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A BRIEF STUDY OF THE EFFECTS OF TURBOFAN-ENGINE BYPASS RATIO ON SHORT- AND LONG-HAUL CRUISE AIRCRAFT

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16. Abstract

A brief study of the effects of turbofan-engine bypass ratio on Breguet cruise range and take-off distance for subsonic cruise aircraft has shown significant differences between short- and long-haul aircraft designs. Large thrust lapse rates at high bypass ratios caused severe reductions in cruise range for short-haul aircraft because of increases in propulsion system weight. Long-haul aircraft, with a higher fuel fraction (ratio of propulsion weight plus total fuel weight to gross take-off weight), are less sensitive to propulsion-system weight and, accordingly, were not significantly affected by bypass-ratio variations. Both types of aircraft have shorter take-off distances at higher bypass ratios because of higher take-off thrust-weight ratios.

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SUMMARY

A brief study has been made of the effects of varying turbofan-engine bypass ratios from 3 to 12 on the Breguet cruise range and balanced-field take-off distance of short- and long-haul aircraft. These aircraft were assumed to cruise at a Mach number of 0.8 at an altitude of 11 000 m (36 089 ft). The study showed that the large thrust lapse rate of high-bypass-ratio engines caused severe reductions in the cruise range of short-haul aircraft (low ratio of propulsion weight plus fuel weight to gross take-off weight, called fuel fraction). This result was due to an increase in the propulsion weight of the high-bypass-ratio engines. Long-haul aircraft (higher fuel fraction) are less sensitive to increases in propulsion weight, and accordingly the net effects of increasing bypass ratio were not significant. Both types of aircraft had shorter take-off distances with increasing bypass ratio because of higher take-off thrust-weight ratios.

INTRODUCTION

Continued development of the turbofan engine has resulted in an increase in bypass ratio from low values (1 to 1.4) to moderately high values (4 to 8); this has brought about significant improvements in subsonic aircraft cruise performance and reductions in aircraft noise. These moderately high-bypass-ratio engines have evolved through technological advances in overall pressure ratio, turbine inlet temperature, hot-parts cooling, and materials. These engines provide (1) better cruise economy because of lower specific fuel consumption, (2) lower noise in and around the airport community because of lower core-engine and fan-jet velocities, and (3) shorter take-off distances and faster climbout because of the higher take-off thrust of engines that are sized for matching of cruise net thrust with cruise drag (hereinafter referred to as cruise thrust-drag matching or thrust-drag matched engines). Shorter take-off distances and faster climbout also reduce community noise.

It has been suggested that engines with bypass ratios even higher than those of present engines would provide further gains in cruise economy, shorter take-off distances, and lower noise. Lower cruise specific fuel consumption is inherent in higher bypass-ratio cycles for basic engines of a given technology level. Thrust lapse rate, the rate at which engine net thrust decays with flight speed, is also a function of bypass ratio, and engines which are sized specifically for cruise thrust-drag matching will certainly produce increases in take-off thrust with increases in bypass ratio. Furthermore, with high bypass ratios, if the exhaust flow, which is at a lower velocity, could be directed over or through wing-flap systems to increase take-off lift coefficients, shorter take-off distances, faster climbout, and still lower noise could be realized. Short take-off and landing aircraft thus could be configured to meet noise requirements expected for future aircraft without sacrifices in flight performance.

The potential improvements offered by high-bypass-ratio engines may not be fully realized, however, because of aircraft installation effects. Since thrust lapse rate increases with bypass ratio, propulsion systems sized to provide cruise thrust-drag matching will become larger and heavier as bypass ratio is increased. Increases in propulsion-system weight would require either an increase in aircraft gross take-off weight to perform the same mission requirement or a displacement of fuel or payload for aircraft having the same gross weight. Performance losses due to engine-installation effects and propulsion-system cruise drag can reduce the advantage of lower cruise specific fuel consumption provided by the high-bypass-ratio engine; the lower fan pressure ratios of high-bypass-ratio engines of a given technological level result in greater sensitivity to installation effects.

Thus, it is not clear that the advantages of lower cruise specific fuel consumption, increased take-off thrust, lower noise, and possibly lift augmentation at take off, which are attributable to increases in bypass ratio, can be attained without important influences on overall aircraft flight efficiency and cruise range. The weight of the engine and propulsion package and the specific fuel consumption are of great importance to short-haul aircraft, for which the total fuel is a relatively small fraction of gross take-off weight. For long-haul aircraft, the weight of the engine and propulsion package is of lesser importance; cruise specific fuel consumption and propulsion-system drag are the more important parameters associated with aircraft performance.

A brief study was therefore made to analyze the influence of turbofan-engine bypass ratio on Breguet cruise range and balanced-field take-off distance for configurations ranging from short-haul, short take-off and landing aircraft to long-haul, conventional aircraft. The parameters varied for the base study were engine bypass ratio, from 3 to 12; take-off wing loading, from 2394 to 4788 Pa $\left(50 \text{ to } 100 \text{ lbf/ft}^2\right)$; and ratios of propulsion-system weight plus fuel weight to gross take-off weight (fuel fractions) from 0.2 to 0.4. For the calculations a cruise Mach number of 0.8 at an altitude of 11 000 m (36 089 ft) was assumed. Lift drag polars of the airframe alone (no propulsion drag) typical of subsonic cruise aircraft with the assumed wing loadings were used in the study. The overall aircraft cruise lift-drag ratio was determined by adjusting the airframe lift-drag ratio to include the isolated propulsion drag of engines sized for cruise thrust-drag matching.

Although it is recognized that selection of a specific cruise speed, altitude, and wing loading would not provide optimum cruise performance for every bypass ratio, these parameters were held constant for the basic part of the study so that the singular effect of bypass ratio on the study parameters could be evaluated. In several instances, sensitivity of cruise range to nacelle drag, propulsion weight, and altitude matching was studied. Engine performance and weights used in the study are considered representative of the advanced technology that would be available in the period 1980 to 1985.

SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

A	cross-sectional area, meters^2 (feet^2)
a	sonic speed, knots
C_D	drag coefficient, $\frac{D}{q_\infty S}$
C_L	lift coefficient, $\frac{L}{q_\infty S}$
D	drag, newtons (pounds force)
d	balanced-field take-off distance, meters (feet)
F_n	net internal engine thrust, newtons (pounds force)
h	altitude, meters (feet)
L	lift, newtons (pounds force)
M	Mach number
q	dynamic pressure, pascals (pounds force per feet^2)
R	Breguet cruise range, nautical miles

S	wing area, meters^2 (feet^2)
SFC	specific fuel consumption, per hour
W	weight, newtons (pounds force)
w	weight flow rate of air, newtons per second (pounds force per second)
X	fuel fraction, or ratio of propulsion-package weight plus total fuel weight to gross take-off weight, $\frac{W_{prop} + W_{fuel,t}}{W_T}$

Subscripts:

cr	cruise
d	descent
f	final
fuel	fuel
i	initial
max	maximum
nac	nacelle
prop	propulsion
r	reserves
T	take-off
t	total
tc	climbout and acceleration from take-off to cruise

wb wing-body (total aircraft less engines)

∞ free stream

Abbreviations:

CTOL conventional take-off and landing

STOL short take-off and landing

PROCEDURE

The present brief study is intended to show only the effects of turbofan-engine bypass ratio on Breguet cruise range and balanced-field take-off distance of subsonic cruise aircraft typical of short- and long-haul designs. A complete analysis of engine-bypass-ratio effects throughout the total flight envelope of such aircraft is beyond the scope of this study. Although the study results would be influenced to an extent by bypass-ratio effects at flight conditions other than cruise, the predominant effects occur during the cruise flight segment.

To perform this analysis, it was necessary to obtain take-off and cruise performance characteristics of turbofan engines defined for a broad range of bypass ratio, weight and cruise drag of the propulsion package, and airframe aerodynamics typical of subsonic cruise aircraft. It was necessary to assume a fuel usage schedule to define the fraction of total fuel that would be available during cruise operation. This section of the paper presents these parameters and describes how they were combined to provide parametrically defined aircraft that are designed to match cruise thrust with cruise drag.

Engine specific performance at static or take-off conditions (fig. 1), ratios of cruise net thrust to take-off thrust, and cruise specific fuel consumption at a Mach number of 0.8 and an altitude of 11 000 m (36 089 ft) (fig. 2) are considered representative of engines possibly in service in the period 1980 to 1985. The data points shown for bypass ratios from 3 to 8 were obtained from engine manufacturers' estimates of engines with overall pressure ratios of 25 and maximum turbine inlet temperatures of 1533 K $(2760^{\circ}$ R). Engine performance for bypass ratios up to 12 was obtained by calculating the performance from extrapolated data for engine component performance, fan pressure ratios, core-engine nozzle pressure ratios, and temperatures. A 100-percent fan-face total pressure recovery, no horsepower for bleed-air extraction, and a nozzle gross thrust coefficient of 0.985 are assumed for all engines.

Drag coefficients of isolated nacelles (propulsion package) as a function of bypass ratio (fig. 3) were obtained from correlations of nacelle drag data D_{nac}/q_{∞} with nacelle diameter at the selected cruise Mach number. In the correlations, engine bypass ratio was known for each of the several nacelle diameters, so that nacelle drag coefficient $D_{nac}/q_{\infty}A_{nac}$ could be determined as a function of bypass ratio.

Thrust-weight ratios of the bare engine and of the total propulsion package for the advanced technology engines are presented in figure 4 as a function of bypass ratio. The solid-line curves for the bare engine and the total propulsion package represent averages of estimated weight data from several engine manufacturers; these engines were originally designed to give different thrust levels with small differences in design fan pressure ratio, overall pressure ratio, maximum turbine inlet temperature, and nacelle-installation weight. The weight for each engine was scaled from the original quoted take-off thrust level to new take-off thrust levels defined by a common cruise thrust from the empirical relation

$$W_f = W_i\left(\frac{F_{n,f}}{F_{n,i}}\right)^{1.15}$$

Estimates of thrust-weight ratio from an aircraft manufacturer's data, converted by the same weight scaling procedure, are shown in figure 4 for comparison. Bare engine thrust-weight ratios of several current operational engines, also scaled with the empirical relation, are indicated by the symbols.

Cruise lift-drag polars for several take-off wing loadings are presented in figure 5. Initially, a single polar for a complete airframe (aircraft without propulsion package) was available from the literature for a take-off wing loading of 4788 Pa $\left(100\ \mathrm{lbf/ft^2}\right)$. Construction of the polars for the intermediate and lowest wing loadings was accomplished by reducing the minimum drag coefficient of the initial polar by 0.0013 and 0.0027, respectively, to maintain the same fuselage drag and thus provide equivalent payload space for the three wing loadings. It was assumed for these incremental drag values that the fuselage skin friction of a subsonic transport aircraft is approximately 30 percent of the total airframe drag.

Breguet cruise range in nautical miles was determined by using the expression

$$R = \left[\frac{M_{\infty}\left(\frac{L}{D}\right)_{cr}}{(SFC)_{cr}}\right] a \ln \frac{W_{i,cr}}{W_{f,cr}}$$

and the balanced-field take-off distance was determined from the empirical relation of reference 1, modified to the SI system of units:

$$d = \left[\frac{23\left(W_T/S\right)}{\left(C_{L,max}\right)_T\left(F_n/W\right)_T} + 750\right]0.3048$$

The procedure used to size the engines for cruise thrust-drag matching and the relationship between cruise range and take-off distance are developed as follows:

Aircraft drag = Engine net internal thrust

or

$$D_{cr} = F_{n,cr} = D_{wb} + D_{prop}$$

In coefficient form,

$$C_{D,cr} = C_{D,wb} + C_{D,prop} = \frac{F_{n,cr}}{q_\infty S} \tag{1}$$

Airframe cruise drag coefficients $C_{D,wb}$ were read from the polars of figure 5 at the appropriate lift coefficient corresponding to the cruise operating conditions $(M_\infty = 0.8,\ h = 11\ 000\ \text{m}\ (36\ 089\ \text{ft}))$ at each take-off wing loading. A reduction in cruise wing loading from the take-off values to account for fuel used from take-off to cruise operation was not considered. The airframe aerodynamic parameters resulting from this procedure are presented in the following table:

W_T/S, Pa	W_T/S, lbf/ft^2	$C_{L,wb}$	$C_{D,wb}$	$(L/D)_{wb}$
2394	50	0.2354	0.01611	14.612
3591	75	.3532	.02141	16.497
4788	100	.4709	.02880	16.351

After the airframe drag coefficients at cruise are determined, the total cruise drag coefficient $C_{D,cr}$ or the engine net thrust coefficient $F_{n,cr}/q_\infty S$ can be obtained from equation (1) if the propulsion drag can be determined. The expression for $C_{D,prop}$ can be written

$$C_{D,prop} = \frac{D_{nac}}{q_\infty A_{nac}} \frac{A_{nac}}{S} \equiv C_{D,nac} \frac{A_{nac}}{S} \tag{2}$$

The term $C_{D,nac}$ $(\text{or } D_{nac}/q_\infty A_{nac})$ is available from figure 3 as a function of bypass ratio. Sizing of the ratio A_{nac}/S for aircraft propulsion combinations that are cruise thrust-drag matched was accomplished by algebraic manipulation of the basic input data from figures 1, 2, 3, and 5. This development is given in equations (3) to (6). The nacelle-wing area ratio can be written as the identity

$$\frac{A_{nac}}{S} \equiv \frac{F_{n,T}}{S} \frac{1}{F_{n,T}/A_{nac}} \tag{3}$$

The factor $F_{n,T}/S$ can be written

$$\frac{F_{n,T}}{S} \equiv \frac{C_{D,wb}}{1 - \dfrac{C_{D,prop}}{C_{D,cr}}} \frac{1}{F_{n,cr}/F_{n,T}} q_\infty \tag{4}$$

and the denominator of the second factor $F_{n,T}/A_{nac}$ can be written

$$\frac{F_{n,T}}{A_{nac}} \equiv \left(\frac{F_n}{w}\right)_T \frac{w_T}{A_{nac}} \tag{5}$$

Take-off weight flow rate per unit nacelle area w_T/A_{nac} (eq. (5)) was determined to be 1436.41 $N/sec\text{-}m^2$ $(30\ lbf/sec\text{-}ft^2)$ by assuming a ratio of fan-disk area to nacelle frontal area of 0.85 and a fan-disk axial Mach number of 0.47, which are values typical of modern turbofan engines.

Equations (3), (4), and (5) can be further manipulated to define a direct solution for A_{nac}/S as follows:

$$\frac{A_{nac}}{S} = \frac{C_{D,wb}}{\dfrac{1}{\left(\dfrac{q_\infty}{F_{n,cr}/F_{n,T}}\right) \dfrac{1}{(F_n/w)_T(w_T/A_{nac})}}} - C_{D,nac} \tag{6}$$

Values of A_{nac}/S calculated from equation (6) and the data of figures 1, 2, 3, and 5 are presented in figure 6 as a function of bypass ratio for several take-off wing loadings at the selected cruise Mach number and altitude. Take-off thrust loadings of equation (4) are presented in figure 7, and cruise propulsion drag (eq. (2)) is presented in the lower part of figure 8. These data satisfy the requirements of equation (1), which in effect states that the various engines are thrust sized to provide a match of engine net cruise thrust with airframe cruise drag plus propulsion-package cruise drag. It should be pointed out that only airframe drag and isolated propulsion-package drag were included in the calculations. Possible interference drag effects of nacelles on the wing-body are not included in the matching process. The nacelle area ratio represents the total nacelle area for an aircraft. Nacelle area ratio, take-off thrust loading, and propulsion drag for a single engine would be obtained by dividing the presented ratios by the number of engines.

The cruise aerodynamic efficiency was determined by adjusting L/D of the airframe to include nacelle drag with the expression

$$\left(\frac{L}{D}\right)_{cr} = \left(\frac{L}{D}\right)_{wb}\left(1 - \frac{C_{D,prop}}{C_{D,cr}}\right) \tag{7}$$

The resultant values of $(L/D)_{cr}$ are presented in the upper part of figure 8 as a function of bypass ratio. The part of the Breguet range equation representing overall cruise flight efficiency $\frac{M_\infty(L/D)_{cr}}{(SFC)_{cr}}$, determined for the selected cruise Mach number of 0.8 and the cruise specific fuel consumption of figure 2, is presented in figure 9 as a function of bypass ratio.

The weight fraction of the Breguet cruise range equation $W_{i,cr}/W_{f,cr}$ can be written in terms of the ratio of propulsion-package take-off thrust to weight, take-off thrust loading, take-off wing loading, and the ratio of propulsion-package weight plus total fuel weight to gross take-off weight $\left(W_{prop} + W_{fuel,t}\right)/W_T$. The assumptions and algebraic manipulations used to determine these quantities are given in the equations that follow.

