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THRUST AND WING LOADING REQUIREMENTS FOR SHORT HAUL AIRCRAFT CONSTRAINED BY ENGINE NOISE AND FIELD LENGTH

Jeffrey V. Bowles, Mark H. Waters, and Thomas L. Galloway

Ames Research Center
Moffett Field, Calif. 94035

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16. Abstract

Propulsion system and wing loading requirements are determined for a mechanical flap and an externally blown flap aircraft for various engine noise levels and two engine cycles. Both aircraft are sized to operate from a 914 m (3000 ft) runway and perform the same mission. For each aircraft concept, propulsion system sizing is demonstrated for two different engine cycles — one having a fan pressure ratio of 1.5 and a bypass ratio of 9, and the other having a fan pressure ratio of 1.25 and a bypass ratio of 17.8. The results presented include the required thrust-to-weight ratio, wing loading, resulting gross weight, and direct operating costs, as functions of the engine noise level, for each combination of engine cycle and aircraft concept.

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SYMBOLS

Physical quantities are given in this report in the International System of units; English unit equivalents are shown parenthetically. All calculations were made in English units.

A	area, m^2 (ft^2)
AEO	all engines operating
a	acceleration along flight path, m/sec^2 (ft/sec^2)
$askmi$	available seat kilometer
asm	available seat statute mile
CEI	critical engine inoperative
DOC	direct operating cost, ¢/$askm$ (¢/asmi)
d	distance, m (ft)
EAS	equivalent air speed, m/sec (knots)
g	acceleration due to gravity, m/sec^2 (ft/sec^2)
h	absolute altitude, m (ft)
M	Mach number
P	total pressure, N/m^2 (lb/ft^2)
PNL	perceived noise level, PNdB
p	static pressure, N/m^2 (lb/ft^2)
q	dynamic pressure, N/m^2 (lb/ft^2)
roc	rate of climb, m/sec (ft/min)
T	thrust, N (lb)
T/W	thrust-to-weight ratio
V	velocity, m/sec (knots)
V_{APP}	landing approach speed, m/sec (knots)

V_{MIN}	minimum flight speed, m/sec (knots)
V_R	rotation speed, m/sec (knots)
V_{STALL}	1-g stall speed, m/sec (knots)
V_1	critical decision speed, m/sec (knots)
V_2	speed at barrier height, m/sec (knots)
W/S	wing loading, kg/m^2 (lb/ft^2)
α	angle of attack, deg
γ	flight path angle, deg; ratio of specific heats
Δn	incremental load factor
δ	engine face stagnation pressure/standard sea level static pressure
δ_f	flap deflection angle, deg
θ	engine face stagnation temperature/standard sea level static temperature
θ_f	fuselage attitude angle, deg

Subscripts:

amb	ambient
f	flap, fuselage
G	gross
N	net
n	nozzle
t	nozzle throat

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SUMMARY

An analytical study was performed to determine the impact of various levels of engine noise suppression treatment on the wing loading and propulsion system requirements of a mechanical flap and an externally blown flap aircraft. For each aircraft concept, propulsion system sizing is demonstrated for two different engine cycles – one having a fan pressure ratio of 1.5 and a bypass ratio of 9, and the other having a fan pressure ratio of 1.25 and a bypass ratio of 17.8.

Factors affecting the final design point wing and thrust loading requirements included the field length constraint of 914 m (3000 ft), various takeoff and landing operational constraints and ground rules, second segment and go-around climb gradient requirements, and engine noise level. Additional consideration was also given to optimum flap setting and rotation speed selection.

The results indicate that as the engine noise level is reduced, there is an increase in the required aircraft thrust-to-weight ratio. However, the wing loading is approximately independent of the engine noise level for both the mechanical flap and externally blown flap aircraft. The takeoff and landing flare time histories, and the takeoff and landing operational envelopes of selected combinations of lift concept, engine cycle, and engine noise level are presented.

In addition, the design point gross weight, direct operating cost, and cruise performance for both aircraft and engine cycles were determined as functions of the engine noise level. It was found that, in general, as the required engine noise level was reduced, there was an increase in gross weight, thrust per engine, direct operating cost, and block fuel requirement.

INTRODUCTION

The purpose of this analysis was to determine the propulsion system and wing loading requirements for mechanical flap (MF) and under-the-wing externally blown flap (EBF) aircraft sized for a 914 m (3000 ft) field length. Included in the study was the impact of various levels of noise suppression treatment on the thrust-to-weight ratio and wing loading requirements, and the resulting gross weight and economic performance of each aircraft. In addition, two distinct engine cycles were chosen for investigation. No attempt was made to find an optimum engine cycle or design; rather, the two engine cycles selected represent the extremes of the engine cycle concepts analyzed in the recently completed STOL engine and aircraft studies conducted for the NASA Lewis Research Center (ref. 1) and NASA Ames Research Center (refs. 2 and 3).

AIRCRAFT

The MF and EBF aircraft are configured to perform the same mission. Sized for a field length of 914 m (3000 ft) on a hot day of 308° K (95° F) at sea level, both aircraft carry 150 passengers and cruise at an altitude of 9150 m (30,000 ft) with a design range of 926 km (500 n.mi.). The quarter-chord sweep is 25° for each, with aspect ratio and span selection based on climb and cruise considerations. A two-engine configuration was chosen at the outset for the MF, based on minimum DOC considerations shown in references 2 and 3. As in the STOL studies of references 2 and 3, the EBF has four engines. The general aircraft configuration layouts are shown in figure 1 for the MF and in figure 2 for the EBF.

The weight of each aircraft was computed, using the computerized techniques and methodology of reference 4, primarily as a function of payload, wing loading, and mission and propulsion requirements, including acoustic treatment. The specific acoustic treatment estimation procedure is presented in Appendix A.

The basic cruise lift and drag coefficients were obtained as functions of Mach number, Reynolds number, wing aspect ratio, quarter-chord sweep, etc., as detailed in reference 4. The lift and drag increments of the high lift devices were computed, using the methods of reference 5, as functions of flap geometry and deflection angle. Both aircraft employ leading edge slats and double-slotted trailing edge flaps with a flap-span/wing-span ratio of 0.75. The flap-chord/wing-chord for the MF and EBF are 0.40 and 0.35, respectively.

The powered lift aerodynamics of the EBF were estimated using the empirical and theoretical methods presented in reference 6. The complete lift and drag coefficients for the concepts were then computed as functions of the total gross thrust coefficient, flap geometry, and angle of attack. In addition, the EBF required the use of spoilers for direct lift control during the landing flare maneuver and for roll control in engine-out situations.

The effect of ground proximity was included in the calculation of the aircraft's lift and drag during takeoff and landing. Both aircraft experience a reduction in the induced drag in the presence of the ground plane. This drag loss was computed as a function of wing aspect ratio, wing span, and the height of the wing above the ground. For the MF, there is an enhancement of the lift in ground effect. This increase in the lift coefficient was computed as a function of wing aspect ratio and span, and height of the wing above the ground, as outlined in reference 7. The powered lift EBF aircraft experiences a negative or "suck down" ground effect. The reduction of the lift coefficient was calculated, using the results presented in reference 2, as a function of wing span, total circulation lift, and wing height above the ground.

During the ground roll of the EBF at low forward speeds, implying large gross thrust coefficients due to low dynamic pressure, the jet exhaust sheet will impinge on the ground, resulting in flow blockage. As a result, the jet sheet will not align with the free stream flow, and the full turning efficiency of the flap system will not be realized. Using the results presented in reference 8, the jet sheet centerline was computed as a function of aircraft speed in order to determine the speed at which the jet sheet would be tangent to the ground plane. For the EBF configuration studied, this speed is approximately 16.5 m/sec (32 knots). When the aircraft speed is less than 16.5 m/sec, the contribution of the propulsive/lift system to the net axial force coefficient, excluding ram drag, is assumed to equal the gross thrust coefficient times the cosine of the jet deflection angle (a function of the flap deflection and flap geometry). At or above 16.5 m/sec, no flow blockage is assumed to occur and the methods of reference 6 are used. It was felt that errors in the estimation of this "unblockage speed" would have little effect on the thrust sizing requirements.

ENGINES

Engine Description

The engines required for either MF or EBF quiet, short field aircraft are by necessity high bypass ratio, low fan pressure ratio, turbofan engines having low jet exit velocities. For this type of engine, the fan machinery is the predominant source of noise, rather than the exhaust jet noise, thus simplifying the problem of noise suppression. For an EBF aircraft, the noise from the interaction of the exhaust and the wing flap may dominate all other noise sources. This flap impingement noise is very difficult to suppress and is usually treated as a noise floor.

Although a high bypass engine requires less suppression to meet a specified noise goal, it also has a large frontal area which leads to added nacelle weight and drag. The proper engine selection can only be found by in-depth analysis to establish the trade-off between noise suppression treatment in the engine and engine size.

The two engine cycles selected for study represent the extremes of the various engine cycle concepts presented in references 2 and 3 for the subject aircraft. Both are conceptual engines developed by the Allison Division of General Motors (ref. 1), and they represent modern, high bypass, turbofan engine design using core gas turbines already under hardware development. Characteristics of the two engines are presented in table 1.

The difference in the fan design of the two engines is noted in table 1. Engine A has a conventional fixed-pitch blade design, and engine B has variable-pitch fan blades which provide the reverse thrust during landing and rejected takeoff rollout. This eliminates the need for the conventional cascade-type thrust reverser, resulting in significant weight savings as shown in reference 1. Both engines are flat rated to provide constant thrust up to an ambient temperature of 305° K (90° F).

TABLE 1.– SELECTED ENGINE PARAMETERS

Engine	A	B
Fan blade design	Fixed pitch	Variable pitch
Fan pressure ratio	1.50	1.25
Overall pressure ratio	20	20
Turbine inlet temperature, °K (°F)	1588 (2400)	1588 (2400)
Bypass ratio	9	17.8
Core exhaust velocity, m/sec (fps)	214 (700)	214 (700)
Engine specific weight[a]	0.154	0.143
Bare engine sideline noise, at 152 m (500 ft)[a]	117	106

[a]For a rated sea level static thrust of 89,000 N (20,000 lb).

Engine Performance

Uninstalled engine thrust, fuel flow, and airflow performance data were provided by Allison (ref. 1). These data were generalized in the following form for use in the aircraft synthesis computer program:

$$\text{Net thrust}/\delta = f\,(\text{flight Mach number, engine temperature ratio}) \qquad (1)$$

$$\text{Fuel flow}/(\delta\sqrt{\theta}) = f\,(\text{engine temperature ratio}) \qquad (2)$$

$$\text{Airflow}\sqrt{\theta}/\delta = f\,(\text{flight Mach number, engine temperature ratio}) \qquad (3)$$

The engine temperature ratio is defined as the ratio of turbine inlet temperature to engine face stagnation temperature. Engine power setting is defined as the net thrust divided by the maximum available net thrust for a given flight condition. The available net thrust at a given Mach number is computed from the generalized form by setting the turbine inlet temperature and computing the engine face stagnation temperature from the flight condition.

In sizing the engine to meet either field length or cruise requirements, the engine performance parameters are scaled assuming that the specific thrust (thrust/airflow) is constant. The gross thrust and ram drag are treated as separate vector forces. Ram drag is computed from the engine airflow and the aircraft flight speed, and gross thrust is the algebraic sum of the net thrust and ram drag.

Noise Suppression

The untreated 152 m (500 ft) sideline noise level, at 89,000 N (20,000 lb) sea level, static-rated thrust, is listed in table 1 for both engines. Sound suppression treatment in both the inlet and fan exhaust ducts is necessary to reduce the sideline noise to the levels specified in this study. It is recognized that the sideline noise is not a completely satisfactory measure of community acceptance. However, this parameter has been widely used in almost all STOL aircraft studies to date, and it is a convenient parameter for preliminary noise comparisons. A complete preliminary design study should also include comparisons of noise contour areas.

For each engine, three distinct values of sideline perceived noise levels at 152 m (500 ft) were selected for study, each representing different levels of noise suppression treatment. The fully treated, moderately suppressed, and unsuppressed noise level *per engine* for engine A are 97, 105, and 117 PNdB, respectively, and 95, 100, and 106 PNdB for engine B. The total sideline PNL for the entire aircraft will, in general, be different, owing to the effects of multiple engines, engine-airframe interaction noise, aircraft shielding, and extra ground attenuation. The fully suppressed engine corresponds to both duct wall treatment and splitter ring installation. The moderately suppressed engine is equivalent to wall treatment only. The third noise level corresponds to that of the untreated engine. The fully suppressed level of 97 PNdB per engine chosen for engine A is 20 PNdB below its unsuppressed level of 117 PNdB. It was felt that a 20 PNdB noise suppression of a single engine could be achieved without incurring prohibitive duct losses and acoustic treatment weight penalties, as shown in Appendix A. The fully suppressed noise level for engine B was chosen somewhat arbitrarily at 95 PNdB. At the suppressed noise levels indicated, it is probable that the flap interaction noise would dominate the engine noise. The noise levels selected for the MF are the same as those for the EBF.

Noise treatment results in engine performance losses due to the pressure drops in the inlet and fan exhaust ducts, and also results in a weight penalty. Often it is necessary to lengthen the inlet duct to provide for additional treatment, which also adds weight. In support of the STOL engine studies at NASA Lewis Research Center, Allison (ref. 1) developed a family of conceptual engines designed for the EBF powered lift concept which included different cycles ranging in fan pressure ratio from 1.2 to 1.5. This has provided a broad data base of engines, each requiring different levels of noise suppression treatment to meet a specified noise goal. These data have been used to develop simple correlations for the engine pressure losses and weight penalties at different levels of noise suppression. These correlations are presented in Appendix A. The difference between the untreated engine sideline noise and the required sideline noise was used to correlate suppression weight per unit engine frontal area and the pressure drop per unit dynamic pressure in the inlet and fan exhaust ducts.

