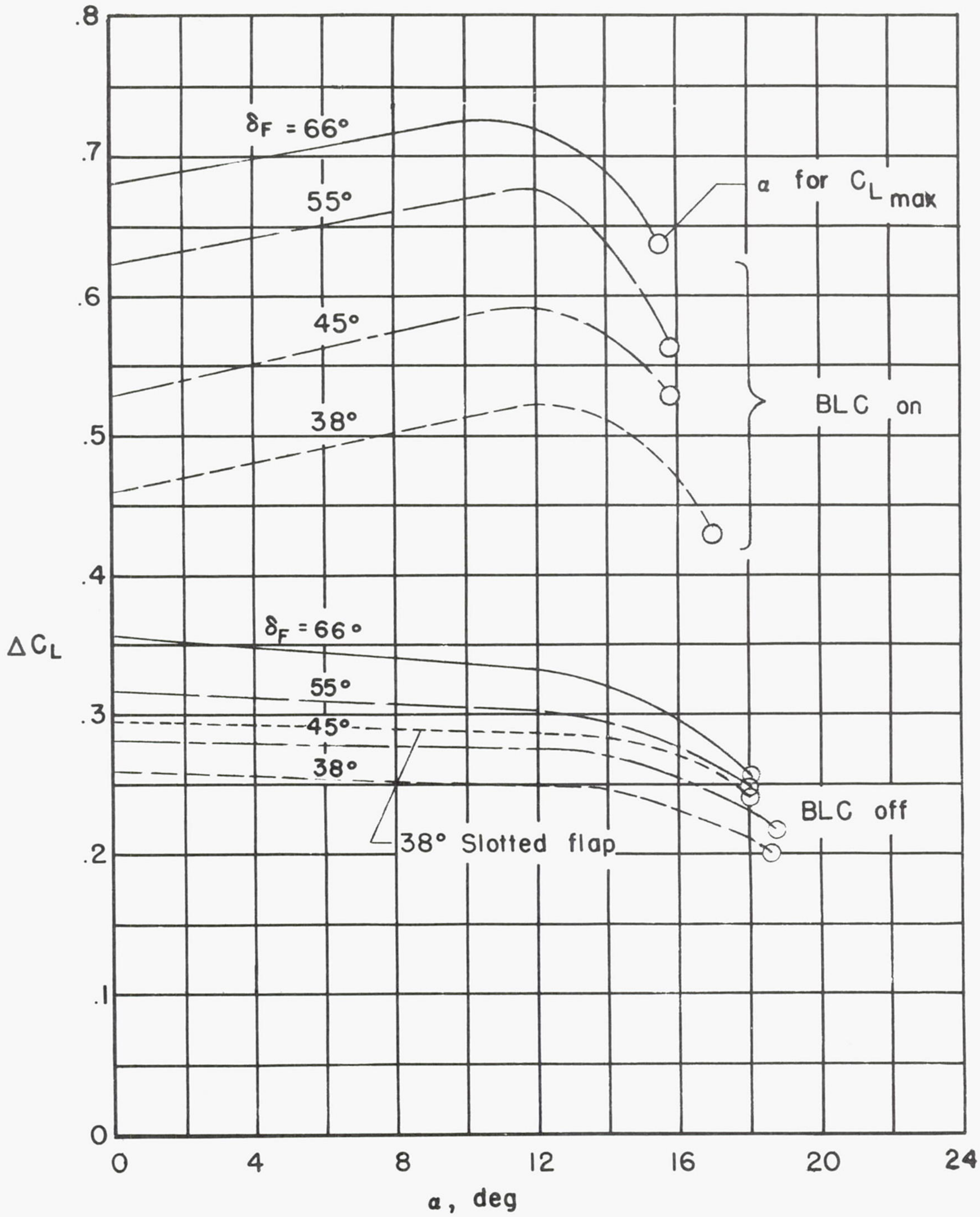
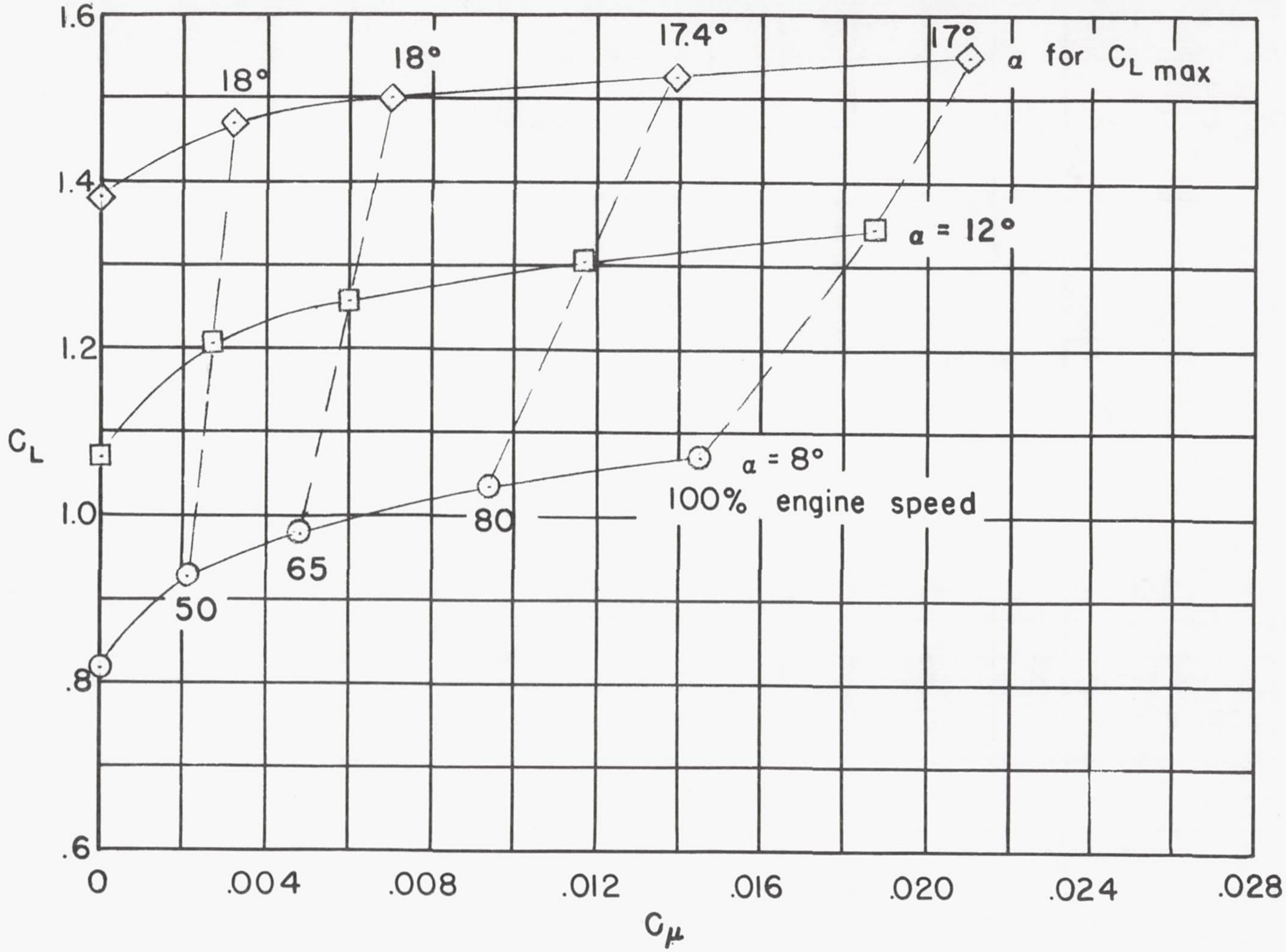
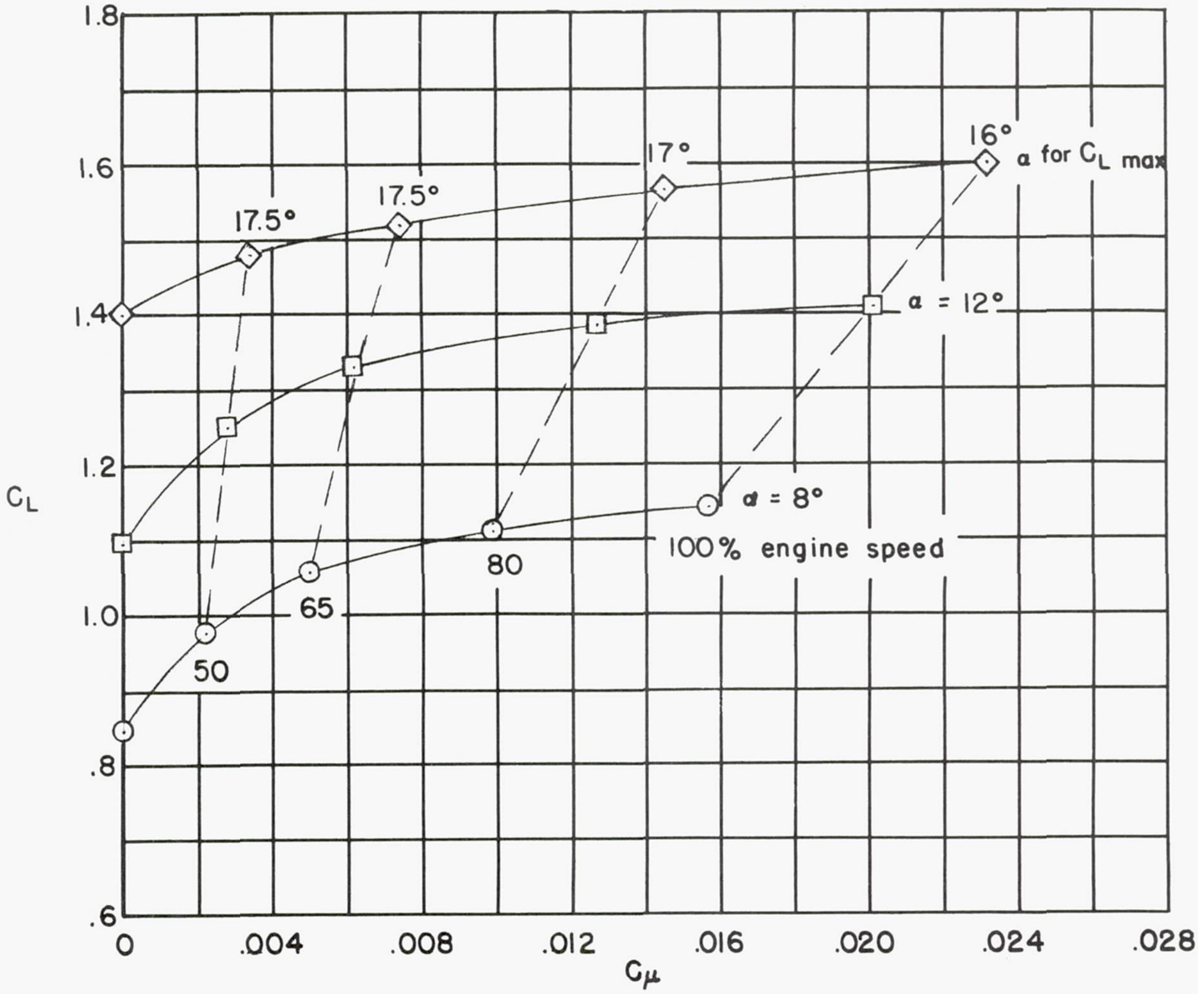


Figure 12.- Variation of flap lift increment with angle of attack for various flap deflections; 100-percent engine rpm, 6-3 slatted leading edge.



