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DESIGN OF A LARGE SPAN-DISTRIBUTED LOAD FLYING-WING CARGO AIRPLANE WITH LAMINAR FLOW CONTROL

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ABSTRACT

A design study was conducted to add laminar flow control to a previously designed span-distributed load airplane while maintaining constant range and payload. With laminar flow control applied to 100 percent of the wing and vertical tail chords, the empty weight increased by 4.2 percent, the drag decreased by 27.4 percent, the required engine thrust decreased by 14.8 percent, and the fuel consumption decreased by 21.8 percent. When laminar flow control was applied to a lesser extent of the chord (approximately 80 percent), the empty weight increased by 3.4 percent, the drag decreased by 20.0 percent, the required engine thrust decreased by 13.0 percent, and the fuel consumption decreased by 16.2 percent. In both cases the required take-off gross weight of the aircraft was less than the original turbulent aircraft.

SUMMARY

A design study was conducted to add laminar flow control to a previously designed span-distributed load airplane while maintaining constant range and payload. With laminar flow control applied to a 100 percent of the wing and vertical tail chords, the empty weight increased by 4.2 percent, the drag decreased by 27.4 percent, the required engine thrust decreased by 14.8 percent, and the fuel consumption decreased by 21.8 percent. When the laminar flow control was applied to a lesser extent of the chord (approximately 80 percent), the empty weight increased by 3.4 percent, the drag decreased by 20.0 percent, the required engine thrust decreased by 13.0 percent, and the fuel consumption decreased by 16.2 percent. In both cases the required take-off gross weight of the aircraft was less than the original turbulent aircraft.

INTRODUCTION

In a continuing NASA and industry effort to increase the fuel efficiency of aircraft, a study has been conducted to further improve the fuel efficiency of the span-distributed load flying-wing airplane concept of reference 1. To accomplish this, the parasite drag of the wing and vertical tails was reduced by inducing the airflow over these surfaces to remain laminar by the addition of a laminar flow control (LFC) system to the airplane. The performance objectives of the LFC and baseline airplane studies were the same and included the design payload of 2.669 MN (600 000 lbf) with a range of 5.926 Mm (3 200 n. mi.). In the study, the positive aspects of the system, such as reduction in fuel required and smaller sized engines, and the associated penalties such as the weight of the LFC system and the power required to operate it, were established.

The performance of two LFC configurations, one totally laminarized and the second partially laminarized, were compared to the turbulent airplane of reference 1, hereafter referred to as the baseline airplane. For ease of reference, the totally and partially laminarized vehicles will be referred to as the 100 percent and 80 percent laminar configurations, respectively. The baseline and laminarized vehicles are configured identically except for the LFC system. Design information and background discussions dealing with the baseline airplane are presented in reference 1. The objectives of this study were to establish the magnitudes of the drag reduction, structural and system weight changes, and suction power requirements, all due to the LFC system, and to evaluate their effects on performance, fuel savings, aircraft gross weight, and engine size. The wing size, as developed in reference 1, was determined by the payload. Since the payload is unchanged in this study, it was not necessary to resize the wing.

Maintenance, cost of the laminarized aircraft, and detailed design of the LFC system are not considered.

SYMBOLS

c	chord
$\bar{c}$	mean aerodynamic chord
C_D	drag coefficient, D/qS
C_{D_p}	parasite drag coefficient, D_p/qS
$C_{D_{SP}}$	suction power drag coefficient equivalent to suction power coefficient
C_f	average skin friction coefficient
C_L	lift coefficient, L/qS
C_p	pressure coefficient, $(P_s - P_\infty)/q_\infty$
C_{SP}	suction power coefficient, $(\frac{\rho_w V_w}{\rho_\infty V_\infty} - C_p \times \frac{V_w}{V_\infty})$
D	drag
f	laminarized wing area factor

k	suction slot efficiency factor
KEAS	equivalent airspeed in knots
L	lift
LFC	laminar flow control
M	Mach number
MAC	mean aerodynamic chord
OWE	operating weight empty
P_s	local static pressure
q	dynamic pressure
R_e	Reynolds number
S	projected wing area
t/c	thickness to chord ratio
s	surface distance from stagnation point
T	thrust
TOGW	take-off gross weight
TSFC	thrust specific fuel consumption
T/W	thrust to weight ratio
V	velocity
W	weight
W/S	wing loading
δ	control surface deflection
ρ	air density

Subscripts:

∞	free stream
w	wall or local condition

p pressure

VT vertical tail

BASIC DESIGN CRITERIA

This study, evaluating the effect of LFC application on the performance capabilities of a span-distributed load aircraft, was guided by specific design criteria. The criteria pertaining to the baseline (turbulent) airplane, presented in reference 1, are still applicable. The configuration is a flying wing, with tip-mounted vertical tails and a relatively small fuselage for flight deck and crew accommodation. The wing planform includes 30° sweep with no taper, and the wing has a symmetrical airfoil section developed by Langley Research Center and having a $t/c = 0.20$. Cargo will be carried in an unpressurized compartment sufficient in size to carry 2.44 m x 2.44 m (8 ft x 8 ft) cargo containers of assorted lengths, and with loading conducted at the wing-tips. Payload of 2.669 MN (600 000 lbf), with a density of 160.2 kg/m^3 (10 lbm/ft^3) including containers, will be carried over a range of 5.926 Mm (3 200 n. mi.) at a cruise Mach number of at least 0.7. The maximum runway length required will be limited to 3.658 km (12 000 ft). The propulsion units will be current production turbofan engines, scaled if necessary.

Additional criteria were established for the LFC equipped aircraft. Two differing extents of LFC will be studied; one vehicle with 100 percent of the chord laminarized on both upper and lower surfaces of the wing and on 100 percent of the chord of the wing mounted vertical tails, and a second vehicle with laminarization on 80 percent of the chord on both upper and lower surfaces, from the leading edge aft to the high-lift and control systems hinge lines of the wing and wing-mounted vertical tails. In both vehicles, the following areas will not be considered to be laminarized: (a) fuselage-wing juncture areas and (b) the wing area affected by engine noise and strut-wing interference. No leading-edge devices will be employed due to laminarization requirements. Note that the baseline airplane did not require leading-edge devices. Operating weight increases due to the LFC system will be based on data contained in studies by systems contractors to NASA in the laminar flow control portion of the Aircraft Energy Efficiency Program (ACEE/LFC). The LFC system will be considered to be capable of maintaining laminar flow only where flight conditions result in a unit Reynolds number less than or equal to 6.56×10^6/m (2×10^6/ft).

CONFIGURATION

The baseline, turbulent vehicle for this study is that of reference 1. The three-view drawing from reference 1 is repeated herein as figure 1. LFC systems have been added internally to this configuration. Two configurations were studied, one with 100 percent wing and vertical tail laminarization, and the other with 80 percent laminarization of these surfaces. The areas laminarized are defined in the Basic Criteria section.

Projected laminarized area for the 100 percent laminar case is defined to include that of the entire wing [1724.3 m^2 (18 560 ft^2)] and vertical tails [219.4 m^2 (2 362 ft^2)], less the estimated areas of the wing-body interference [37.2 m^2 (400 ft^2)] and wing-engine interference [24.5 m^2 (264 ft^2)]. This resulted in 1882.0 m^2 (20 258 ft^2) of projected laminarized area, of which 1662.6 m^2 (17 896 ft^2) is wing area.

The projected laminarized area for the 80 percent laminar case was determined to be equal to the 100-percent laminar-case area, less the projected flap, elevon, and spoiler areas [351.9 m^2 (3 788 ft^2)], and less the rudder areas [30.7 m^2 (330 ft^2)], which resulted in 1499.5 m^2 (16 140 ft^2). This consists of 1310.7 m^2 (14 108 ft^2) of laminarized wing area and 188.8 m^2 (2 032 ft^2) of laminarized vertical tail area.

MASS PROPERTIES

The basis for the weights data utilized in determining the performance of the span-distributed load airplane with LFC are presented in this section. These data are presented in two subsections. The first contains weight penalty parameters establishing weight increases due to the structural requirements for incorporating an LFC system and the weight increases due to the LFC system itself. In the second subsection, the weight breakdowns of the study configurations are defined for both the first airplane-sizing step with 240.2 kN (54 000 lbf) engines, and the second sizing step with minimum thrust engines for the LFC equipped aircraft. Operating weight variations as a function of both engine size and fuel loading are also covered. The baseline airplane weights data in this section are from reference 1.

LFC Wing Structure and Suction System Weight Penalty Parameters

System contractors in the ACEE/LFC studies have provided data for determining the weight increases in wing structure and suction systems attributable to adding an LFC system to an airplane. One of the ACEE/LFC study airplanes was selected for the derivation of the weight penalty parameter. This airplane was evaluated with and without LFC in the above study and, from the data provided, weight penalties were derived in the following way:

Structural weight penalty parameter. - For the airplane without LFC in the ACEE/LFC study, a conventional aluminum skin-stringer wing structure was used with a total wing structural weight of 220. kN (49 460 lbf). The LFC configuration had an aluminum honeycomb structural concept and a resulting wing structural weight of 232. kN (52 220 lbf). Thus, the wing structural weight penalty for LFC is the difference between the two and is equal to 232. kN - 220. kN = 12. kN (2 760 lbf). The projected laminarized wing area of the selected ACEE/LFC configuration is 203.5 m^2 (2 190 ft^2). Based on this area and the preceding structural weight penalty, the structural weight penalty per unit of laminarized wing area becomes: 12. kN/203.5 m^2 = 60.33 Pa (1.26 lbf/ft^2).

LFC system weight penalty parameter. - Based on the same data source that produced the preceding parameter, the weight increase due to the LFC system, which includes pumps, power unit, ducting, and other equipment, was established as 33.52 Pa (0.70 lbf/ft^2) per unit of laminarized area.

Weight Analysis

The weight data for the baseline aircraft are as previously published in reference 1. The weight increases due to LFC are based on the unit weight criterion discussed in the previous subsection. This criterion, the sum of structural and system weight penalties, is equal to 93.85 Pa (1.96 lbf/ft^2). Note that the weight penalties are based on projected laminarized areas. The same criteria were also applied to the vertical tails. A breakdown of the LFC system weights is presented in Table I, for both the 100 percent and 80 percent laminar configurations. The areas affected are defined in the section entitled "Configuration".

The vehicle weights, discussed in the following paragraph and presented in Tables II and III, were computed utilizing a mass properties computer program developed by the Vought Corporation Hampton Technical Center.

The effects on OWE of the introduction of LFC to the aircraft with the same powerplants [240.2 kN (54 000 lbf) each] and mission are shown in Tables II and III(a). In analyzing these data, it was observed that without the LFC weight penalty, OWE actually decreased with increasing laminarization, a consequence of the reduction in required fuel. The extent of these OWE decreases is presented in the table below.

	Baseline	100% Laminar	80% Laminar
OWE, MN , (lbf)	1.720 386 000	1.870 420 500	1.846 414 900
*ΔWeight, kN , (lbf)	0 0	176.6 39 700	140.6 31 600
OWE without LFC, MN , (lbf)	1.720 386 600	1.644 380 800	1.705 383 300

* LFC weight penalty from Table I.

For the aircraft with varying size engines, the effects of LFC on OWE are presented in Tables II and III(b).b).

The above weights data, for both the constant and varying size engines configurations, were used in the Mission Analysis section to size the aircraft.