The weight penalty follows directly from the engine size, which determines the frontal area. Also, thrust penalties will result when there are pressure drops in the inlet or the fan exhaust duct. These penalties become severe when rings of noise suppression material are added to the inlet and fan exhaust duct. Small thrust loss penalties result from wall treatment only. The methods used to compute the thrust losses due to these pressure drops are given in Appendix B.

AIRCRAFT SIZING

For a selected range of wing loadings, the required uninstalled engine-thrust to aircraft-gross-weight ratio was determined for the takeoff and landing using the computer programs described in reference 9. The field length assumptions are presented in figure 3. In each case, for a given wing loading, an iteration is made on the thrust to determine the desired value for the 914 m (3000 ft) field performance on a hot day.

For the takeoff, both the all-engine and engine-out/accelerate-stop cases are evaluated. The takeoff distances are computed subject to the following constraints and ground rules:

1. Rolling coefficient of friction = 0.02

2. Rotation rate = 5.0°/sec

3. Rotation speed $V_R \geqslant 1.1\ V_{STALL}$

4. Fuselage attitude $\leqslant 15°$ (tail scrape angle)

5. Load factor $\leqslant 1.20$

6. No deceleration along flight path

7. Speed at 10.7 m (35 ft) altitude $V_2 \geqslant 1.2$ times V_{STALL} for the MF, $V_2 > V_{min} + 15.0$ knots for the EBF

8. For accelerate-stop, a 3.0 sec delay after engine failure, followed by a 0.4 g deceleration to a stop

The critical engine failure speed, V_1, is determined for each case and the balanced field length computed from this speed. The takeoff distance is then defined to be the greater of the balanced field length and 115 percent of the all-engine takeoff distance. All pilot decision speeds (e.g., V_R and V_1) are based on equivalent air speeds. It is assumed that an elapsed time of 0.25 sec is required for an engine to fail, and that during that period the thrust of that engine varies linearly with time from 100 percent to 0.0 percent power. During the airborne portion of the takeoff, the flight path control is accomplished by variations in the angle of attack to satisfy the load factor, non-deceleration, and fuselage angle constraints. Also, a search is conducted for the rotation speed V_R resulting in a minimized distance, subject to constraints 3 and 7. Rotation at speeds near 110 percent of V_{STALL} usually results in screen speeds less than 120 percent of V_{STALL} for the engine-out takeoff. Because no methodology was available to analytically compute V_{min} for the EBF, rotation speed for the EBF was selected as 15 knots higher than the 1 g stalling speed. It was felt that this would adequately meet constraint 7 for the powered lift aircraft.

Takeoff, approach, and landing flap selection has a significant impact on the propulsion system sizing requirements. The takeoff flap setting was optimized to give a minimum required thrust-to-weight ratio satisfying the field length and the FAR engine-out, second-segment climb requirements. Typical examples of the required T/W determination as a function of the takeoff flap deflection are presented in figures 4(a) and 4(b). For the MF (fig. 4(a)), the optimum flap setting resulting in the minimum required T/W occurred at the intersection of the balanced field length and second-segment climb requirement curves. For the EBF (fig. 4(b)), a minimum required T/W and corresponding flap setting occurred at the minimum of the balanced field length requirement. As a result, the EBF aircraft exceeded the FAR Part XX engine-out, second-segment climb gradient requirement.

The landing field length is defined as the distance from 10.7 m (35 ft) altitude to a complete stop divided by a factor of 0.60. The ground rules and constraints for the landing are as follows:

1. Approach rate of sink = 4.57 m/sec (900 fpm)

2. Fuselage attitude $\leqslant$ 15.0°

3. Rotation rate $\leqslant$ 5.0°/sec

4. Rate of sink at touchdown = 3.05 m/sec (10.0 fps)

5. 1.0 sec delay after touchdown before braking

6. A 0.35 g stop

For the landing approach, the angle of attack and thrust required for zero acceleration along and normal to the flight path are computed. These values of thrust and angle of attack for the steady state approach are functions of the aircraft velocity and flight path angle, and the specific aircraft configuration (e.g., flap setting and spoiler deflection). In searching for the required approach thrust, an iteration on the thrust per engine is performed to match the required thrust at a specified power setting. Using this procedure for a given aircraft configuration and flight condition, the required thrust-to-weight ratio for the landing is determined. From engine-out trim drag considerations for the four-engine EBF, as shown in reference 2, an approach power setting of 65.0 percent is selected. Because the wing loading of the MF is essentially independent of the thrust-to-weight ratio for the landing, the power setting is not specified beforehand but is computed internally to the program. Engine sizing is also done for a missed approach go-around situation – both for all engines operating and the critical engine inoperative. If the rated thrust required to meet FAR go-around climb gradients is critical, then the power setting for the landing approach will be less than 65 percent.

A typical landing operational envelope for an EBF aircraft is presented in figure 5. The landing approach conditions are determined by the intersection of the 914 m (3000 ft) field length and the 4.57 m/sec (900 fpm) sink-rate curve. For a given flap deflection angle, an iteration is performed on T/W so that these landing conditions occur at 65 percent power. The required T/W to meet the two go-around requirements and the approach power setting requirement are then computed as functions of the flap setting. A typical example for an EBF aircraft is presented in figure 6. The minimum flap deflection that provides the required angle of attack flaring margin to meet the 15° fuselage attitude at touchdown is selected for the landing approach configuration. Because the required rated thrust for the steady state landing approach and go-around climb requirements increases rapidly with higher flap deflection, this flap setting represents the minimum required thrust-to-weight ratio for the landing sizing. For the MF, the landing flap setting was determined by the approach-speed to stall-speed ratio requirement of FAR Part 25 ($V_{APP} = 1.3\ V_{STALL}$).

RESULTS

Effect of Noise Level on Aircraft Thrust Loading and Wing Loading

The final plots of the standard day uninstalled engine thrust to aircraft gross weight ratio (T/W) versus wing loading (W/S) are presented in figure 7. Two families of curves, one corresponding to the takeoff sizing, the other to the landing sizing, are shown as functions of engine noise. These values of *PNL* are the noise levels corresponding to a single engine, and will usually differ from the total noise level of the entire aircraft. This would be particularly true for the EBF aircraft at the lower engine noise levels. As discussed earlier, the combination of the two noise sources (engine and flap) would increase the overall perceived noise level.

For both the MF and the EBF, the selected design thrust-to-weight ratio and wing loading are determined by the intersection of the takeoff and landing sizing curves. Based on the results of references 2 and 3, this point will generally correspond to the minimum gross weight and *DOC* for a 914 m (3000 ft) MF or propulsive lift aircraft. The final design values for T/W, W/S, and other parameters are presented in table 2. Since the T/W presented in figure 7 is for uninstalled bare engine performance, the sensitivity of T/W to engine noise reflects the losses in performance due to acoustic treatment in the inlet and fan exhaust ducts.

For the MF, the wing loading for a given landing distance is primarily a function of the maximum lift coefficient and the approach-speed to stall-speed ratio, and is independent of the thrust-to-weight ratio of the aircraft. For a 914 m (3000 ft) landing field length, the required approach speed is 49.2 m/sec (98.3 knots). Combined with an approach-speed to stall-speed ratio of 1.3, as specified in FAR Part 25, and a maximum lift coefficient of 3.4 in the landing configuration, the required wing loading for the MF on a hot day is found to be 301 kg/m^2 (61.6 psf).

For the twin engine MF, the engine-out takeoff distance is greater than 1.15 times the all-engine distance. Thus, the engines for the MF are sized for a balanced field length of 914 m (3000 ft). To obtain the minimum required T/W for a given wing loading, the flap deflection that simultaneously satisfied the 914 m (3000 ft) balanced field length requirement and the second segment engine-out climb gradient requirement is selected for the takeoff flap setting. From figures 7(a) and 7(b), it is seen that the required takeoff T/W increases with wing loading. As the wing loading is increased at a fixed lift coefficient, the stall speed, and hence the rotation speed, also increases. Therefore, for a fixed field length the T/W must increase with wing loading.

The EBF exhibits a similar takeoff sizing behavior to the MF for the required takeoff T/W versus wing loading (figs. 7(c) and 7(d)). Even though the EBF is a four-engine aircraft, the engine-out distance to 10.7 m (35 ft) is the critical takeoff distance criterion. This is due to the substantial increases in drag and the loss of lift coefficient associated with engine-out yaw and roll control for this aircraft. The EBF engines are therefore sized for a balanced field length of 914 m (3000 ft), with takeoff flap selection similar to that of the MF.

Because the EBF derives lift from the propulsion system, there exists an interdependency between the T/W and wing loading required to meet the desired landing field length performance. As the wing loading is increased, the required T/W for the 914 m (3000 ft) field length also

TABLE 2.– FINAL DESIGN AIRCRAFT CHARACTERISTICS

Aircraft	Engine	Engine noise level, PNdB	T/W	W/S, kg/m^2 (psf)	Gross weight, kg (lb)	DOC, ¢/askm (¢/asmi)	Thrust per engine, N (lb)	Acoustic treatment weight, kg (lb)	Nacelle diameter, m (ft)	Cruise Mach no.	Block fuel, kg (lb)	Aspect ratio	Span, m (ft)
MF	A	117	0.402	300.8	78,503	1.23	154,798	0	2.68	0.747	6402	9.0	48.5
				(61.6)	(173,067)	(1.99)	(34,786)		(8.8)		(14,113)		(159.5)
	A	105	0.413	300.8	82,235	1.32	164,970	497	2.80	0.707	7161	9.0	49.6
				(61.6)	(181,295)	(2.14)	(37,072)	(1096)	(9.2)		(15,788)		(162.8)
	A	97	0.461	300.8	94,648	1.63	211,428	1893	3.11	0.596	9876	9.0	53.2
				(61.6)	(208,660)	(2.64)	(47,512)	(4173)	(10.2)		(21,773)		(174.6)
	B	106	0.413	300.8	71,655	1.19	145,163	0	3.08	0.687	4797	9.0	46.3
				(61.6)	(157,970)	(1.92)	(32,621)		(10.1)		(10,575)		(151.9)
	B	100	0.418	300.8	72,475	1.20	148,710	134	3.14	0.680	4971	9.0	46.6
				(61.6)	(159,778)	(1.95)	(33,418)	(295)	(10.3)		(10,959)		(152.8)
	B	95	0.428	300.8	74,082	1.24	154,290	601	3.17	0.671	5229	9.0	47.1
				(61.6)	(163,320)	(2.01)	(34,672)	(1324)	(10.4)		(11,528)		(154.5)
EBF	A	117	0.462	500.4	67,271	1.15	76,224	0	1.89	0.82[a]	5544	8.0	32.8
				(102.5)	(148,305)	(1.86)	(17,129)		(6.2)		(12,223)		(107.6)
	A	105	0.476	502.9	68,826	1.18	80,216	276	1.92	0.82[a]	5922	8.0	33.1
				(103.0)	(151,732)	(1.91)	(18,026)	(608)	(6.3)		(13,056)		(108.6)
	A	97	0.493	500.0	71,863	1.23	87,153	818	2.01	0.82[a]	6640	8.0	33.9
				(102.4)	(158,429)	(1.99)	(19,585)	(1803)	(6.6)		(14,639)		(111.3)
	B	106	0.481	508.7	62,354	1.11	73,559	0	2.19	0.769	4377	8.0	31.3
				(104.2)	(137,465)	(1.80)	(16,530)		(7.2)		(9649)		(102.7)
	B	100	0.487	506.8	62,678	1.12	74,818	0	2.23	0.771	4448	8.0	31.5
				(103.8)	(138,180)	(1.81)	(16,813)		(7.3)		(9807)		(103.2)
	B	95	0.495	505.3	63,681	1.14	77,417	330	2.26	0.771	4769	8.0	31.8
				(103.5)	(140,390)	(1.84)	(17,397)	(726)	(7.4)		(10,513)		(104.2)

[a]Cruised at maximum operating Mach number.

increases. For the entire range of noise levels and wing loadings investigated, the design criterion that sized the engines for the landing was the engine-out, go-around climb gradient requirement.

The takeoff and landing flare time histories, and the takeoff and landing operational envelopes for the fully suppressed final design point aircraft, are presented in Appendix C. The moderately and unsuppressed cases are quite similar to the fully suppressed case shown for each combination of engine cycle and lift concept.

The final design values of thrust-to-weight ratio and wing loading as functions of the engine noise level are presented in figure 8. For both engines A and B, the lower the specified noise level the higher the required T/W. This increase in the required thrust is needed primarily to overcome the losses due to the noise suppression treatment. This trend is true for both the MF and EBF. For the untreated engine, the required T/W is less for engine A on both the MF and the EBF. This is due to the lower bypass ratio of this engine and hence lower thrust lapse at increased forward speed and altitude.

As stated above, the wing loading for the MF is independent of the thrust and is therefore independent of the engine noise level. The EBF also displays a similar behavior with very little variation in the design wing loading as a function of the engine noise level, but for a different reason. As the amount of noise suppression is increased, both the takeoff and landing sizing curves shift vertically upward, with the net thrust requirements remaining essentially unchanged. An increase in the engine rated thrust is required to overcome the losses due to increased noise treatment, resulting in higher required T/W but in little change in the design wing loading.