Gross take-off weight of an aircraft can be written as

$$W_T = W_{structure} + W_{payload} + W_{prop} + W_{fuel,t} \tag{8}$$

Total fuel weight can be written as the sum of the fuel used in cruise flight, the fuel used from take-off to cruise, the fuel used in descent from cruise to landing, and the fuel allocated for reserves, or

$$W_{fuel,t} = W_{fuel,cr} + W_{fuel,tc} + W_{fuel,d} + W_{fuel,r} \tag{9}$$

The ratio of aircraft initial cruise weight to final cruise weight can be written as

$$\frac{W_{i,cr}}{W_{f,cr}} = \frac{W_T - W_{fuel,tc}}{W_T - \left(W_{fuel,tc} + W_{fuel,cr}\right)} \tag{10}$$

If specific ratios of propulsion weight plus total fuel weight to gross take-off weight are assigned, an expression can be written

$$X = \frac{W_{prop} + W_{fuel,t}}{W_T} \tag{11}$$

and if the following breakdown of total fuel is assumed,

$$W_{fuel,cr} = 0.79W_{fuel,t}$$

$$W_{fuel,tc} = 0.1W_{fuel,t}$$

$$W_{fuel,d} = 0.01W_{fuel,t}$$

$$W_{fuel,r} = 0.1W_{fuel,t}$$

the expression for $W_{i,cr}/W_{f,cr}$ can be rewritten as

$$\frac{W_{i,cr}}{W_{f,cr}} = \frac{W_T - 0.1\left(XW_T - W_{prop}\right)}{W_T - 0.89\left(XW_T - W_{prop}\right)} \tag{12}$$

By utilizing the identity

$$\frac{W_{prop}}{W_T} = \frac{1}{F_{n,T}/W_{prop}} \frac{F_{n,T}}{S} \frac{1}{W_T/S} \tag{13}$$

the expression for the cruise weight ratio can be written as

$$\frac{W_{i,cr}}{W_{f,cr}} = \frac{1 - 0.1\left(X - \frac{1}{F_{n,T}/W_{prop}} \frac{F_{n,T}}{S} \frac{1}{W_T/S}\right)}{1 - 0.89\left(X - \frac{1}{F_{n,T}/W_{prop}} \frac{F_{n,T}}{S} \frac{1}{W_T/S}\right)} \tag{14}$$

It should be noted that the assumed breakdown of total fuel usage was strictly arbitrary. It is obvious that engines with different bypass ratio would consume different percentages of total fuel in the off-design segments of flight (conditions other than cruise). For even a specified flight profile of climb, acceleration to cruise, and descent, calculation of such fuel usage would require a great deal more aerodynamic and propulsion performance data than were available for the study. The large amount of fuel assigned for cruise (79 percent of total fuel) is significantly greater than that available for cruise of current transport airplanes, particularly short-range aircraft. This high value, however, was selected because of the benefit of lower cruise specific fuel consumption of the high-bypass-ratio engines.

By using the cruise weight fraction $W_{i,cr}/W_{f,cr}$ from equation (14), the overall cruise flight efficiency from figure 9, and the speed of sound at cruise altitude, the Breguet cruise-range equation presented earlier was evaluated. The expression for balanced-field take-off distance can also be written as

$$d = \left[\frac{23\left(W_T/S\right)^2}{\left(C_{L,max}\right)_T\left(F_{n,T}/S\right)} + 750\right]0.3048 \tag{15}$$

DISCUSSION

Breguet Cruise Range

Cruise range computations are presented in figure 10 as a function of bypass ratio. The range data are shown for fuel fractions X of 0.2, 0.3, and 0.4, and for take-off wing loadings of 2394, 3591, and 4788 Pa $\left(50, 75, \text{ and } 100 \text{ lbf/ft}^2\right)$. These values were assumed to represent aircraft which include short-haul STOL's and long-haul CTOL's. It should be emphasized that the range values are Breguet cruise range and not total range. Total range would include the distances covered in take-off, climb and acceleration to cruise, and descent; in the present study these flight operations were considered to consume 11 percent of the total fuel, but no credit was given for range. Relative cruise range is presented in figure 11 for the take-off wing loadings and weight fractions; the base for each curve corresponds to the cruise range of the bypass-ratio-3 engine for each variable.

Increases in bypass ratio at $X = 0.2$ produced large range reductions at all take-off wing loadings (fig. 10(a)). In fact, the range for a bypass ratio of 12 was only about 60 percent of that for a bypass ratio of 3 for the lowest wing loading, even though cruise specific fuel consumption was substantially lower for a bypass ratio of 12 (fig. 2). As a result of increased thrust lapse rate with increasing bypass ratio (fig. 2) and the requirement for cruise thrust drag matching, the take-off thrust loading of the bypass-ratio-12 engine was about 1.57 times greater than that of the bypass-ratio-3 engine (fig. 7). Because of this higher thrust loading and an approximate 18-percent decrease in total propulsion-package thrust-weight ratio (fig. 4) the bypass-ratio-12 engine required an increase in propulsion-package weight of nearly 92 percent over that for the bypass ratio 3. For these two cases the propulsion-package weight ratio W_{prop}/W_T was 0.0695 and 0.1332, respectively.

Thus, much less fuel was available at a bypass ratio of 12 for cruise at $X = 0.2$ and the lower cruise specific fuel consumption could not make up the range loss due to differences in fuel. The only possible ways to attain greater Breguet cruise range at the higher bypass ratios would be to increase the propulsion-package thrust-weight ratio and/or reduce cruise Mach number and vary altitude to effect a decrease in thrust lapse rate, which would reduce the thrust requirement of the engine and, consequently, the propulsion-package weight. At any rate, the sensitivity of range to weight at such values of fuel fraction X is quite high.

An increase in take-off wing loading to 3591 Pa $\left(75\ \mathrm{lbf/ft^2}\right)$ produced range increases for each bypass ratio; the increases ranged from about 20 percent at a bypass ratio of 3 to almost 40 percent at a bypass ratio of 12 for $X = 0.2$ (fig. 10(a)). The range increases were caused by two factors: the first and largest was a higher value of L/D at cruise (fig. 8), which provided higher cruise efficiency (fig. 9); the second was a reduction in propulsion-system weight. Even though the take-off thrust loading increased with take-off wing loading (fig. 7), the ratio of propulsion weight to take-off weight was reduced about 11 percent for the range of bypass ratios. More fuel was available for cruise at a higher cruise efficiency. It is also interesting to note that because of increased efficiency for the intermediate wing loading and increased propulsion weight with increasing bypass ratio, the value of Breguet cruise range (fig. 10(a)) for a bypass ratio of 3 at a wing loading of 2394 Pa $\left(50\ \mathrm{lbf/ft^2}\right)$ was equal to that for a bypass ratio of about 8 at a wing loading of 3591 Pa $\left(75\ \mathrm{lbf/ft^2}\right)$.

Comparison of the intermediate and highest wing loadings $\left(3591\ \mathrm{Pa}\ \left(75\ \mathrm{lbf/ft^2}\right)\right.$ and $\left.4788\ \mathrm{Pa}\ \left(100\ \mathrm{lbf/ft^2}\right)\right)$ shows a slightly lower range for the highest loading at all bypass ratios and fuel fractions X intermediate. The wing loading gave a higher value of L/D at cruise and the weight of the propulsion package as a fraction of gross take-off weight was slightly lower. The range increases for the range of bypass ratio and fuel fraction were between 1 and 2 percent.

The bypass-ratio-12 engines produced a loss of cruise range relative to the range of the bypass-ratio-3 engine for every set of fixed variables (wing loadings and fuel fractions). The range losses varied from about 40 percent at the lowest fuel fraction and wing loading to about 2 percent at the highest loading and fuel fraction (figs. 11(a) and 11(c), respectively). At the highest fuel fraction of 0.4, the small range reduction of 2 to 5 percent for the wing-loading range shows that the increased cruise flight efficiency and the propulsion-weight increase for the bypass-ratio-12 engine were nearly compensating. In the range of bypass ratios between 3 and about 7, the rapidly increasing cruise flight efficiency with increasing bypass ratio compensated for the reduced thrust-weight ratio, and relative range increases of about 4 percent resulted.

Range Sensitivity Studies

The nacelle drag coefficients of figure 3 were shown to have large effects on L/D at cruise (fig. 8) for the study range of bypass ratio. Similarly the propulsion-package thrust-weight ratio (fig. 4) in combination with nacelle drag was shown to produce significant reductions in cruise range at high bypass ratios, especially at the low fuel fractions characteristic of short-range aircraft. A sensitivity study of the influence of these two parameters was conducted for combinations of both the lowest and highest wing loadings and the lowest and highest values of X. These results are presented in figure 12.

As shown in figure 12 resizing all the engines for a constant nacelle drag coefficient $D_{nac}/q_\infty A_{nac}$ of 0.055, the value used for the bypass-ratio-3 engine, produced maximum increases in relative cruise range of only about 2 to 3 percent for any condition. Zero nacelle drag, on the other hand, produced relative range increases of 5 to 20 percent, the 20-percent increase occurring at a bypass ratio of 12 for both wing loadings at $X = 0.2$. This large increase for the bypass-ratio-12 engine again points out that because of propulsion drag, the range is highly sensitive to both cruise flight efficiency and propulsion weight associated with engine size changes. For this case the relative-range increase was caused by approximately equal percentage increases in cruise efficiency (reductions in propulsion drag) and reductions in propulsion weight fraction.

Zero propulsion drag at the highest fuel fraction and both wing loadings resulted in relative-range increases of about 4 to 16 percent, with the bypass-ratio-12 engine again having the largest increase. It should be pointed out again that the relative range has been proportioned to the absolute cruise range of the base bypass-ratio-3 engine at each wing loading and value of X. For zero nacelle drag of the bypass-ratio-12 engine, the 20-percent increase in relative range at $X = 0.2$ and the 16-percent increase at $X = 0.4$ correspond to absolute range increases of 227 and 522 n. mi., respectively, at the highest wing loading.

The relative range of the basic configuration is seen to be even more sensitive to constant propulsion-system thrust-weight ratio than to zero propulsion drag at a bypass ratio of 12 for the lowest fuel fraction X. For the lowest wing loading, the relative range increase was about 23 percent for an increase in take-off thrust-weight ratio from the basic value (2.965) to 3.614, the take-off thrust-weight ratio of the bypass-ratio-3 engine (fig. 4). This result points out again that propulsion-weight increase due strictly to the increased thrust lapse rate at high bypass ratios was so great that the portion of fuel remaining for cruise at the lowest value of X was quite small. In fact at a bypass ratio of 12, even though cruise flight efficiency was about 22 percent higher than that at a bypass ratio of 3 (fig. 9), the propulsion system thrust-weight ratio would have had to increase by about 45 percent from the 2.965 value to provide equal range at the low fuel fraction and the lowest wing loading.

Constant propulsion thrust-weight ratio at $X = 0.4$ and both wing loadings provided about half the increase in relative range afforded by zero propulsion drag (figs. 12(b) and 12(d)) for a bypass ratio of 12. The increases in relative range were about 10 percent from the base cases for both wing loadings. The decreased sensitivity of relative range to propulsion thrust-weight ratio at the higher fuel fraction is due strictly to the proportionately higher weight of fuel available for cruise.

As shown by the table of aerodynamic parameters in the section "Procedure," the assigned cruise altitude caused the engines to be thrust-drag matched at different lift and drag coefficients for the several airframe polars (fig. 5) for the three take-off wing loadings. Such arbitrary altitude selection would not be expected to provide optimum cruise range for any engine at a specific take-off wing loading. The engines with bypass ratios of 3, 8, and 12 were rematched at several altitudes above and below the initially selected cruise altitude to determine the cruise-range sensitivity. The ratios of engine cruise thrust to take-off thrust of figure 2 were assumed to vary with altitude directly because of ambient pressure variations. For small excursions in altitude above the tropopause (11 000 m (36 089 ft)), where the ambient temperature is constant, the assumed variations in thrust are valid and specific fuel consumption is constant with altitude. For excursions below 11 000 m (36 089 ft), however, both ambient pressure and temperature vary, so that the ratio of engine thrust to ambient pressure alone would result in optimistic (higher) thrust levels or smaller engine sizes and weights for the lower altitudes. Operation of an engine at conditions producing constant corrected speed would tend to eliminate the effects of ambient temperature increases at the lower altitudes and the present cruise specific fuel consumptions, and adjustments in net thrust with altitude variations would be more nearly correct.

Take-off thrust loading, cruise flight efficiency, and cruise range relative to that for the initially selected cruise altitude of 11 000 m (36 089 ft) are presented in figure 13 as a function of altitude for the three engines resized and thrust-drag matched for different altitudes. The results for relative cruise range are presented for two wing loadings and three values of X.

At the low wing loading, 2394 Pa (50 lbf/ft^2) (figs. 13(a) and 13(b)), significant increases in cruise flight efficiency were obtained for the three bypass ratios at altitudes above the tropopause. At the same time, take-off thrust loading also increased because of the greater thrust required for drag-coefficient matching at the higher altitudes. In effect, higher altitudes required higher lift coefficients for the given wing loading, which in turn defined operation at a higher airframe drag coefficient with a resultant greater value of airframe L/D. The configuration with a fuel fraction of 0.2 showed a 5- to 6-percent increase in relative range at a bypass ratio of 3 but almost no increase at bypass ratios of 8 and 12. Although the bypass-ratio-3 engine was optimized for cruise at about 12 800 m (42 000 ft), the engines with ratios of 8 and 12 were optimized for cruise at very near the initially selected altitude. Higher fuel fractions gave progressive increases in relative range for all bypass ratios; the maximum increase was about 13 percent at a bypass ratio of 3 but only about 5 percent at a bypass ratio of 12 for $X = 0.4$. The highest bypass ratio required the greatest excursion in altitude to produce peak range as the fuel fraction was increased from 0.2 to 0.4.

Unique relationships exist between propulsion weight, fuel fraction, and cruise flight efficiency for the bypass ratios of the study at the low take-off wing loading. On the basis of aerodynamic efficiency L/D alone, aircraft at this loading would cruise at high altitudes. The engines would grow in size and weight, however, as cruise altitude is increased. At a low fuel fraction, the low-bypass-ratio engine could tolerate some increase in propulsion weight to maximize cruise flight efficiency for maximum cruise range. The engine with the highest bypass ratio could not. Propulsion weight increases and displaces cruise fuel faster than cruise flight efficiency increases.

For the highest fuel fraction, the low-bypass-ratio engine could tolerate still further propulsion weight gains to achieve higher cruise flight efficiency, and maximum range occurs very near $(L/D)_{max}$. The engine with the highest bypass ratio also could grow in weight because cruise flight efficiency increases rapidly as altitude increases. Maximum range, however, occurs well below $(L/D)_{max}$. It is quite apparent that for the take-off wing loading of 2394 Pa (50 lbf/ft^2), the cruise-range deficiencies of the high-bypass-ratio engines at the initially selected altitude of the basic study will become progressively worse with altitude optimization relative to low-bypass-ratio engines.

The altitude-optimization data for the wing loading of 4788 Pa (100 lbf/ft^2) are presented in figures 13(c) and 13(d). Cruise flight efficiency reached a maximum at altitudes very near the initial altitude for all three bypass ratios. Take-off thrust loading for cruise thrust-drag matching, however, increased rapidly with altitude. The trends of relative range with changes in altitude and fuel fraction were exactly opposite those for the low wing loading. The maximum relative range at the lowest values of X was about 8 percent greater for a bypass ratio of 3 and about 33 percent greater for a bypass ratio of 12 as cruise altitude was reduced from the base cruise altitude to about 9140 m (30 000 ft) and 8230 m (27 000 ft), respectively. For the highest fuel fraction, relative range increases and altitude variations from the initial case were smaller, with range increases varying from about 3 percent for a bypass ratio of 3 to about 8 percent at a bypass ratio of 12. The same unique relationship between propulsion weight, fuel fraction, and cruise flight efficiency that existed at the low take-off wing loading also existed for these cases. Aircraft with low fuel fractions tended to have better performance at altitudes where low propulsion weight was the dominant factor, and those with high fuel fractions tended to have optimum performance at altitudes where cruise flight efficiency was dominant. It should be pointed out again that the particular procedure used to generate engine performance at cruise altitudes below 11 000 m (36 089 ft) resulted in engine sizes and weights that would produce optimistic estimates of cruise range.

