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EVALUATION OF A LONG-ENDURANCE-SURVEILLANCE REMOTELY-PILOTED VEHICLE WITH AND WITHOUT LAMINAR FLOW CONTROL

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SUMMARY

This design study was conducted to determine the improvement in mission time due to the application of a laminar flow control (LFC) system on a remotely-piloted vehicle (RPV) flying a long-endurance-surveillance mission. Two aircraft were evaluated, using a derated TF34-GE-100 turbofan engine, one with LFC and one without. The mission of the RPV is one of high-altitude loiter at maximum endurance. For the airfoils selected the wing is naturally laminar over the forward 40 percent of its area. The LFC system was incorporated in the remaining portion extending to the wing trailing edge. The fuel quantity and engine are identical for the RPV with and without LFC. With the LFC system maximum mission time increased by 6.7 percent, L/D in the loiter phase improved 14.2 percent, and the minimum parasite drag of the wing was reduced by 65 percent resulting in a 37 percent reduction for the total airplane. Except for the minimum parasite drag of the wing, the preceding benefits include the offsetting effects of weight increase, suction power requirements, and drag of the wing-mounted suction pods.

In a supplementary study using a scaled-down, rather than derated, version of the engine, on the LFC configuration, a 17.6 percent increase in mission time over the airplane without LFC and an incremental time increase of 10.2 percent over the LFC airplane with derated engine were attained. This improvement was due principally to reductions in both weight and drag of the scaled engine.

INTRODUCTION

A continuing effort is being made by the NASA and industry toward improving the fuel efficiency of aircraft. One method being studied for achieving such improvement is Laminar Flow Control (LFC). In this application, suction is used to reduce the parasite drag of a surface by inducing airflow over the wing surface to remain laminar. In this study the mission capability of a representative long-endurance-surveillance remotely-piloted vehicle (RPV) configuration is evaluated with and without LFC. The mission includes a 24 hour loiter at altitudes between 15.24 km (50 000 ft) and 21.34 km (70 000 ft) at speeds between M = 0.50 and 0.60, with a 5.34 kN (1 200 lbf) payload.

Both the LFC wing and the non-LFC (baseline) wing have the same airfoil sections. These are NACA 65 series which have the characteristic of maintaining a natural laminar flow over a significant chord segment. On the LFC airplane, the remaining wing area is equipped with an LFC system to provide laminar flow over its entire upper and lower wing surfaces. This represents an upper boundary on LFC capability inasmuch as the control surface areas are included. The baseline and LFC airplanes are configured identically, except for the LFC system. The only external differences are the wing-mounted suction engine pods required for the LFC system. For this study laminar flow control was applied only to the wing.

The objectives of this study were to establish the magnitudes of the parasite drag reduction, the structural and system weight changes, and the suction power requirements for the LFC system, and to evaluate the effect on mission performance. The detailed design, maintenance, and cost of the LFC system were not considered in this study. Also not included were stability analyses and sizing studies for surfaces (ailerons, flaps, etc.). Takeoff and landing performance were not analyzed since wing loadings and thrust-to-weight ratios are similar to those of existing, comparable RPV's.

SYMBOLS AND DEFINITIONS

Where applicable, values are given in this report in both International System of Units (SI) and U.S. Customary Units. All calculations were made in U.S. Customary Units.

AR	aspect ratio
b	span
c	chord
$\bar{c}$	mean aerodynamic chord
C_D	drag coefficient, D/qS

C_{D_i}	induced drag coefficient, $C_L{}^2/\pi eAR$
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 based on component wetted area, F/S_{wet}
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
e	potential-flow efficiency factor, $C_L{}^2/\pi ARC_{D_i}$
F	drag area
fpm	feet per minute
KCAS	knots calibrated airspeed
L	lift
LFC	laminar flow control
M	Mach number
MAC	mean aerodynamic chord
mpm	meters per minute
MRT	military rated thrust
NRT	normal rated thrust
OWE	operating weight empty
P	pressure

q	dynamic pressure
R/C	rate-of-climb
R_e	Reynolds number
s	distance along airfoil surface from stagnation point
S	projected wing area
SFC	specific fuel consumption
t/c	thickness to chord ratio
V	true velocity
ρ	air density
Subscripts:	
∞	free stream
min	minimum
s	static

BASIC CONSIDERATIONS

Design Criteria and Configuration Description

This study, evaluating the effect of LFC application on the performance capabilities of a long-endurance-surveillance RPV, was guided by specific criteria. The baseline vehicle should have the capability of loitering for a minimum of 24 hours with an additional four hours allotted for flying from the base airfield to the loiter area and return, resulting in a total mission time of 28 hours. The RPV, with and without LFC, is to loiter with a 5.34 kN (1 200 lbf) payload, at altitudes between 15.24 km (50 000 ft) and 21.34 km (70 000 ft) at maximum endurance speeds between 0.5 and 0.6 Mach number. The baseline and LFC RPV are to have the same quantity of fuel, based on that required by the baseline vehicle to perform the mission. Take-off and reserve fuel requirements are to be similar to those in MIL-C-5011A (ref. 1). All performance calculations will be based on standard day atmospheric conditions.

The propulsion unit specified for the study is a General Electric Company TF34-GE-100 engine, derated to the requirements of the baseline airplane. The full power rating of this turbofan engine is 40.26 kN (9 050 lbf) static sea level standard day take-off thrust. This thrust level has been derated to 35.69 kN (8 023 lbf) for this study. All fuel is carried internally in wing tanks. The fuel tankage available is adequate for both the baseline and LFC airplanes.

The design criteria for wing airfoil sections specified that they be capable of natural laminar flow over the forward 40 percent of the upper and lower surfaces. The selected airfoil sections are the same for both the baseline and LFC airplanes and are the NACA 65_4-621 at the root and 65_3-618 at the tip. For the LFC airplane, suction was applied to the upper and lower surfaces of the wing, starting from the end of the natural laminar flow region to the wing trailing edge. The projected, exposed wing area laminarized by the LFC system is 25.27 m^2 (272 ft^2). The LFC system is internal except for underwing suction pods. The pods are a scaled down version of those developed by a system contractor to the NASA in the Aircraft Energy Efficiency Program (ACEE/LFC) studies. The LFC system was considered to be capable of maintaining laminar flow only where flight conditions resulted in a unit $R_e \leq 6.56 \times 10^6$/m ($2 \times 10^6$/ft).

Operating weight increases due to the LFC system were based on data contained in studies by systems contractors to the NASA in the laminar flow control portion of the ACEE/LFC program. An ultimate load factor of 3.0, aluminum honeycomb structure, and conventional tricycle landing gear were used in the determination of RPV weights.

A general arrangement of the resulting vehicle is presented in figure 1 with a listing of its physical characteristics in table I. These data apply to both airplanes except for the underwing pods, shown in figure 1, which are required for the LFC system.

RESULTS AND DISCUSSION

Weight Analysis

The basis for the weights data utilized in determining the performance capabilities of the RPV with and without LFC are presented in this section. Included are design criteria, weight penalty parameters established to determine weight increases due to the structural requirements for incorporating the LFC system, the weight of the system itself, and the weight breakdowns for the baseline and LFC equipped RPV's.

In addition to the items discussed in the preceding section, the weight analysis is based partly on the following items:

(1) Nominal fuel weight = 3 742 kg (8 250 lbm)

(2) LFC unit weight penalty = 93.85 Pa (1.96 psf)

(3) Bare TF34-GE-100 engine weighing 6.32 kN (1 421 lbf).

System contractors in the NASA ACEE/LFC studies have provided data for determining the weight increase 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. The airplane was evaluated with and without LFC in the above study. From the data provided, a specific (or unit) weight penalty of 93.83 Pa (1.96 psf) of projected laminarized area was determined. This value allocates a structural weight penalty of 60.33 Pa (1.26 psf) and a LFC system weight penalty of 33.52 Pa (0.70 psf) which includes pumps, power unit(s), ducting, and other equipment (ref. 2).

Applying the LFC structure and systems weight penalty produced a wing weight increase of 2.36 kN (530 lbf) for the 25.27 m^2 (272 ft^2) of projected laminarized wing area. An additional .18 kN (40 lbf) penalty is included in systems and other structural weight and results in a gross weight increase of 2.54 kN (570 lbf) or 3.72 percent. The weight breakdown by subsystems is given in table II for the baseline and LFC configurations.

Propulsion Analysis

The TF34-GE-100 is a two-spool turbofan engine with separate fan and primary exhaust nozzles. Sea level static standard day design characteristics of the basic engine (design rated) are given below:

- ° Overall compression ratio = 20:1
- ° Gross engine thrust = 40.26 kN (9 050 lbf)
- ° Specific fuel consumption = 0.0377 kg/hr/N (0.370 lbm/hr/lbf)
- ° Corrected airflow = 151 kg/sec (333 lbm/sec).

The basic engine as supplied by the manufacturer does not include the inlet, nozzles, thrust reverser, or cowling and weighs 6.32 kN (1421 lbf). The nacelle configuration developed to house the engine is shown in figure 1.

Installed TF34-GE-100 engine performance provided by the General Electric Company in reference 3 is based on the following conditions:

> 1962 U.S. standard atmosphere, reference inlet ram recovery, no service airbleed, no power extraction, no external drag.

The study criteria specified that the engine for the baseline and LFC airplanes be a derated version of the TF34-GE-100 with a thrust level based on the baseline airplane's requirements. Derating simply means a reduction in the thrust ratings and in no way alters the engine performance below the new thrust ratings. Engine operation in a derated mode is less severe than in the normal mode, therefore, derating an engine usually results in increased reliability and longer service life. This is particularly important for extended duration missions as flown by the RPV's of this study.

Derating was accomplished by reducing the available maximum rated climb thrust of 3.914 kN (880 lbf) at the initial endurance conditions of $M = 0.50$ and 15.24 km (50 000 ft) altitude to the required maximum thrust of 3.470 kN (780 lbf). Fuel flow and airflow rates were then determined at this thrust level and altitude/Mach number condition. Thrust, fuel flow rate, and airflow rate at maximum cruise and take-off ratings, throughout the engine operating envelope, were then reduced by the ratios of these parameters.

Engine performance is presented graphically for maximum climb, and for maximum and part power cruise in figures 2 through 5. Since the available engine data terminated at 18.29 km (60 000 ft), extrapolations were made as necessary to cover the altitudes flown by the RPV's, up to about 20.42 km (67 000 ft). Installed engine performance presented does not include the effects of compressor service airbleed or power extraction inasmuch as no requirements were established. However, a compensating drag factor was introduced, as explained in the Drag Analysis section. It was assumed that flight inlet and nozzles could be designed to perform the same as the corresponding reference hardware, therefore, the engine performance was not corrected for these effects. Nacelle external drag is accounted for in the airplane drag polars.

LFC Suction Power

The NACA 65 series airfoil sections were first analyzed without suction. The results, obtained with the STAYLAM program, reference 4, indicated a laminar boundary layer from the leading edge to between 40 and 50 percent of the chord, which corresponds to the characteristics of this airfoil series as outlined in reference 5. After the chordwise extent of the natural laminarization was established for the upper and lower surfaces of both the root and tip airfoils, the minimum amount of suction required to expand the laminar boundary layer to the trailing edge was determined.

The power required by the LFC system, to provide the necessary suction, has been determined theoretically. This suction power has been derived in coefficient form and expressed as an equivalent incremental drag coefficient for airplane performance calculation purposes. The evaluation of the required suction was based on the start of cruise conditions, altitude = 15.24 km (50 000 ft), Mach number = 0.55, and C_L = 0.85. The Reynolds numbers corresponding to the above velocity and altitude are 4.57×10^6 at the root and 2.22×10^6 at the wing tip.

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

$$C_{SP_{local}} = \left[\frac{\rho_w V_w}{\rho_\infty V_\infty} - C_p \times \frac{V_w}{V_\infty}\right]$$

The derivation of the above equation is presented in the Appendix of reference 2. 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. The pressure coefficient distribution along the airfoil surface was computed with a two-dimensional transonic analysis program (ref. 6 and 7). The surface density (ρ_w) and suction flow velocity (V_w) distribution were computed with the STAYLAM boundary layer program (ref. 4). The results are presented for the root and tip chords in figures 6 through 11 and show the chordwise distributions of C_p, $(\rho V)_w/(\rho V)_\infty$, and ρ_w/ρ_∞. The resulting chordwise distribution of the suction power coefficient along the upper and lower wing surfaces are presented in figure 12 for the root chord and figure 13 for the tip chord.

The areas under the curves in figures 12 and 13 were integrated graphically to obtain the airfoil suction power coefficients based on the chord, per unit length of wing span. The suction power coefficients were determined at the wing root and tip and the variation in C_{SP} between the two was assumed to be linear. The value of C_{SP} based on wing area was then determined with the following equation.

$$C_{SP_{wing}} = \frac{\left[(C_{SP} \times c)_{root} + (C_{SP} \times c)_{tip}\right] \times \frac{1}{2} \times b}{S}$$

The resulting C_{SP} for the RPV wing is 0.00187.

The coefficient C_{SP} can be considered to represent either power or equivalent drag, depending on whether it is dimensionalized using $1/2\rho_\infty V_\infty^3 S$ for power or $1/2\rho_\infty V_\infty^2 S$ for drag. In this report it is used as an equivalent drag coefficient and to be consistent with drag coefficient terminology, C_{SP} is designated $C_{D_{SP}}$ with a magnitude of 0.00187. This value, although based on start of cruise conditions, was considered to be usable throughout the speed-altitude range of LFC operation.

Drag Analysis

Drag polars were established for the baseline and LFC RPV's. Both vehicles were considered to have an entirely turbulent boundary layer except for the wing. In the case of the baseline vehicle the forward 40 percent of the wing area was determined to be in a natural laminar flow state and the remaining 60 percent in turbulent flow. The LFC wing differed in that the aft 60 percent of the wing area was maintained in laminar flow through the use of an LFC system on both the upper and lower surfaces.

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

The magnitudes of the parasite drag coefficients of this RPV, due to its flight envelope of sea level to 21.34 km (70 000 ft) and low Mach numbers (.378 M to .6 M), are comparatively sensitive to the effect of R_e since the slope of the skin friction coefficient versus R_e curve increases comparatively rapidly with decreasing R_e, in the R_e range of the RPV. Therefore, drag polars were developed which corresponded to the Mach number-altitude combinations of the mission profile instead of a single drag polar based on average mission conditions. This was done to more accurately represent the laminar flow characteristics of each configuration and to determine more precisely the improvement in mission performance from the baseline to the LFC airplane.

The flight conditions necessary to carry out the mission requires operating at relatively high C_L's. Therefore in the NACA 65 series, airfoil sections were selected having both a high design lift coefficient and a fairly extensive C_L range for favorable pressure gradients. The data source for the selection was the Summary of Airfoil Data (ref. 5). The airfoils chosen were the NACA

65_4-621 for the wing root and 65_3-618 at the wing tip. A minimum speed criteria was not used in this study. The proximity of the speeds required for best mission performance to stalling speed should be noted. Extrapolating available $C_{L_{max}}$ versus R_e data from reference 5 for the 65_3-618 airfoil section indicates that at the lowest Reynolds numbers encountered by the RPV's, approximately 2.1 x 10^6, $C_{L_{max}}$ may be on the order of 1.36. This represents about 1.24 V_{stall} for the LFC airplane and 1.31 V_{stall} for the baseline airplane, based on the C_L's at M = 0.50, as presented in the Mission Analysis section.

Since no requirements were established for either compressor service airbleed or power extraction, the nacelle flat plate C_f was increased by 20 percent. The suction pods shown in figure 1 house the suction unit power generator, low and high pressure pumps. The pods are scaled down versions of those utilized in a study conducted by a system contractor to the NASA Aircraft Energy Efficiency (ACEE) Program. Scaling was based on ratioing the area to be laminarized on the RPV to the laminarized area of the ACEE airplane. This resulted in a pod 0.3 m (1.0 ft) in diameter by 1.8 m (5.9 ft) in length. From empirical data presented in reference 8, page 13-16, a C_D of 0.09 was obtained, based on frontal area of the pod as the reference area. This converted to a $\Delta C_{D_{P_{min}}}$ of .00031 for the two pods based on the projected wing area.

The minimum parasite drag coefficients of the components of the baseline and LFC RPV's are presented in table III for one particular set of endurance conditions. Except for the wing, the components common to both aircraft have the same C_{D_p}. The LFC configuration has the added drag coefficient increments of the suction pods (.00031) and the equivalent suction power (.00187). The coefficients in the table are based on the Reynolds numbers corresponding to a typical endurance condition, i.e., M = .525 and altitude = 17.53 km (57 500 ft).

Analysis of the tabulated values show that LFC reduces $C_{D_{P_{min}}}$ of the wing about 65 percent, from .00867 to .00303. In terms of the complete airplane, the reduction is from a $C_{D_{p_{min}}}$ of .01539 to .00975 or approximately 37 percent. Finally, taking into account the suction pods and suction power requirement, the comparison of the baseline vehicle $C_{D_{p_{min}}}$ (.01539) to that of the LFC configuration (.01193) indicates a net improvement of about 23 percent in minimum parasite drag.

The variations of $C_{D_{p_{min}}}$ with altitude and Mach number are presented in figure 14 for the baseline and LFC RPV's. The speeds shown cover those flown in the missions. The mission profile, after take-off, starts with a 250 KCAS climb and continues at that airspeed until the desired endurance Mach number (.50 to .60) is reached. The remainder of the climb is at the endurance Mach number.