SUCTION POWER REQUIREMENTS

One of the penalties of an LFC system is in the form of the power required to provide the suction. This suction power has been theoretically determined in coefficient form, and it was expressed as an equivalent incremental drag coefficient for airplane performance calculation purposes.

The suction power coefficient at any point on the surface is defined as follows:

$$C_{SP} = \frac{\rho_w V_w}{\rho_\infty V_\infty} - C_p \cdot \frac{V_w}{V_\infty} \qquad (1)$$

The derivation of equation (1) is shown in the Appendix. System losses such as those in pumps, ducts, valves, etc., are not accounted for in the C_{SP} coefficient.

The chordwise solution of the C_{SP} equation was accomplished with the aid of two computer programs provided by NASA/LaRC. The first program was a two dimensional transonic analysis program based on references 2 and 3, and the second was the STAYLAM boundary layer program (ref. 4). With input data consisting of airfoil coordinates and the flight conditions of interest, the first program produced the surface pressure (C_p) and Mach number distributions around the upper and lower surfaces of the airfoil. This output was then used as the input to the STAYLAM program which computed the local density (ρ_w) and the suction velocity (V_w) required to maintain laminar flow along both the upper and lower wing surfaces.

The conditions for which the suction power was determined correspond approximately to those at the start of cruise and are: altitude = 10 120 m (33 200 ft); Mach no. = 0.75; C_L = 0.325; and R_e = 122.9 x 10^6. Suction power was only calculated at the start of cruise because of the extensive computation time involved. The calculated results are presented in figures 2, 3, and 4 which show the chordwise distributions of C_p, ρ_w/ρ_∞, and V_w/V_∞, respectively. These values were then used to evaluate equation (1). The resulting chordwise distribution of the local power coefficient along the upper and lower wing surfaces is presented in figure 5.

The areas under the curves in figure 5 were integrated graphically to obtain the airfoil power coefficient based on chord per unit of wing span. Since two laminarization levels were to be considered, 100 percent and 80 percent, the integration was performed from the stagnation point to the trailing edge and again from the stagnation point to the control surface hinge lines. Three-dimensional effects along the span were ignored; thus the power coefficient for the airfoil is the same as that for the entire wing except that the nonlaminar areas of the wing-body and wing-nacelle intersections have to be accounted for. Thus the power coefficient for the wing $C_{SP_{wing}}$ = $C_{SP_{airfoil}}$ x f, where f = 0.9 (estimated). The magnitude of the power required is obtained with the value of the power coefficient and the following equation:

$$\text{Power} = C_{SP_{wing}} \times \frac{1}{2} \rho_\infty V_\infty^3 \times S \qquad (2)$$

Equation (2) can be rewritten as follows:

$$\text{Power} = (C_{SP_{wing}} \times \frac{1}{2} \rho_\infty V_\infty^2 \times S) \times V_\infty \qquad (3)$$

Since power equals the product of force and speed, the part within the parenthesis in equation (3) will have the units of a force, and it can be viewed as an equivalent drag with $C_{SP_{wing}}$ as an equivalent drag coefficient (designated

$C_{D_{SP}}$ in this report).

For the wing alone the $C_{D_{SP}}$ values were found to be .0015 and .0014 for the 100 percent and 80 percent laminarization cases, respectively.

The suction power coefficients for the vertical tails could not be determined by the method employed for the wing since the airfoil section and airloads on the fins were not defined in sufficient detail during the study of reference 1. An estimate of the $C_{SP_{VT}}$ was made by multiplying $C_{SP_{wing}}$ by the ratio of vertical tails area to wing area (0.1273).

Therefore, the total suction power (or equivalent drag) coefficients for wing and vertical tails combined are equal to .0017 for the 100 percent laminar vehicle and .0016 for the 80 percent laminar vehicle.

PROPULSION

The installed engine performance data base, used in mission studies of the laminarized configuration of the span-distributed load airacraft, is identical to that of the baseline vehicle (ref. 1). As in reference 1, the JT9D-7 turbofan engine performance and size has been scaled (based on the data of reference 5) to meet the mission requirements.

Performance scaling (thrust and fuel flow) is accomplished by applying the relative thrust ratio (thrust desired to base thrust) to the base thrust and fuel flow. Base installed thrust is 185.1 kN (41 613 lbf) at sea-level static standard-day conditions and is the value to which the corresponding desired thrust is proportioned to obtain the relative thrust ratio. Scale factors for engine weight, length and diameter are obtained from reference 5 as a function of the relative thrust ratio.

Engine performance is normally scaled to the proper size in the Langley Research Center long-range-cruise-mission computer program by inputting the relative thrust ratio to the program. Based on the relative thrust, the program adjusts the base engine thrust to the required level, and then determines the corresponding engine fuel flow rate.

DRAG

The drag polars for the fully (100 percent) and partially (80 percent) laminarized versions of the span-distributed load aircraft are derived from the polars of the baseline vehicle. Since the baseline polars are for a fully turbulent aircraft, these were modified to reflect the reduced skin friction and associated effects due to laminarization. A detailed breakdown of those drag items which differ between configurations is presented in Table IV.

Parasite drag coefficients were calculated by standard methods, using flat-plate turbulent and laminar skin-friction coefficients adjusted for the effects of supervelocity, interference, pressure, roughness, and excrescences. Nacelle parasite-drag coefficients were also adjusted for boattail effects and loss of leading edge suction.

The magnitude of the laminarization effect on the $C_{D_{p_{min}}}$ of the airplane components directly affected and on the total airplane can be obtained from the data in Table IV. The wing plus vertical tails $C_{D_{p_{min}}}$ decreased from the baseline airplane by 86.1 percent for the 100 percent laminar airplane and 67.4 percent for the 80 percent laminar airplane. For the total airplane, the decreases in $C_{D_{p_{min}}}$ amounted to 61.8 percent and 48.3 percent, for the 100 percent and 80 percent laminar configurations, respectively. It is also interesting to note that, for the 100 percent laminar configuration, approximately 79 percent of the surface area of the aircraft is laminarized, while in the 80 percent laminar vehicle the equivalent ratio is approximately 63 percent.

The resulting polars for the laminarized configurations are equal to the baseline polars shifted by a constant increment in C_D. These polars are presented in figures 6 and 7, for the 100 percent and 80 percent laminar aircraft, respectively. Note that the polars for the laminarized configuration do not include the $C_{D_{SP}}$ equivalent to the suction power required to operate the LFC system, as derived in the section on suction power requirements. Adding this $C_{D_{SP}}$ (.0017 for the 100 percent and .0016 for the 80 percent laminar cases) to the basic minimum parasite drag coefficient reduces the gains discussed in the preceding paragraph. For the wing plus vertical tails, the $C_{D_{P_{min}}}$ decrease from the baseline airplane becomes 63.7 percent for the 100 percent laminar airplane and 46.3 percent for the 80 percent laminar airplane. The total airplane $C_{D_{P_{min}}}$ decrease is reduced to 45.7 percent and 33.2 percent for the 100 percent and 80 percent laminar cases, respectively.

The effect of laminarization on lift-drag ratio is presented in figure 8 in the form of L/D versus lift coefficient for a cruise Mach number of 0.75. Note that the L/D curves are shown for the laminarized configurations with and without the suction power $C_{D_{SP}}$.

MISSION ANALYSIS

The aircraft's basic mission is that of cargo transport, with a design range of 5.926 Mm (3 200 n. mi.) and with a 2.67 MN (600 000 lbf) payload. The cruise speed (M = 0.75) and reserves were left unchanged from the previous study, reference 1. Taxi, take-off, and descent fuels were scaled according to engine size (thrust) from JT9D-7 engine data discussed in the section on propulsion.

The main objectives of this mission analysis were to determine the LFC aircraft weight, engine size, and fuel required for the specified design mission. An analysis was also conducted to establish the effects on performance of LFC system weights and suction-power equivalent drag, separately and combined. Mission calculations were conducted with the Langley Research Center long-range-cruise-mission computer program. All performance was based on standard-day atmospheric conditions. The aircraft climbs as it cruises to maintain a constant Brequet range factor.

The equivalent drag increase resulting from operation of the LFC system has been applied only to that part of the mission where fully effective operation of the LFC system can be expected; that is, in the latter part of the climb and in cruise. The criterion for such effective operation is a R_e per unit length less than or equal to 6.56 x 10^6/m (2 x 10^6/ft). To insure that this criterion was met prior to the start of cruise, the climb speed of the baseline aircraft, 518.6 km/hr (280 KEAS), was reduced to 463 km/hr (250 KEAS). This revised climb schedule allowed effective LFC to begin while still climbing at 9.7 km (31 800 ft) altitude and M = 0.72, somewhat before reaching the initial cruise altitudes [which are 10.2 km (33 500 ft) for the 100 percent laminar case and 10.5 km (34 500 ft) for the 80 percent laminar case].

Initial Airplane Sizing
(constant engine size)

Through an iterative procedure involving changes in airplane empty weight as a function of gross weight which, in turn, is determined by the total required mission fuel, the LFC equipped aircraft were sized for 5.926 Mm (3 200 n. mi.) range with 2.67 MN (600 000 lbf) payload. During these initial sizings, the LFC aircraft were equipped with the same six 240.2 kN (54 000 lbf) thrust engines which powered the baseline airplane (ref. 1). For the 100 percent laminar case, the fuel required for the mission was determined to be 138.6 Mg (305 500 lbm) at a corresponding OWE of 1.870 MN (420 500 lbf), and a resulting take-off gross weight of 5.898 MN (1 326 000 lbf). The 80 percent laminar case required 146.6 Mg (323 300 lbm) of fuel, had an OWE of 1.846 MN (414 900 lbf), and a take-off gross weight of 5.953 MN (1 338 200 lbf) to accomplish the same mission. The above values are included in Table II.

Effect of Engine Sizing on Range

Due to the reduced drag levels and consequently reduced fuel and gross weights of the LFC equipped span-distributed load aircraft compared to the baseline airplane, an investigation was made to determine the minimum size engines for the design range. The investigation was conducted in two steps. First, range was determined as a function of engine size, and the engine that resulted in the longest range was selected. In this first step, fuel was held constant and equal to that required by the configuration to perform the design mission with 240.2 kN (54 000 lbf) thrust engines.

The OWE for each engine size was obtained from the weight analysis section. The constant fuel quantities determined in the first iteration are 138.6 Mg (305 500 lbm) and 146.6 Mg (323 300 lbm) for the 100 percent and 80 percent laminar cases, respectively. The resulting first-step take-off gross weights and ranges, together with OWE, are presented in figure 9 and 10 for the 100 percent and 80 percent laminar configurations, respectively. Note that the range increases with decreasing engine size. This trend continued down to 204.6 kN (46 000 lbf) thrust engine size for the 100 percent laminar case, and to 209.1 kN (47 000 lbf) thrust engines for the 80 percent laminar case. In both LFC cases, engines of lesser thrust had cruise ceilings less than the altitude for starting LFC operation.

For the second step, both LFC aircraft with minimum thrust engines, were then re-sized to the 5.926 Mm (3 200 n. mi.) design range. The mission results and finalized aircraft characteristics are presented in detail in Tables V and VI, for the 100 percent and 80 percent laminar cases, respectively. The last value in the tables is fuel efficiency.