The values of wing loading and thrust-to-weight ratio of a present-day CTOL (Boeing 727-200) with a 2440 m (8000 ft) takeoff field length are shown, for reference, in figure 8. The noise level of the Pratt and Whitney JT8D-15 engine was estimated to be 120 PNdB at 152 m (500 ft) sideline. Other corresponding values of aircraft parameters for this CTOL aircraft are also presented, for reference, in figures 10 and 11.

Effect of Noise Level on Aircraft Size, Operating Cost and Cruise Performance

The thrust per engine, normalized by the unsuppressed thrust per engine and the acoustic treatment weight divided by the propulsion system weight, are presented in figure 9 as functions of the engine noise level. The variation in thrust per engine with engine noise level is similar to that of the required T/W. For engine A on the MF, the required thrust per engine rises much faster with lower noise levels compared to the other combinations of engine cycles and lift concepts. Because of the high unsuppressed noise level of engine A, the amount of suppression treatment to reduce the noise to a desired level is substantial. Associated with this high level of noise treatment are increased weight and thrust losses. Thus, to produce a given amount of thrust at the tailpipe, the rated thrust of the engine must be increased to overcome these losses. Because the amount of noise suppression is a function of the magnitude of the thrust, additional losses are incurred with this increased thrust. Hence, there is a compounding effect on the required thrust by the installation of noise suppression treatment. This effect is accentuated for the MF, since the MF is a twin-engine configuration, resulting in higher thrust per engine for a given thrust-to-weight ratio.

As the desired noise level is reduced, the acoustic treatment weight, as a fraction of the propulsion system weight, is seen to increase. The propulsion system weight is defined to be the sum of the weights of the engine, nacelle, pylon, and acoustic treatment. The weight penalties and thrust losses are more severe for the lower bypass ratio engine, with the EBF being less penalized than the MF (four engines as opposed to two) throughout the range of noise levels studied.

The gross weight and *DOC* for 500 n.mi. stage length are presented in figure 10. Not only is the MF heavier than the EBF, which is primarily due to the lower design wing loading for the MF, but its gross weight is much more sensitive to the noise suppression level. In addition, aircraft employing engine B require lower gross weights throughout the range of noise levels studied. The variable-pitch fan design of this engine, which eliminates the need for a thrust reverser, is a significant factor in this result.

As the engine noise is allowed to increase, there is a reduction in the *DOC*. The lowest *DOCs* were exhibited by the EBF using the higher bypass ratio engine. The MF using engine B, and the EBF using engine A, have similar *DOC* values throughout their comparable range of noise levels. The MF with engine A is subject to substantial increases in *DOC* with lower noise levels. It should be noted that both engines A and B are assumed to have the same specific cost, thus no economic penalty is assessed to the variable pitch concept of engine B.

Shown in figure 11 are the cruise Mach number and the block fuel for the 926 km (500 n.mi.) mission. The cruise Mach number resulted from the engines sized for the 914 m (3000 ft) field length performance, the thrust lapse characteristics of each engine, and the cruise drag characteristics of the sized aircraft. For cruise Mach numbers higher than those shown, the engines would be cruise-sized. The higher cruise Mach numbers for the EBF result from the higher wing loading of the EBF. The EBF cruises at higher speeds with engine A due to the lower bypass ratio, hence lower thrust lapse, for this engine. For the EBF and the MF with engine B, the cruise Mach number decreases only moderately with lower engine noise level. The MF with engine A suffers substantial thrust losses due to the extensive noise treatment required for the low noise levels. The result is a marked reduction in cruise Mach number for this aircraft at the lower noise levels. The relatively low cruise speed and high gross weight combine to give the MF using engine A the high *DOCs* at the lower noise levels (as shown in fig. 10).

As the level of engine noise is allowed to increase, the required block fuel is seen to decrease. For each engine, it is the EBF that has the lower required block fuel. The higher bypass ratio engine, with its lower specific fuel consumption, requires less fuel for both the MF and the EBF. The combination of low cruise speed and large engines for the MF with the lower bypass ratio engine results in the higher values of block fuel, with marked increases in fuel consumption at the lower noise levels.

CONCLUSIONS

For the two aircraft concepts studied, the above results showed the following.

1. The lower the specified engine noise level, the higher the required thrust-to-weight ratio and thrust per engine. For duct wall treatment only, there is roughly a 3 percent increase in the required

T/W and approximately a 6 percent increase in the required thrust per engine. When splitter rings are added, there is an increase in required *T/W* ranging from 3 to 15 percent and an increase of 6 to 37 percent in the required thrust per engine.

2. As the required engine noise level is decreased, there is a general increase in the resulting gross weight and *DOC*. Full suppression treatment results in an increase in gross weight ranging from 2 to 20 percent, depending on lift concept and engine cycle. *DOC* can be expected to increase from 3 to 32 percent correspondingly.

3. As the desired engine noise level is reduced, there is a general increase in the required block fuel. Increases ranging from 10 to 54 percent in block fuel occurred with the addition of duct wall and splitter ring treatment.

Formal comparisons between the mechanical flap and the externally blown flap aircraft for a 914 m (3000 ft) field length cannot be drawn from the results of this study. An investigation of other engine cycles and the determination of some suitable parameter to measure community acceptance (e.g., noise contour areas and shape) should be performed before any such conclusions are made. For the engine cycles, mission, and field length studied, the following conclusions are drawn:

1. For both the MF and the EBF, flap performance and selection have a significant impact on the propulsion system requirements.

2. For both the MF and the EBF, the required wing loading is essentially independent of the engine noise level. The design wing loading of the MF is fixed by landing requirement constraints and hence not dependent upon engine size or noise level. For the EBF, both the takeoff and landing sizing curves shift vertically upward as the amount of noise suppression is increased, resulting in higher required *T/W*, but in little change in the design wing loading. Thus, the penalty due to noise treatment for both lift concepts is in terms of higher required thrust-to-weight ratio, with little or no penalty in wing loading.

3. For a given required noise level, the impact of acoustic treatment is much greater for the high fan pressure ratio, low bypass ratio engine, due to the higher untreated noise level of this engine. The results of this study suggest that it is better to initially select a low source noise engine rather than to suppress a given high source noise engine.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif. 94035, July 8, 1975

APPENDIX A

CORRELATION OF ACOUSTIC TREATMENT WEIGHT AND ENGINE PERFORMANCE PENALTIES

The simple correlations developed here are based on the required suppression of sideline noise. This suppression is the difference of the bare engine sideline noise at rated thrust and the required sideline noise. The data are for noise measurements at a 500-ft sideline.

The data for these correlations are derived from the studies performed by the Allison Division of General Motors, for the Quiet Clean STOL Experimental Engine (QCSEE) program, sponsored by the NASA Lewis Research Center. Only high bypass turbofan engines with single stage fans are included in these data. Bypass ratio varies from 9 to 22 and fan pressure ratio from 1.5 to 1.15. It is presumed the resulting correlations are valid for all single stage fan engines.

Figure 12 relates the acoustic treatment weight to the required noise suppression. By giving the ratio of treatment weight to engine frontal area, the effect of both engine thrust level and bypass ratio is accounted for. Note that the data indicate no weight penalty for noise suppression of 6 dB or less. This is consistent with the assumption that this level of suppression can be achieved with wall treatment only. At the upper end it would appear that no amount of acoustic treatment can be installed to suppress more than 25 to 30 dB.

Similar correlations are given in figures 13 and 14 for the inlet and fan duct pressure drop, respectively. The correlations include the dynamic pressures in the inlet and fan exhaust duct, which are computed from the airflow and the duct annulus areas, and pressures ahead of and behind the fan.

APPENDIX B

TURBOFAN ENGINE THRUST PENALTIES DUE TO INLET AND FAN DUCT PRESSURE DROPS

Thrust loss penalties will result from pressure drops in the inlet duct ahead of the engine and in the fan duct downstream of the fan and ahead of the fan flow nozzle. As shown in Appendix A, these pressure drops can be significant when acoustic treatment is added to the engine.

THRUST LOSS DUE TO AN INLET PRESSURE DROP

For a given engine operating point and flight Mach number, the engine corrected net thrust (T_N/δ) will be constant. Therefore, the thrust penalty due to an inlet pressure drop can be found directly as:

$$\Delta\delta/q = (\Delta P/q)_{\text{inlet}}/\text{sea level static pressure}$$

$$\Delta T_N = (T_N/\delta)\,(\Delta\delta/q)q$$

where T_N is the engine net thrust, $(\Delta P/q)_{\text{inlet}}$ is the inlet pressure drop correlation from Appendix A, and q is the free stream dynamic pressure.

THRUST LOSS DUE TO A FAN DUCT PRESSURE DROP

The pressure drop in the fan duct will result in a reduced nozzle pressure ratio across the fan exhaust nozzle. The loss in thrust can be found using the relation between nozzle gross thrust and the nozzle pressure ratio for a convergent nozzle in either subcritical or supercritical flow.

$$TAP \equiv \left(\frac{T_G}{A_t}\,p_{amb}\right) = \frac{2\gamma_n}{(\gamma_n - 1)}\left[NPR^{(\gamma_n - 1)/\gamma_n} - 1\right] \qquad \text{(Subcritical Flow)}$$

$$= \left[\frac{\gamma_n + 1}{\left(\frac{\gamma_n + 1}{2}\right)^{\gamma_n/(\gamma_n - 1)}}\right] NPR - 1 \qquad \text{(Supercritical Flow)}$$

where

T_G nozzle gross thrust

A_t nozzle throat area

P_{amb} ambient static pressure

NPR nozzle pressure ratio

γ_n ratio of specific heats for the exhaust flow

For engines having separate fan and core nozzles, the ratio of fan nozzle gross thrust to the core nozzle gross thrust is defined as follows:

$$T_{split} = T_{G_{fan}} / T_{G_{core}}$$

$$\therefore T_{G_{fan}} = T_{G_{total}} [T_{split}/(1 + T_{split})]$$

The value of T_{split} can be approximated and, for high bypass ratio engines, the value of the parameter $T_{split}/(1 + T_{split})$ will be close to 1.0 (and T_{split} need not be known precisely). The total gross thrust will be the sum of the engine net thrust and the ram drag.

Let subscript 1 refer to the nozzle without the fan duct pressure drop, and subscript 2 refer to the nozzle with the fan duct pressure drop. Then the thrust loss penalty is given by the following equation:

$$NPR_2 = NPR_1 [1 - (\Delta P/q_{duct}) (q/P)_{duct}]$$

where the ratio of dynamic pressure to total pressure in the fan duct, a function of the duct Mach number, M_{duct}, is given by:

$$\left(\frac{q}{P}\right)_{duct} = \left(\frac{\gamma_n}{2}\right) (M_{duct})^2 \left\{\left[1 + \frac{\gamma_n - 1}{2} (M_{duct})^2\right]^{\gamma_n/(\gamma_n - 1)}\right\}$$

and $(\Delta P/a)_{duct}$ is the fan duct pressure drop correlation from Appendix A, and q is the fan duct dynamic pressure.

Since the throat area and the discharge ambient pressure are constant,

$$\left(T_{G_{fan}}\right)_2 = \left(T_{G_{fan}}\right)_1 (TAP_2/TAP_1)$$

For constant ram drag and core thrust, it follows that

$$\Delta T_N = \Delta T_G = \left(T_{G_{fan}}\right)_1 [1 - (TAP_2/TAP_1)]$$

APPENDIX C

TAKEOFF AND LANDING FLARE TIME HISTORIES AND OPERATIONAL ENVELOPES

Presented in figures 15 through 30 are the time histories of the takeoff and landing flare maneuver and the takeoff and landing configuration operational envelopes for the fully suppressed aircraft/engine combinations. The moderately and unsuppressed cases are quite similar to the corresponding fully suppressed cases shown. The operational envelopes also indicate the selected flap settings for the various aircraft configurations. The plotted performance parameters are as follows:

Variable	Symbol	Unit
ALPHA	α	deg
ROC	roc	m/sec (fpm)
ACCEL	a	m/sec^2 (ft/sec^2)
VEL	V	m/sec (knots)
DIST	d	m (ft)
GAMMA	γ	deg
THETA	θ_f	deg
ΔLF	Δn	–
THRUST	T	N (lb)
ALT	h	m (ft)

REFERENCES

1. Helms, H. E.: Quiet Clean STOL Experimental Engine Study Program, Task IV – Comparison STOL Aircraft System Study Coordination. Allison Report EDR-7738; Feb. 1973.

2. Study of Quiet Turbofan STOL Aircraft for Short-Haul Transportation. Final Report, vol. II, Aircraft. Douglas Aircraft Company, Long Beach, CA; NASA CR-114607, June 1973.

3. Renshaw, J. H.: Quiet Turbofan STOL Aircraft for Short-Haul Transportation. Final Report, vol. I; Lockheed-California Company, Burbank, CA, and Lockheed-Georgia Company, Marietta, GA; NASA CR-114612, June 1973.

4. Schoen, A. H., and Wisniewski, J. S.: VASCOMP II Users' Manual. The Boeing Company, Vertol Division, Philadelphia, PA, Oct. 1971.

5. Sanders, Karl L.: High-Lift Devices, A Weight and Performance Trade-off Methodology. Ryan Aeronautical Company, San Diego, CA, May 1969.