A summary of cruise-range and altitude data resulting from the altitude sensitivity study is presented in the following table:

Bypass ratio	Base range (at h = 11 000 m (36 089 ft)), n. mi.	Optimum cruise range, n. mi.	Optimum cruise altitude	
			m	ft
W_T/S = 2394 Pa (50 lbf/ft^2); X = 0.2				
3	1000	1058	12 800	42 000
8	792	794	11 580	38 000
12	606	606	11 000	36 089
W_T/S = 2394 Pa (50 lbf/ft^2); X = 0.4				
3	2853	3216	13 410	44 000
8	2792	3020	12 800	42 000
12	2707	2860	12 800	42 000
W_T/S = 4788 Pa (100 lbf/ft^2); X = 0.2				
3	1187	1280	9 140	30 000
8	1000	1178	8 230	27 000
12	827	1093	7 620	25 000
W_T/S = 4788 Pa (100 lbf/ft^2); X = 0.4				
3	3279	3382	9 750	32 000
8	3267	3449	9 140	30 000
12	3217	3480	9 140	30 000

The data presented here and elsewhere in the paper point out quite clearly that for aircraft designed specifically for short range (low fuel fraction) with a low take-off wing loading, the high-bypass-ratio engines are vastly inferior to low-bypass-ratio engines on a cruise-range basis. If the low noise levels attributable to high-bypass-ratio engines (not discussed in this paper) and the short take-off distances afforded by high take-off thrust (discussed later) are the desirable design criteria for a particular aircraft, the cruise-range deficiencies associated with the weight of cruise thrust-drag matched high-bypass-ratio engines should be recognized. Optimization of cruise altitude for the range of engines studied did not overcome the cruise-range deficiencies of high-bypass-ratio engine. High-wing-loading designs at optimized altitudes showed increases in cruise range for high bypass ratios. The engine with the lowest bypass ratio, however, still had a range advantage of about 15 percent for the low fuel fraction. Significant increases in the propulsion thrust-weight ratio of high-bypass-ratio engines would make them competitive.

If cruise Mach number is reduced below the study value of 0.8, thrust lapse rates at high bypass ratios should be reduced and lower propulsion-system weight would result. The criticality of propulsion-system weight to the low fuel fractions would be reduced and higher cruise ranges could be attained. It should be pointed out, however, that cruise flight efficiency $M_\infty(L/D)_{cr}/(SFC)_{cr}$ would probably suffer at lower flight speeds.

Results of the basic and sensitivity study are also of special significance for aircraft designed for high fuel fractions, such as long-range CTOL aircraft. At the low wing loading, the low-bypass-ratio engine continued to be superior in cruise range to the high-bypass-ratio engines, even when cruise altitude was optimized. At the highest wing loading, however, the situation was reversed and the engines with the highest bypass ratio provided about a 3-percent increase in cruise range. As mentioned previously, increasing the propulsion thrust-weight ratio would further increase the range for the high-bypass-ratio engines. Again, if the noise reduction attributable to the high-bypass-ratio engine is taken into account, long-range CTOL aircraft could benefit significantly from high-bypass-ratio engine designs.

Take-Off Distance

Balanced-field take-off distances were calculated for the various engines (fig. 14) from the empirical relation of reference 1. Since the cruise thrust-drag matched engines produced the take-off thrust loadings of figure 7, take-off distance was simply a function of take-off wing loading and maximum take-off lift coefficient. For this study it was assumed that with the wing flaps in the maximum take-off position and some method of blowing the engine exhaust flow over the flap, a take-off lift coefficient of 4 could be generated. Obviously, with higher or lower take-off lift coefficients, the take-off distances would change accordingly.

The relative effects of engine bypass ratio on take-off distance, however, are believed to be reasonable.

Increasing engine bypass ratio from 3 to 12 reduced take-off distance at the lowest wing loading (2394 Pa (50 lbf/ft^2)) by about 22 percent, from 577 m (1890 ft) to 450 m (1476 ft). The distances were reduced by 26 percent at a wing loading of 3591 Pa (75 lbf/ft^2) and by 28 percent at 4788 Pa (100 lbf/ft^2). These reductions in take-off distance with increasing bypass ratio were a direct result of the 57-percent increase in take-off thrust loading caused by increased thrust lapse rates at higher bypass ratios when all engines are sized for cruise thrust-drag matching.

Increases in cruise altitude for any engine would have the effect of increasing the take-off thrust loading and would cause reductions in the take-off distances shown for the selected cruise altitude. At lower cruise altitudes the reverse would be true.

CONCLUDING REMARKS

Results of the present study indicate that if aircraft are designed specifically for short range and are to cruise efficiently at speeds of present-day transports, engines with a bypass ratio 3 or perhaps lower will provide the optimum propulsion-aerodynamic arrangement. Although engines with bypass ratios up to 12 provide increases in take-off thrust and lower jet noise, they result in higher propulsion-system weight and would require aircraft oversizing to attain the same cruise range. If, through technology advances, the propulsion-system thrust-weight ratio assigned by the present study to bypass-ratio-12 engines could be increased by about 45 percent, the advantage in cruise specific fuel consumption would provide a range about equal to that attributed to the bypass-ratio-3 engine.

The present study also showed that aircraft designed for long cruise ranges would not suffer significant range penalties with high-bypass-ratio engines. The advantage in specific fuel consumption at high bypass ratios would compensate for the oversizing and higher propulsion weight for aircraft with high fuel fractions. Improvement in propulsion-system thrust-weight ratio and drag of the high-bypass-ratio engine would provide significant increases in cruise range. The take-off thrust advantage of high-bypass-ratio engines will also allow take-off distance to be reduced significantly from that for low-bypass-ratio engines.

Langley Research Center
National Aeronautics and Space Administration
Hampton, Va. 23665
September 19, 1975

REFERENCE

1. Weirich, Robert L.: Analytical Determination of the Take-Off Performance of Some Representative Supersonic Transport Configurations. NASA TN D-2308, 1964.

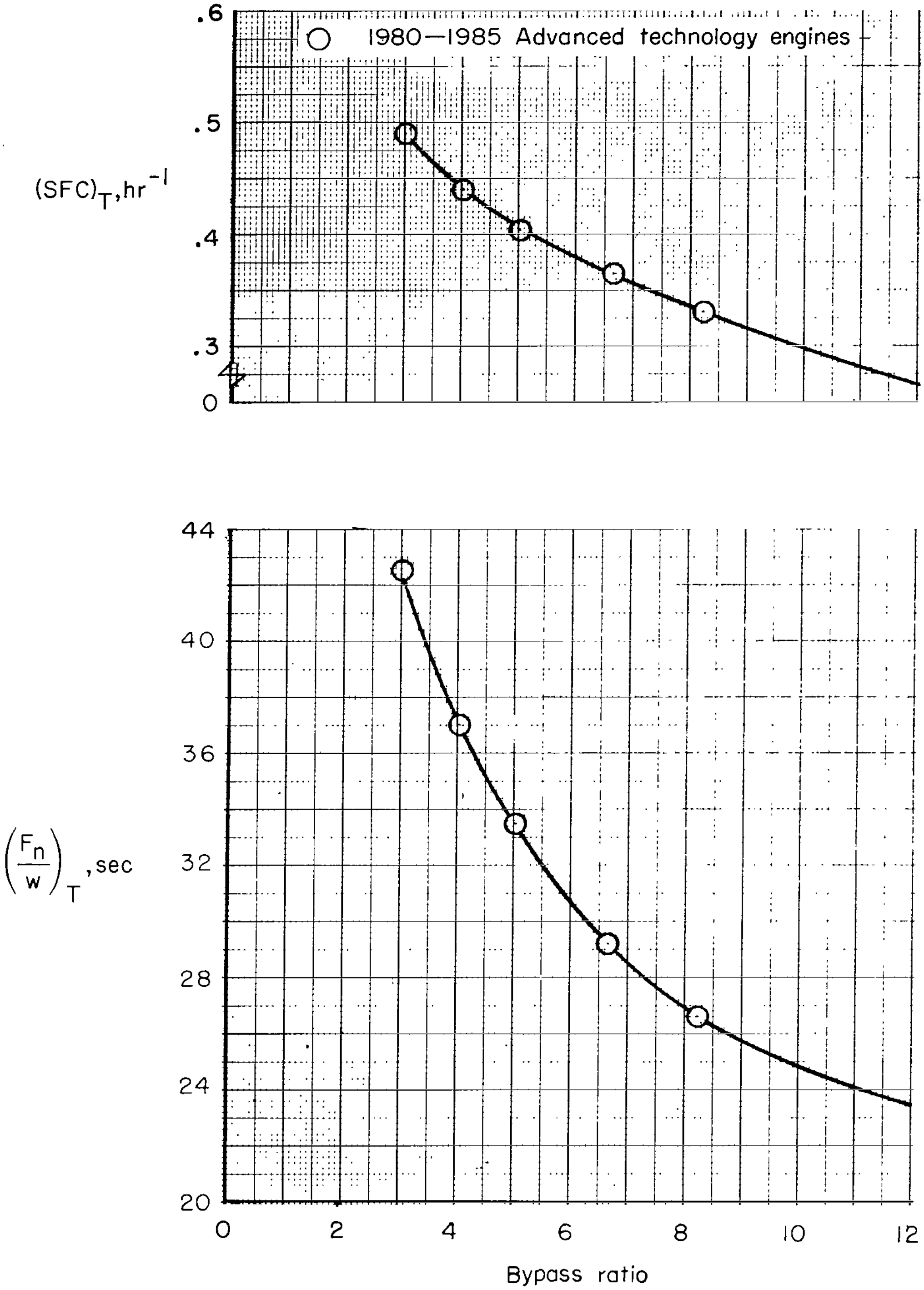


Figure 1.- Take-off performance of advanced technology turbofan engines. $M_\infty = 0$; $h = 0$.

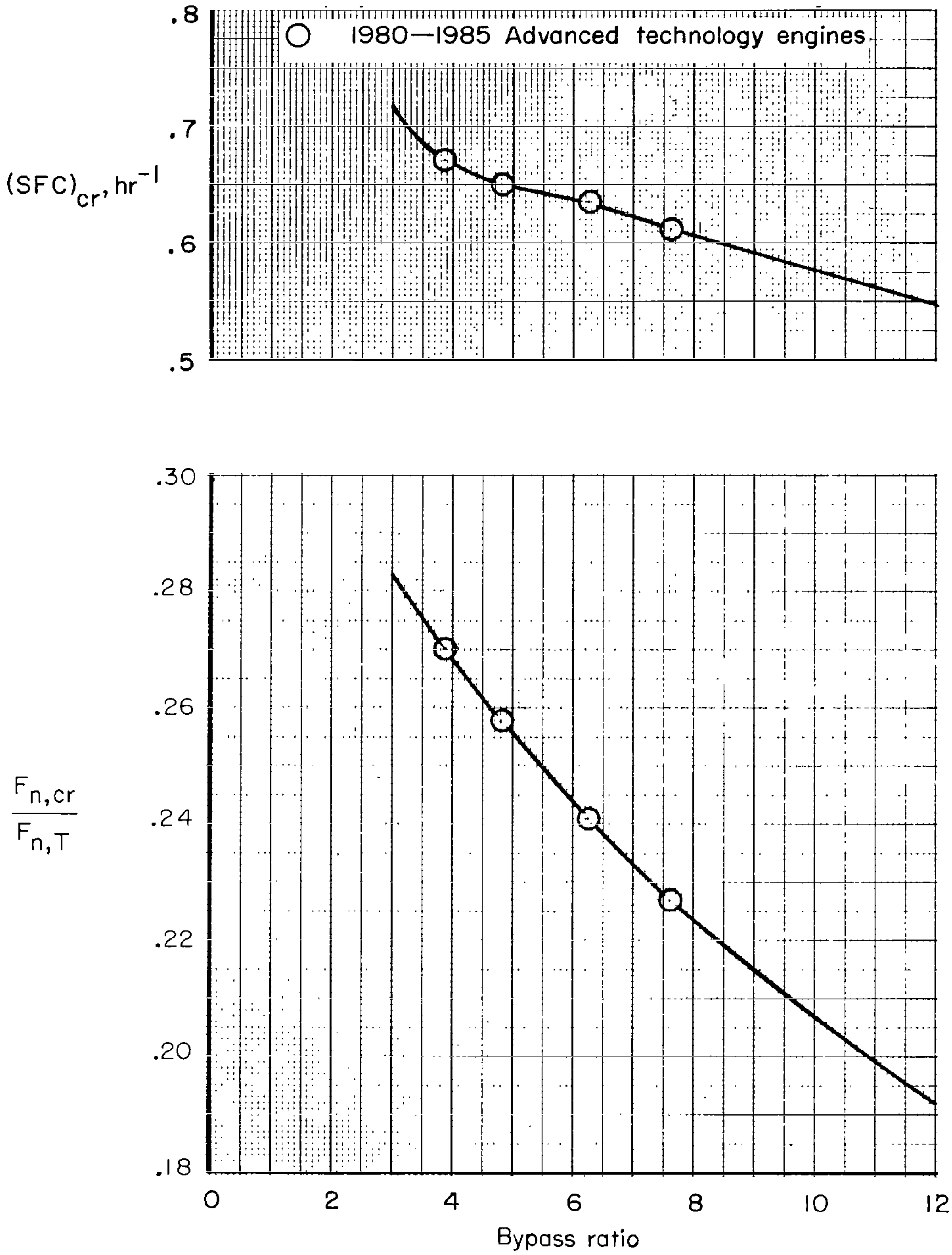


Figure 2.- Cruise performance of advanced technology turbofan engines. $M_\infty = 0.8$; h = 11 000 m (36 089 ft).

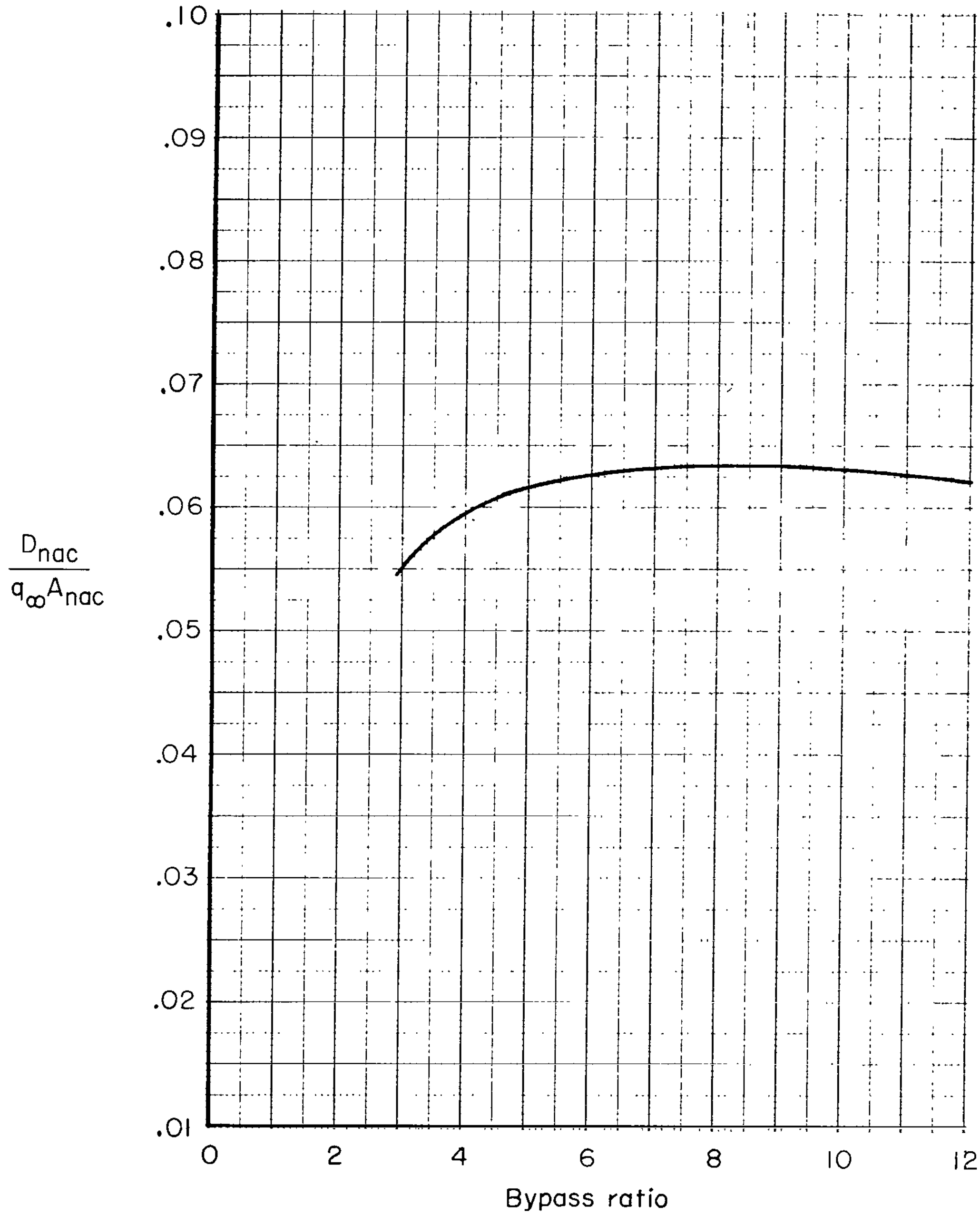


Figure 3.- Cruise drag coefficients $D_{nac}/q_\infty A_{nac}$ of isolated nacelles as a function of bypass ratio for turbofan engines. $M_\infty = 0.8$; h = 11 000 m (36 089 ft).