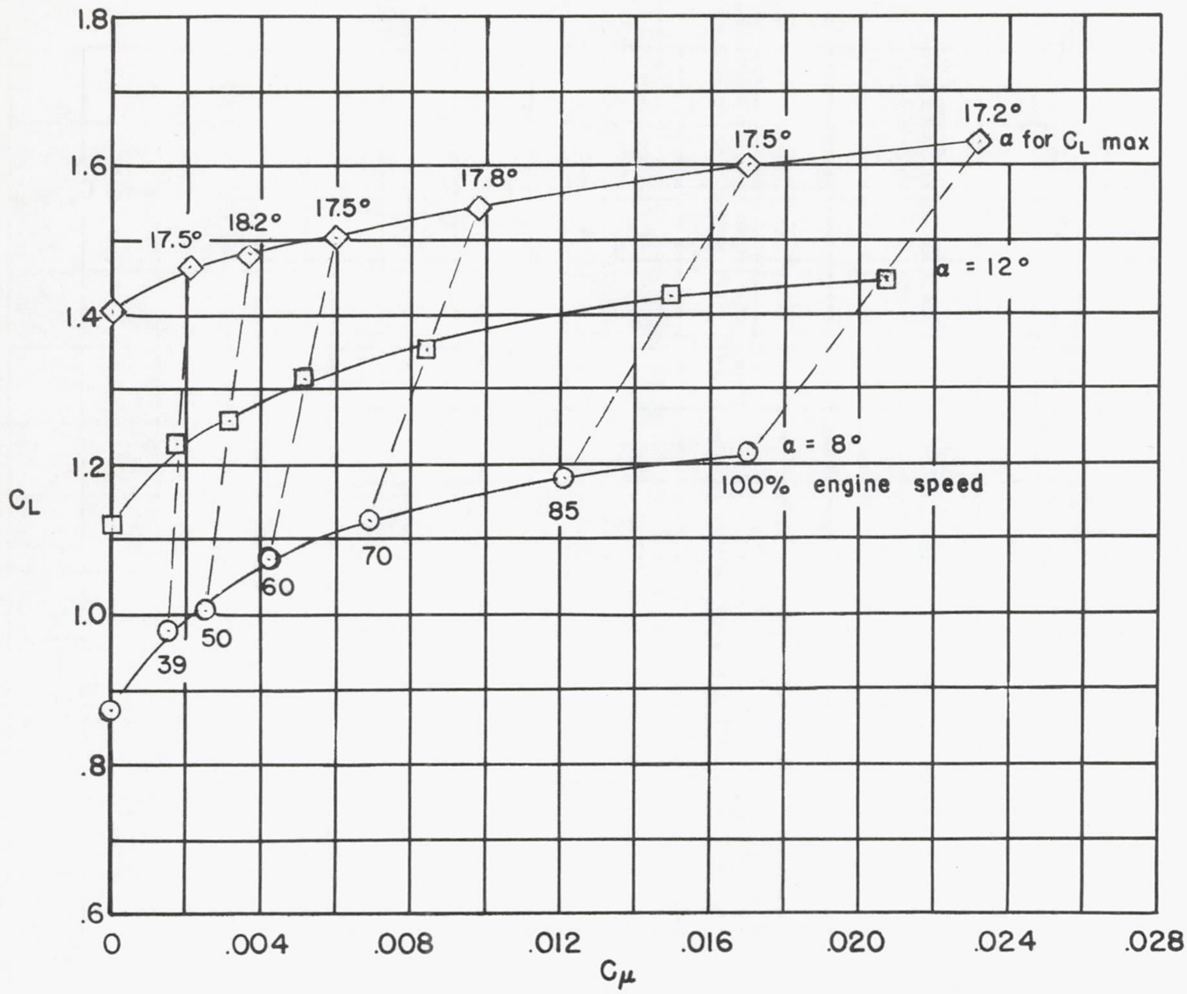
(a) $\delta_f = 38^{\circ}$

Figure 13.- Variation of C_L with C_μ; 6-3 slatted leading edge.



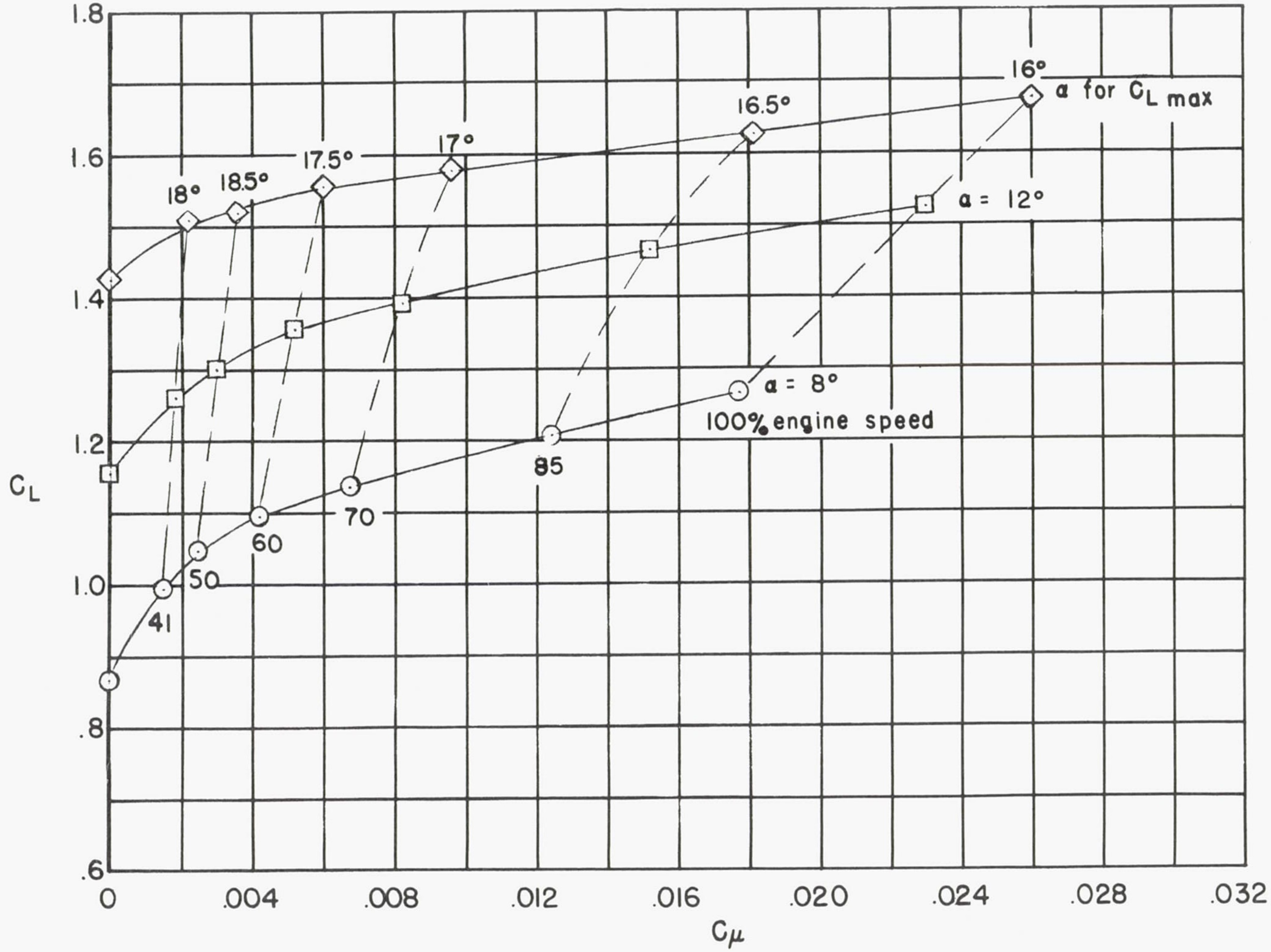
(b) $\delta_f = 45^\circ$

Figure 13.- Continued.