6. May, Fred, and Widdison, Colin A.: STOL High-Lift Design Study. Vol. I, The Boeing Company, April 1971.

7. Corning, Gerald: Supersonic and Subsonic Airplane Design. 2nd Edition, Edwards Brothers, Inc., Ann Arbor, MI, 1960, pp. 2:66, 4:10.

8. Gielow, R. L.: Performance Prediction and Evaluation of Propulsion-Augmented High Lift Systems for STOL Aircraft. AIAA Paper No. 71-990, Oct. 1971.

9. Bowles, J. V., and Galloway, T. L.: Computer Programs for Estimating Aircraft Takeoff and Landing Performance. NASA TM X-62,333, July 1973.

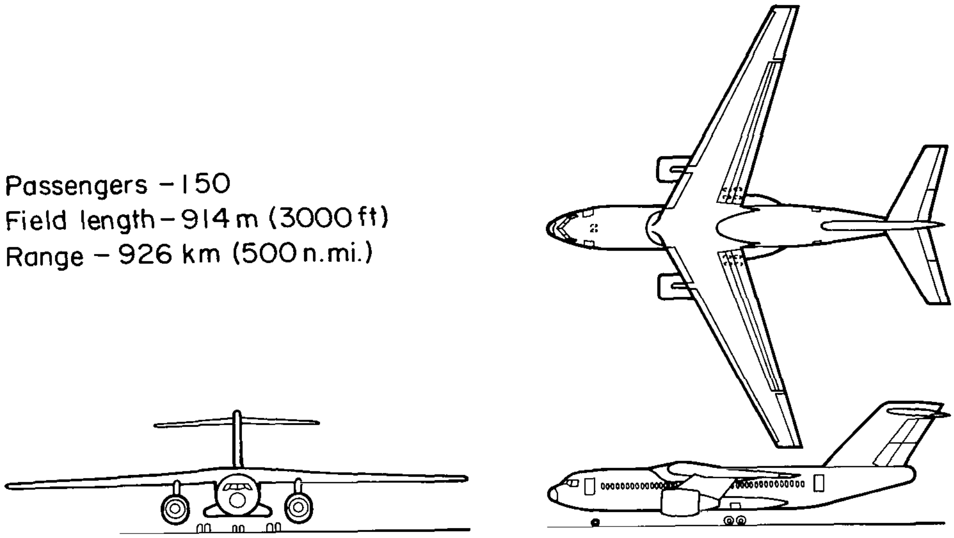


Figure 1.– Mechanical flap aircraft configuration.

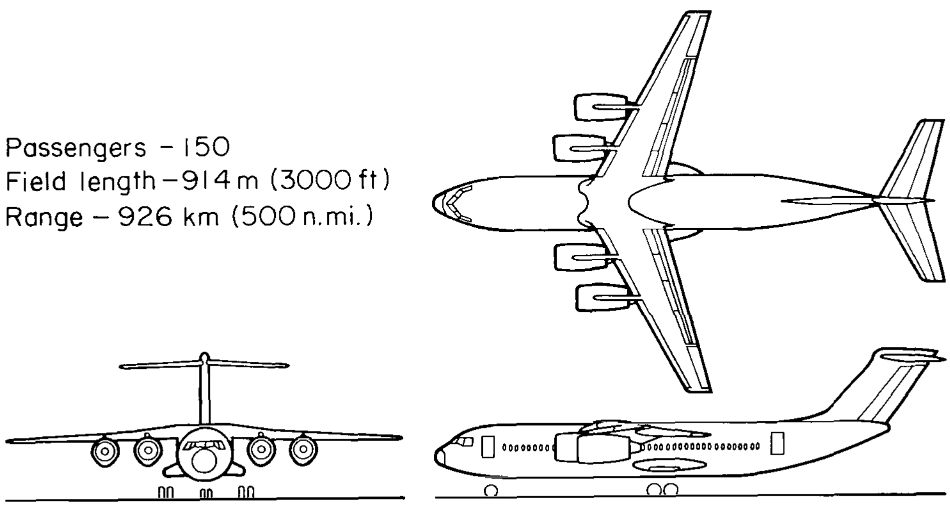


Figure 2.– Externally blown flap aircraft configuration.

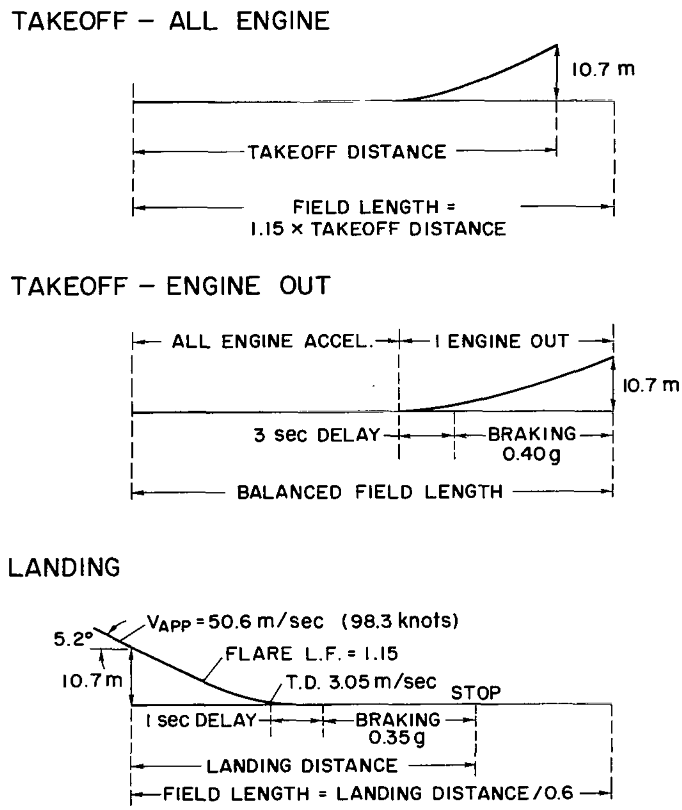
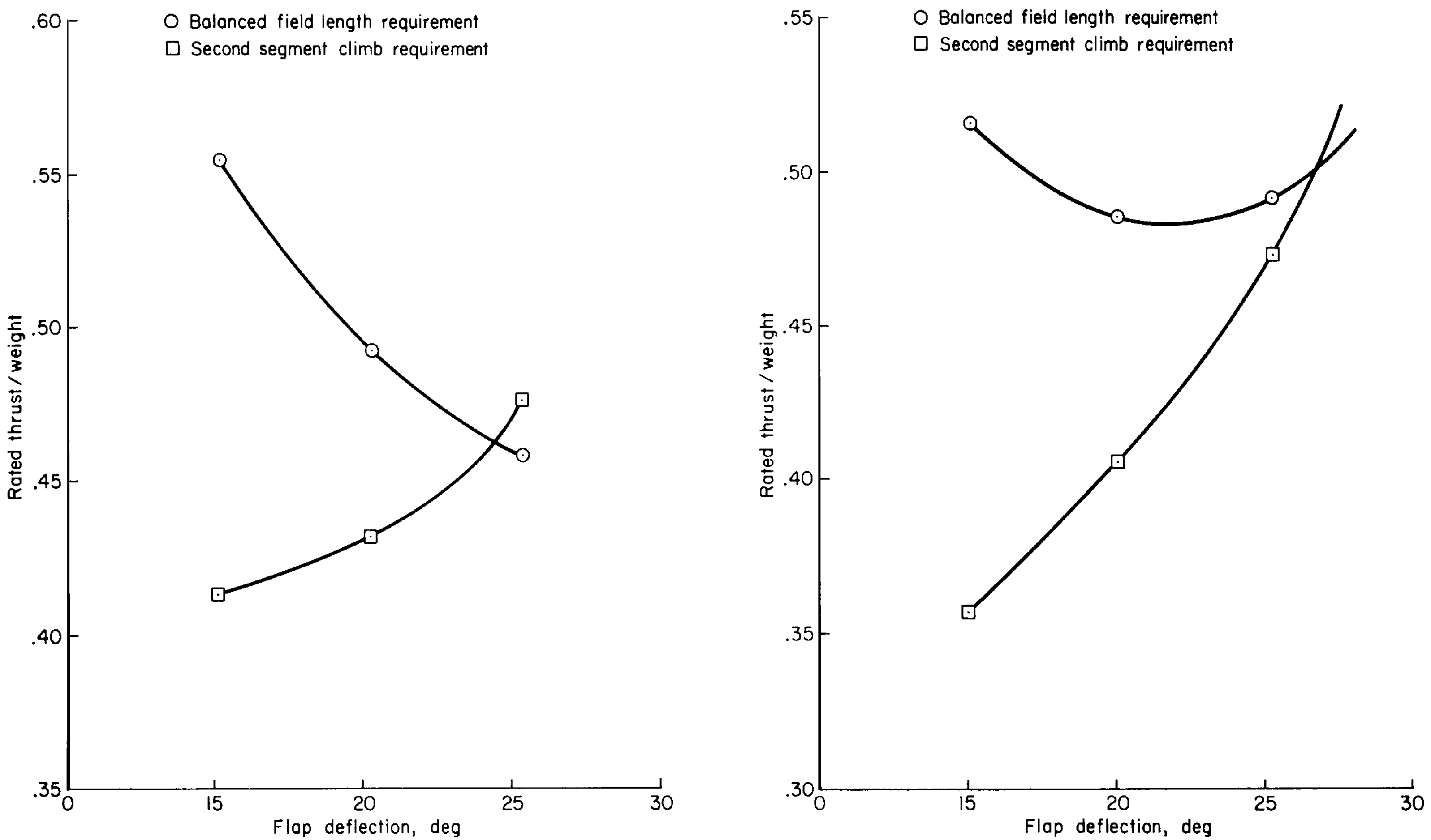


Figure 3.– Field performance ground rules and field length definitions.



(a) MF

(b) EBF

Figure 4.– Required takeoff T/W as function of flap deflection.

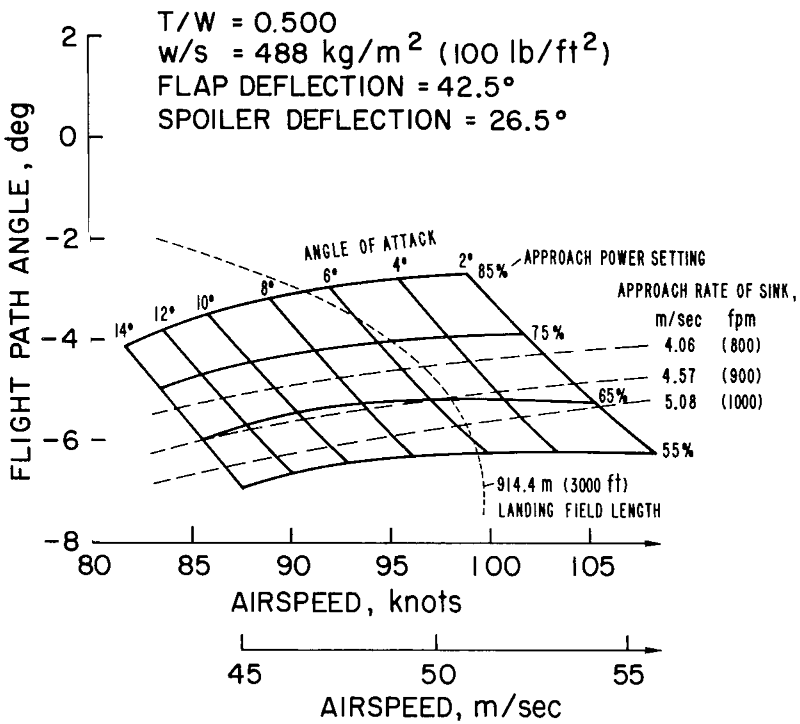


Figure 5.– Landing operational envelope for an EBF with engines approach sized.