The degree of accuracy attained in sizing the laminar airplanes was considered to be reasonable for this study. Slight additional accuracy could have been achieved if the iteration had been carried one step further by repeating the preceding parametric study with variable engine size and constant fuel, but also with the newly determined amount of fuel. The effect of an additional iteration was approximated by assuming that T/W remains unchanged during an iteration. It appears that engine size could have been reduced by an additional one percent.

The take-off field lengths of the LFC equipped aircraft with minimum thrust engines were determined based on the take-off study conducted for the baseline airplane (ref. 1). In that study, take-off field lengths were determined as a function of wing loading and thrust to weight ratio. The resulting curve is presented in figure 11. The field lengths for the LFC equipped aircraft are indicated on the figure; these are 2.658 km (8 720 ft) for the 100 percent laminar case and 2.676 km (8 780 ft) for the 80 percent laminar case. These distances are well below the required field length value of 3.658 km (12 000 ft).

Drag Coefficient Change

A study was conducted involving the sensitivity of the ranges of the laminarized airplanes to changes in C_D. Both the 100 percent and 80 percent laminar cases were evaluated over a range of engine sizes. As in the preceding engine sizing study, fuel available was held constant and equal to the fuel required for 5.926 Mm (3 200 n. mi.) range with 240.2 kN (54 000 lbf) thrust engines. Take-off gross weights were based on OWE versus engine thrust from the Weights Summary section. The resulting performance in the form of ΔRange per ΔC_D, km per drag count (n. mi. per drag count), is presented in figure 12. Note that one drag count = .0001.

CONCLUDING REMARKS

A design study was conducted to add laminar flow control to a previously designed span-distributed load airplane while maintaining constant range and payload. With laminar flow control applied to 100 percent of the wing and vertical tail chords, the empty weight increased by 4.2 percent, the drag decreased by 27.4 percent, the required engine thrust decreased by 14.8

percent, and the fuel consumption decreased by 21.8 percent. When laminar flow control was applied to a lesser extent of the chord (approximately 80 percent), the empty weight increased by 3.4 percent, the drag decreased by 20.0 percent, the required engine thrust decreased by 13.0 percent, and the fuel consumption decreased by 16.2 percent. In both cases the required take-off gross weight of the aircraft was less than the turbulent aircraft.

APPENDIX

REQUIRED SUCTION POWER EQUATION AND DERIVATION

This appendix presents a derivation of an equation which can be used to determine the theoretical suction power required for laminar flow control. The resulting expression for the suction power does not account for system losses such as those experienced in ducts, valves, pumps, etc. The derivation is basically the same as that developed in reference 6 except that the difference in densities of the air at the LFC surface and in the free stream is accounted for.

Derivation

The absolute pressure on the inside of a suction opening in a LFC surface p_i must be lower than that on the outside p_o in order to suck the air in. If this pressure difference is denoted as Δp

$$p_i = p_o - \Delta p$$

Now, subtract the free stream pressure p_∞ from both sides of the equation and divide all terms by the free stream dynamic pressure q_∞, to obtain

$$C_{p_i} = C_{p_o} - \frac{\Delta p}{q_\infty} \tag{1}$$

Power is required to create the pressure difference Δp and to overcome efficiency losses in the suction opening. The power required to achieve the pressure difference is equal to the product of the pressure difference Δp and the velocity of the sucked air V_w. This pressure difference accelerates the incoming air from zero at the surface (in the boundary layer) to V_w in the suction opening. Thus, the power to create Δp is converted to kinetic energy except for that wasted to overcome losses. The kinetic energy of the sucked air is

$$V_w \, \Delta P = \frac{1}{2k} \rho_w V_w^3$$

where k is the efficiency factor of the opening.

Division of both sides of the equation by $V_w q_\infty$ yields

$$\frac{\Delta p}{q_\infty} = \frac{1}{2} \frac{\rho_w V_w^2}{q_\infty} \tag{2}$$

Substitute equation (2) into equation (1) to obtain the coefficient of the pressure C_{p_i} within the surface as

$$C_{p_i} = C_{p_o} - \frac{1}{k} \frac{1}{2} \frac{\rho_w V_w}{q_\infty} \tag{3}$$

The captured air at pressure p_i has to be pushed out again against the outside pressure p_∞ and also reaccelerated to the free stream velocity V_∞. The power necessary to overcome the pressure differential $p_\infty - p_i$ is the product of this pressure difference and the air velocity; that is

$$P_p = -(p_i - p_\infty) V_w$$

$$= \frac{-(p_i - p_\infty)}{q_\infty} \frac{V_w}{V_\infty} q_\infty V_\infty \tag{4}$$

$$= -C_{p_i} \frac{V_w}{V_\infty} q_\infty V_\infty$$

Substitution of the expression for C_{p_i} (eq. 3) into equation (4) results in

$$P_p = -(C_{p_o} - \frac{1}{k}\ \frac{1}{2}\ \frac{\rho_w V_w^2}{q_\infty})\ \frac{V_w}{V_\infty}\ q_\infty V_\infty$$

or, since

$$q_\infty = \frac{1}{2}\ \rho_\infty V_\infty^2$$

$$P_p = -(C_{p_o} - \frac{1}{k}\ \frac{\rho_w}{\rho_\infty}\ \frac{V_w^2}{V_\infty^2})\ \frac{V_w}{V_\infty}\ \frac{1}{2}\ \rho_\infty V_\infty^3 \qquad (5)$$

The kinetic energy of the air per unit time when it leaves the exhaust at free stream velocity equals one-half of the product of the mass flow and the second power of the free stream velocity. The mass flow of the exhaust air is the same as that of the entering air ($m = \rho_w V_w$). If losses and the initial (entrance) speed V_w are ignored, the power required to regain the free stream speed is equal to the kinetic energy of the exhaust flow.

Thus:

$$P_V = \frac{1}{2}\ \rho_w V_w\ V_\infty^2 \quad \text{or}$$

$$P_V = \frac{1}{2}\ \frac{\rho_w V_w}{\rho_\infty V_\infty}\ \rho_\infty V_\infty^3 \qquad (6)$$

The total power used to suck the air and subsequently exhaust it at free stream pressure and velocity is the sum of equations (5) and (6); that is

$$P_{total} = [\ \frac{\rho_w V_w}{\rho_\infty V_\infty} - (C_{p_o} - \frac{1}{k}\ \frac{\rho_w}{\rho_\infty}\ \frac{V_w^2}{V_\infty^2})\ \frac{V_w}{V_\infty}\ ]\ \frac{1}{2}\ \rho_\infty V_\infty^3 \qquad (7)$$

Equation (7) represents the power per unit suction area. The internal velocity of the sucked air V_w is substantially lower than the free stream velocity V_∞. It is, therefore, reasonable to ignore terms in the third power of V_w/V_∞ in comparison to terms in the first power; thus equation (7) simplifies to

$$P_{total} = \left(\frac{\rho_w V_w}{\rho_\infty V_\infty} - C_{p_0} \frac{V_w}{V_\infty}\right) \frac{1}{2} \rho_\infty V_\infty^3 \qquad (8)$$

or, in coefficient form

$$P_{total} = C_{SP} \frac{1}{2} \rho_\infty V_\infty^3 \qquad (9)$$

where C_{SP}, the suction power coefficient, is

$$C_{SP} = \left(\frac{\rho_w}{\rho_\infty} - C_{p_0}\right) \frac{V_w}{V_\infty} \qquad (10)$$

REFERENCES

1. Jernell, Lloyd S.: Design of a Large Span-Distributed Load Flying-Wing Cargo Airplane. NASA TM X-74031, April 1977.

2. Bauer, Frances; Garabedian, Paul; Korn, David; and Jameson, Antony: Supercritical Wing Sections II. Volume 108 of Lecture Notes in Economics and Mathematical Systems, Springer-Verlag, 1975.

3. Bauer, Frances; Grabedian, Paul; and Korn, David: Supercritical Wing Sections III. Volume 150 of Lecture Notes in Economics and Mathematical Systems, Springer-Verlag, 1977.

4. Carter, James E.: STAYLAM: A FORTRAN Program for the Suction Transition Analysis of a Yawed Wing Laminar Boundary Layer. NASA TM X-74013, March 1977.

5. Anderson, B. A.: Scaling the JT9D-7 Engine. TDM 1990, Pratt and Whitney Aircraft, East Hartford , Connecticut, April 17, 1978.

6. Riegels, Dr. Friedrich Wilhelm: Airfoil Sections. Butterworth, London, 1961.

TABLE I. - LFC SYSTEM WEIGHT SUMMARY

	100% Laminar Configuration			80% Laminar Configuration		
	Area m^2 $(ft)^2$	Specific Weight Pa (lbf/ft^2)	Weight Increment kN (lbf)	Area m^2 $(ft)^2$	Specific Weight Pa (lbf/ft^2)	Weight Increment kN (lbf)
Wing weight increase due to LFC system (structure, ducts, and valving).	*1662.6 (17 896)	60.33 (1.26)	100.3 (22 549)	1310.7 (14 108)	60.33 (1.26)	79.1 (17 776)
Suction engine weight for wing laminarization.	1662.6 (17 896)	33.52 (.7)	55.7 (12 527)	1310.7 (14 108)	33.52 (.7)	43.9 (9 875)
Suction engine weight for vertical tail laminarization, (assumed to be part of wing weight).	219.4 (2 362)	33.52 (.7)	7.4 (1 653)	188.8 (2 032)	33.52 (.7)	6.3 (1 423)
Total increase in wing weight due to LFC.			163.4 (36 729)			129.3 (29 074)
Vertical tail LFC system weight (without suction engine).	219.4 (2 362)	60.33 (1.26)	13.2 (2 976)	188.8 (2 032)	60.33 (1.26)	11.4 (2 560)
Total OWE increase due to LFC.			176.6 (39 705)			140.7 (31 634)

* Laminarized wing area reduced 37.2 m^2 (400 ft^2) and 24.5 m^2 (264 ft^2) for wing-body and wing-engine interference effects, respectively.