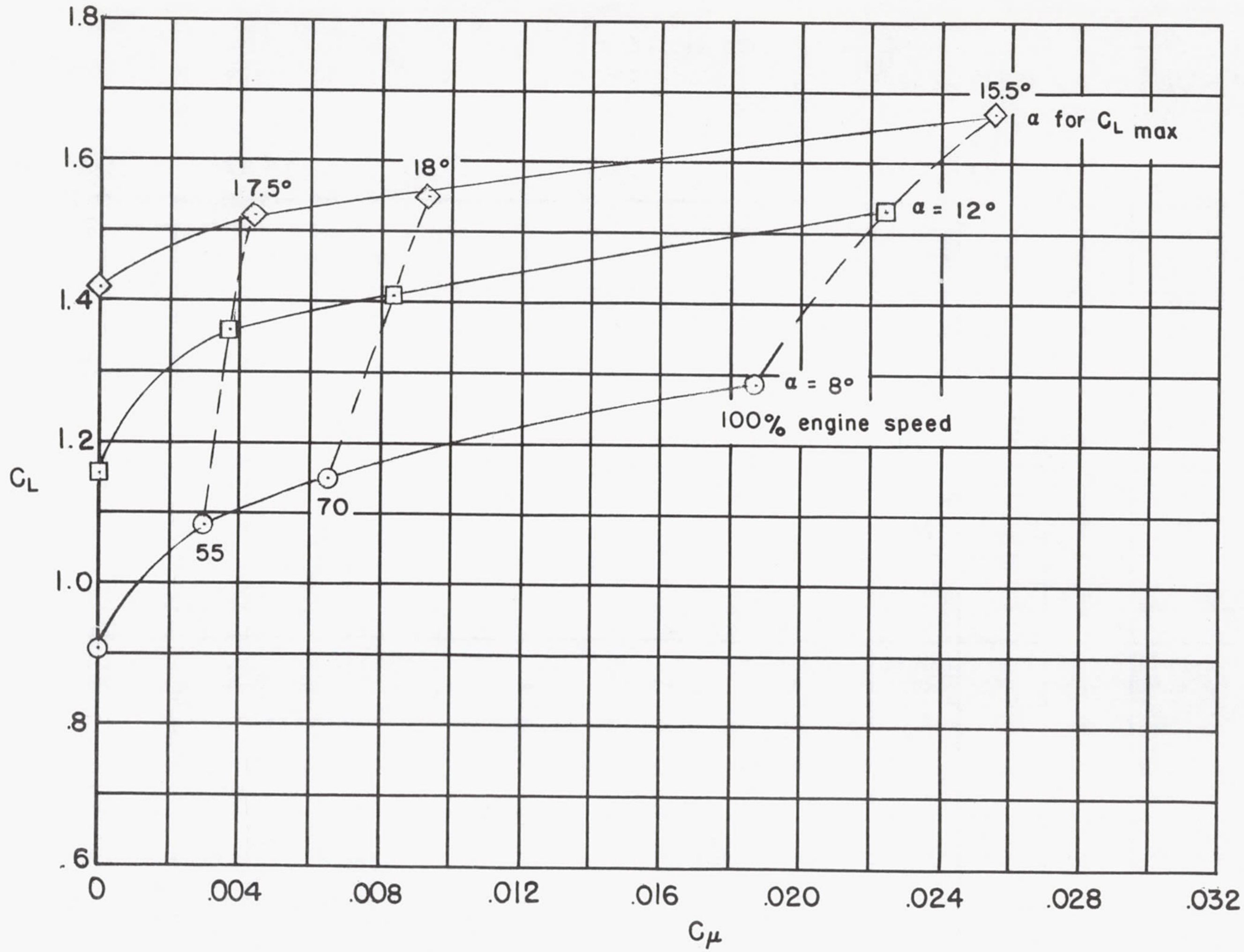
(c) $\delta_f = 55^{\circ}$

Figure 13.- Continued.



(d) $\delta_f = 60^\circ$

Figure 13.- Continued.



(e) $\delta_f = 66^{\circ}$

Figure 13.- Concluded.

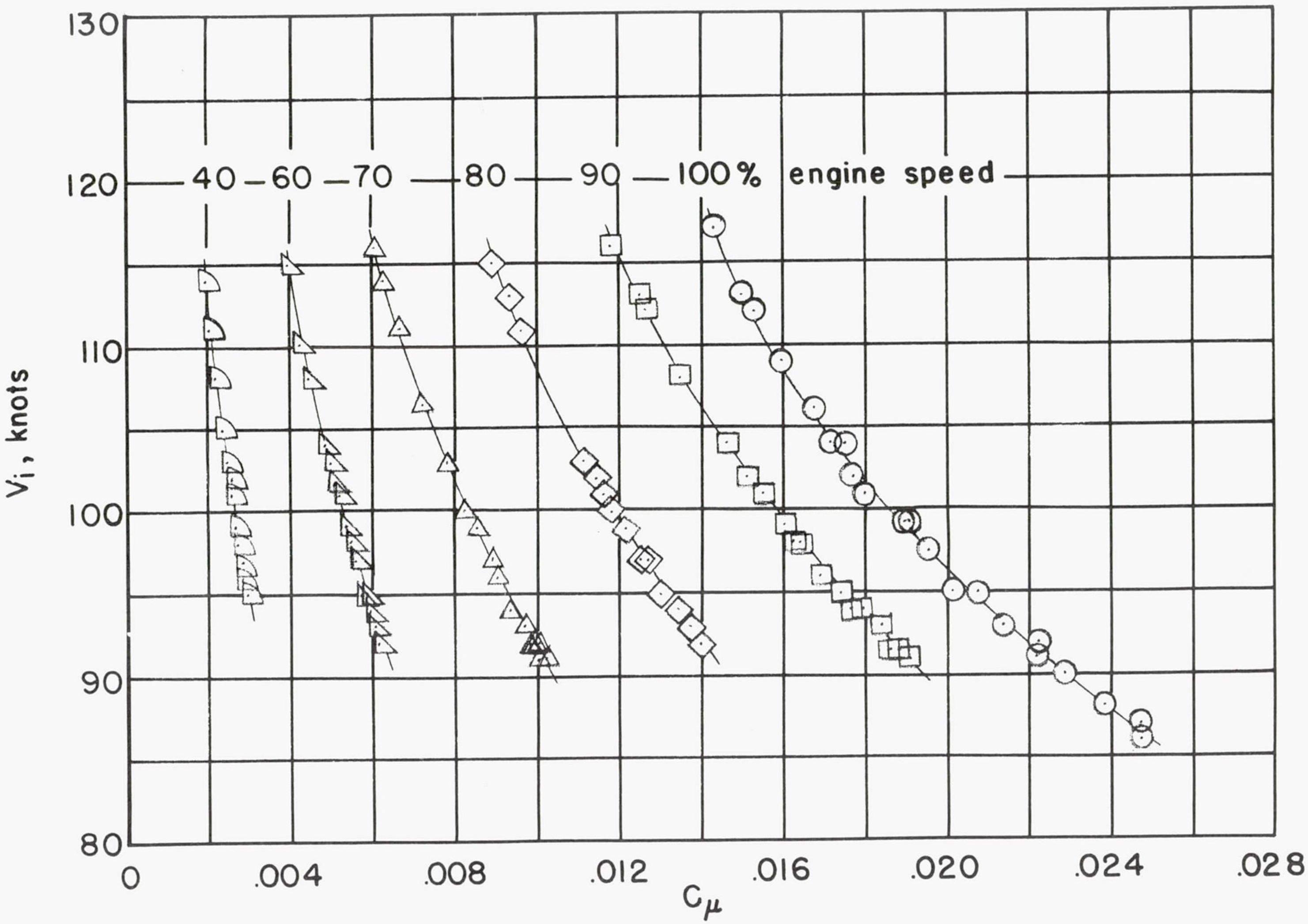


Figure 14. - Variation of C_μ with indicated airspeed for various engine speeds; gear down, flaps 60°.