The break in the LFC configuration curves in figure 14 is due to the operation of the LFC system and corresponds to a unit $R_e = 6.56 \times 10^6$/m (2×10^6/ft). This unit R_e, or lower, was the criterion used for fully effective LFC operation. The equivalent suction power increment ($\Delta C_{D_{p_{min}}}$ = .00187) is included in the segment of the curves with LFC operating. The curves also show that at any altitude $C_{D_{p_{min}}}$ decreases with increasing speed, which results from the trend of C_f with R_e, i.e., C_f decreases with increasing R_e. No growth of parasite coefficient with lift coefficient was assumed for the NACA 65 series airfoils because they have a minimum drag bucket over a significant increment in lift coefficient range. This increment in lift coefficient range becomes larger as Reynolds number is reduced. Figure 14 of reference 5 indicates this minimum drag lift increment range to be ±.43 and ±.55 at Reynolds numbers of 8×10^6 and 3×10^6, respectively, from the design lift coefficient.

The induced drag coefficients (C_{D_i}) were based on a potential-flow efficiency factor e = 1.0. It can be shown analytically that with selection of wing taper ratio and judicious application of wing twist, a value of e close to

1.0 is possible. Even if these conclusions were optimistic, the performance comparison of the baseline to the LFC airplane would be affected very little. For example, the resulting incremental change in C_{D_i} between the two configurations in changing from e of 1.0 to .95 would only be .00016.

Drag polars with and without LFC, at typical endurance conditions of M = .525 and 17.53 km (57 500 ft) altitude, are presented in figure 15.

Mission Analysis

The mission profile, as defined in the Basic Criteria section, calls for the vehicle to loiter at speeds and altitudes that will maximize mission time. For the baseline airplane, the objective is to remain on station for 24 hours, with a 5.34 kN (1 200 lbf) payload. An additional capability to cruise two hours out and two hours return to base is required, for a total mission time of 28 hours. The mission capabilities of the LFC equipped version of the RPV are based on the fuel quantity and derated engine established for the baseline RPV.

Based on the criteria for the study, the endurance segment of the flights were limited to Mach numbers between 0.50 and 0.60, and altitudes from 15.24 km (50 000 ft) to 21.34 (70 000 ft). In calculating the missions, military ground rules have been applied in accordance with MIL-C-5011A (ref. 1). The requirements which were applied to the mission are: (1) fuel allowance for starting engines, take-off and accelerate to climb speed is equal to sea level operation for 1 minute at MRT plus 5 minutes at NRT; (2) descent at the end of the return cruise is made with no distance credit or fuel used; and (3) fuel allowance for landing and reserves is the sum of 5 percent of the initial fuel plus operation for 30 minutes at sea level at maximum endurance speed.

Mission performance was calculated using an available computer program. In the program the endurance segment of the mission is flown in a cruise-climb mode, i.e., Mach number and lift coefficient are held constant and altitude is increased as the airplane becomes lighter. As a result the final endurance altitudes were considerably higher, approximately 4 km

(13 000 ft), than the initial endurance altitudes.

The take-off gross weights, for the mission calculations, were 67.93 kN (15 270 lbf) for the baseline airplane and 70.47 kN (15 840 lbf) for the LFC airplane, including in both cases 36.70 kN (8 250 lbf) of fuel.

The climb speed schedule used in calculating mission performance was a combination of constant calibrated airspeed and constant Mach number. The climbs were started at constant airspeed (250 KCAS), which was maintained until the endurance Mach number of the particular mission was reached, and the remainder of the climb was made at that Mach number. This procedure applied to the baseline and LFC RPV's. The LFC airplane had an additional criterion in the climb and that was establishing the altitude for effective LFC operation from which point the remaining climb was based on completely laminar flow over the wing. The $C_{D_{p_{min}}}$ curves associated with this are presented in figure 14. Note that climb times do not exceed 0.5 hours, for any mission, which in all cases is less than 2 percent of total mission time. Also, in the missions with the LFC airplane, climb to the altitudes at which LFC operation was started required no more than 0.1 hours.

Mission time was determined for a series of Mach numbers between 0.50 and 0.575, and for a number of initial endurance altitudes, from 15.24 km (50 000 ft) to 16.76 km (55 000 ft). For both the baseline and LFC RPV, it was found that the total mission time, for a given Mach number, increased as the initial endurance altitude was increased. However, as the initial altitude increased so did the final altitude, until climb ceilings were reached. The ceilings used were service ceilings at which the rate-of-climb is 30.5 mpm (100 fpm) with maximum climb power. These trends are shown in figure 16 for the baseline airplane and figure 17 for the LFC airplane, in the form of total mission time versus initial endurance altitude. The mission times are based on a fuel quantity of 3 742 kg (8 250 lbm), which was the amount selected for the baseline airplane in order for it to achieve the required 28 hours total mission time. Cross-plotting the mission times at the climb ceilings resulted in the curves in figure 18. Note that the mission time required of the baseline airplane occurs at about M = 0.527.

The initial and final endurance altitudes of the maximum time missions are presented in figure 19. Other significant parameters occurring in the endurance leg of the maximum time missions are the average L/D and SFC in figure 20, and C_L and C_D in figure 21.

An evaluation of figure 18 shows that the improvement in total mission time due to LFC is 6.7 percent at M = 0.50, and increases with increasing Mach number to 13.6 percent at M = 0.575. It appears, from an analysis of figures 16 and 17, that the climb-ceilings criteria has a more detrimental effect on the attainable mission times of the baseline airplane than the LFC airplane. This is probably due to the lower climb performance of the baseline airplane at endurance altitudes. This trend is illustrated in figure 22, for representative endurance altitudes.

For the baseline vehicle the climb ceiling limitation also resulted in endurance being flown at C_L lower than those required for peak L/D. This is a consequence of the lower initial endurance altitude, which for a given Mach number yielded a higher dynamic pressure and, therefore, a lower C_L. The variation of L/D with C_L, for endurance Mach numbers and altitude combinations, is presented in figure 23 for the baseline airplane and figure 24 for the LFC airplane. To illustrate where, relative to the peak L/D, the maximum mission times were flown, a line was added to the figures connecting the average L/D and C_L at each endurance Mach number. The improvement in endurance L/D, due to LFC, is about 14.3 percent at M = 0.50 and keeps increasing with Mach number to approximately 23.5 percent at M = 0.575. Note that these improvements include the effect of the equivalent suction power drag ($C_{D_{SP}}$).

Endurance (E) can be calculated from the Breguet equation: $E = (1/SFC)(L/D)(\log_e W_1/W_2)$, where W_1 is the airplane gross weight at the start of the endurance segment of the mission and W_2 is the weight at the end of the endurance segment of the mission. The following tabulation illustrates why the L/D increase is not translatable into a comparable increase in mission time. Consider the following typical case, using the Breguet equation at the conditions for maximum mission time at M = 0.50:

	Baseline RPV	LFC RPV	Percent Change
$1/SFC_{avg}$	1.5106	1.4903	-1.34
$(L/D)_{avg}$	28.78	32.87	14.21
$\log_e (W_1/W_2)$	.6567	.6212	-5.41
*Cruise Plus endurance, hours	28.55	30.40	6.5
* Cruise = 4 hours			

The effect of the 14.21 percent improvement in L/D on mission time has been reduced by the multiplier effect of the two parameters which did not improve through the addition of the LFC system. The weight fraction of the RPV with the LFC system and required structural changes is less since additional weight must be carried throughout the flight. Since the thrust level of the engine was based on the requirements of the baseline airplane, the baseline airplane operated in a slightly better SFC range than did the LFC airplane. All of these factors influence the net improvement in endurance capability shown in the table. Also, it should be recalled that the L/D of the LFC airplane, in the above table, has been reduced by inclusion of the suction power requirement and the drag of the suction pods of the LFC system.

Effect of Scaled Engines

The main part of this study as reported herein was based on the LFC airplane using the baseline airplane's engine; however, another potential benefit of an LFC system is that, by lowering the vehicle's drag, less thrust is required. Consequently, a smaller engine may then be used as long as take-off performance is adequate.

The benefits of a scaled-down, rather than derated, engine are: lower drag and weight, since in scaling an engine's size is physically reduced. As a result of being properly sized for the particular airplane configuration, the engine operates in a more efficient SFC range.

Scaling factors were not available for the TF34-GE-100 engine. However, they were available for a comparable turbofan engine and are presented in figure 25. With these factors and methods described in the main part of this report, weight breakdowns were determined for the engine sizes (thrust levels) of interest. The resulting weights summary is contained in table IV. Note that the base engine thrust level used for scaling was the full rated thrust of the TF34-GE-100 engine, 40.26 kN (9 050 lbf) and not the derated value, 35.69 (8 023 lbf).

The reduced engine size, and accompanying reduction in nacelle size, lowered $C_{D_{p_{min}}}$ by .00021 for the 35.59 kN (8 000 lbf) engine size and by .00041 for the 31.14 kN (7 000 lbf) engine size.

Based on the same criteria and limitations applied to the derated engine version of the LFC airplane, missions were calculated with scaled engines, starting with the fully rated 40.26 kN (9 050 lbf) engine. It was found that mission time increased as either Mach number or engine size was reduced. The maximum mission time for each engine size/Mach number combination is presented in figure 26, with the best mission time occurring with M = 0.50 and engine thrust of 31.14 kN (7 000 lbf). For thrust levels lower than those shown, the final endurance altitudes for best mission times were higher than the ceiling based on the 30.5 mpm (100 fpm) rate-of-climb criterion used throughout this study. For comparison, the performance of the baseline and LFC airplanes with the derated engines are also shown in figure 26. At M = 0.50 the longest time for the LFC airplane with a scaled engine has increased to 34.15 hours, which represents a 17.6 percent increase over the baseline airplane. This can be compared to the 6.7 percent increase between the LFC and baseline airplanes with the derated engines.

The Breguet equation parameters which principally determine mission time (see Mission Analysis section) are presented in figure 27, for both the scaled and derated engine configurations at M = 0.50. The following tabulation compares the baseline airplane to the LFC airplane with the 31.14 kN (7 000 lbf) scaled engine and with the derated engine.

	1. Baseline RPV	LFC RPV with 2. Scaled Engine	3. Derated Engine	Percentage Change from 1. to 2.	from 1. to 3.
$1/SFC_{avg}$	1.5106	1.4992	1.4903	-0.75	-1.34
$(L/D)_{avg}$	28.78	33.87	32.87	17.69	14.21
$\log_e (W_1/W_2)$	.6567	.6633	.6212	1.01	-5.41
*Cruise plus endurance, hrs.	28.55	33.68	30.40	18.0	6.48
* Cruise = 4 hours					

For the LFC airplane, all three Breguet parameters are more favorable with the scaled engine than they are with the derated engine. This effect is particularly true of the weight fraction, where the extent of the improvement indicates that the effect of the weight increases due to the LFC system are more than offset by the weight reductions resulting from scaling down the size of the engine.

CONCLUSIONS

The effects of adding a laminar flow control (LFC) system to a long-endurance-surveillance remotely-piloted vehicle (RPV) have been determined. The baseline (non-LFC) airplane has a wing which is naturally laminar over the forward 40 percent of its area. The LFC airplane laminarizes the remainder of the wing area with an LFC system. The mission of the RPV is to loiter at altitudes between 15.24 km (50 000 ft) and 21.34 km (70 000 ft), and at speeds between M = 0.50 and 0.60, with a 5.34 kN (1 200 lbf) payload. The performance of both vehicles is based on a fuel load of 36.70 kN (8 250 lbf). Following are the significant results of the study:

1. Maximum total mission time occurs at M = 0.50 for both airplanes. The baseline airplane has a capability of 29.1 hours and the LFC airplane 31.0 hours, an increase of 6.7 percent.

2. For the flight conditions yielding the maximum total mission times, and including all LFC effects, the average L/D of the LFC airplane (32.9) is 14.2 percent greater than that of the baseline airplane (28.8).

3. The purely aerodynamic benefit of the LFC system, i.e., reduction in skin friction and associated drag coefficients, at typical endurance flight conditions is a 65 percent reduction in minimum parasite drag of the wing which is a 37 percent reduction in total airplane minimum parasite drag.

4. The suction power required to maintain laminar flow, expressed as an incremental drag coefficient, is .00187. At endurance speeds and altitudes this represents, on the average, 15.1 percent of the parasite drag and 7.0 percent of the total drag of the LFC airplane.

5. The LFC system and structural modifications required for its installation produced a weight increase of 9.8 percent in operating weight empty and 3.7 percent in take-off gross weight.

6. The engine for the above performance is a TF34-GE-100, derated to 35.69 (8 023 lbf) standard day static sea level take-off thrust and its selection was based on the requirements of the baseline vehicle. Using the same engine in the LFC airplane resulted in slightly higher SFC's than were encountered by the baseline airplane under similar flight conditions.

In a supplementary study, a version of the TF34-GE-100 engine scaled, rather than derated, to a sea level standard day static take-off thrust rating of 31.14 kN (7 000 lbf) was used in the LFC airplane. With this engine the maximum total mission occurs at M = 0.50 and is 34.15 hours, an increase of 17.6 percent over the baseline airplane's capability and 10.2 percent over the LFC airplane with derated engine. The principal reasons for the improved performance, over that of the LFC airplane with the derated engine, are a three percent increase in endurance L/D, due to the smaller nacelle, and an 8.5 percent lower operating weight empty.

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TABLE I. - PHYSICAL CHARACTERISTICS OF THE BASELINE AND LFC AIRPLANES.

WING	
Area, m^2 (ft^2)	44.04 (474)
Aspect ratio	17.1
Sweep, c/4, rad (deg)	.063 (3.58)
Taper ratio	0.475
Span, m (ft)	27.43 (90.0)
MAC, m (ft)	1.66 (5.45)
Root chord, m (ft)	2.18 (7.14)
Chord at body, m (ft)	2.13 (7.00)
Tip chord, m (ft)	1.03 (3.39)
$(t/c)_{root}$ (65_4-621)	21 percent
$(t/c)_{tip}$ (65_3-618)	18 percent
Wetted area, m^2 (ft^2)	87.4 (940.7)
FUSELAGE	
Max diameter, m (ft)	1.12 (3.67)
Length, m (ft)	15.24 (50.0)
Wetted area, m^2 (ft^2)	34.7 (373.9)
HORIZONTAL TAIL	
Area, m^2 (ft^2)	4.72 (50.8)
Aspect ratio	4.1
Taper ratio	1.00
Span, m (ft)	4.37 (14.33)
MAC, m (ft)	1.08 (3.54)
Root chord, m (ft)	1.08 (3.54)
Tip chord, m (ft)	1.08 (3.54)
(t/c), constant	13.0 percent
Tail volume coefficient	0.420
Wetted area, m^2 (ft^2)	9.7 (103.9)

TABLE I. - Concluded.

VERTICAL TAILS

Area, m^2 (ft^2)	4.02 (43.3)
Aspect ratio	1.8
Taper ratio	0.43
Span, m (ft)	1.91 (6.26)
MAC, m (ft)	1.11 (3.63)
Root chord, m (ft)	1.47 (4.83)
Tip chord, m (ft)	0.63 (2.08)
(t/c), constant	13.0 percent
Tail volume coefficient	0.022
Wetted area, m^2 (ft^2)	8.2 (88.6)

ENGINE STRUT

Length, m (ft)	4.40 (14.42)
Max. thickness, m (ft)	0.61 (2.00)
Wetted area, m^2 (ft^2)	3.66 (39.4)

NACELLE

Length, m (ft)	3.43 (11.24)
Max. diameter, m (ft)	1.35 (4.42)
Wetted area, m^2 (ft^2)	9.68 (104.2)

TABLE II. - WEIGHT SUMMARY OF BASELINE AND LFC AIRPLANES

	Airplane Configuration			
	Baseline		LFC	
	kN	lbf	kN	lbf
Structure - excluding wing	7.78	1750	7.92	1780
- wing	6.58	1480	8.94	2010*
Propulsion	7.76	1745	7.76	1745
Systems	3.54	795	3.58	805
Weight Empty	25.66	5770	28.20	6340
Operating Items	.22	50	.22	50
Operating Weight Empty	25.88	5820	28.42	6390
Payload	5.34	1200	5.34	1200
Zero Fuel Weight	31.22	7020	33.76	7590
Mission Fuel	36.70	8250	36.70	8250
Take-off Gross Weight	67.92	15270	70.46	15840

* Includes LFC wing weight penalties.

TABLE III. - MINIMUM PARASITE DRAG COEFFICIENTS AT TYPICAL ENDURANCE CONDITIONS OF BASELINE AND LFC AIRPLANES

Aircraft Parts	Reynolds No.	Drag Item	Baseline C_f	Baseline $\Delta C_{D_{Pmin}}$	LFC C_f	LFC $\Delta C_{D_{Pmin}}$
Wing	$2.26\ (10)^6$	Uncorr. flat plate	.002745	.00545	.000875	.00174
		Supervelocity		.00171		.00054
		Pressure drag		.00049		.00000
		Wing/body interf.		.00062		.00062
		Excrescences		.00024		.00008
		Surface roughness		.00016		.00005
Horizontal Tail	$1.54\ (10)^6$	Uncorr. flat plate	.00394	.00086	.00394	.00086
		Supervelocity		.00018		.00018
		Pressure drag		.00002		.00002
		Interference		.00004		.00004
		Excrescences		.00006		.00006
		Surface roughness		.00003		.00003
Vertical Tails	$1.58\ (10)^6$	Uncorr. flat plate	.00393	.00074	.00393	.00074
		Supervelocity		.00015		.00015
		Pressure drag		.00001		.00001
		Interference		.00003		.00003
		Excrescences		.00005		.00005
		Surface roughness		.00002		.00002
Fuselage	$2.18\ (10)^7$	Uncorr. flat plate	.00251	.00198	.00251	.00198
		3-dim. effect		.00002		.00002
		Supervelocity		.00006		.00006
		Pressure drag		.00001		.00001
		Non-optimum shape		.00004		.00004
		Excrescences		.00008		.00008
		Surface roughness		.00006		.00006

TABLE III. - Concluded.