TABLE II. - SPAN-DISTRIBUTED LOAD FLYING-WING CARGO AIRPLANE EMPTY AND TAKE-OFF GROSS WEIGHT WITH CONSTANT FUEL

Thrust per engine, kN , lbf	204.6 46 000	222.4 50 000	231.3 52 000	*240.2 54 000	249.1 56 000	258.0 58 000
	BASIC (NON-LFC) VEHICLE, FUEL WEIGHT = 1.664 MN (374 000 lbf)					
OWE, MN , lbf	1.647 370 200	1.683 378 400	1.701 382 500	*1.720 386 600	1.738 390 740	1.757 394 900
TOGW, MN , lbf	5.979 1 344 200	6.016 1 352 400	6.034 1 356 500	*6.052 1 360 600	6.071 1 364 740	6.089 1 368 900
	100% LAMINAR CONFIGURATION, FUEL WEIGHT 1.358 MN (305 500 lbf)					
OWE, MN , lbf	1.798 404 100	1.834 412 300	1.852 416 400	1.870 420 500	1.889 424 600	1.907 428 700
TOGW, MN , lbf	5.825 1 309 600	5.862 1 317 800	5.880 1 321 900	5.898 1 326 000	5.917 1 330 100	5.935 1 334 200
	80% LAMINAR CONFIGURATION, FUEL WEIGHT = 1.438 MN (323 300 lbf)					
OWE, MN , lbf	1.773 398 490	1.810 406 900	1.828 410 900	1.846 414 900	1.864 419 100	1.882 423 200
TOGW, MN , lbf	5.880 1 321 790	5.917 1 330 200	5.935 1 334 200	5.953 1 338 200	5.971 1 342 400	5.990 1 346 500

* Baseline Airplane

TABLE III(a). - WEIGHT SUMMARY

CONSTANT ENGINE THRUST OF 240.2 kN (54 000 lbf)

	Configuration					
	Baseline		100% Laminar		80% Laminar	
	Newton, MN	Pound Force lbf	Newton, MN	Pound Force lbf	Newton, MN	Pound Force lbf
STRUCTURE	1.079	242 514	1.238	278 204	1.209	271 853
PROPULSION	.426	95 736	.422	94 836	.424	95 225
SYSTEMS	.188	42 350	.184	41 460	.186	41 822
WEIGHT EMPTY	1.693	380 600	1.844	414 500	1.819	408 900
OPERATING ITEMS	.027	6 000	.027	6 000	.027	6 000
OPERATING WEIGHT	1.720	386 600	1.871	420 500	1.846	414 900
PAYLOAD	2.669	600 000	2.669	600 000	2.669	600 000
ZERO FUEL WEIGHT	4.339	986 600	4.540	1 020 500	4.515	1 014 900
MISSION FUEL	1.664	374 000	1.359	305 500	1.438	323 300
TAKE-OFF GROSS WEIGHT	6.053	1 360 600	5.899	1 326 000	5.953	1 338 200

TABLE III(b). - WEIGHT SUMMARY

FINAL ENGINE SIZES

	Configuration					
	Baseline Thrust = 240.2 kN (54 000 lbf)		100% Laminar Thrust = 204.6 kN (46 000 lbf)		80% Laminar Thrust = 209.1 kN (47 000 lbf)	
	Newton, MN	Pound Force lbf	Newton, MN	Pound Force lbf	Newton, MN	Pound Force lbf
STRUCTURE	1.079	242 514	1.184	266 122	1.163	261 581
PROPULSION	.426	95 736	.404	90 719	.408	91 627
SYSTEMS	.188	42 350	.176	39 659	.179	40 241
WEIGHT EMPTY	1.693	380 600	1.764	396 500	1.750	393 450
OPERATING ITEMS	.027	6 000	.027	6 000	.027	6 000
OPERATING WEIGHT	1.720	386 600	1.791	402 500	1.777	399 450
PAYLOAD	2.669	600 000	2.669	600 000	2.669	600 000
ZERO FUEL WEIGHT	4.389	986 600	4.460	1 002 500	4.446	999 450
MISSION FUEL	1.664	374 000	1.301	292 500	1.394	313 440
TAKE-OFF GROSS WEIGHT	6.053	1 360 600	5.761	1 295 000	5.840	1 312 890

TABLE IV. - SPAN-DISTRIBUTED LOAD FLYING-WING CARGO AIRPLANE

BULENT AND LAMINAR MINIMUM PARASITE DRAG COEFFICIENTS

Aircraft Part	Reynolds No.	Drag Item	Baseline-Turbulent C_f	Baseline-Turbulent $\Delta C_{D_{pmin}}$	100% Laminar C_f	100% Laminar $\Delta C_{D_{pmin}}$	80% Laminar C_f	80% Laminar $\Delta C_{D_{pmin}}$
Wing	$1.18(10)^8$	Uncorr. flat plate	.001921	.00405	.000110	.00023	.000546	.00117
		Supervelocity		.00130		.00007		.00037
		Pressure Drag		.00039		.00002		.00011
		Roughness		.00012		.00001		.00001
		Excrescences		.00036		.00018		.00018
		Wing/Body Interf.		.00011		.00011		.00011
		Total Wing		.00633		.00062		.00195
Vertical Tails	$4.46(10)^7$	Uncon. flat plate.	.002210	.00057	.000180	.00005	.000505	.00013
		Supervelocity		.00009		.00001		.00002
		Pressure Drag		0		0		0
		Roughness		.00002		0		0
		Excrescences		.00005		.00002		.00002
		Interference		.00054		.00036		.00036
		Total Tails		.00127		.00044		.00053
$C_{D_{Pmin}}$		Total Wing and Tails		.00760		.00106		.00248
		Total Aircraft-(Wing and Tails)		.00299		.00299		.00299
		Total Aircraft		.01059		.00405		.00547

Total Laminar $C_{D_{Pmin}}$ = total turbulent $C_{D_{Pmin}}$ - (turbulent $\Delta C_{D_{pmin}}$)wing+tails + (laminar $\Delta C_{D_{Pmin}}$)wing+tails

TABLE V. - MISSION PERFORMANCE

100 PERCENT LFC AIRCRAFT

MISSION: Design (Cruise M = .75)

MODEL: Span-Distributed Load Flying-Wing Cargo Aircraft with 100% LFC

AIRCRAFT CHARACTERISTICS:

Take-off gross weight - MN (lbf)	5.760 (1 295 000)
Operating weight empty - MN (lbf)	1.790 (402 500)
Payload (gross) - MN (lbf)	2.669 (600 000)
Wing area - m^2 (ft^2)	1724.3 (18 560)
Sea level static thrust per engine (std. day) Installed - kN (lbf)	204.6 (46 000)
Take-off installed thrust to weight ratio	.213
Take-off wing loading - kPa, (lbf/ft^2)	3.341 (69.7)

Design Mission

Flight Mode	Gross Weight MN (lbf)	ΔFuel Mg (lbm)	ΔRange Mm (n. mi.)	ΔTime min.
Take-off	5.760 (1 295 000)			
		2.18 (4 800)	0	11
Start Climb	5.739 (1 290 200)			
		15.56 (34 300)	.393 (212)	36
Start Cruise	5.587 (1 255 900)			
		84.28 (185 800)	5.154 (2 783)	386
End Cruise	4.760 (1 070 100)			
		1.95 (4 300)	.370 (200)	20
End Descent	4.741 (1 065 800)			
Taxi-In		.70 (1 535)	0	5
Block Fuel and Time		104.67 (230 735)		458
Trip Range			5.917 (3 195)	

TABLE V. - Concluded

MODEL: Span-Distributed Load Flying-Wing Cargo Aircraft with 100% LFC

Reserve Fuel Breakdown, kg (lbm):

1.	10% trip time	8.93 (19 700)
2.	Missed approach	1.54 (3 400)
3.	370 km (200 n. mi.) to alternate airport	11.61 (25 600)
4.	30 min. holding at 457 m (1 500 ft)	6.62 (14 600)
	Total Reserve	28.70 (63 300)

Initial Cruise Conditions:

Lift coefficient		.3207
Drag coefficient		.01253
Lift/Drag		25.60
TSFC, kg/hr/N (lbm/hr/lbf)	.0649	(.636)
Altitude, km (ft)	10.21	(33 500)

Fuel Efficiency:

Tonne-kilometers per kg of fuel burned = 15.53

(Ton-nautical miles per pound of fuel burned = 4.19)

NOTES:

1. Taxi-in fuel taken out of reserves at destination.
2. C.A.B. range corresponding to block time and fuel equals trip range minus traffic allowances for maneuver, traffic and airway distance.
3. Lift-drag ratio and drag coefficient include ΔC_D = .0017 equivalent to LFC suction power requirement.

TABLE VI. - MISSION PERFORMANCE

80 PERCENT LFC AIRCRAFT

MISSION: Design (Cruise M = .75)

MODEL: Span-Distributed Load Flying-Wing Cargo Aircraft with 80% LFC

AIRCRAFT CHARACTERISTICS:

Take-off gross weight - MN (lbf)	5.840 (1 312 890)
Operating weight empty - MN (lbf)	1.777 (399 450)
Payload (gross) - MN (lbf)	2.669 (600 000)
Wing area - m^2 (ft^2)	1724.3 (18 560)
Sea level static thrust per engine (std. day)	
Installed - kN (lbf)	209.1 (47 000)
Take-off installed thrust to weight ratio	.215
Take-off wing loading - kPa, (lbf/ft^2)	3.387 (70.7)

Design Mission

Flight Mode	Gross Weight MN (lbf)	ΔFuel Mg (lbm)	ΔRange Mm (n. mi.)	ΔTime min.
Take-off	5.840 (1 312 890)			
		2.21 (4 870)	0	11
Start Climb	5.818 (1 308 020)			
		16.38 (36 100)	.419 (226)	37
Start Cruise	5.658 (1 271 920)			
		91.99 (202 800)	5.137 (2 774)	386
End Cruise	4.756 (1 069 120)			
		2.00 (4 400)	.370 (200)	20
End Descent	4.736 (1 064 720)			
Taxi-In		.71 (1 570)	0	5
Block Fuel and Time		113.29 (249 740)		459
Trip Range			5.926 (3 200)	

TABLE VI. - Concluded

MODEL: Span-Distributed Load Flying-Wing Cargo Aircraft with 80% LFC

Reserve Fuel Breakdown, kg (lbm):

1.	10% trip time	9.69 (21 370)
2.	Missed approach	1.57 (3 470)
3.	370 km (200 n. mi.) to alternate airport	11.65 (25 680)
4.	30 min. holding at 457 m (1 500 ft)	6.65 (14 650)
	Total Reserve	29.56 (65 170)

Initial Cruise Conditions:

Lift coefficient		.3404
Drag coefficient		.01462
Lift/Drag		23.28
TSFC, kg/hr/N (lbm/hr/lbf)	.0640	(.628)
Altitude, km (ft)	10.2	(34 500)

Fuel Efficiency:

Tonne-kilometers per kg of fuel burned = 14.33

(Ton-nautical miles per pound of fuel burned = 3.87)

NOTES:

1. Taxi-in fuel taken out of reserves at destination.
2. C.A.B. range corresponding to block time and fuel equals trip range minus traffic allowances for maneuver, traffic and airway distance.
3. Lift-drag ratio and drag coefficient include ΔC_D = .0016 equivalent to LFC suction power requirement.