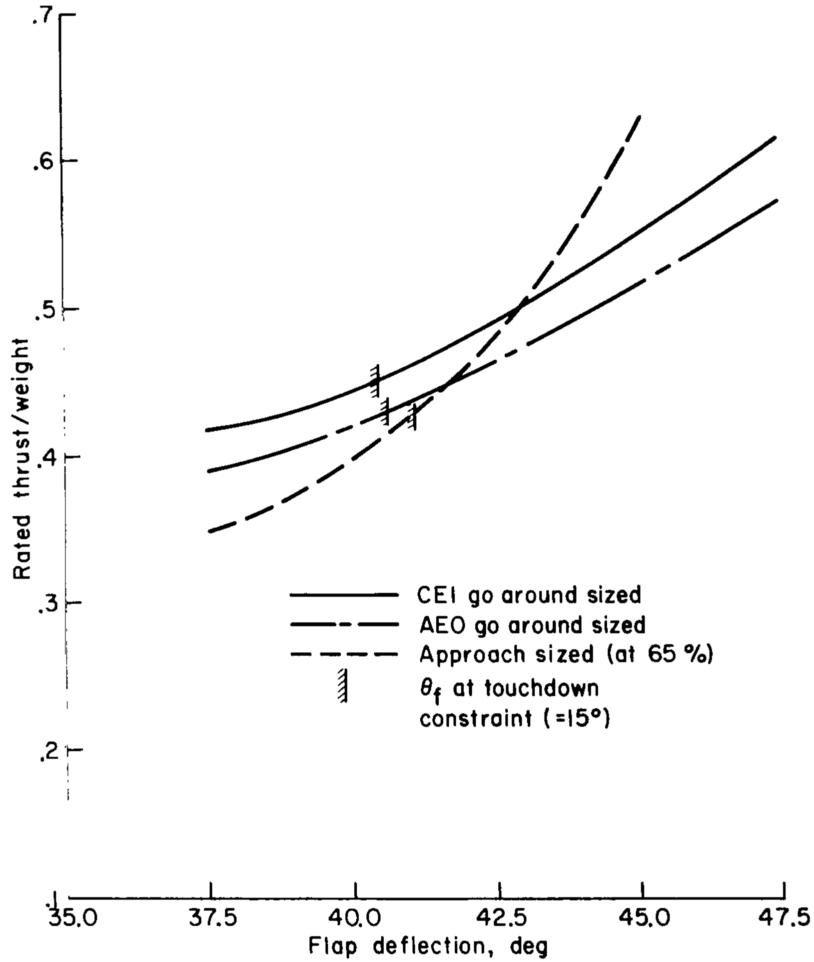
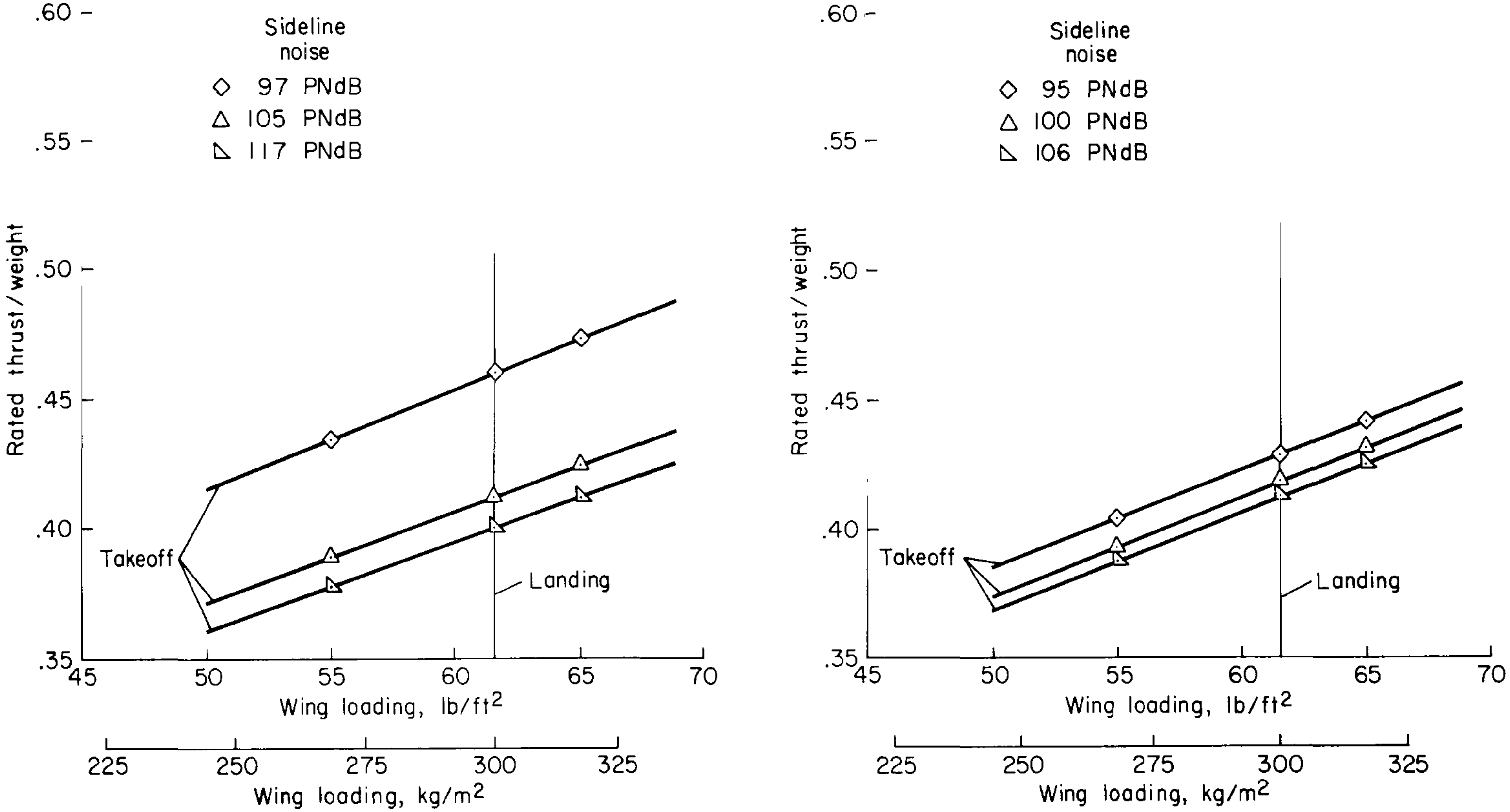


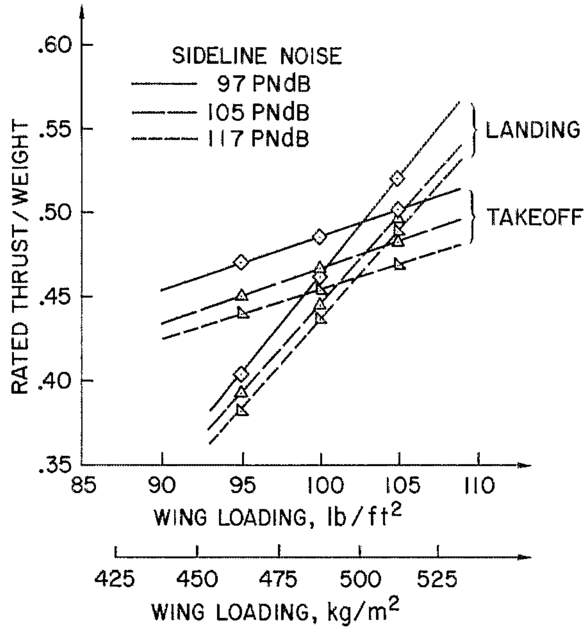
Figure 6.– Required approach and go-around T/W as function of flap deflection for EBF aircraft.



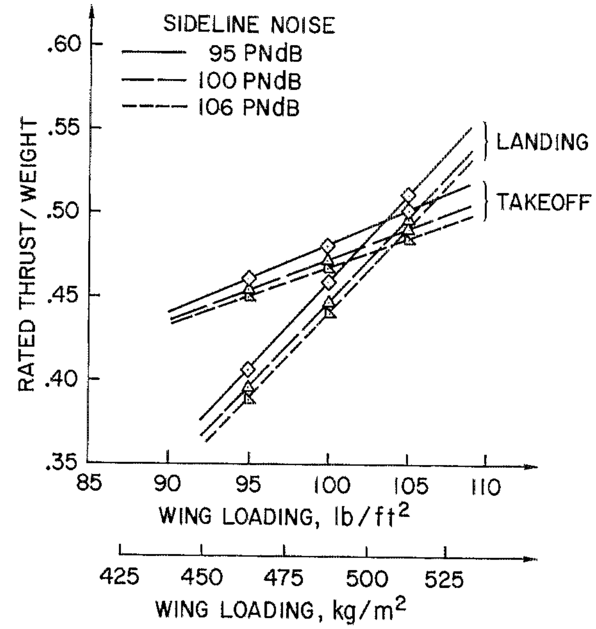
(a) MF with engine A

(b) MF with engine B

Figure 7.– Thrust to weight versus wing loading curves.



(c) EBF with engine A



(d) EBF with engine B

Figure 7.– Concluded.

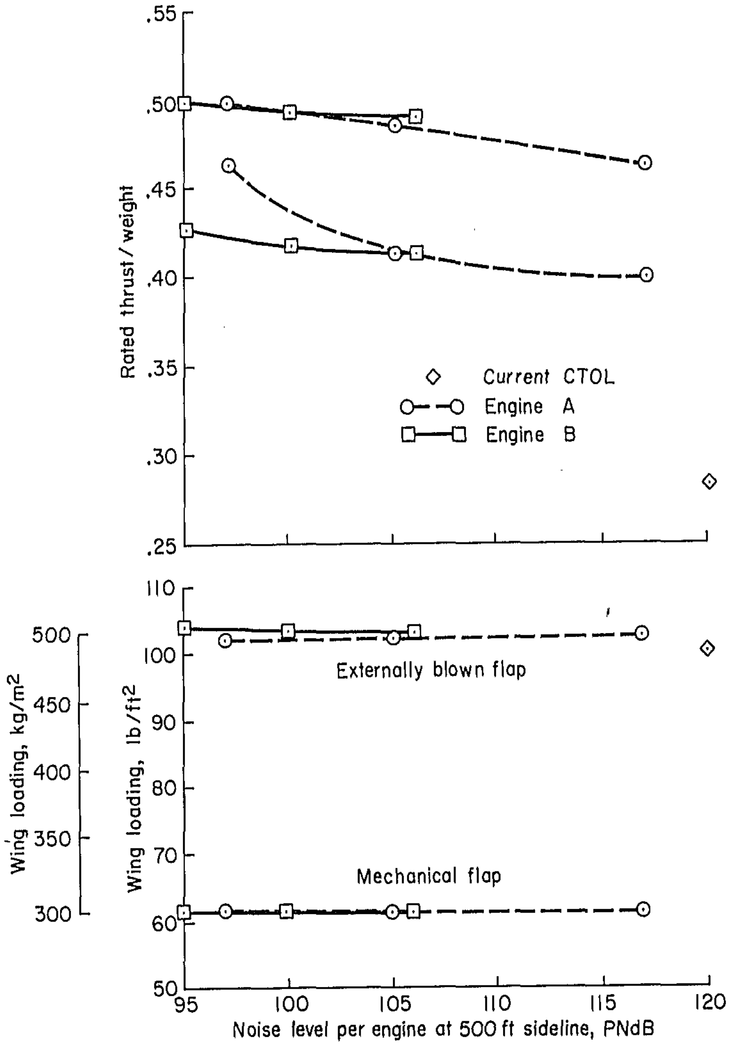


Figure 8.– Design thrust to weight and wing loading as a function of noise level per engine.

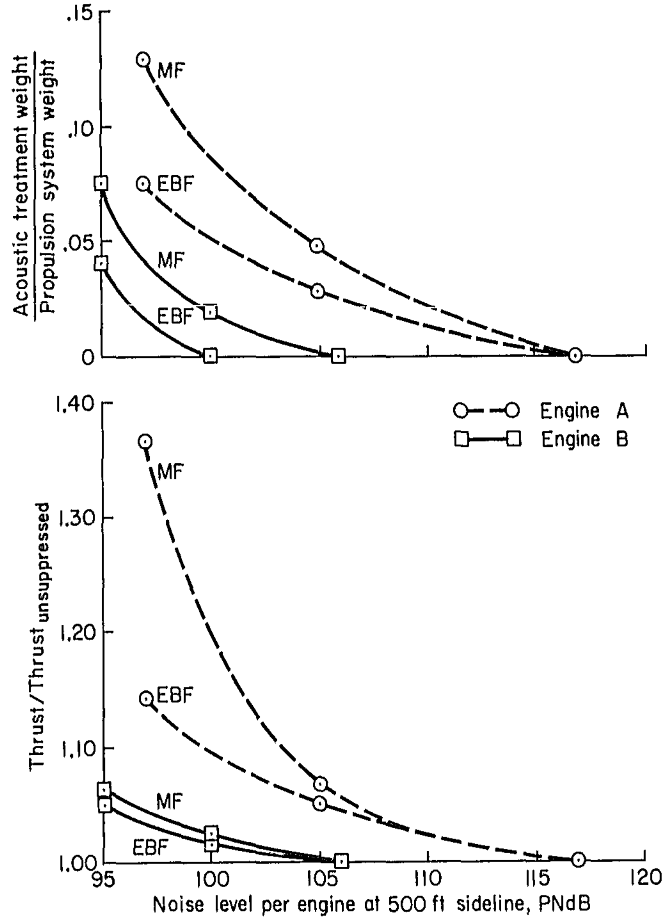


Figure 9.– Required thrust normalized by unsuppressed required thrust and acoustic treatment weight fraction of total propulsion system as a function of noise level per engine.

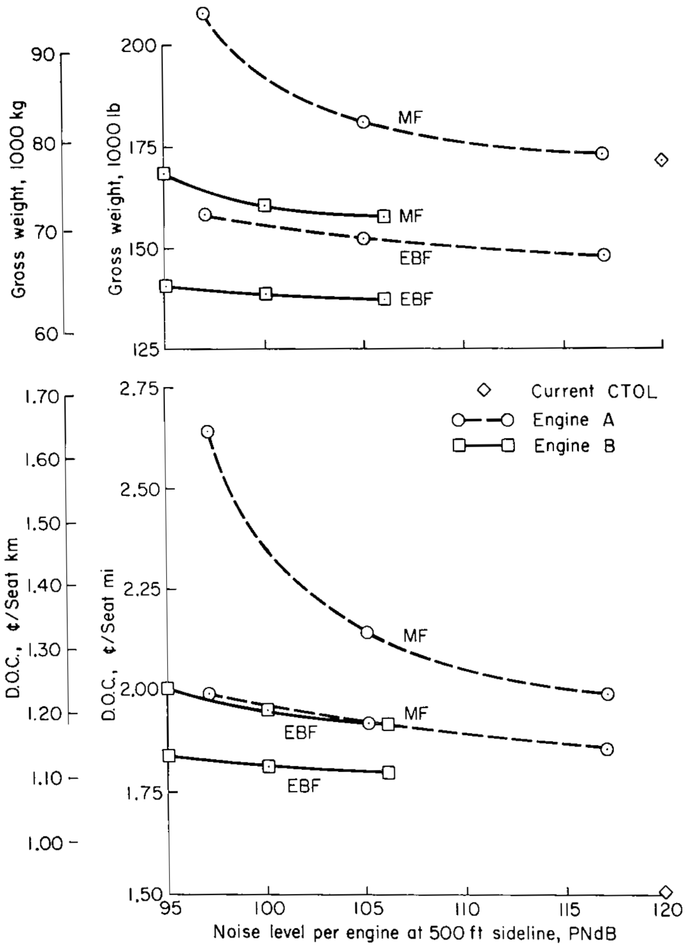


Figure 10.– Design gross weight and direct operating cost as a function of noise level per engine.