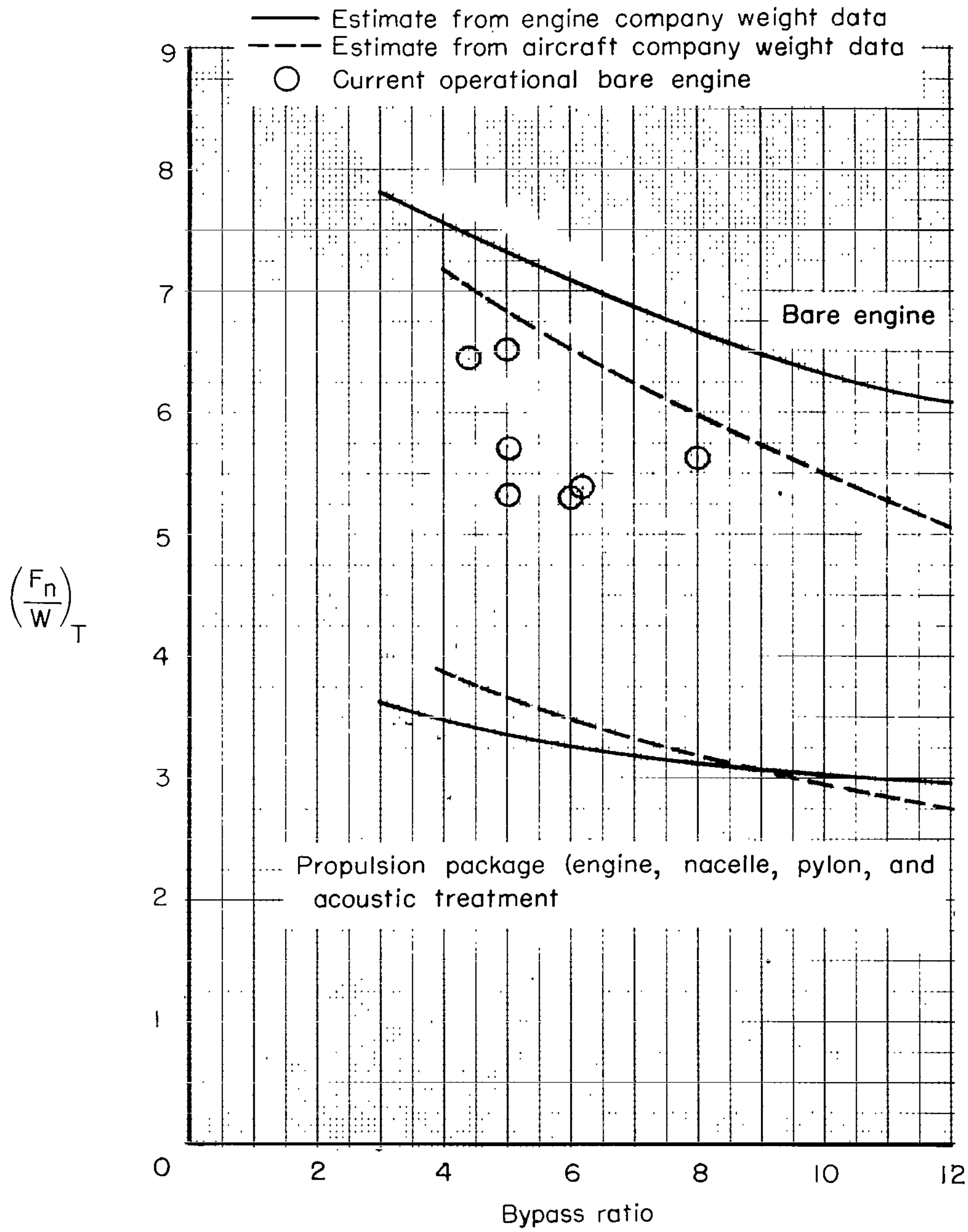


Figure 4.- Take-off thrust-weight ratios of bare engine and installed propulsion package of advanced turbofan engines sized for constant cruise net thrust.

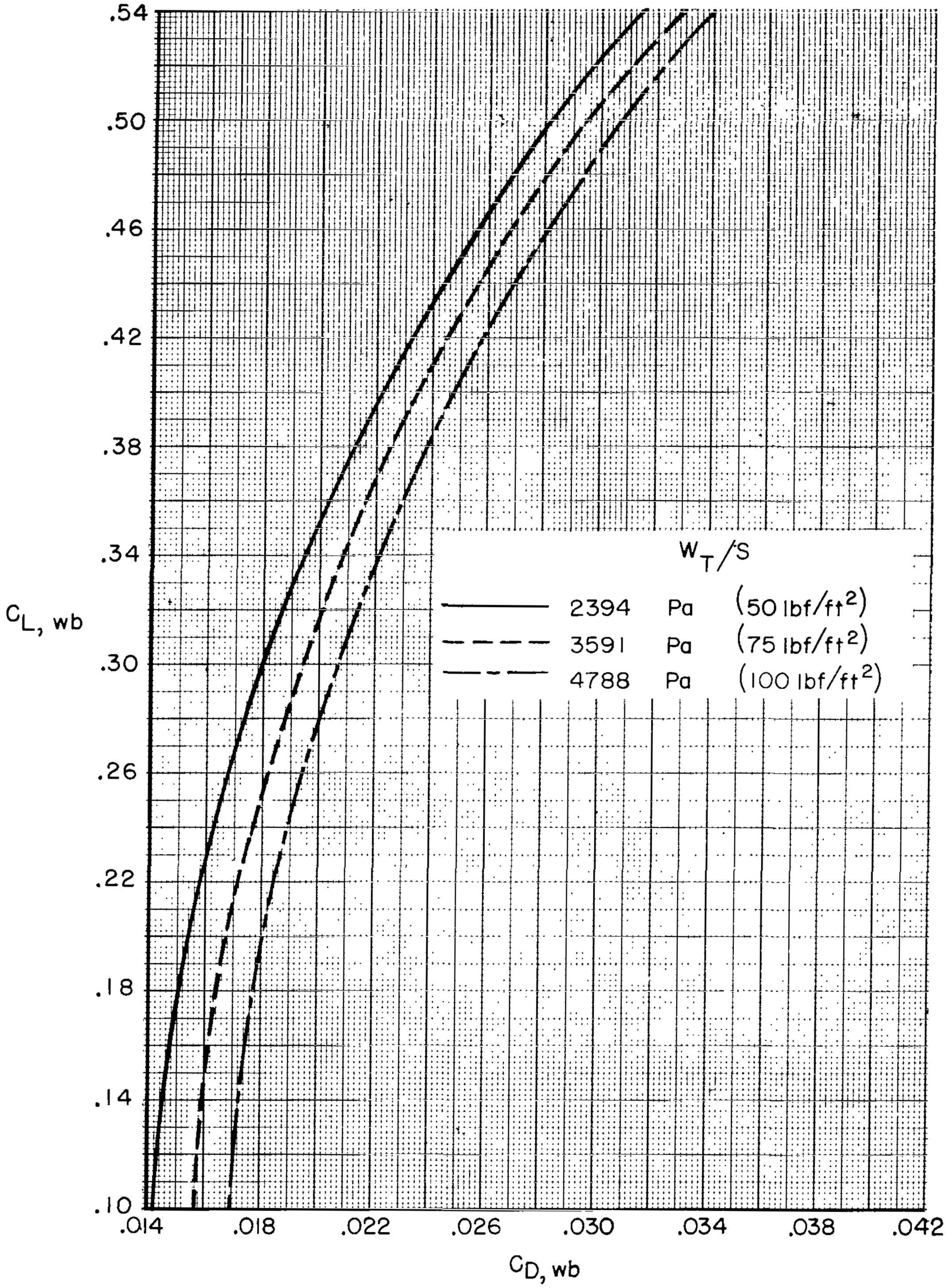


Figure 5.- Basic airframe lift-drag polars for several take-off wing loadings at cruise flight conditions. $M_\infty = 0.8$; h = 11 000 m (36 089 ft).

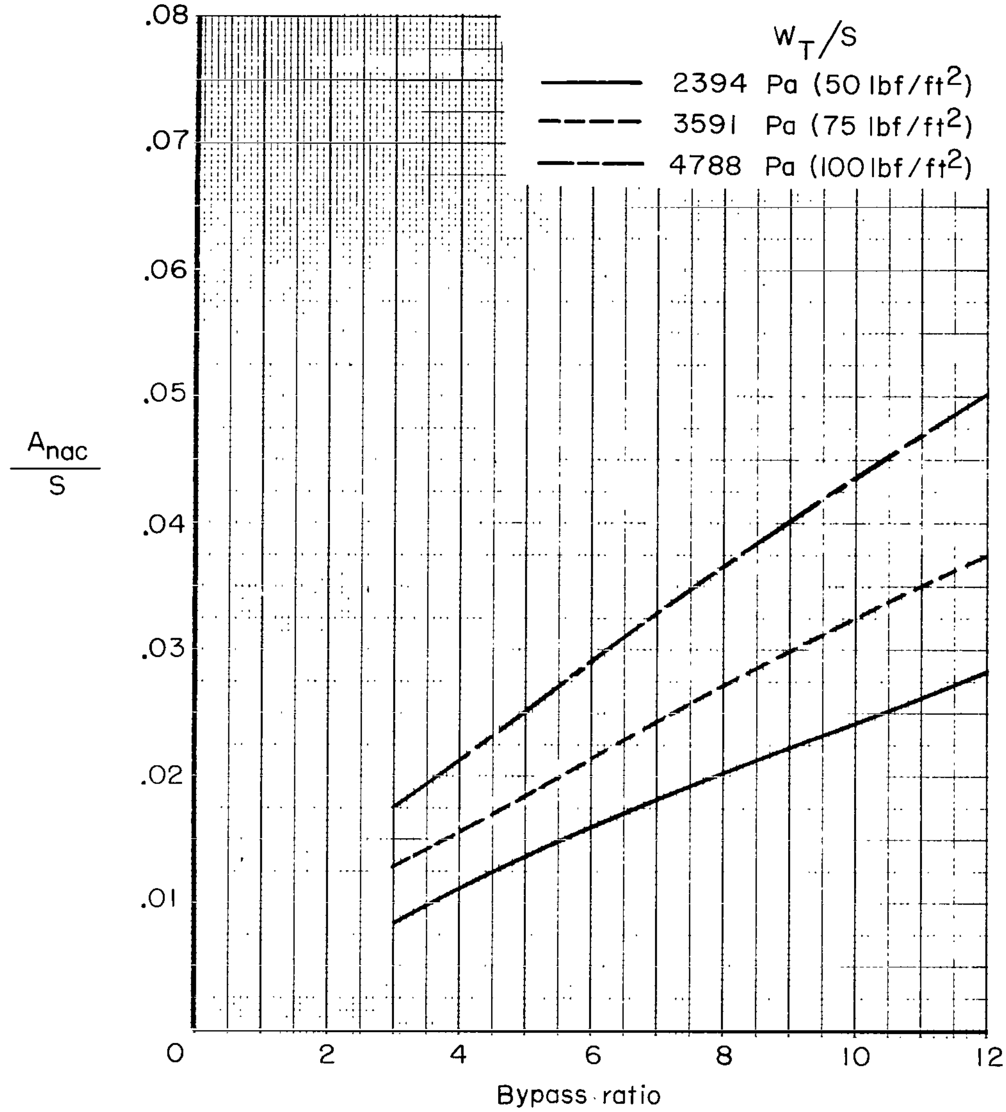


Figure 6.- Effect of engine bypass ratio on ratio of nacelle area to wing area for engines sized to produce cruise thrust-drag matching at $M_\infty = 0.8$ and h = 11 000 m (36 089 ft).

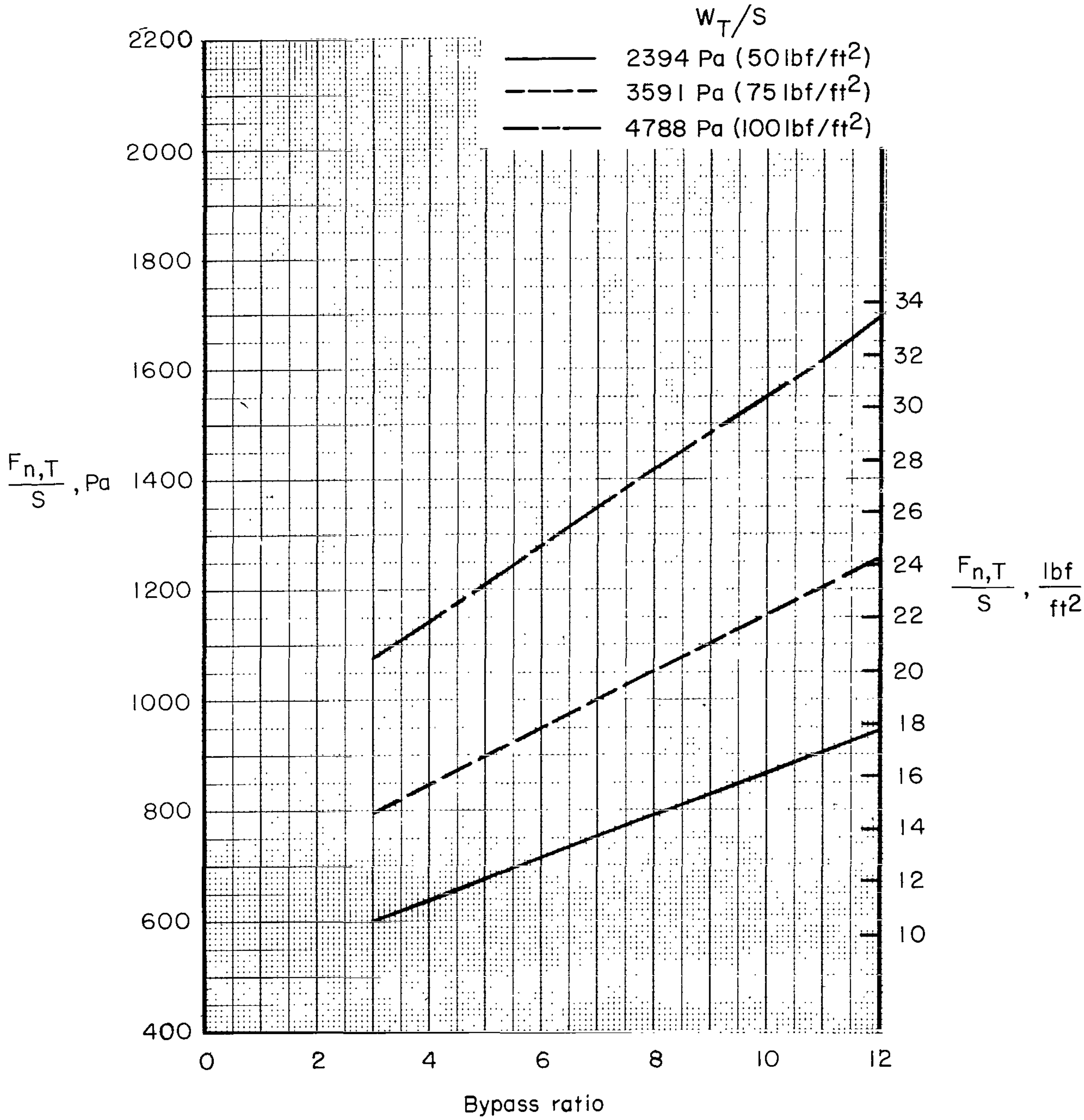


Figure 7.- Effect of engine bypass ratio on take-off thrust loading of turbofan engines sized for cruise thrust-drag matching at $M_\infty = 0.8$ and $h = 11\ 000$ m (36 089 ft).