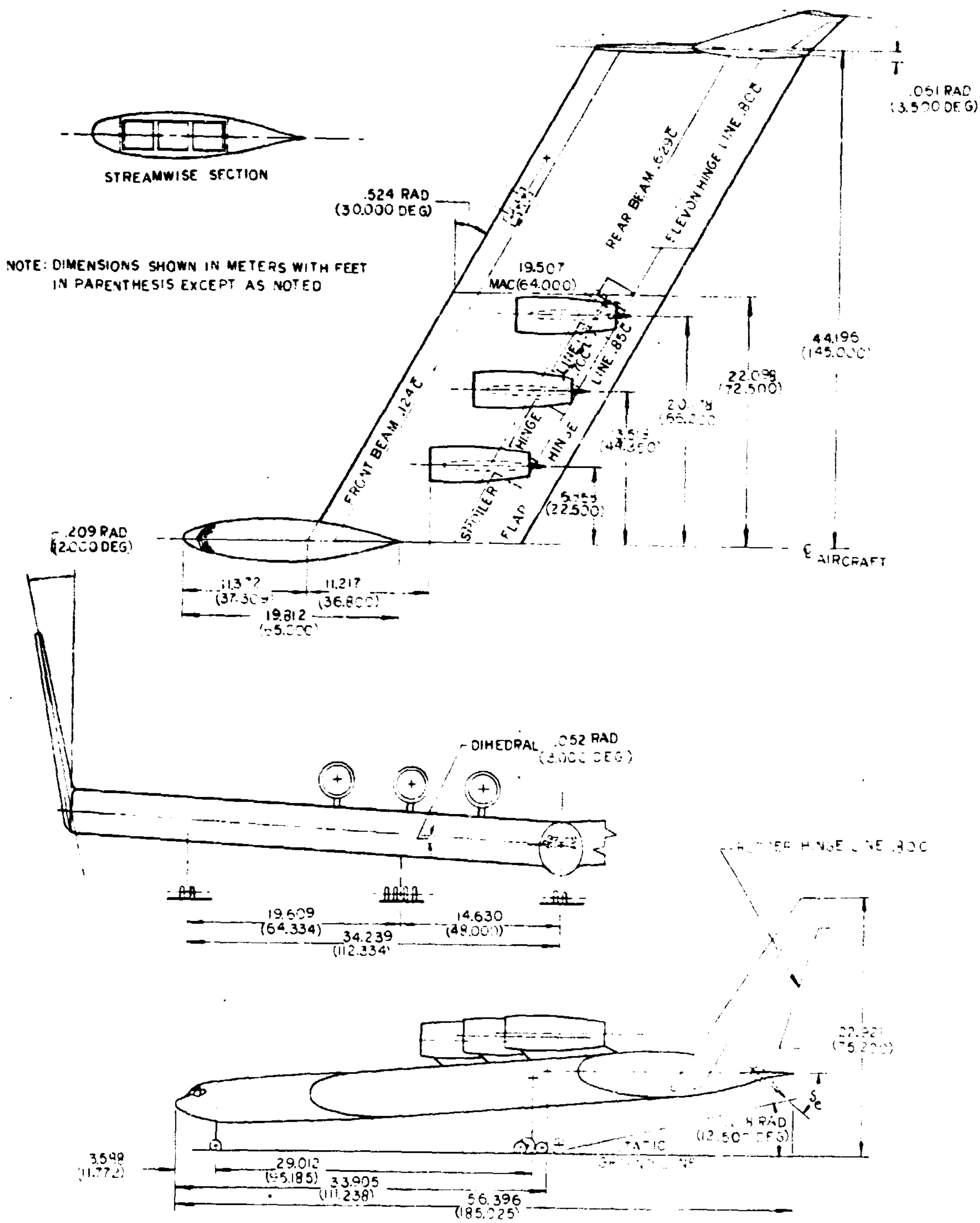

Figure 1. - Span-distributed load flying-wing cargo airplane.

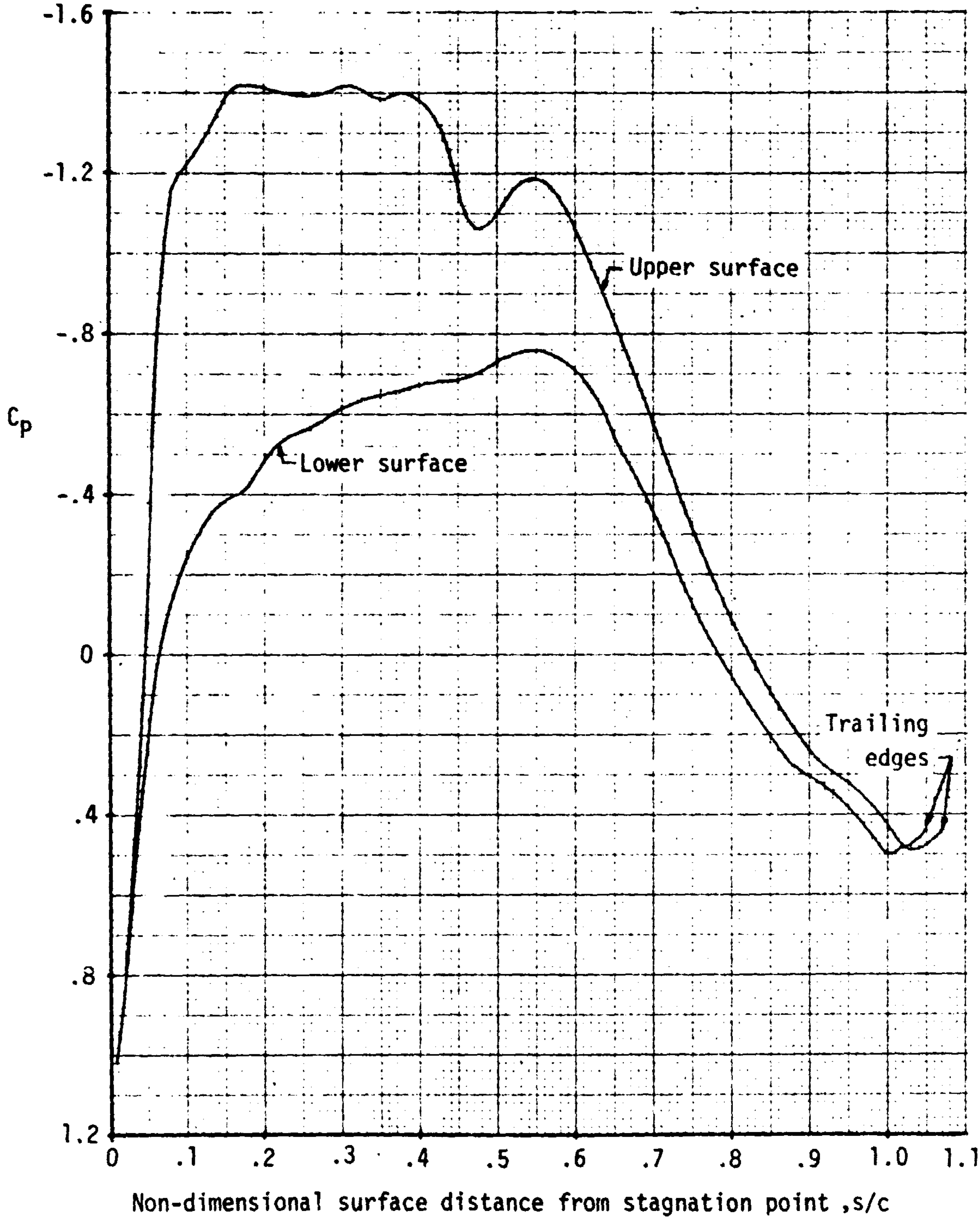

Figure 2. - Pressure distribution along airfoil surface.

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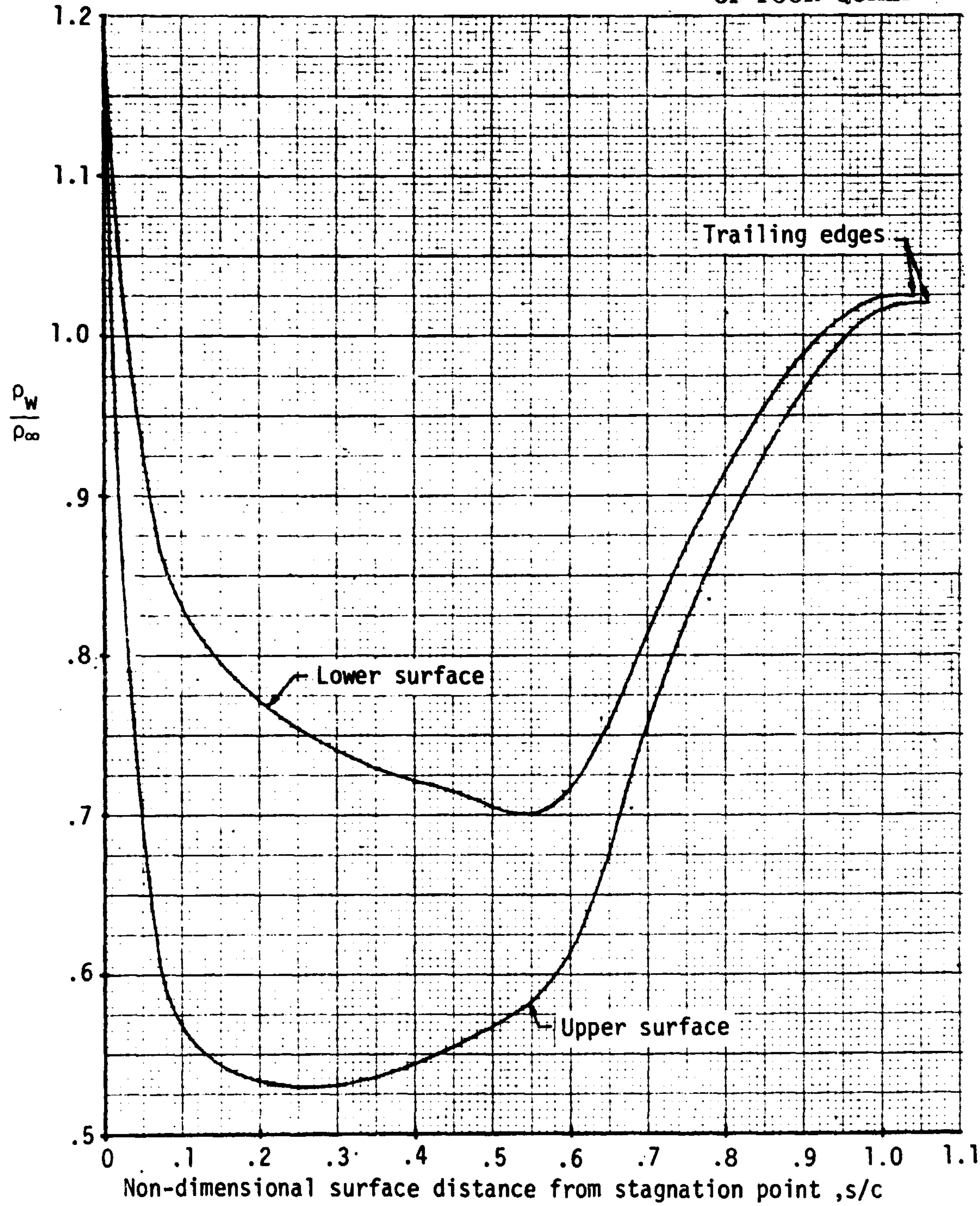

Figure 3. - Air density distribution along airfoil surface.