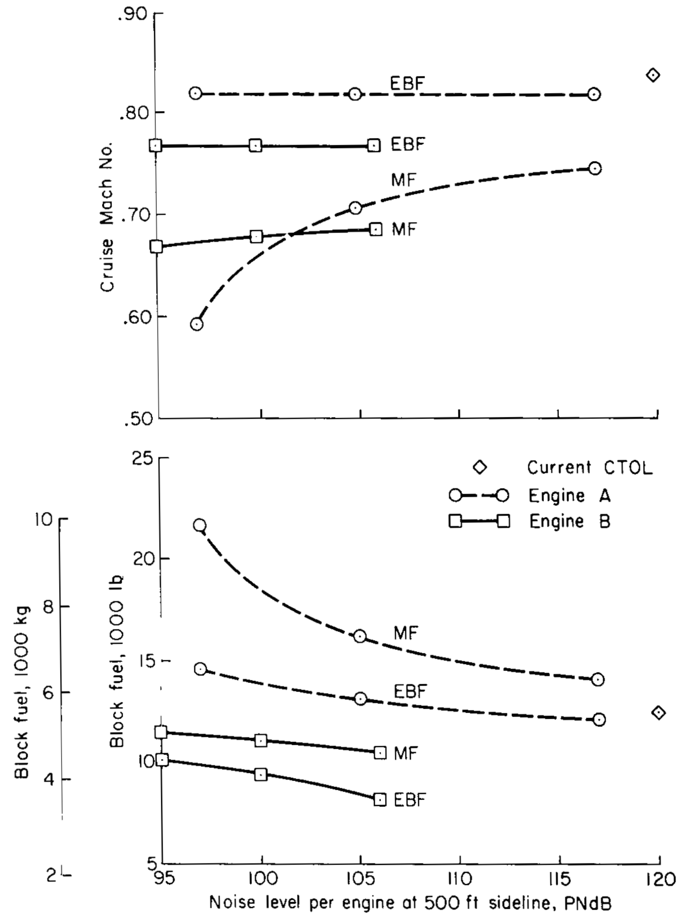


Figure 11.– Cruise Mach number and block fuel as a function of noise level per engine.

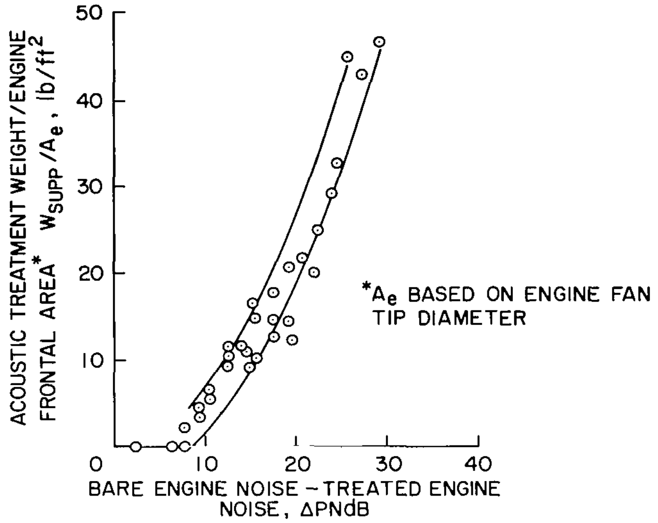


Figure 12.– Acoustic treatment weight per engine as a function of required noise suppression.

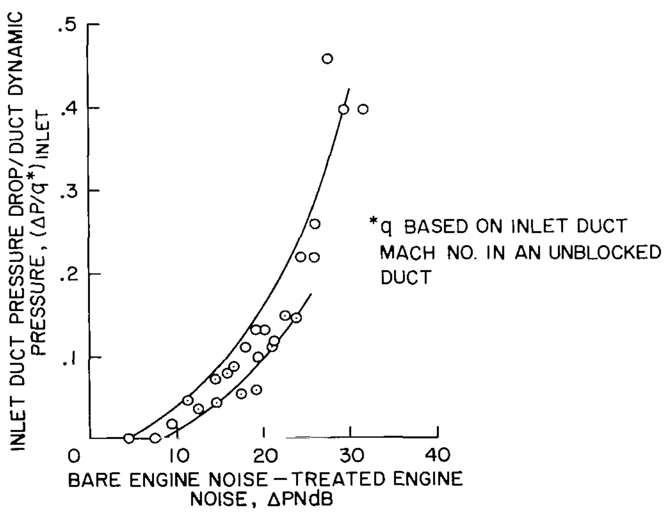


Figure 13.– Inlet duct pressure drop as a function of required noise suppression.

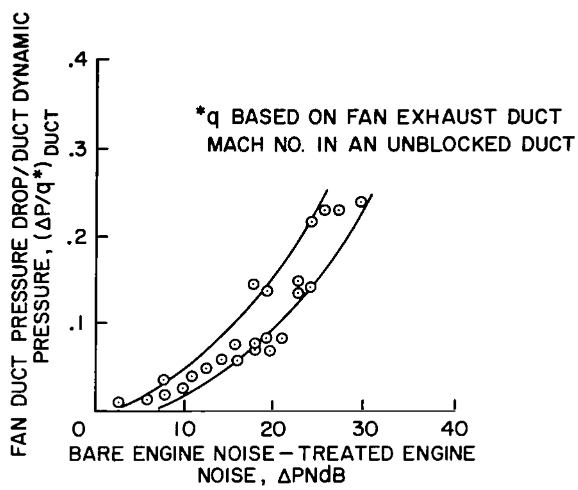


Figure 14.– Fan duct pressure drop as a function of required noise suppression.

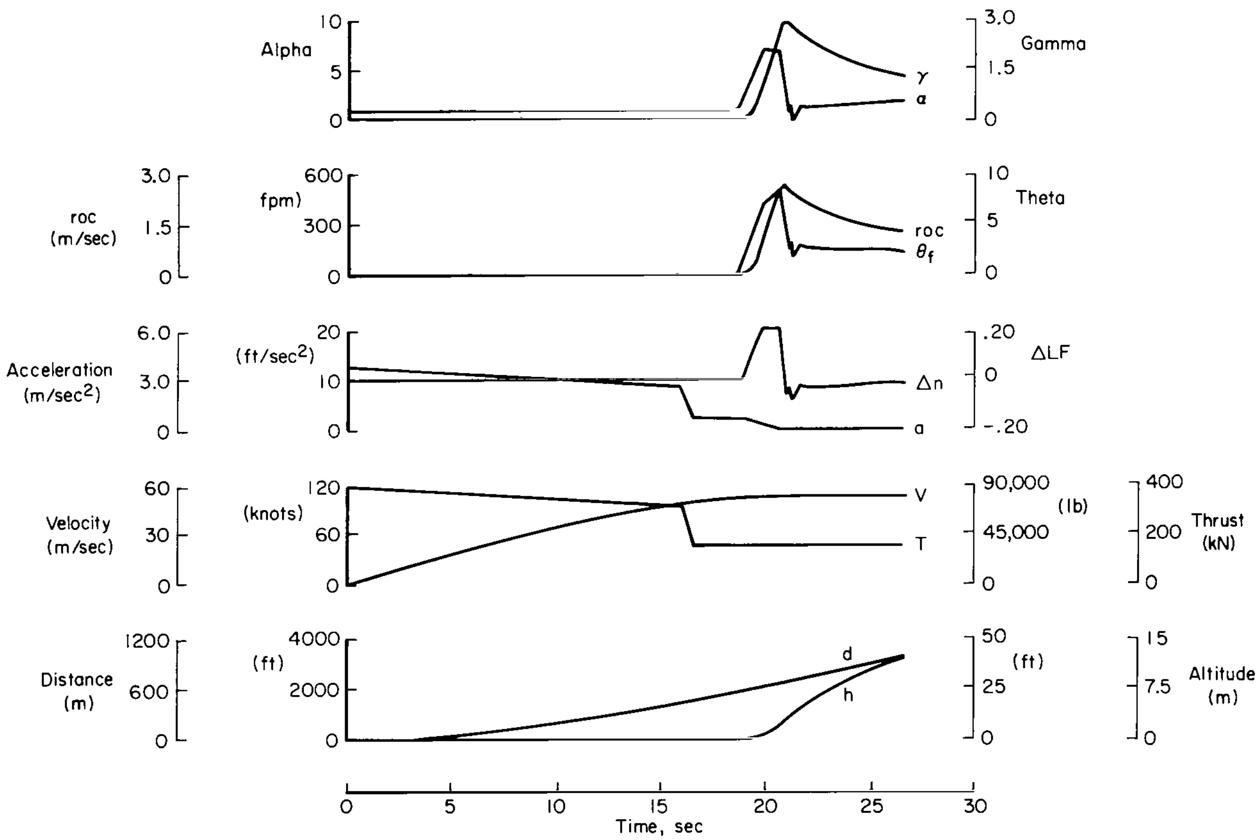


Figure 15.– Takeoff time history of MF with fully suppressed engine A.

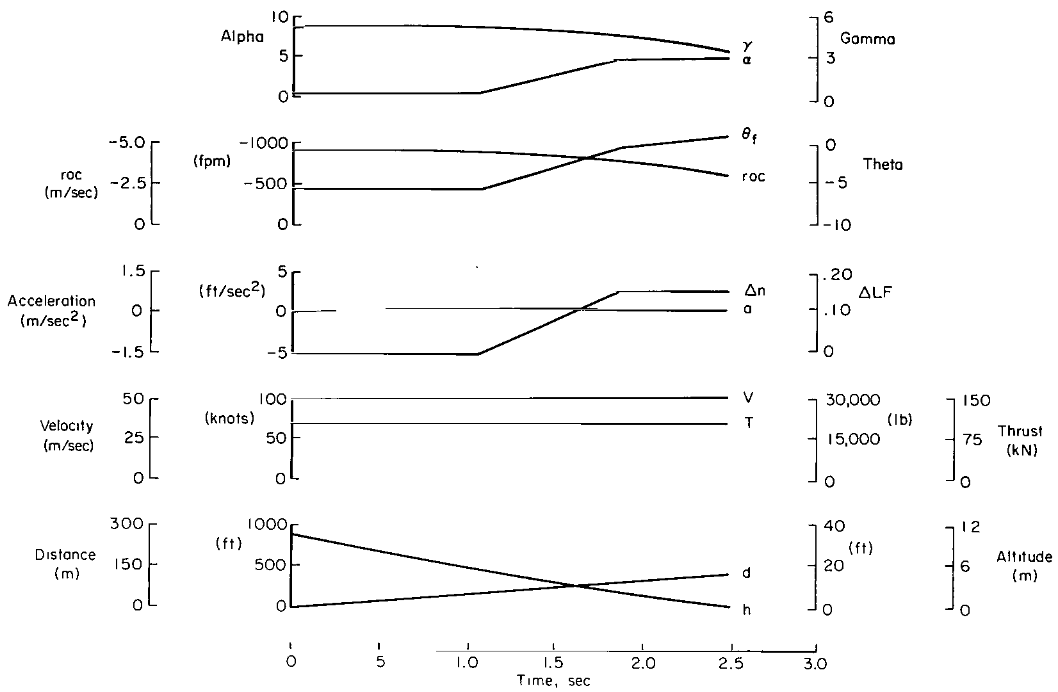


Figure 16.– Landing flare time history of MF with fully suppressed engine A.

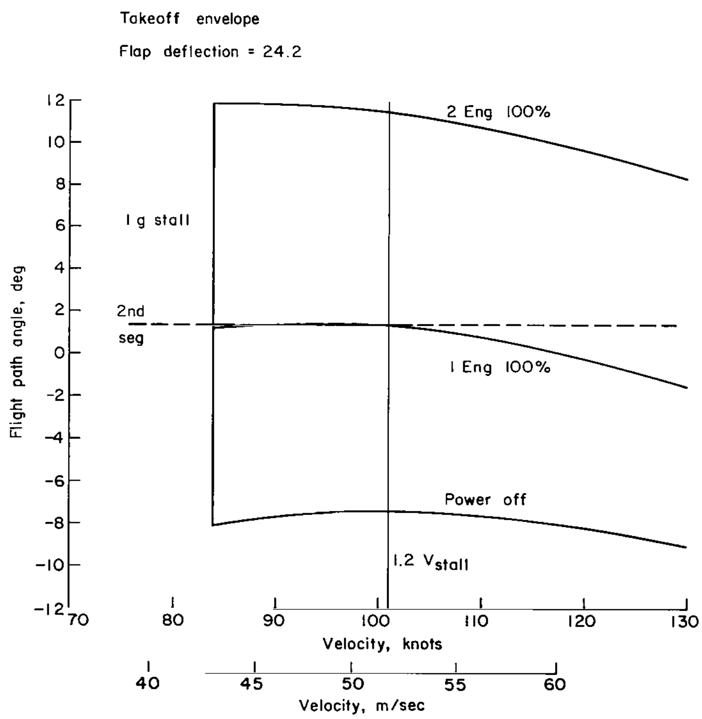


Figure 17.– Takeoff operational envelope for MF with fully suppressed engine A.