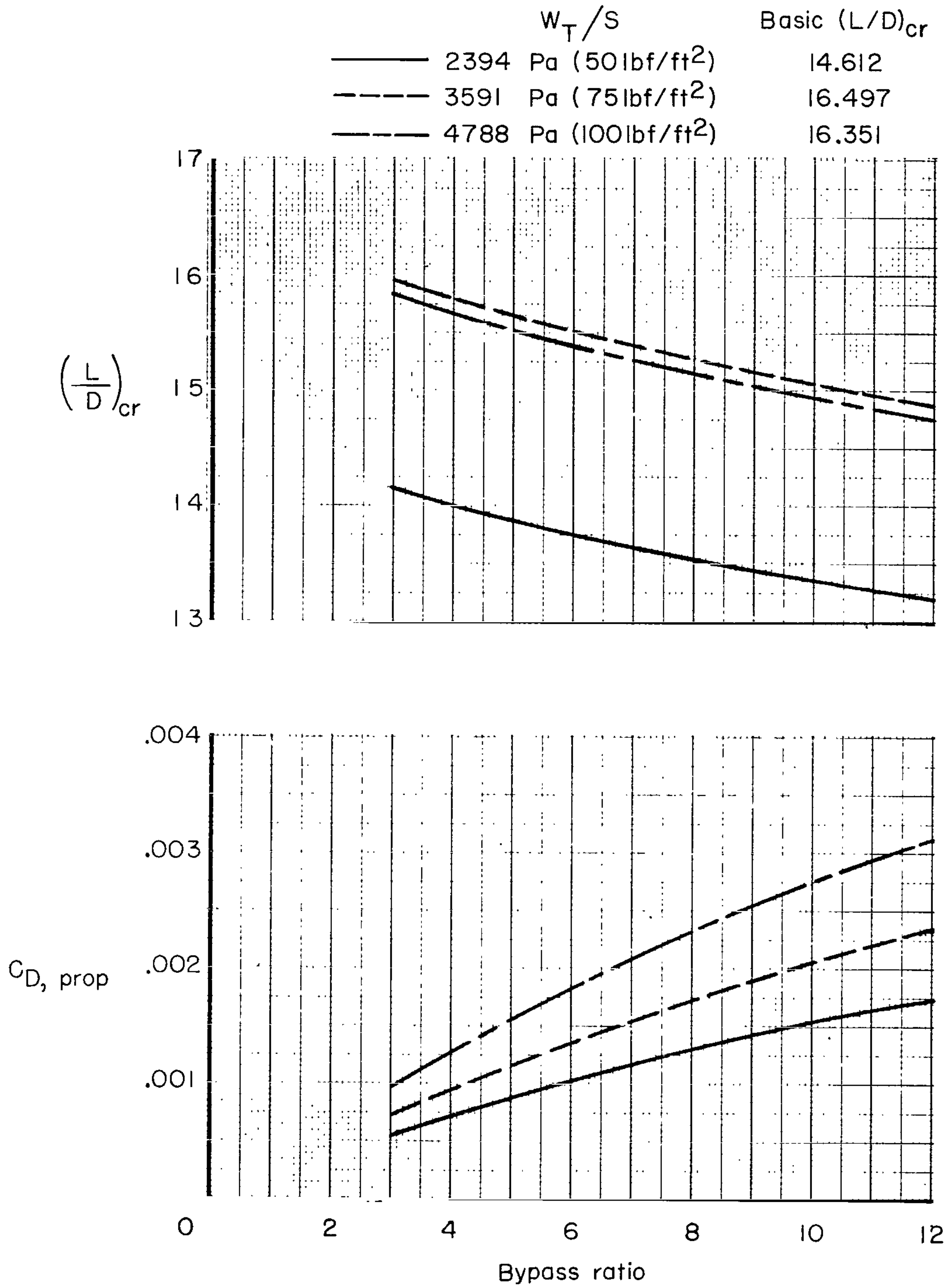


Figure 8.- Changes in isolated propulsion-system drag and aerodynamic efficiency L/D resulting from sizing the various engines for cruise thrust-drag matching at $M_\infty = 0.8$ and h = 11 000 m (36 089 ft).

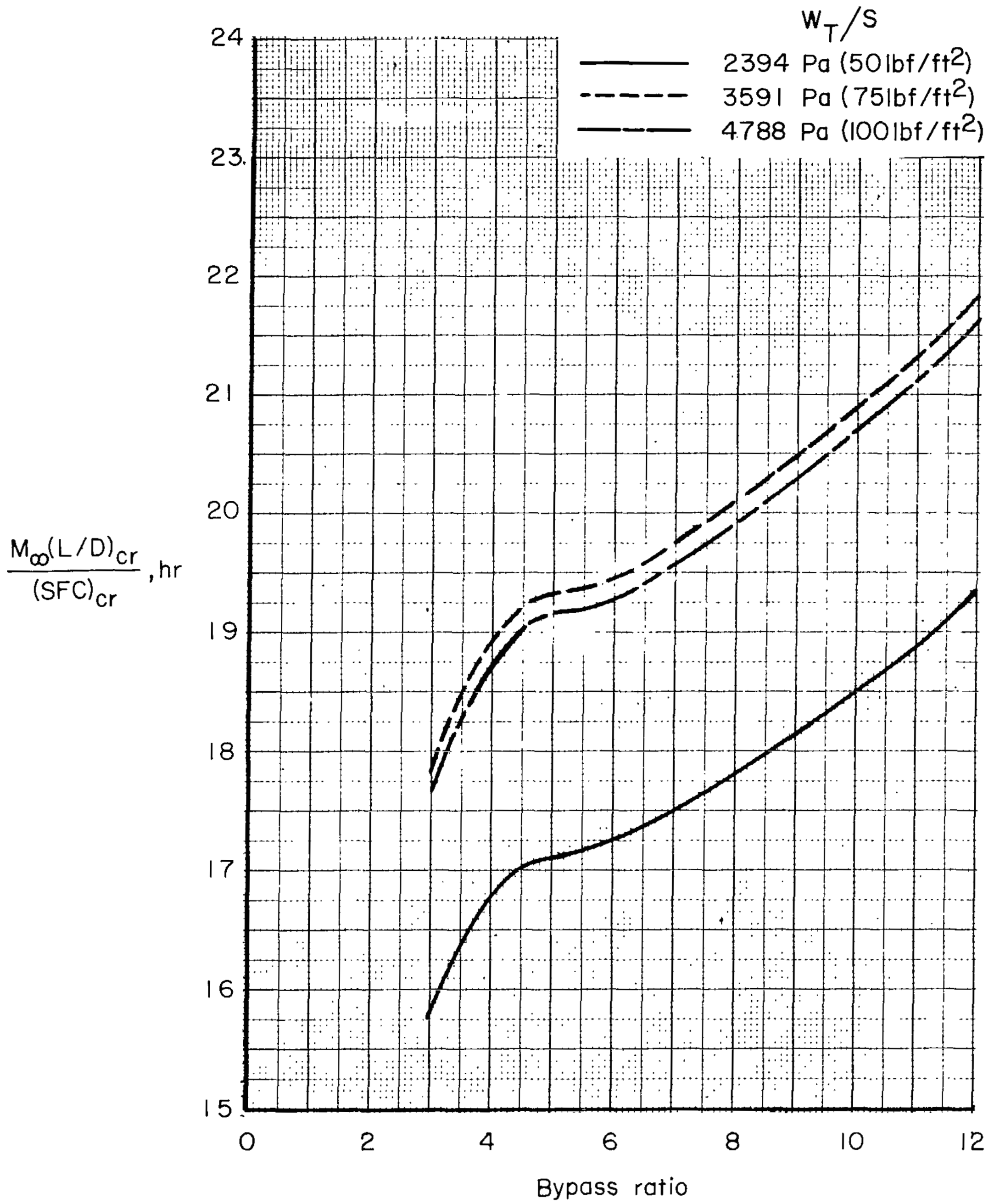
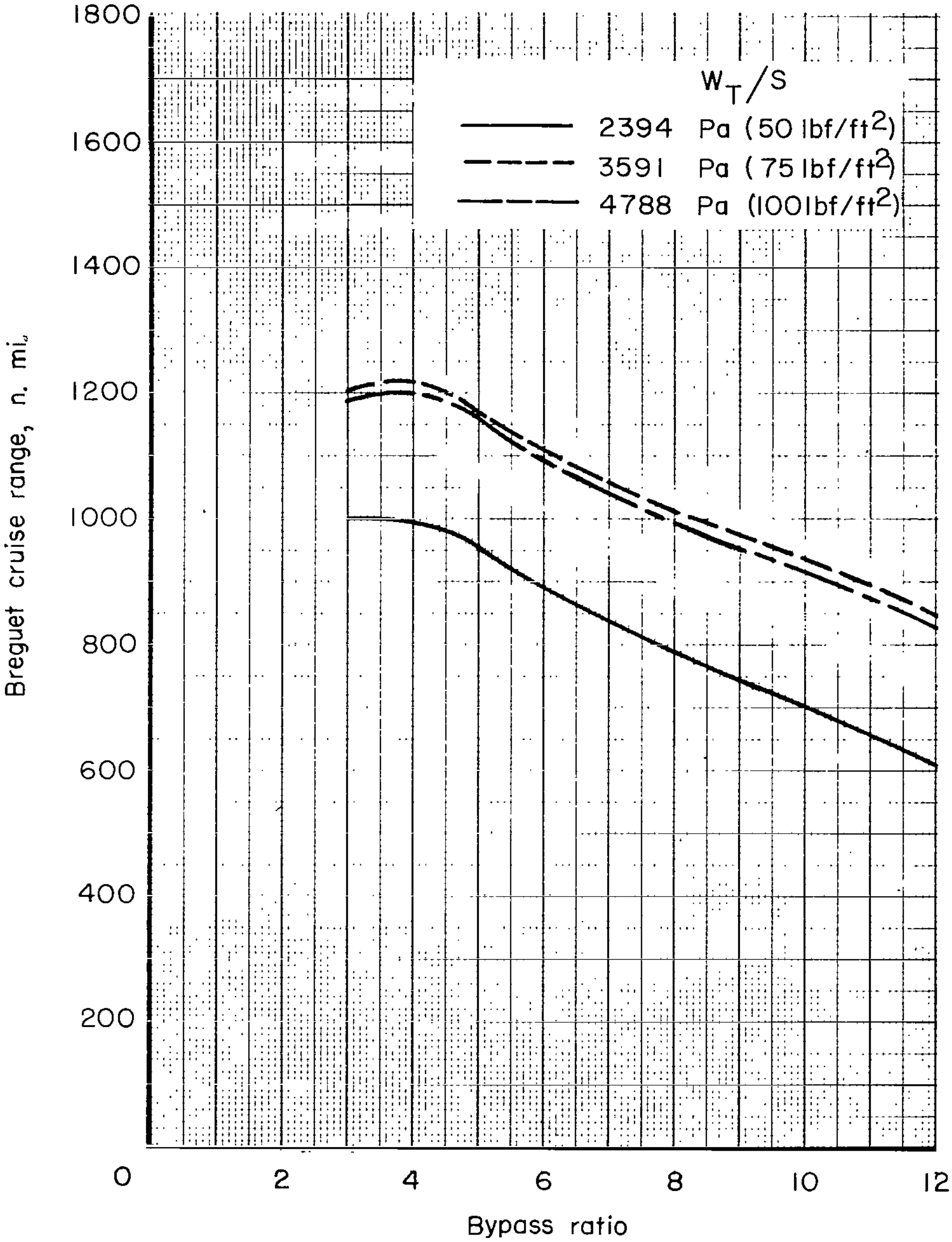
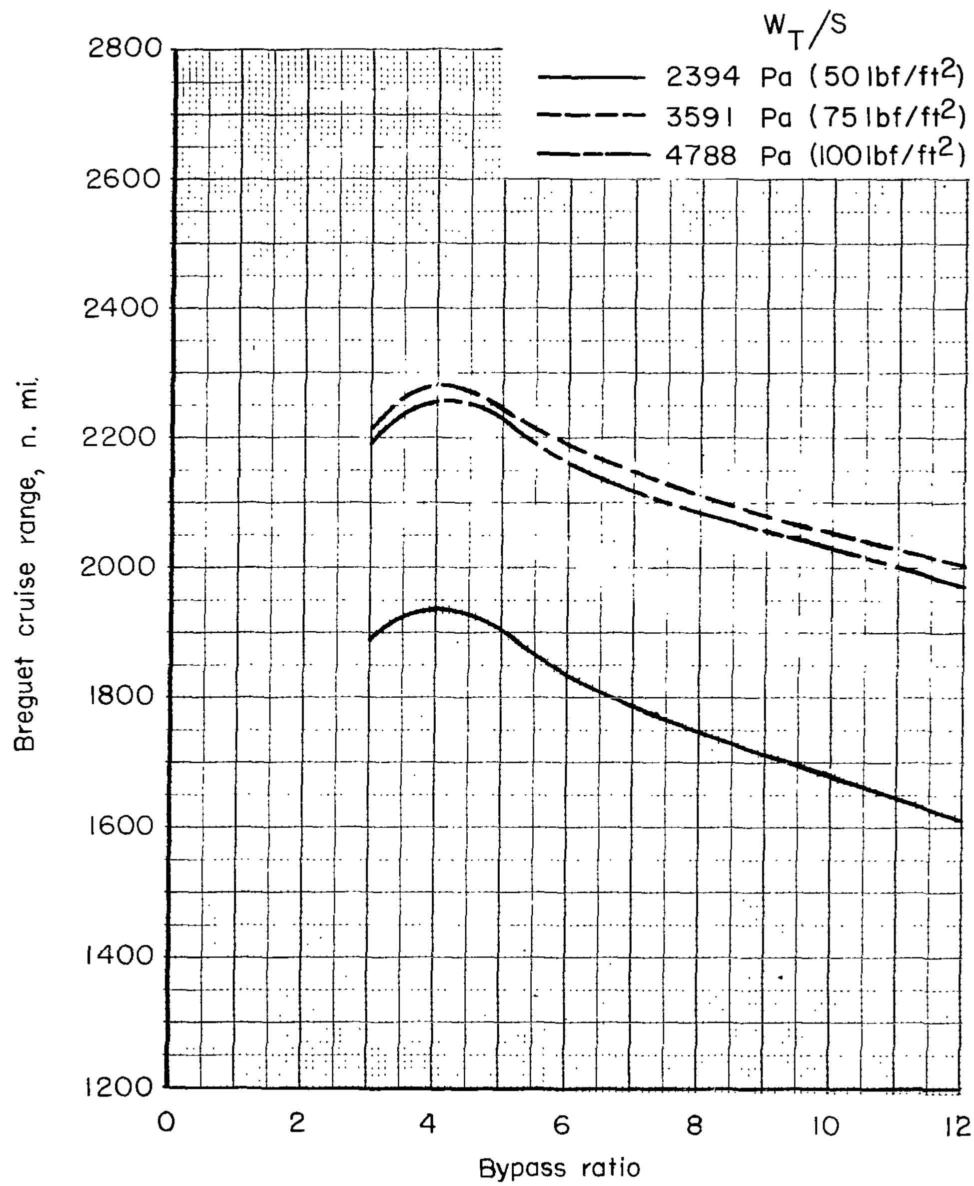


Figure 9.- Variation in overall cruise flight efficiency with engine bypass ratio for cruise thrust-drag matched aircraft. $M_\infty = 0.8$; h = 11 000 m (36 089 ft).