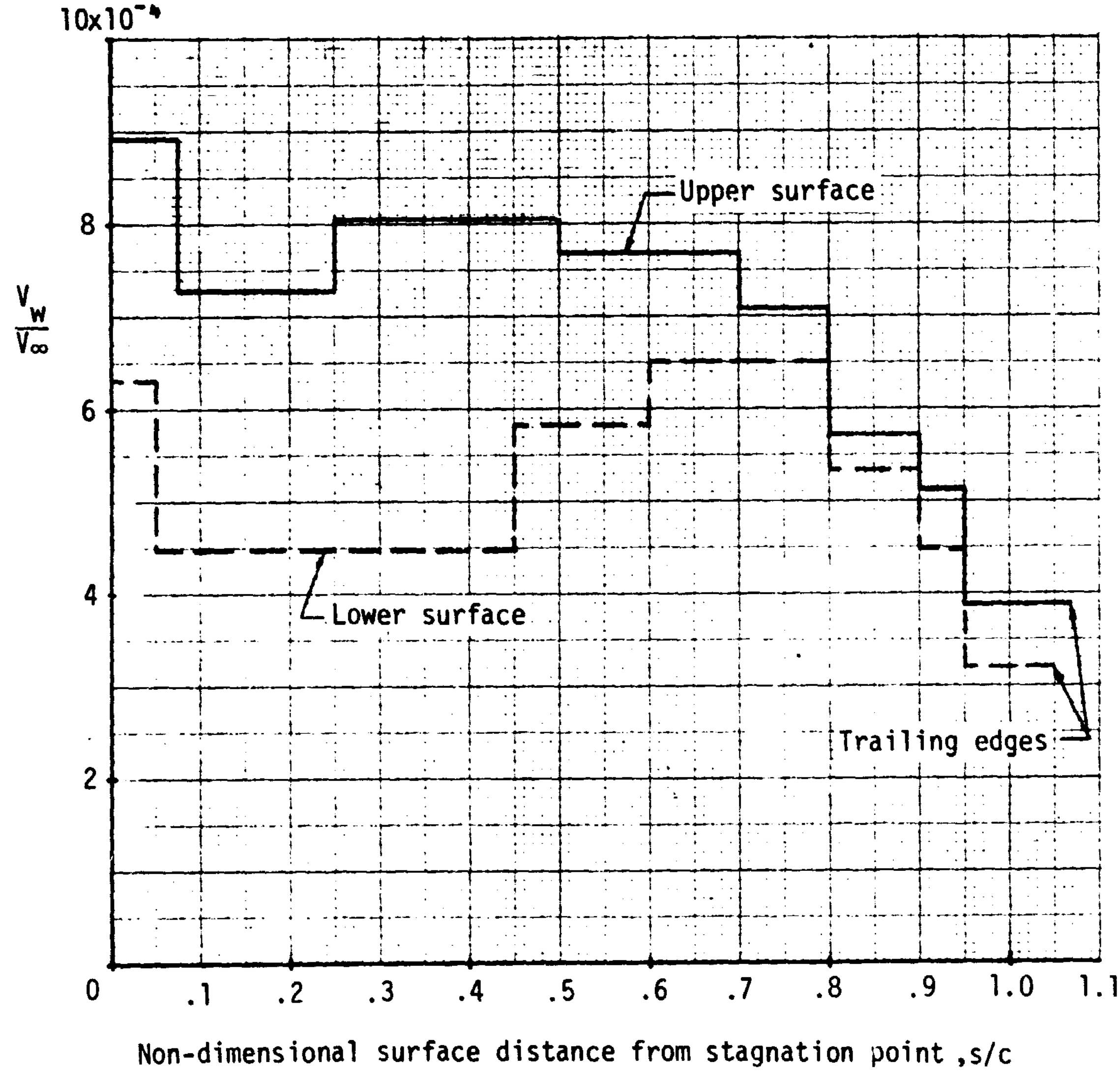

Figure 4. - Suction velocity distribution along airfoil surface.

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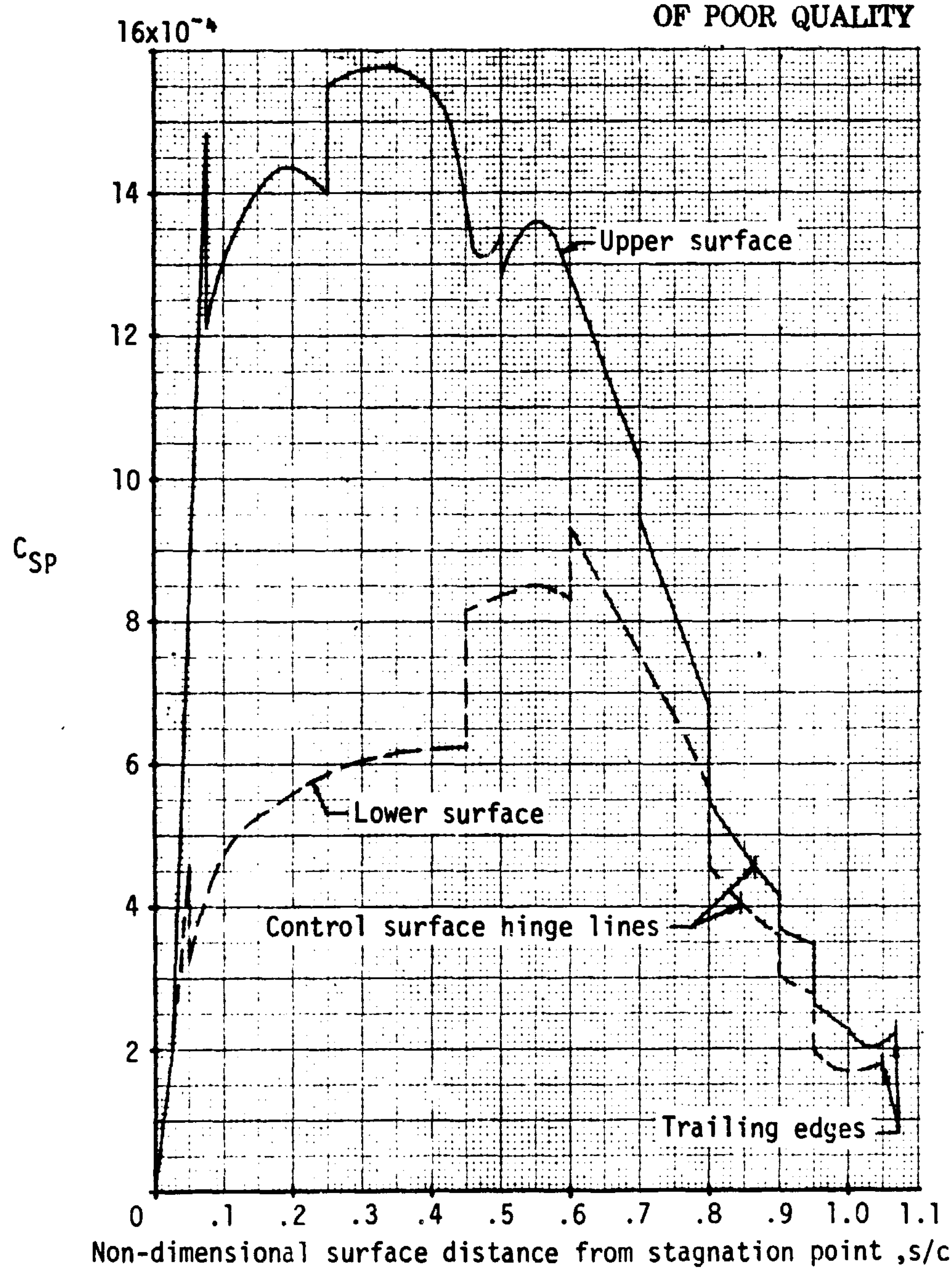

Figure 5. - Local suction power coefficient distribution along airfoil surface.

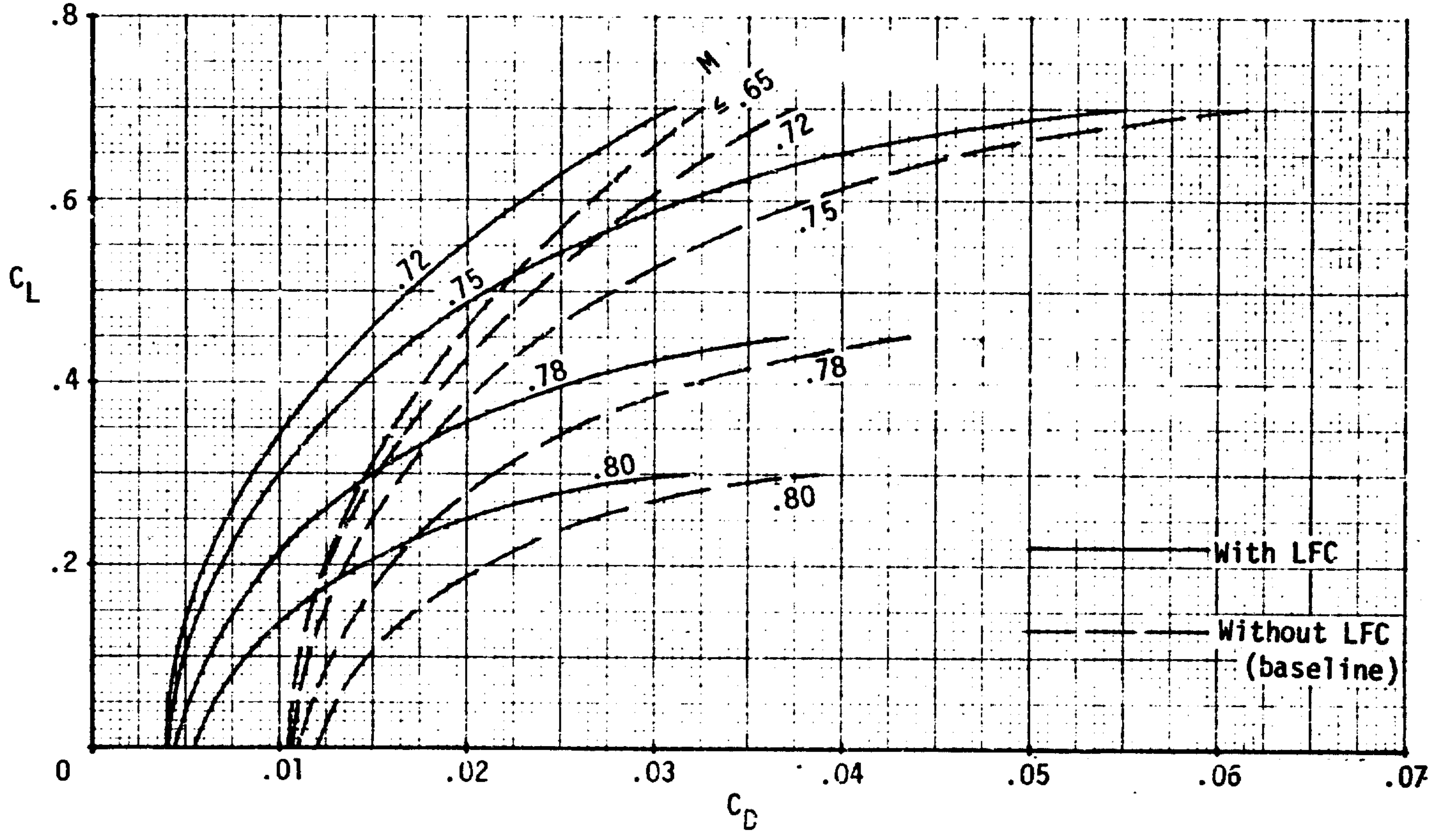

Figure 6. - Drag polars with and without laminar flow control $C_{D_{SP}}$ (.0017) is not included, 100 percent laminar case.