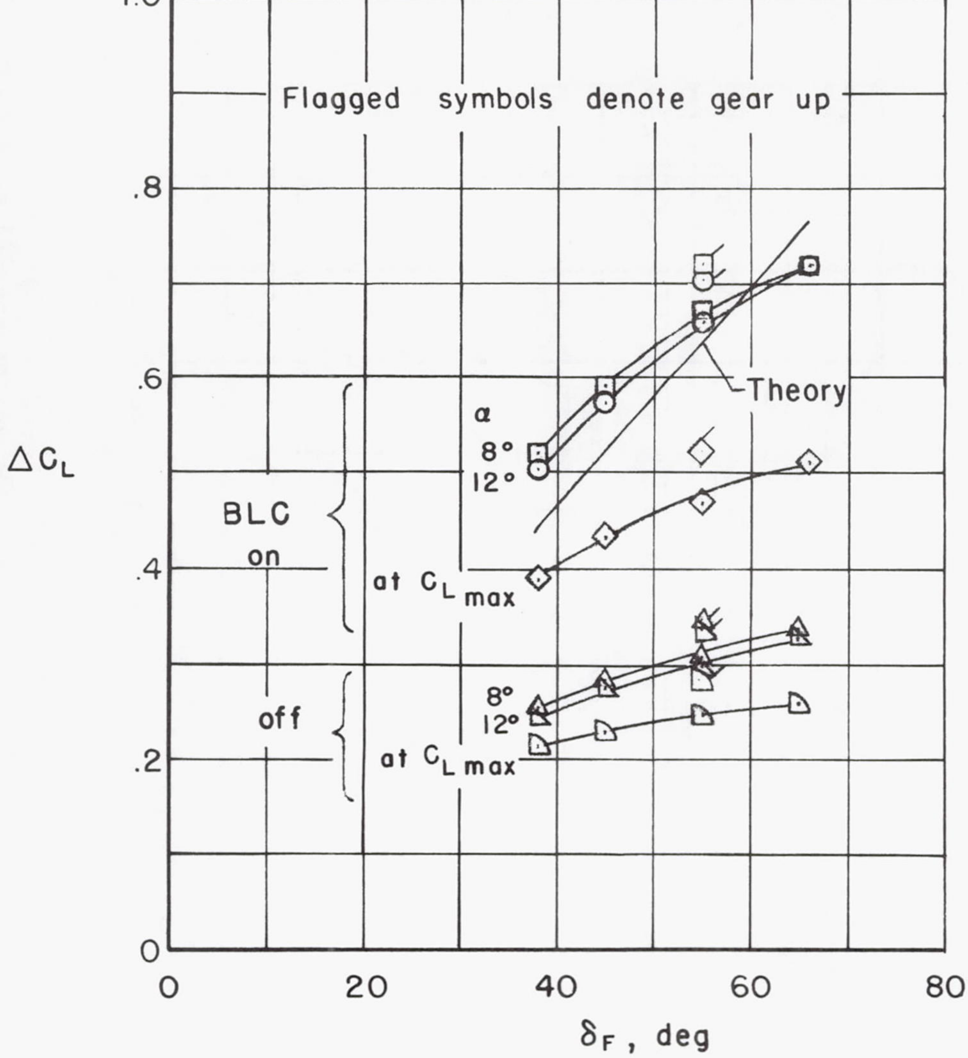
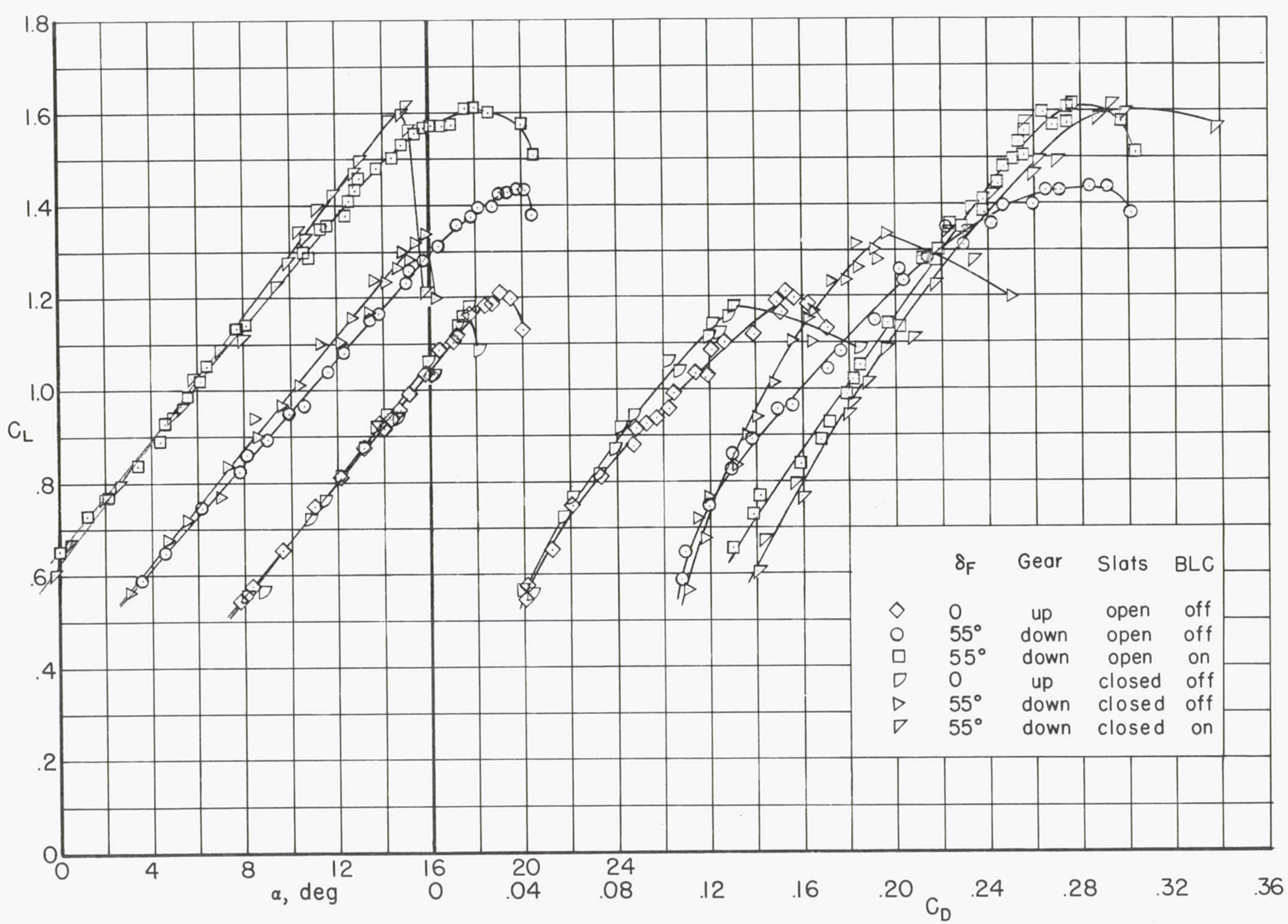
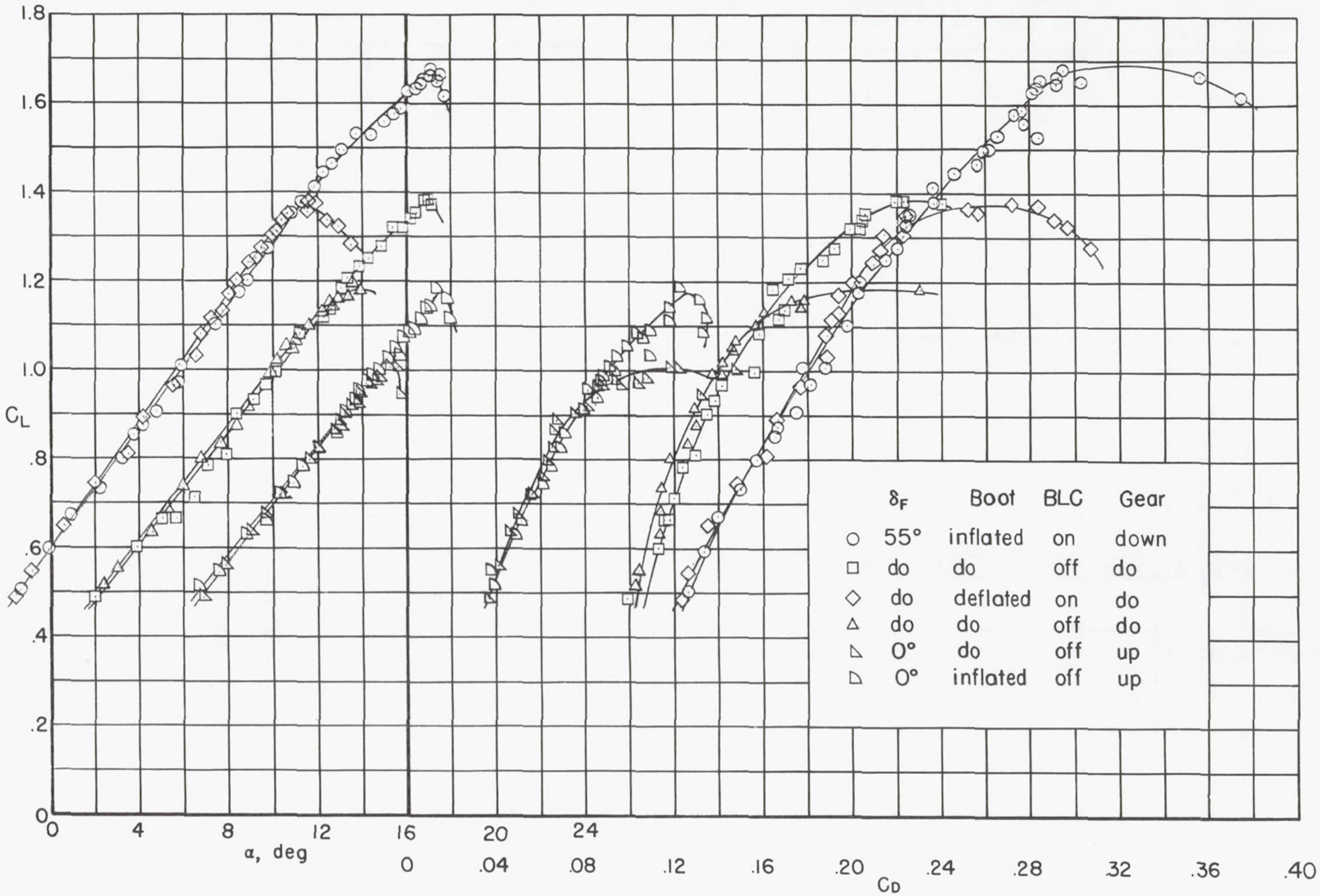


Figure 15.- Variation of flap lift increment with flap deflection for various angles of attack; 100-percent engine speed.



(a) F-86D-type slats; open and closed.

Figure 16.- Lift and drag curves for various leading-edge devices; 80-percent engine speed.



(b) Inflatable leading edge.

Figure 16.- Concluded.