Aircraft Parts	Reynolds No.	Drag Item	Baseline C_f	Baseline $\Delta C_{D_{P_{min}}}$	LFC C_f	LFC $\Delta C_{D_{P_{min}}}$
Engine Strut	$6.27 (10)^6$	Uncorr. flat plate	.00307	.00025	.00307	.00025
		Supervelocity		.00008		.00008
		Pressure drag		.00001		.00001
		Excrescences		.00001		.00001
		Surface roughness		.00001		.00001
Nacelle	$4.89 (10)^6$	Uncorr. flat plate	.00320	.00070	.00320	.00070
		3-dim. effect		.00000		.00000
		Excrescences		.00014		.00014
		Supervelocity		.00025		.00025
		Loss of lip suction		.00014		.00014
		Boattail drag		.00013		.00013
		Surface roughness		.00002		.00002
		Interference		.00049		.00049
Trim				.00005		.00005
Suction Pods				-		.00031
Suction Power ($C_{D_{SP}}$)				-		.00187
Total Aircraft $C_{D_{p_{min}}}$				.01539		.01193

NOTE: Reynolds numbers are based on 0.525 M and 17.53 km (57 500 ft).

TABLE IV. - WEIGHT SUMMARY OF LFC AIRPLANE WITH SCALED ENGINES

Sea level static thrust Units	31.14 kN	7000 lbf	35.59 kN	8000 lbf	40.26 kN	9050 lbf
Structure, excluding wing	7.52	1691	7.80	1754	8.10	1821
, wing	8.67	1950	8.35	1990	8.98	2020*
Propulsion	6.06	1363	6.87	1545	7.76	1745
Systems	3.55	796	3.56	801	3.58	804
Weight Empty	25.80	5800	27.08	6090	28.42	6390
Operating Items	.22	50	.22	50	.22	50
Operating Weight Empty	26.02	5850	27.30	6140	28.64	6440
Payload	5.34	1200	32.64	1200	5.34	1200
Zero Fuel Weight	31.36	7050	32.64	7340	33.18	7640
Mission Fuel	36.70	8250	36.70	8250	36.70	8250
Take-off Gross Weight	68.06	15300	69.34	15590	70.68	15890

* Includes LFC wing weight penalties.

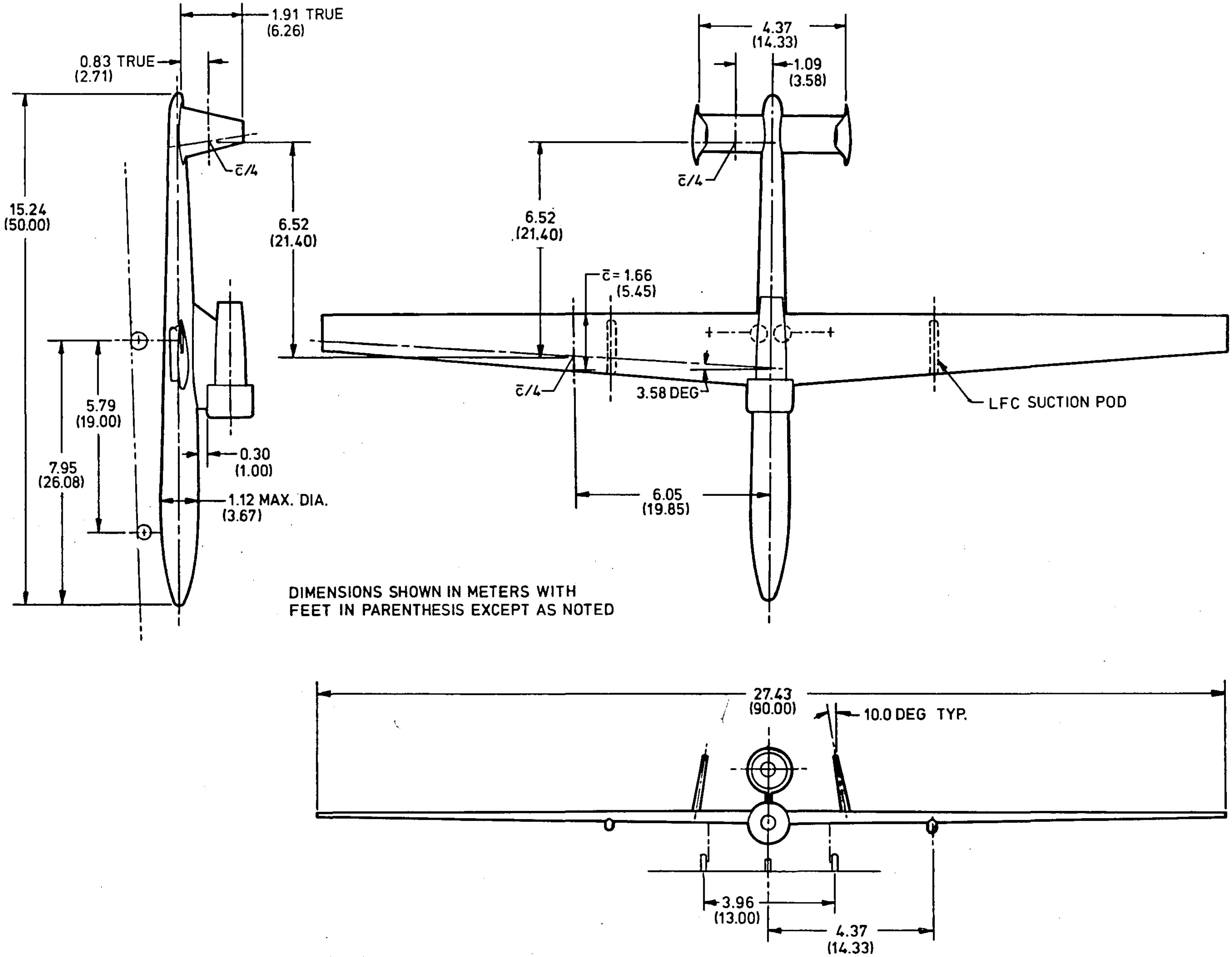


Figure 1. - Long endurance surveillance remotely piloted vehicle

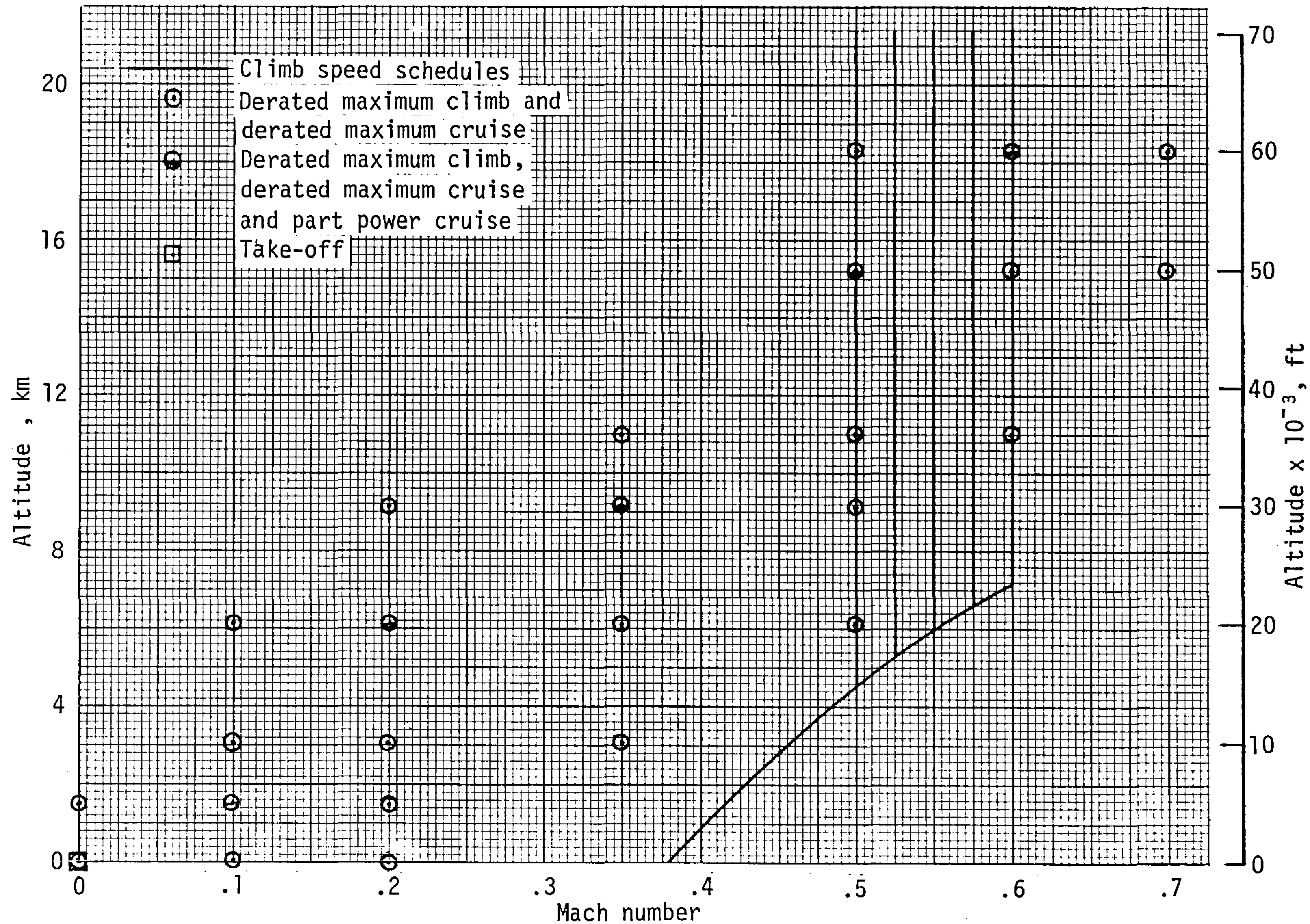


Figure 2. - Engine performance data.

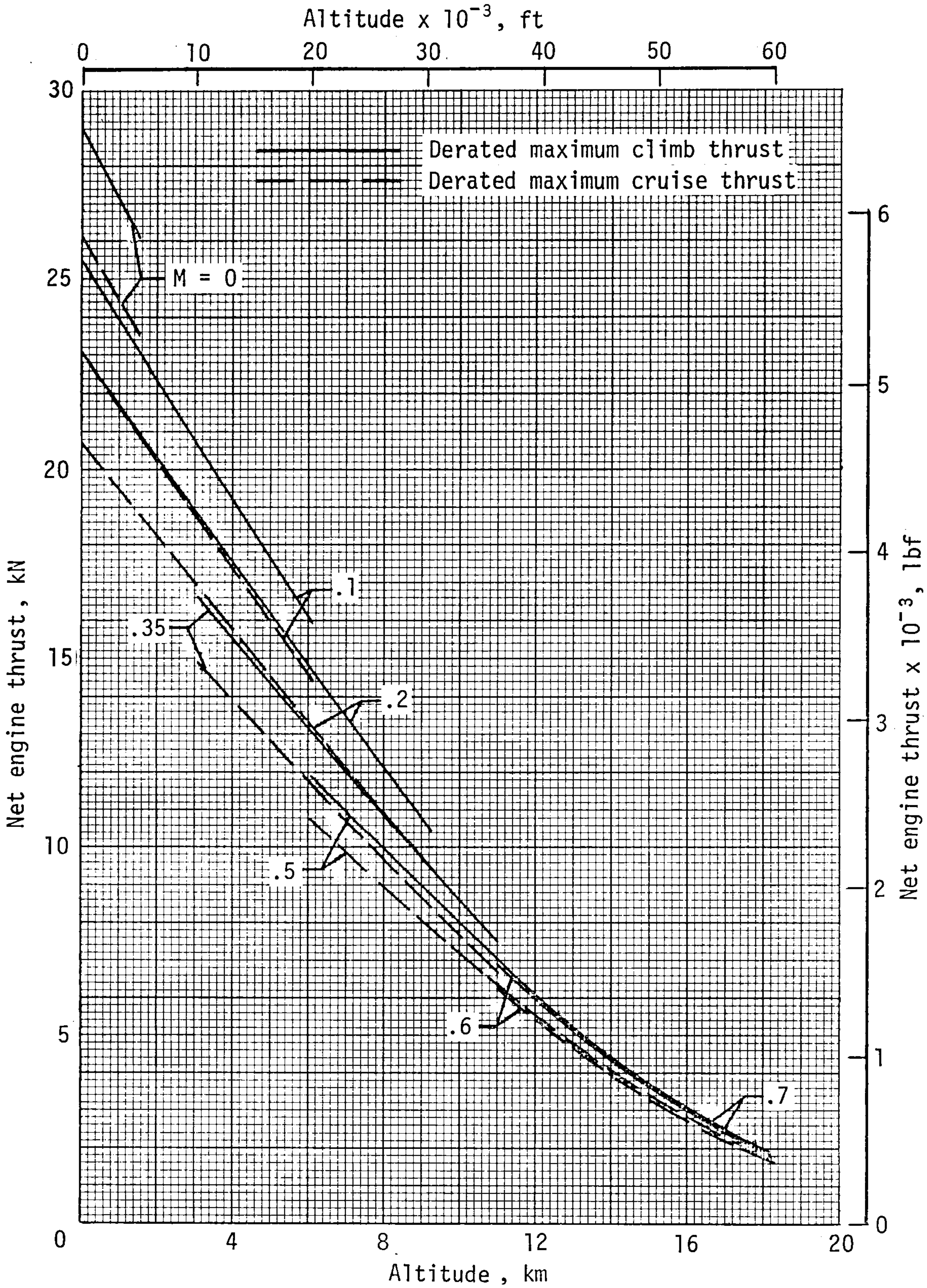


Figure 3 . - Derated net engine thrust for maximum climb and cruise.

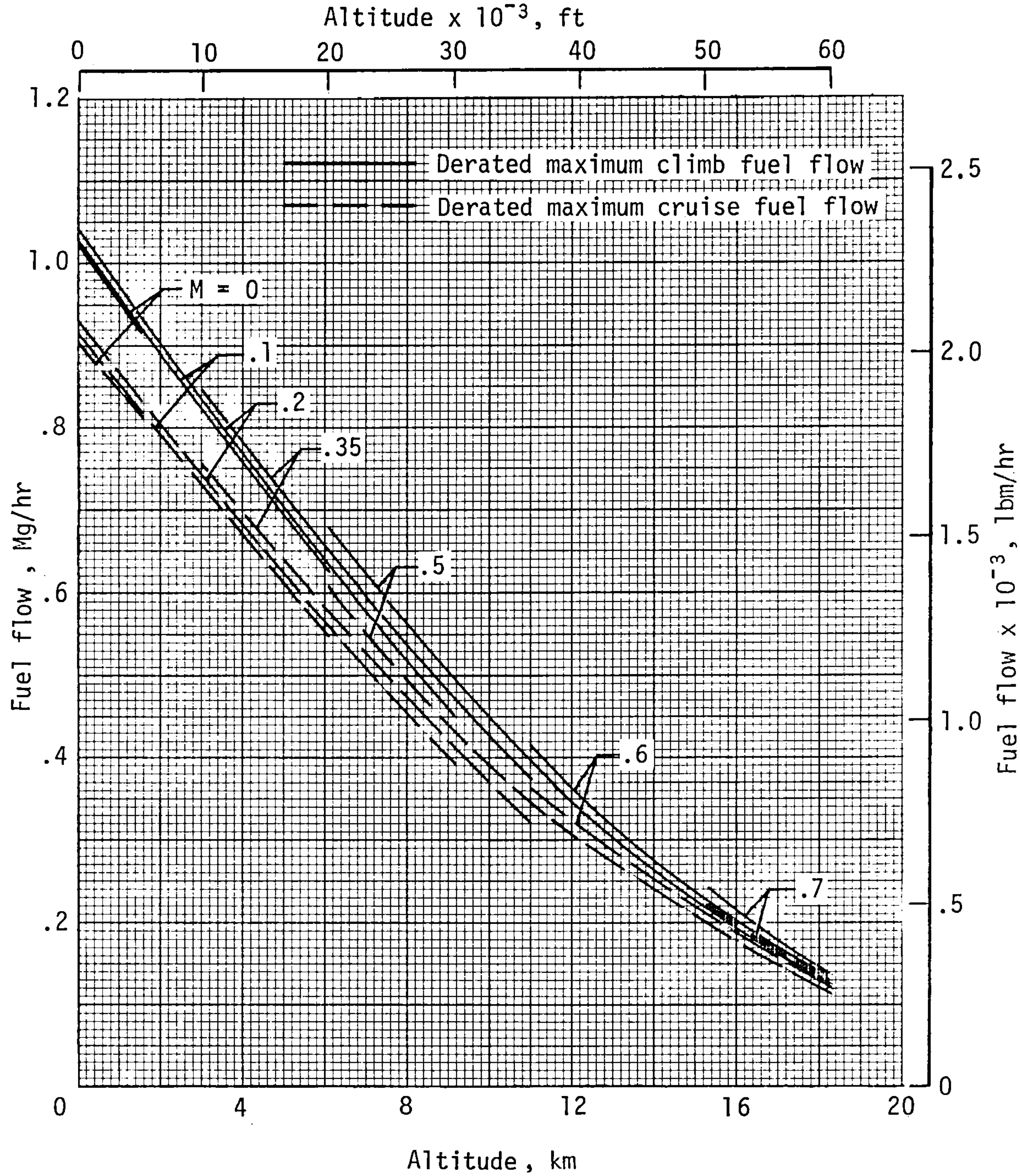


Figure 4. - Derated fuel flow for maximum climb and cruise.