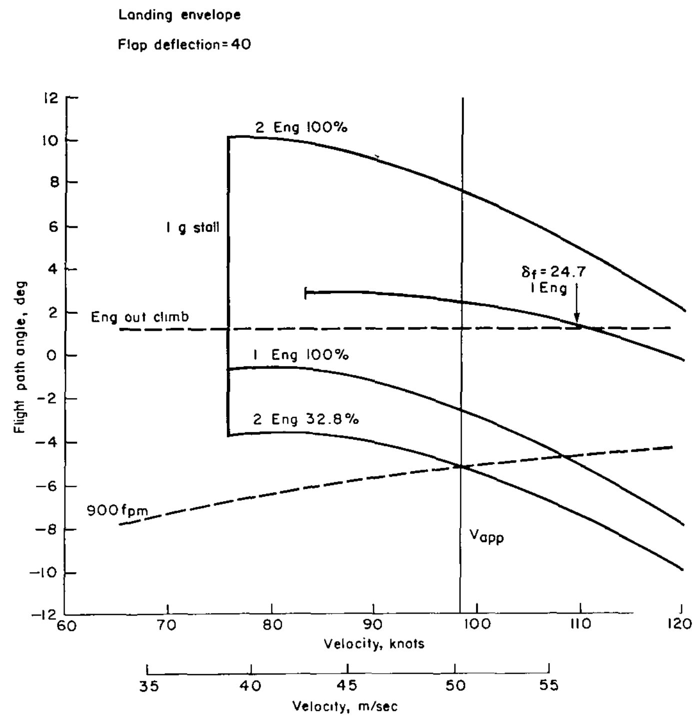


Figure 18.– Landing operational envelope for MF with fully suppressed engine A.

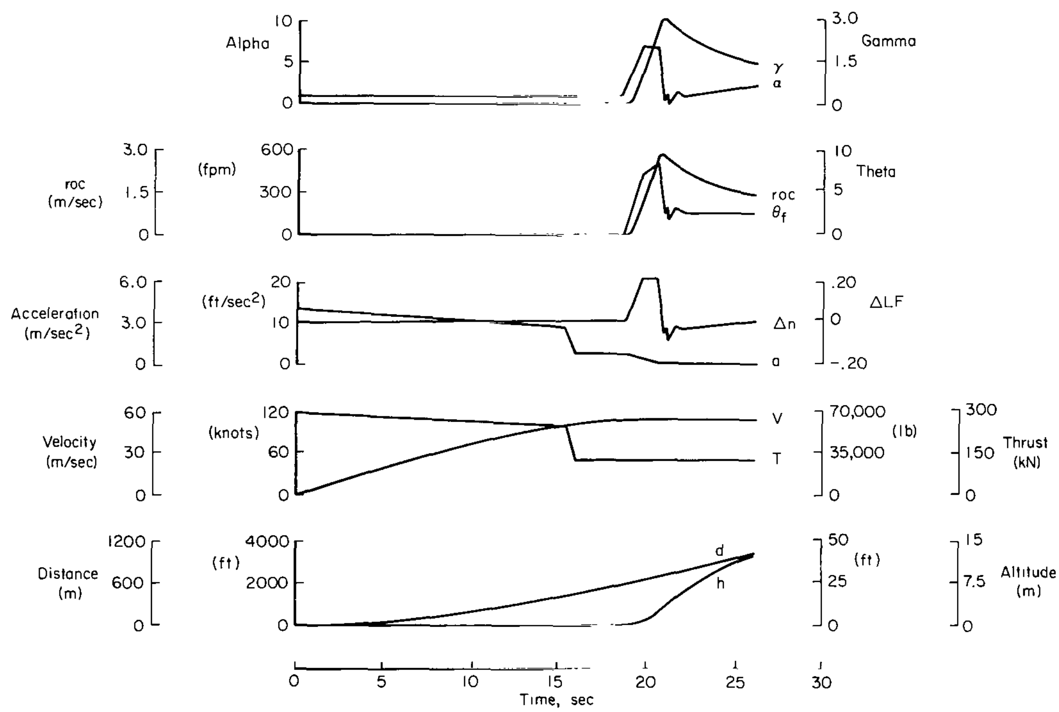


Figure 19.– Takeoff time history of MF with fully suppressed engine B.

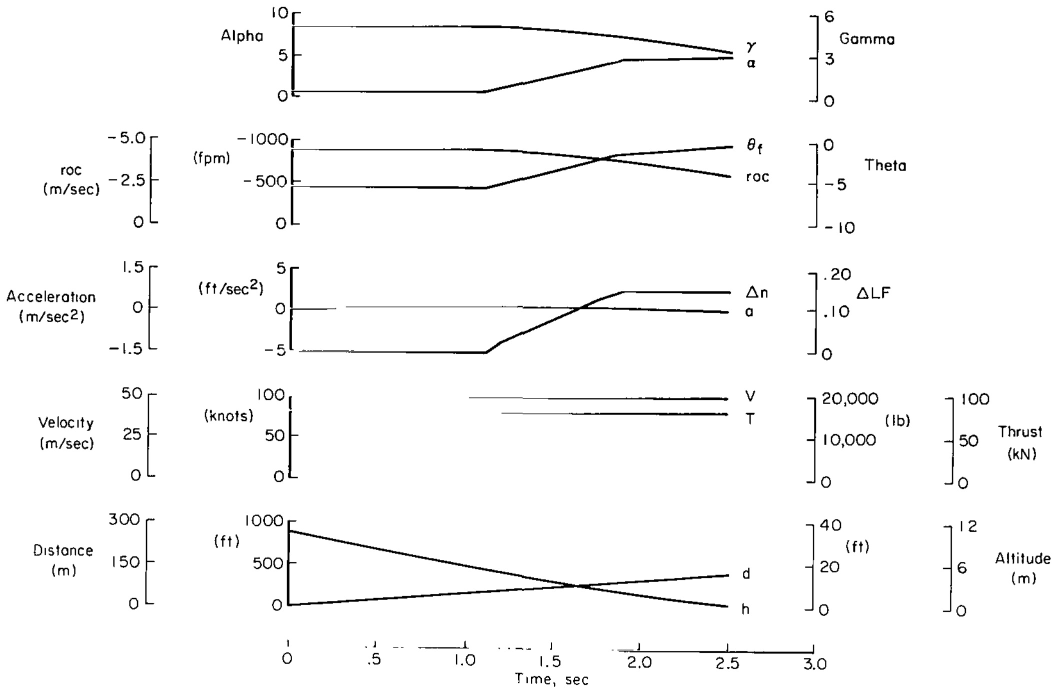


Figure 20.– Landing flare time history of MF with fully suppressed engine B.

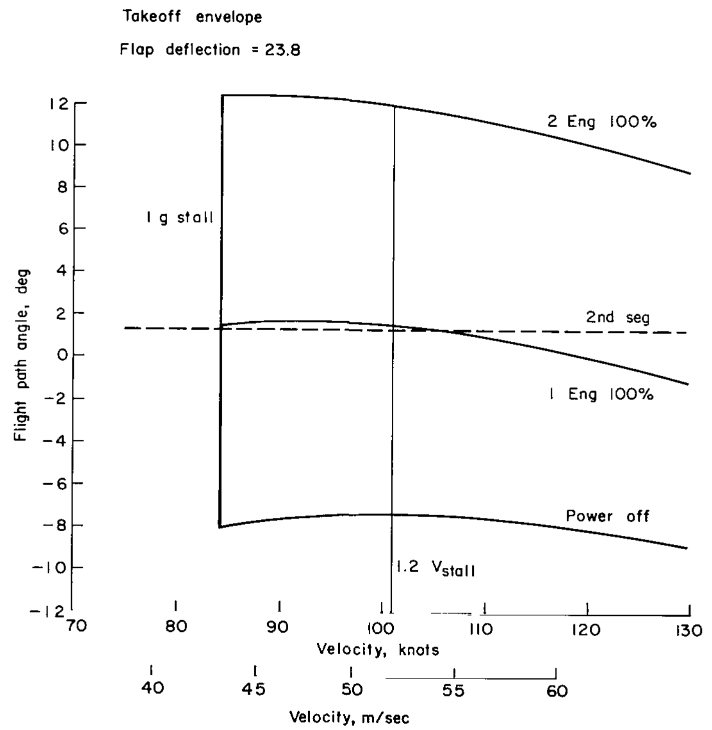


Figure 21.– Takeoff operational envelope for MF with fully suppressed engine B.

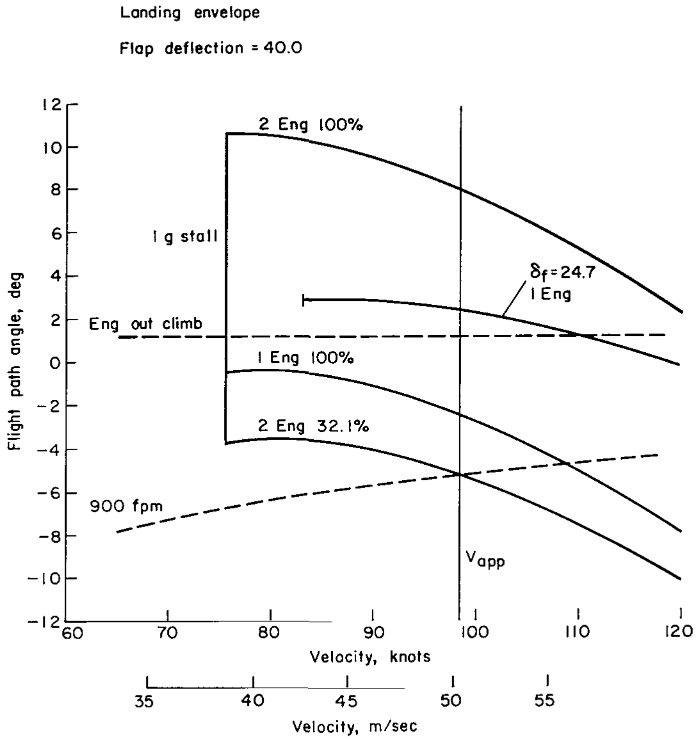


Figure 22.– Landing operational envelope for MF with fully suppressed engine B.

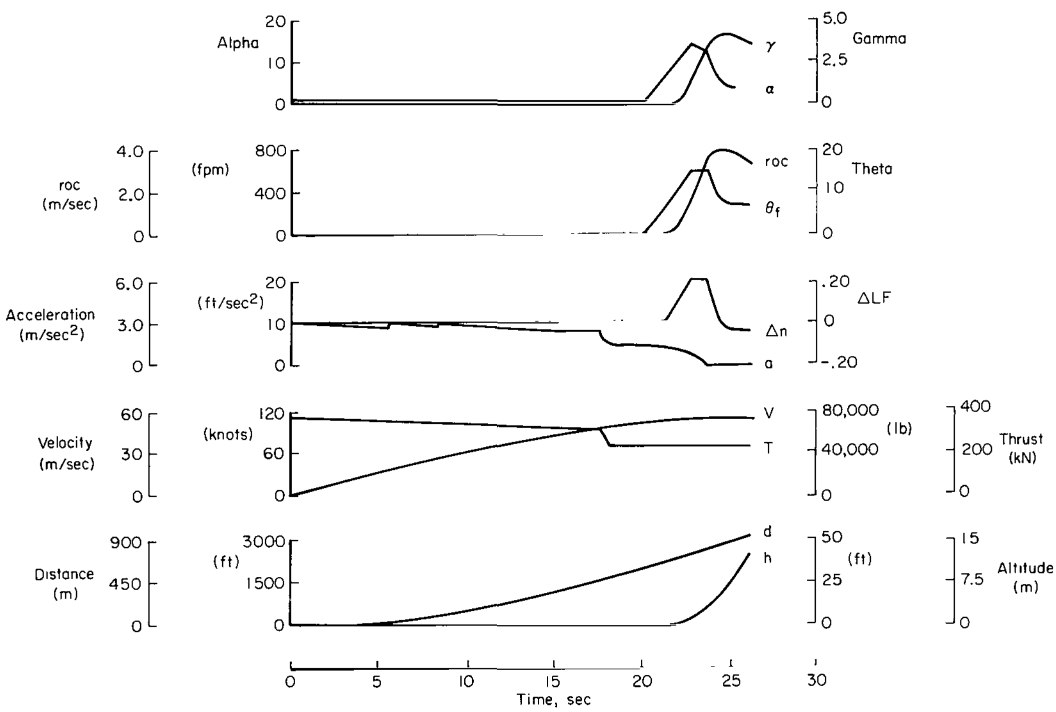


Figure 23.– Takeoff time history of EBF with fully suppressed engine A.