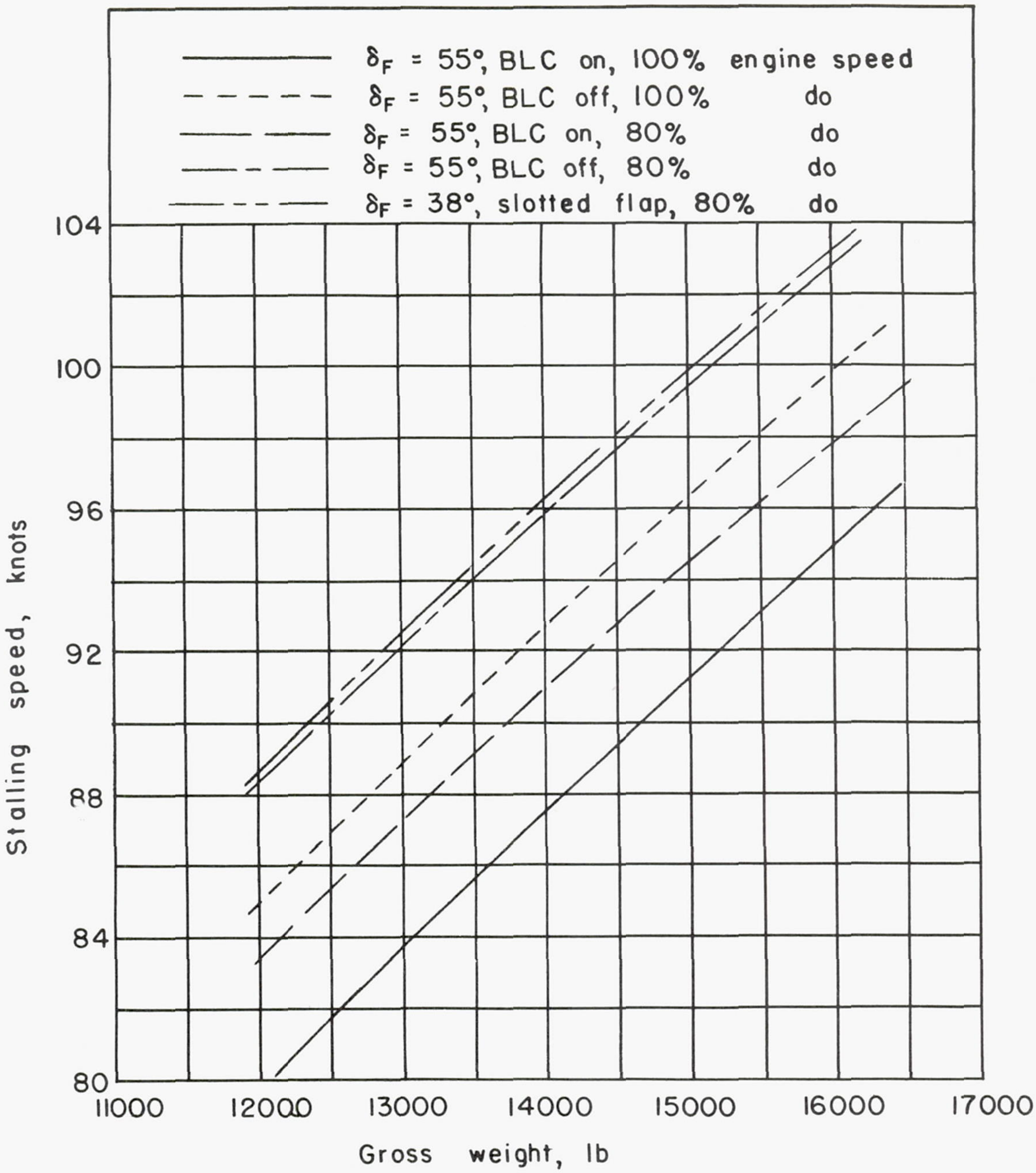


Figure 17.- Variation of stalling speed with gross weight for various flap deflections and engine speeds; sea level, 6-3 slatted leading edge.

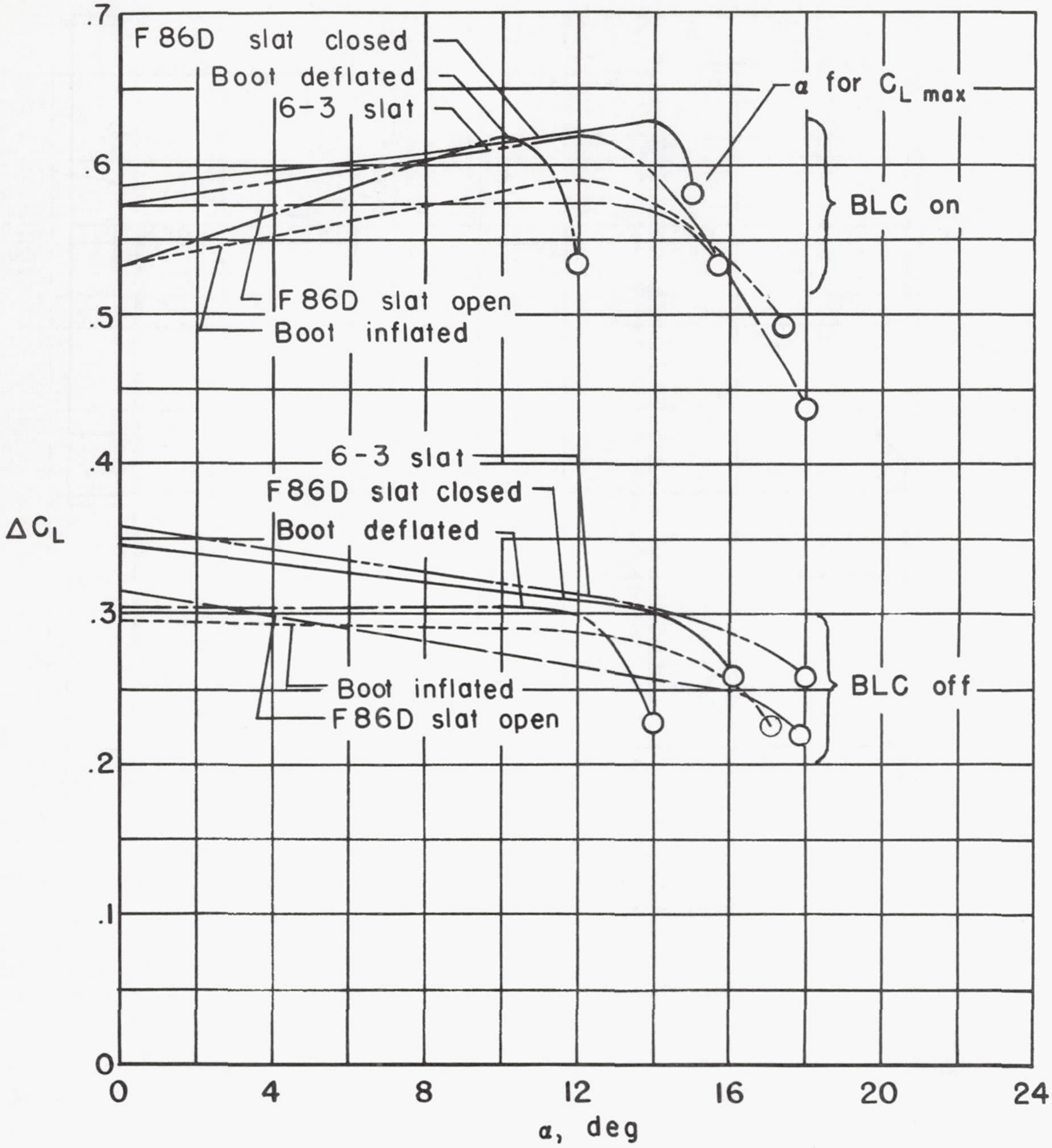


Figure 18.- Variation of flap lift increment with angle of attack for various leading-edge devices; $\delta_f = 55^\circ$, 80-percent engine speed.

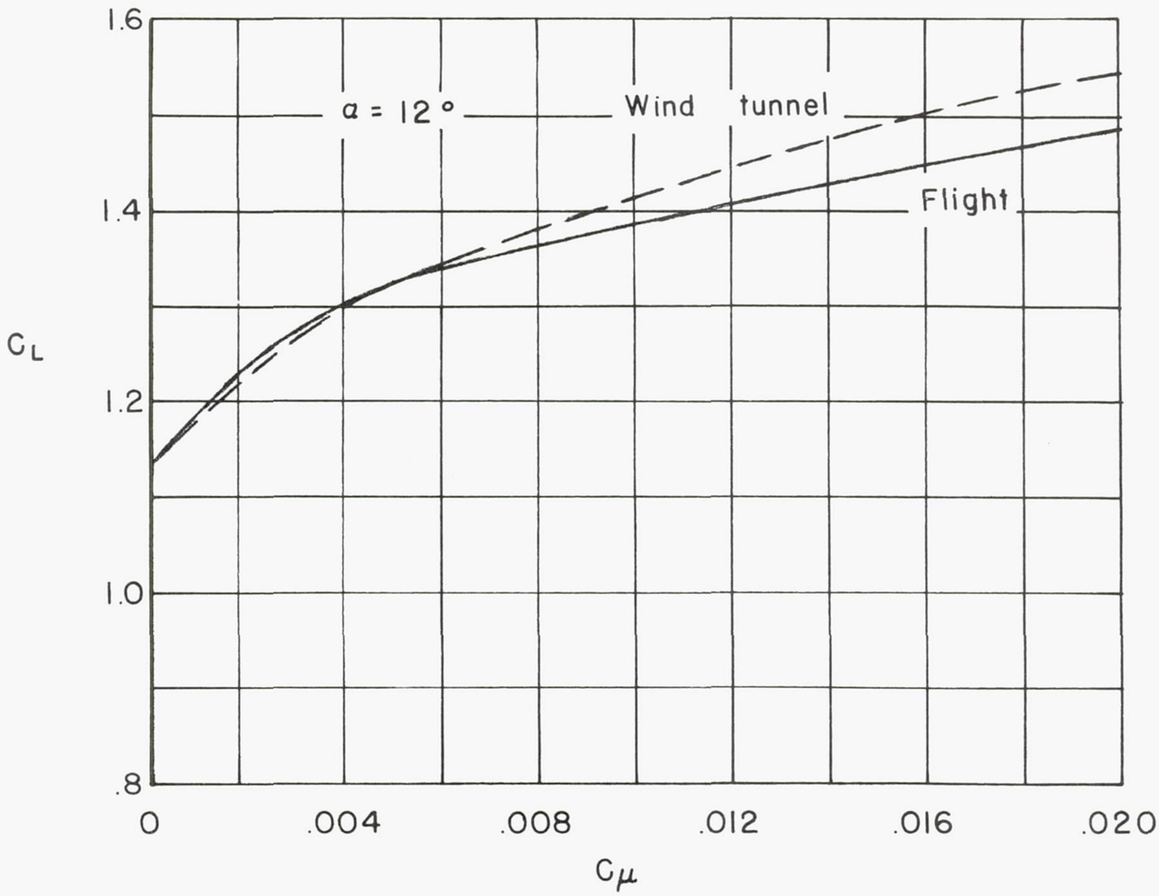


Figure 19.- Variation of C_L with C_μ for wind tunnel and flights; F-86D slatted leading edge, $\delta_f = 60^\circ$, gear up.