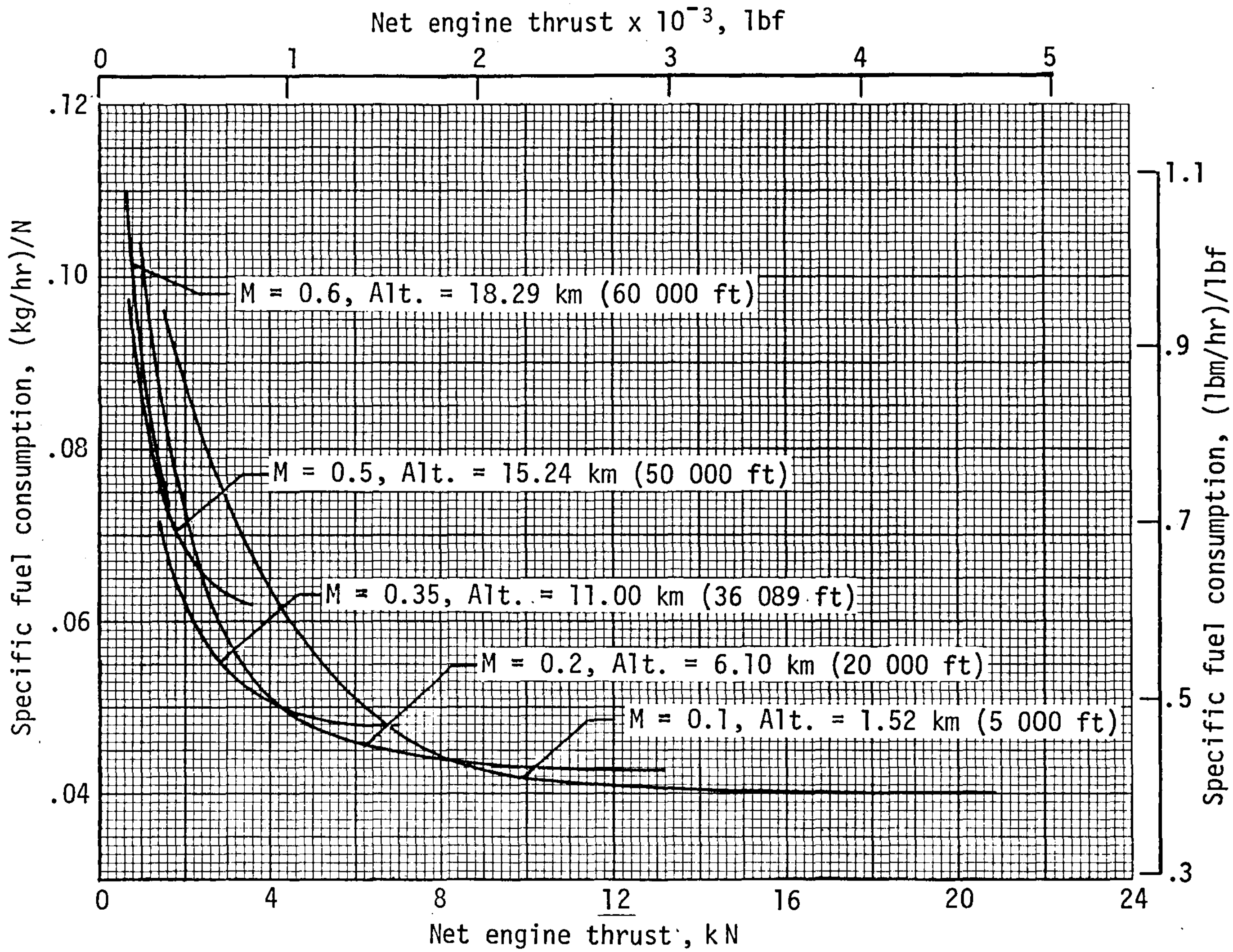


Figure 5. - Thrust and fuel flow for derated maximum cruise and part power cruise.

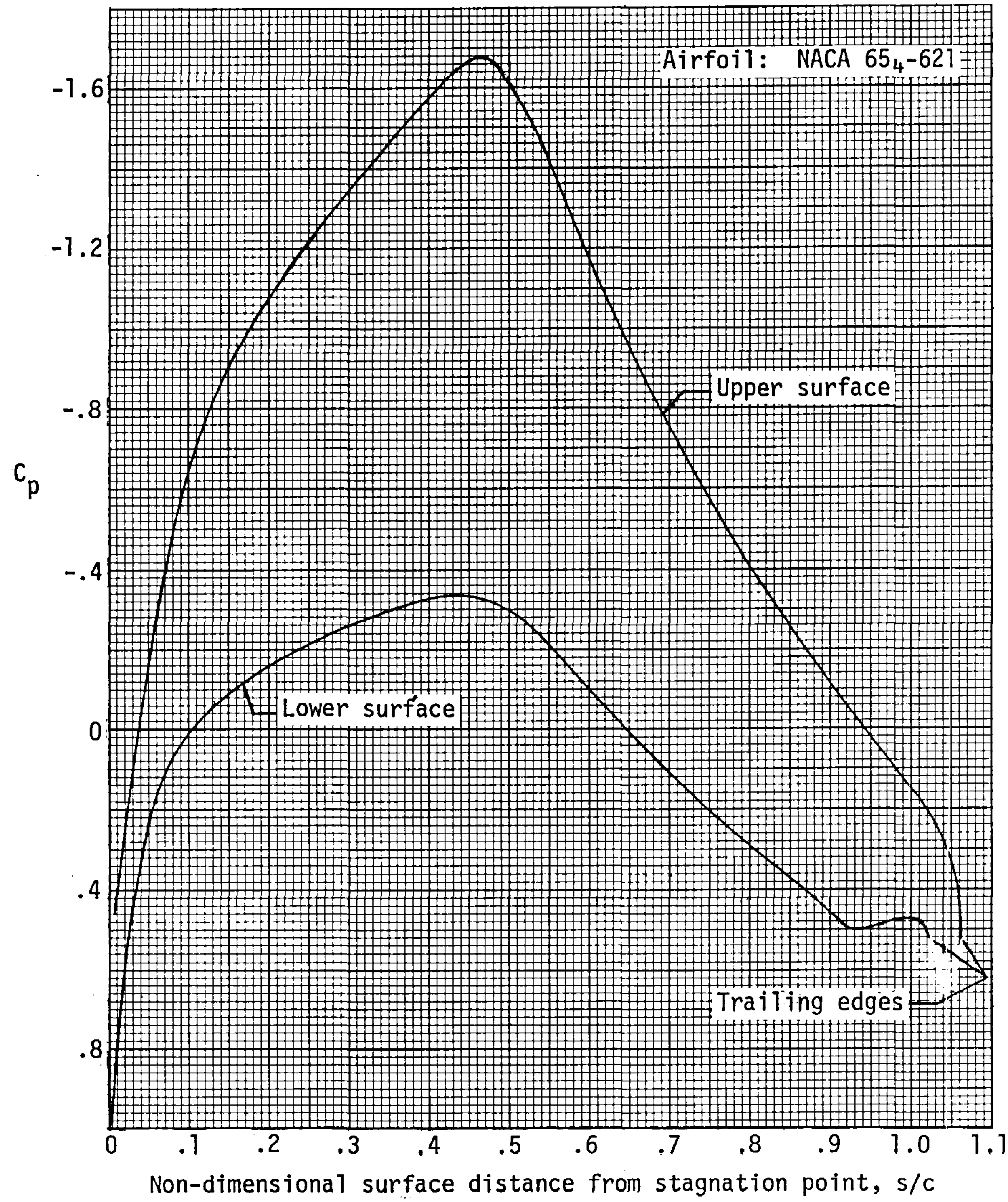


Figure 6 . - Pressure distribution along airfoil surface; root chord.

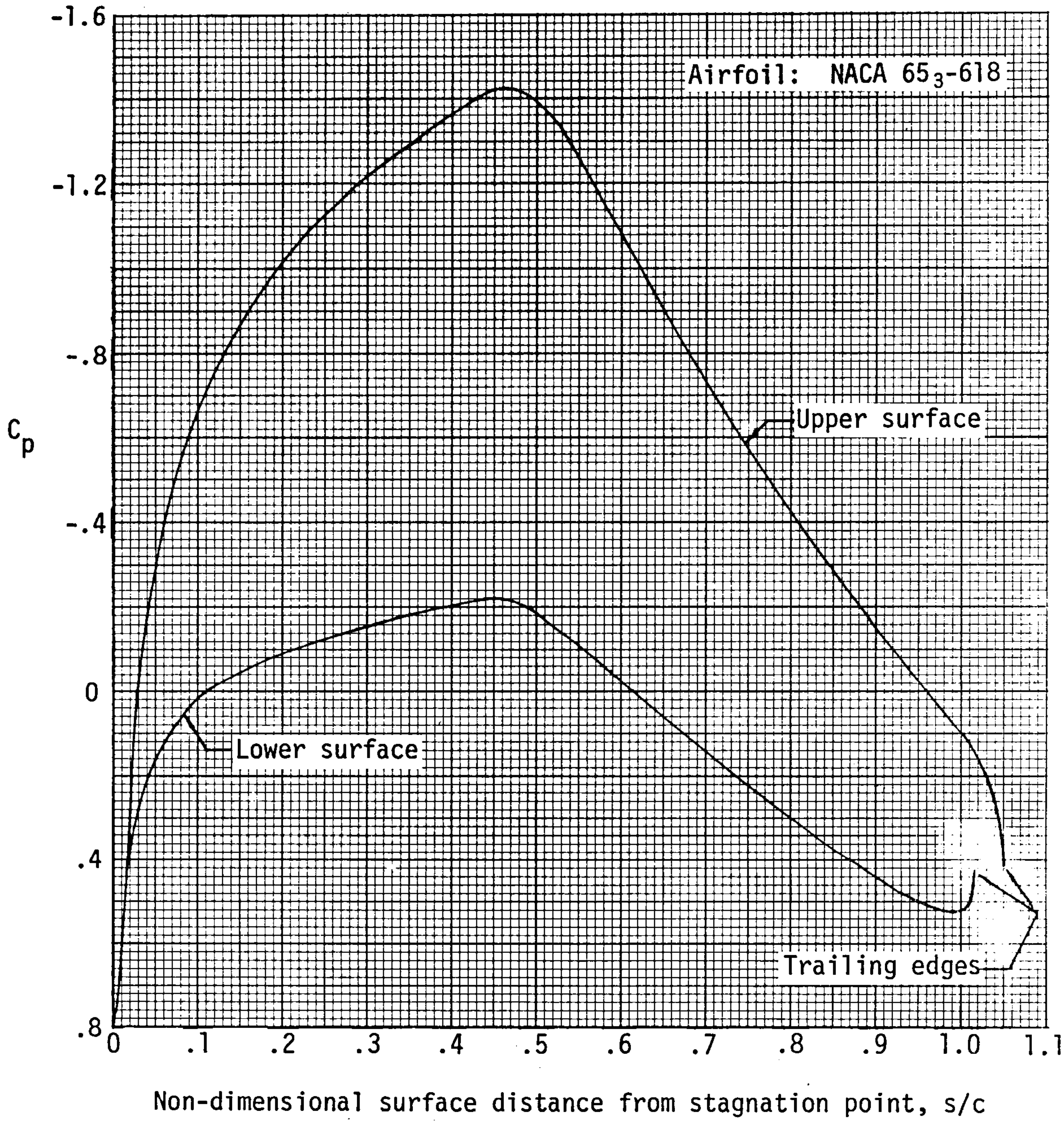


Figure 7. - Pressure distribution along airfoil surface; tip chord.

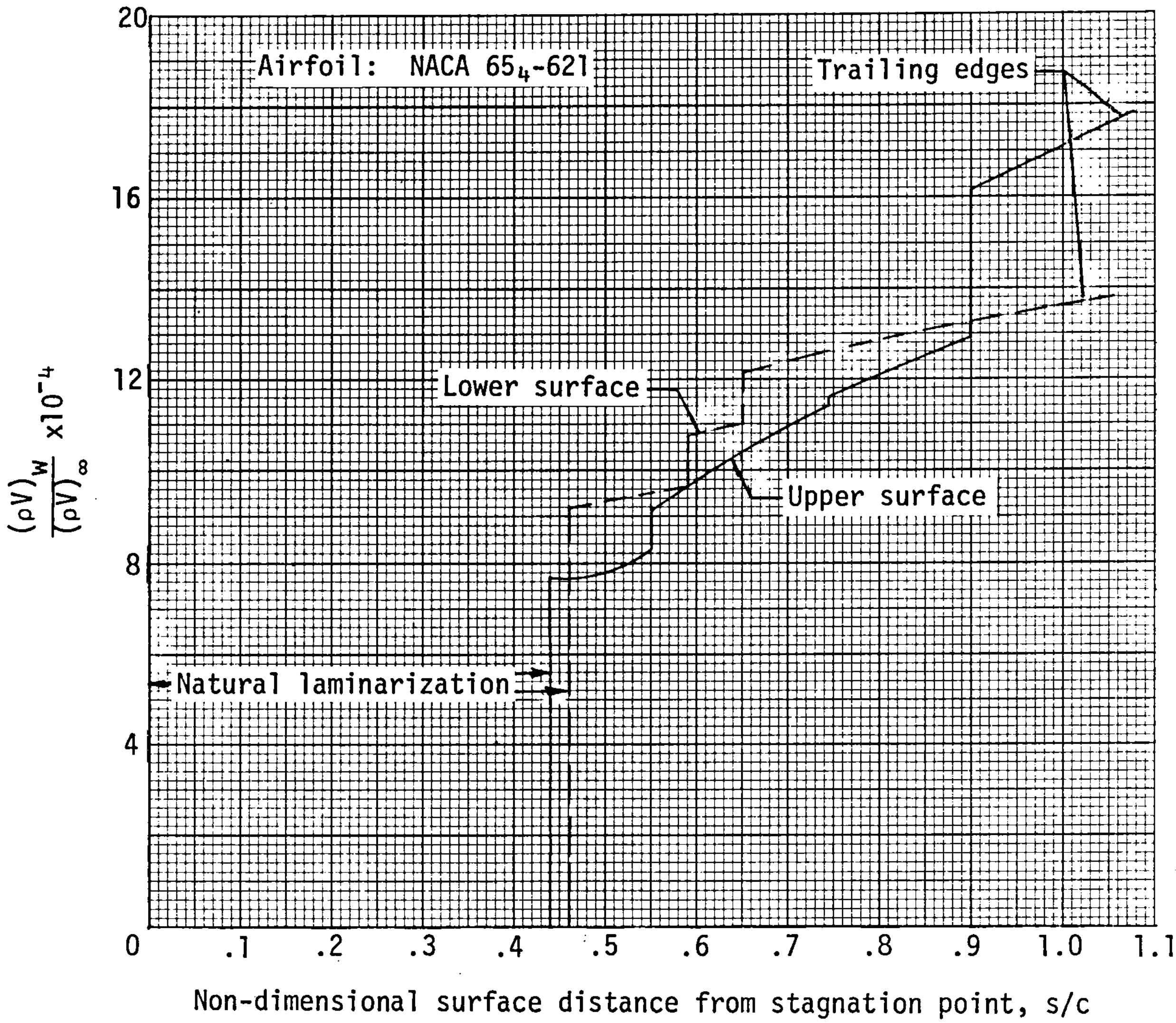


Figure 8 . - Suction mass flow distribution along airfoil surface; root chord.