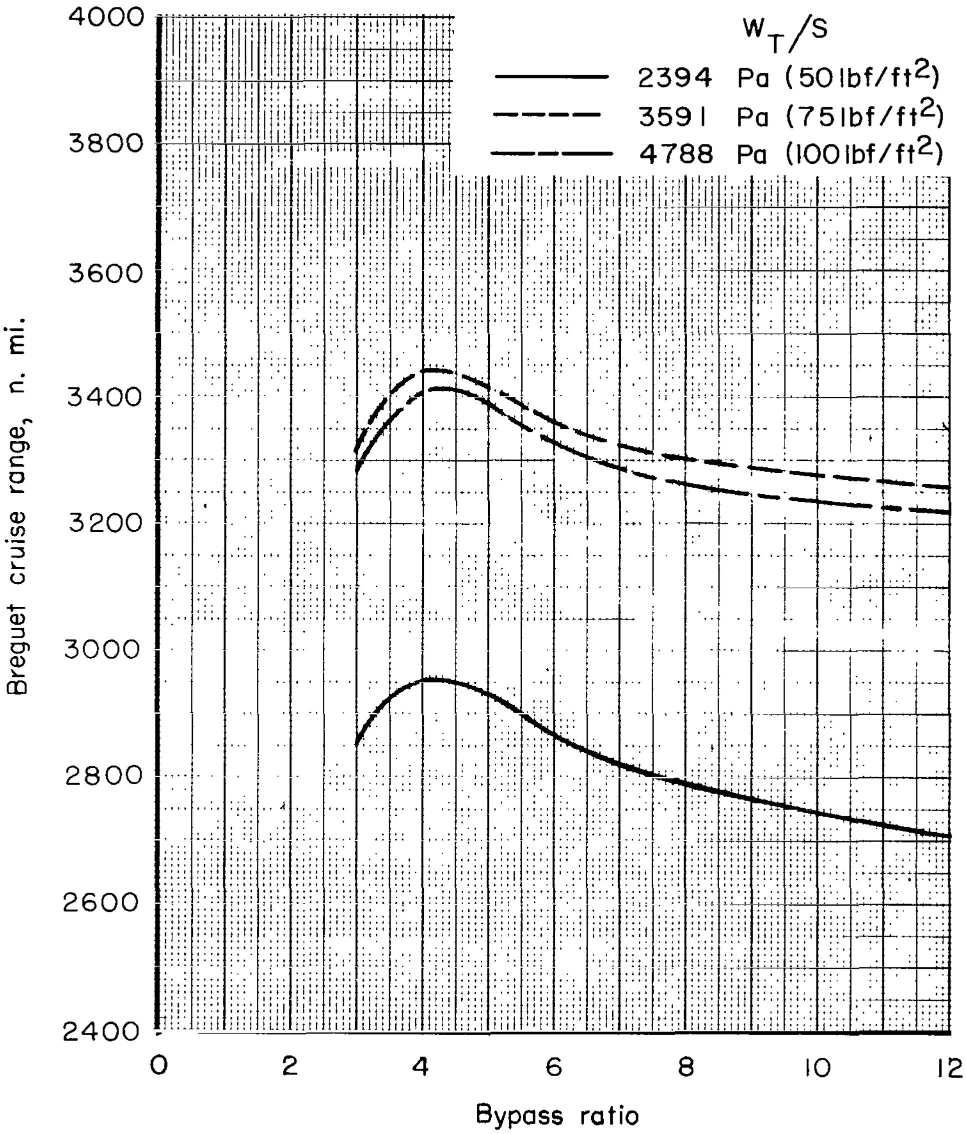
(a) X = 0.2.

Figure 10.- Effects of engine bypass ratio on Breguet cruise range for several take-off wing loadings and fuel fractions. $M_\infty = 0.8$; h = 11 000 m (36 089 ft).



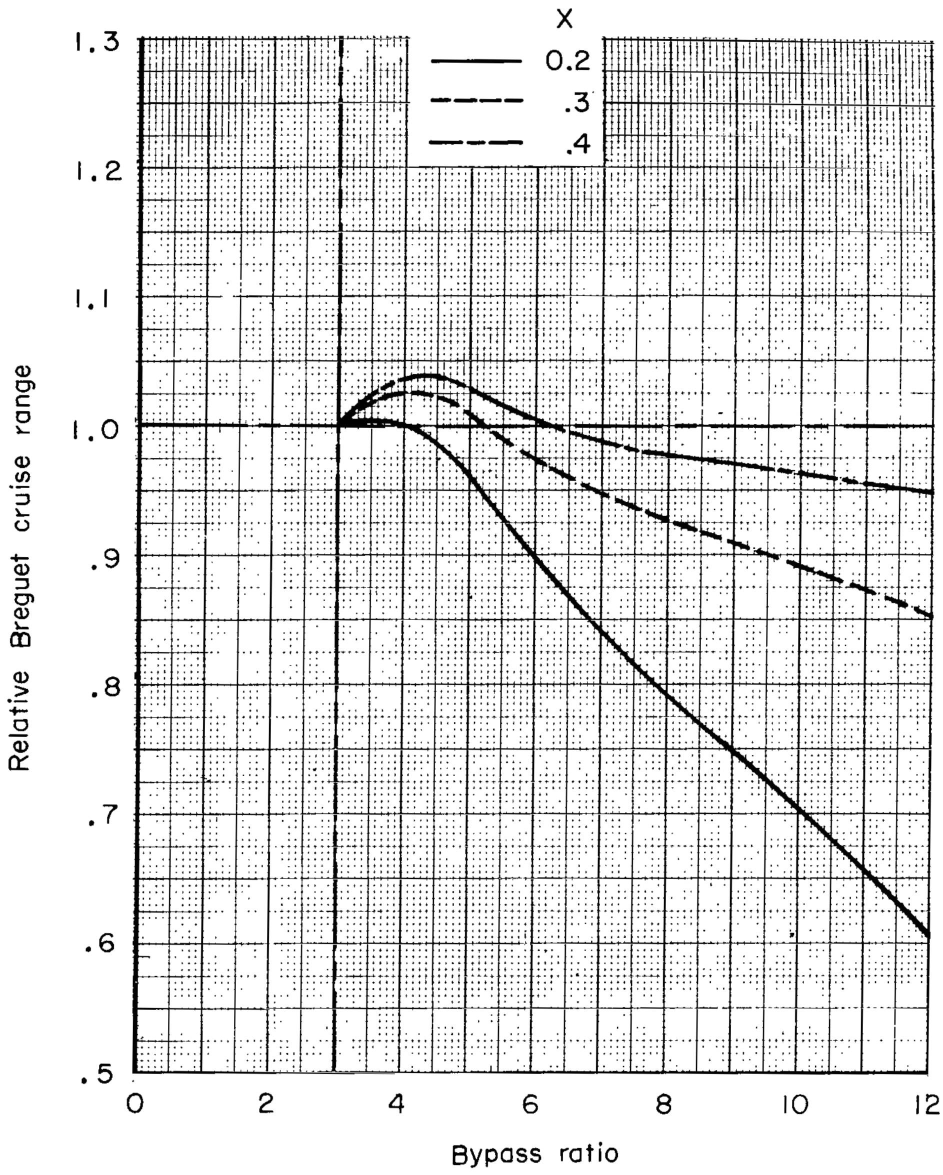
(b) X = 0.3.

Figure 10.- Continued.



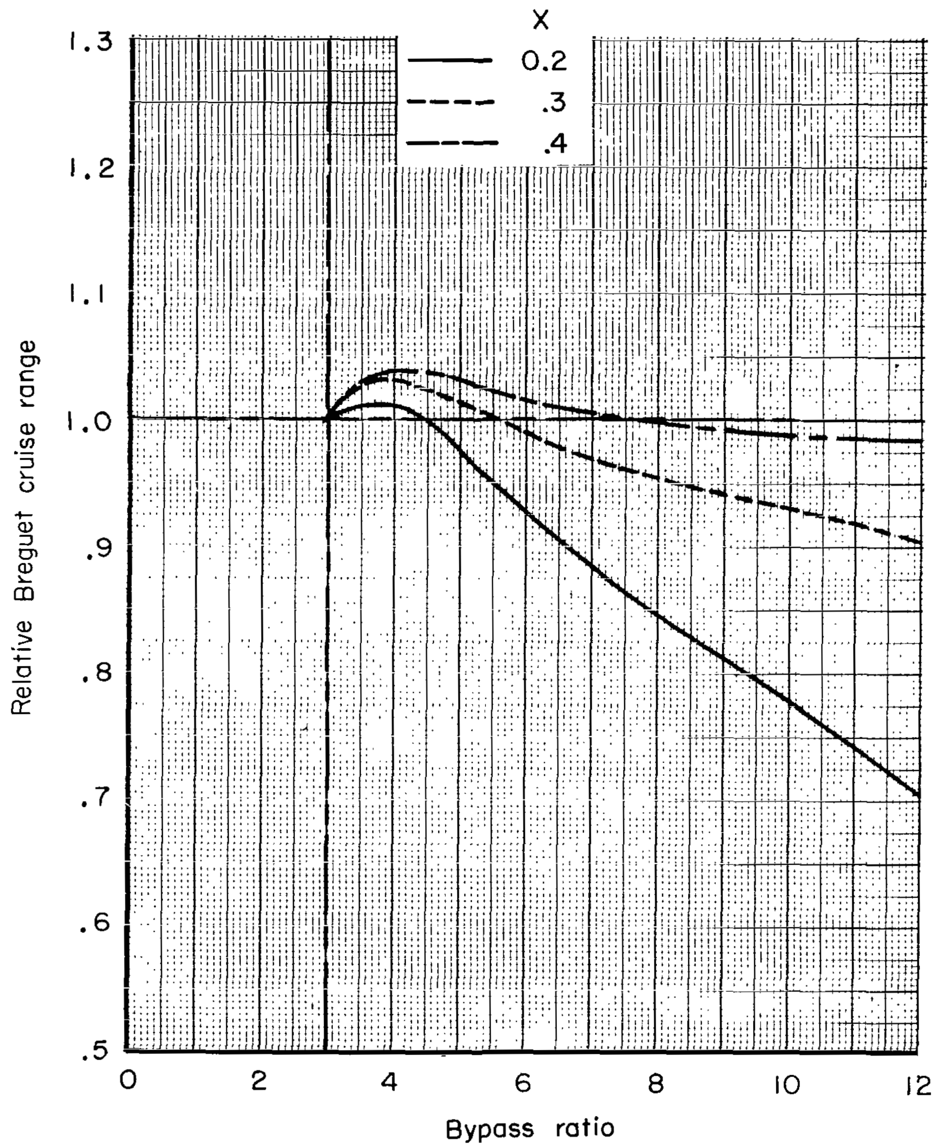
(c) X = 0.4.

Figure 10.- Concluded.



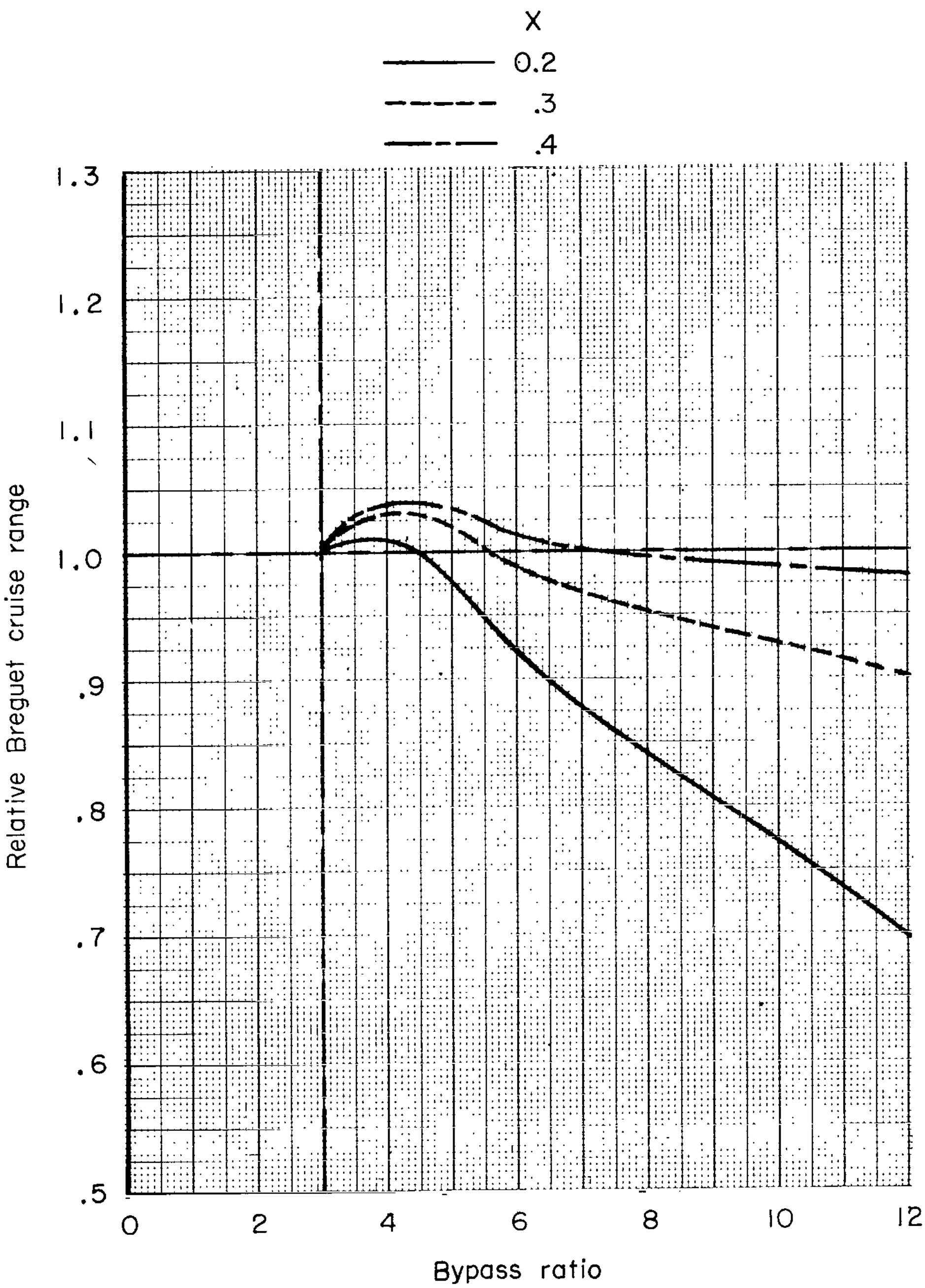
(a) W_T/S = 2394 Pa $\left(50\ \mathrm{lbf/ft^2}\right)$.

Figure 11.- Effects of engine bypass ratio on Breguet cruise range relative to range of bypass-ratio-3 engine for several take-off wing loadings and fuel fractions. $M_\infty = 0.8$; h =11 000 m (36 089 ft).



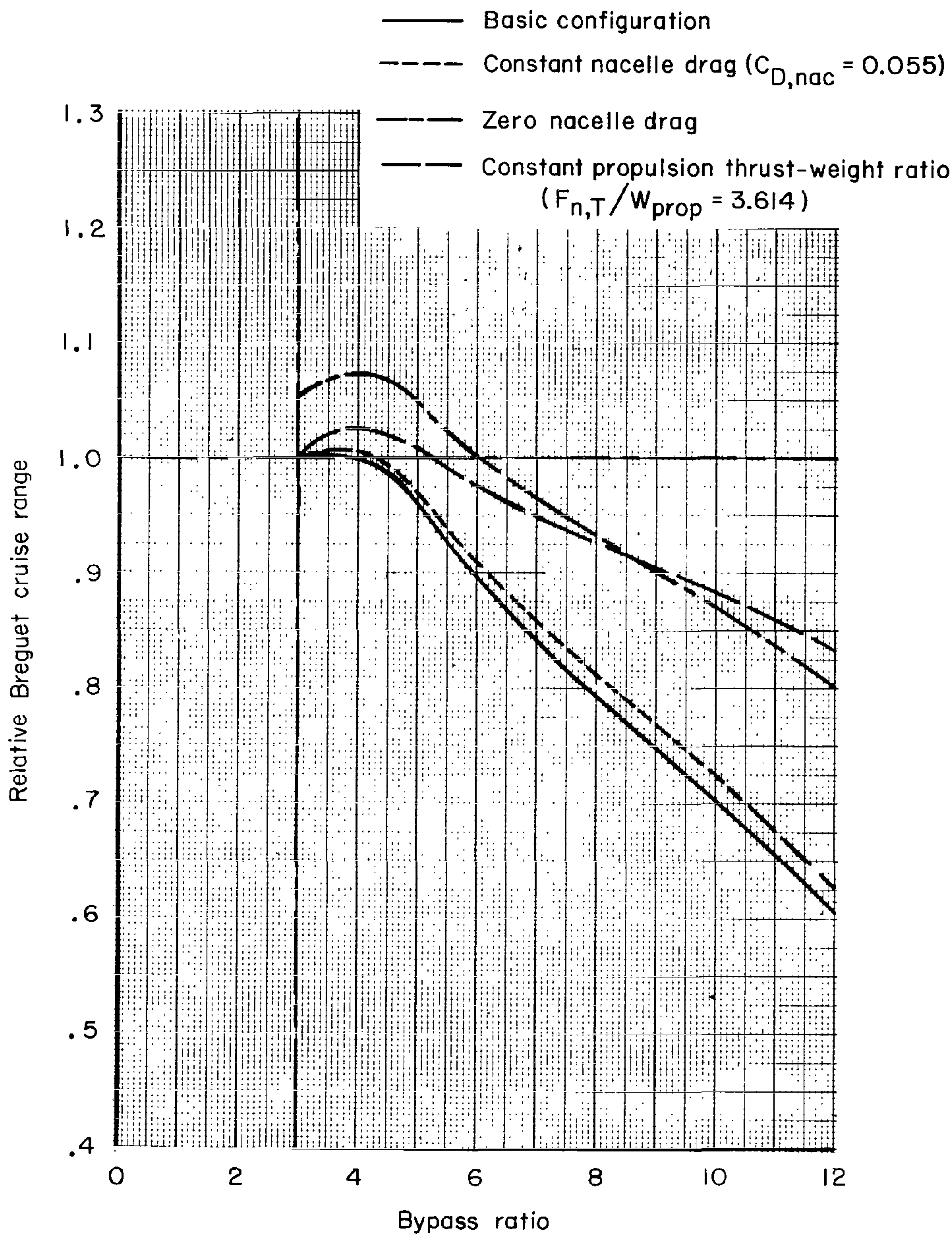
(b) W_T/S = 3591 Pa $\left(75\ \mathrm{lbf/ft^2}\right)$.