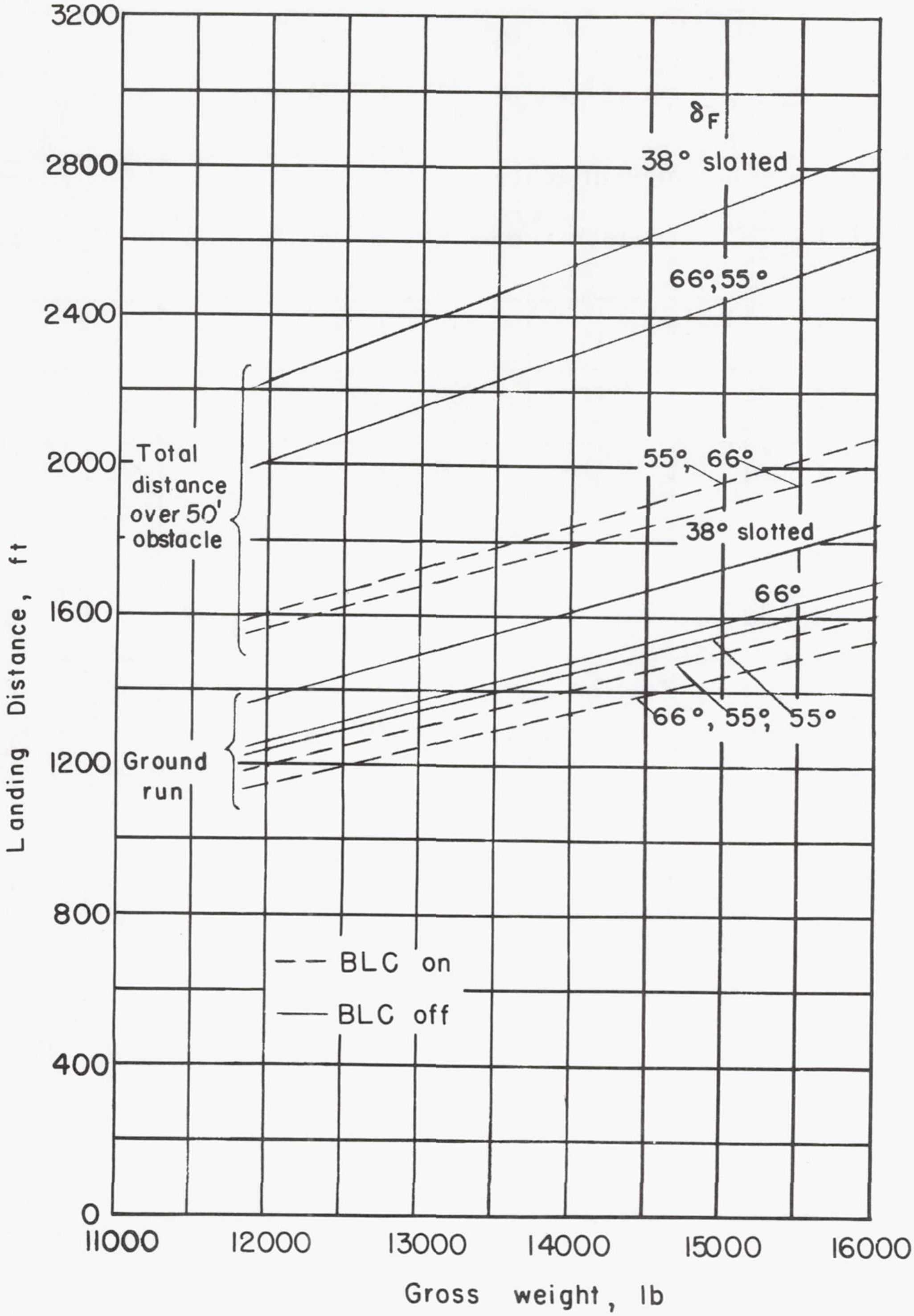


Figure 20.- Variation of landing distance with gross weight for various flap deflections; 6-3 leading edge, sea level.

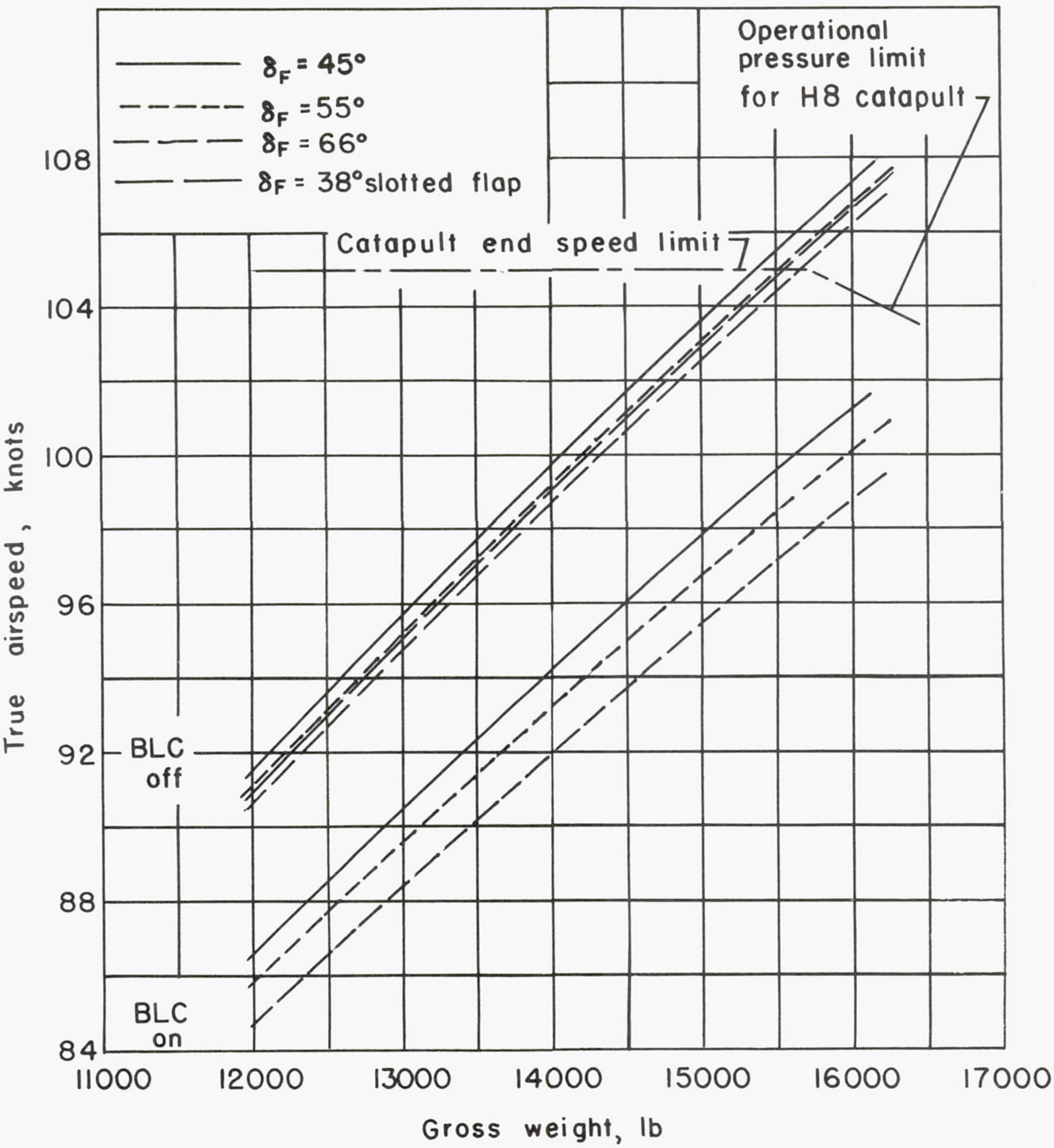


Figure 21.- Variation of catapult take-off velocity with gross weight for various flap deflections with blowing on and off; 6-3 slatted leading edge, sea level.

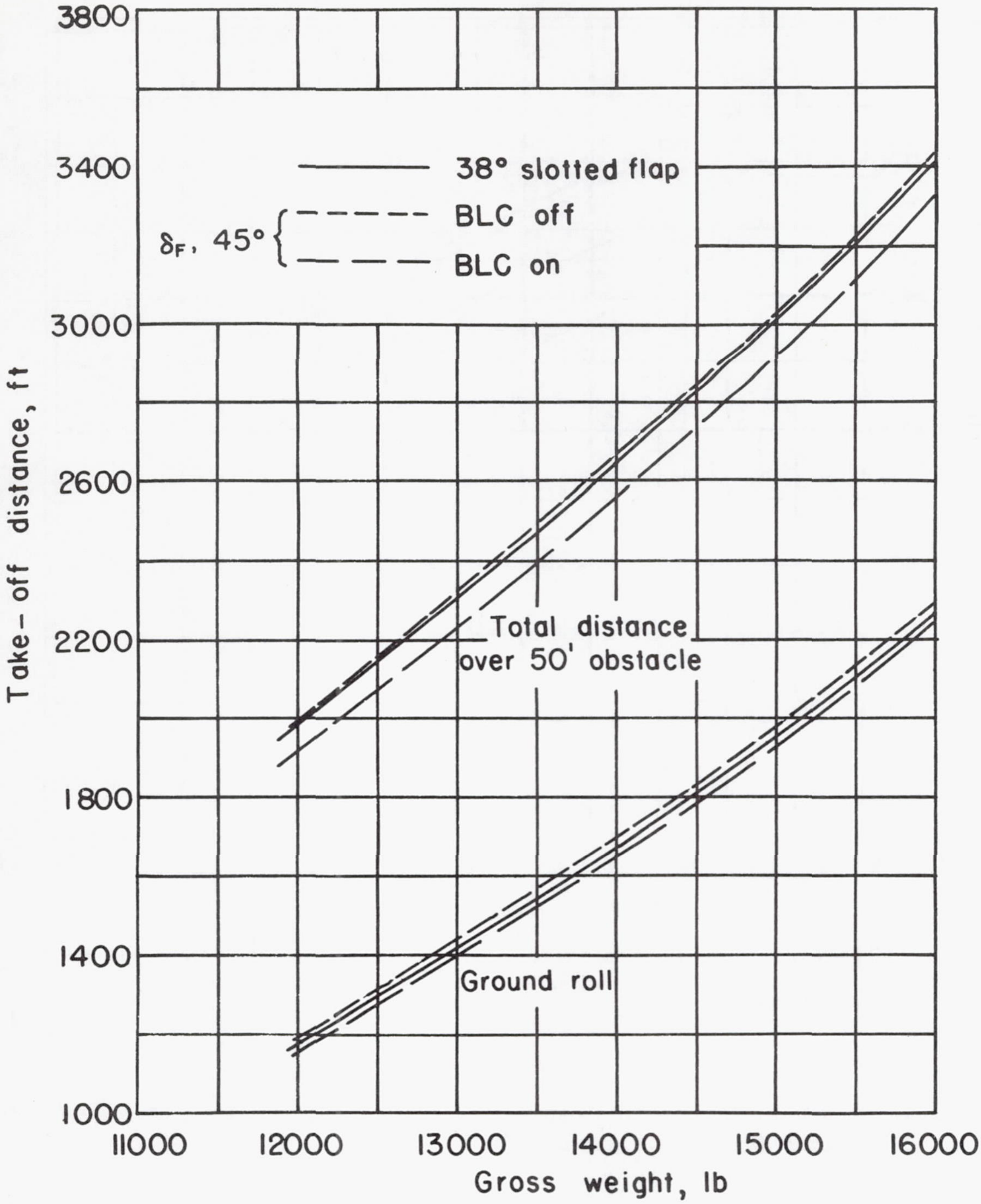


Figure 22.- Variation of take-off distance with gross weight for various flap deflections; blowing on and off, 6-3 slatted leading edge, sea level.