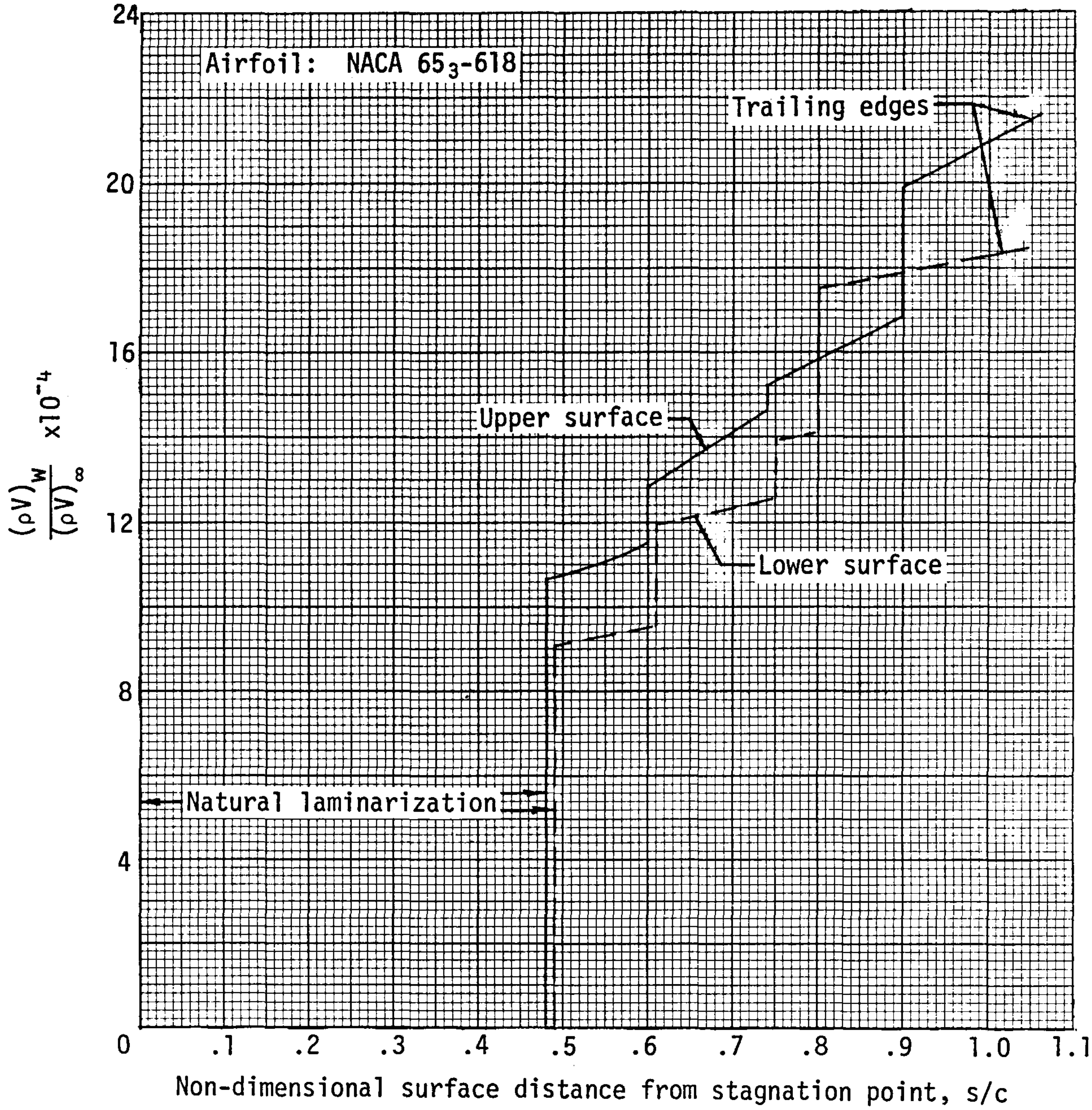


Figure 9. - Suction mass flow distribution along airfoil surface; tip chord.

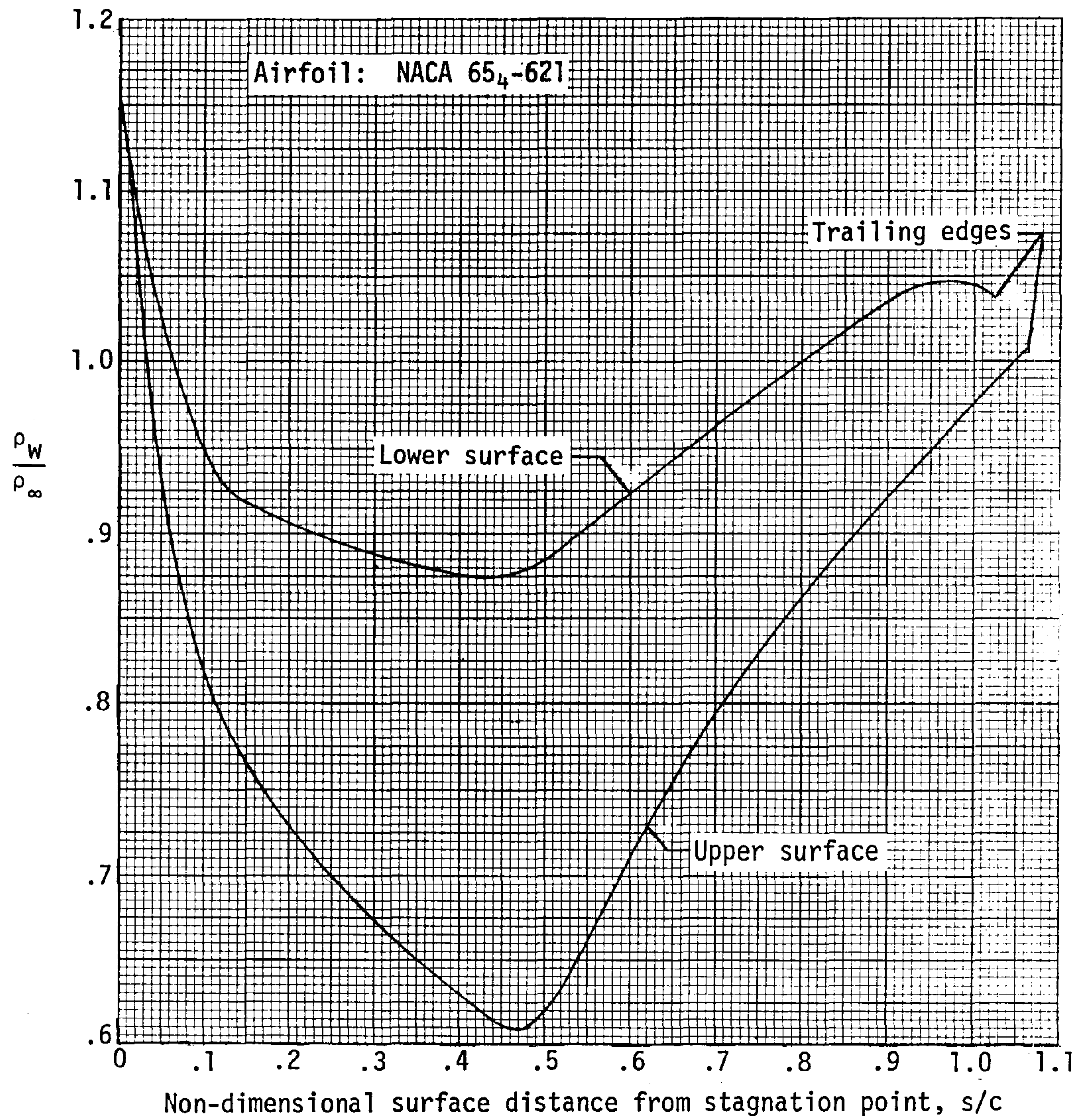


Figure 10. - Air density distribution along airfoil surface; root chord.

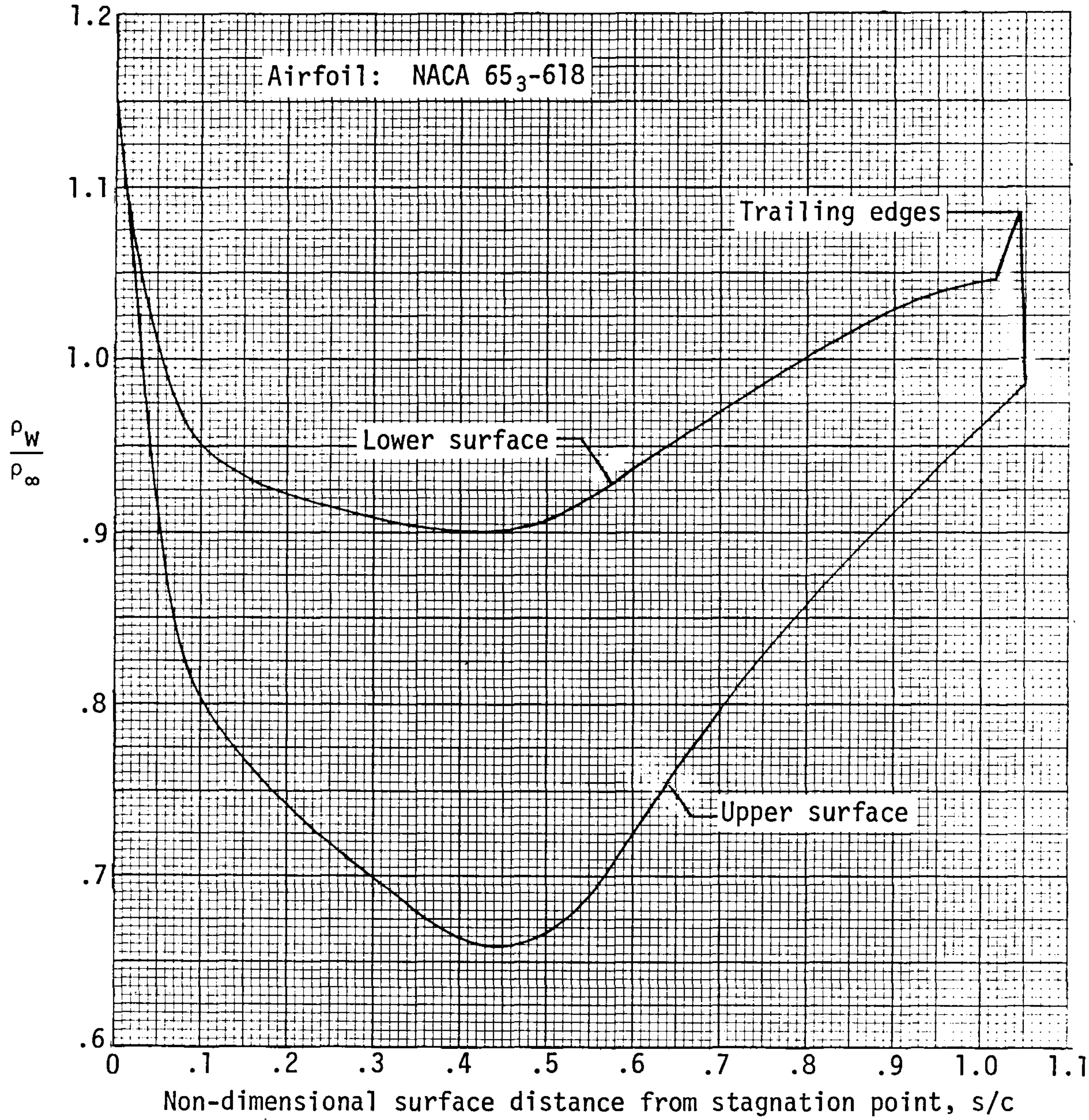


Figure 11. - Air density distribution along airfoil surface; tip chord.

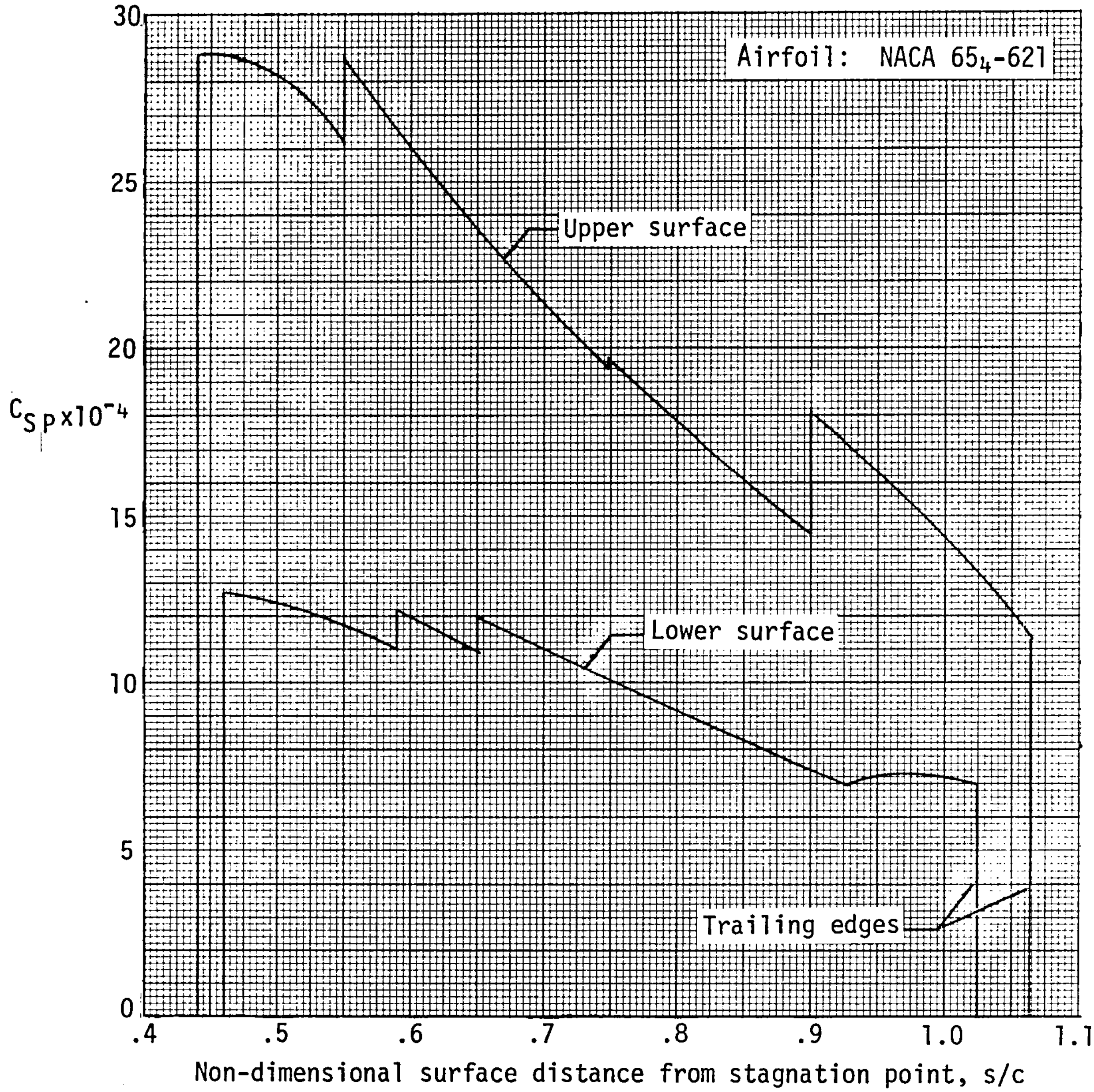


Figure 12. - Local suction power coefficient distribution along airfoil surface; root chord.

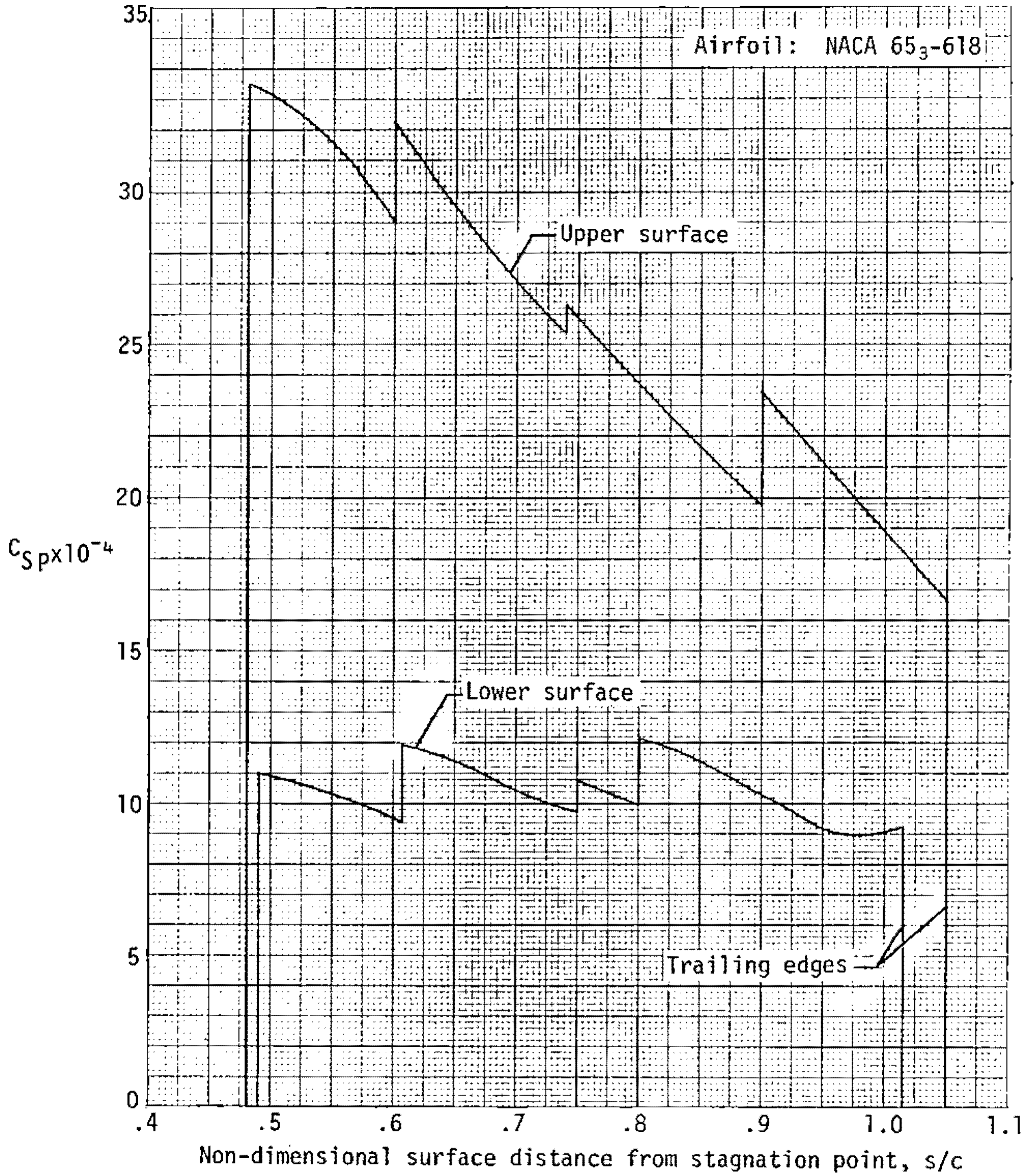


Figure 13. - Local suction power coefficient distribution along airfoil surface; tip chord.