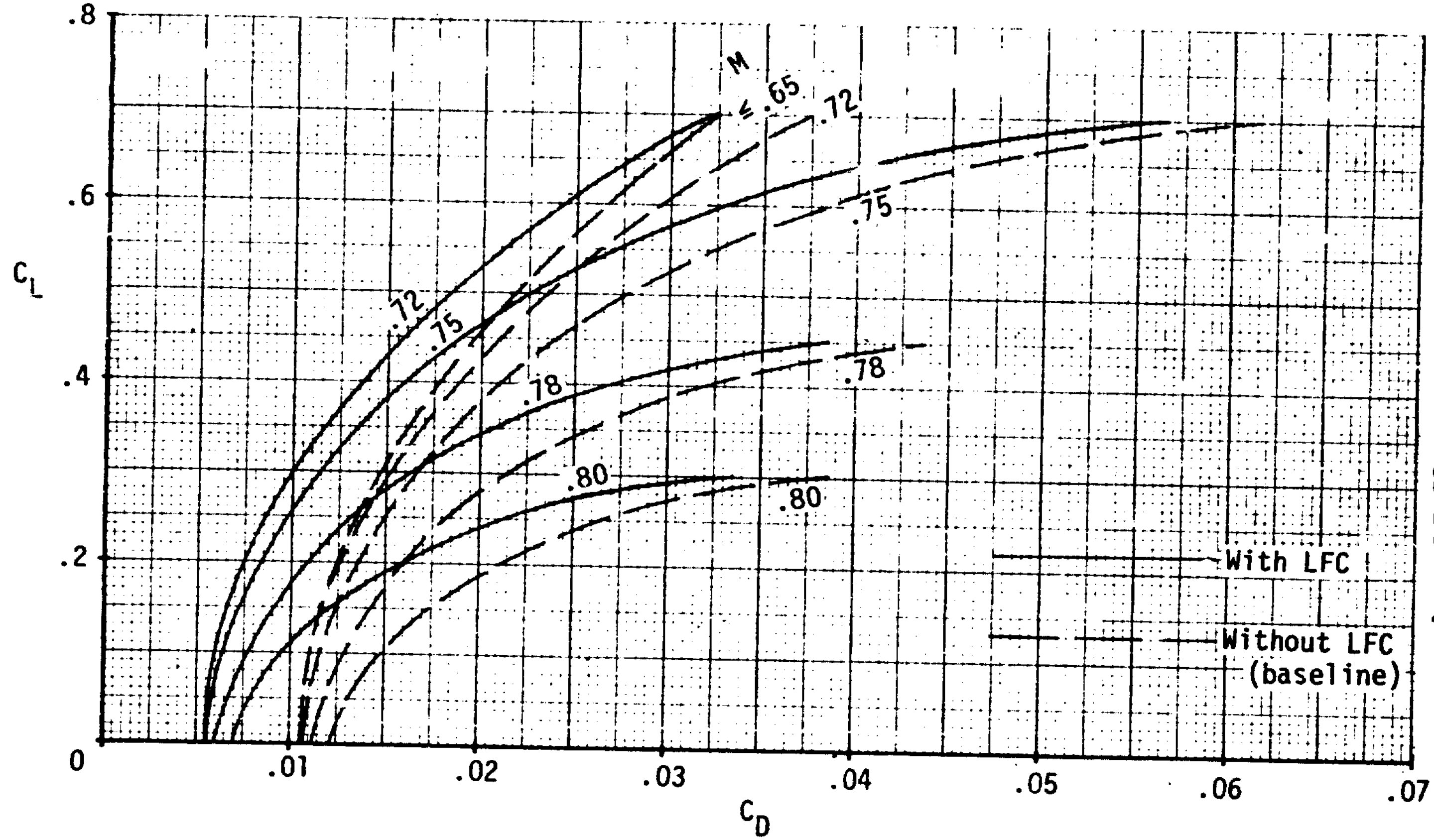

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Figure 7. - Drag polars with and without laminar flow control C_{DSP} (.0016) is not included, 80 percent laminar case.

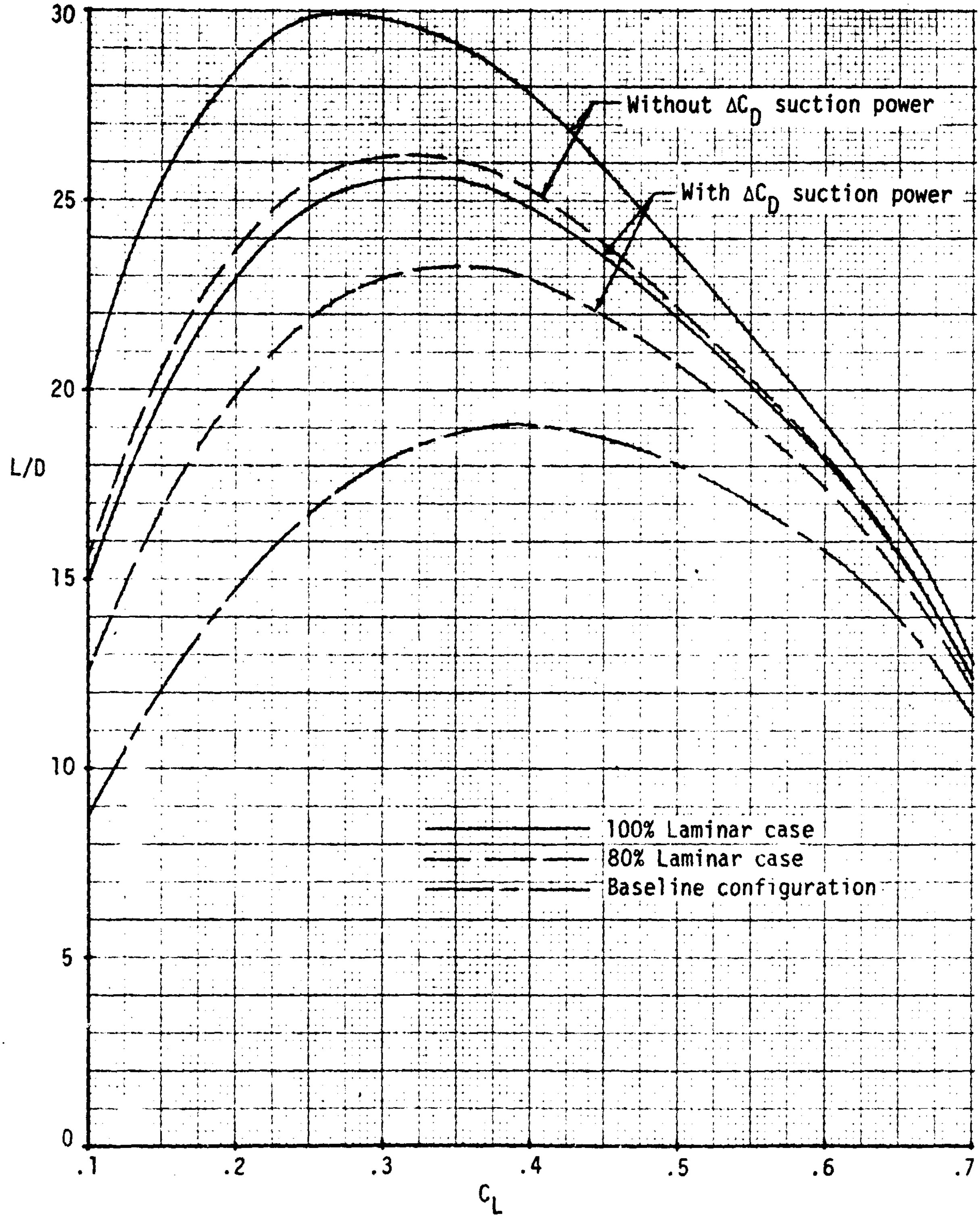

Figure 8. - Cruise lift/drag ratios with and without suction power $\Delta C_D \cdot M = 0.75$

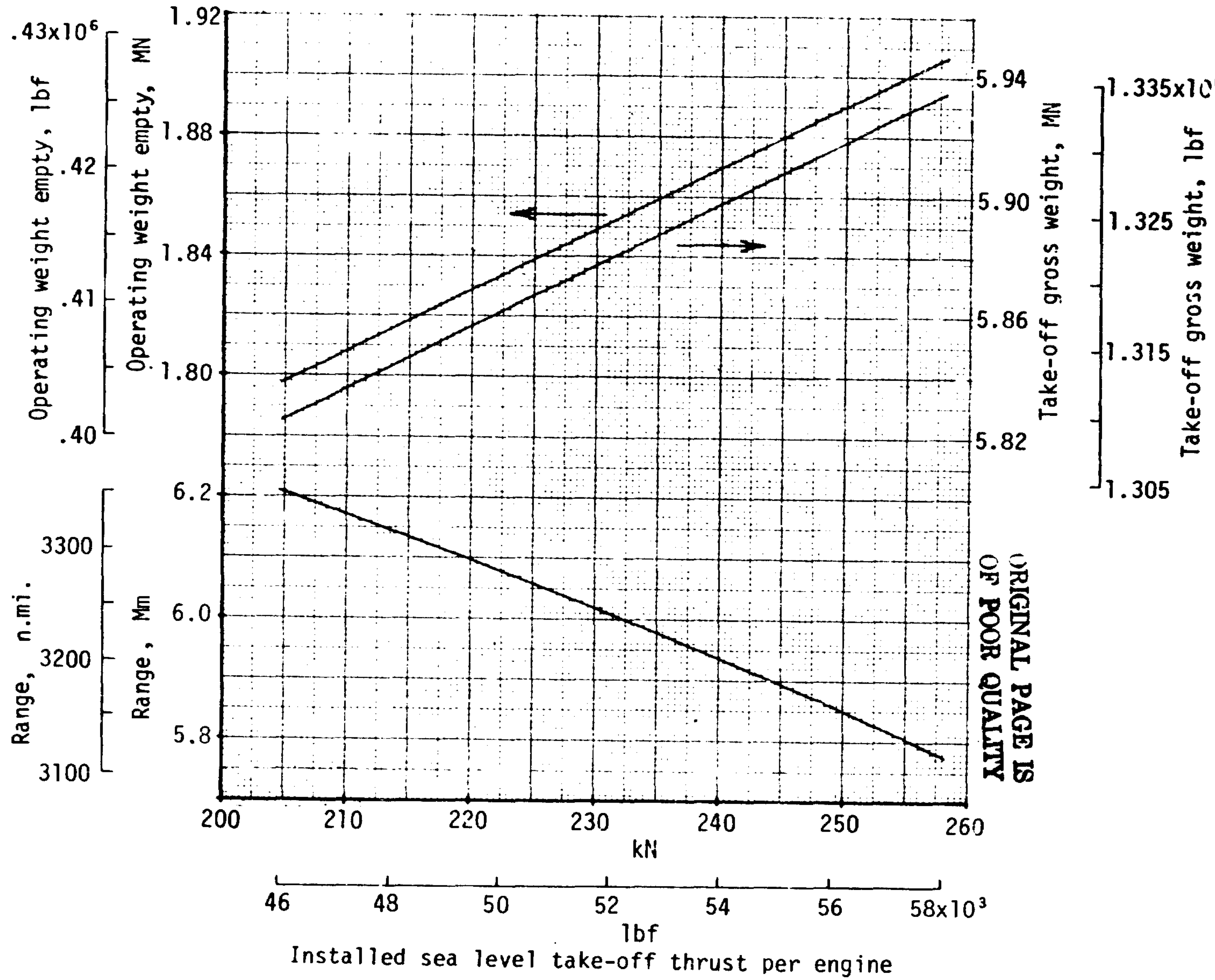

Figure 9. - Effect of engine size on weights and range, 100% laminar case.