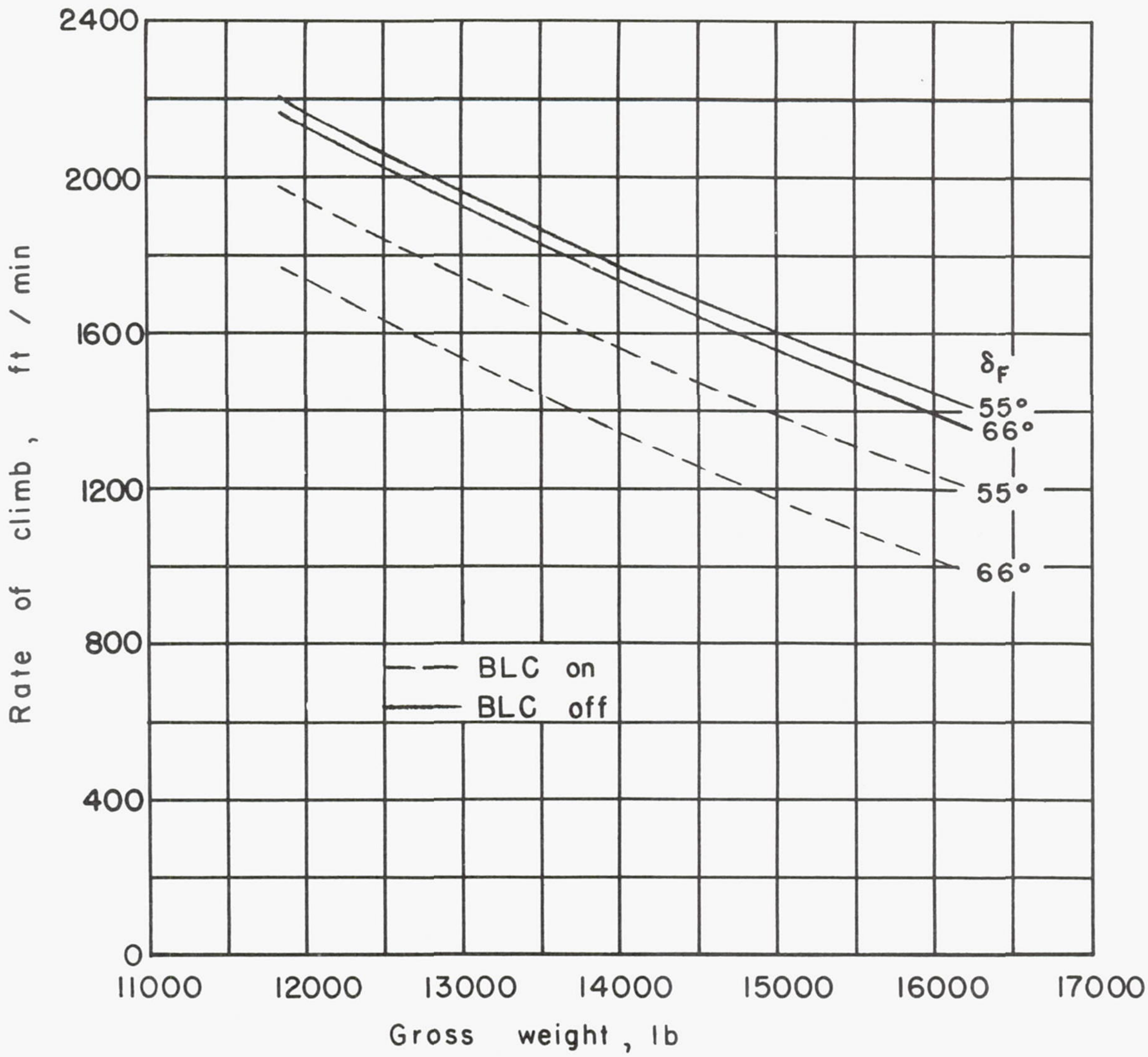


Figure 23.- Variation of rate of climb with gross weight for various flap deflections with blowing on and off; wave-off speed = 1.05 V_s, 6-3 leading edge, sea level.

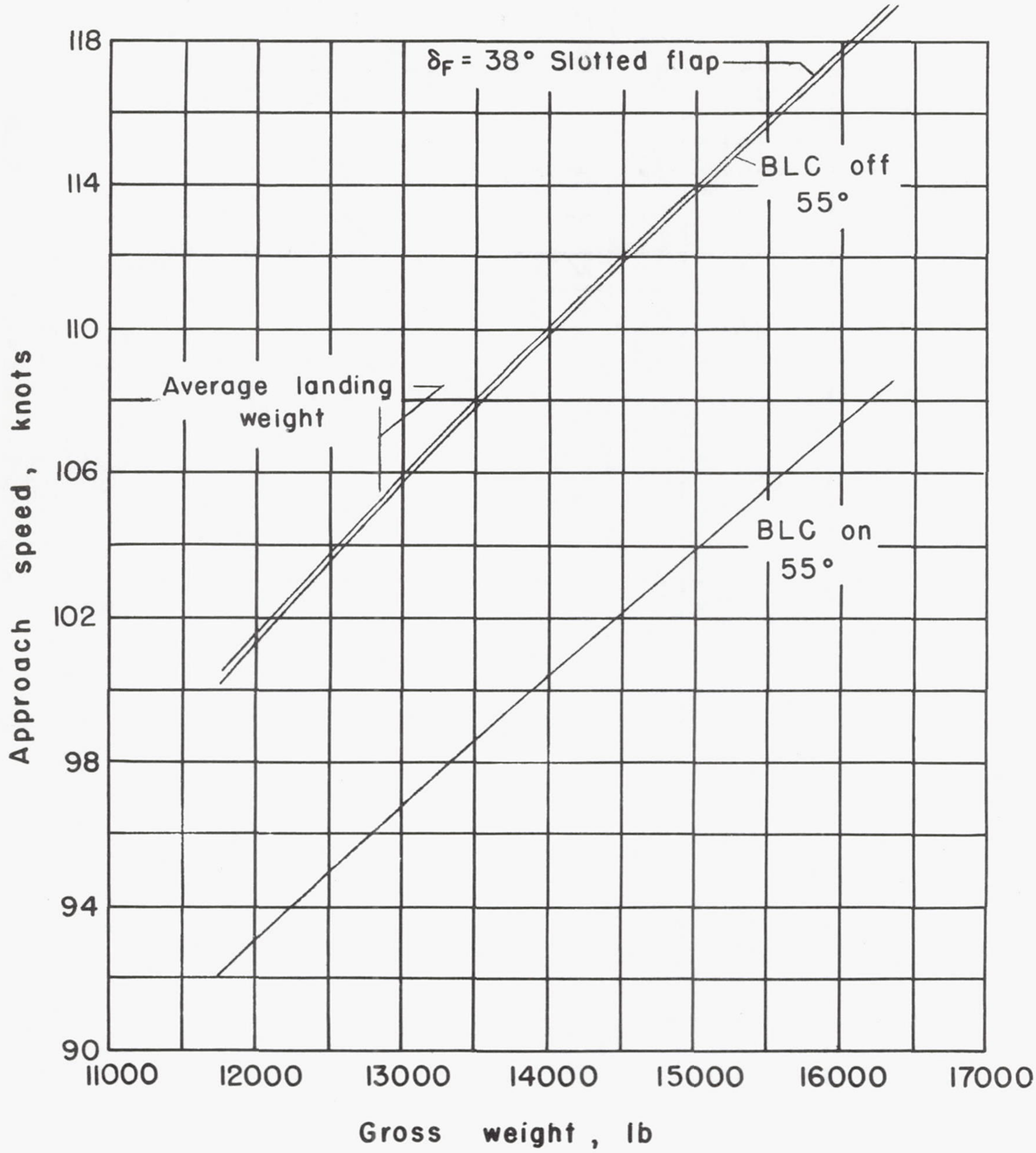


Figure 24.- Variation of approach speed with gross weight for various flap deflections; 6-3 slatted leading edge.