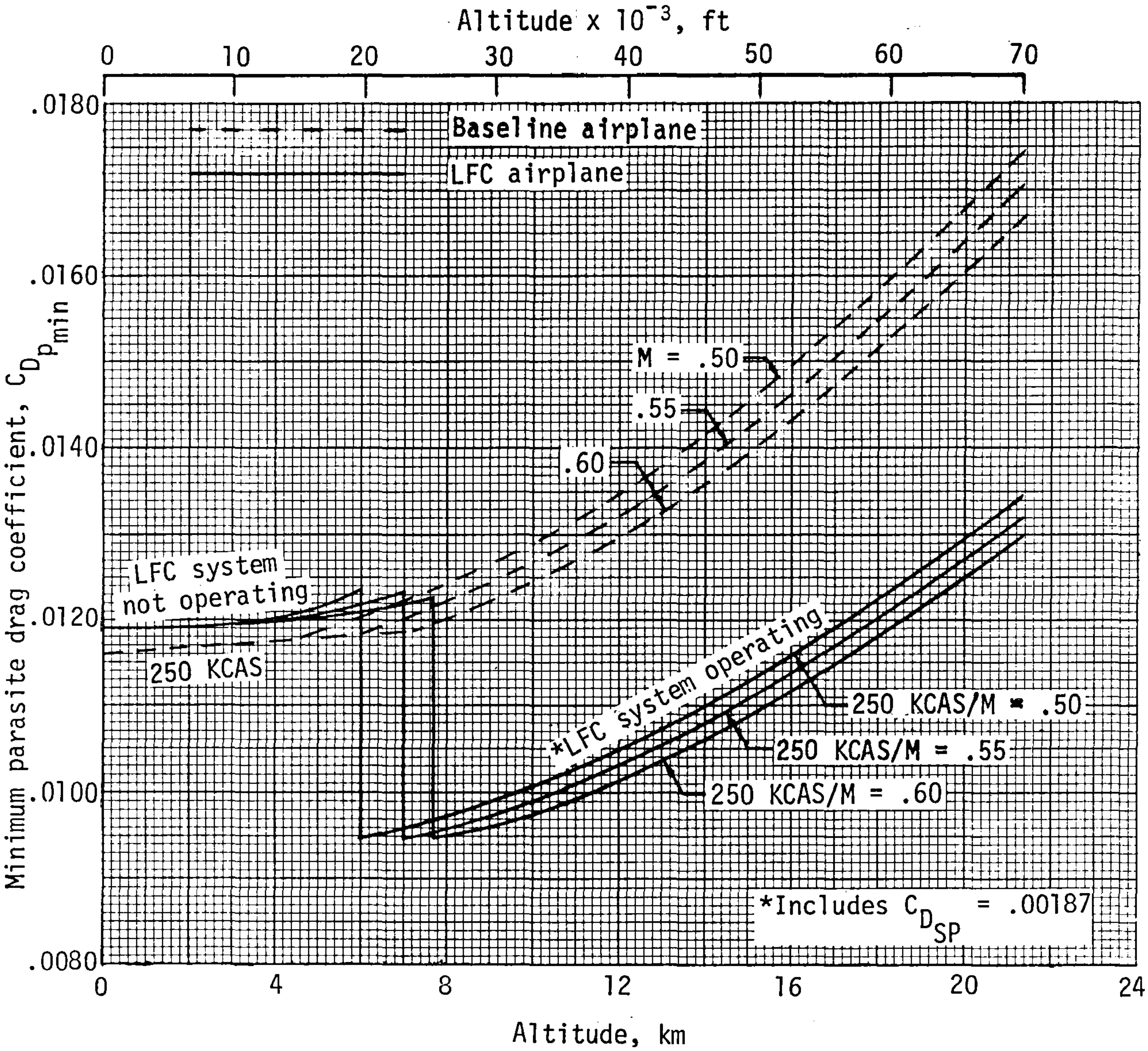


Figure 14. - Minimum parasite drag coefficients.

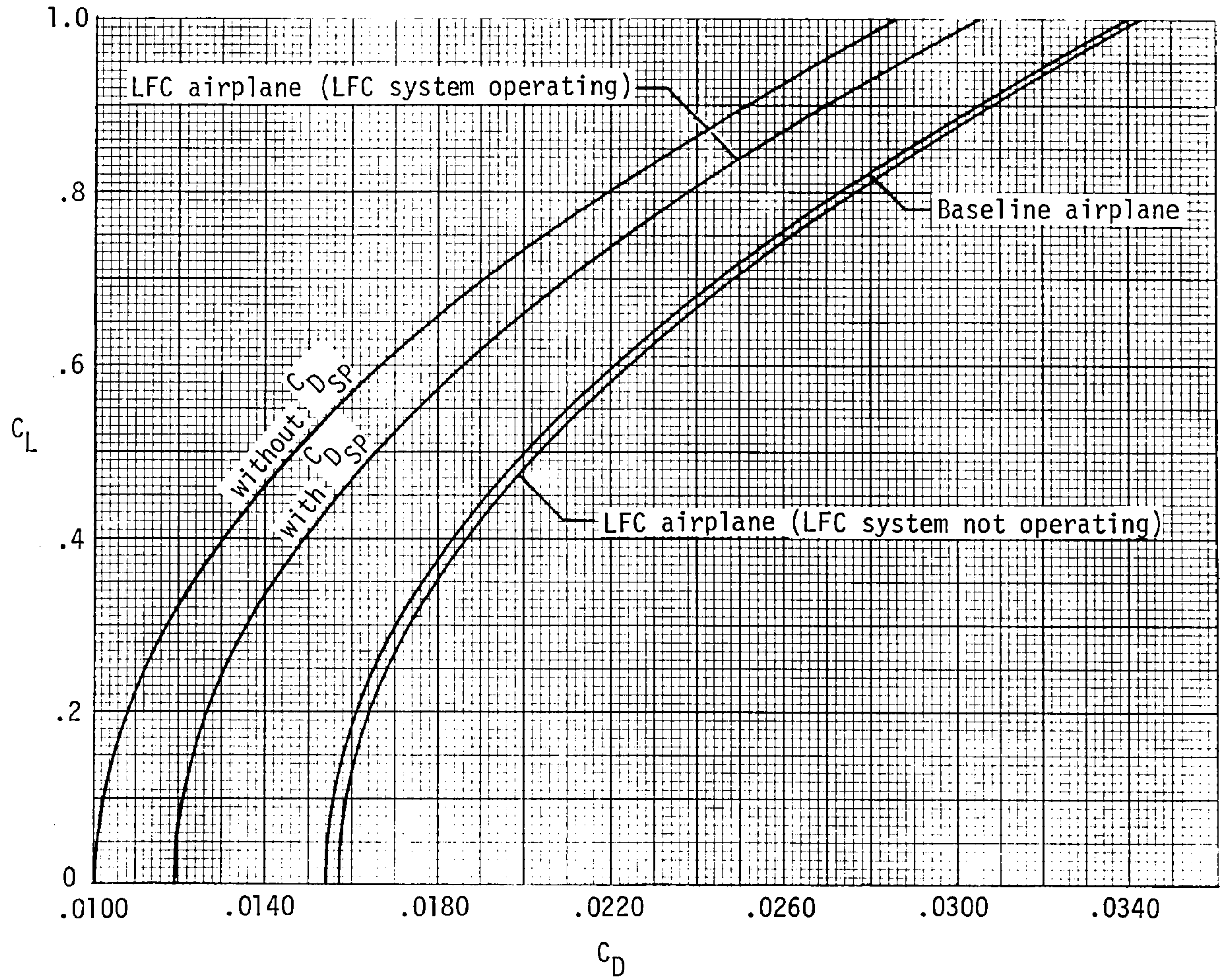


Figure 15. - Drag polars at typical endurance conditions of M = .525 and altitude = 17.53 km (57 500 ft).

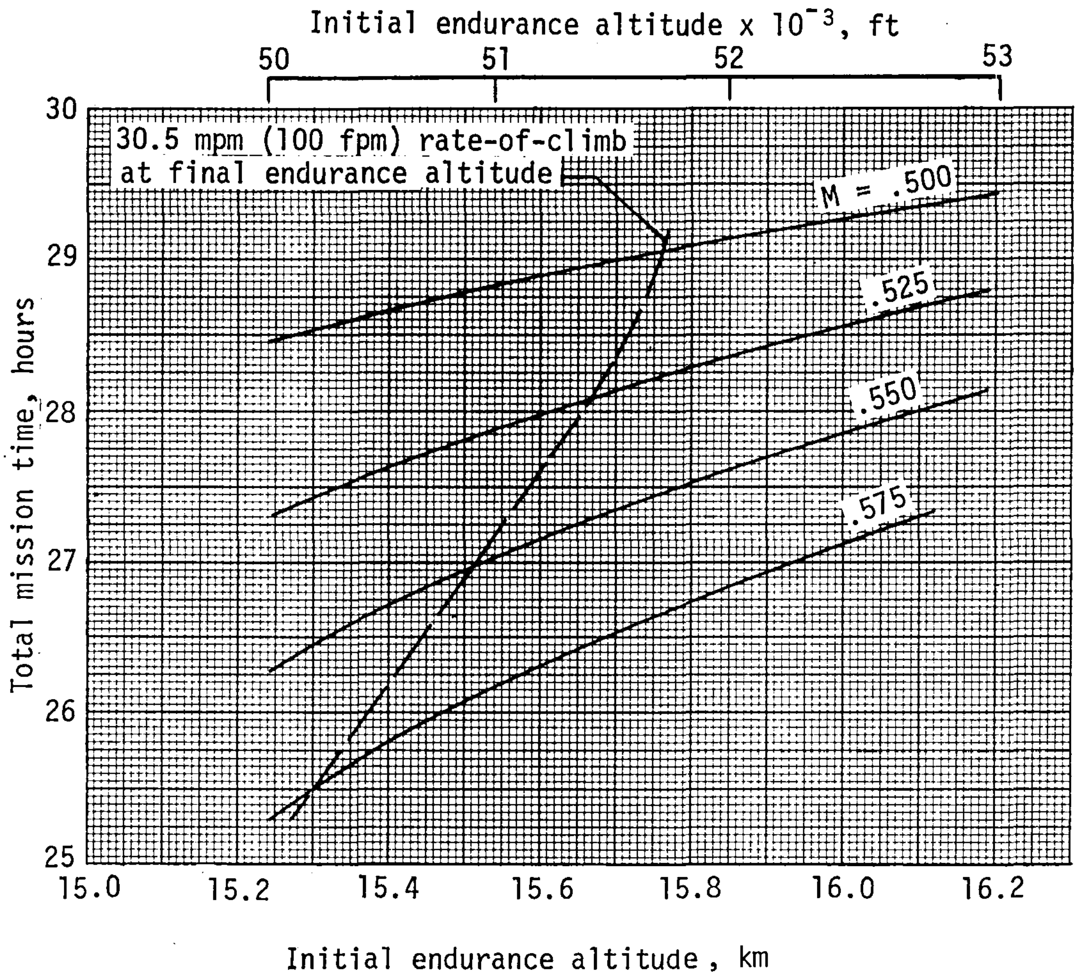


Figure 16. - Mission time variation with Mach number and initial endurance altitude for the baseline airplane.

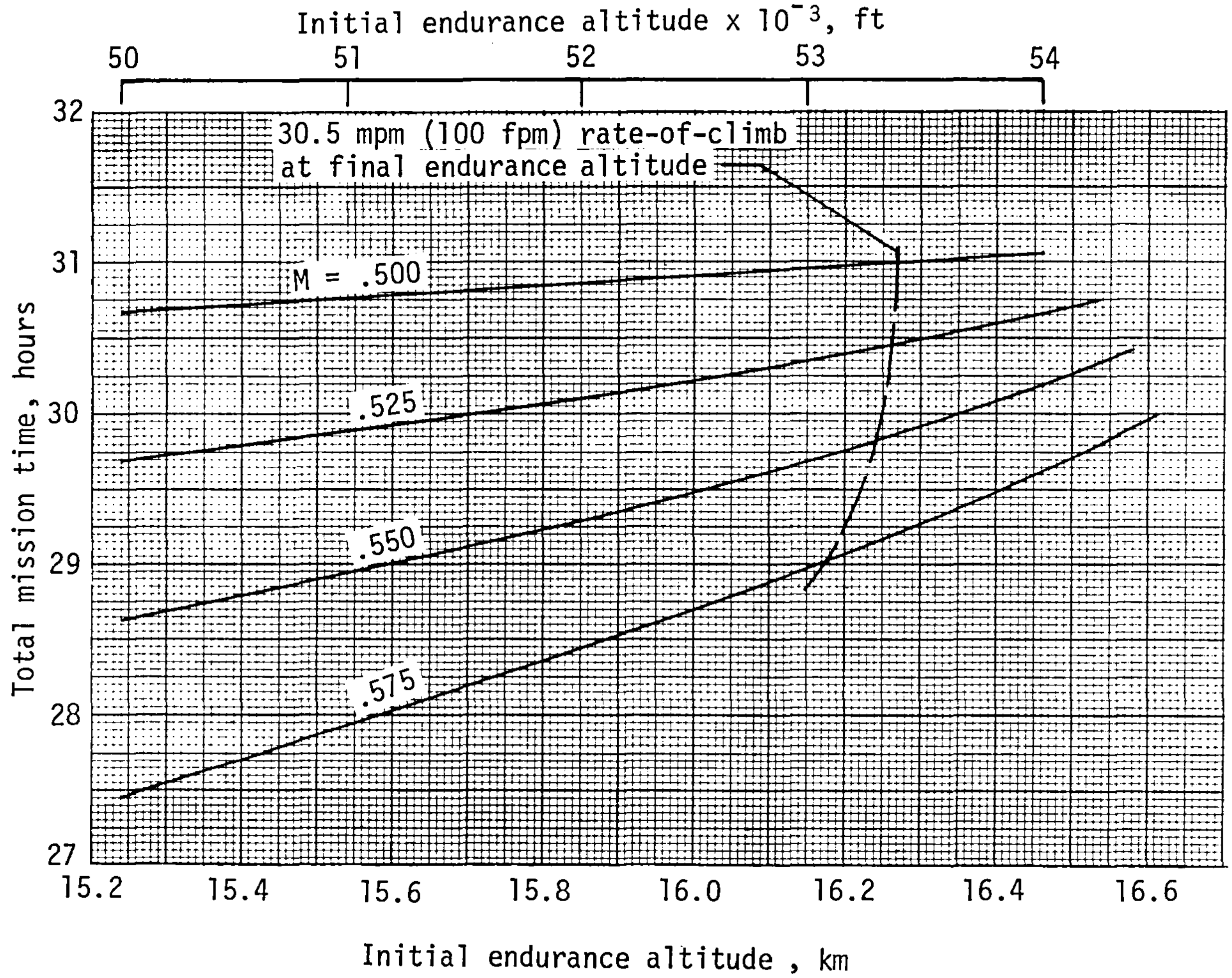


Figure 17. - Mission time variation with Mach number and initial endurance altitude for the LFC airplane.

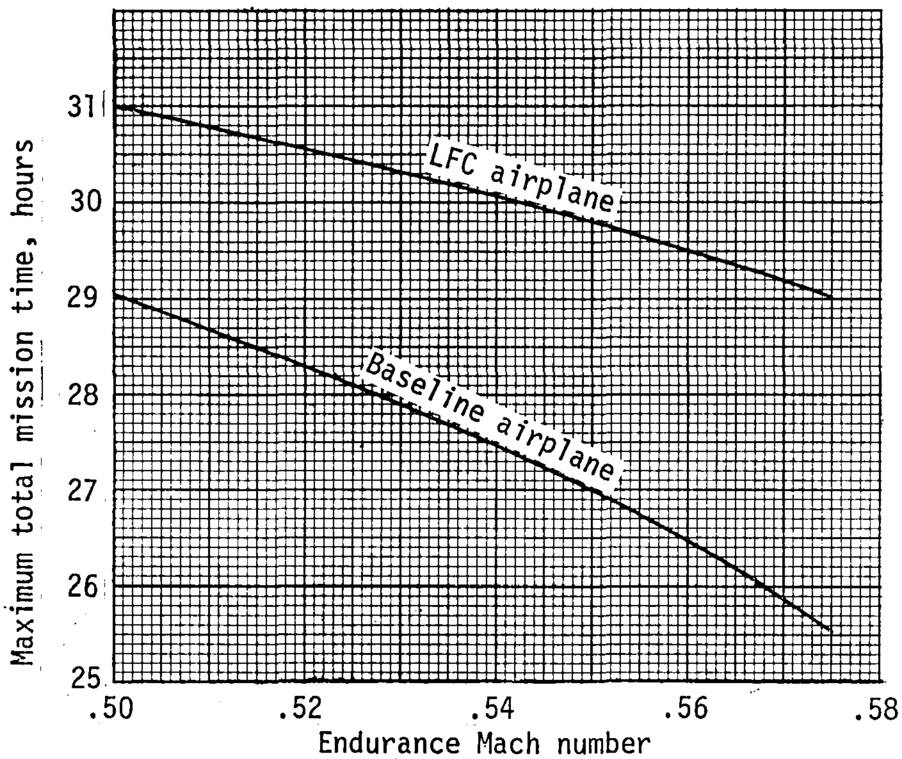


Figure 18. - Maximum total mission times with and without LFC. Fuel = 3.742 Mg (8 250 lbm).