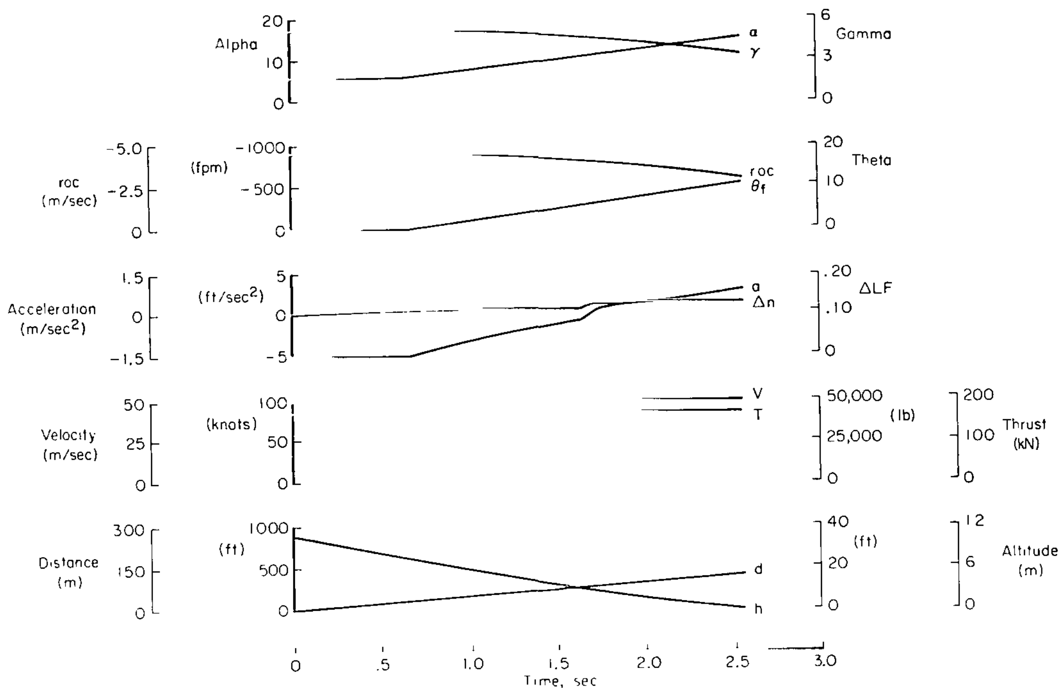


Figure 24.– Landing flare time history of EBF with fully suppressed engine A.

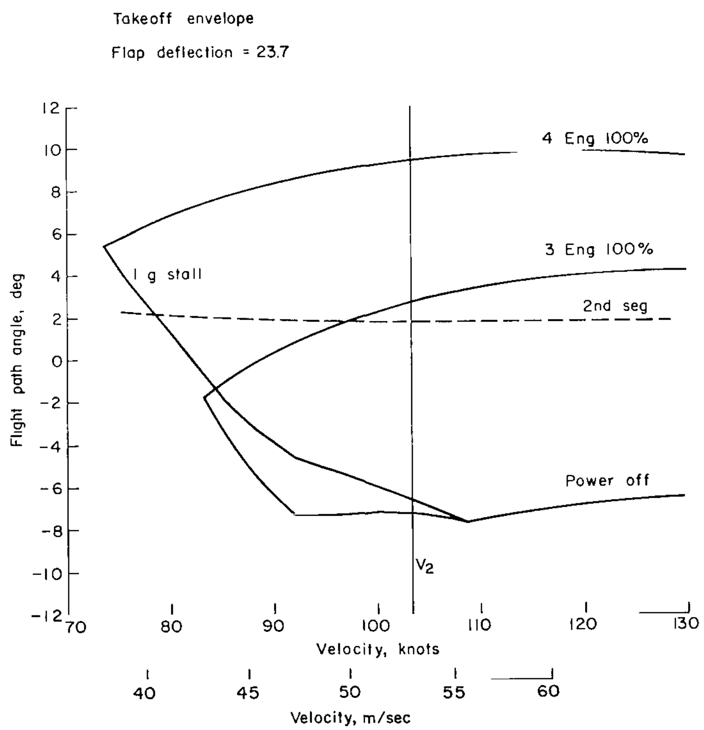


Figure 25.– Takeoff operational envelope for EBF with fully suppressed engine A.

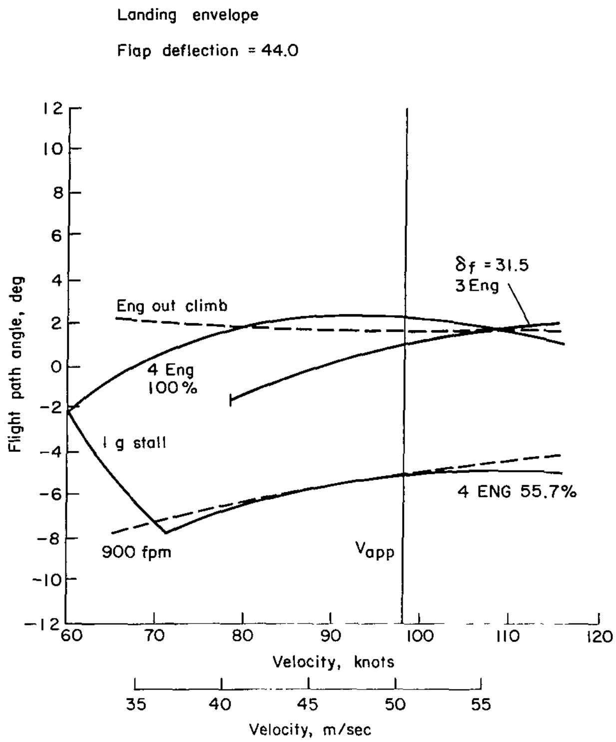


Figure 26.– Landing operational envelope for EBF with fully suppressed engine A.

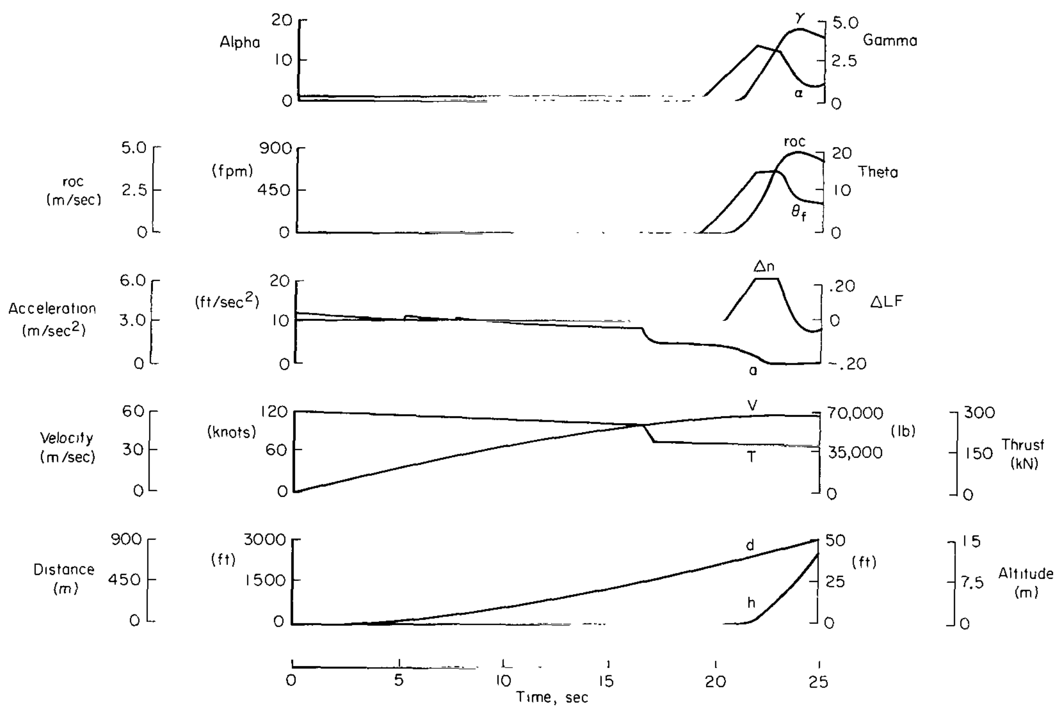


Figure 27.– Takeoff time history of EBF with fully suppressed engine B.

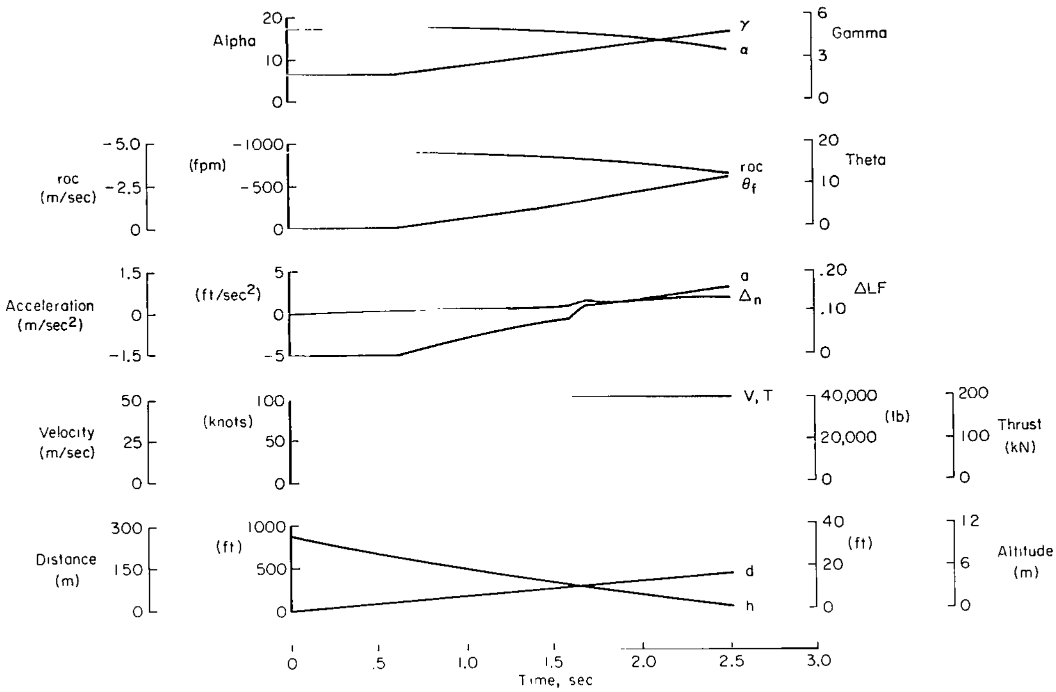


Figure 28.– Landing flare time history of EBF with fully suppressed engine B.

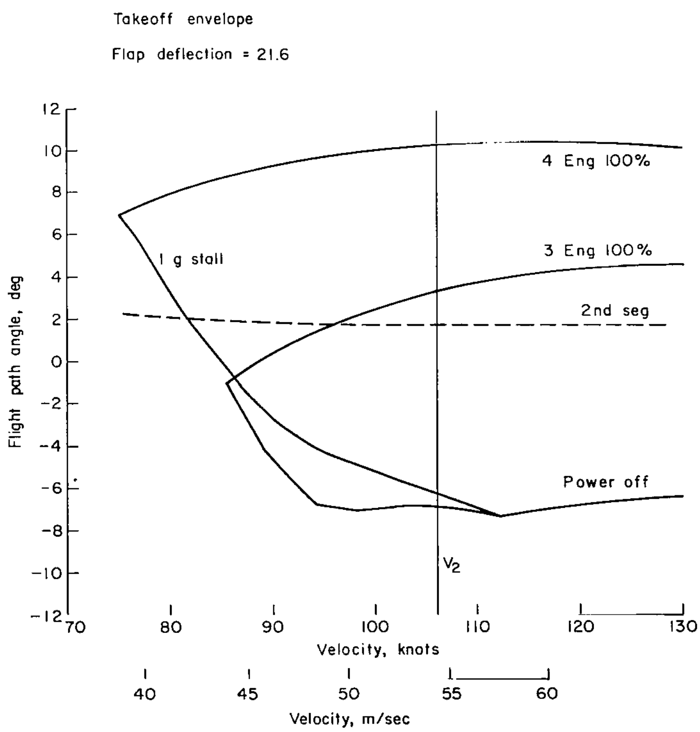


Figure 29.– Takeoff operational envelope for EBF with fully suppressed engine B.

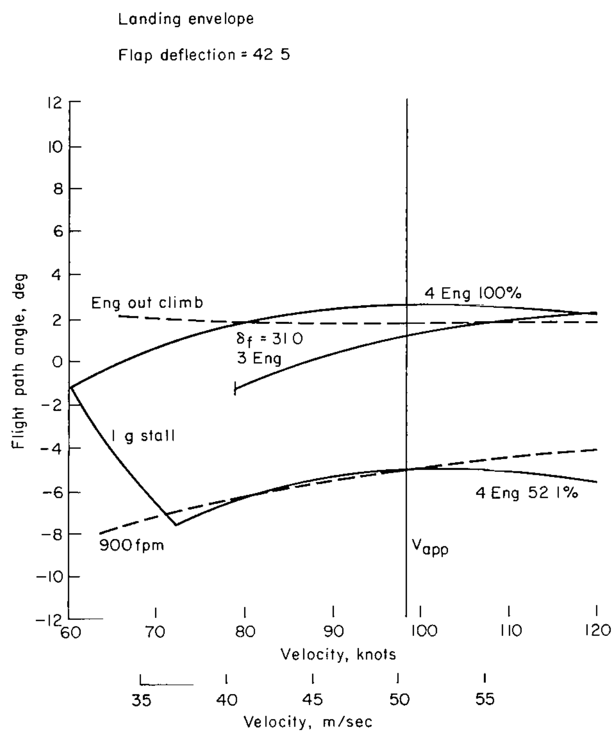


Figure 30.— Landing operational envelope for EBF with fully suppressed engine B.

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