Figure 11.- Continued.



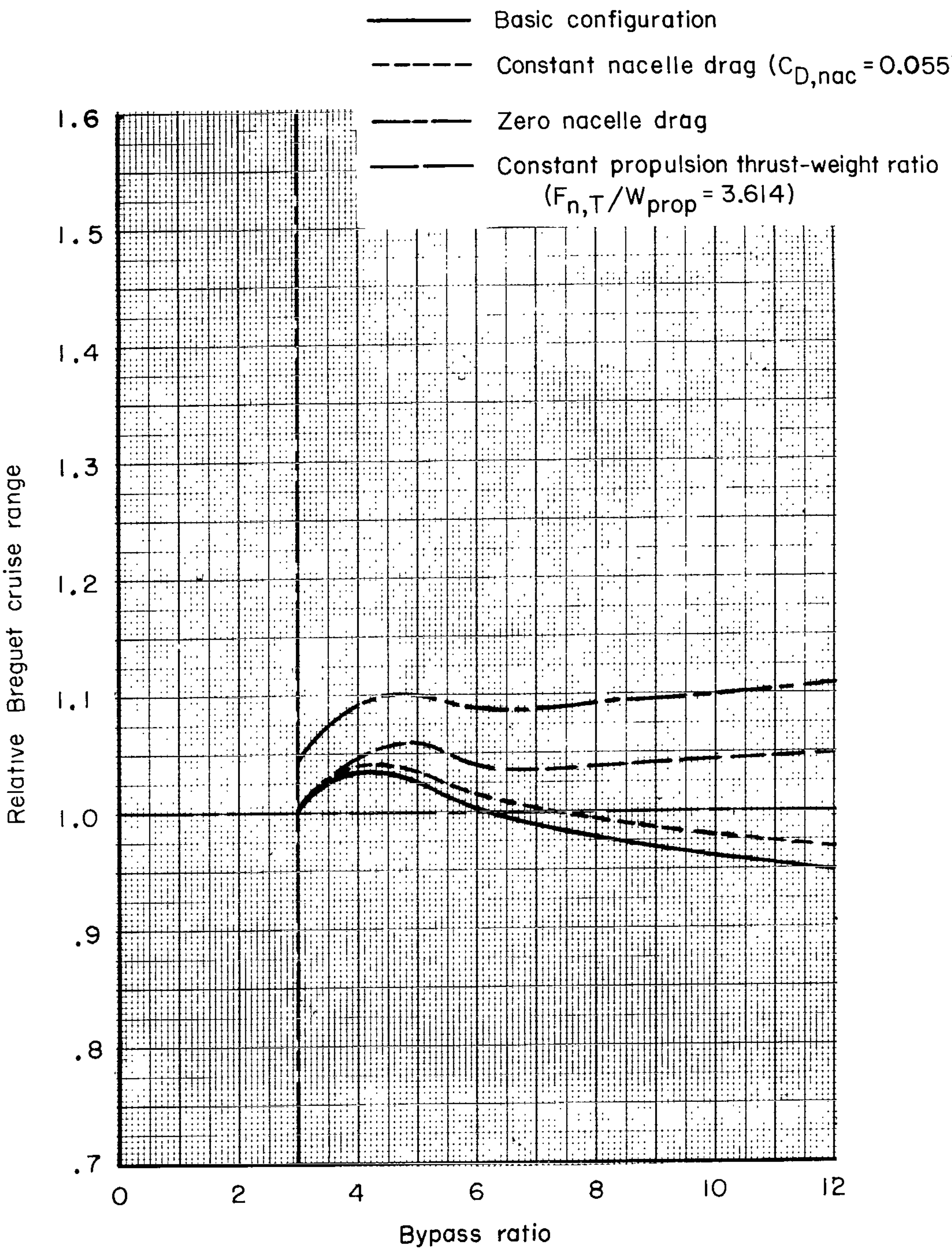
(c) W_T/S = 4788 Pa $\left(100\ \text{lbf/ft}^2\right)$.

Figure 11.- Concluded.



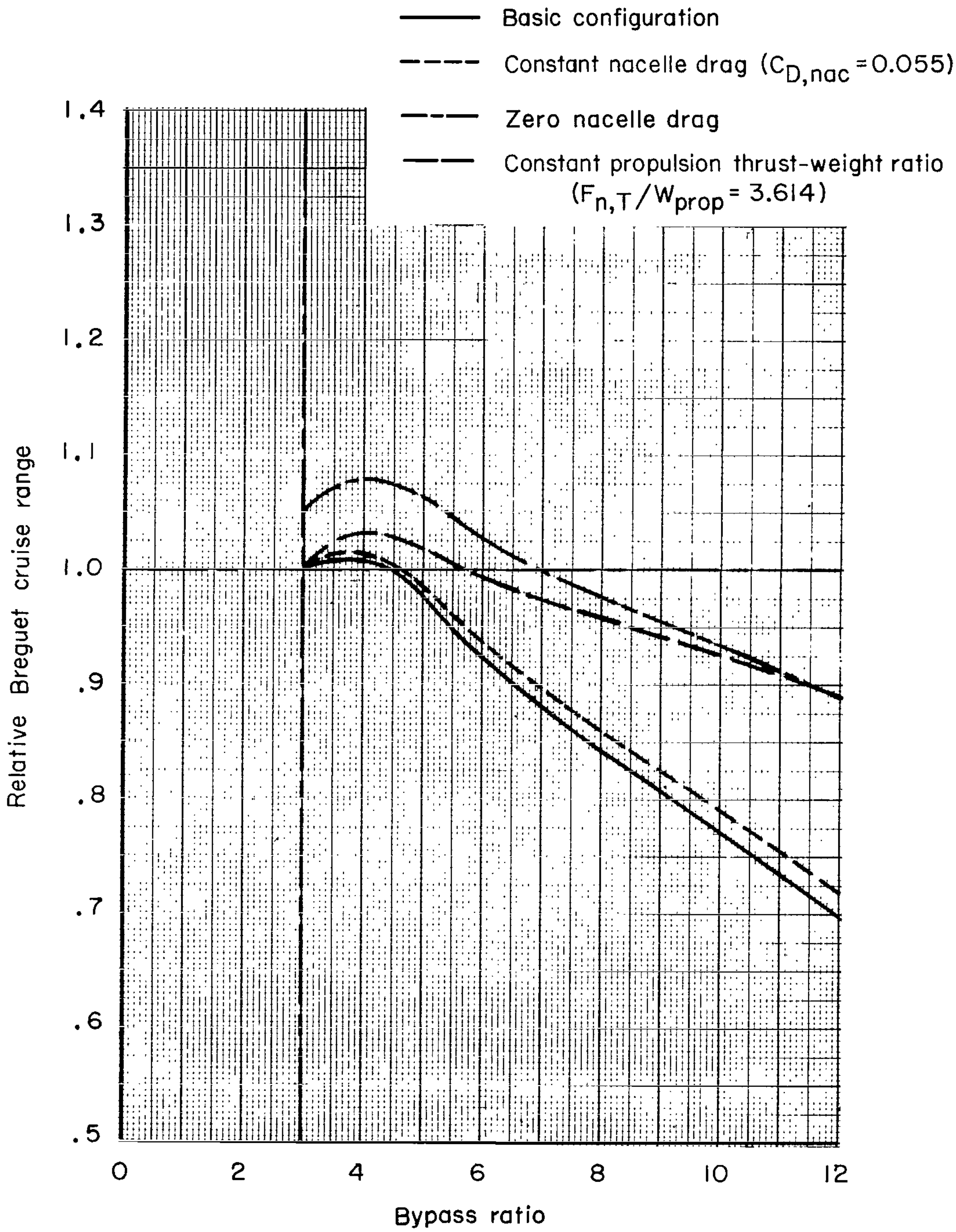
(a) W_T/S = 2394 Pa $\left(50 \text{ lbf/ft}^2\right)$; X = 0.2.

Figure 12.- Sensitivity of relative Breguet cruise range to propulsion-system drag and engine take-off thrust-weight ratio.



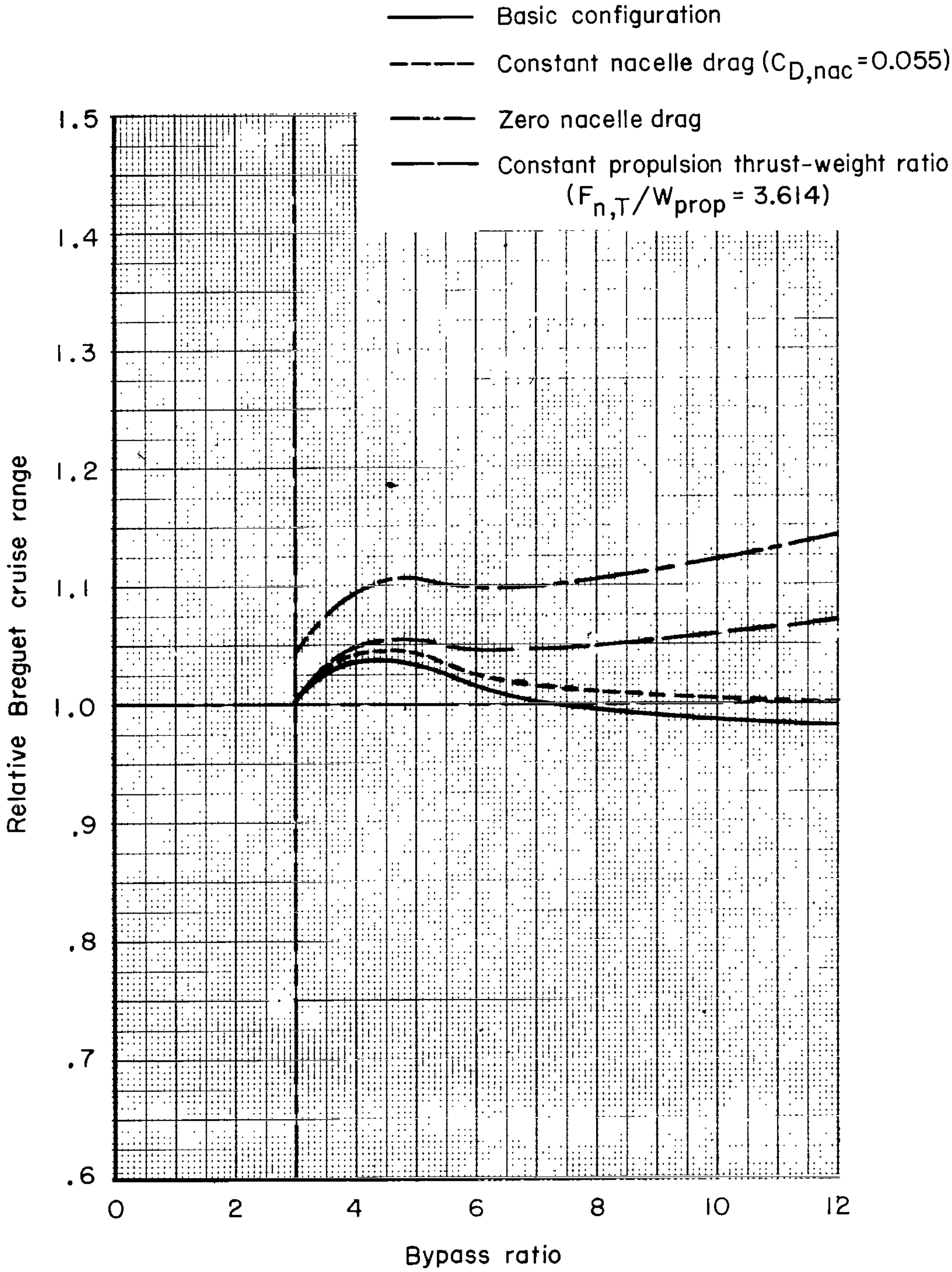
(b) W_T/S = 2394 Pa $\left(50 \text{ lbf/ft}^2\right)$; X = 0.4.

Figure 12.- Continued.



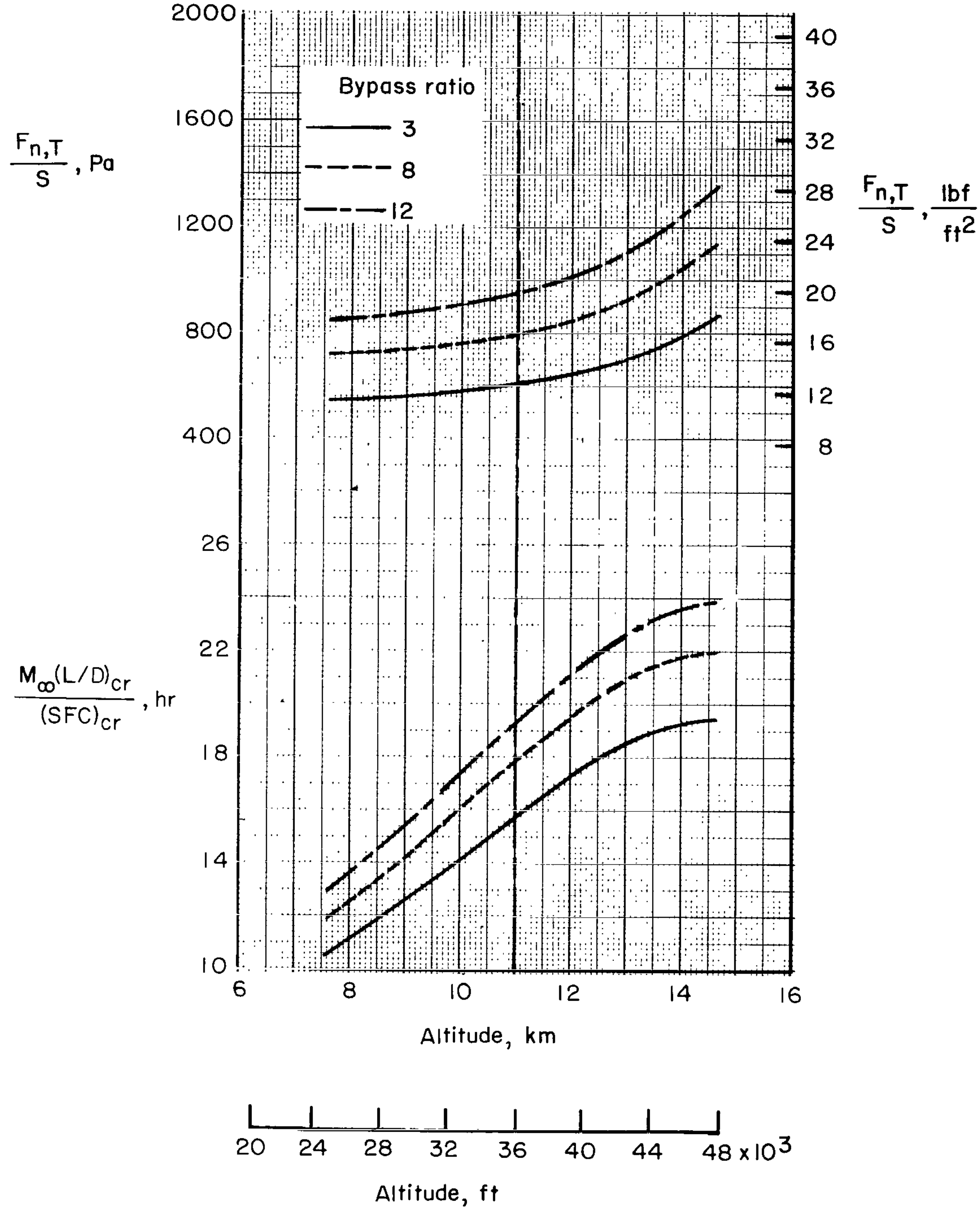
(c) W_T/S = 4788 Pa (100 lbf/ft^2); X = 0.2.