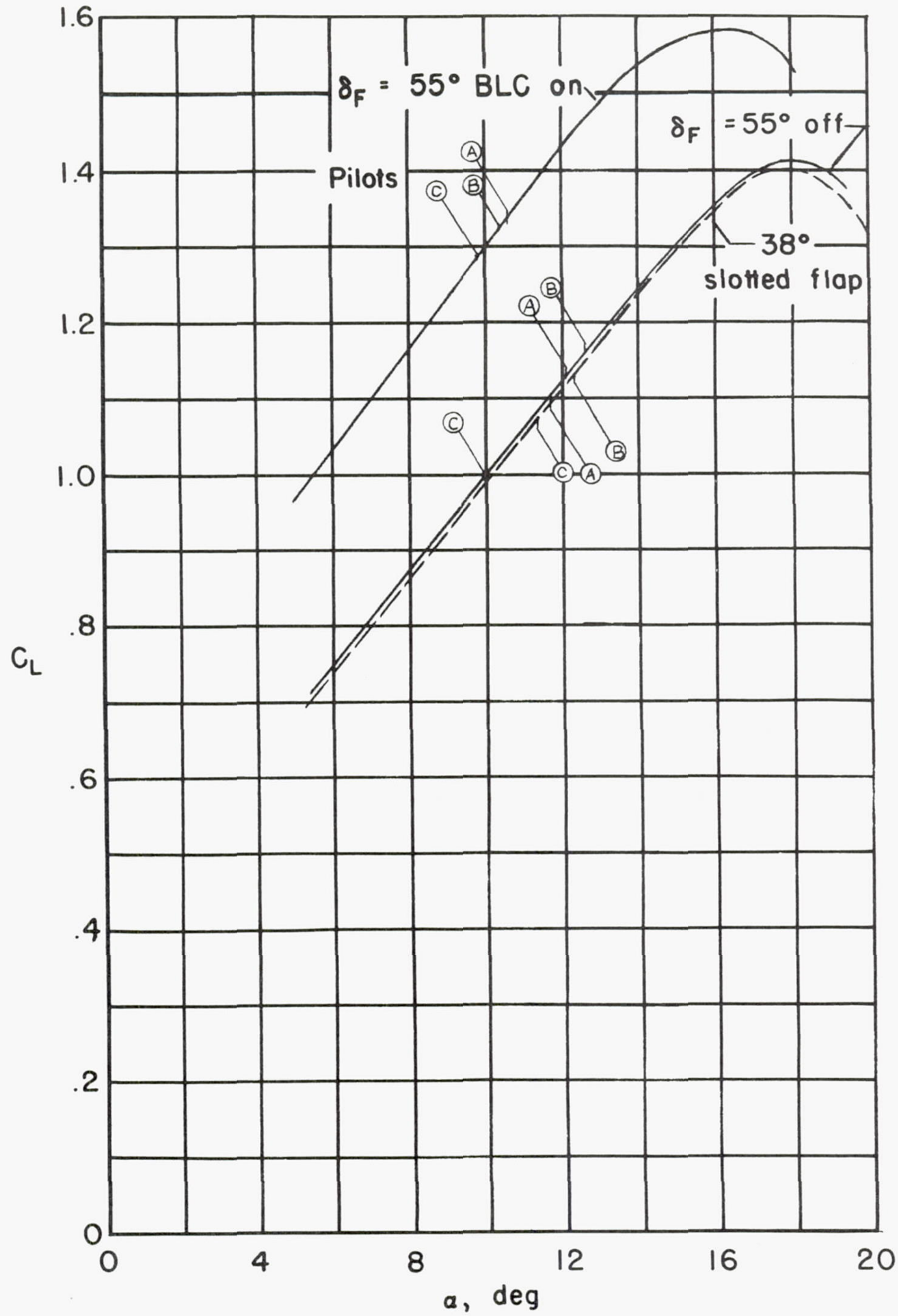


Figure 25.- Relationship of pilots' selected approach speeds to lift curves for various flap deflections; 6-3 slatted leading edge, 80-percent engine speed, W/S = 42.5.

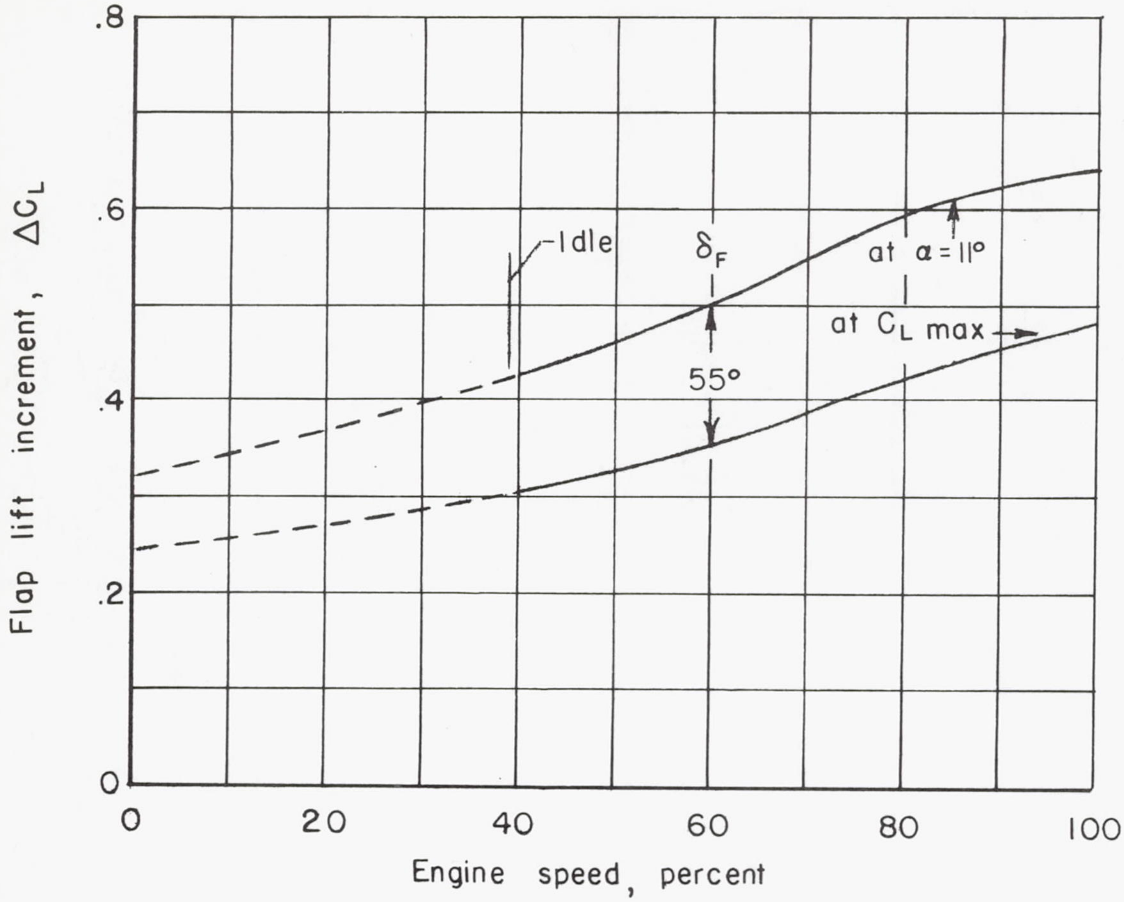


Figure 26.- Variation of flap lift increment with engine speed; 6-3 slatted leading edge.

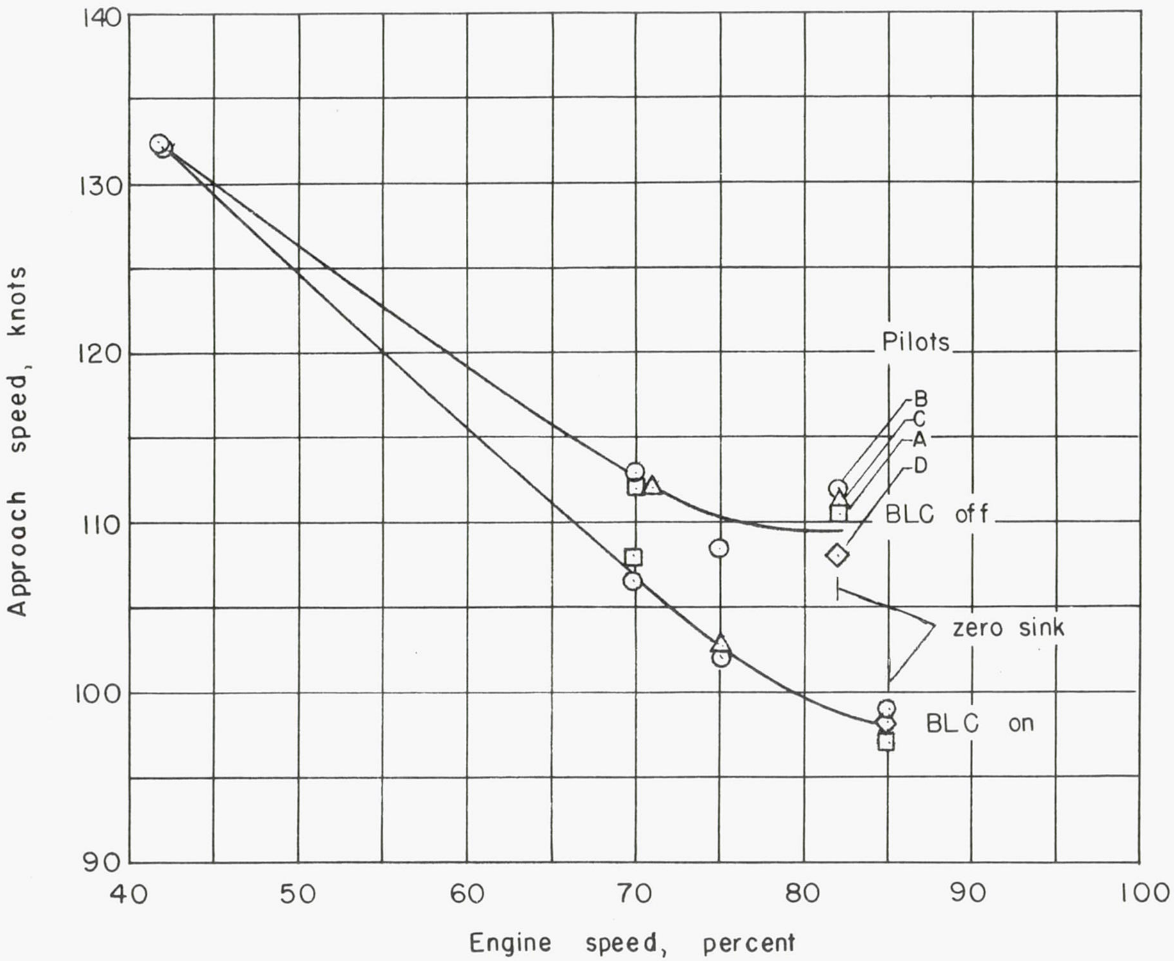


Figure 27.- Effect of engine speed on approach speed; blowing off and on, $\delta_f = 55^{\circ}$, 6-3 slatted leading edge, sinking-type approach.