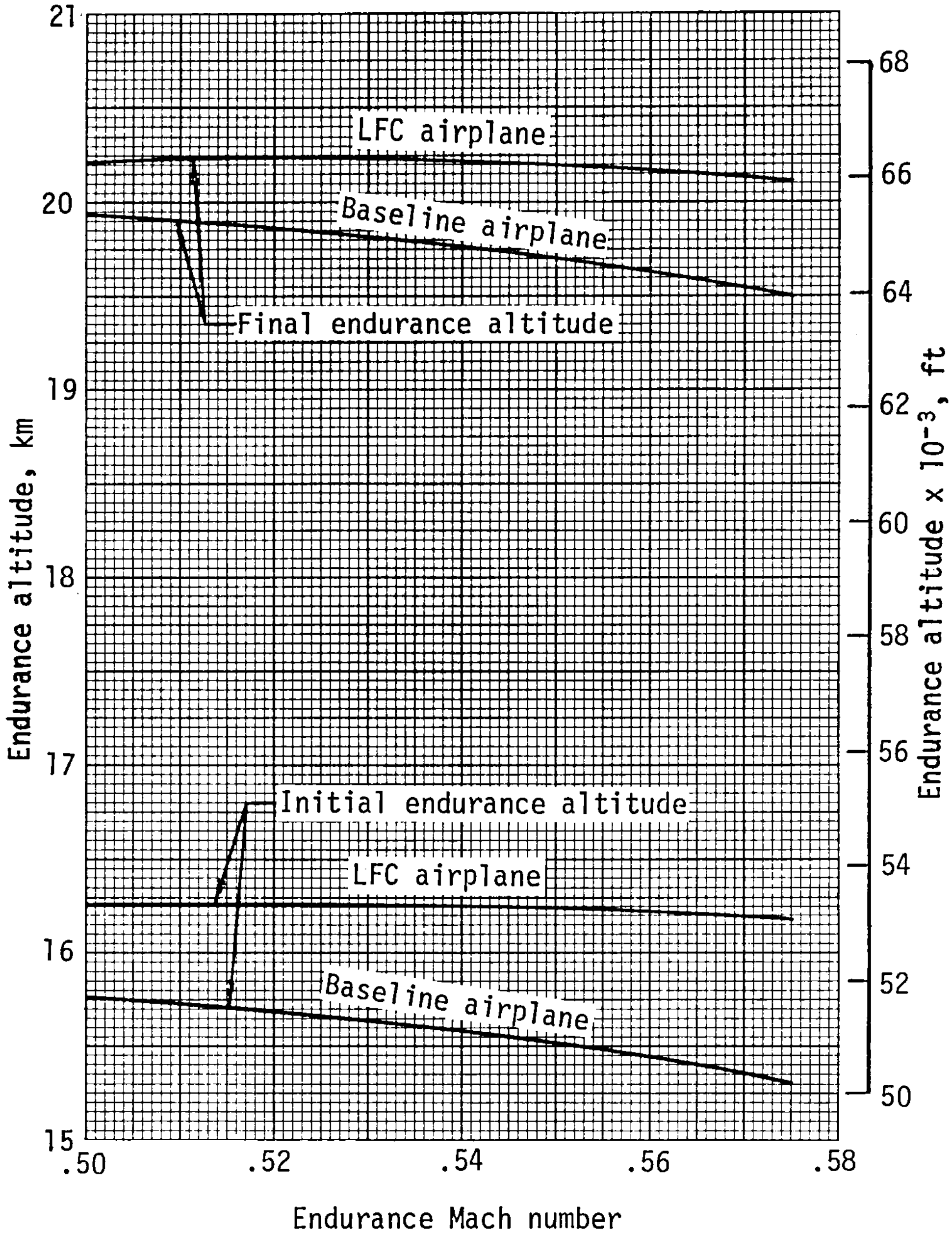
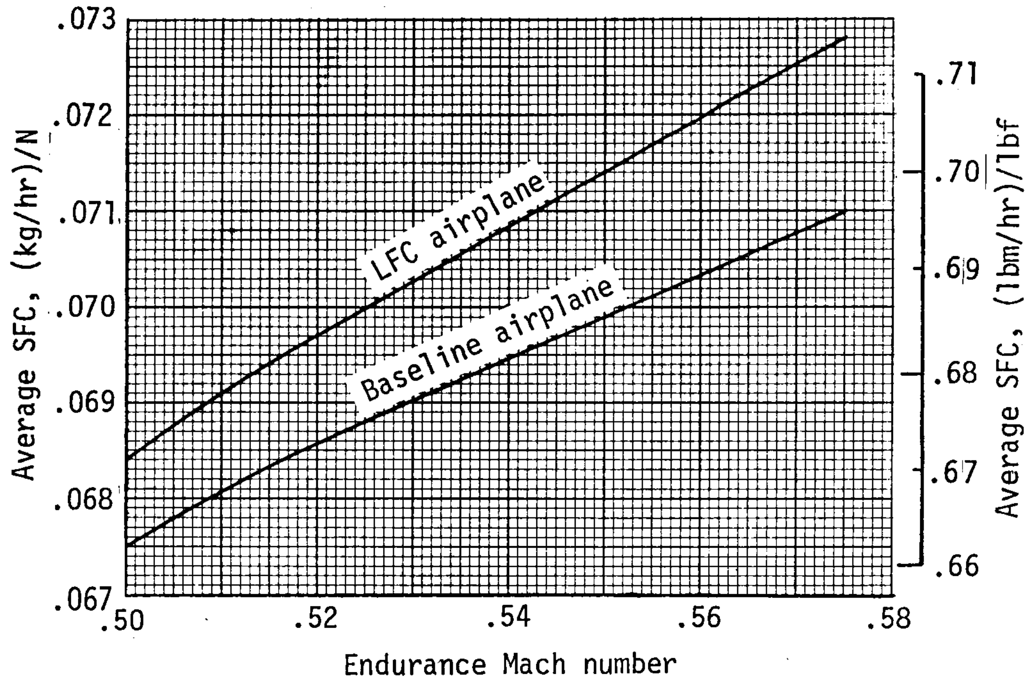


Figure 19. - Initial and final endurance altitudes for maximum time missions.



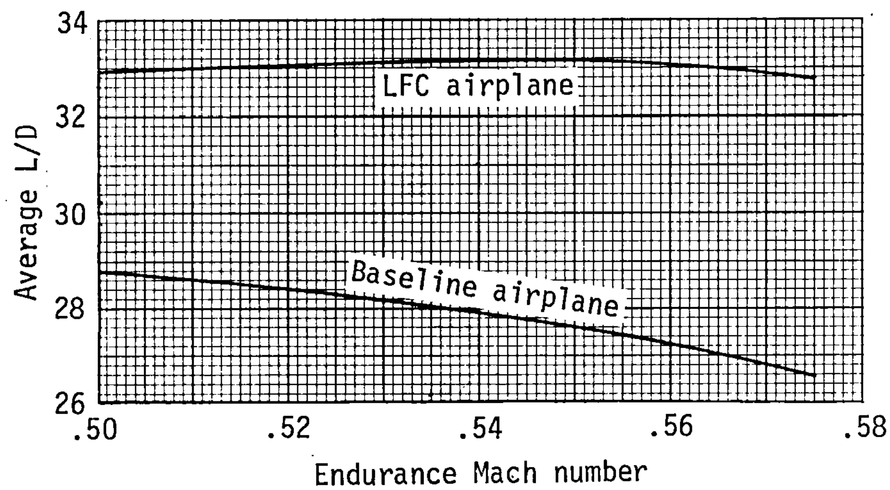


Figure 20. - Endurance L/D and SFC for maximum time missions.

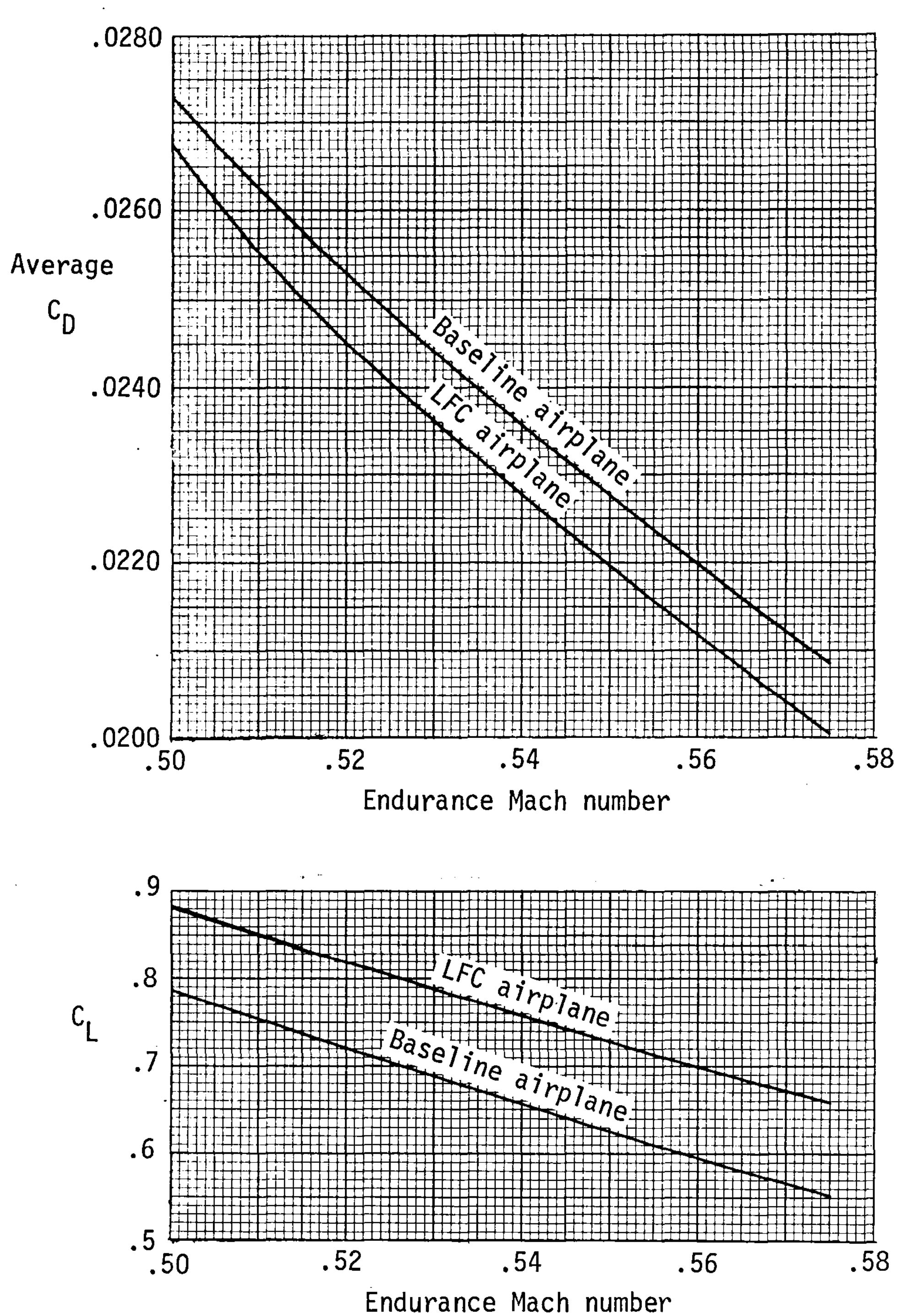


Figure 21. - Endurance lift and drag coefficients for maximum time missions.

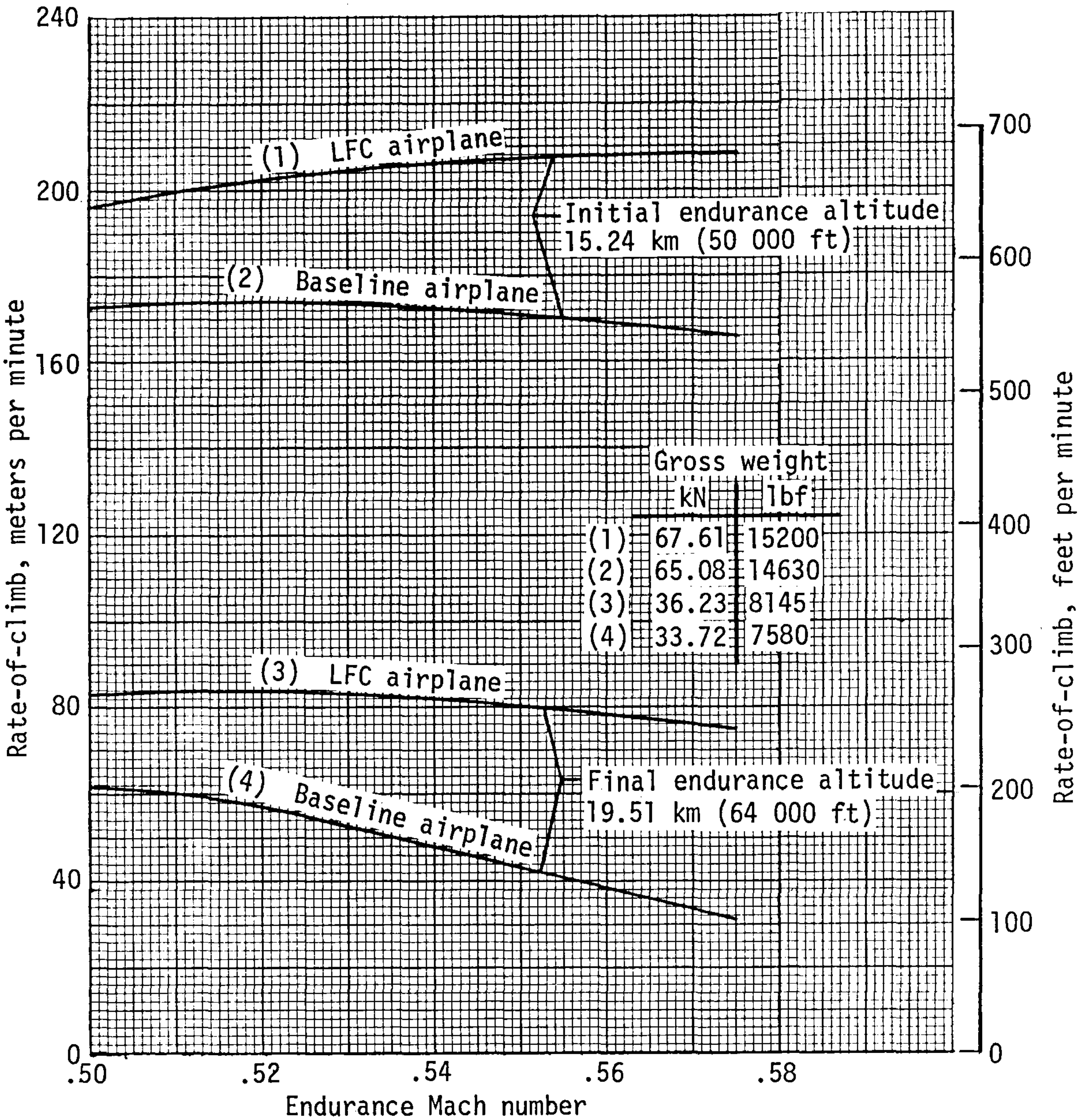


Figure 22. - Rate-of-climb at altitudes representative of initial and final endurance altitudes.

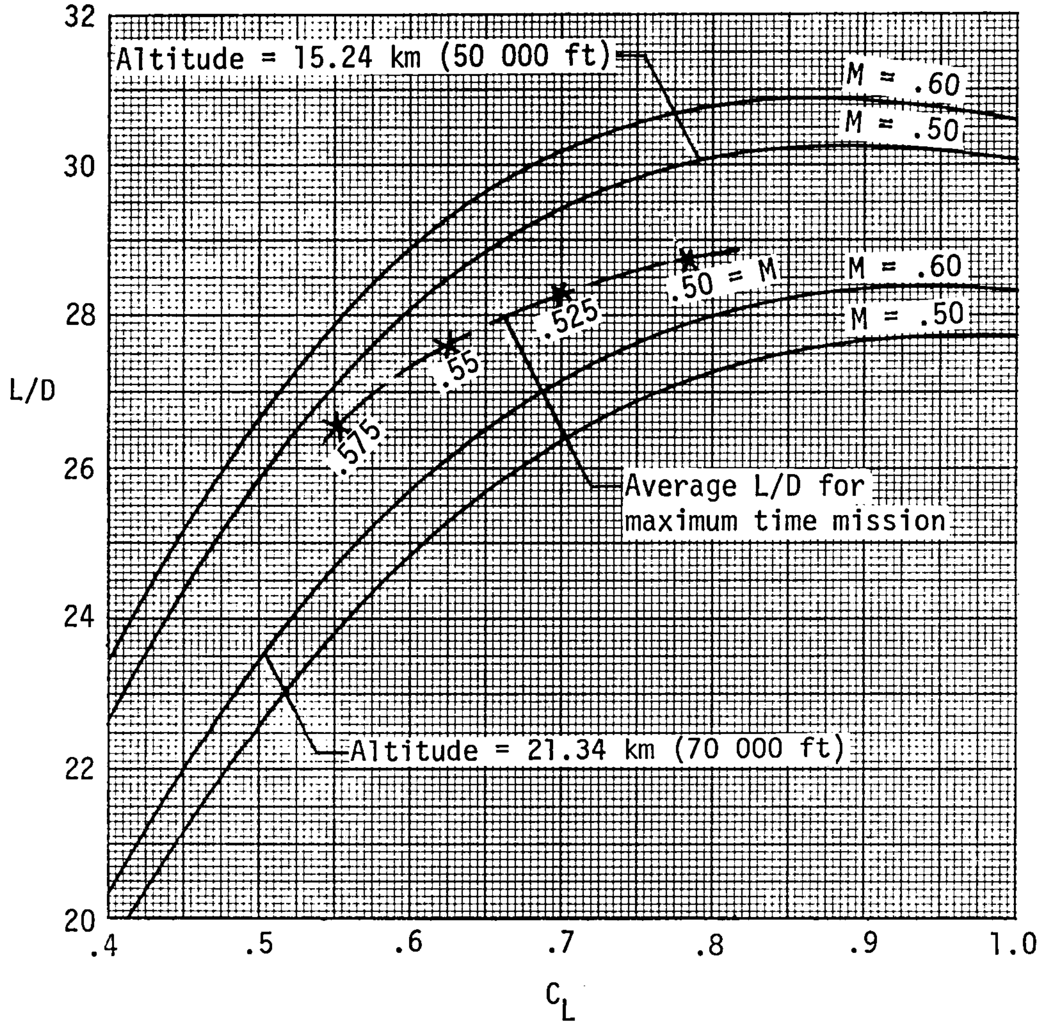


Figure 23. - Endurance L/D ratios of baseline airplane.