Figure 12.- Continued.



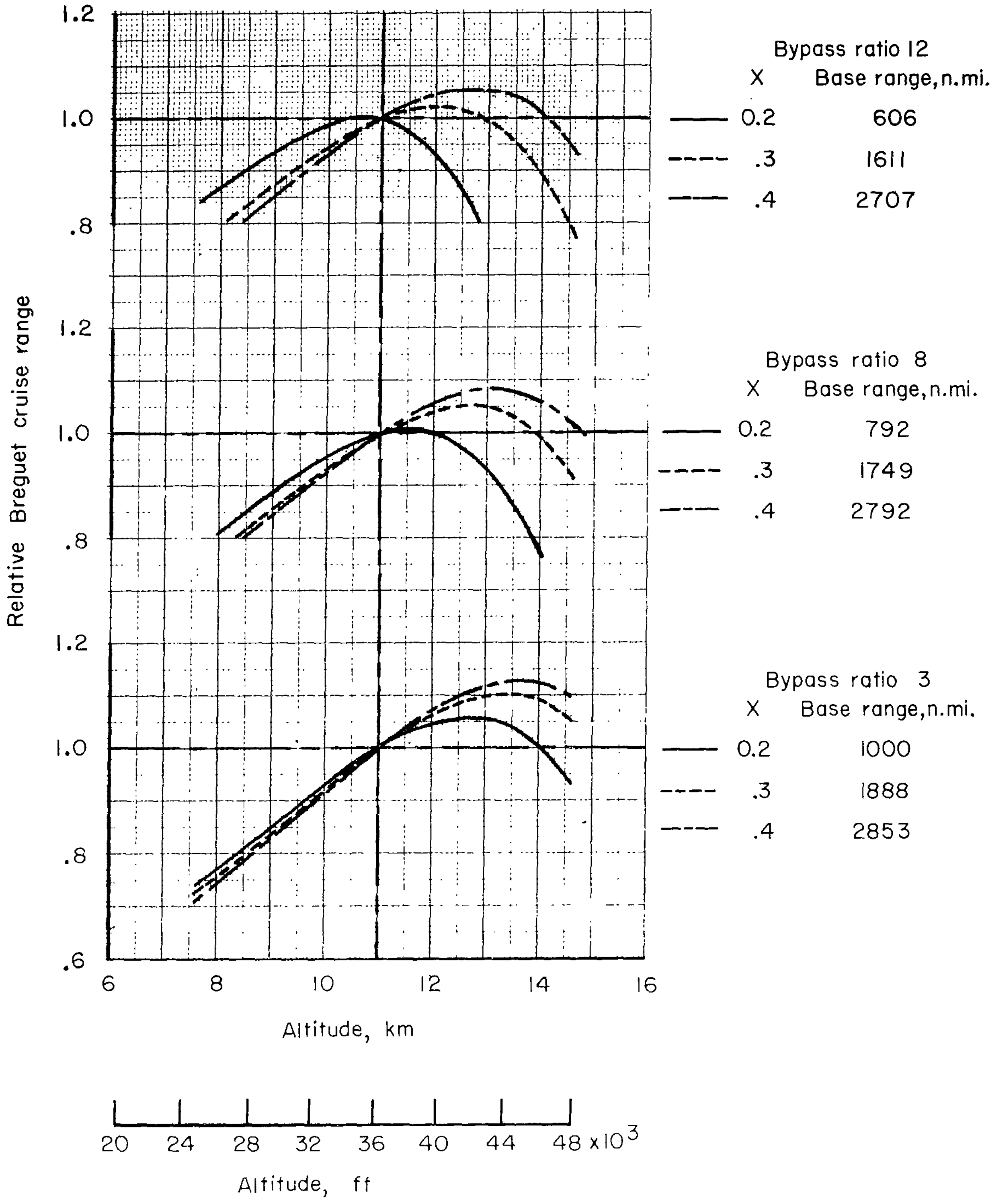
(d) W_T/S = 4788 Pa $\left(100\ \mathrm{lbf/ft^2}\right)$; X = 0.4.

Figure 12.- Concluded.



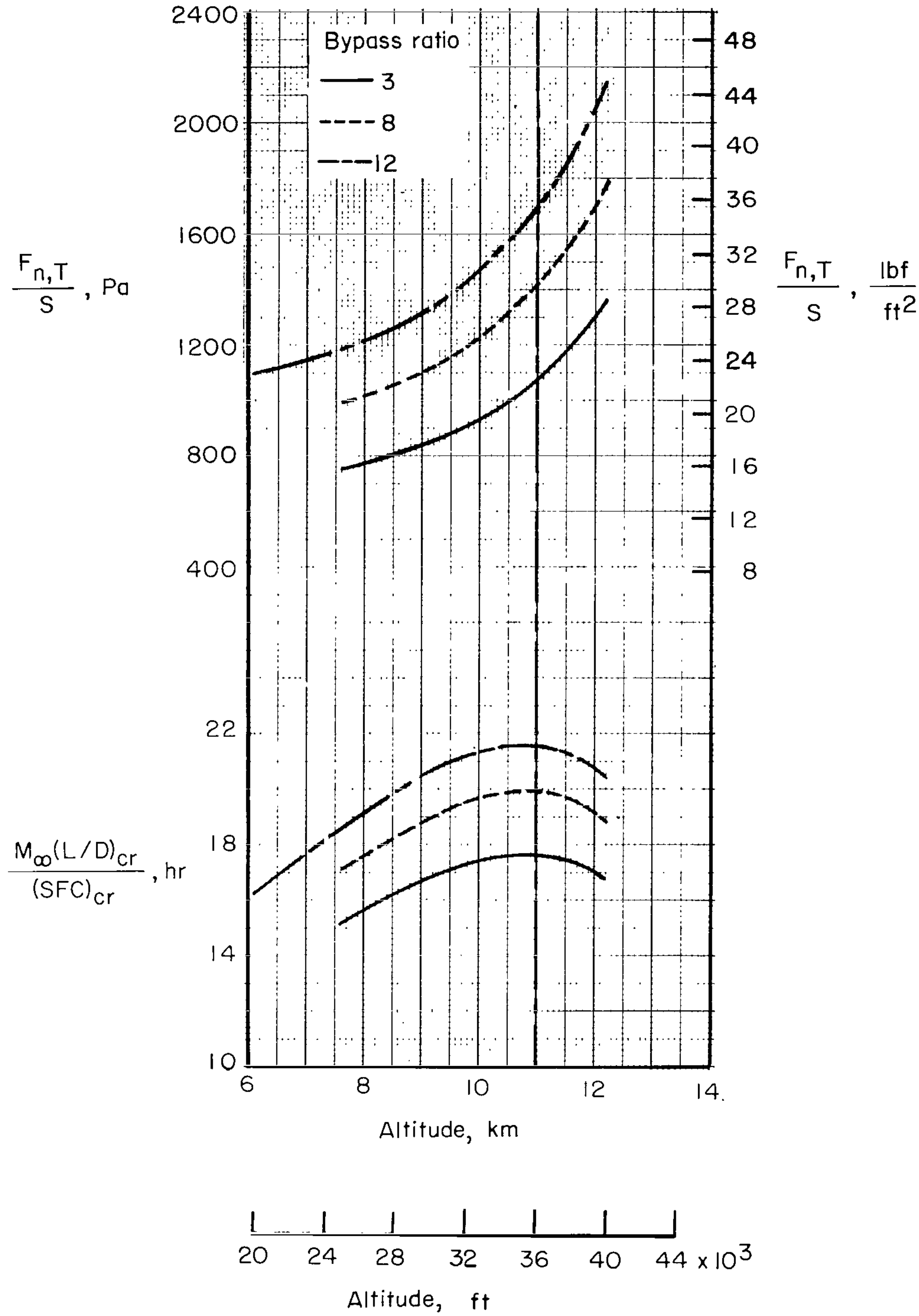
(a) Take-off thrust loading and overall cruise flight efficiency at $W_T/S = 2394$ Pa $(50\ \text{lbf/ft}^2)$.

Figure 13.- Effect of cruise altitude on engine resizing and cruise performance for bypass ratios of 3, 8, and 12.



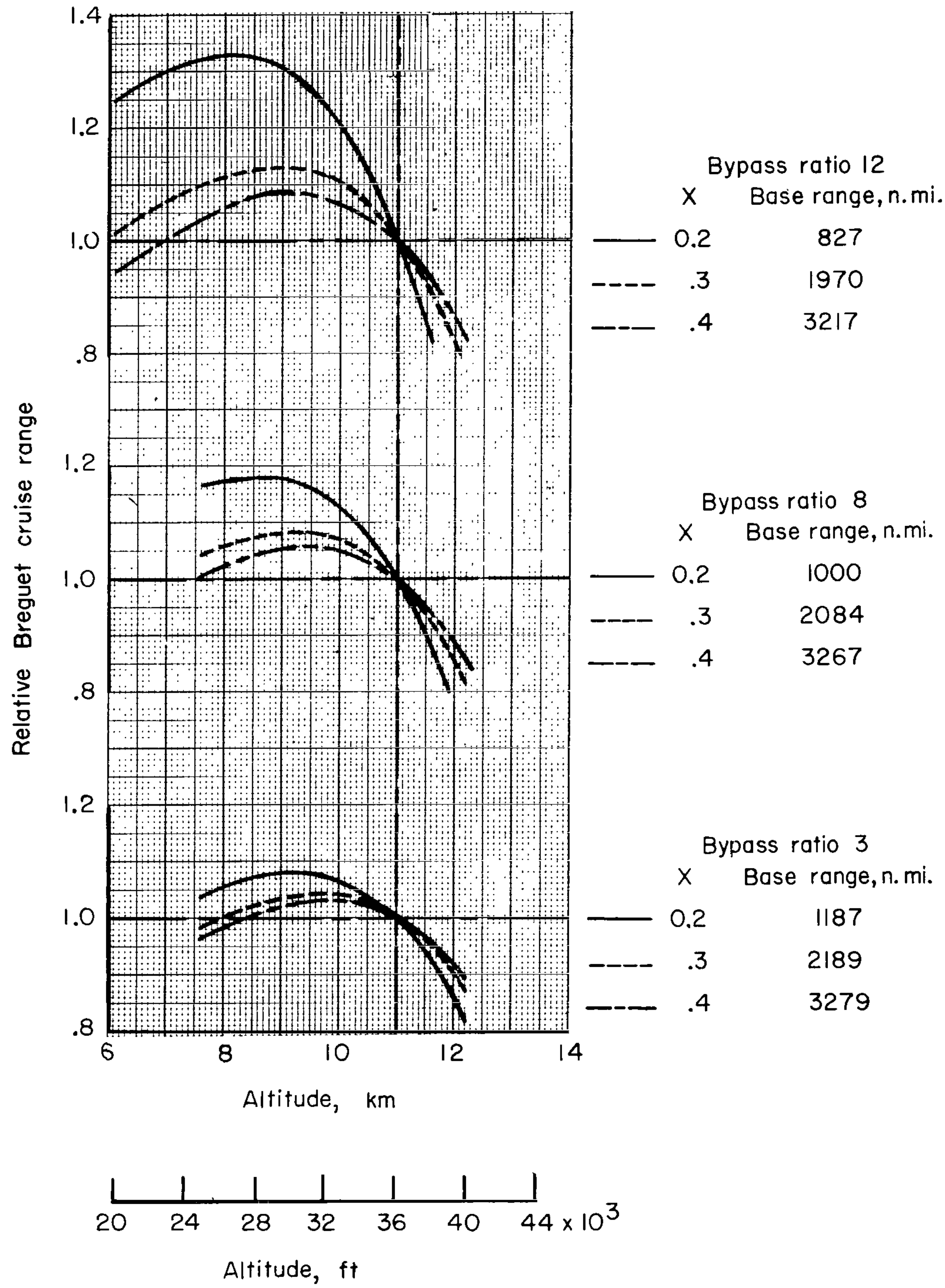
(b) Breguet cruise range relative to range at base altitude of 11 000 m (36 089 ft) at W_T/S = 2394 Pa (50 lbf/ft^2).

Figure 13.- Continued.



(c) Take-off thrust loading and overall cruise flight efficiency at $W_T/S = 4788$ Pa (100 lbf/ft^2).

Figure 13.- Continued.



(d) Breguet cruise range relative to range at base altitude of 11 000 m (36 089 ft) at W_T/S = 4788 Pa $\left(100 \text{ lbf/ft}^2\right)$.

Figure 13.- Concluded.

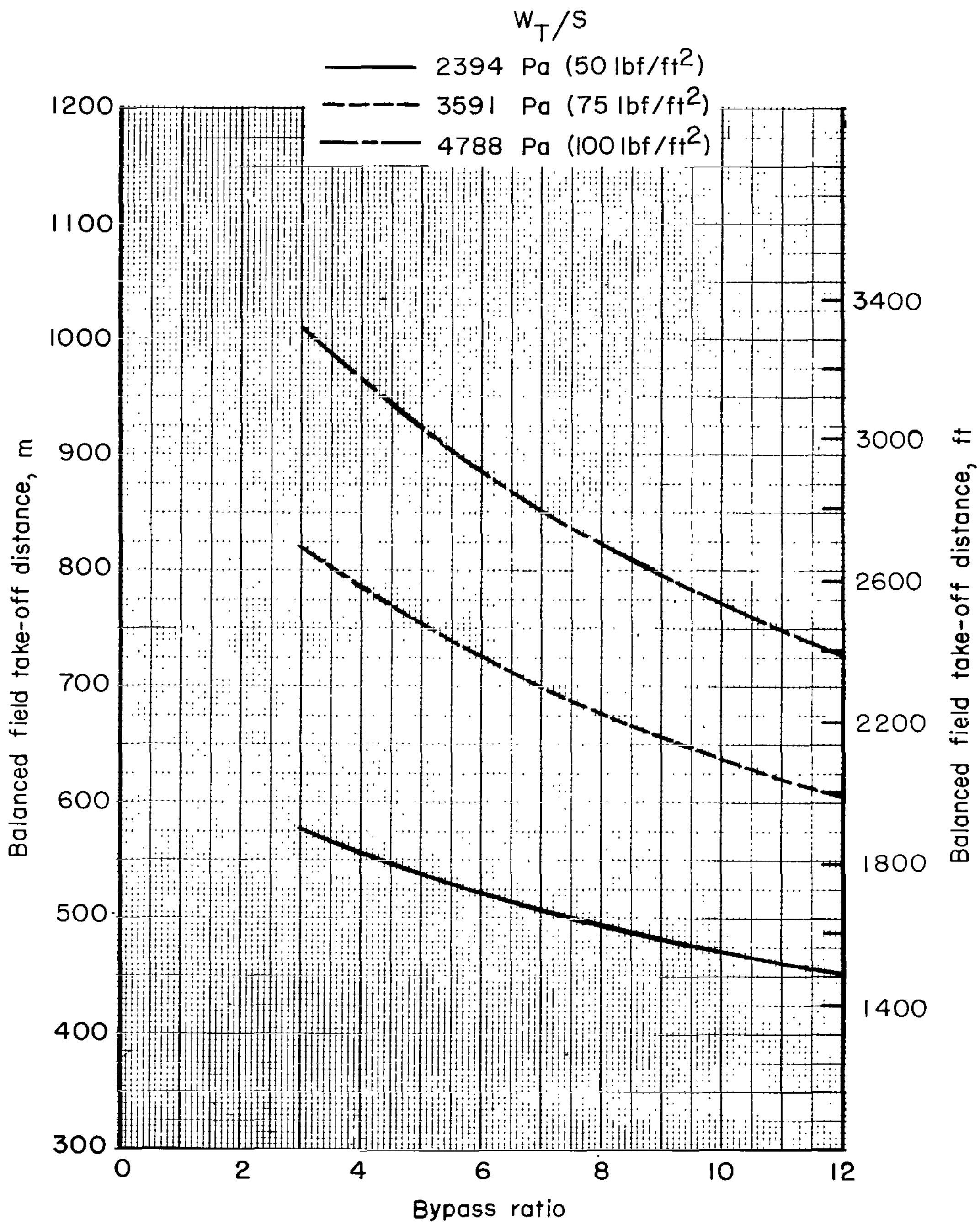


Figure 14.- Effects of engine bypass ratio on balanced-field take-off distance for several take-off wing loadings. $\left(C_{L,max}\right)_T = 4.0$.

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