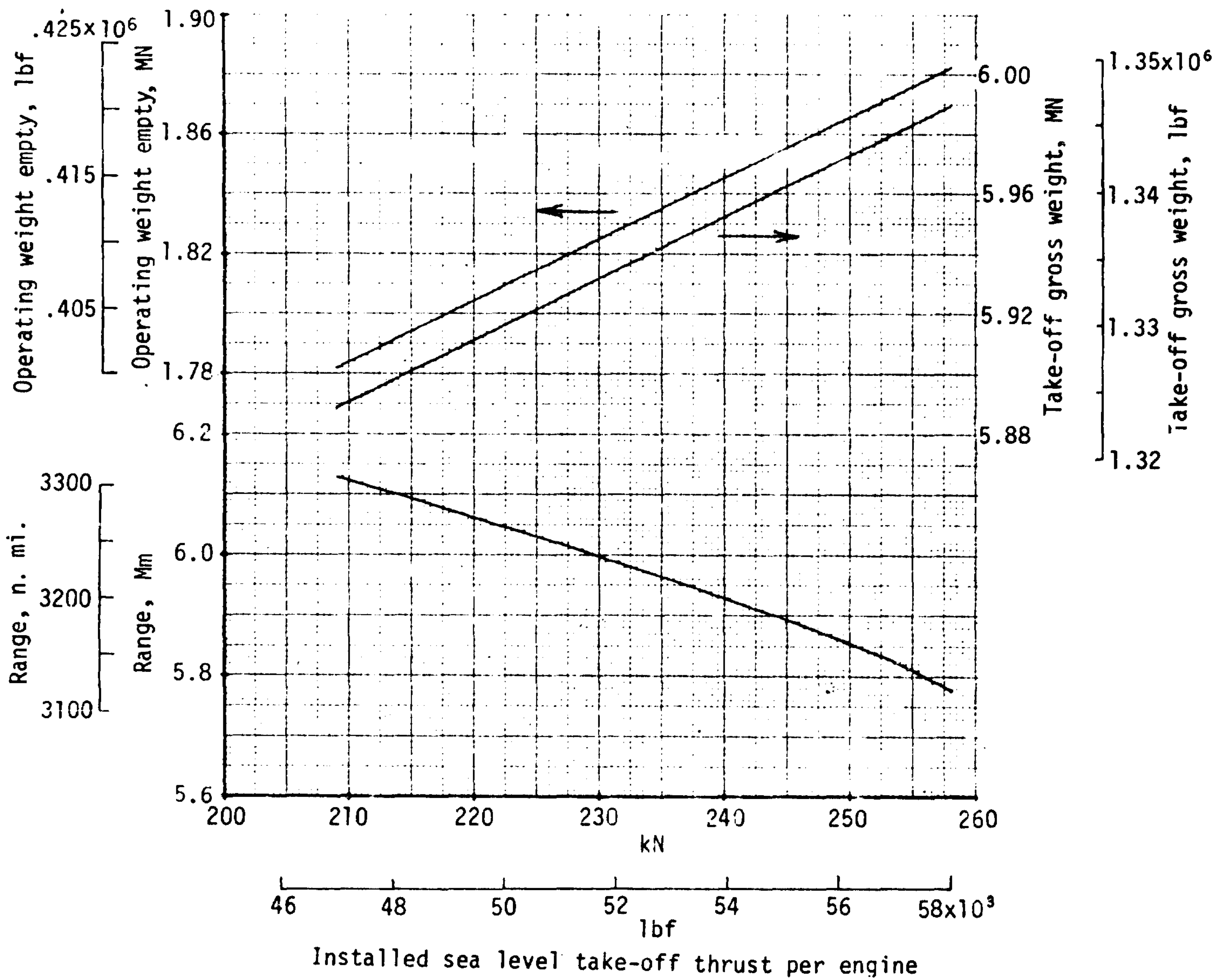

Figure 10. - Effect of engine size on weights and range, 80% laminar case.

100% Laminar case	80% Laminar case
T = 204.6 kN = (46 000 lbf) W = 5.760 MN = (1 295 000 lbf)	T = 209.1 kN = (47 000 lbf) W = 5.840 MN = (1 312 890 lbf)

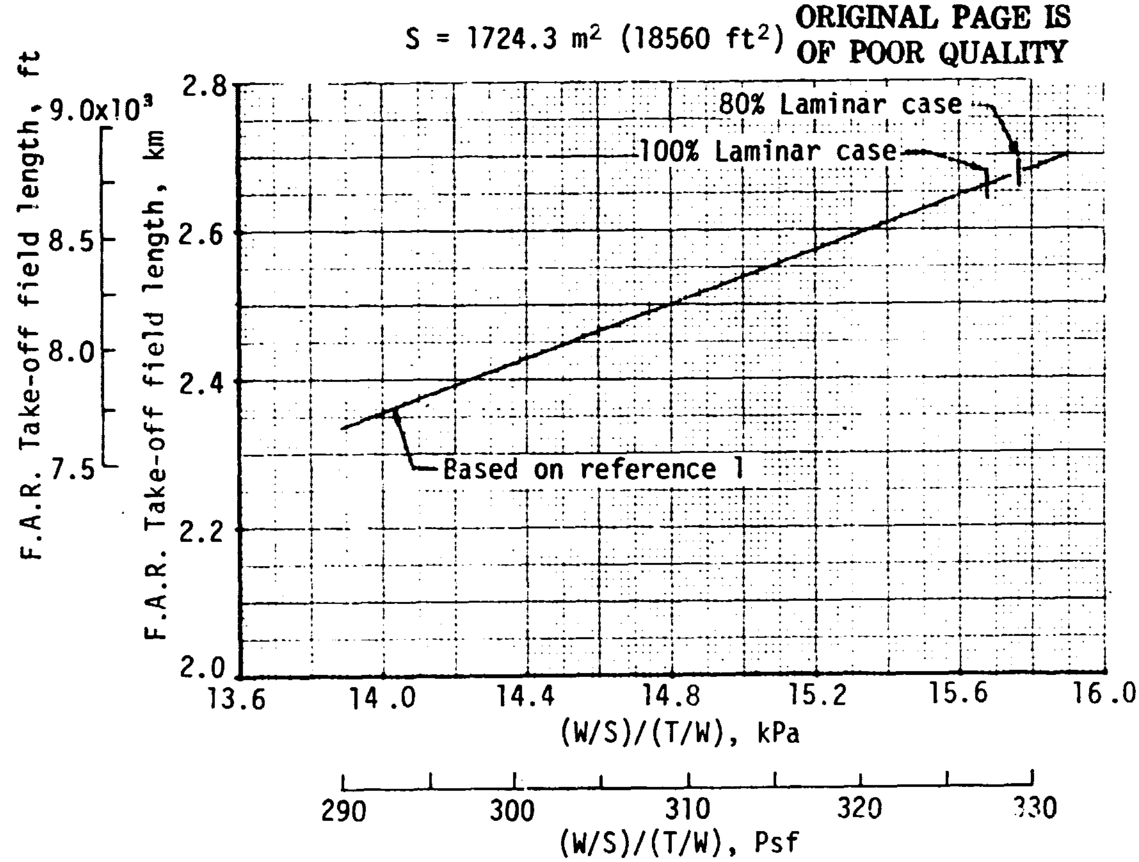

Figure 11. - Estimated take-off field length.

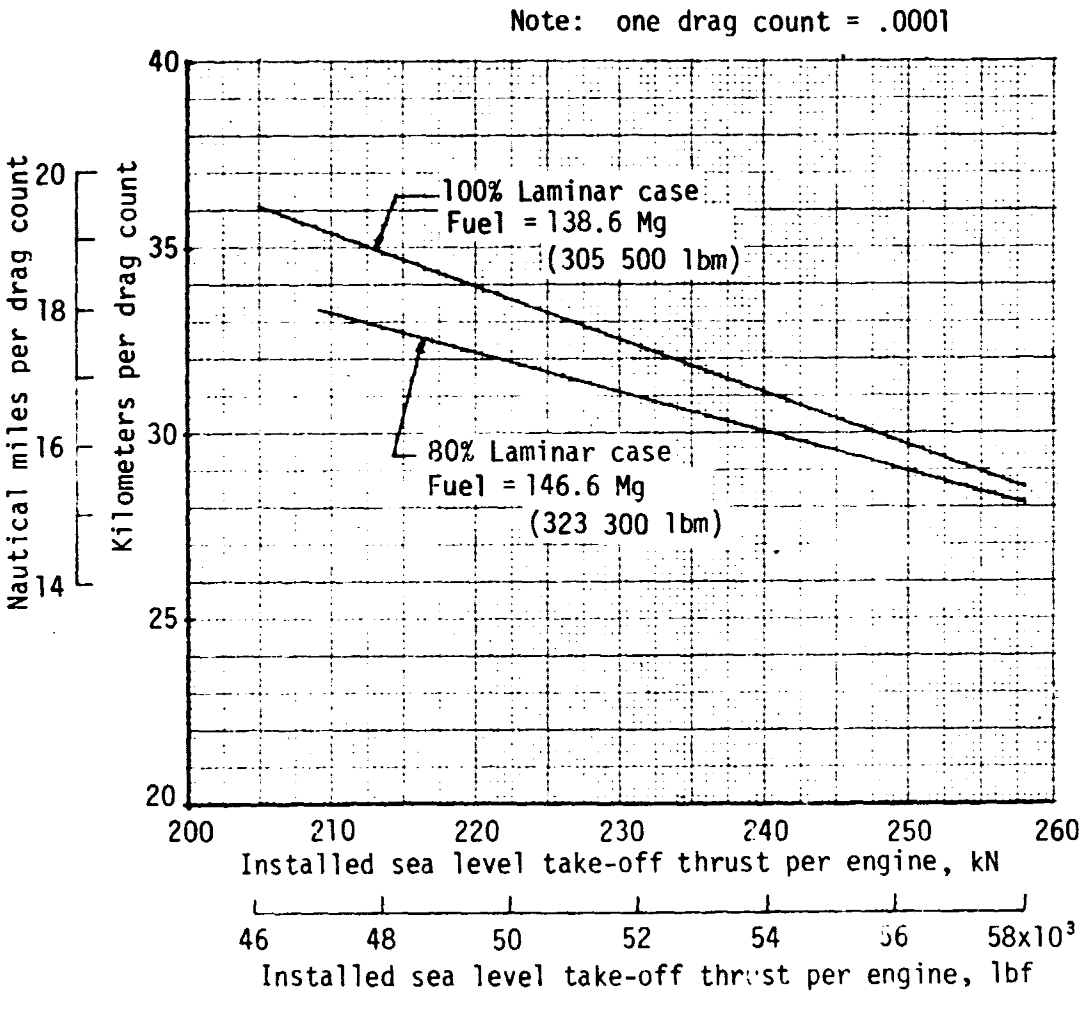

Figure 12. - Change in range per drag count.

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16. Abstract

A design study was conducted to add laminar flow control to a previously designed span-distributed load airplane while maintaining constant range and payload. With laminar flow control applied to a 100 percent of the wing and vertical tail chords, the empty weight increased by 4.2 percent, the drag decreased by 27.4 percent, the required engine thrust decreased by 14.8 percent, and the fuel consumption decreased by 21.8 percent. When the laminar flow control was applied to a lesser extent of the chord (approximately 80 percent), the empty weight increased by 3.4 percent, the drag decreased by 20.0 percent, the required engine thrust decreased by 13.0 percent, and the fuel consumption decreased by 16.2 percent. In both cases, the required takeoff gross weight of the aircraft was less than the original turbulent aircraft.

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