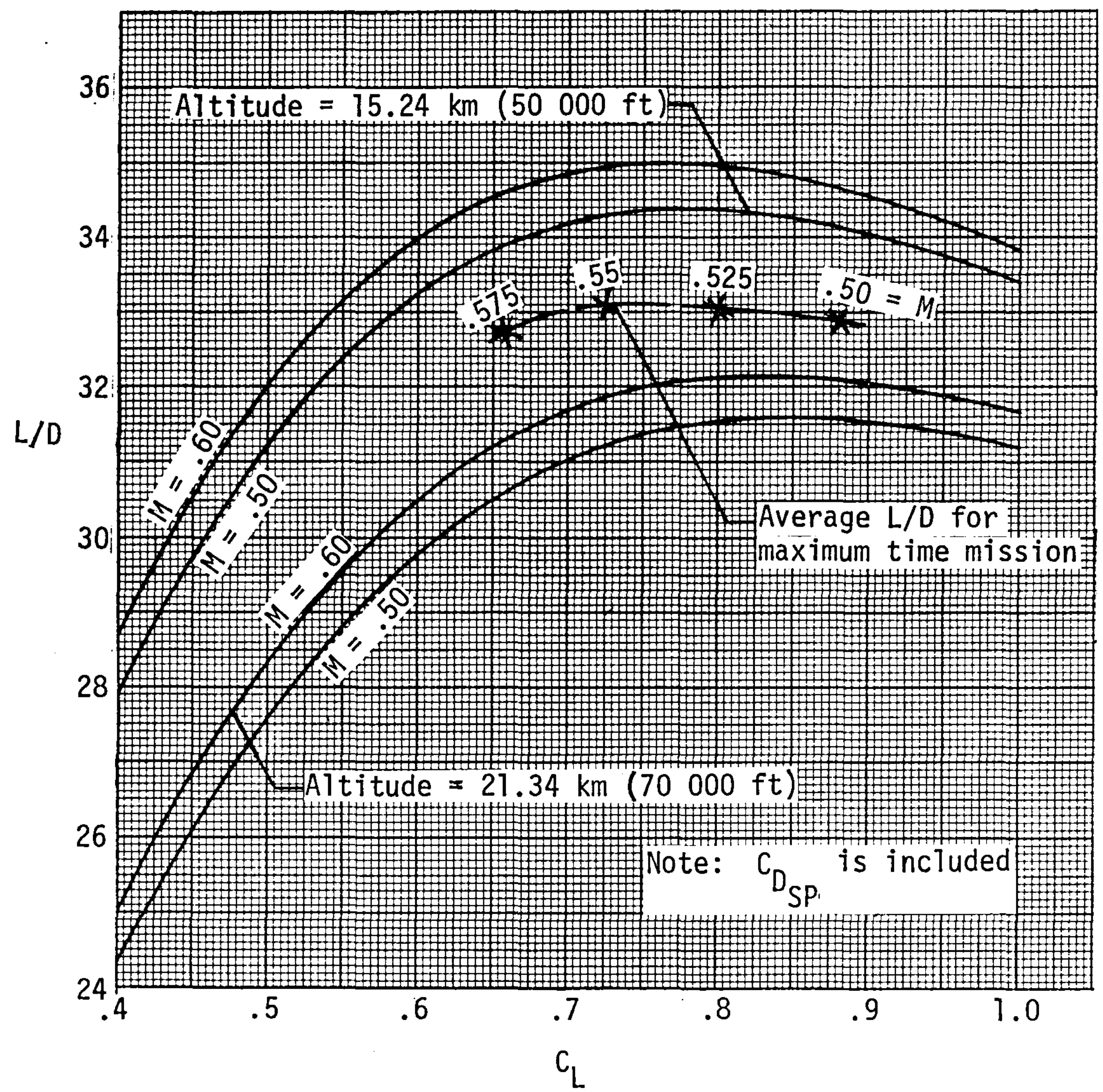


Figure 24. - Endurance L/D ratios of LFC airplane.

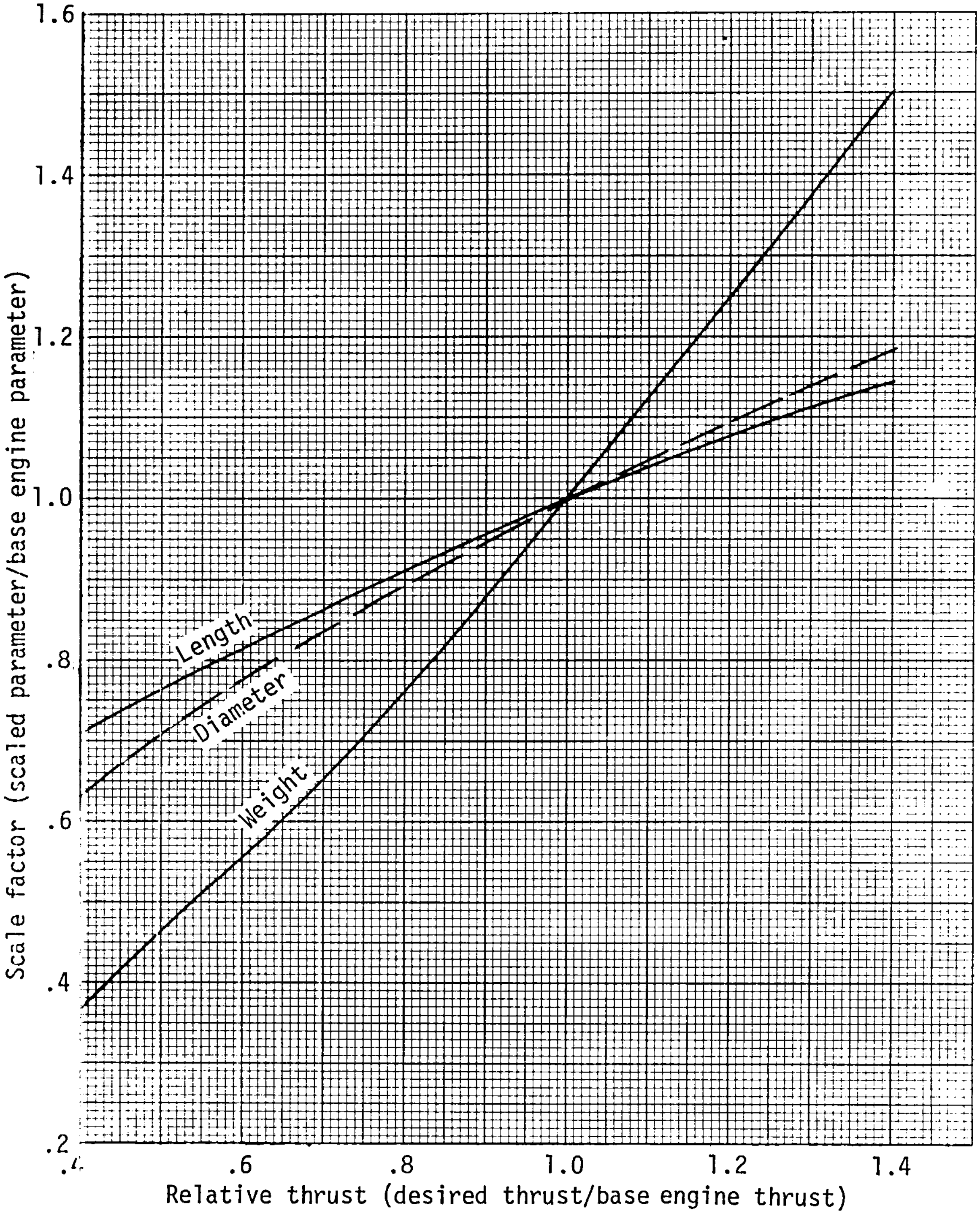


Figure 25. - Turbofan engine scaling factors.

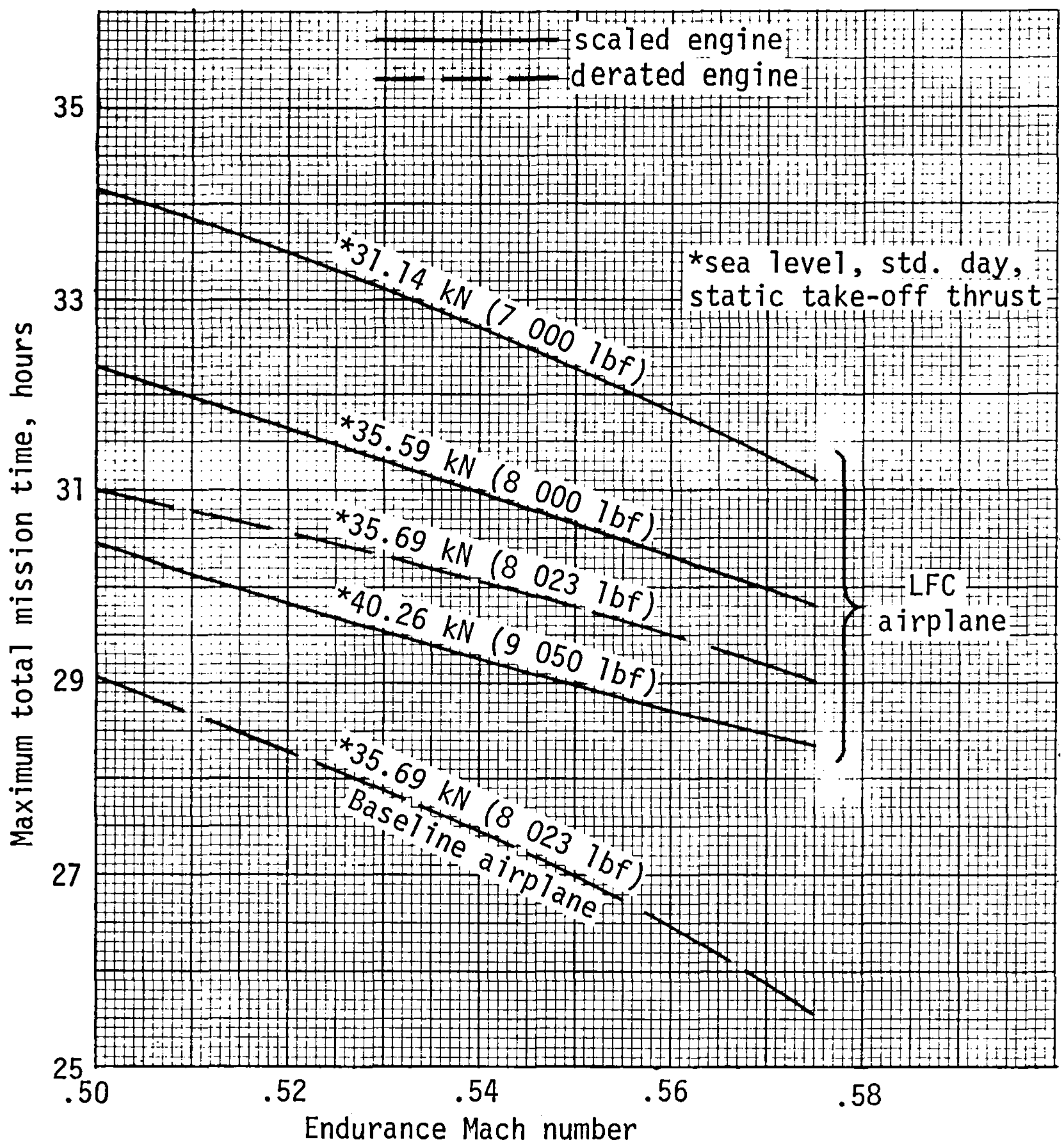


Figure 26. - Maximum total mission times with scaled and derated engines. Fuel = 3.742 Mg (8250 lbm).

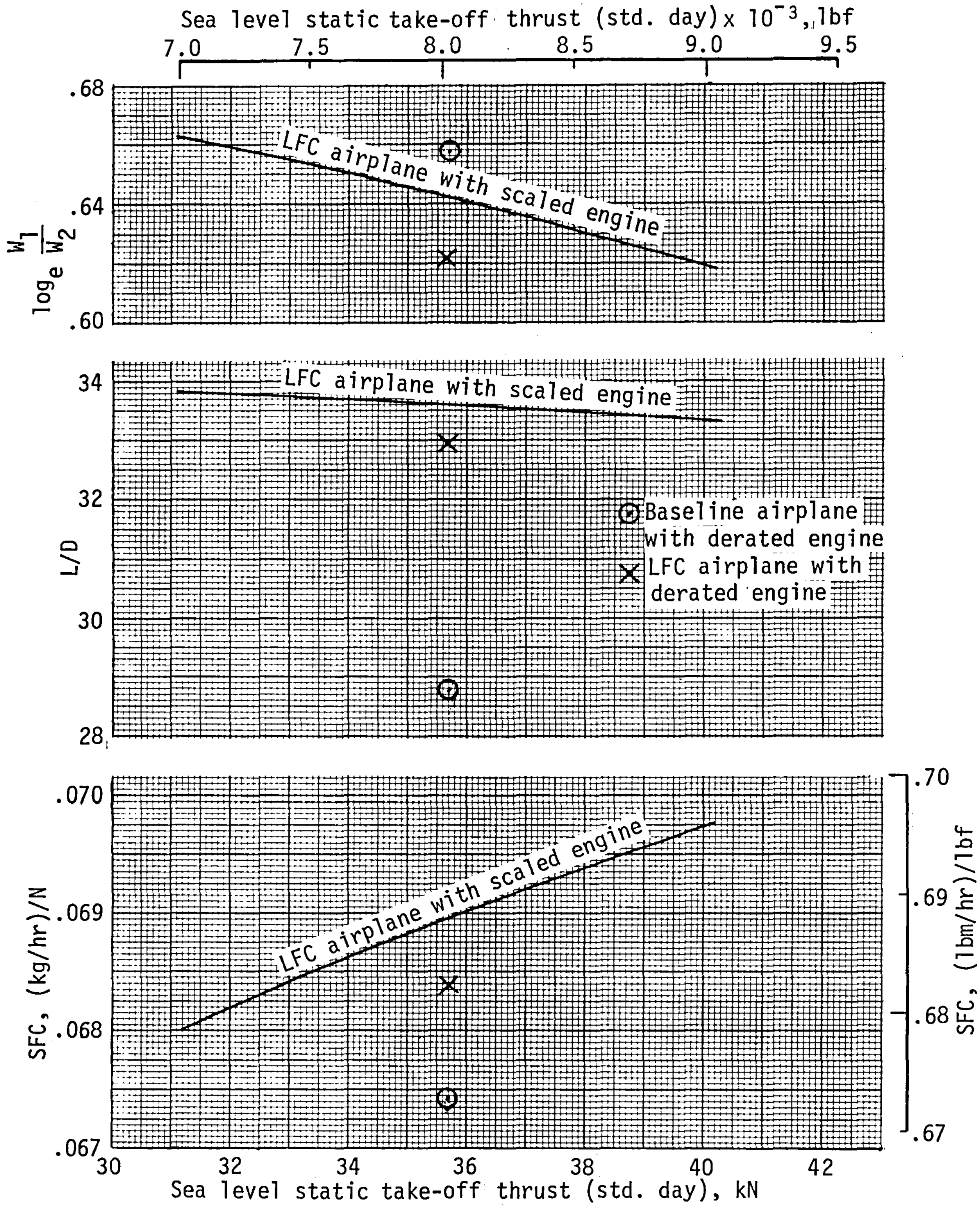


Figure 27. - Weight factors, L/D's and SFC's for maximum total time missions, M = 0.50.

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15. Supplementary Notes

Langley Technical Monitor: Harry H. Heyson

16. Abstract

This design study was conducted to determine the improvement in mission time due to the application of a laminar flow control (LFC) system on a remotely-piloted vehicle (RPV) flying a long-endurance-surveillance mission. Two aircraft were evaluated, using a derated TF34-GE-100 turbofan engine, one with LFC and one without. The mission of the RPV is one of high-altitude loiter at maximum endurance. For the airfoils selected the wing is naturally laminar over the forward 40 percent of its area. The LFC system was incorporated in the remaining portion extending to the wing trailing edge. The fuel quantity and engine are identical for the RPV with and without LFC. With the LFC system maximum mission time increased by 6.7 percent, L/D in the loiter phase improved 14.2 percent, and the minimum parasite drag of the wing was reduced by 65 percent resulting in a 37 percent reduction for the total airplane. Except for the minimum parasite drag of the wing, the preceding benefits include the offsetting effects of weight increase, suction power requirements, and drag of the wing-mounted suction pods.

In a supplementary study using a scaled-down, rather than derated, version of the engine, on the LFC configuration, a 17.6 percent increase in mission time over the airplane without LFC and an incremental time increase of 10.2 percent over the LFC airplane with derated engine were attained. This improvement was due principally to reductions in both weight and drag of the scaled engine.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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